Charged-current quasi-elastic ν_μ / $\bar{\nu}_\mu$ scattering with MINERνA

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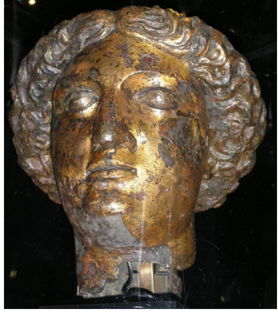
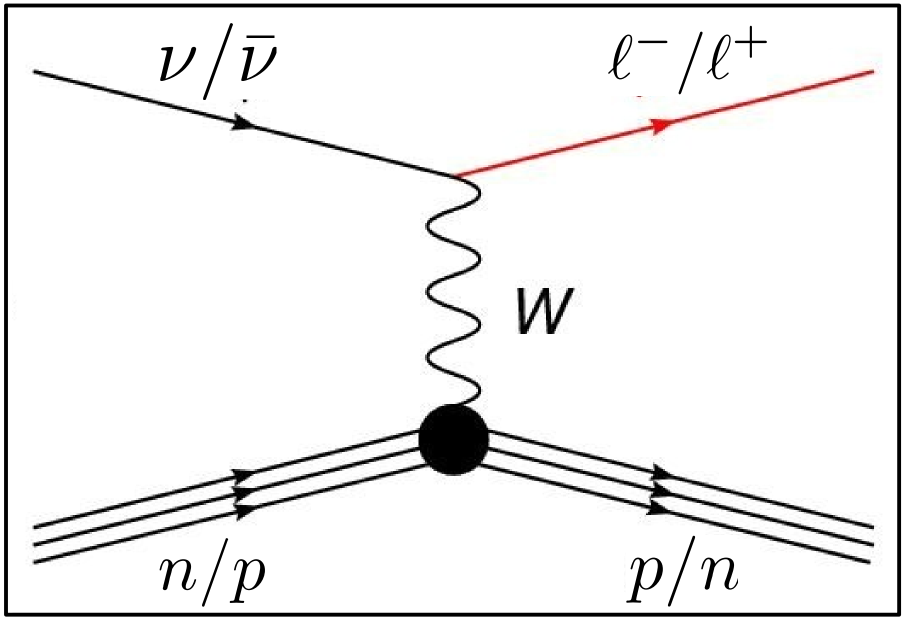
for the MINERνA collaboration

NuFact 2013 – Beijing, China
20 August, 2013

Quasi-elastic scattering





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

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

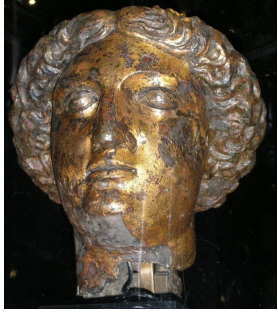
Assuming quasi-free nucleons at rest, E_ν and Q^2 can be estimated from lepton kinematics:

$$E_\nu^{QE} = \frac{2(M_n - E_B)E_l - [(M_n - E_B)^2 + m_l^2 - M_p^2]}{2[M_n - E_B - E_l + p_l cos\theta_l]}$$

$$Q^2_{QE} = -m_l^2 + 2E_\nu^{QE}(E_l - \sqrt{E_l^2 - m_l^2} cos\theta_l)$$

M_n, M_p = neutron, proton mass
E_B = nuclear binding energy
m_l, E_l, θ_l = mass, energy, angle of final state lepton

Present-day MC generators

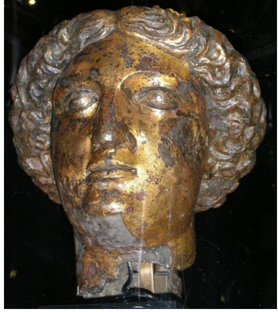


- Relativistic Fermi Gas (RFG): free nucleons in mean field
- Free nucleon cross-section formula: Llewellyn Smith

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

$$\boxed{\begin{aligned} A(Q^2) = \frac{m_l^2 + Q^2}{M^2}&[(1+\tau)|F_A|^2 - (1-\tau)|F_1^V|^2 + \tau(1-\tau)|F_2^V|^2 + 4\tau F_1^V F_2^V] \\ &- \frac{m_l^2 + Q^2}{M^2}\frac{m_l^2}{M^2}[|F_1^V + F_2^V|^2 + |F_A + 2F_P|^2 - 4(1+\tau)F_P^2] \\ B(Q^2) = 4\tau F_A(F1^V + F_2^V) \qquad & C(Q^2) = \frac{1}{4}(|F_A|^2 + |F_1^V|^2 + \tau|F_2^V|^2) \end{aligned}}$$

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

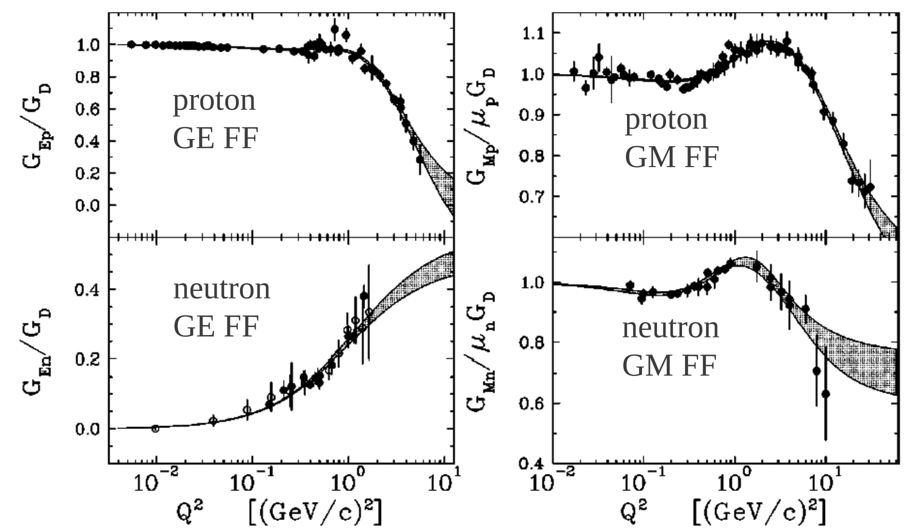


Present-day MC generators

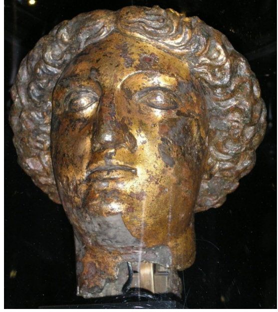
- Relativistic Fermi Gas (RFG): free nucleons in mean field
- Free nucleon cross-section formula: Llewellyn Smith
- F_V from electron scattering
- Assume dipole form of F_A

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

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

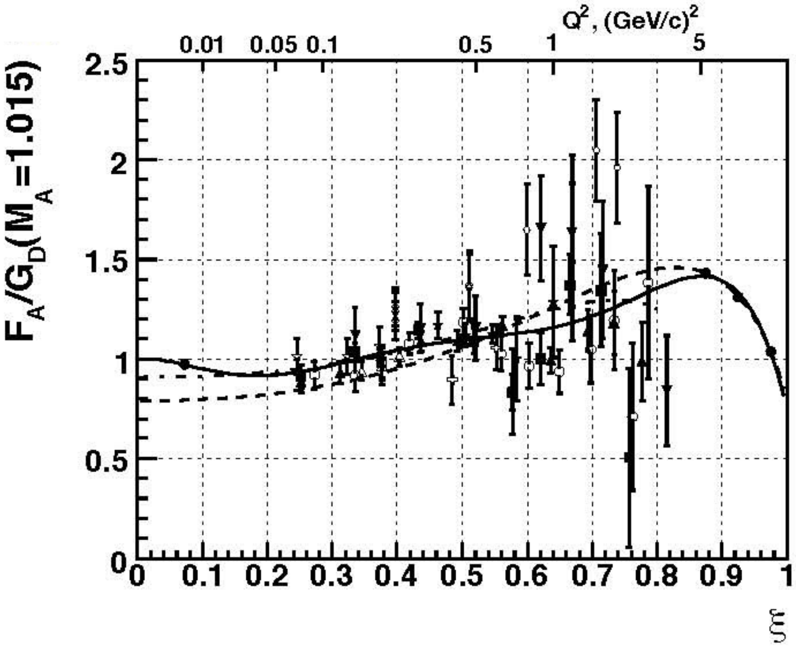


Present-day MC generators



- Relativistic Fermi Gas (RFG): free nucleons in mean field
- Free nucleon cross-section formula: Llewellyn Smith
- F^V from electron scattering
- Assume dipole form of F_A
- Measure M_A in deuterium bubble chambers

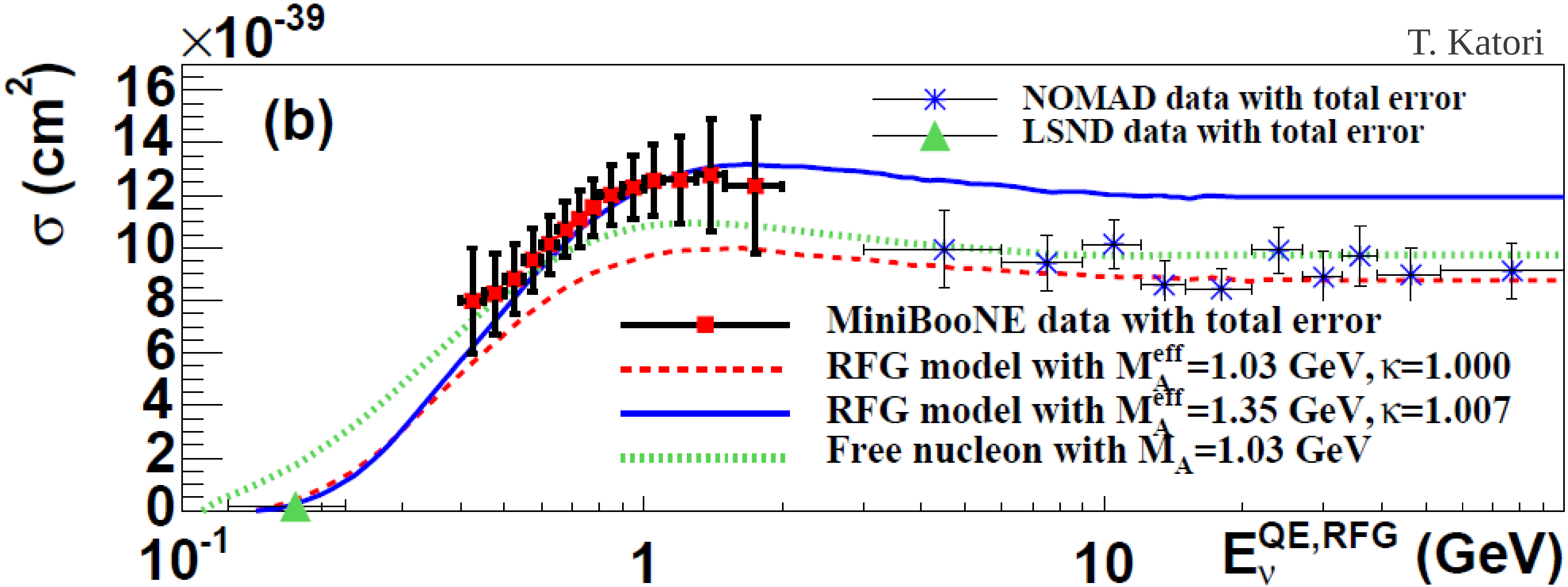
$$F_A(Q^2) = \frac{F_A(0)}{(1 + \frac{Q^2}{M_A^2})^2}$$



Bodek, *et. al.*, J.Phys.Conf.Ser. **110** 082004 (2008)

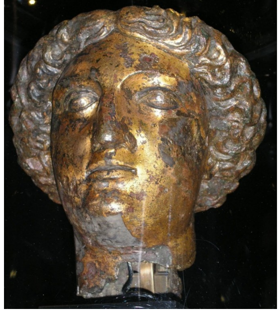
Good enough?

T. Katori

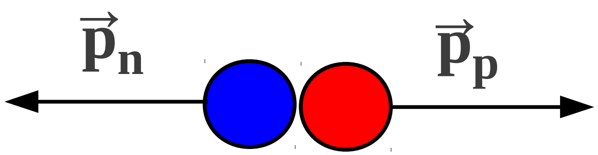


- NOMAD data at 3 – 100 GeV consistent with M_A from deuterium bubble chambers
- MiniBooNE data at 0.4 – 2 GeV favors higher M_A

Multi-nucleon effects

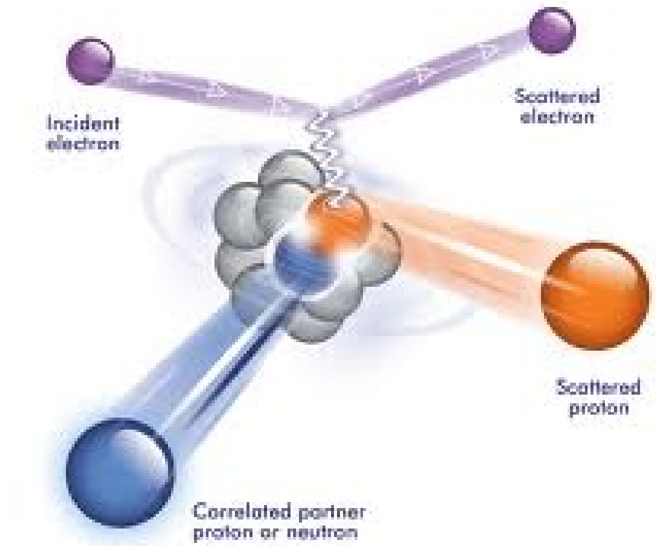


- Electron scattering data indicates short-range correlations (SRC) affect ~20% of nucleons
- Meson exchange currents (MEC) could result in multi-nucleon emission
- Low-momentum correlated pair can have high-momentum constituent nucleons

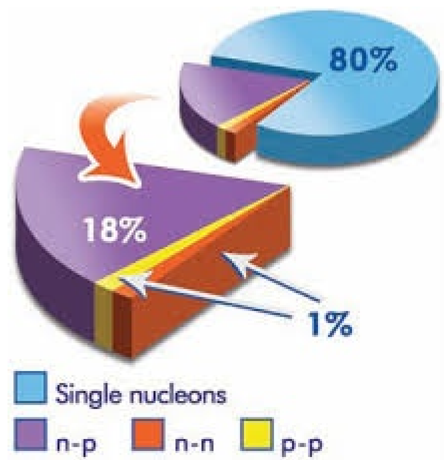


- Get wrong neutrino energy:

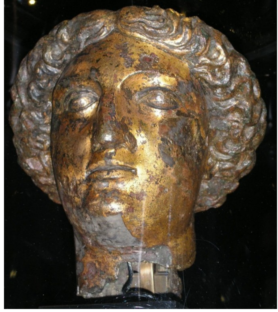
$$E_\nu^{QE} \neq \frac{2(M_n - E_B)E_l - [(M_n - E_B)^2 + m_l^2 - M_p^2]}{2[M_n - E_B - E_l + p_l cos\theta_l]}$$



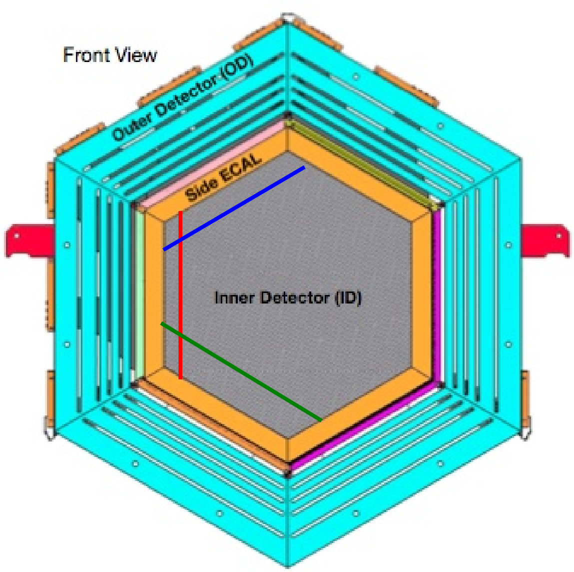
R. Subedi et al., Science 320, 1476 (2008)

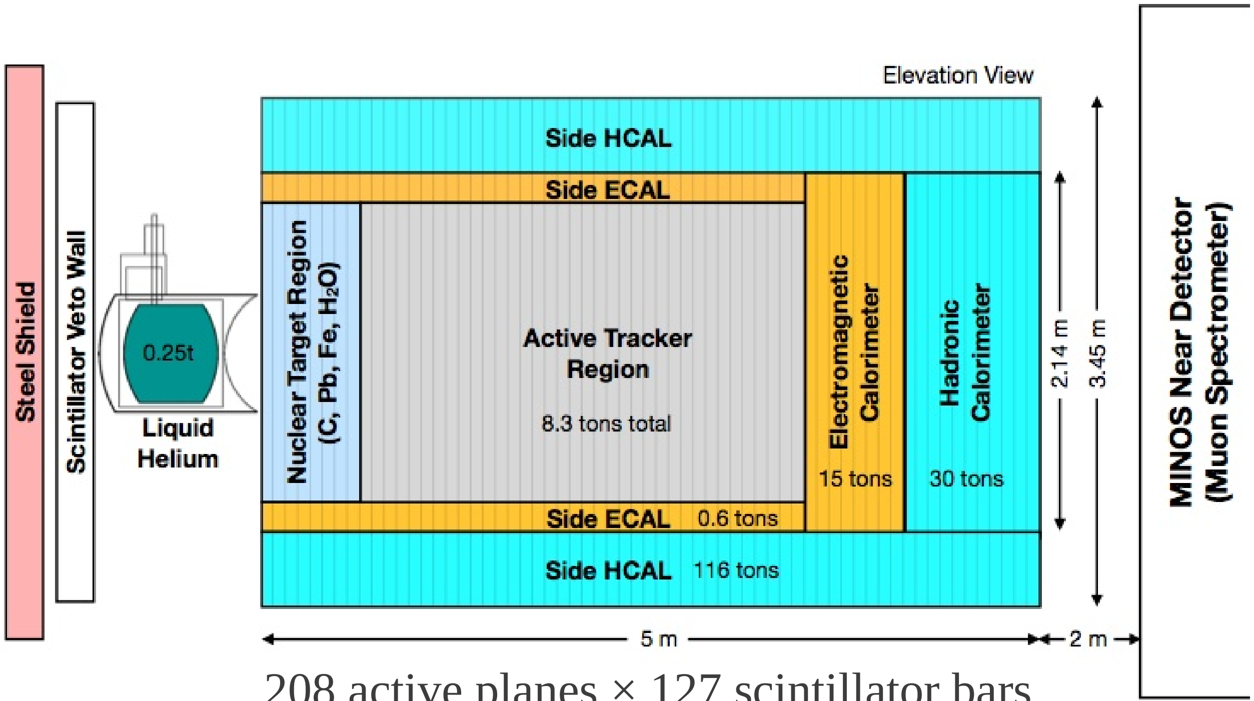


Enter Minerva



arXiv:1305.5199 [physics.ins-det]

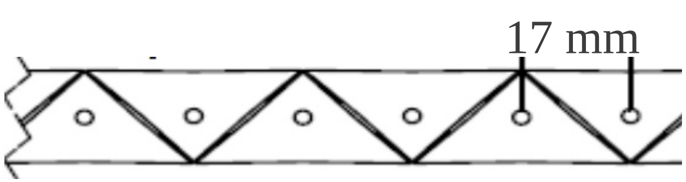




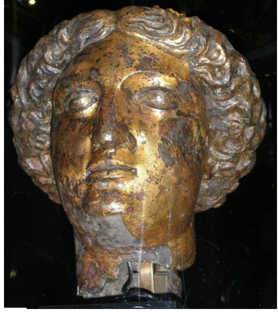
208 active planes × 127 scintillator bars

Plane views:

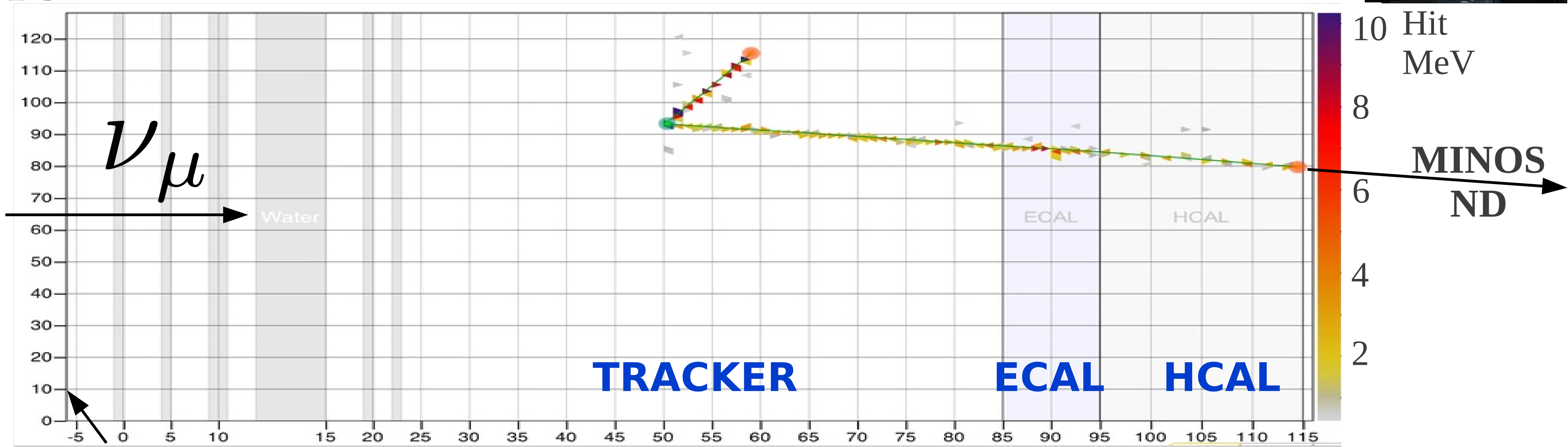
1. Vertical bars
2. +60°
3. –60°



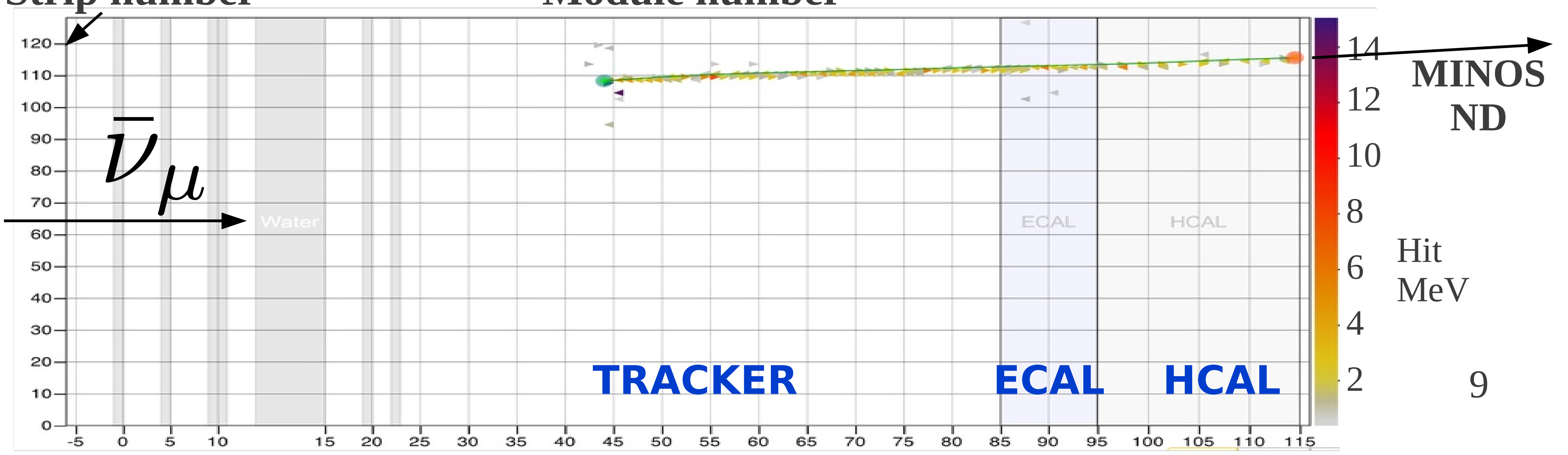
Charge-sharing triangular strips for ~3mm position resolution



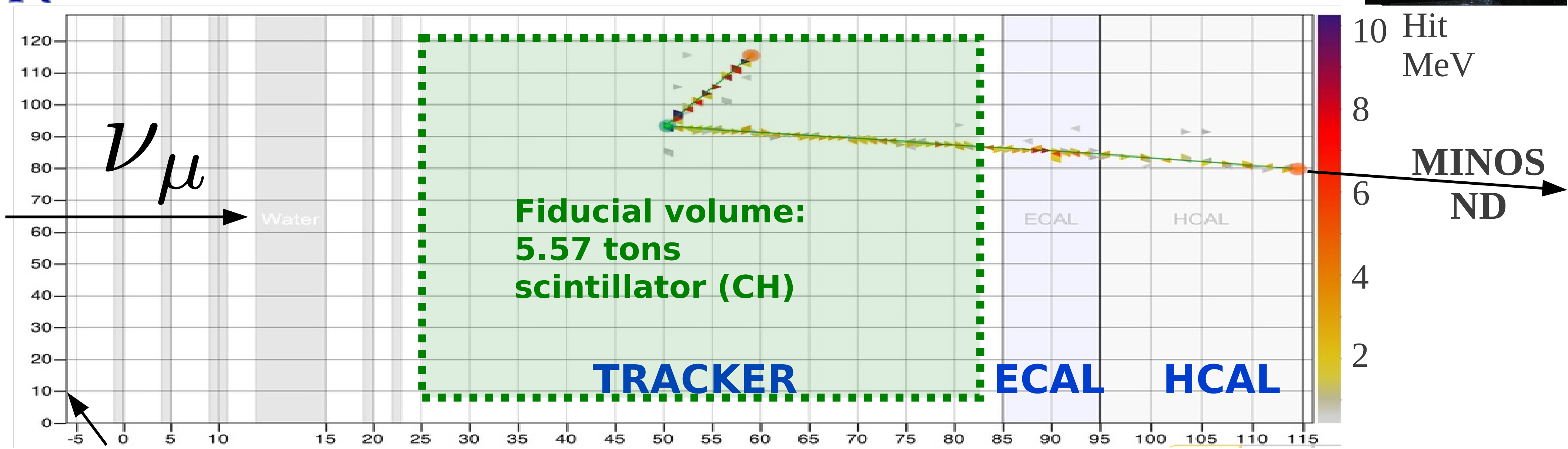
CCQE events



Strip number
Module number

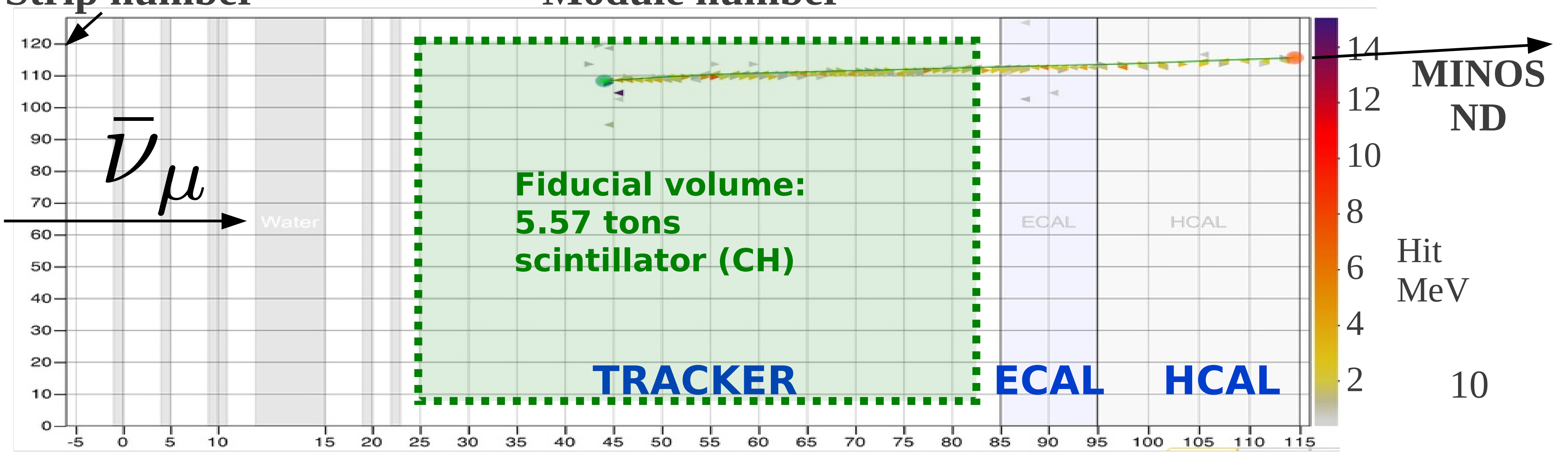


CCQE events

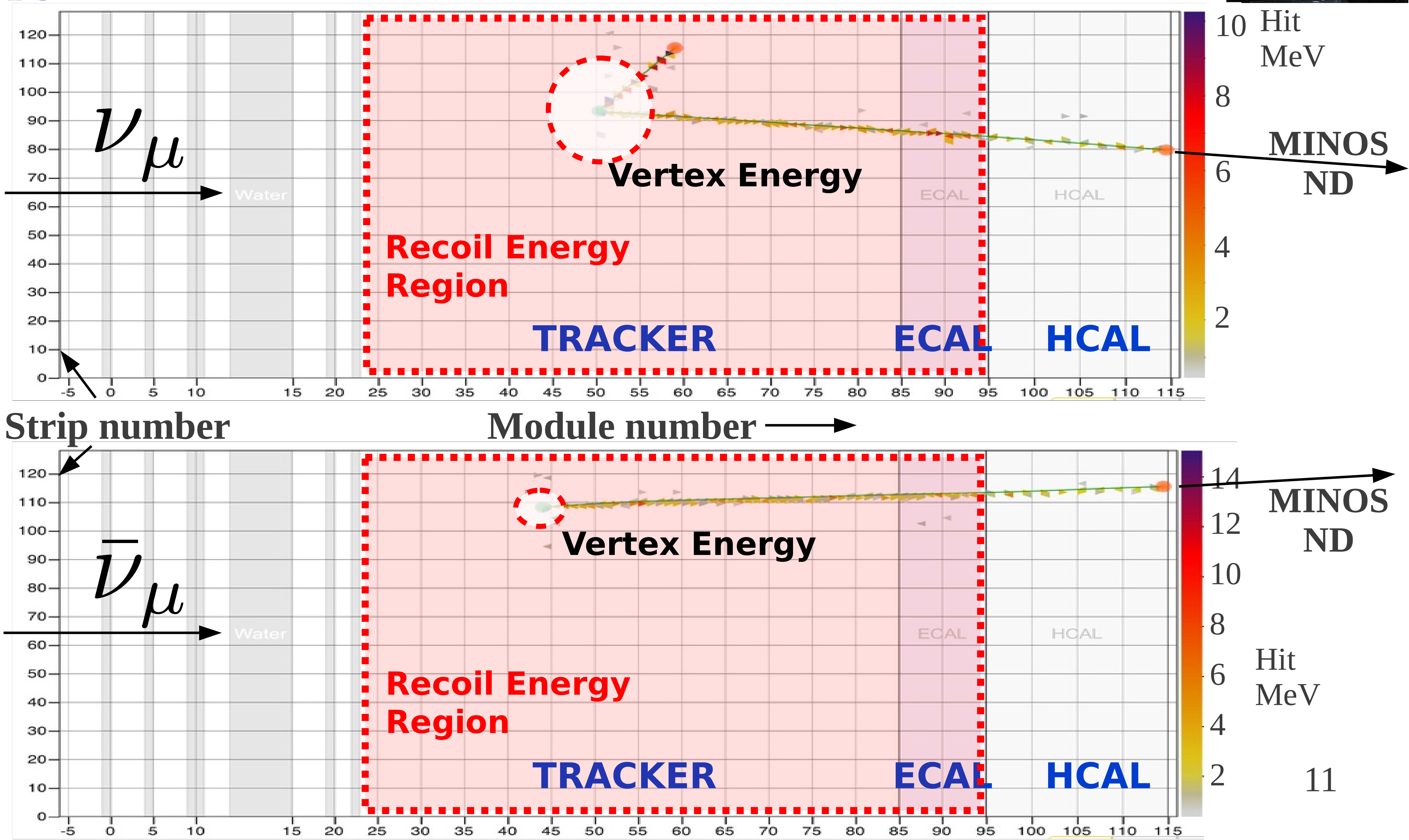


Strip number

Module number

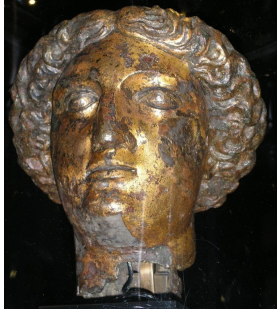


CCQE events



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

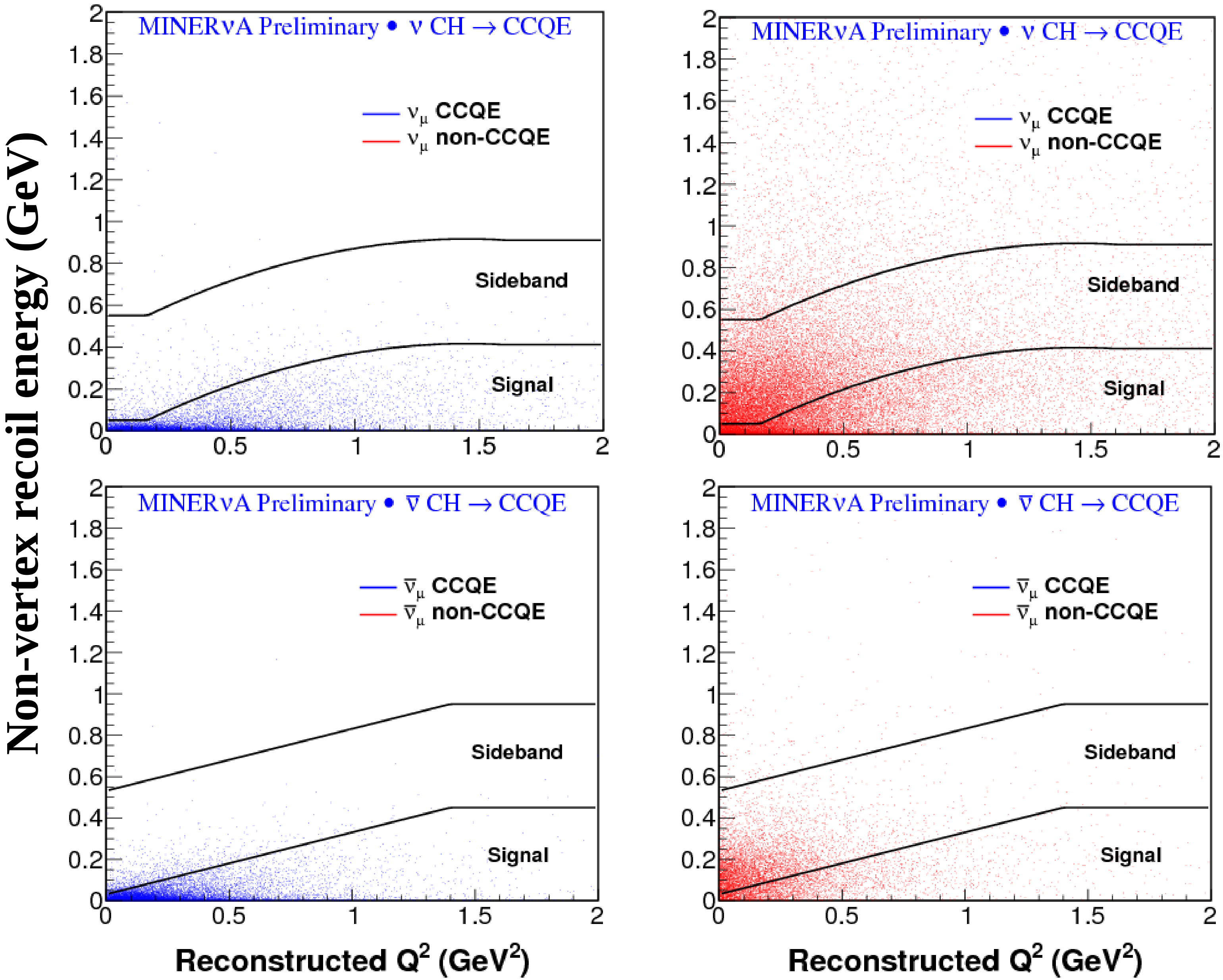
CCQE event selection



ν_μ

QE

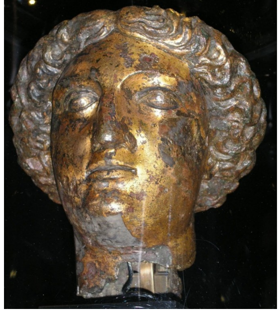
$\bar{\nu}_\mu$



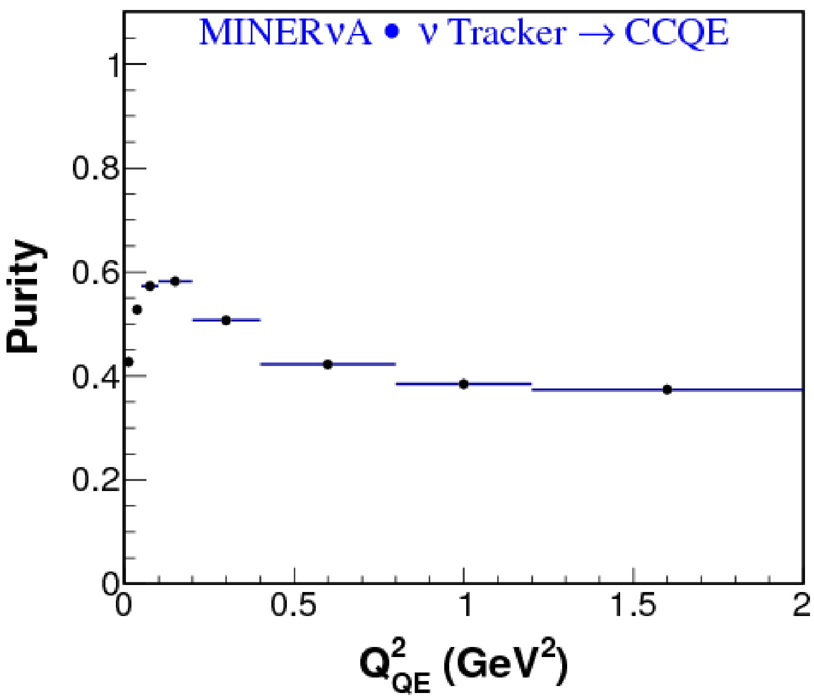
ν_μ

$\cancel{\text{QE}}$

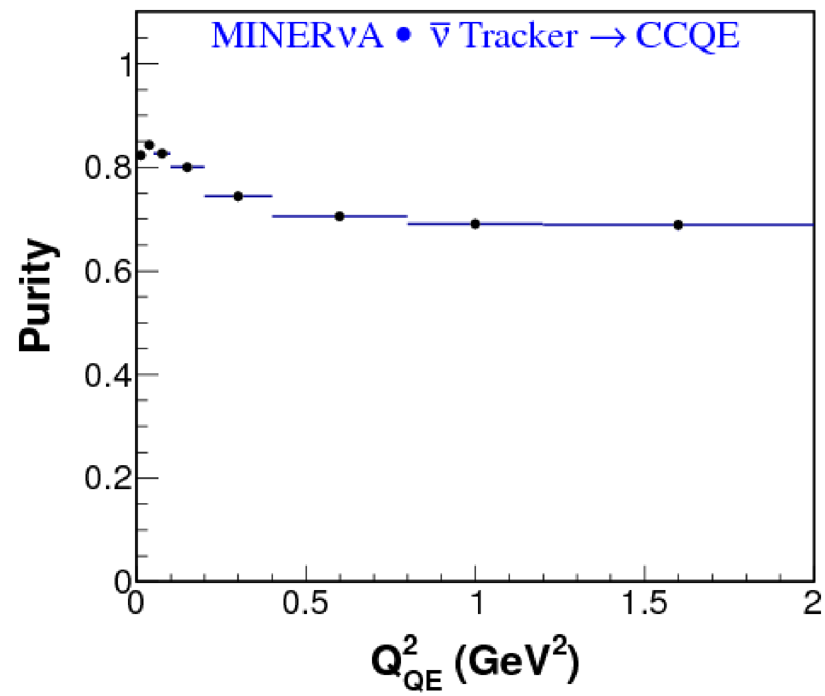
$\bar{\nu}_\mu$



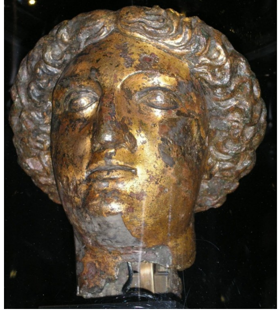
Selected sample



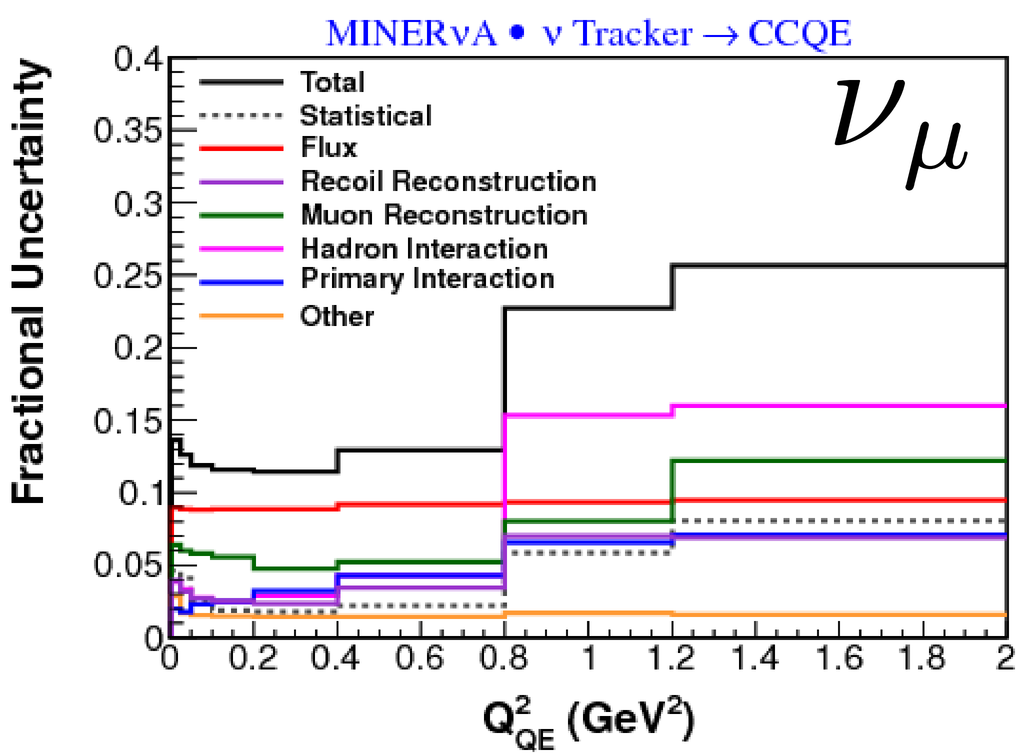
29,620 events
47% efficiency
49% purity

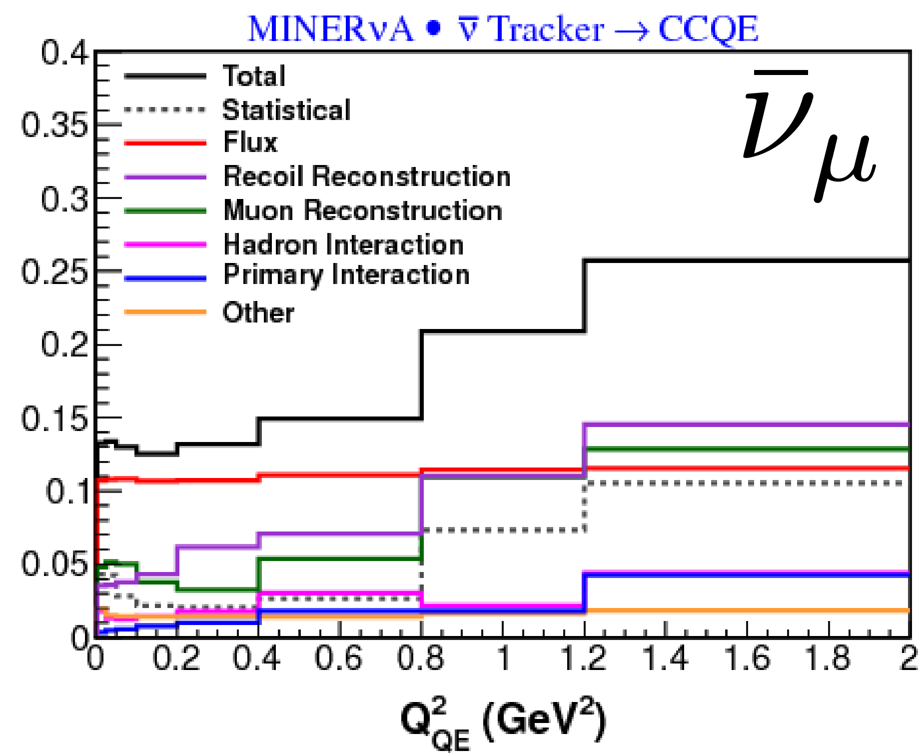


16,467 events
54% efficiency
77% purity



Error summary





Neutrino flux prediction

Energy scale reconstruction

Muon

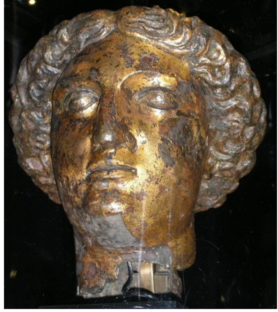
Hadron

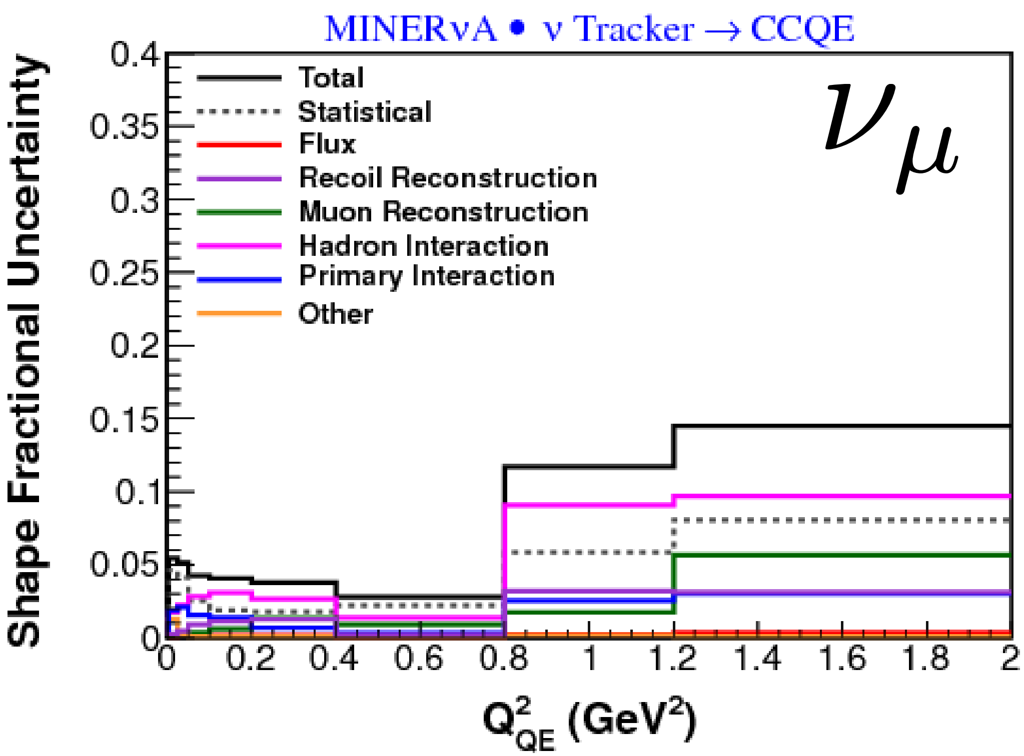
Interaction modeling

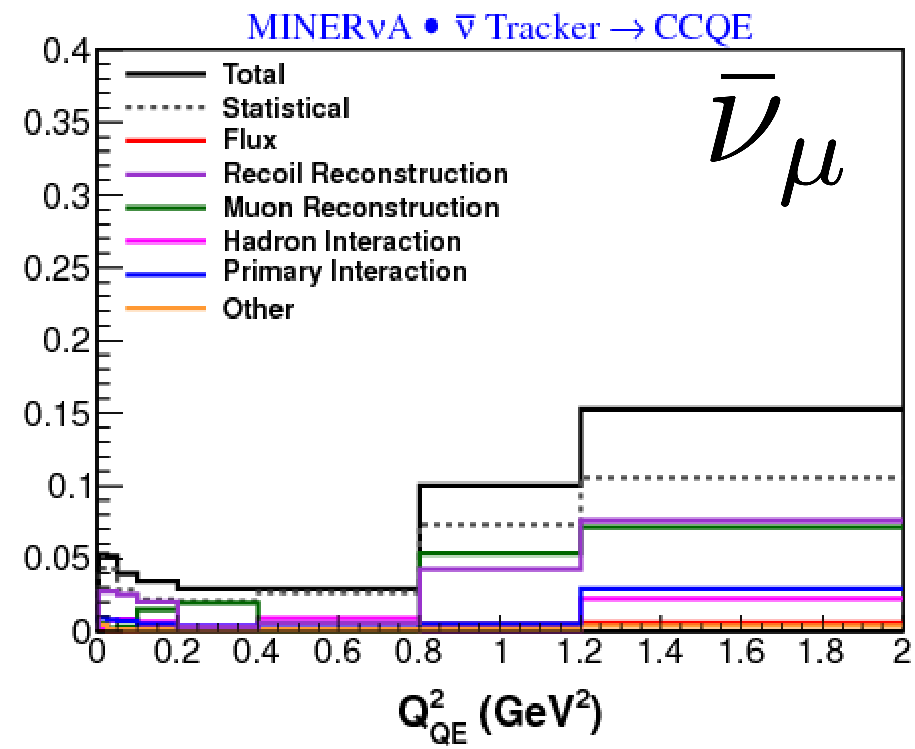
Primary

FSI

Shape-only error summary





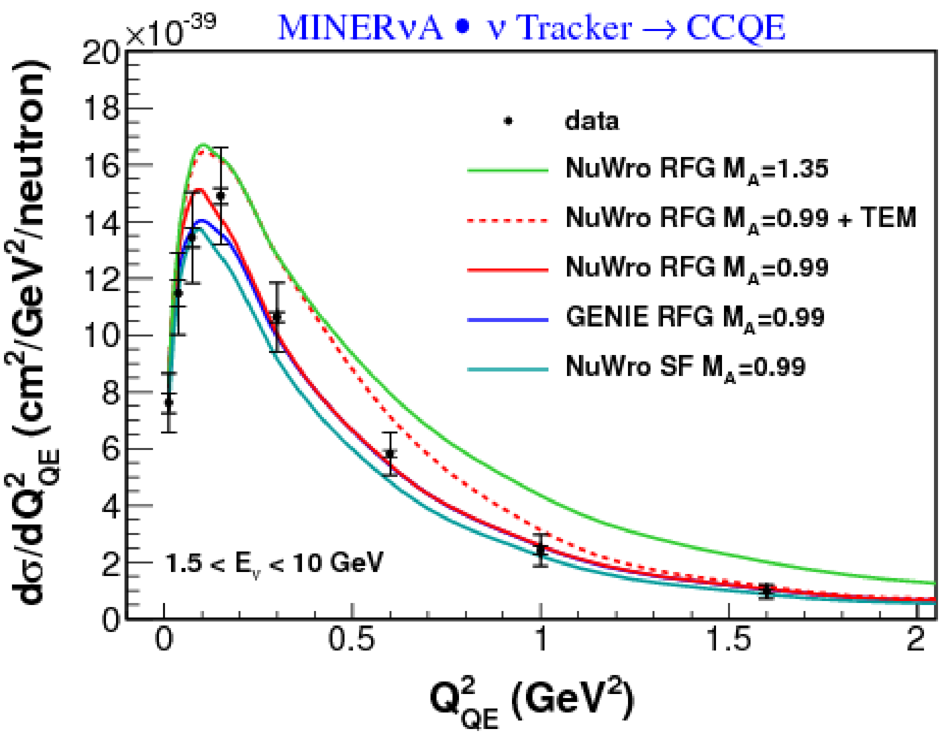


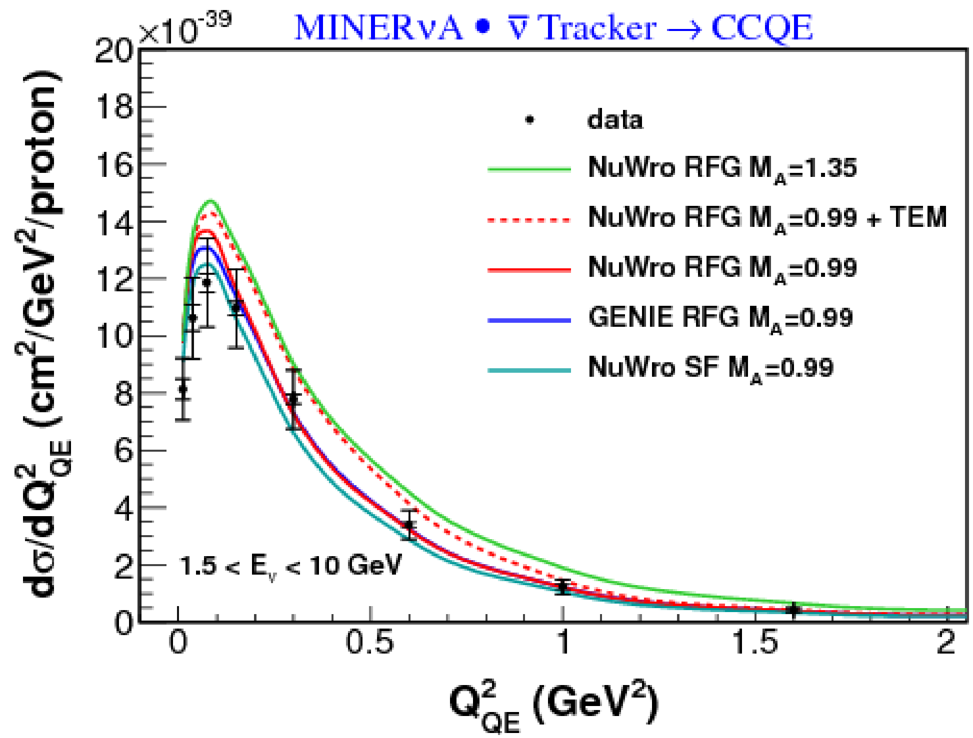
Neutrino flux prediction

Energy scale reconstruction → Muon, Hadron

Interaction modeling → Primary, FSI

Absolute cross section





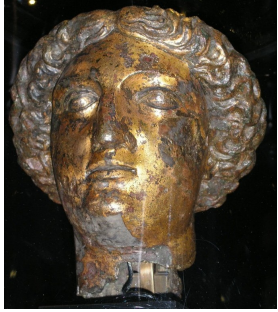
$M_A = 1.35$ best fit to MiniBooNE data

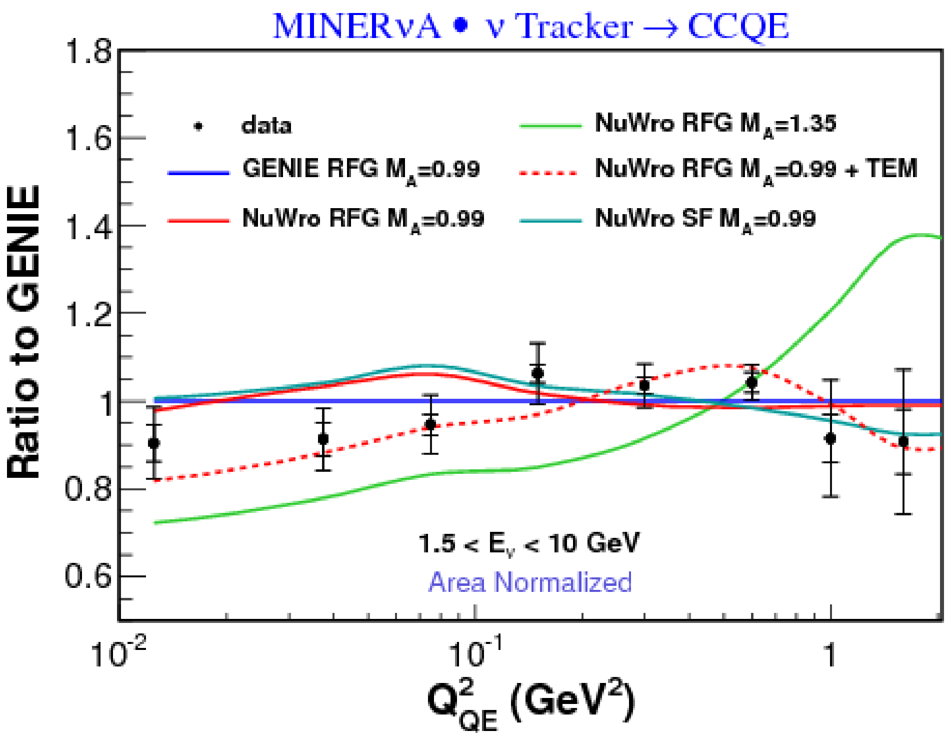
TEM empirical model based on electron scattering data

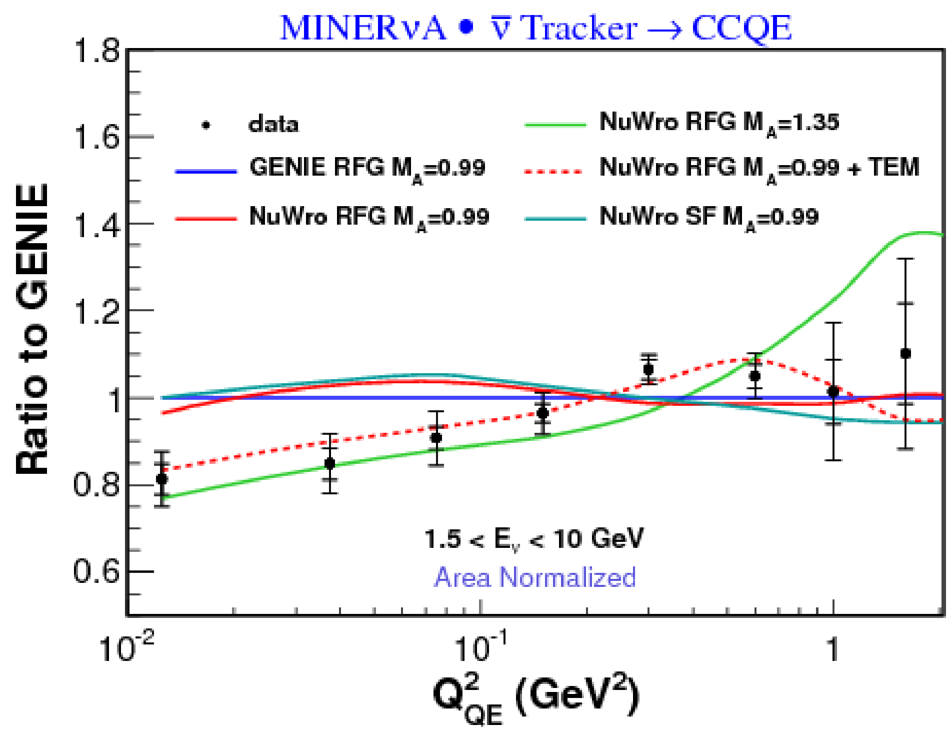
GENIE independent nucleons in mean field

SF more realistic nucleon momentum-energy relation

Shape-only ratio







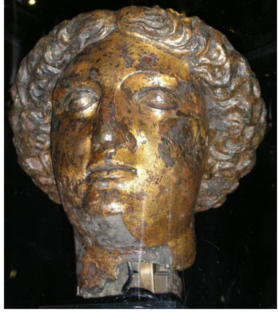
M_A = 1.35 Phys.Rev.Lett. 100, 032301 (2008)

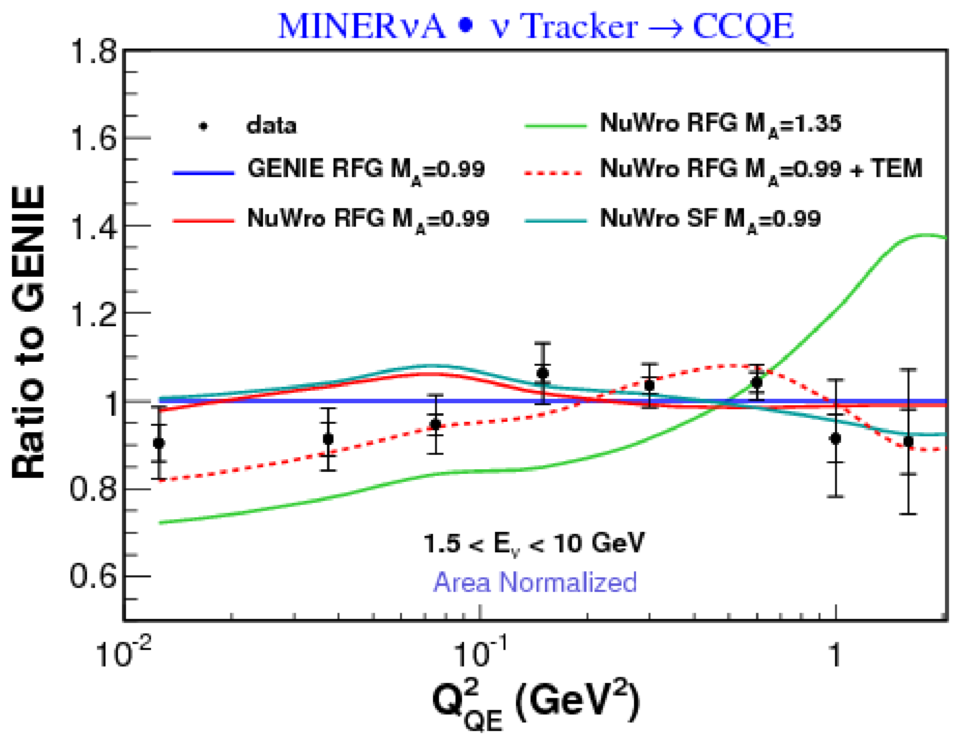
TEM Eur. Phys. J. C 71, 1726 (2011)

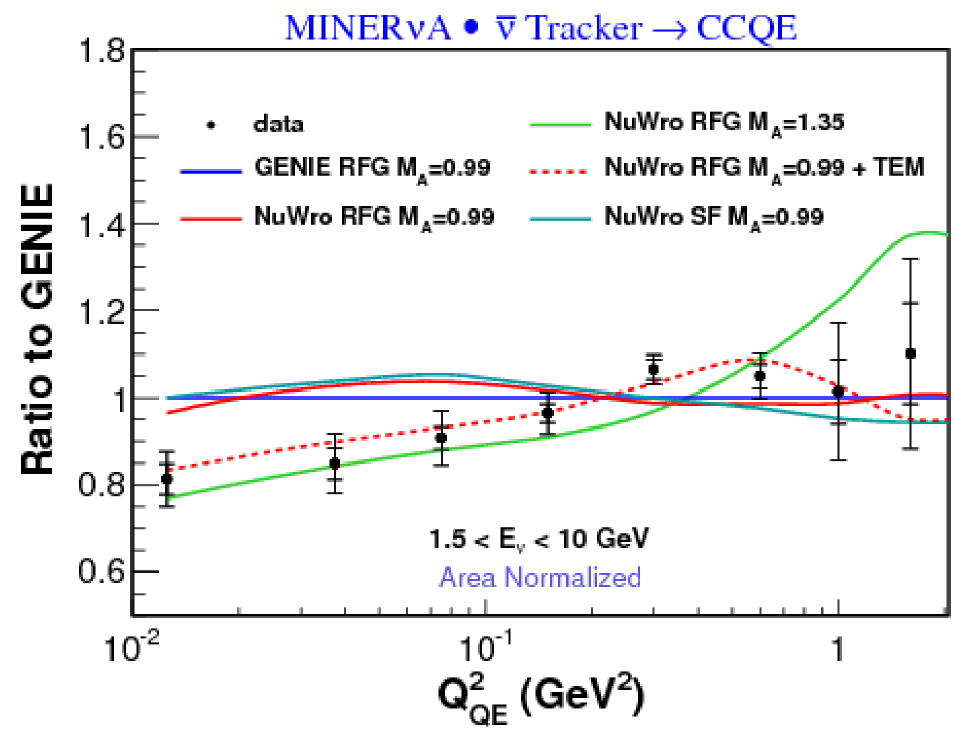
GENIE Nucl.Instrum.Meth. A 614:87-104 (2010)

SF Nucl.Phys. A579, 493 (1994)

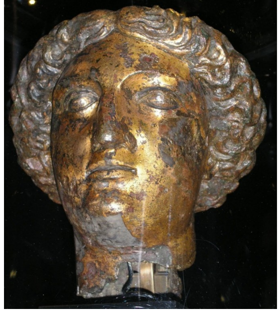
Model χ^2



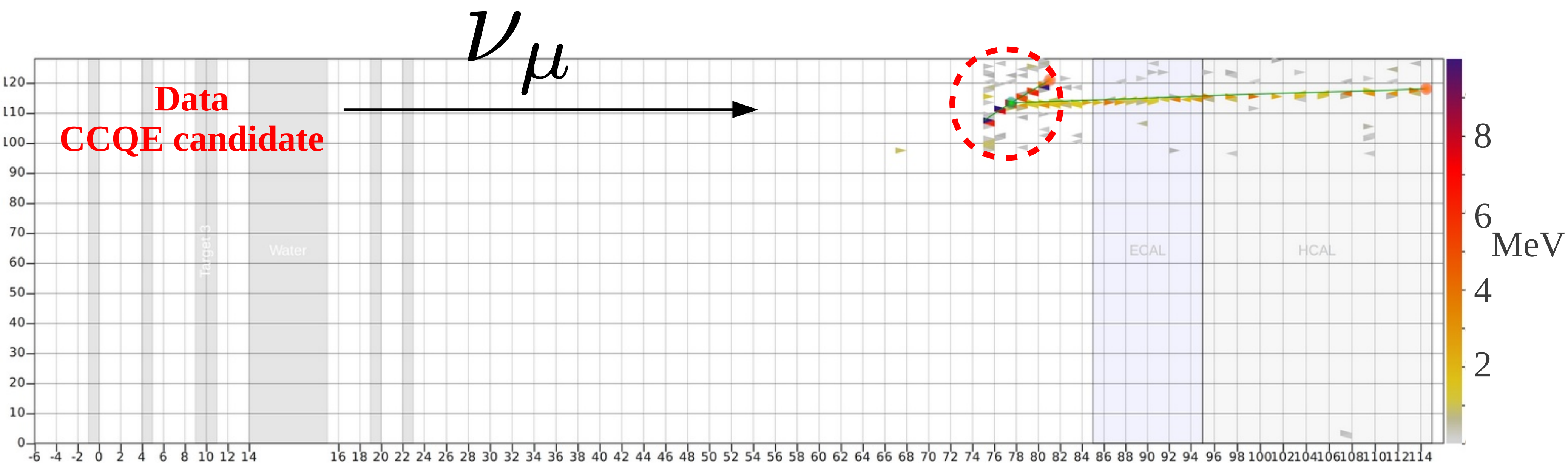




NuWro model	RFG $M_A = 0.99$	RFG + TEM $M_A = 0.99$	RFG $M_A = 1.35$	SF $M_A = 0.99$
ν shape χ^2/d.o.f.	4.1	1.7	2.1	3.8
$\bar{\nu}$ shape χ^2/d.o.f.	2.9	0.7	1.7	3.0

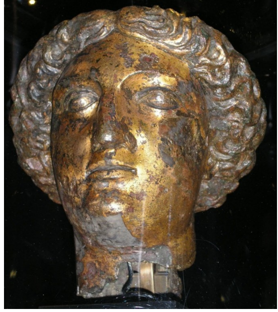


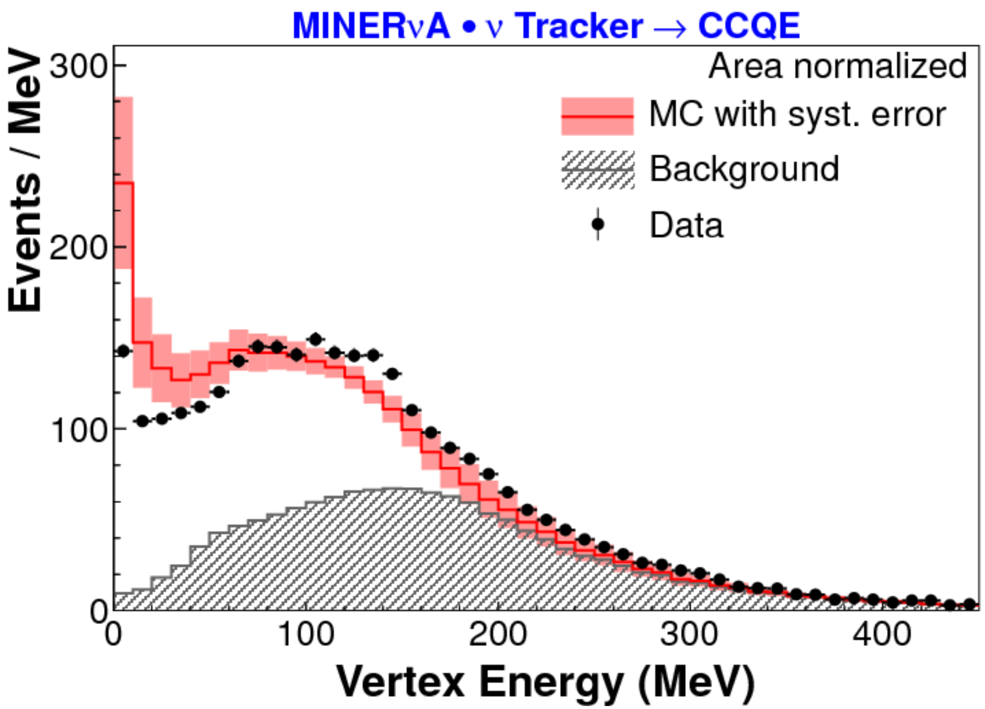
Look inside vertex region



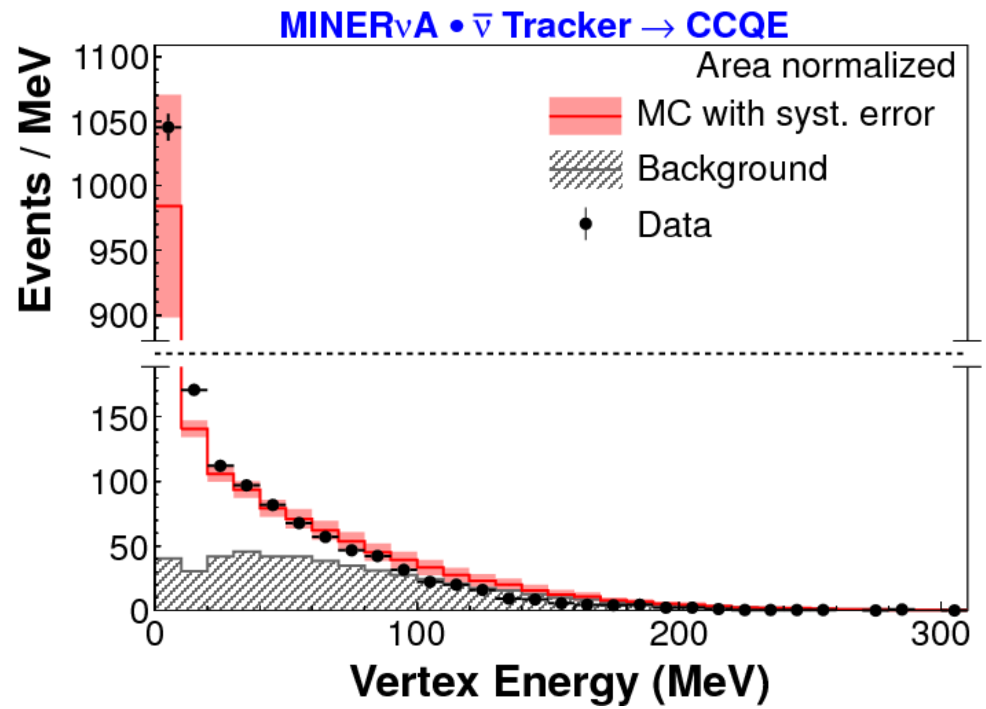
- Look for evidence of extra energy inside “vertex region”
- Fit to data assuming extra energy is due to protons
- Ignored this region for CCQE event selection

Energy in vertex region



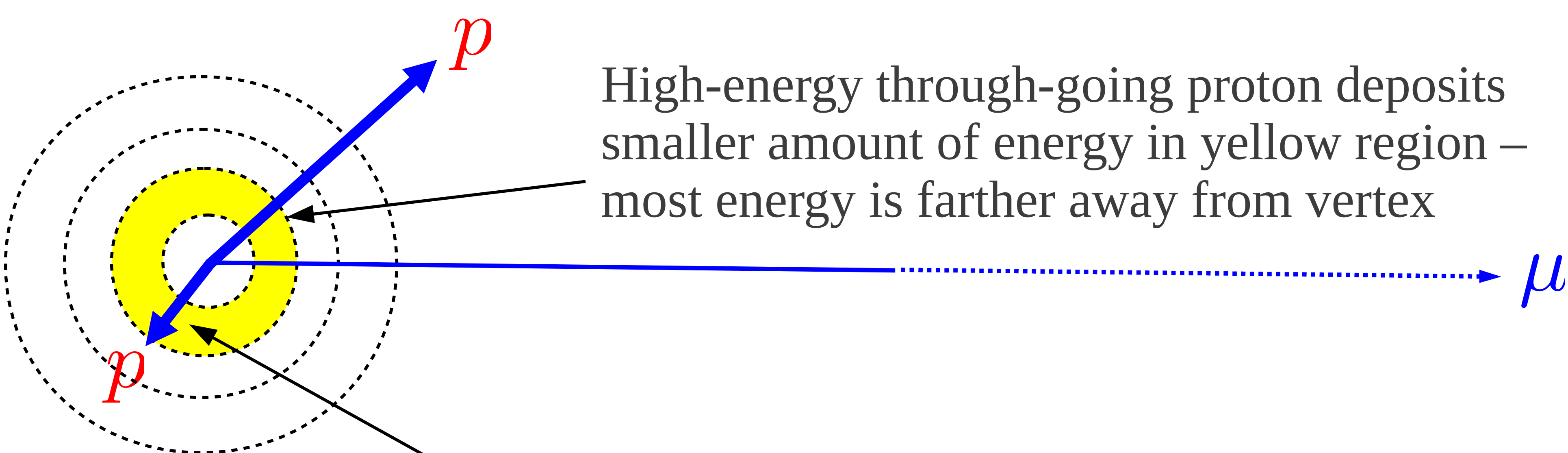


Neutrino mode - 30cm



Antineutrino mode - 10cm

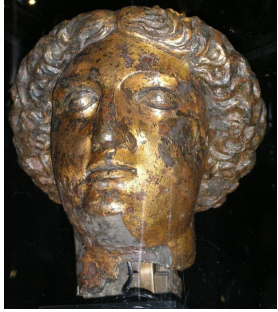
Look in "annuli"

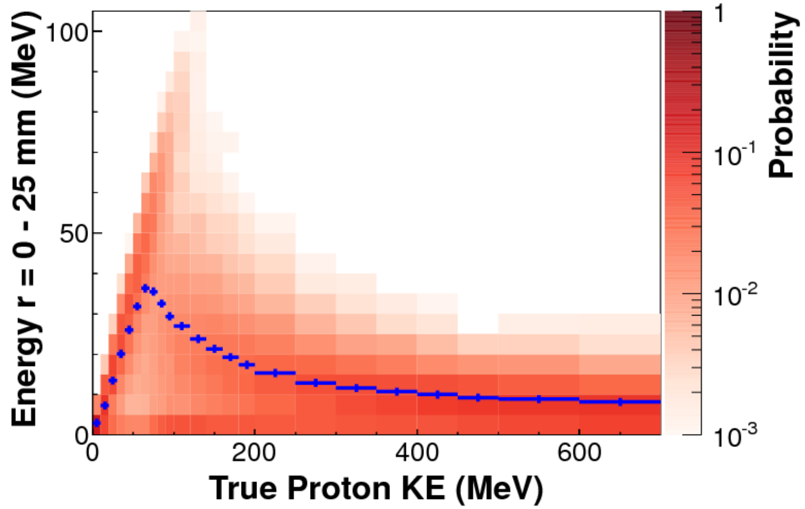


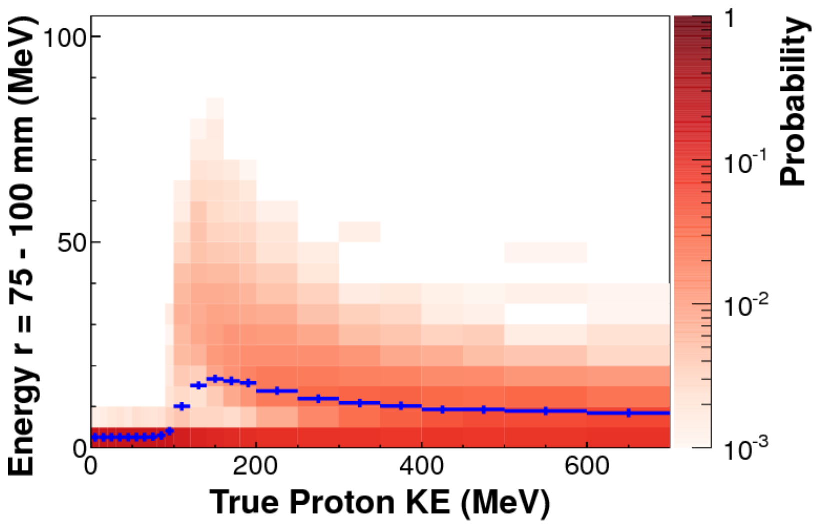
High-energy through-going proton deposits smaller amount of energy in yellow region – most energy is farther away from vertex

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

Vertex energy due to 1 proton





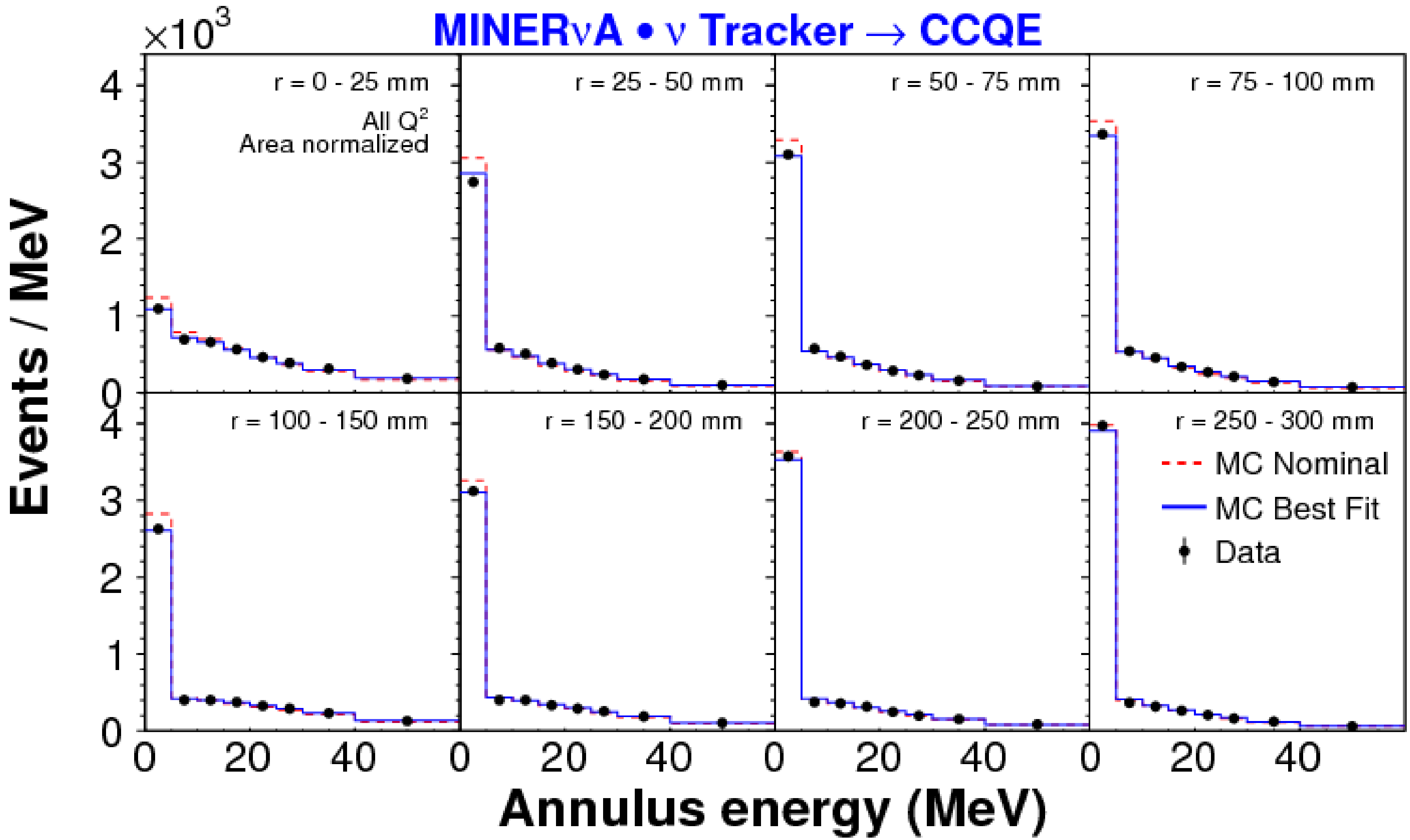


Simulated CC events with exactly 1 proton, no π/γ

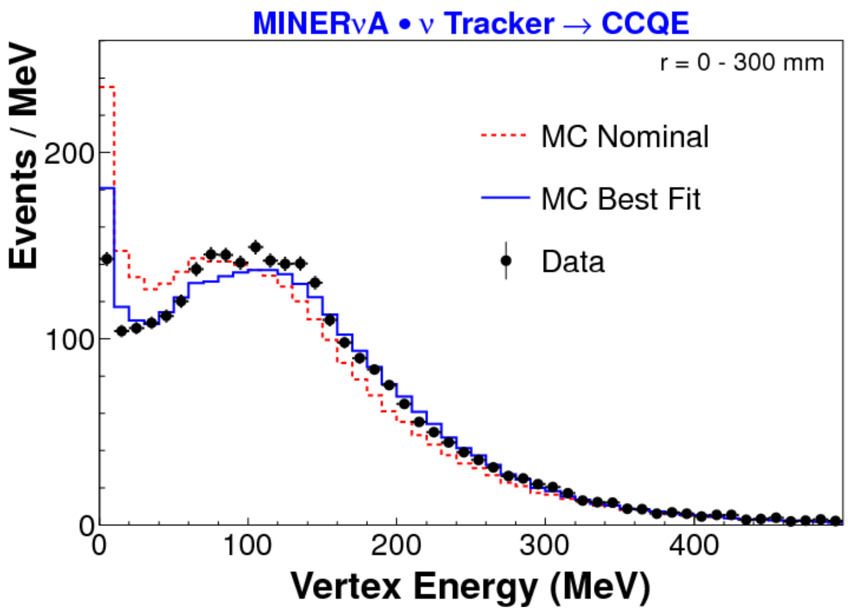
For proton of given KE, column represents probability distribution for energy deposit in given region

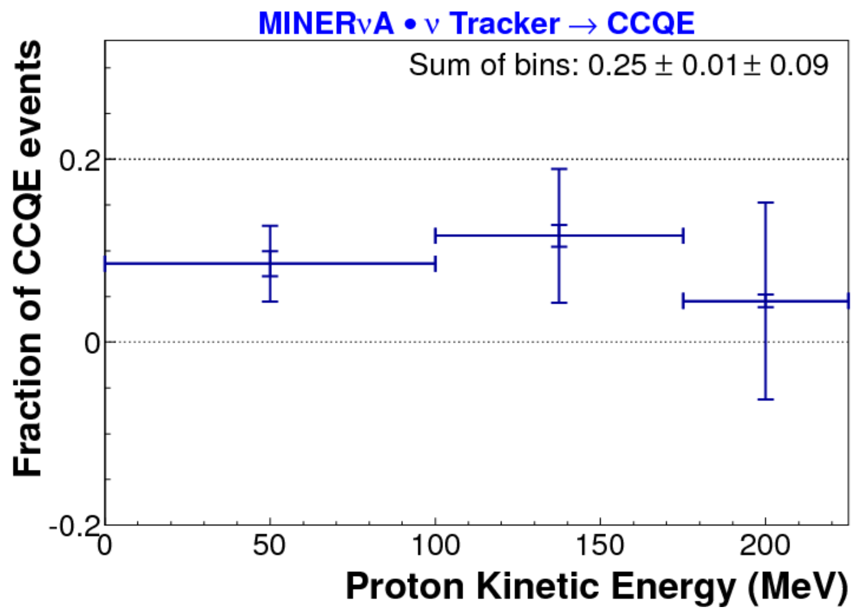
Fit by adding energy to some fraction of events based on these distributions

Annulus fits



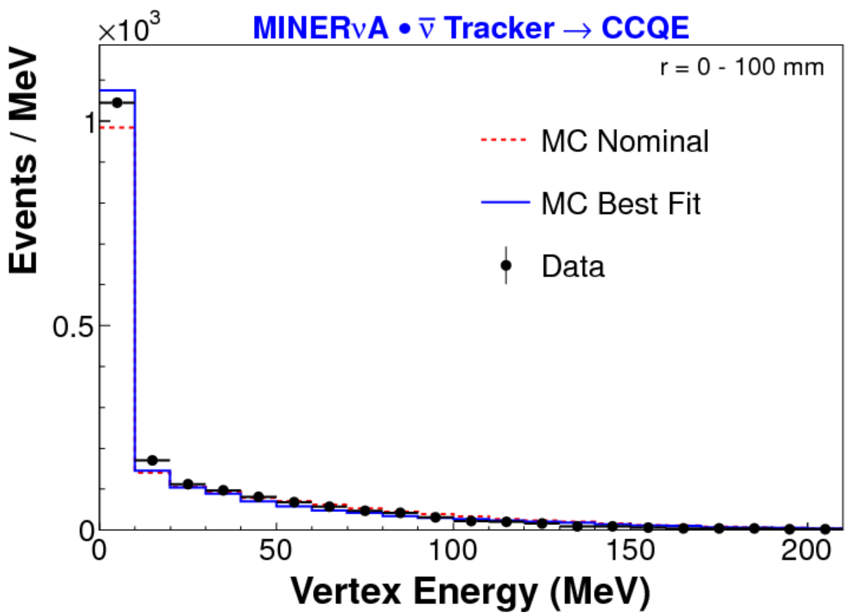
Fit results - neutrino

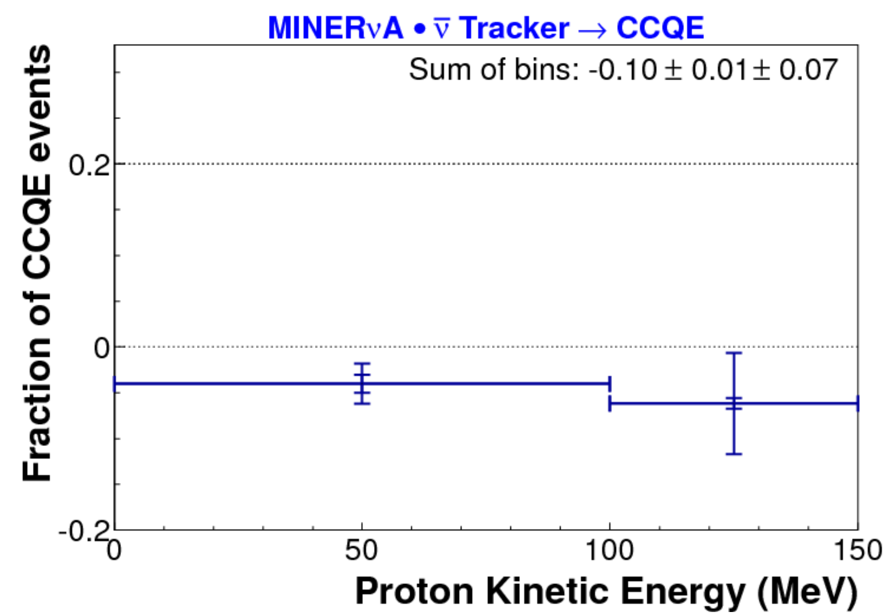




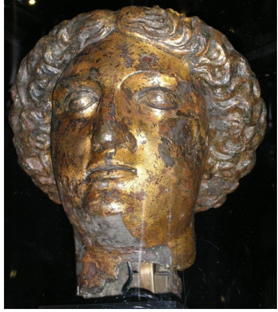
- Fit wants to add low-energy protons to (25 ± 10)% of CCQE events

Fit results - antineutrino





- Consistent with no additional protons
- Fit wants to “add” proton to (-10 ± 8)% of CCQE events

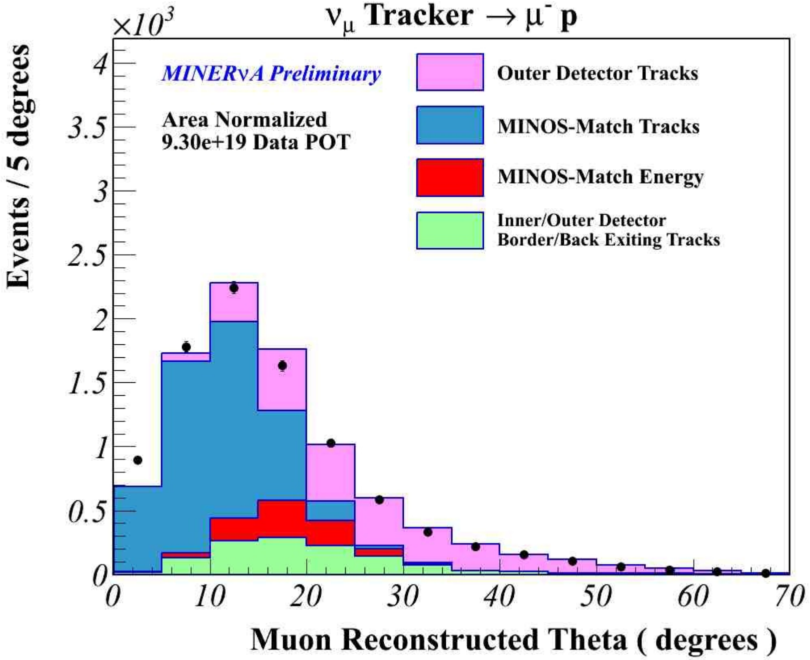


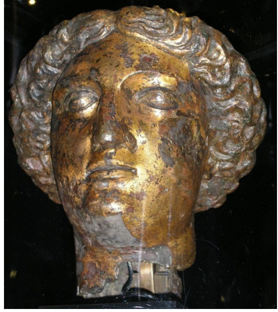
Conclusions

- CCQE $d\sigma/dQ^2$ shape distributions prefer RFG+TEM model with $M_A \approx 1$ GeV for both neutrino and antineutrino
- Extra energy near vertex suggests additional protons in 25% of CCQE events in *neutrino mode only*, consistent with np initial state pairs

Future directions

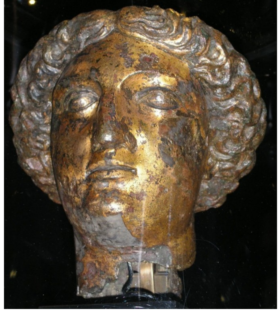
- Michel electron tag to reject $\pi \rightarrow \mu \rightarrow e$
- Improve acceptance at high Q^2 by reconstructing E_ν and Q^2 from proton
- $\sigma(E)$ and $d^2\sigma/dT_\mu d\theta_\mu$
- CCQE in nuclear targets



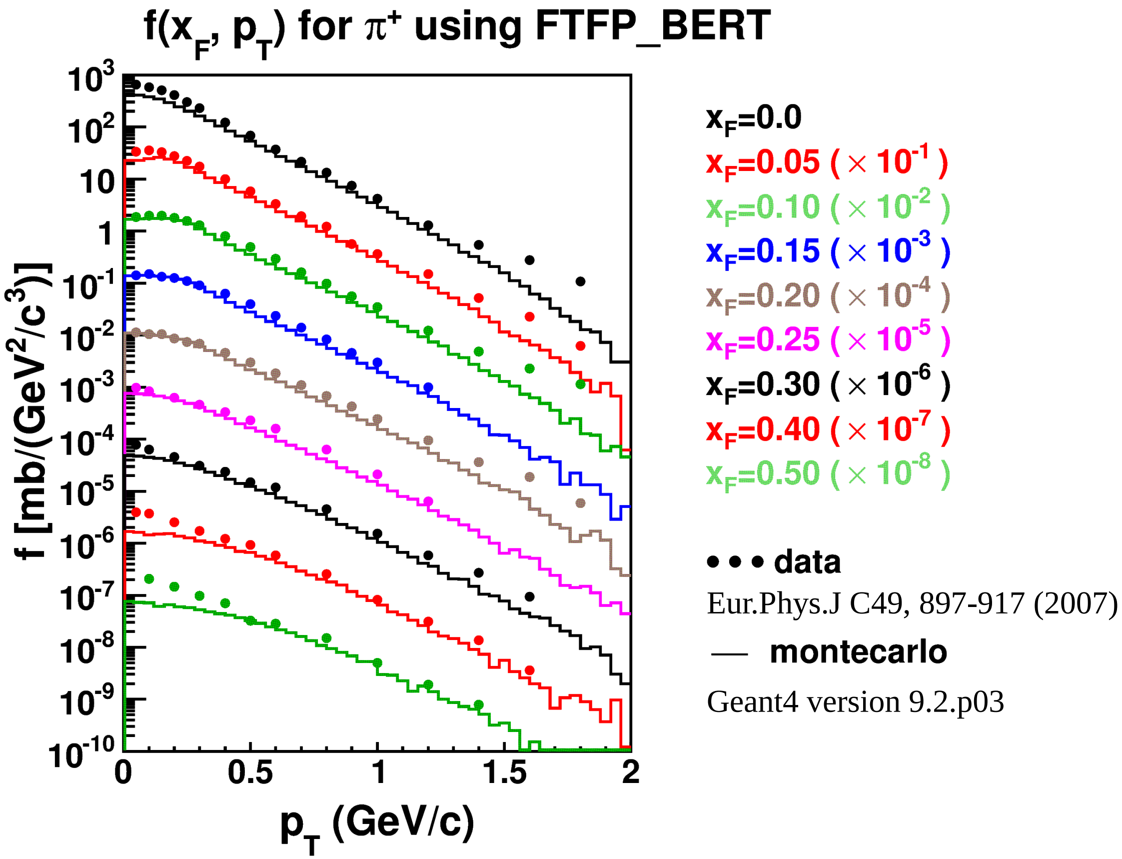


Thank you

Systematic uncertainties

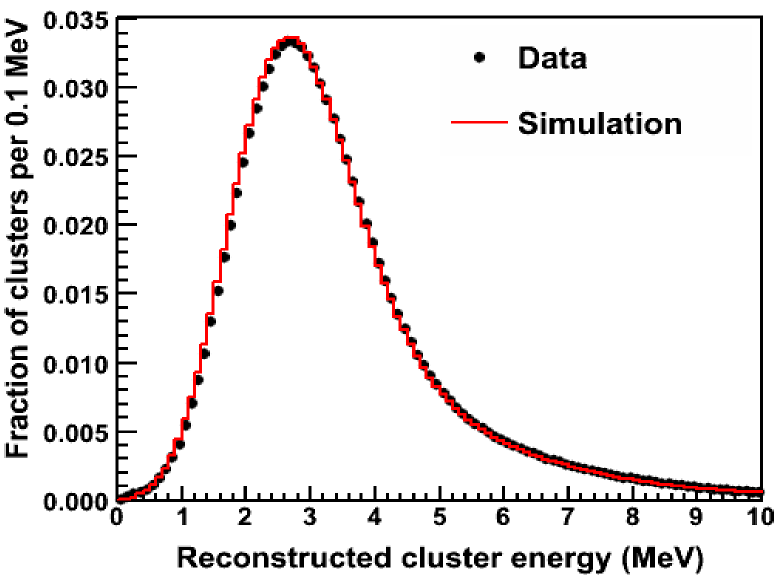


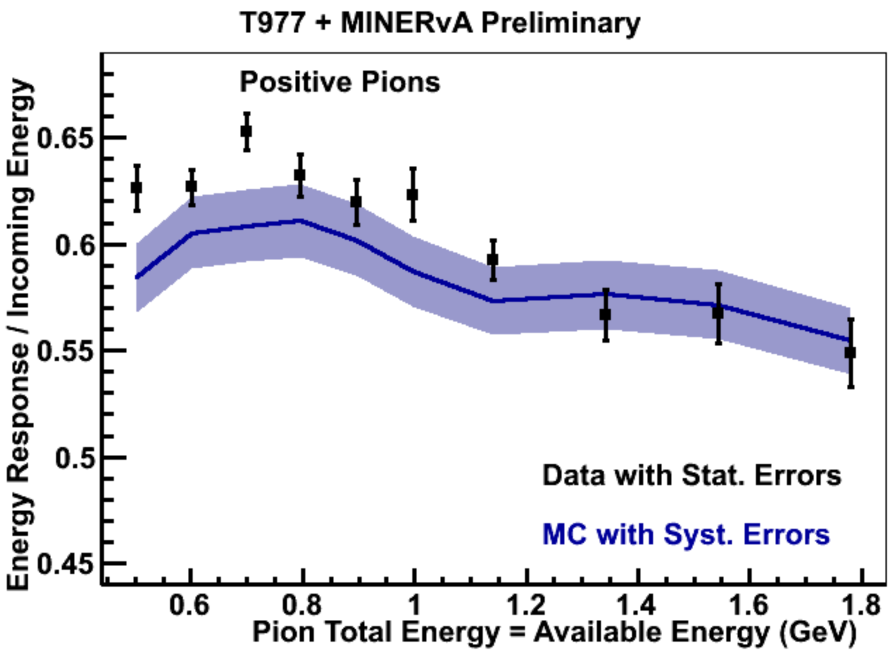
- Flux
  - Simulated with GEANT4, reweighted by NA49 data



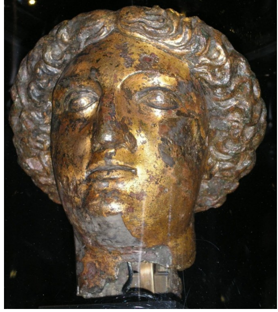
Systematic uncertainties

- Flux
  - Simulated with GEANT4, reweighted by NA49 data
- Recoil energy reconstruction
  - Overall scale from muons, test beam for hadrons





UNIVERSITY of ROCHESTER

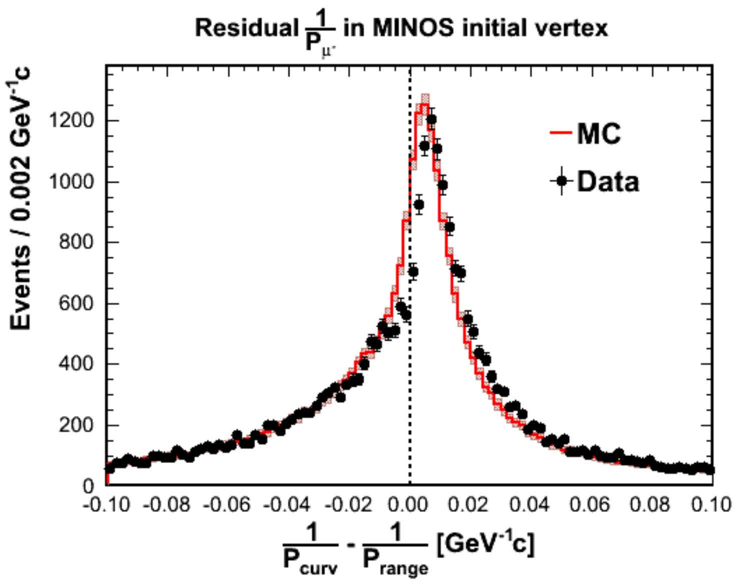


Systematic uncertainties

- 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

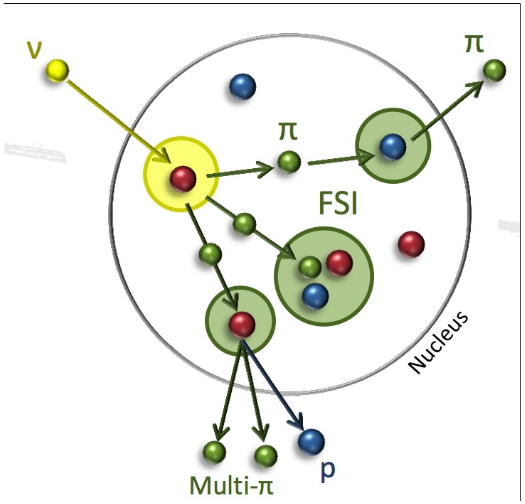
Reconstructed by	Uncertainty
Range (all p)	2.0%
Curvature (p < 1.0 GeV)	2.1%
Curvature (p > 1.0 GeV)	3.3%

MINOS NIM A 596, 190 (2008)

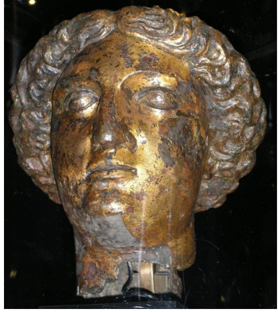


Systematic uncertainties

- 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
  - Final state interaction uncertainties

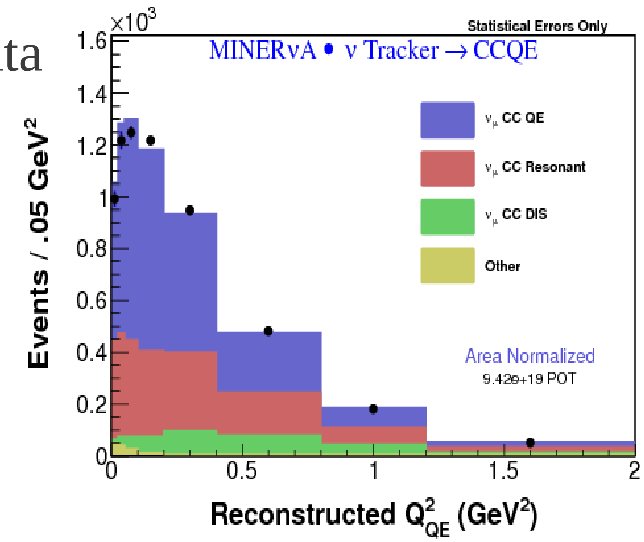


Model parameter	Uncertainty
Pion/nucleon mean path	20%
Pion/nucleon charge exchange	50%
Pion absorbtion	30%
Pion/nucleon inelastic cross section	40%
Elastic cross sections	10-30%



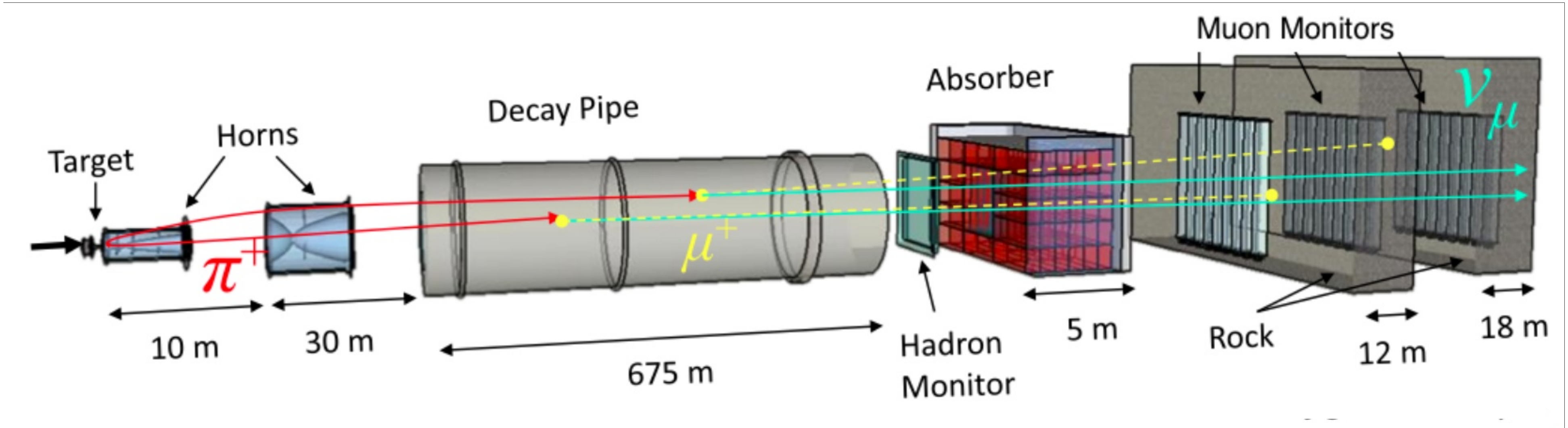
Systematic uncertainties

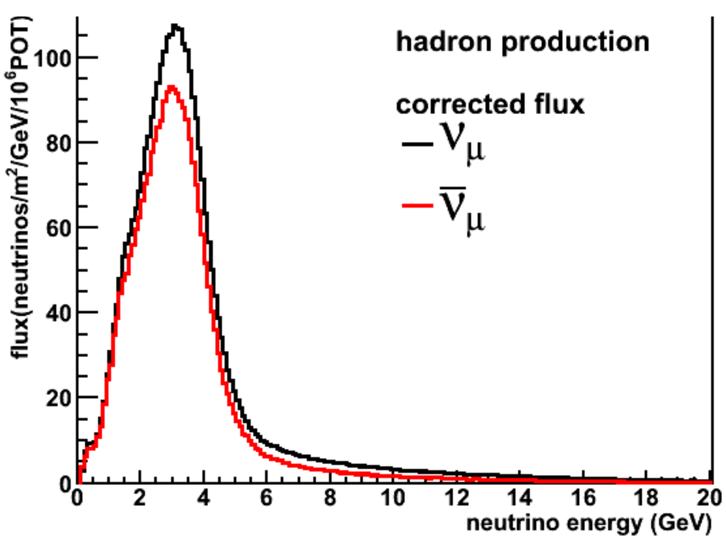
- Flux
  - Simulated with GEANT4, reweighted by NA49 data
- Recoil energy reconstruction
  - Overall scale from muons, test beam for hadrons
- Muon energy reconstruction
  - Dominated by MINOS momentum errors
- Hadron interaction model
  - Final state interaction uncertainties
- Primary interaction (GENIE)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



Model parameter	Uncertainty
CC Resonance Norm.	20%
Resonance M_A	20%
Non-resonance pion production	50%

NuMI beamline

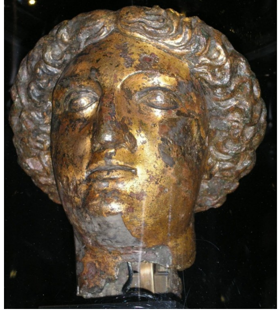




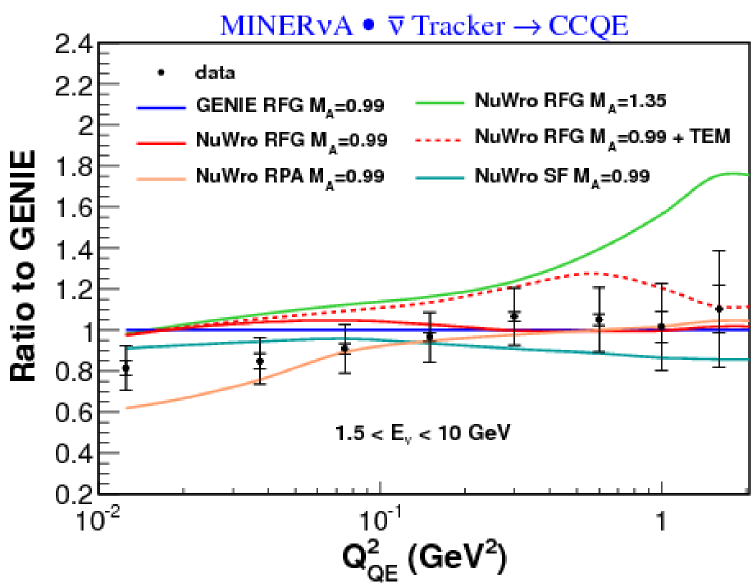
120 GeV protons from Main Injector incident on graphite target

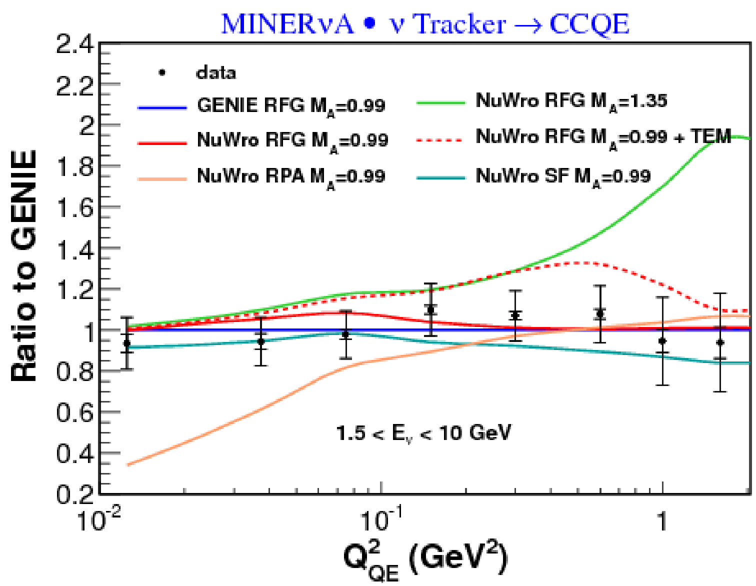
Pions focused by two horns, decay in 675-meter pipe

210 meters of rock before Minerva



Absolutely normalized XS





MA = 1.35 good fit to MiniBooNE data

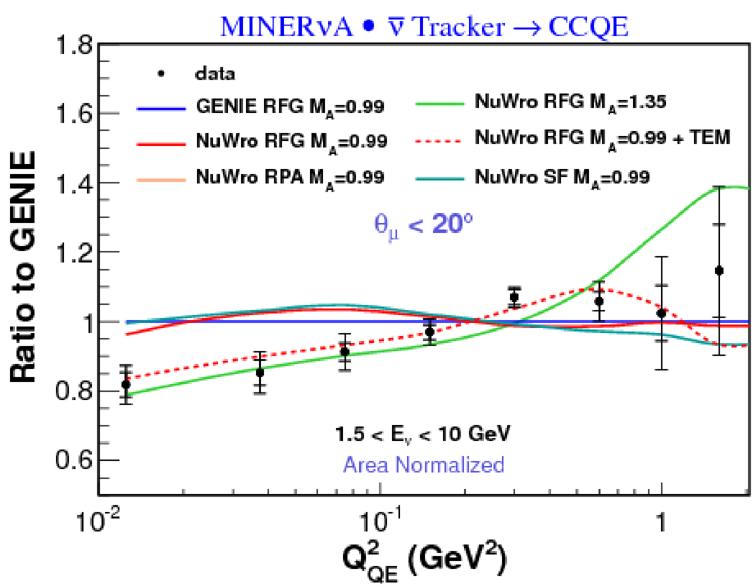
TEM parameterization of electron scattering data

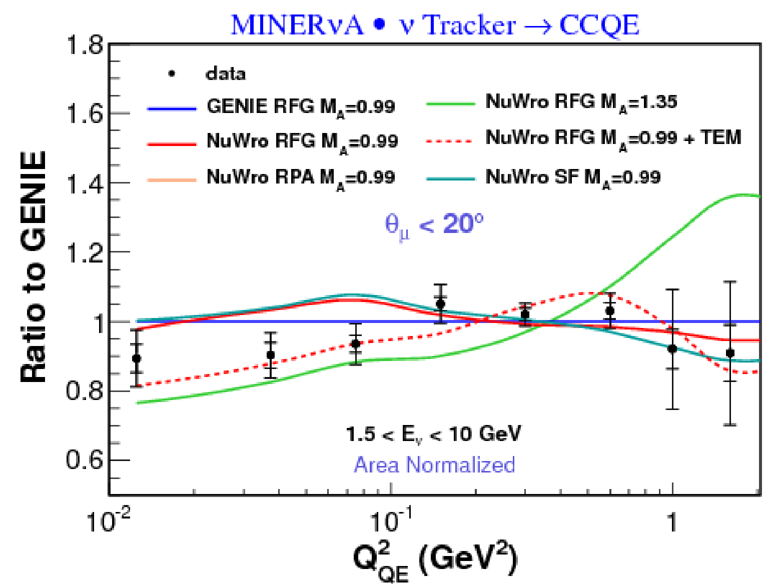
GENIE independent nucleons in mean field

SF more realistic nucleon momentum

RPA Random phase approximation

$\theta_\mu < 20^\circ$





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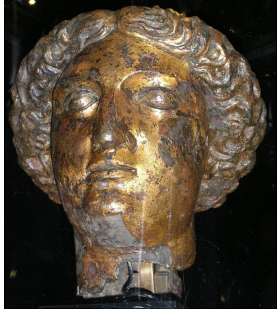
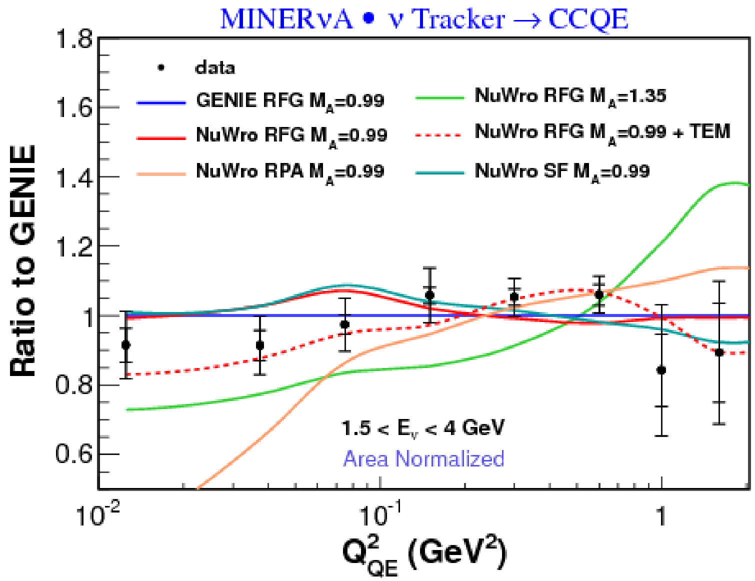
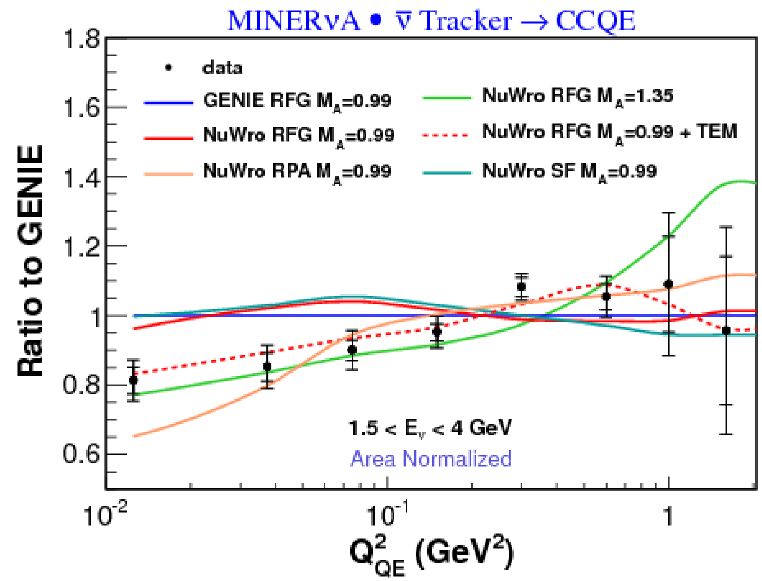
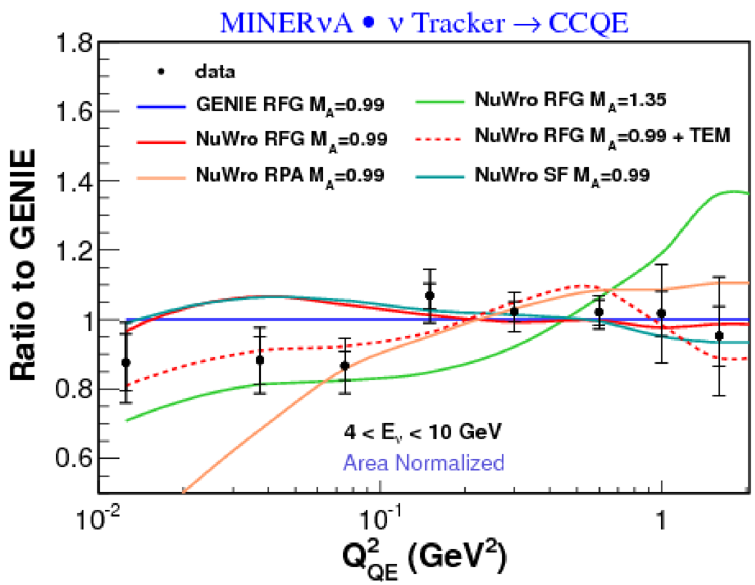
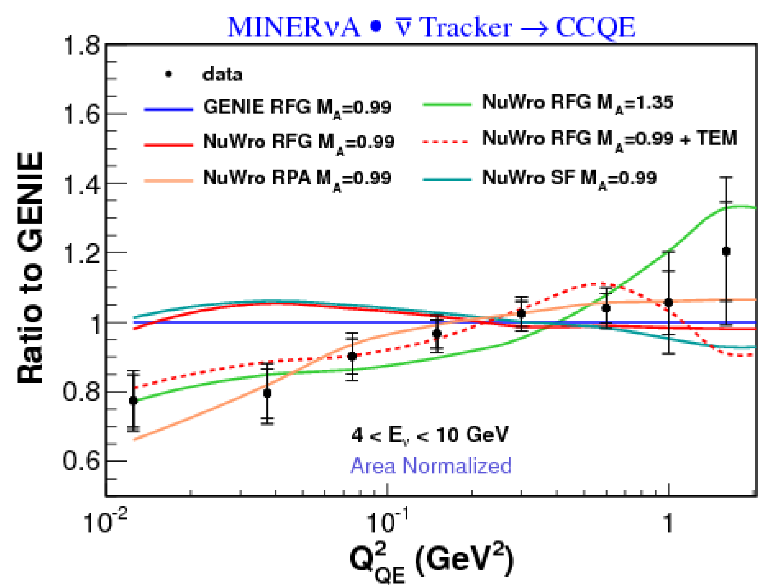


Split by neutrino energy

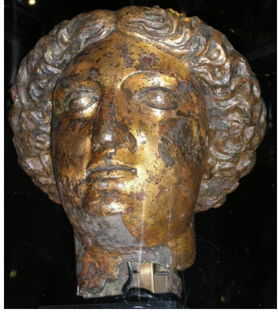


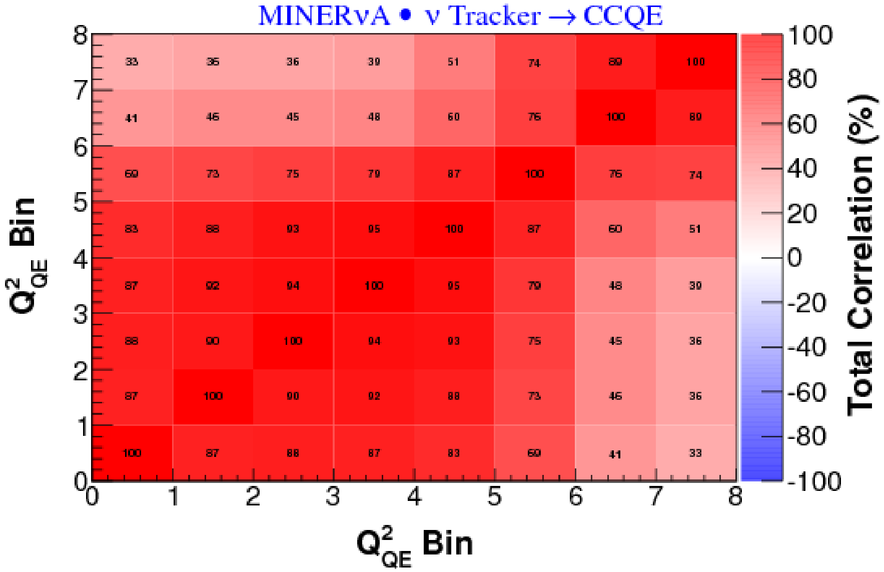


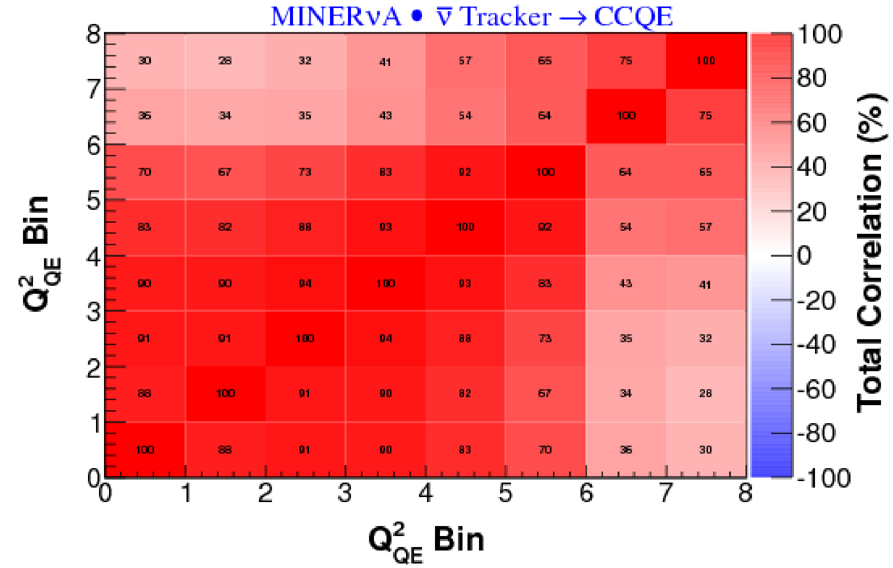


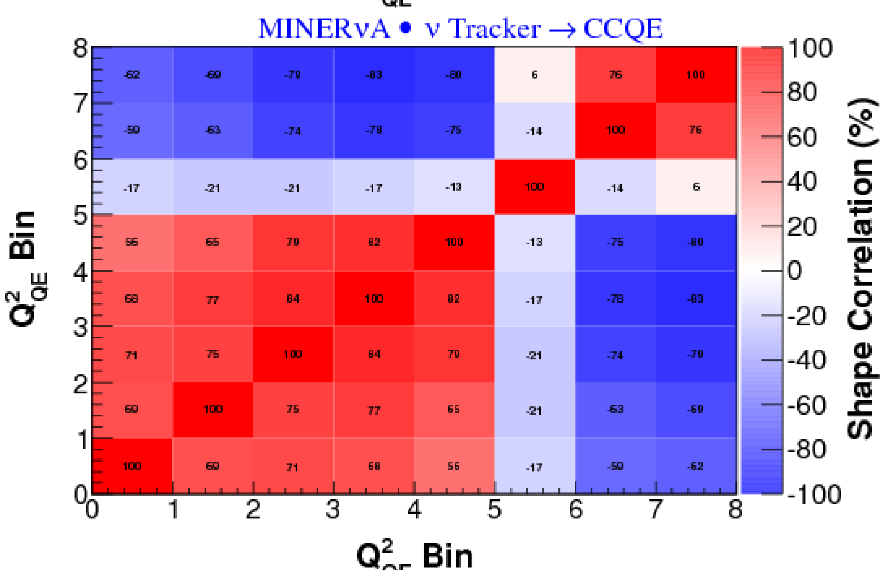


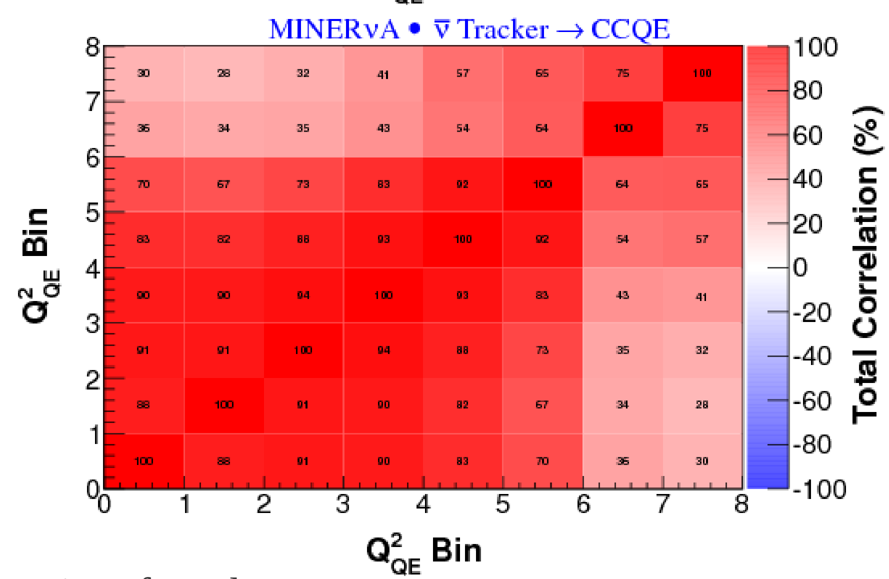
Correlation matrices

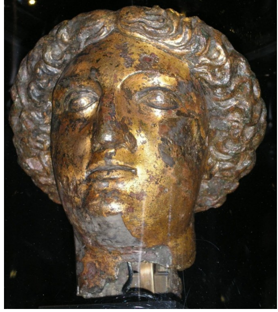




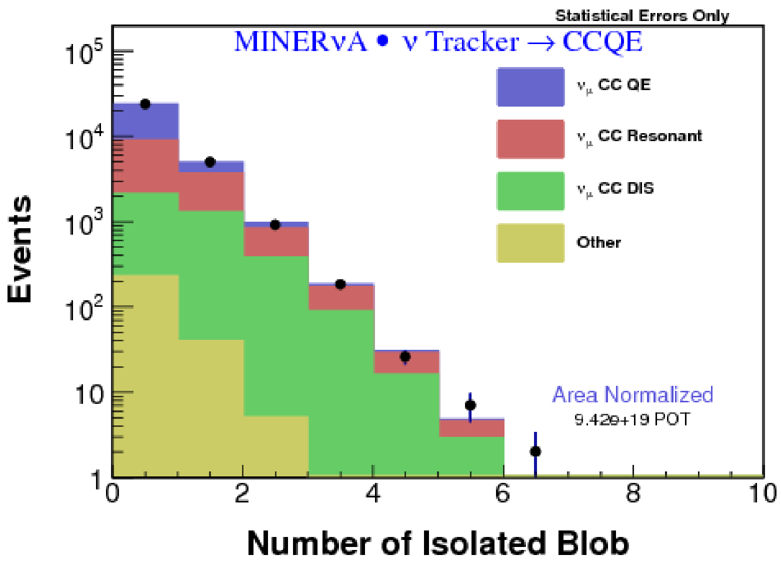


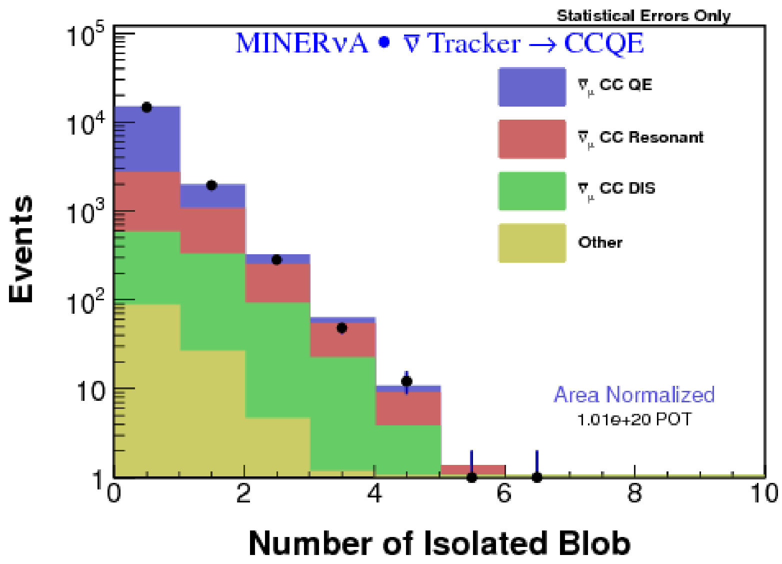




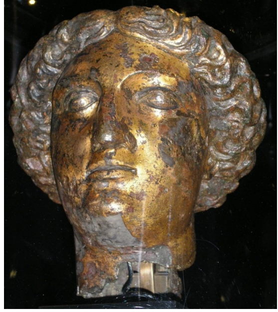


Isolated showers cut

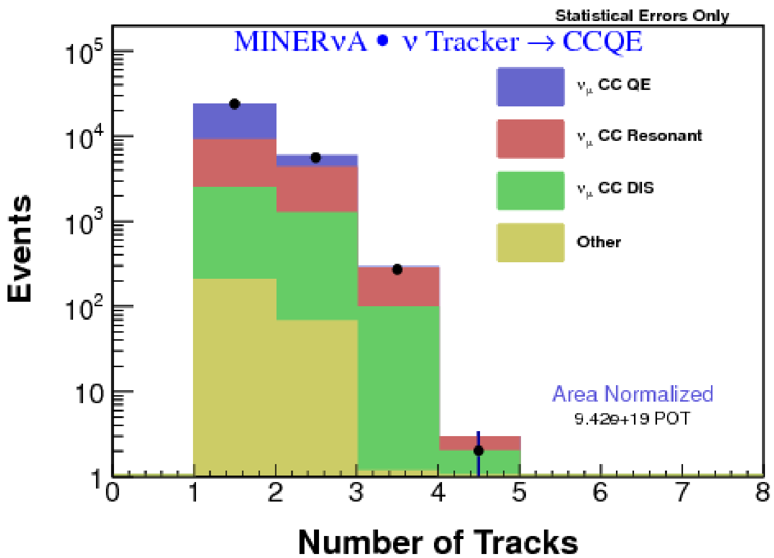


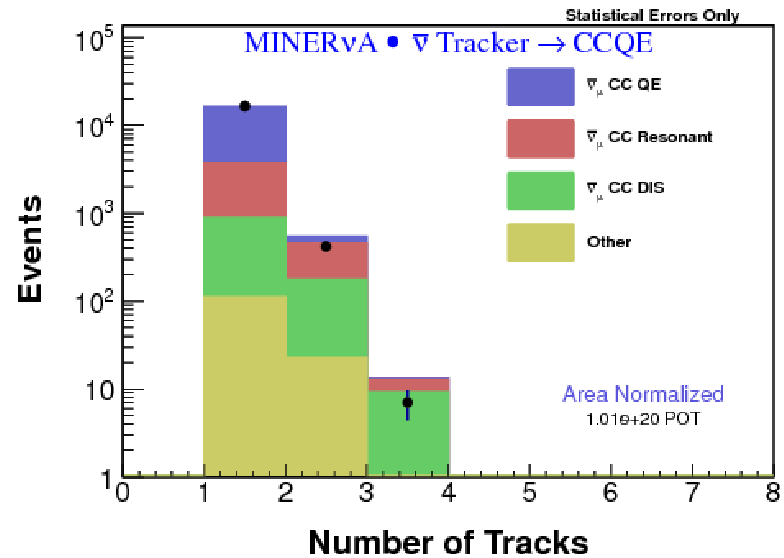


- <=2 for neutrino, <=1 for nubar



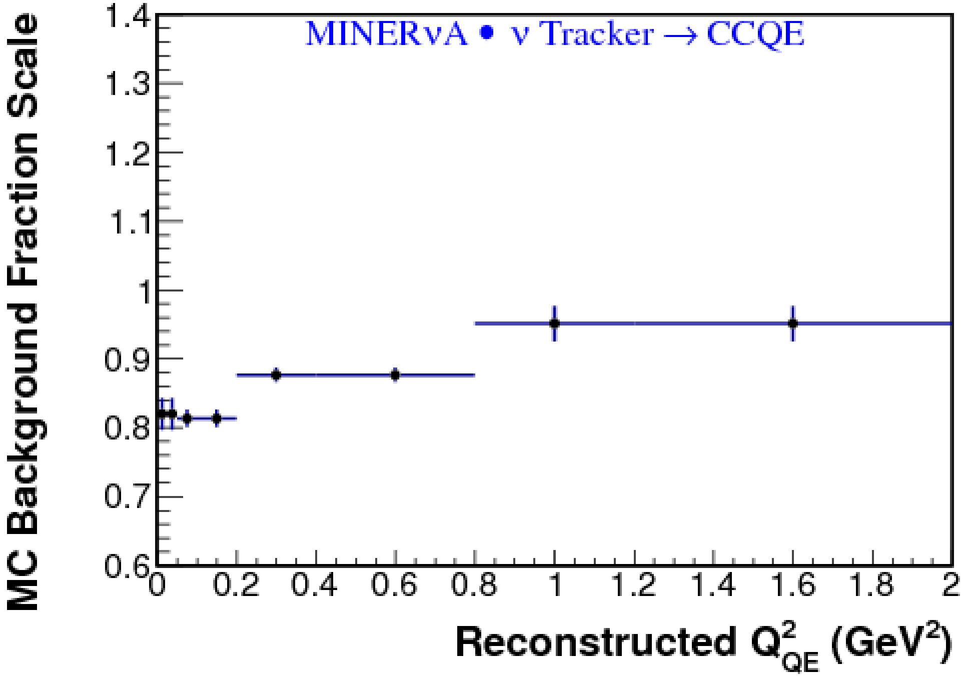
Number of tracks cut

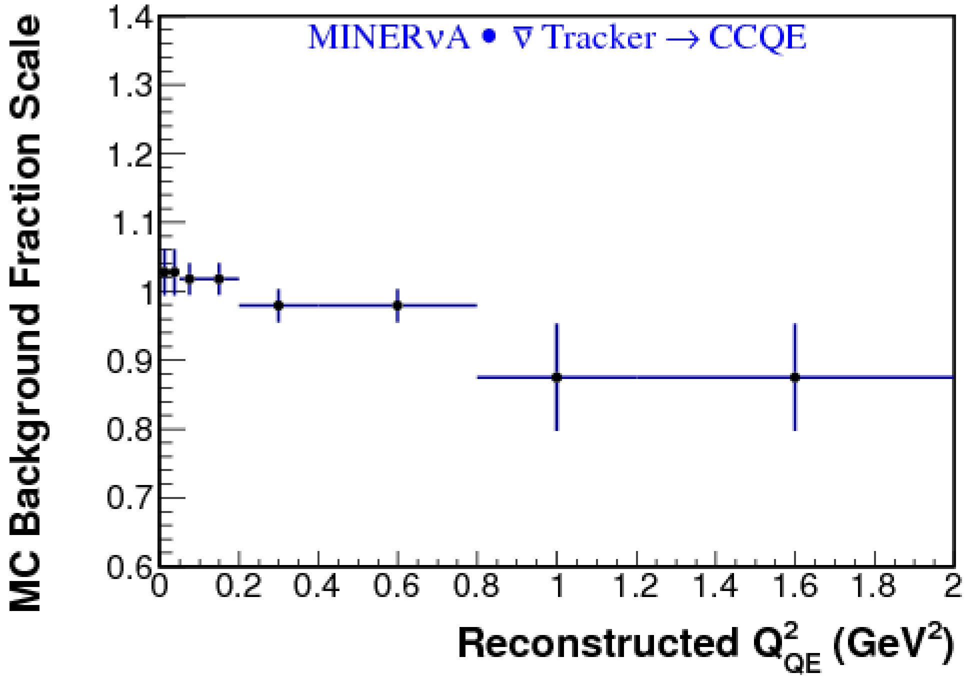




- No more than 1 for nubar, no cut for neutrino

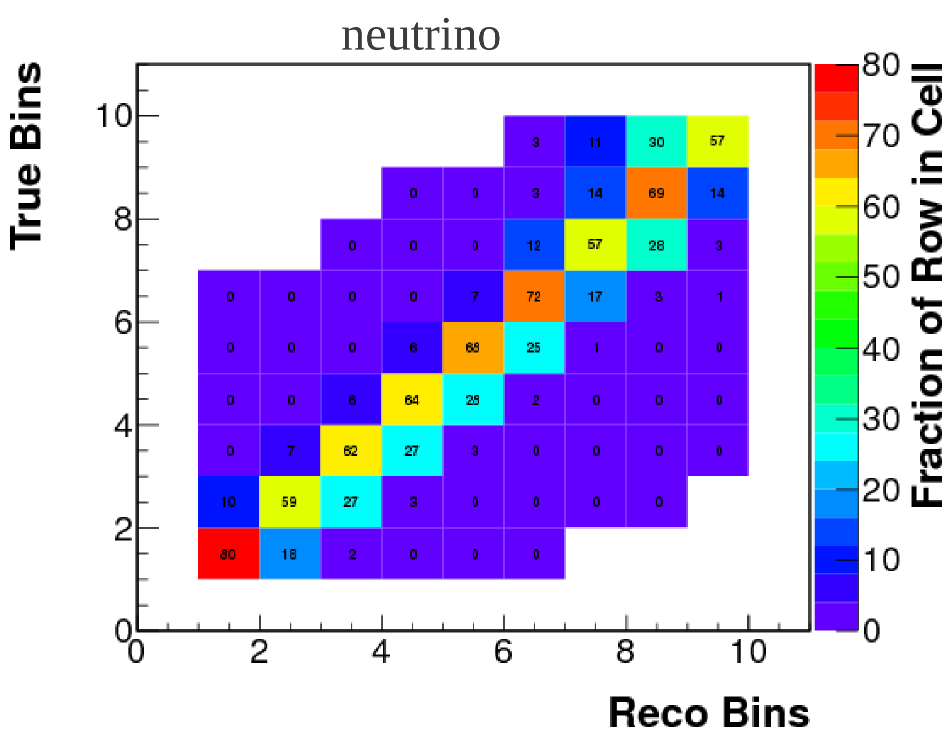
Background subtraction

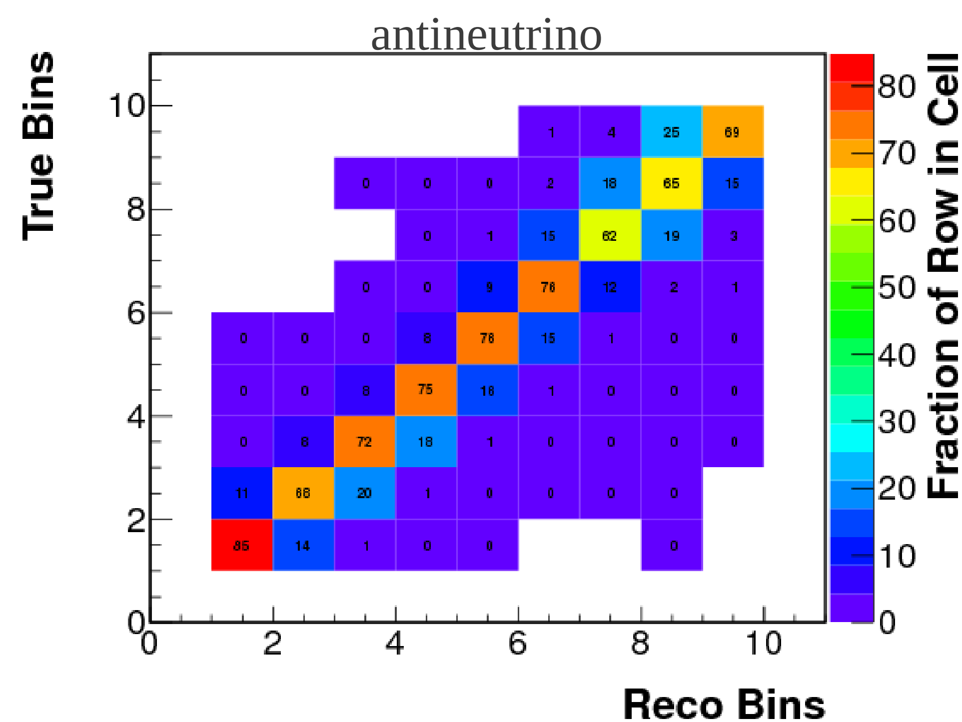




- Sideband of recoil energy in 4 bins of Q^2_{QE}
- Fit background normalization to match data
- Allow MC templates to fluctuate within stat errors

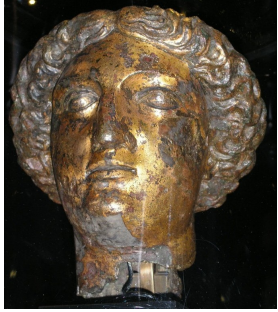
Unfolding matrices

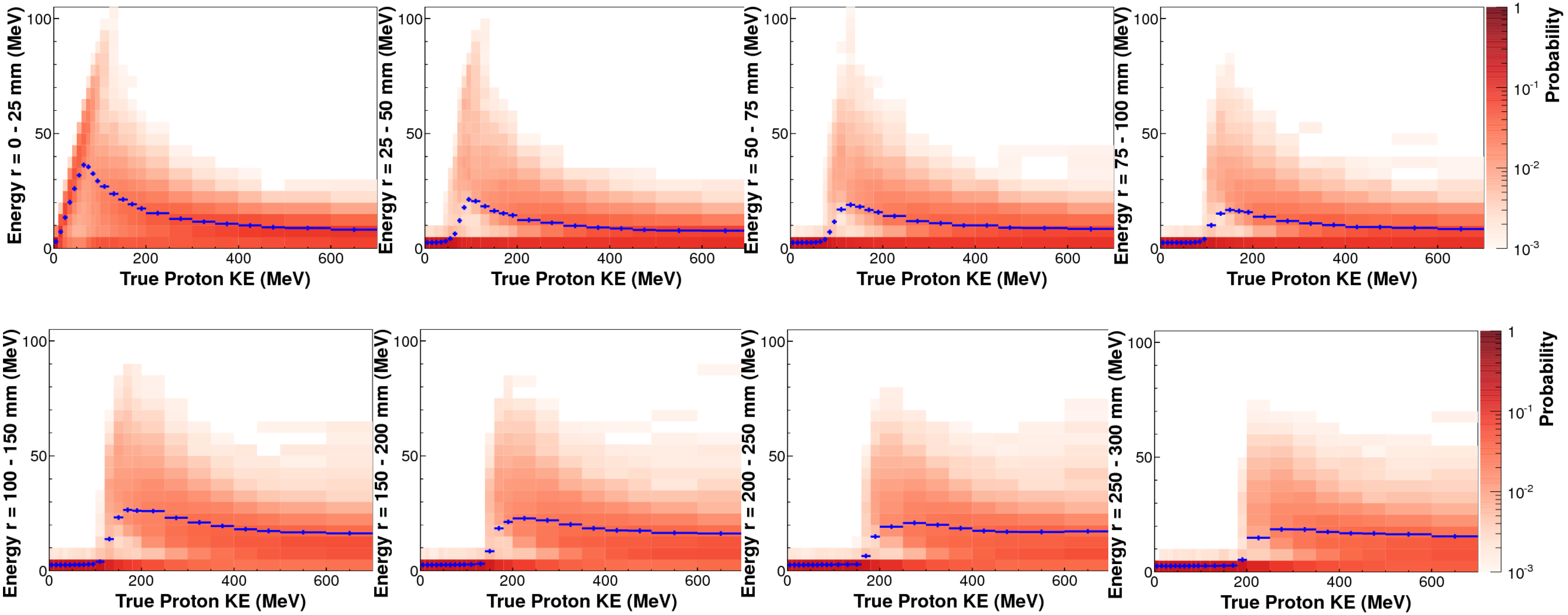




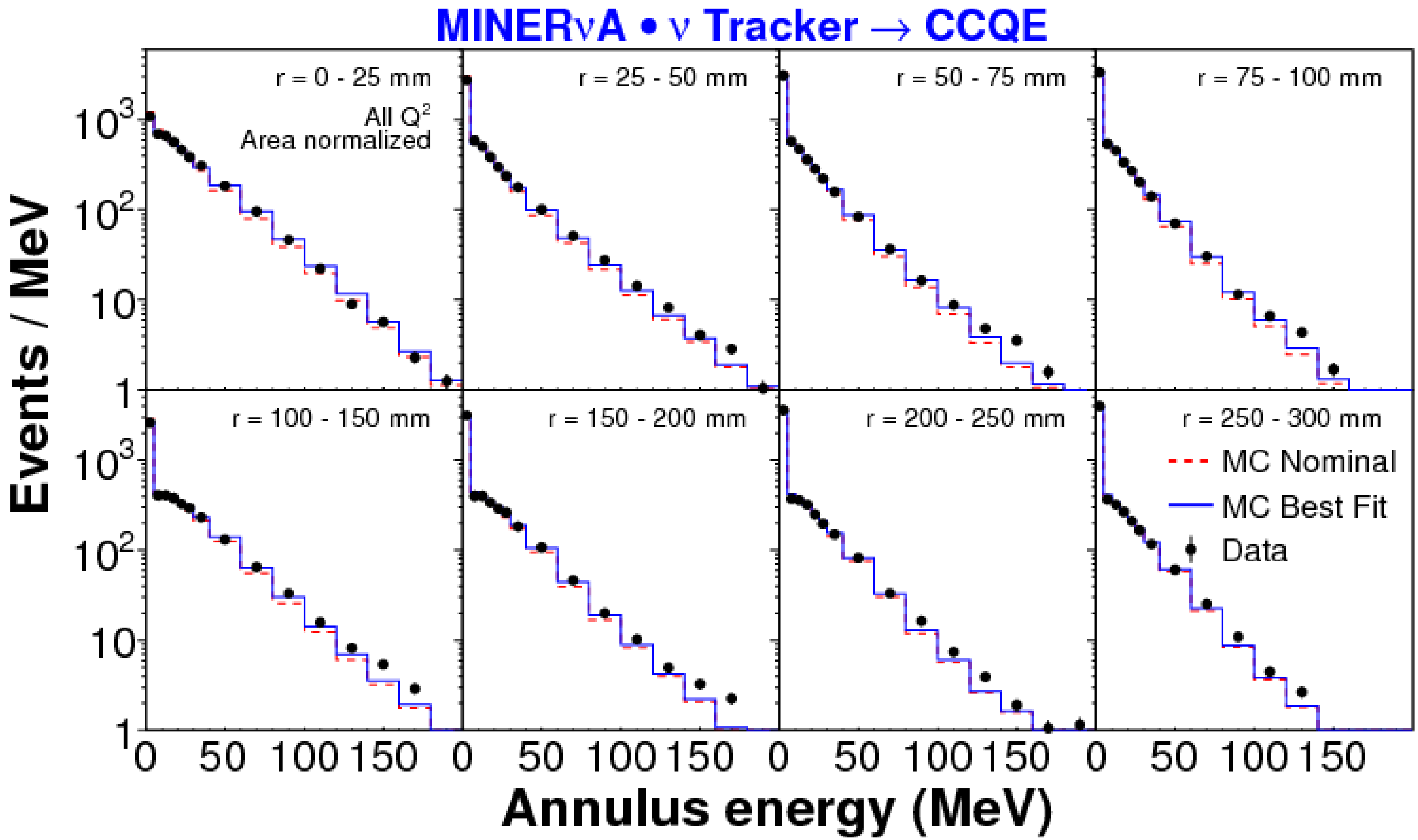
- Bins of Q^2_{QE}
- Unfolded using Bayesian method with 4 iterations

Vertex energy due to 1 proton

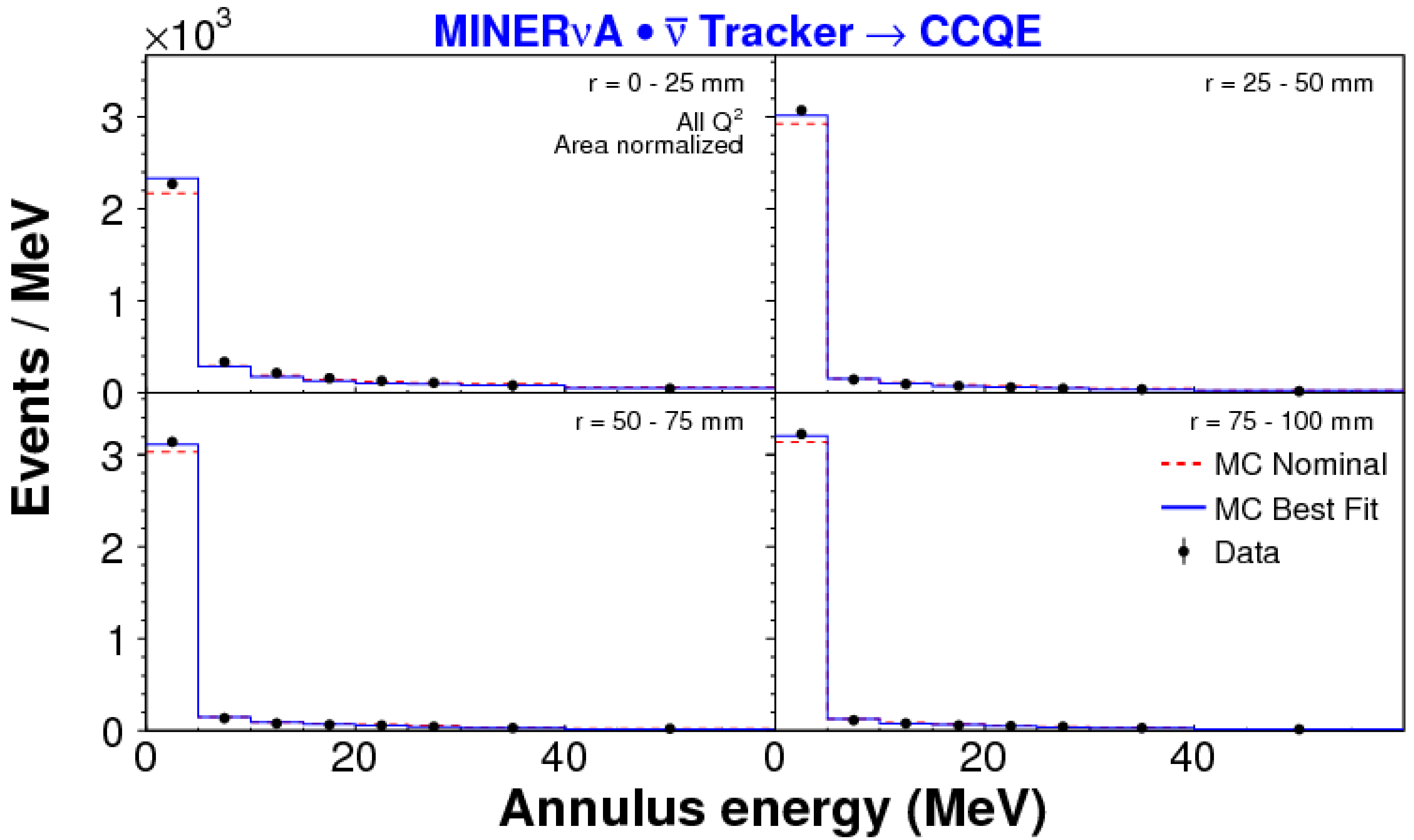


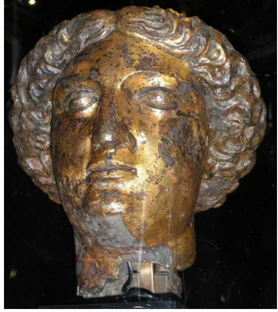


Annulus fits – log Y

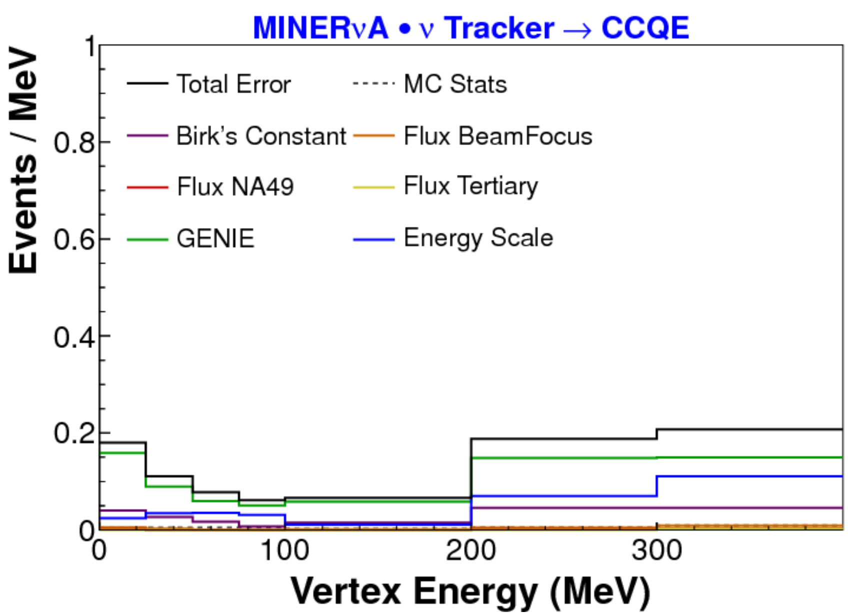


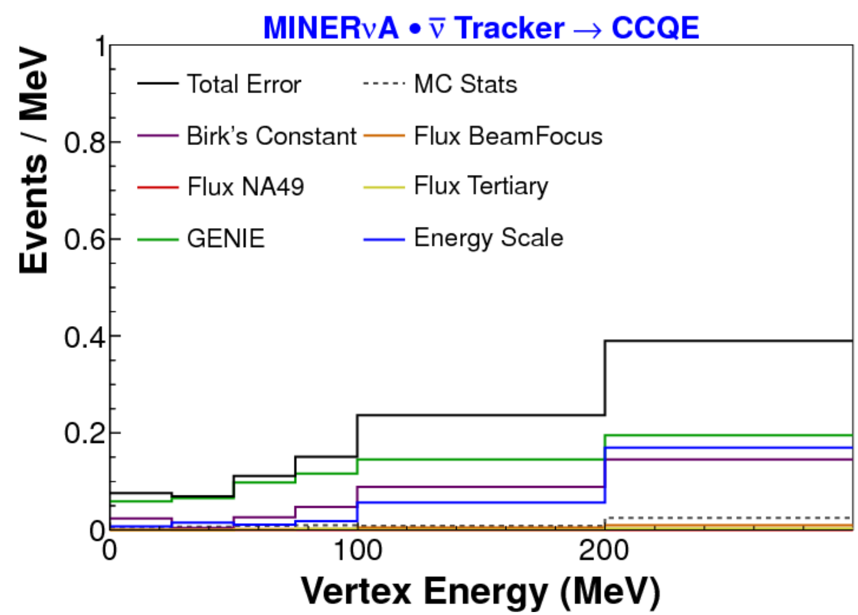
Annulus fits - NuBar



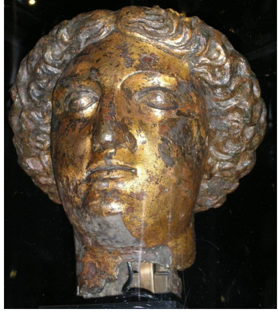


Vertex energy error summary



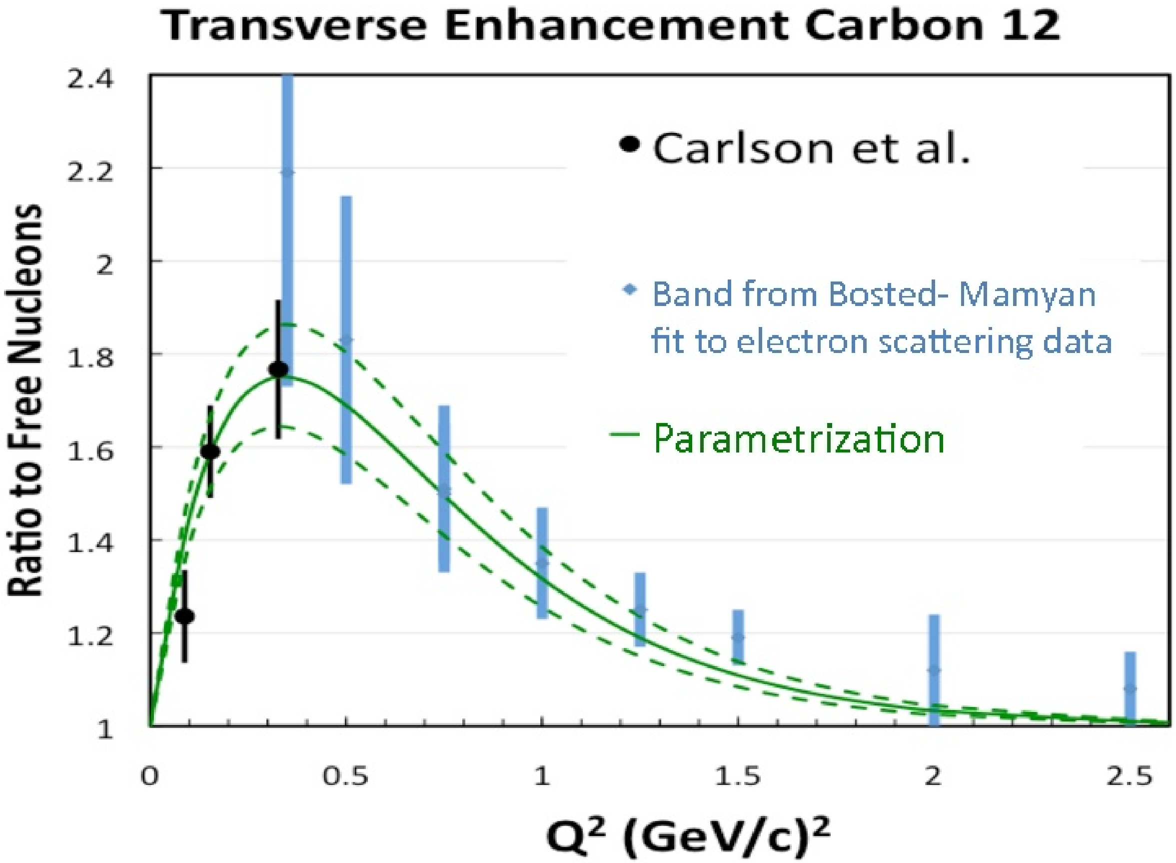


- Dominated by modeling uncertainties (GENIE)



TEM model

A. Bodek, H. Budd, M.E. Christy, Eur. Phys. J. C 71, 1726 (2011)



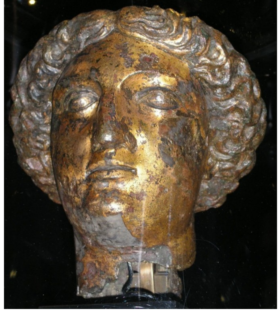
Phys.Rev. **C65** 024002 (2002)

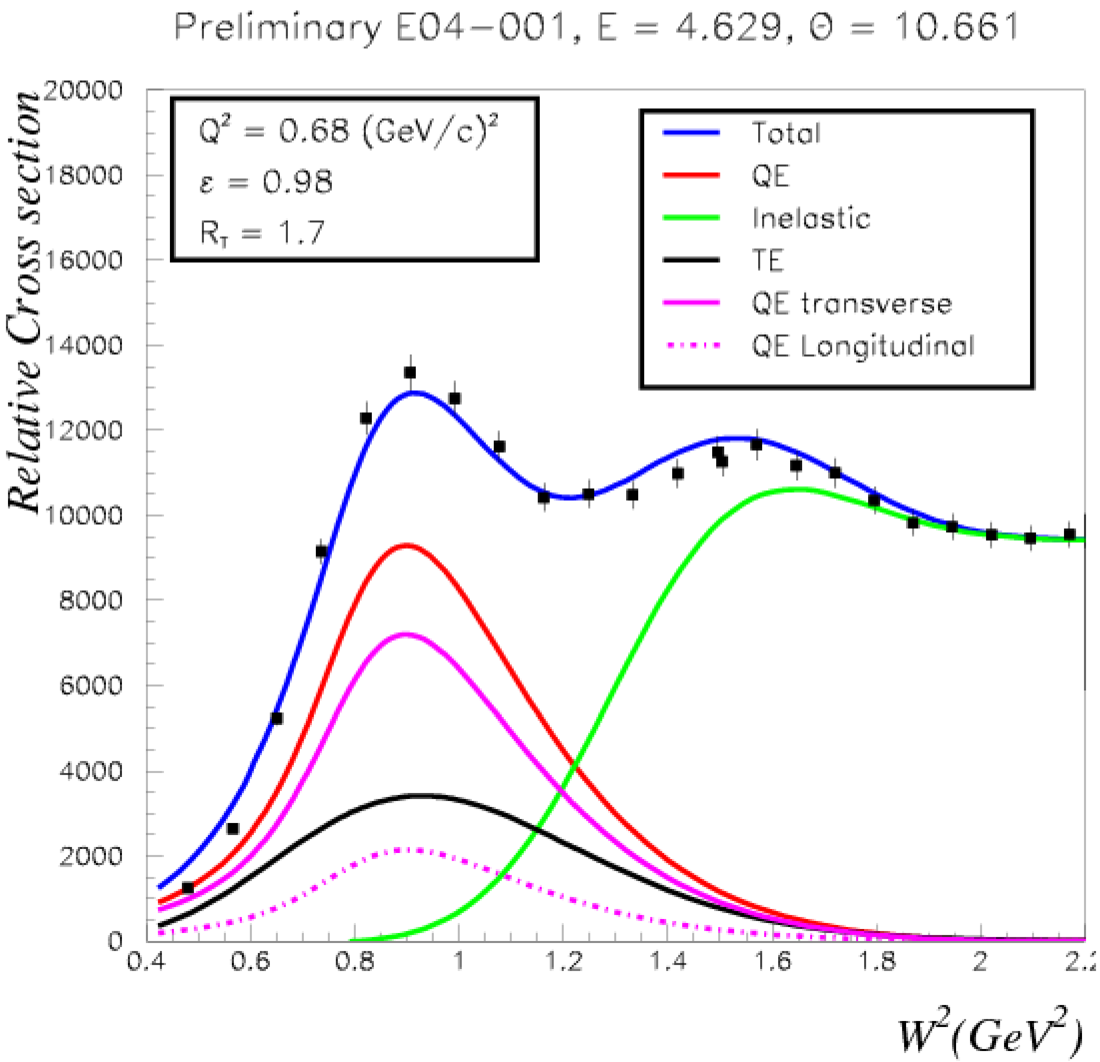
V. Mamyan, Ph.D. dissertation,
University of Virginia, 2010

Fit to JUPITER data (JLab E04-001)

BBC TEM model

A. Bodek, H. Budd, M.E. Christy, Eur. Phys. J. C 71, 1726 (2011)



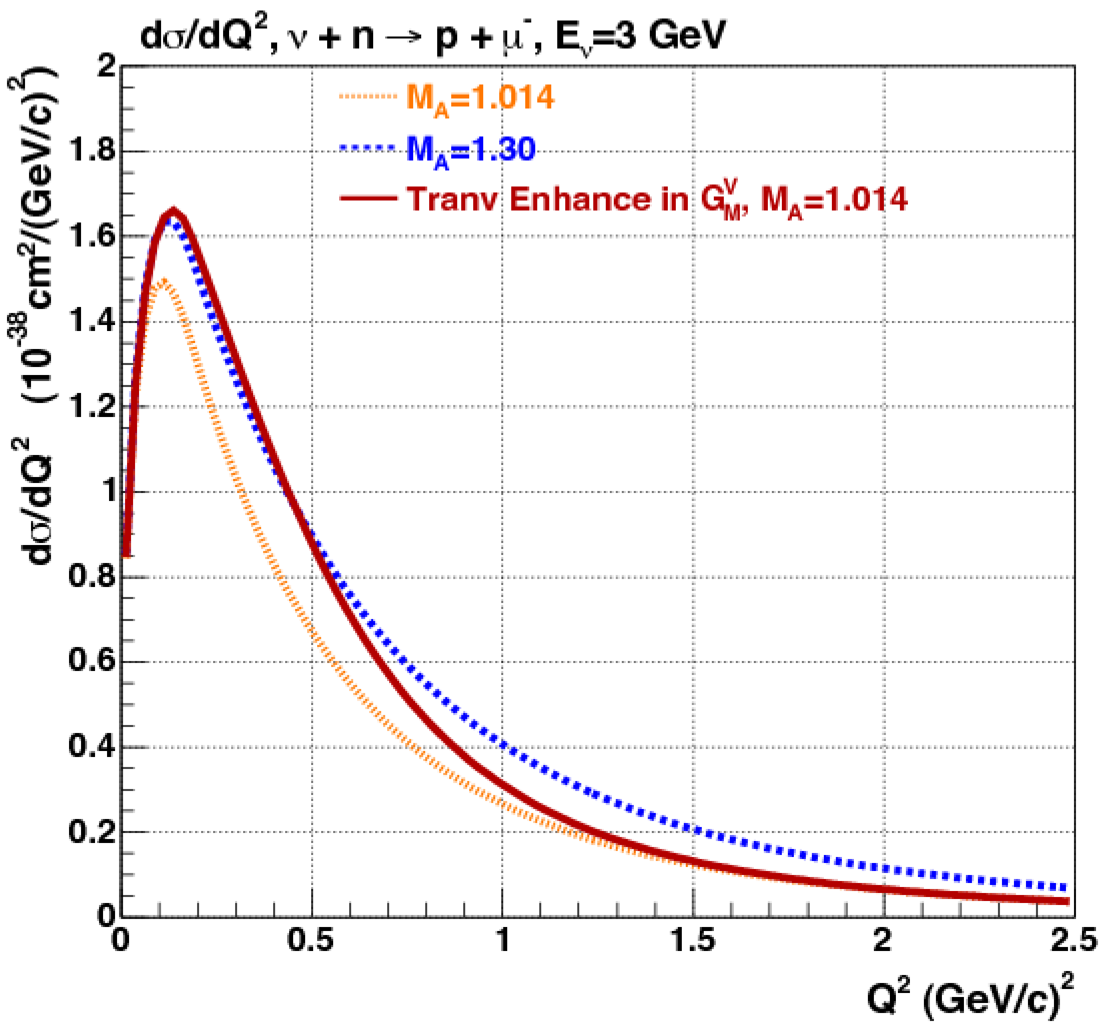


Example: one bin of $Q^2 \sim 0.68$

Ratio of integrated transverse response function: ^{12}C / free

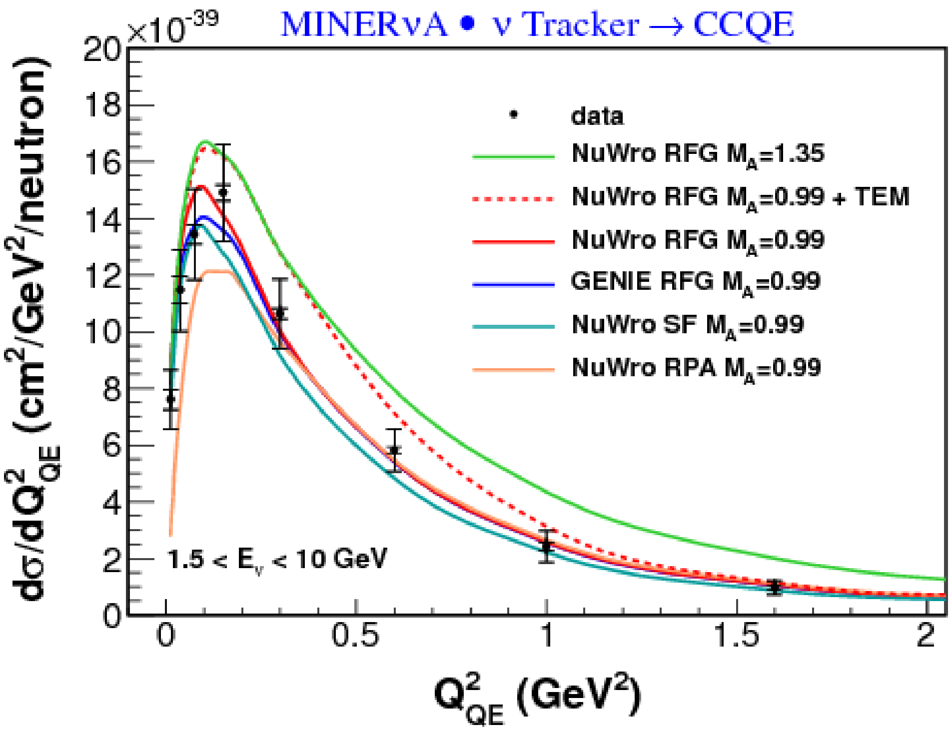
BBC TEM model

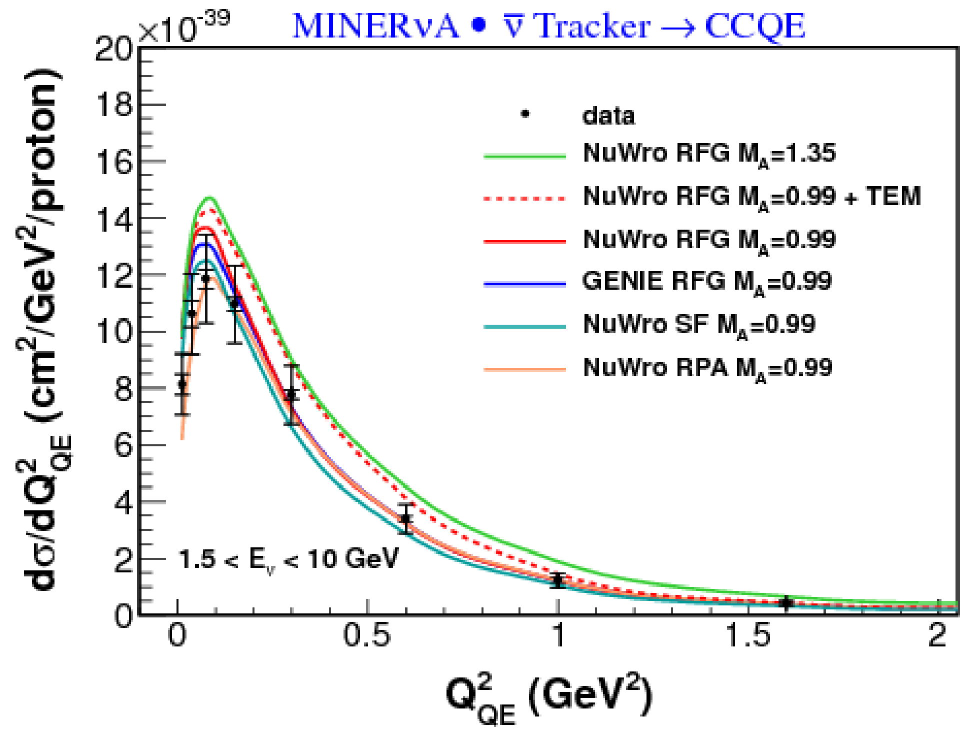
A. Bodek, H. Budd, M.E. Christy, Eur. Phys. J. C 71, 1726 (2011)



At MINERvA peak energy, TEM is like $M_A = 1.35$ at low Q^2 and like $M_A = 1.01$ at high Q^2

With NuWro RPA model





$M_A = 1.35$ best fit to MiniBooNE data

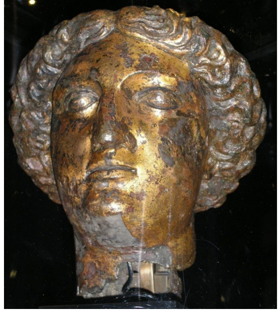
TEM empirical model based on electron scattering data

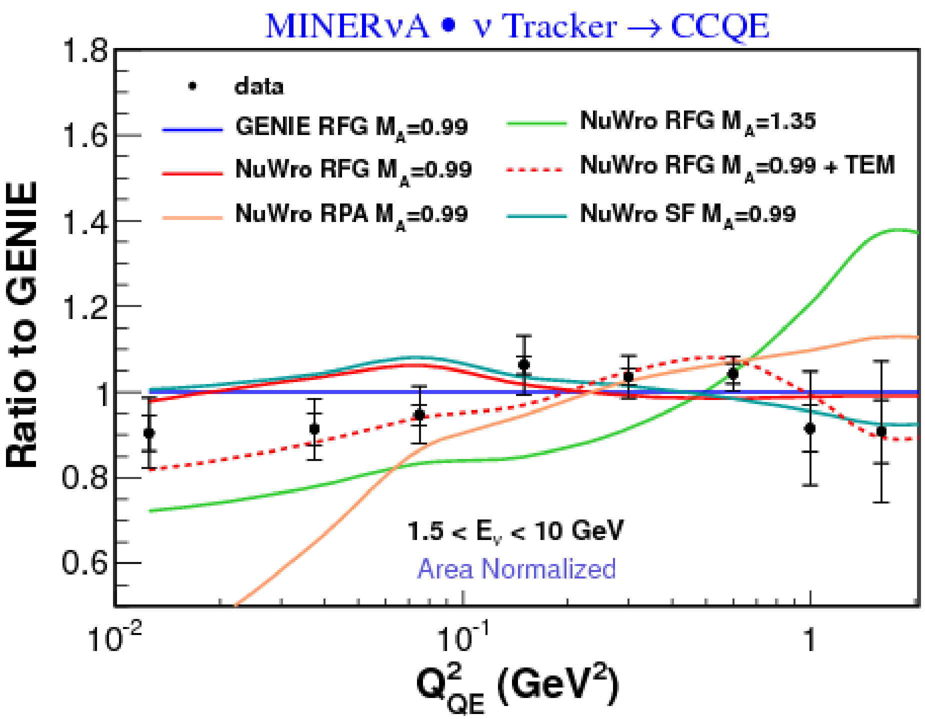
GENIE independent nucleons in mean field

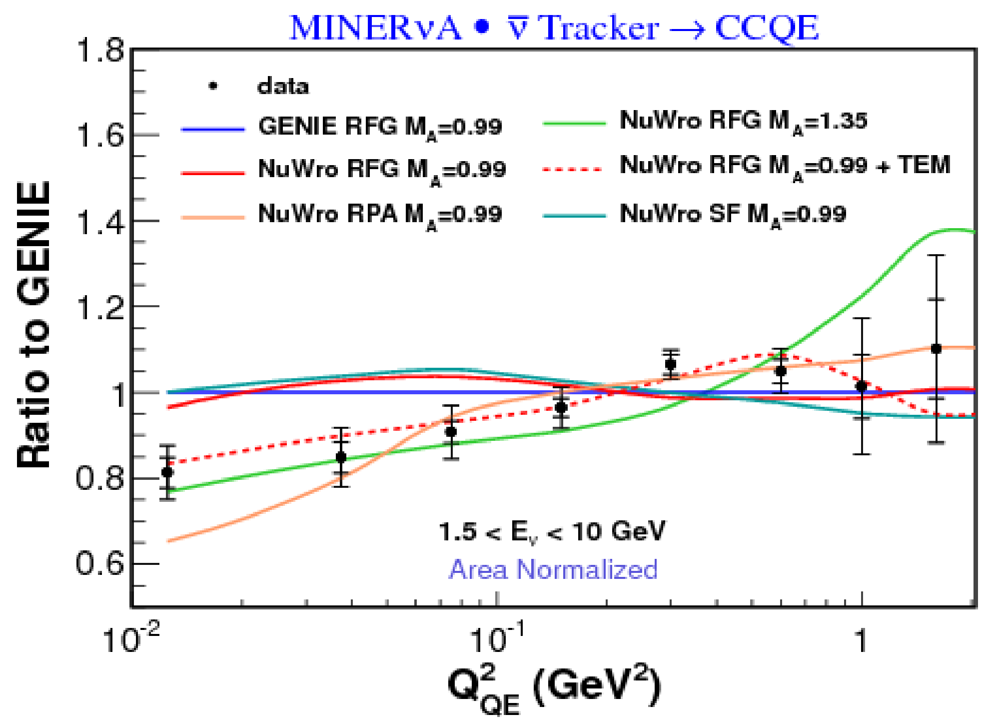
SF more realistic nucleon momentum-energy relation

RPA random phase approximation

NuWro RPA – shape only







$M_A = 1.35$ Phys.Rev.Lett. 100, 032301 (2008)

TEM Eur. Phys. J. C 71, 1726 (2011)

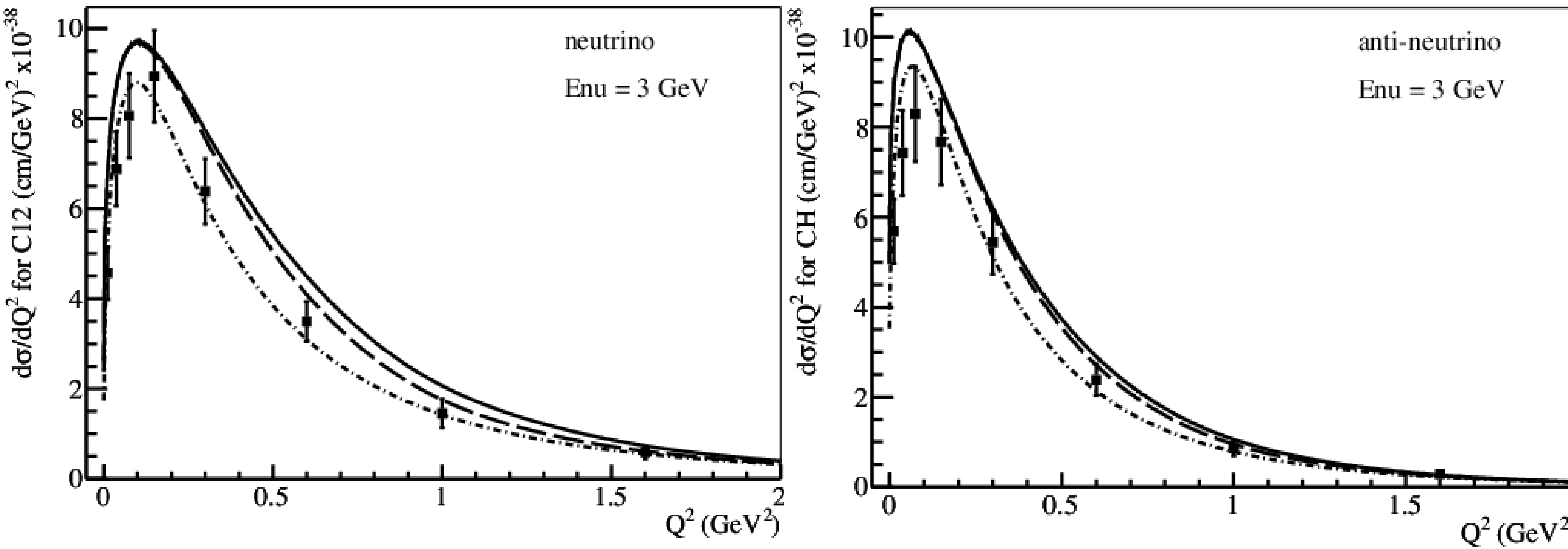
GENIE Nucl.Instrum.Meth. A 614:87-104 (2010)

SF Nucl.Phys. A579, 493 (1994)

RPA random phase approximation

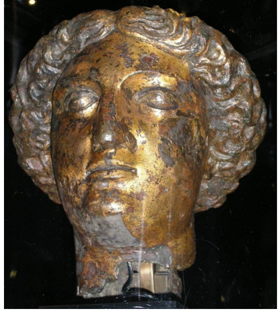
Valencia 2p2h RPA model

Gran *et. al.*, arXiv:1307.8105 [hep-ph]



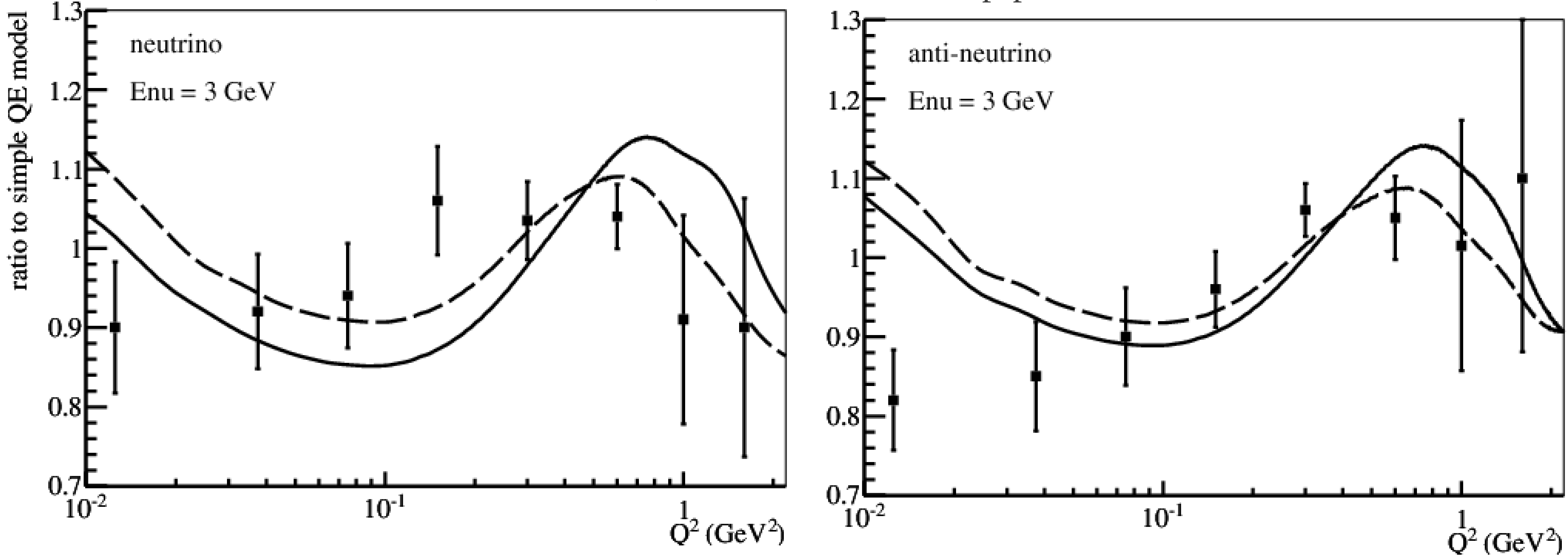
- RPA 2p2h
- Alternate high-Q^2 behavior
- No RPA no 2p2h

CAVEAT: Calculation at 3 GeV, true Q^2
Data is flux-integrated from 1.5 to 10 peaking at 3 GeV, true Q^2_{QE}



Valencia 2p2h RPA model

Gran *et. al.*, arXiv:1307.8105 [hep-ph]



RPA 2p2h
Alternate high-Q^2 behavior
No RPA no 2p2h = 1.00

CAVEAT: Calculation at 3 GeV, true Q^2
Data is flux-integrated from 1.5 to 10 peaking at 3 GeV, true Q^2_{QE}