Fermilab

NORTHWESTERN UNIVERSITY





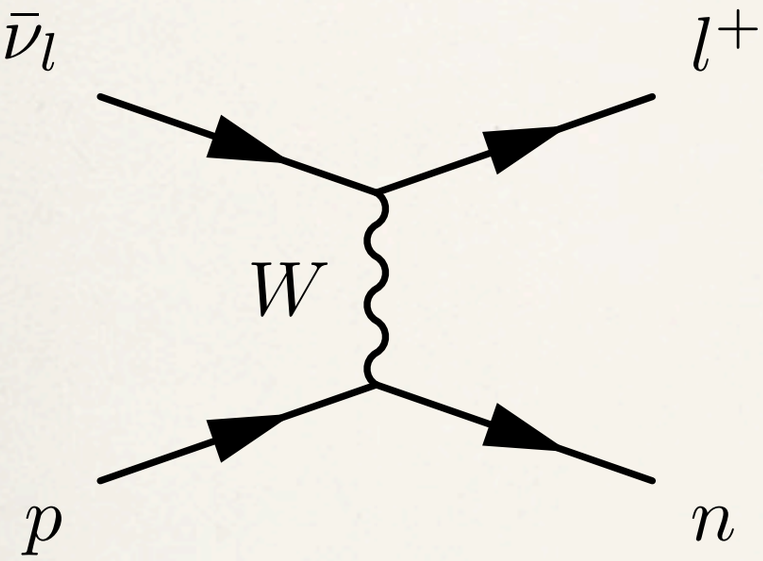
Charged Current Quasi-Elastic Scattering at MINERvA

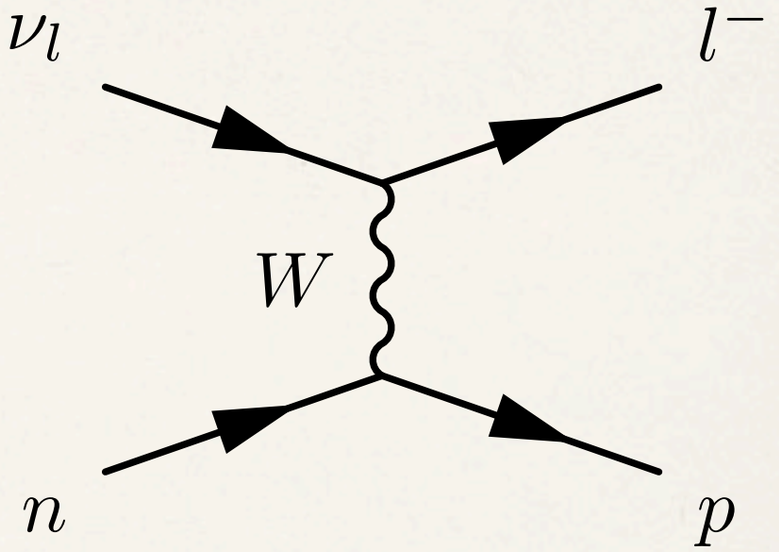
Cheryl Patrick, Northwestern University, USA, for the MINERvA collaboration

EPS-HEP, July 18-24 2013, Stockholm

Quasi-elastic scattering

No pions are in the final state; there should be just one muon and one nucleon





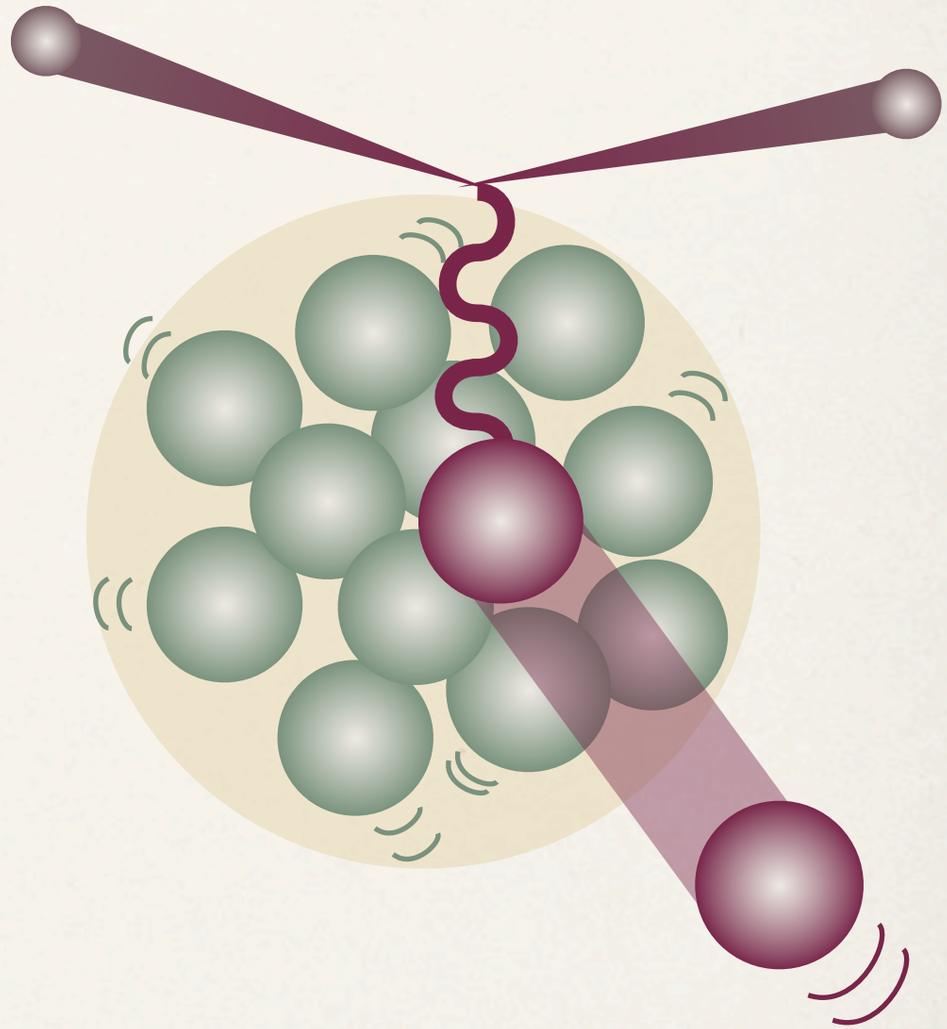
We can reconstruct the neutrino energy and Q^2 just from the muon kinematics

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

$$E^{QE}_\nu = \frac{m^2_n - (m_p - E_b)^2 - m^2_\mu + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

Relativistic Fermi Gas model

- RFG is a frequently-used nuclear model
- Nucleons behave as if they are independent in the mean field of the nucleus
- Initial-state momenta are Fermi distributed
- Cross-sections can be modeled by a multiplier to the Llewellyn Smith cross-section for a free nucleon
- Its free parameters (form-factors) can be determined from electron scattering, except for the axial mass, M_A, which must be measured in neutrino scattering

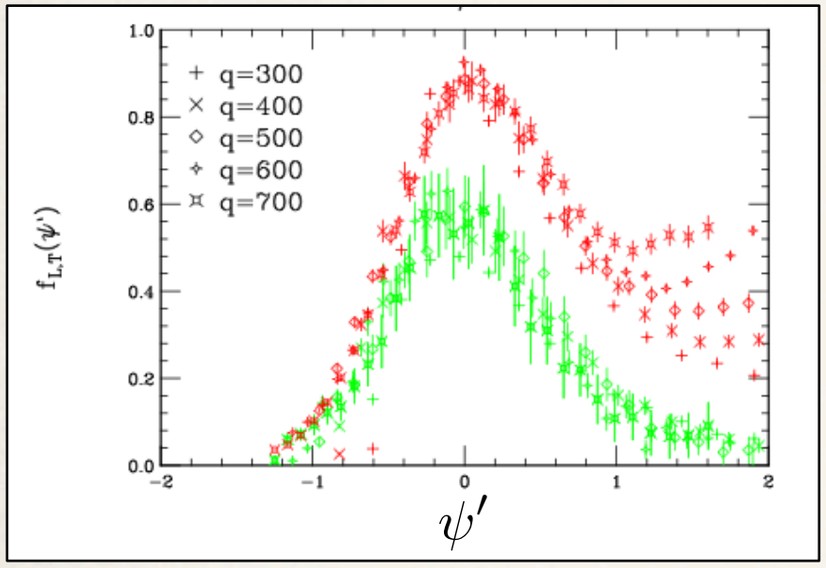


$$F_A(Q^2) = -\frac{g_A}{\left(1+\frac{Q^2}{M_A^2}\right)^2}$$

Axial form factor

Axial mass

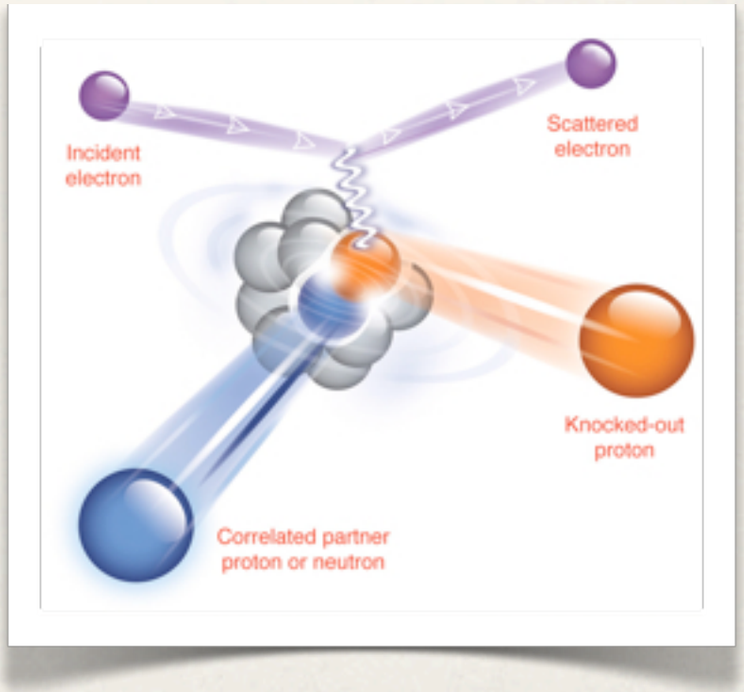
Nuclear effects - correlations



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

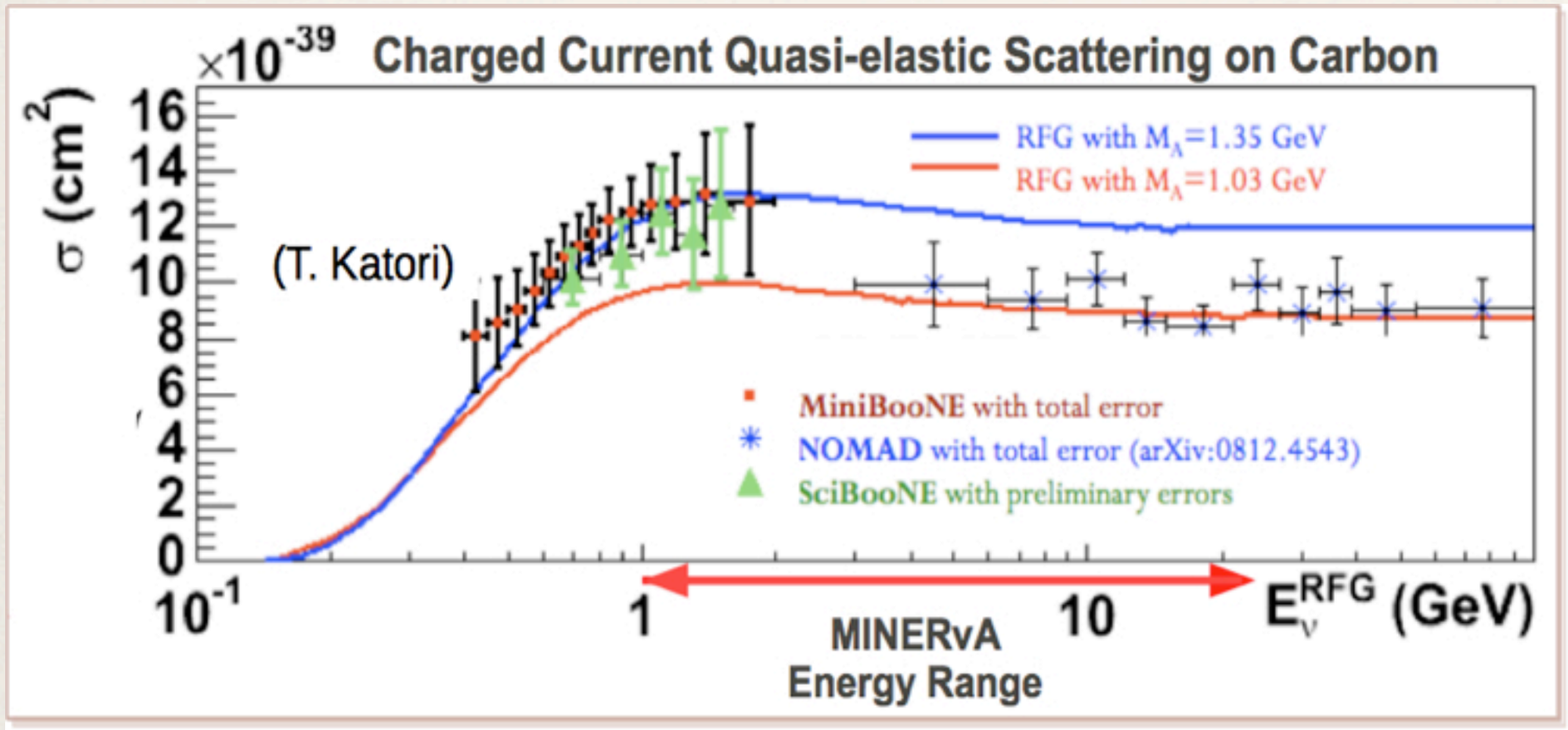
- **Transverse enhancement** is seen in electron-scattering cross-sections at J-Lab
- Transverse and longitudinal cross-sections differ
  - The RFG model predicts no difference
- The exact physical process is unclear, but the effect can be parameterized

- **Correlations** between initial-state nucleons could lead to:
  - Initial momenta above the Fermi cut-off
  - "Partner" nucleons being ejected
  - Wrongly-reconstructed neutrino energies



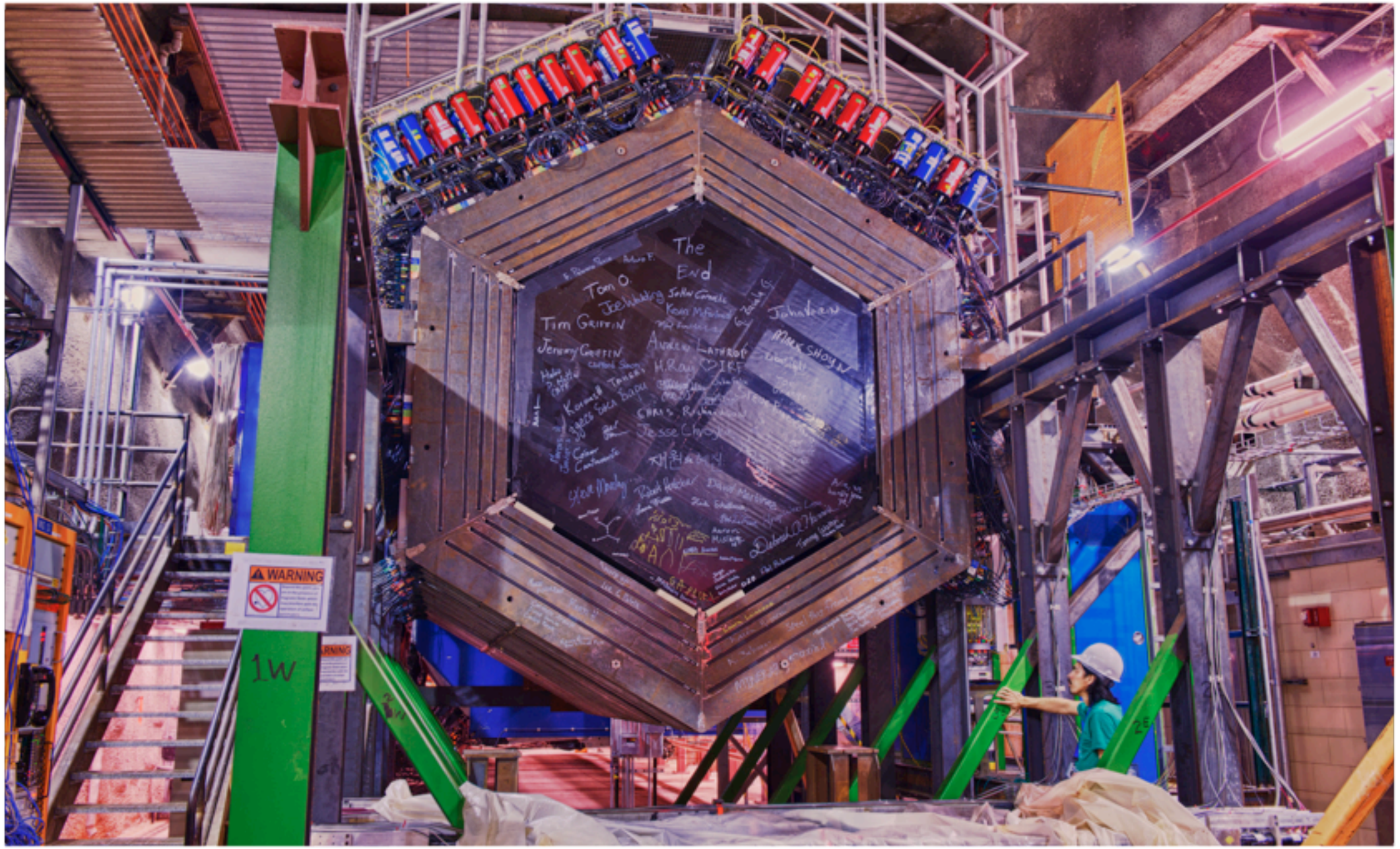
R. Subedi et al, Science 320 1476 (2008)

Other experiments' results



A.A. Aguilar-Arevalo et al. [MiniBooNE Collaboration], Phys. Rev. D 81, 092005 (2010)

- This shows best fits of MiniBooNE, SciBooNE and NOMAD cross-sections to the RFG model for carbon
- Lower-energy experiments predict M_A=1.35 GeV, NOMAD predicts M_A=1.03 GeV when fitting to the same model
- This is a hint that we could be seeing additional nuclear effects beyond the RFG model

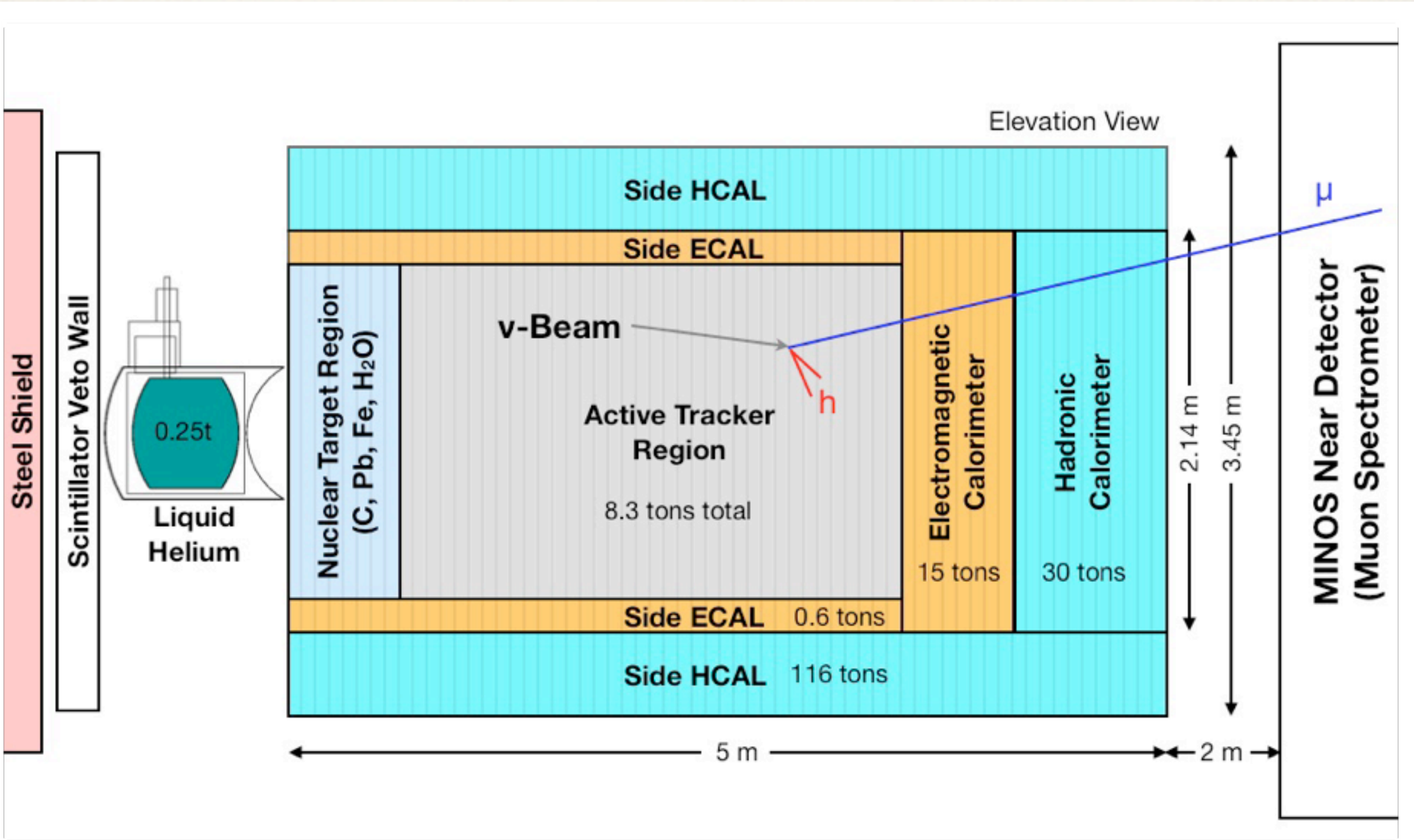


MINERvA

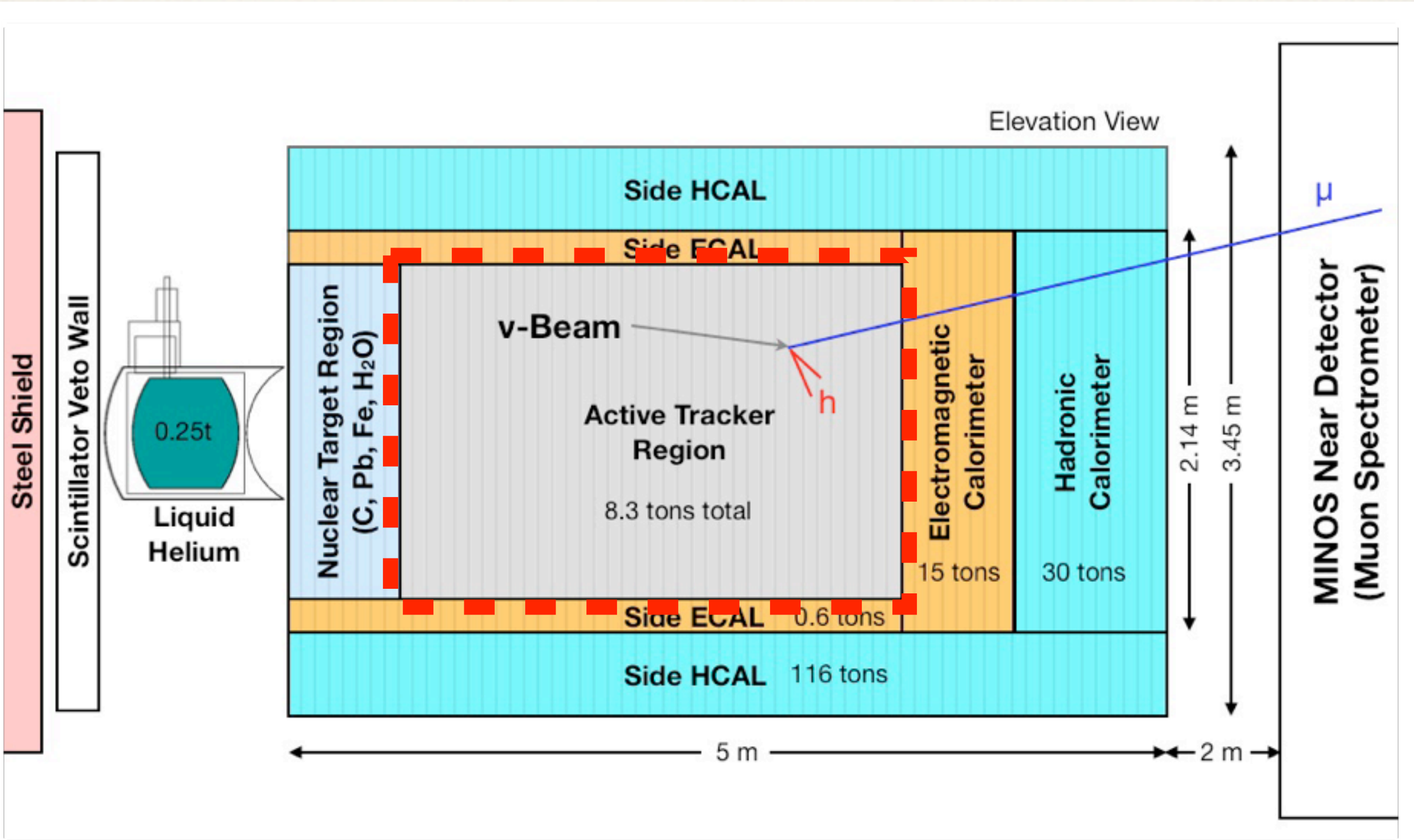
A neutrino-scattering experiment at Fermilab

EPS-HEP, July 18-24 2013, Stockholm

MINERvA detector



MINERvA detector



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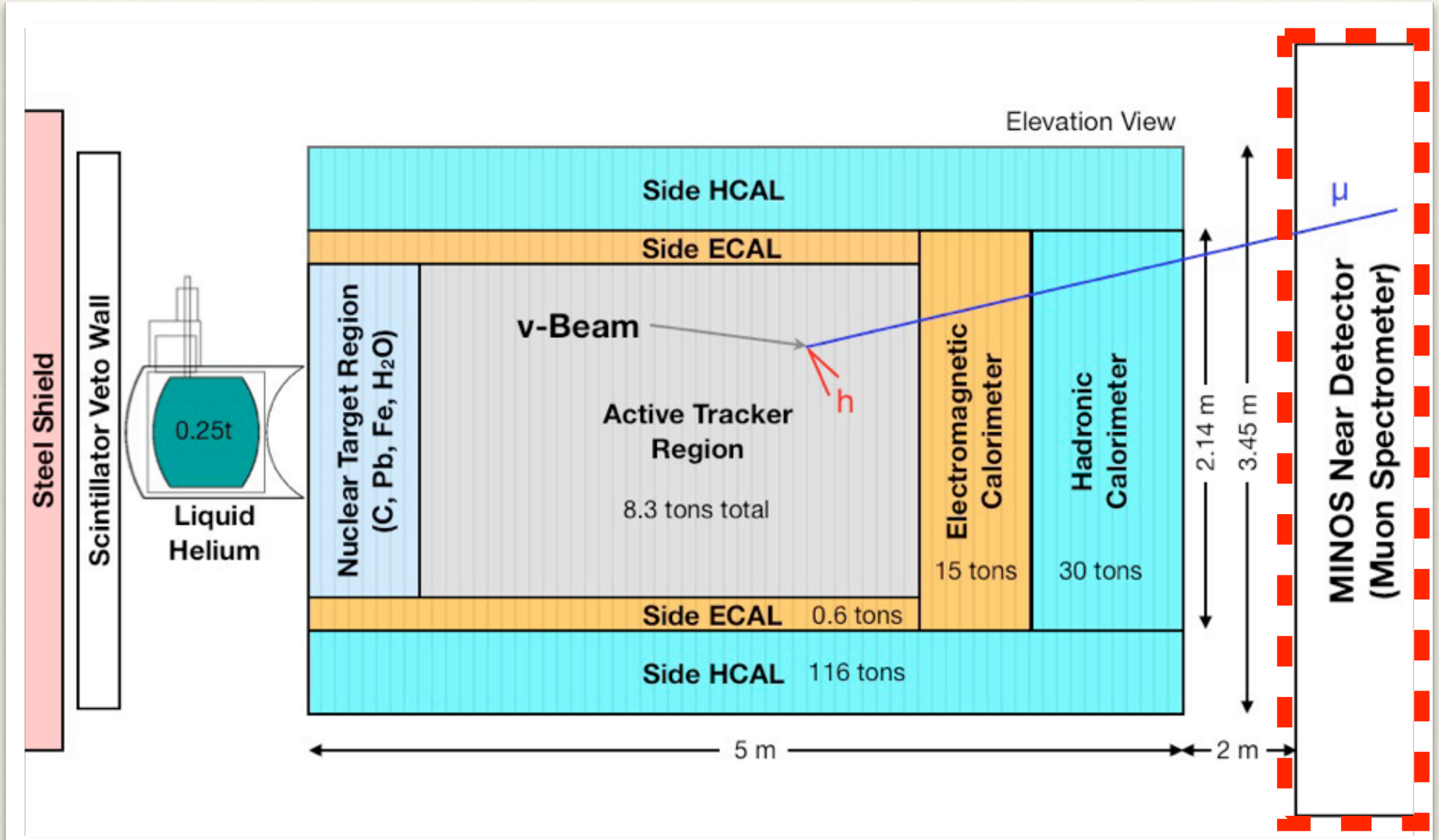
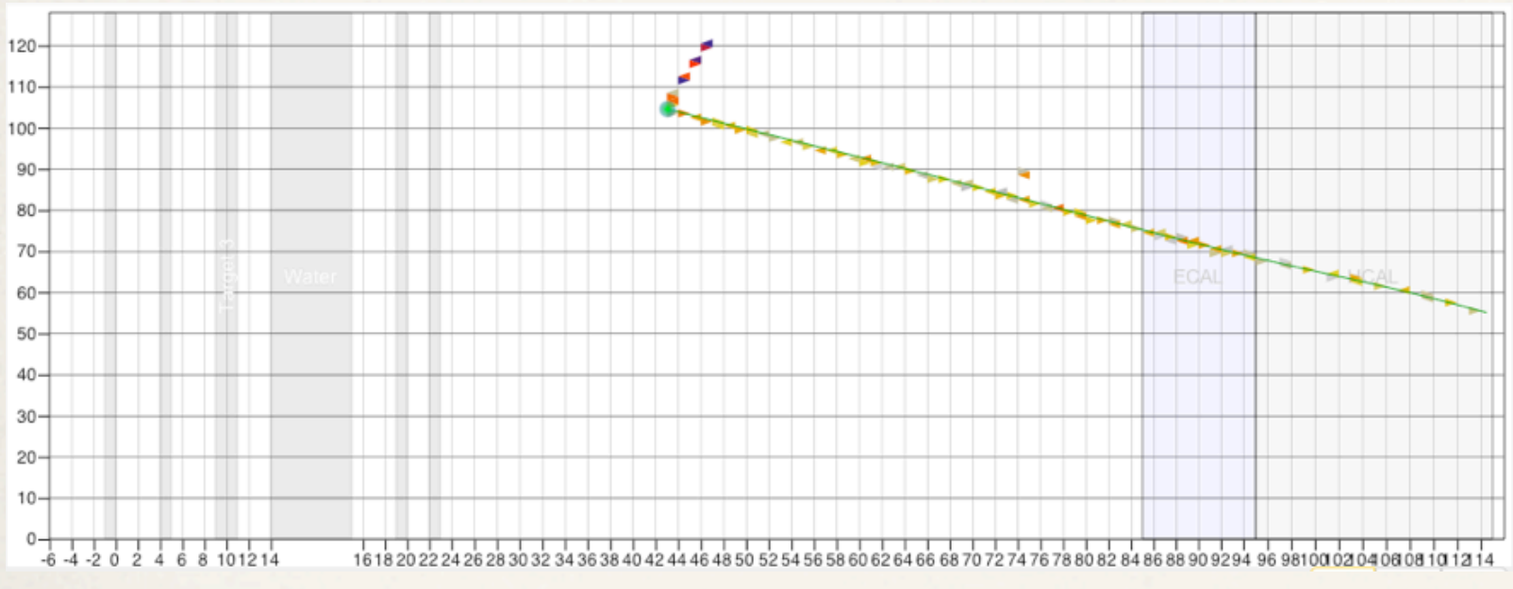


Quasi-elastic events in MINERvA

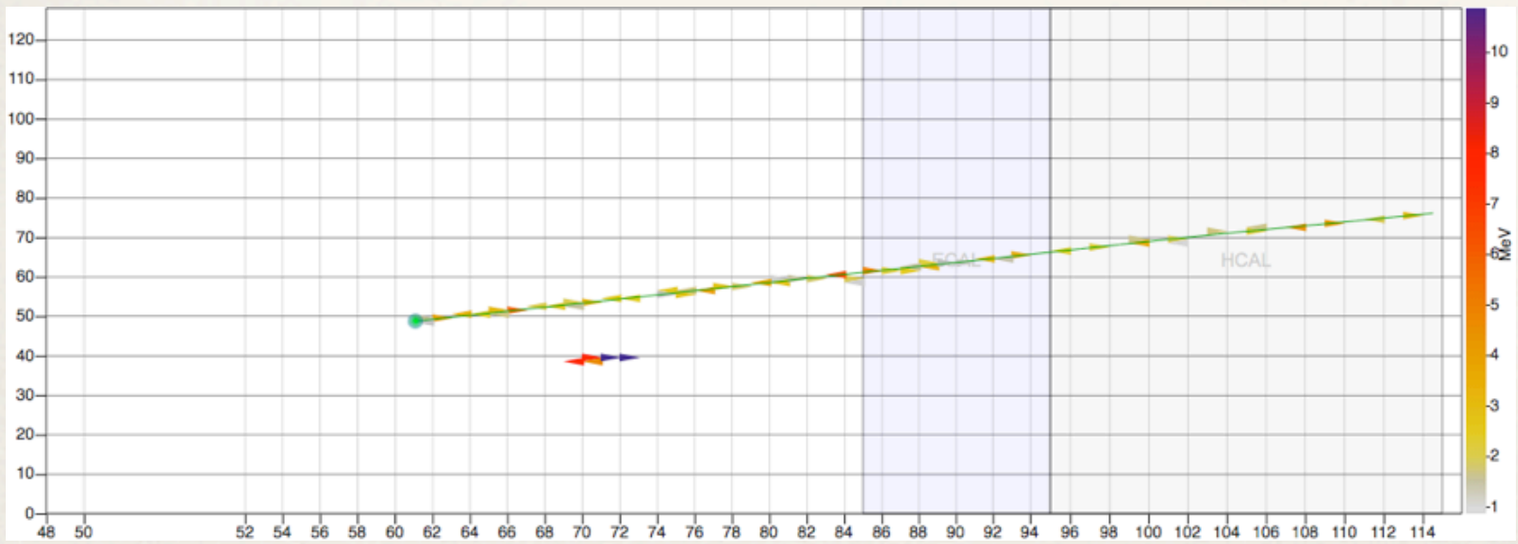
Neutrino mode

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



Antineutrino mode

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



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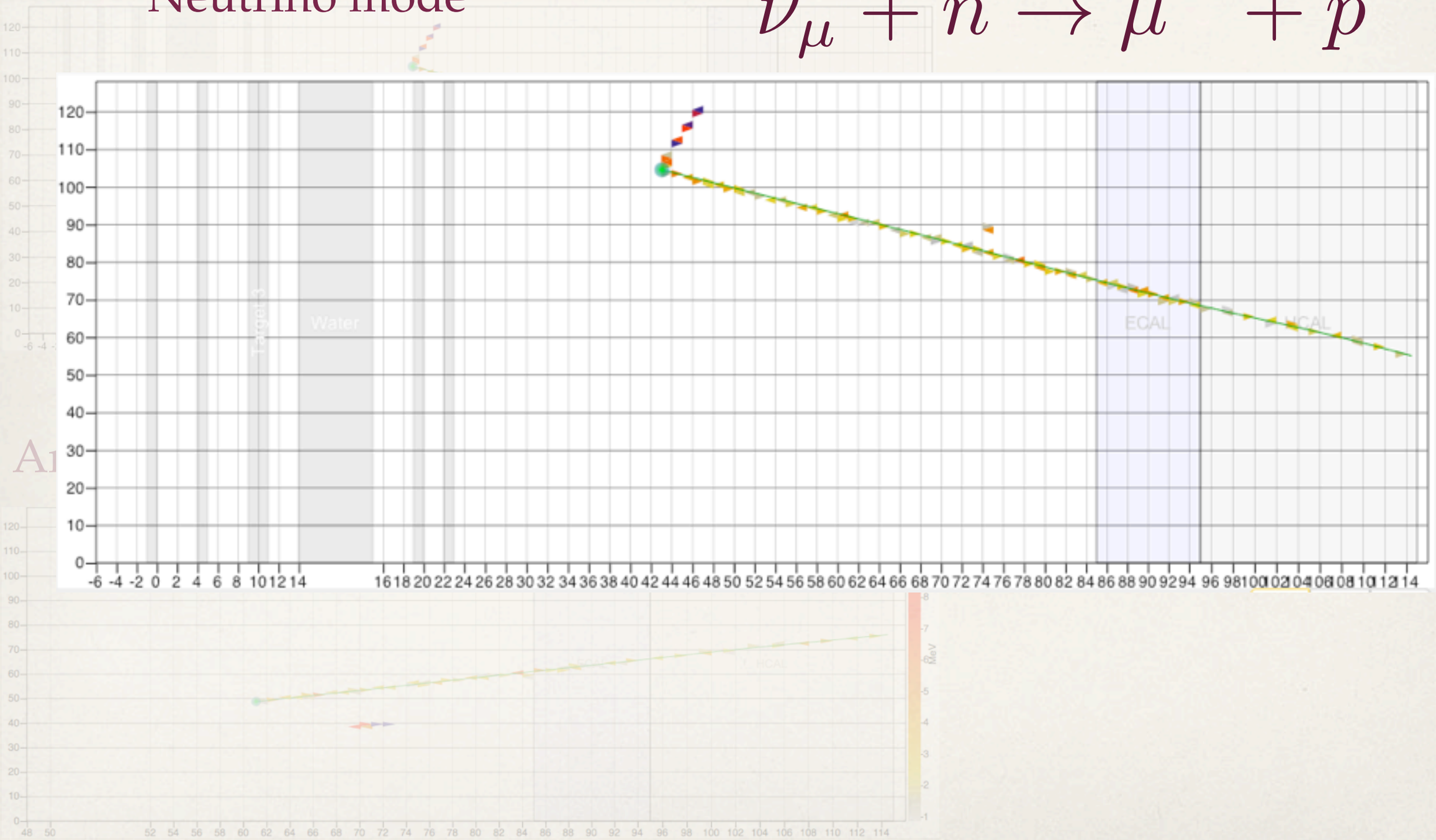

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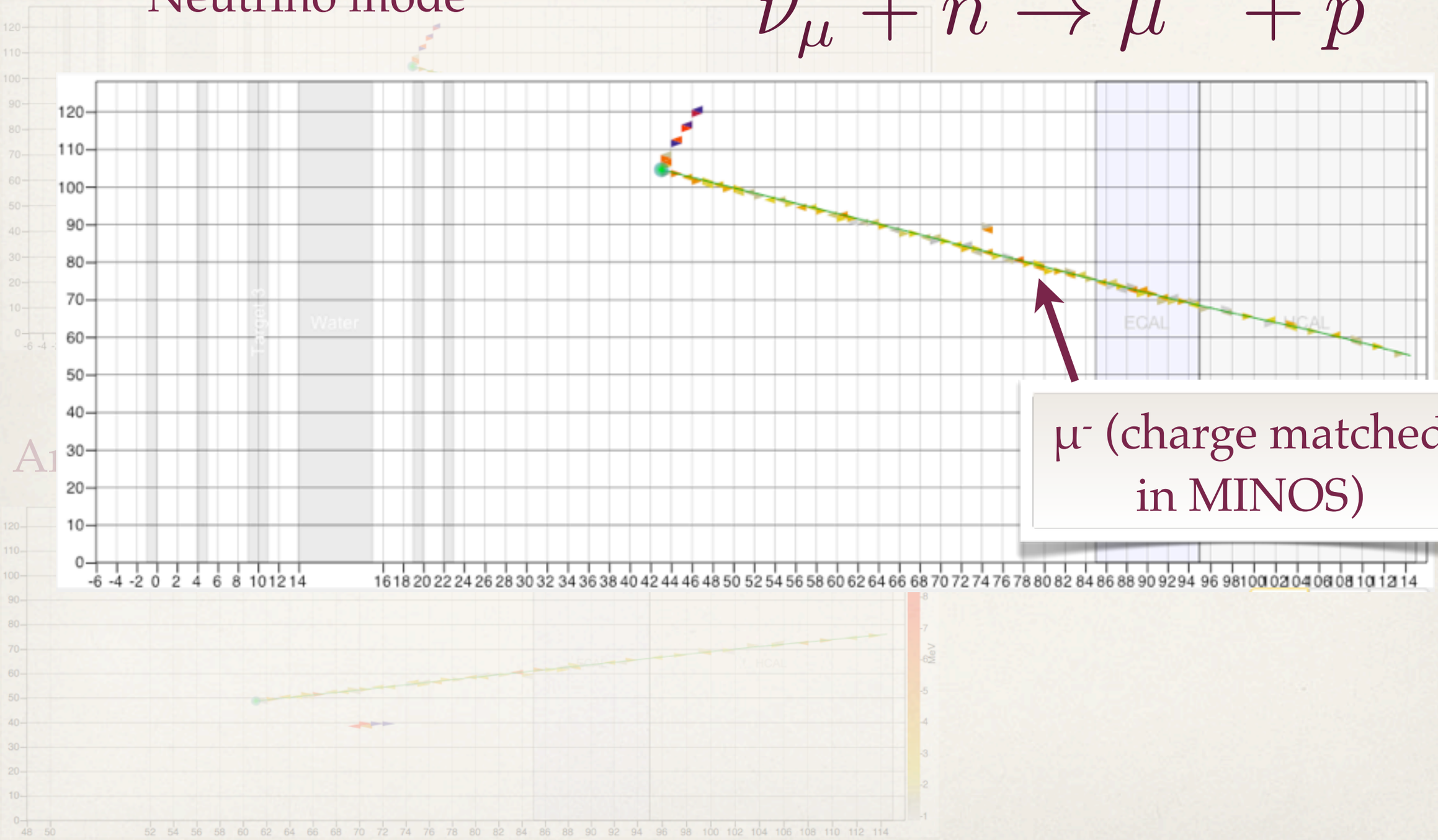

μ^- (charge matched in MINOS)

Quasi-elastic events in MINERvA

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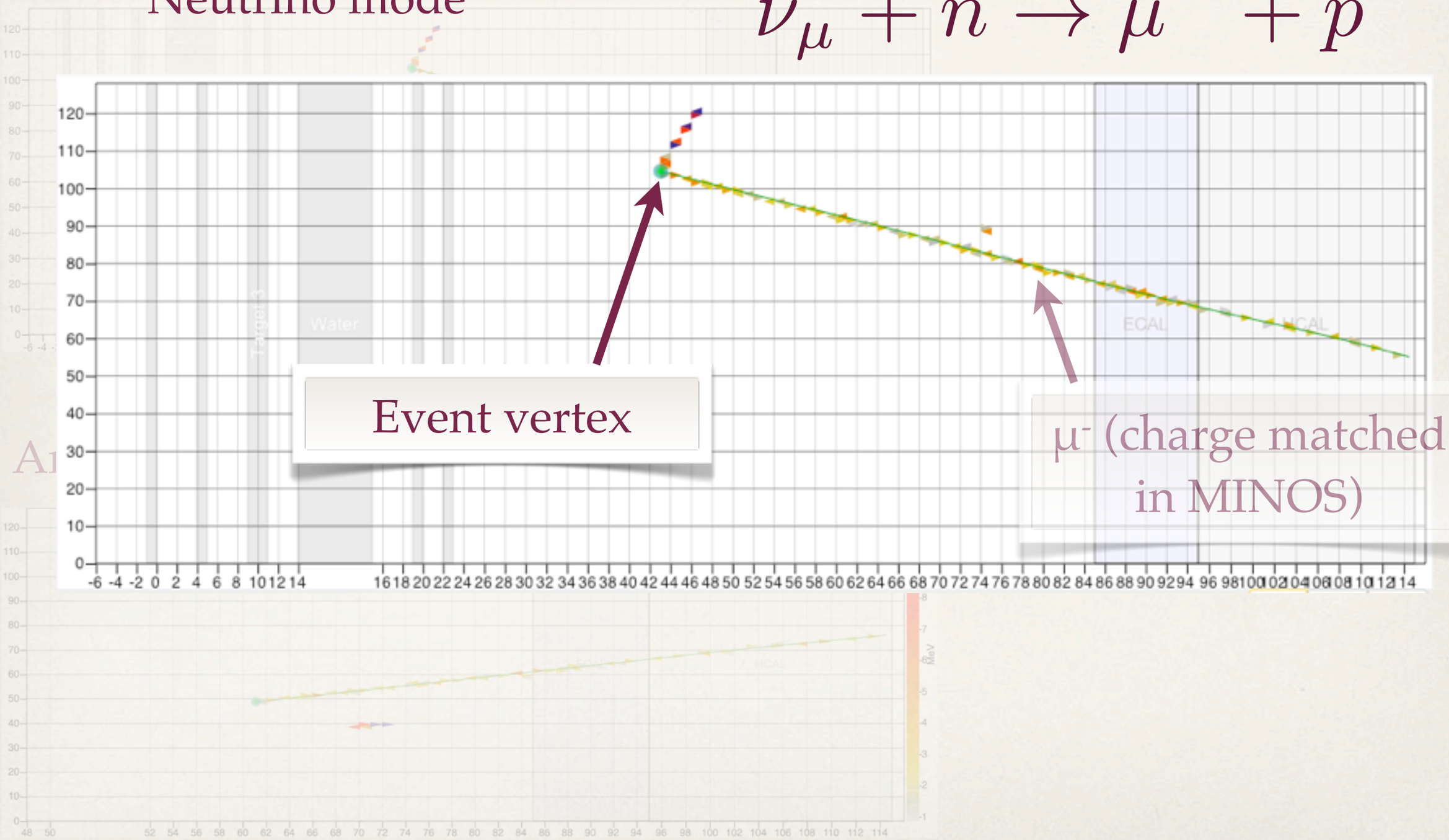


Quasi-elastic events in MINERvA

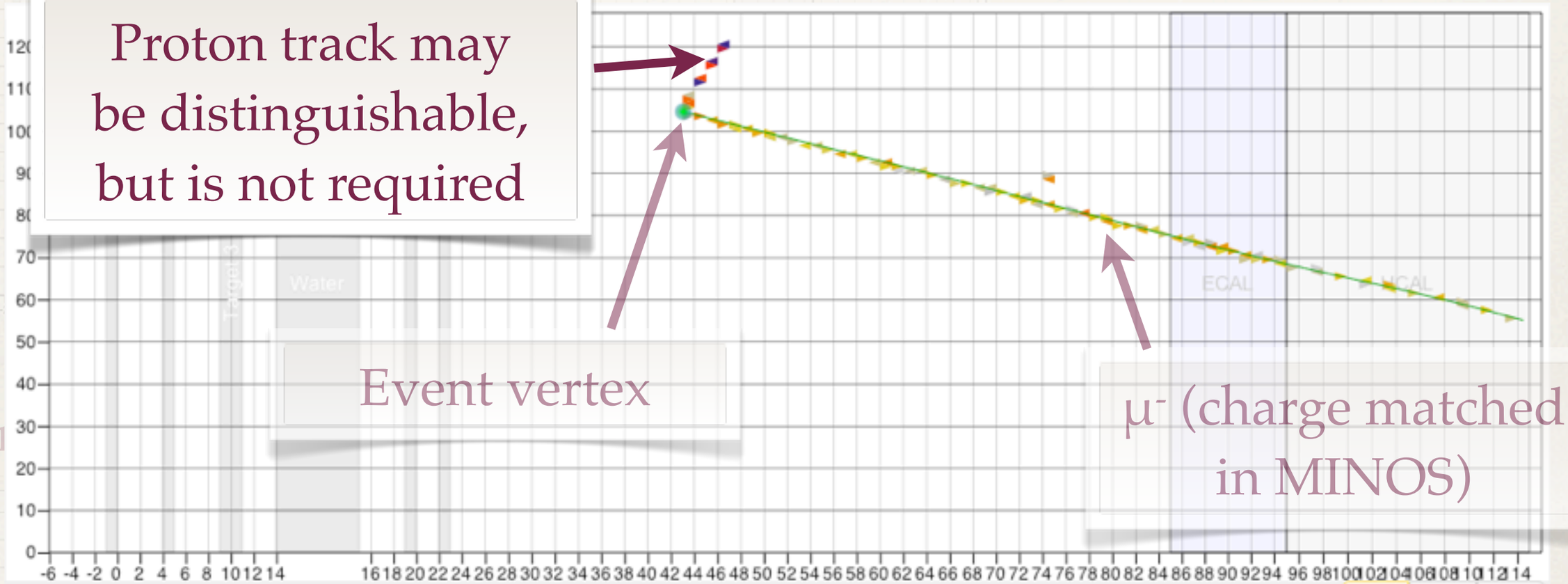
Neutrino mode

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

Neutrino mode

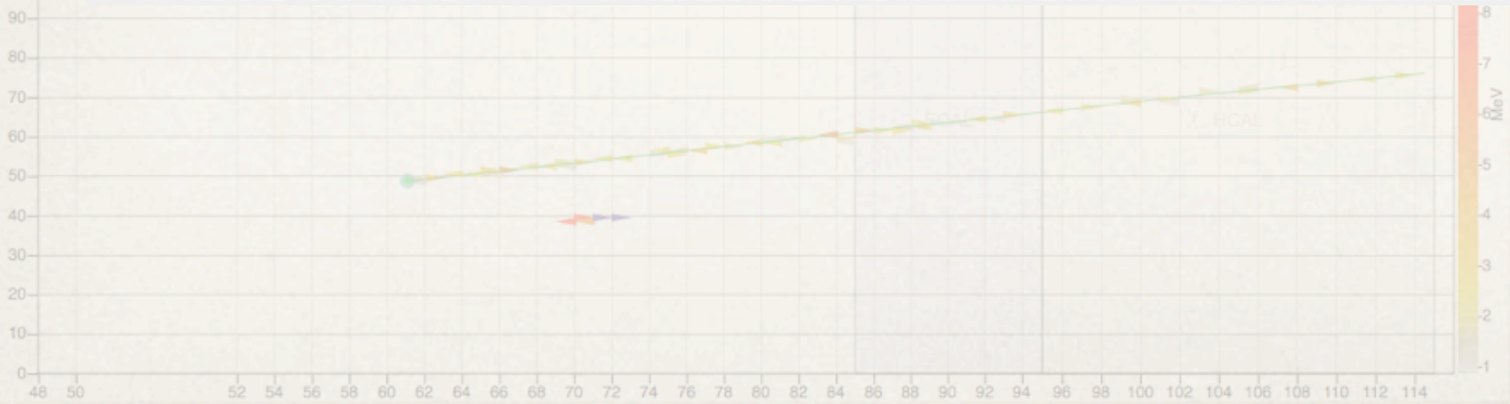
$\nu_\mu + n \to \mu^- + p$

Proton track may be distinguishable, but is not required



Event vertex

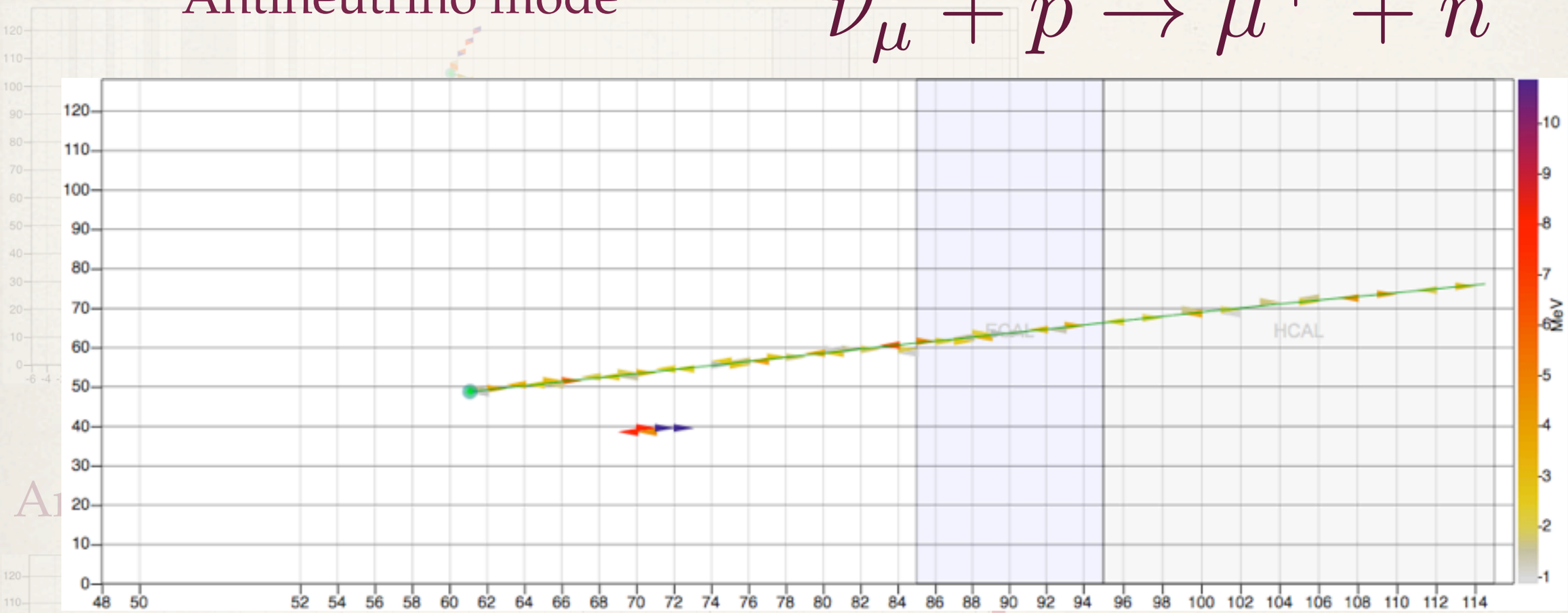
μ^- (charge matched in MINOS)



Quasi-elastic events in MINERvA

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

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



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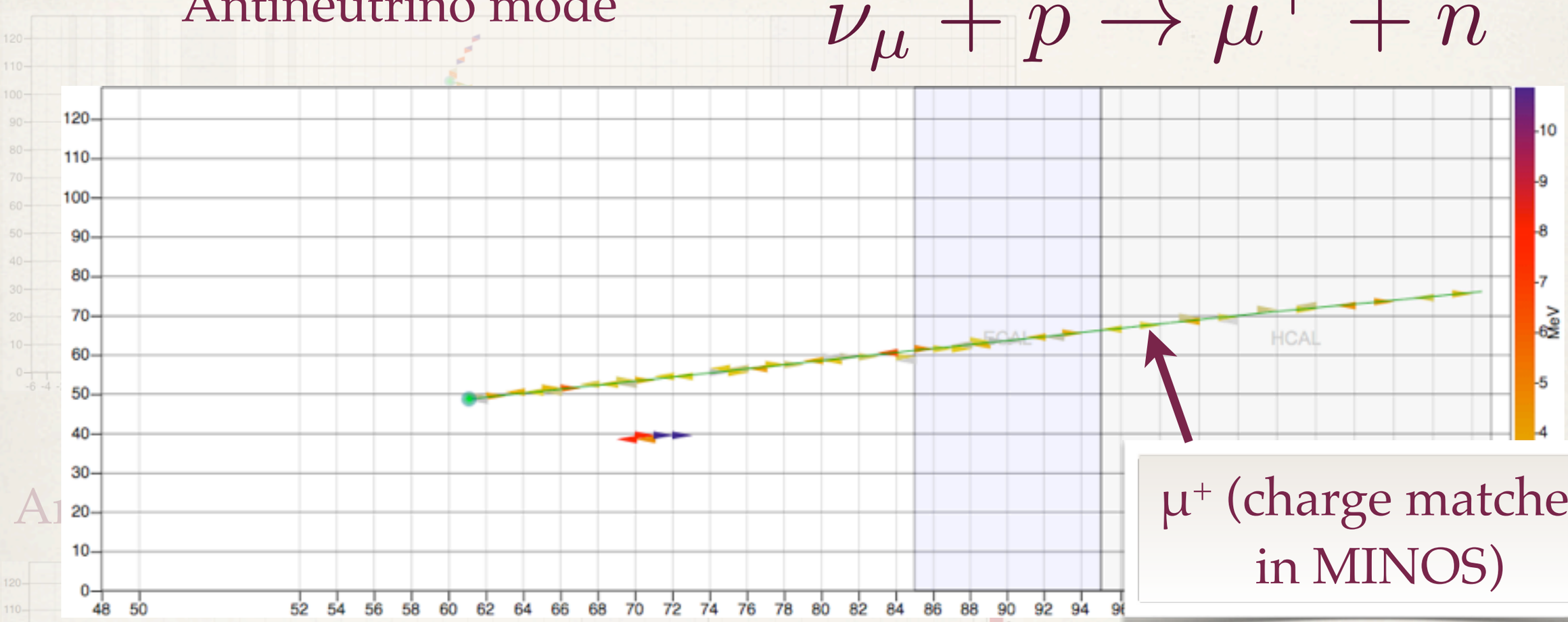

μ^+ (charge matched in MINOS)

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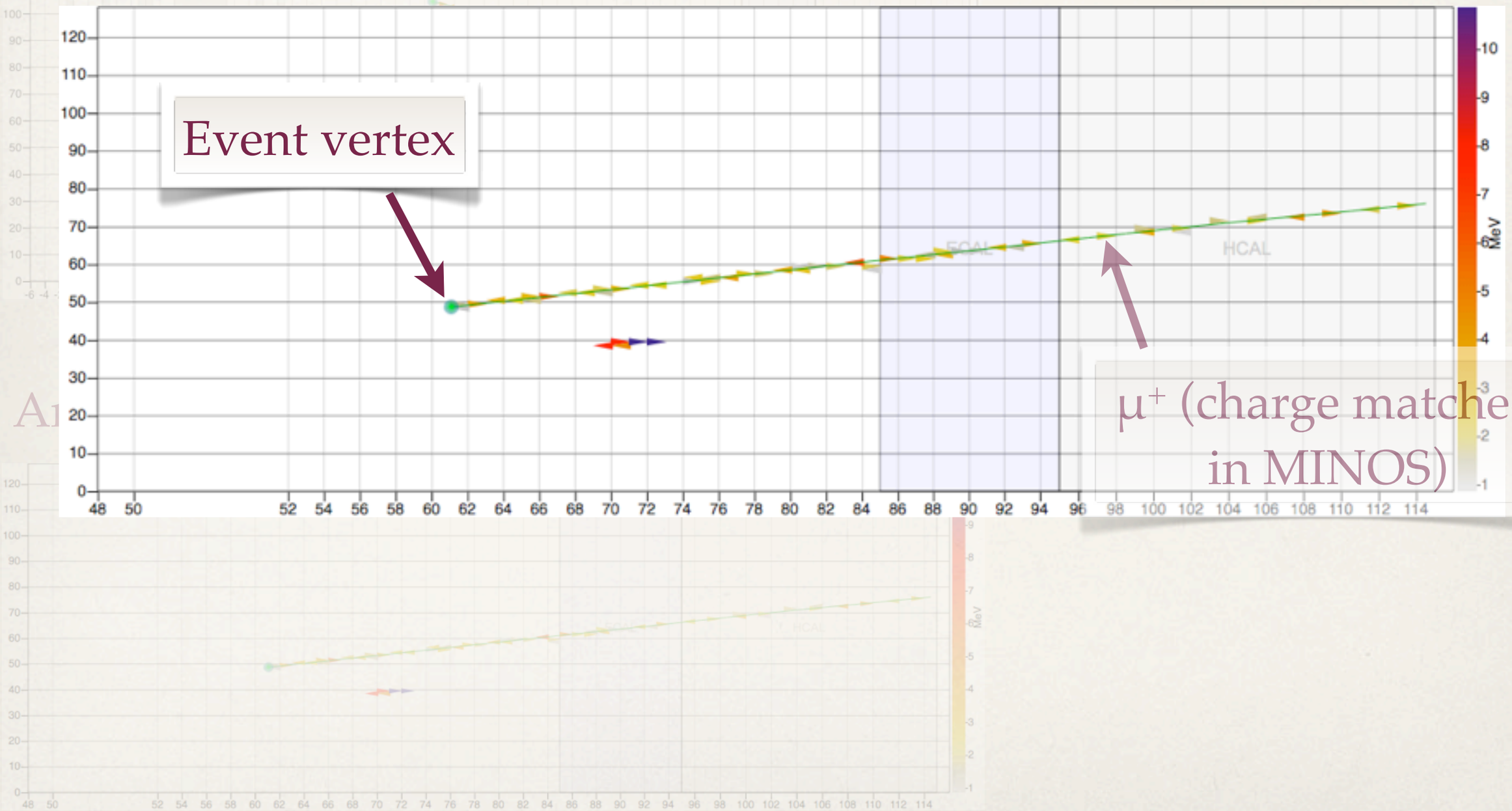

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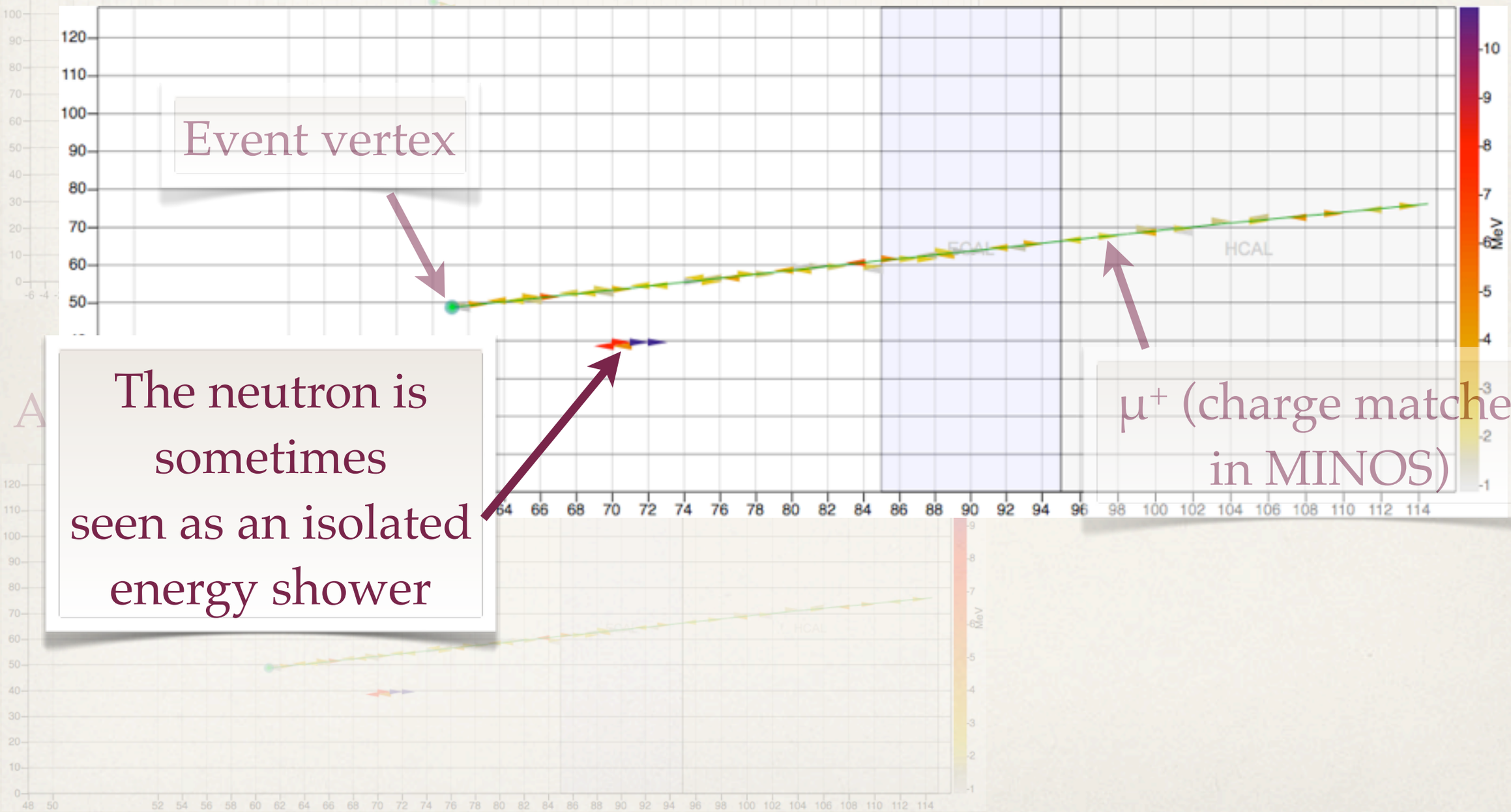

The neutron is sometimes seen as an isolated energy shower

μ^+ (charge matched in MINOS)

Selecting QE events

- The muon must be matched to a MINOS track
  - μ^- for neutrino mode; μ^+ for antineutrino mode
- The event vertex must be within the fiducial volume
  - within the central 110 planes of the scintillator tracking region
  - no closer than 22cm to any edge of the planes
- We limit the number of isolated energy showers
  - maximum 2 for neutrino mode, 1 for antineutrino mode
- We cut on recoil energy

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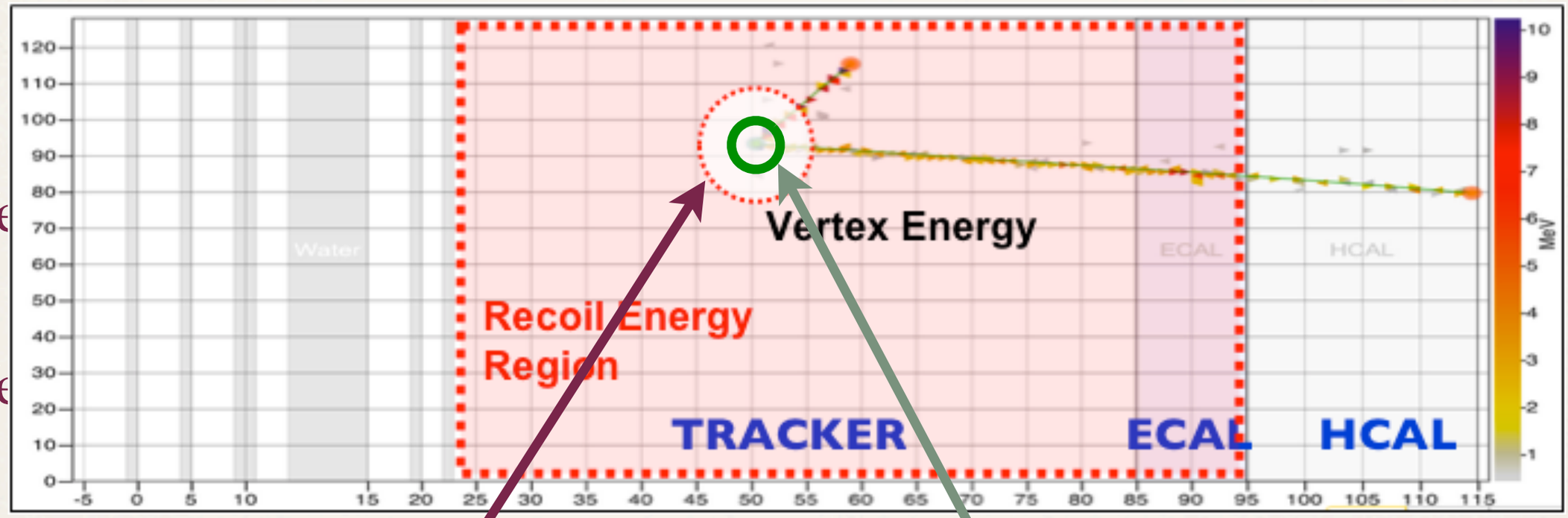

Exclude sphere around vertex
30 g/cm² for neutrino mode
Contains <225 MeV protons

Antineutrino mode
exclude 10 g/cm²
Contains <120 MeV protons

Selecting QE events

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- We
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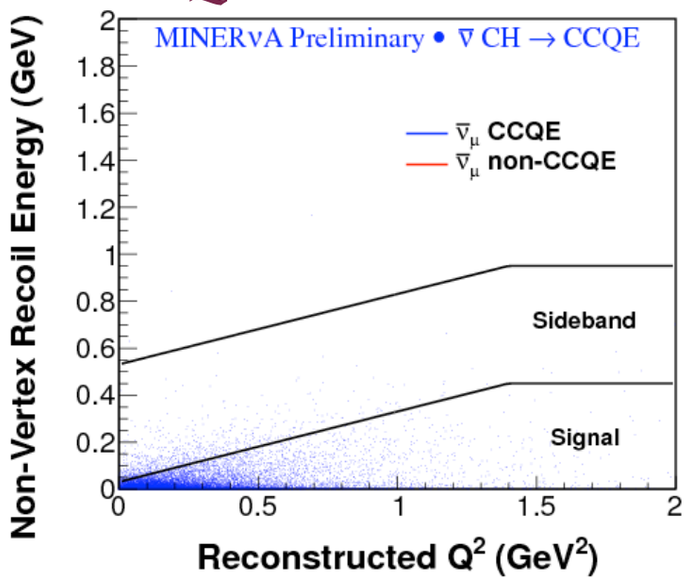
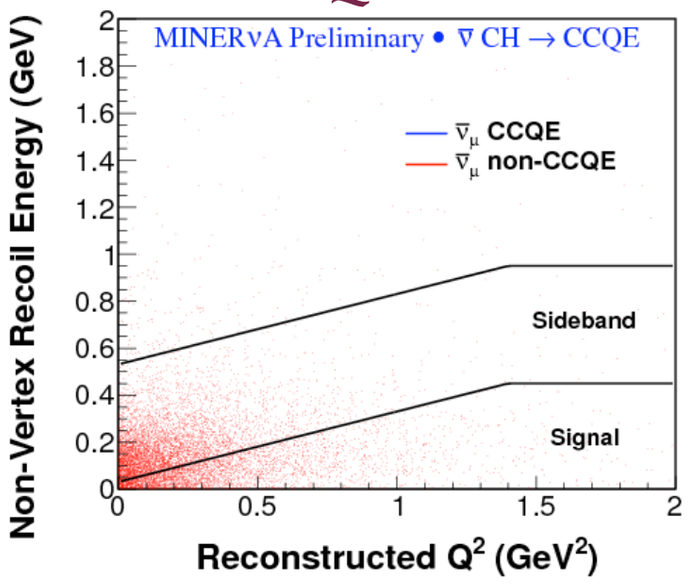
- We

QE

Not QE

$\bar{\nu}$





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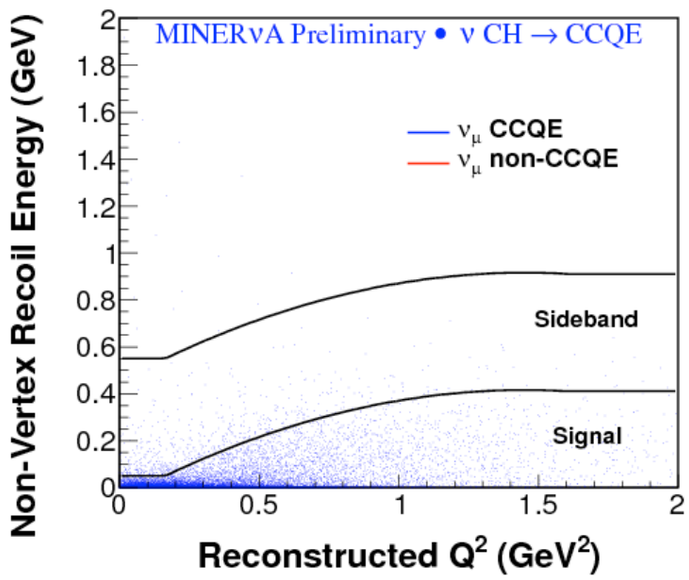

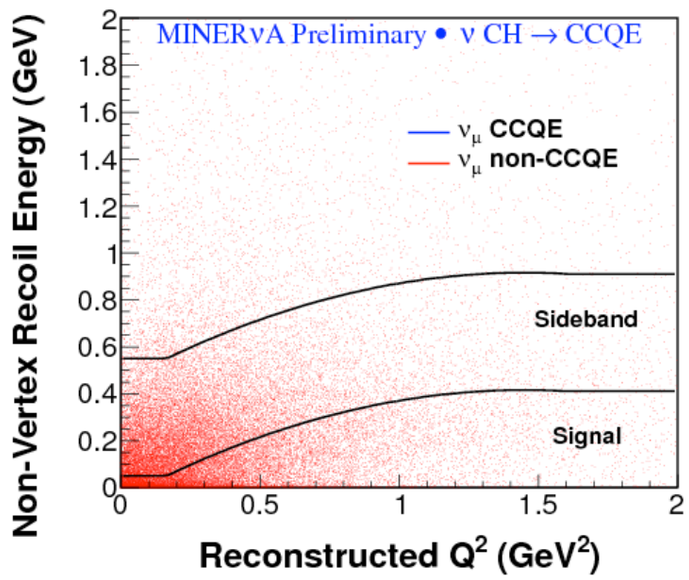

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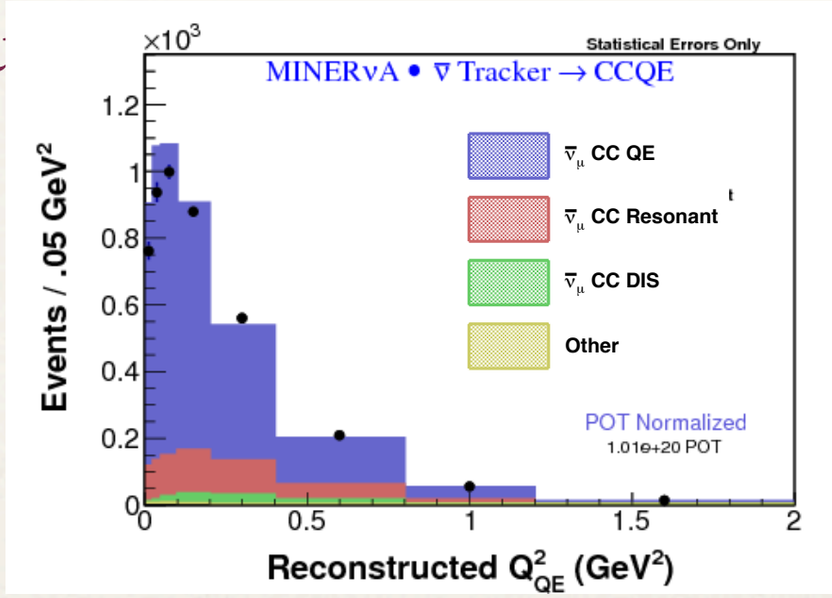
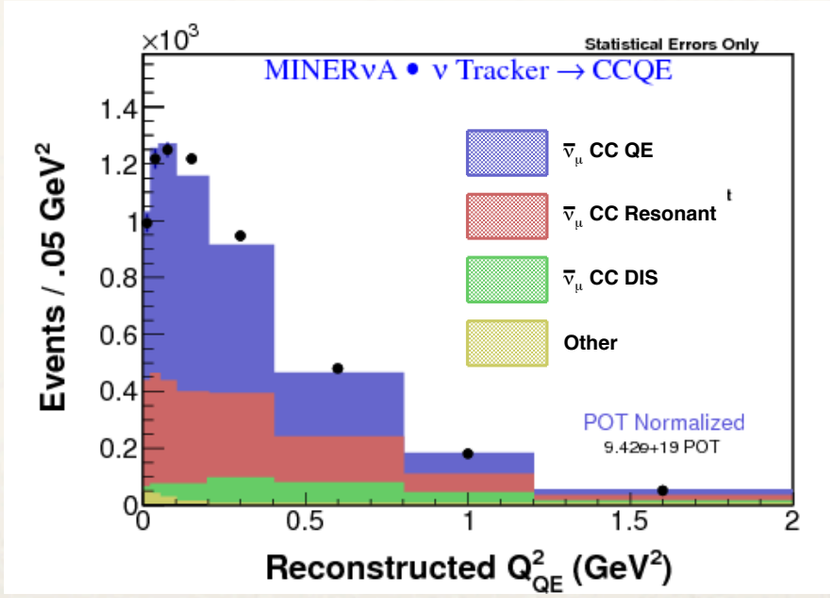
$\bar{\nu}$



54% eff, 77% purity

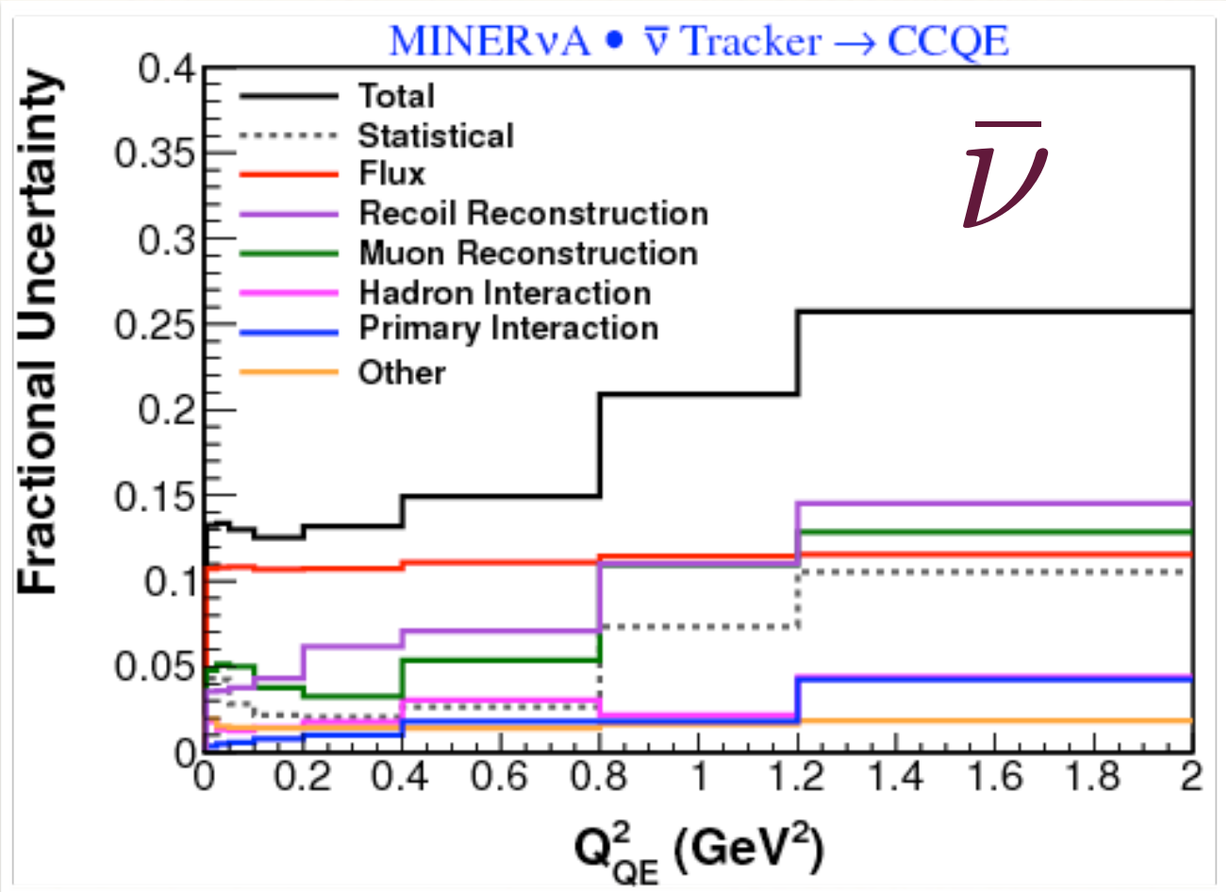
ν

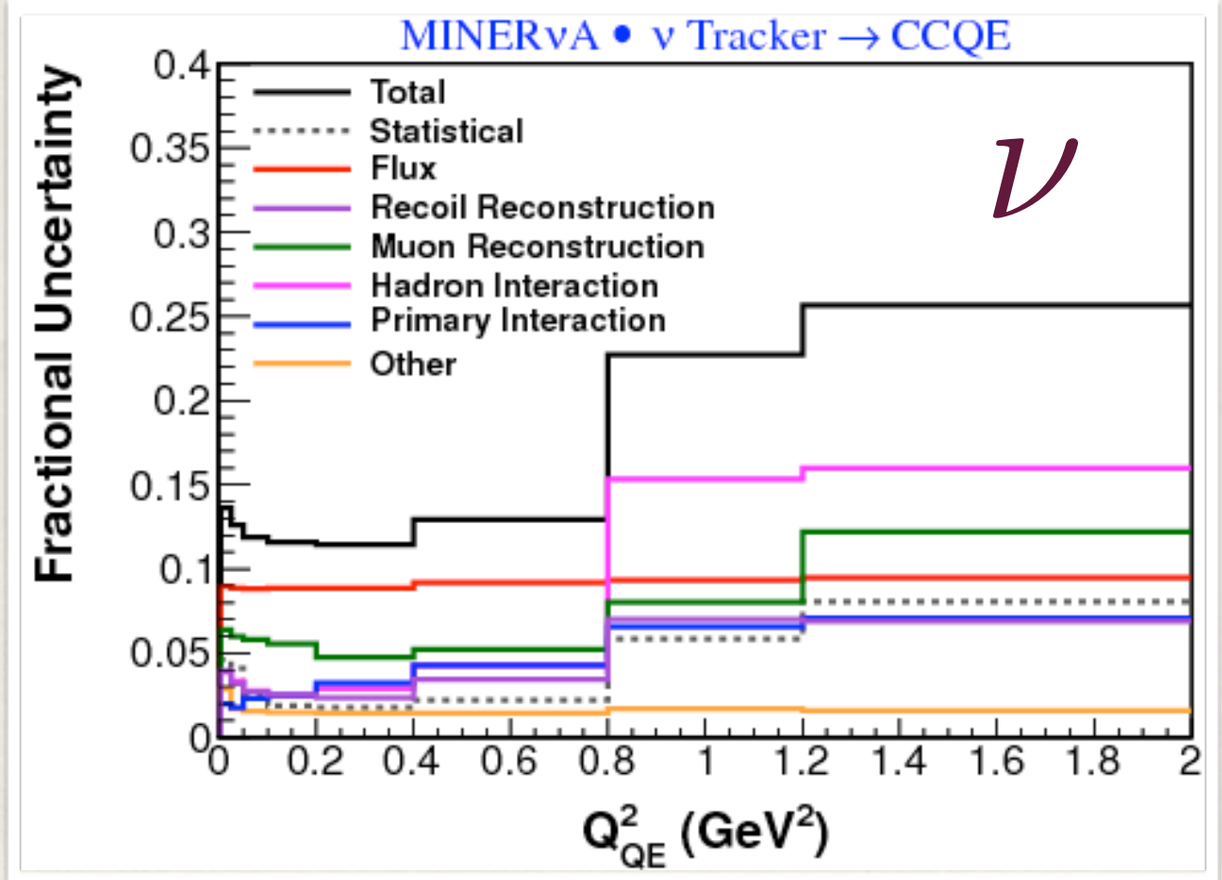


47% eff, 49% purity

Uncertainties

- Flux uncertainty
- Statistical uncertainty
- Hadron interaction model uncertainty
- Total uncertainty





Uncertainties

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- Statistical uncertainty
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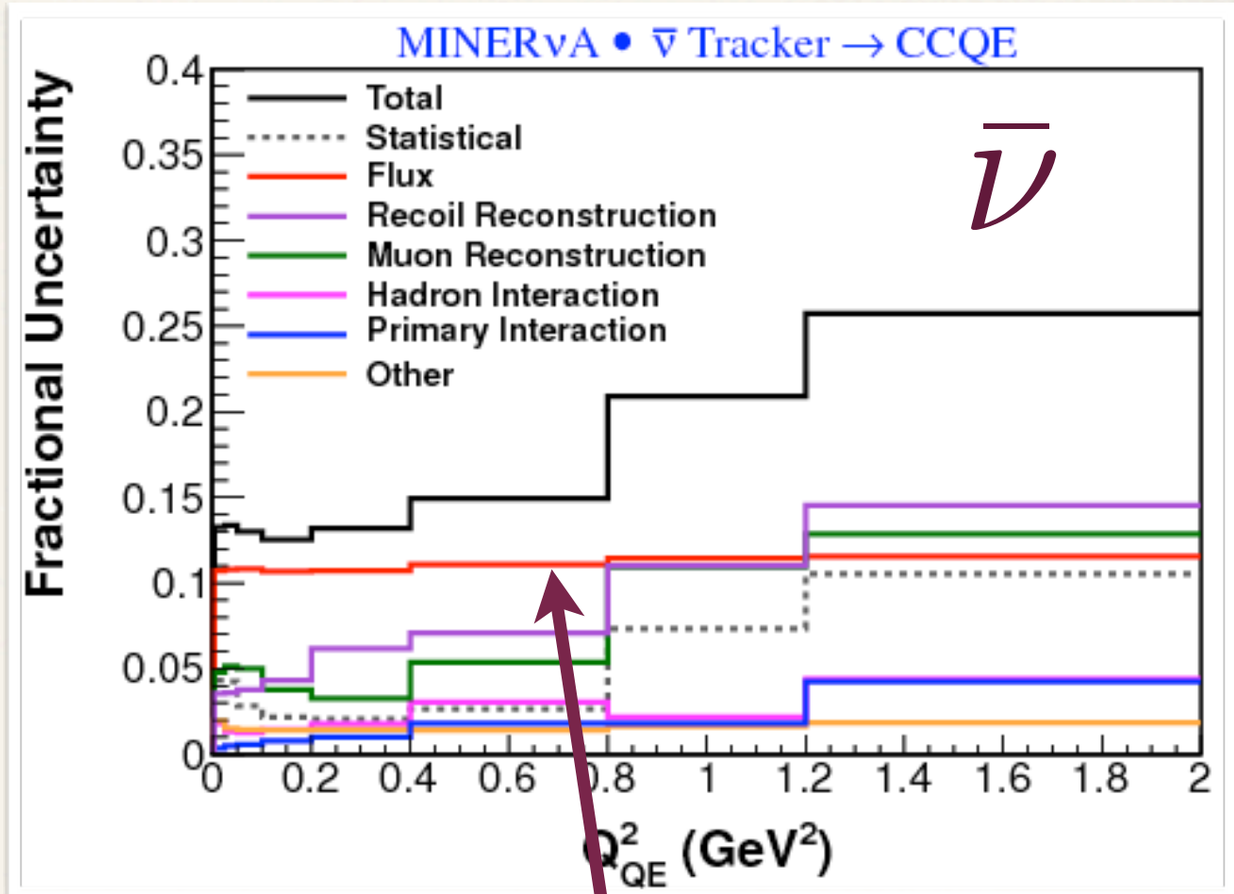
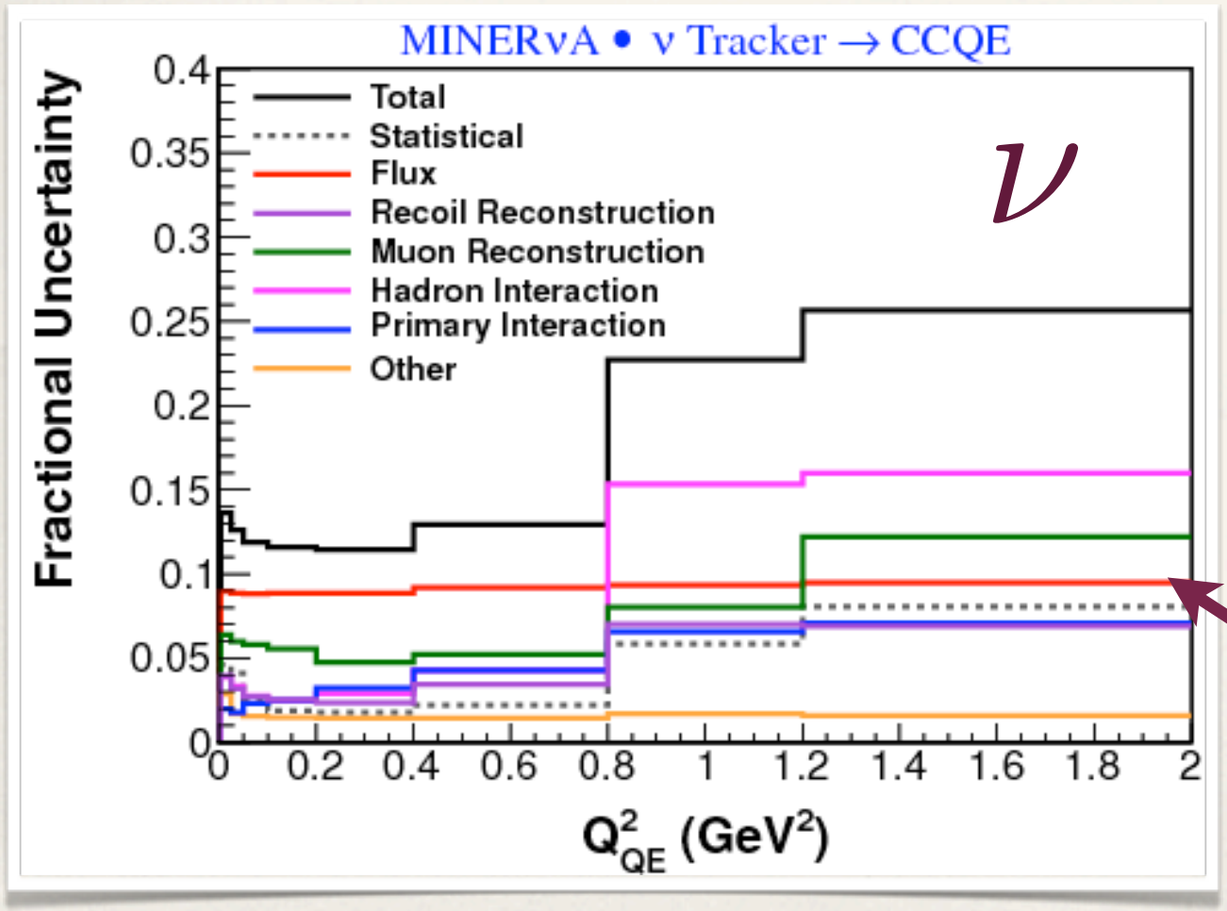


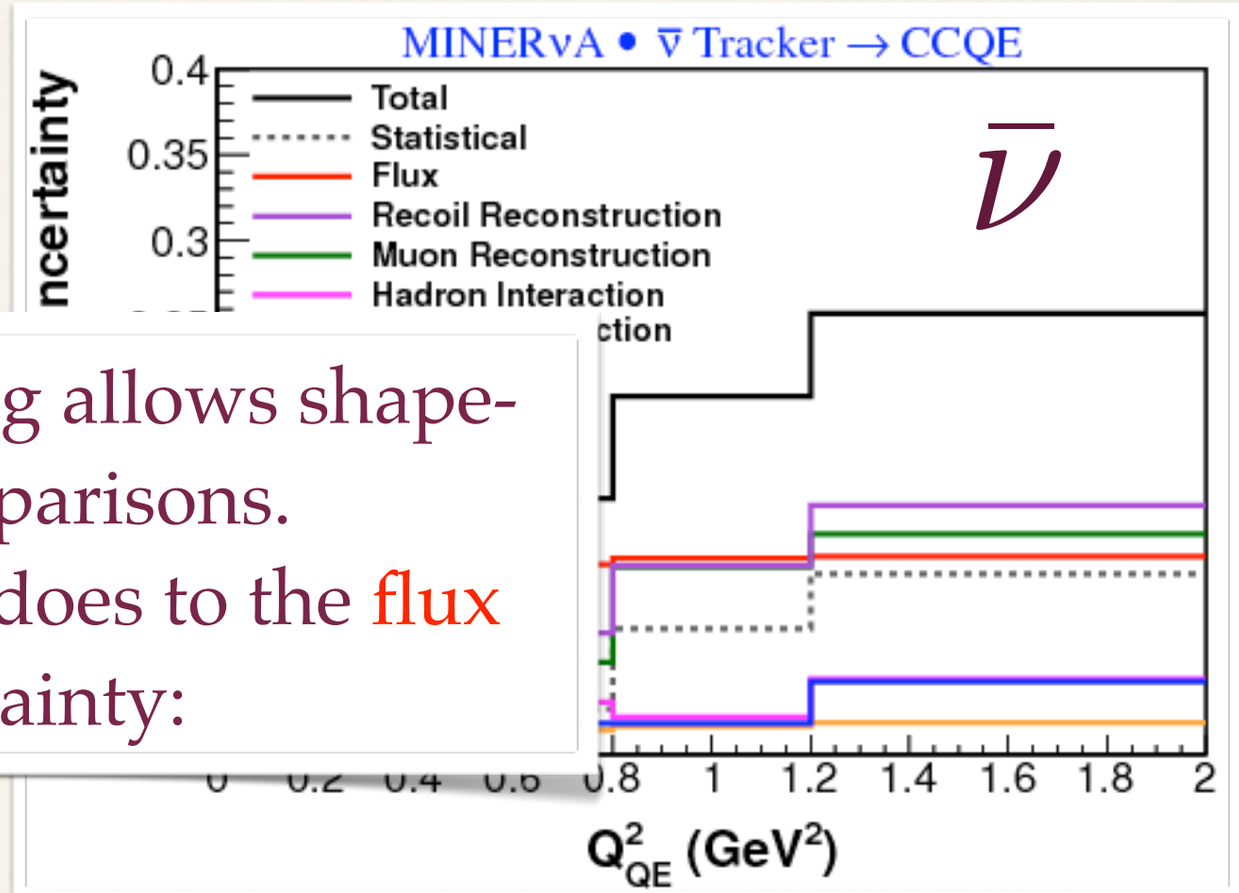


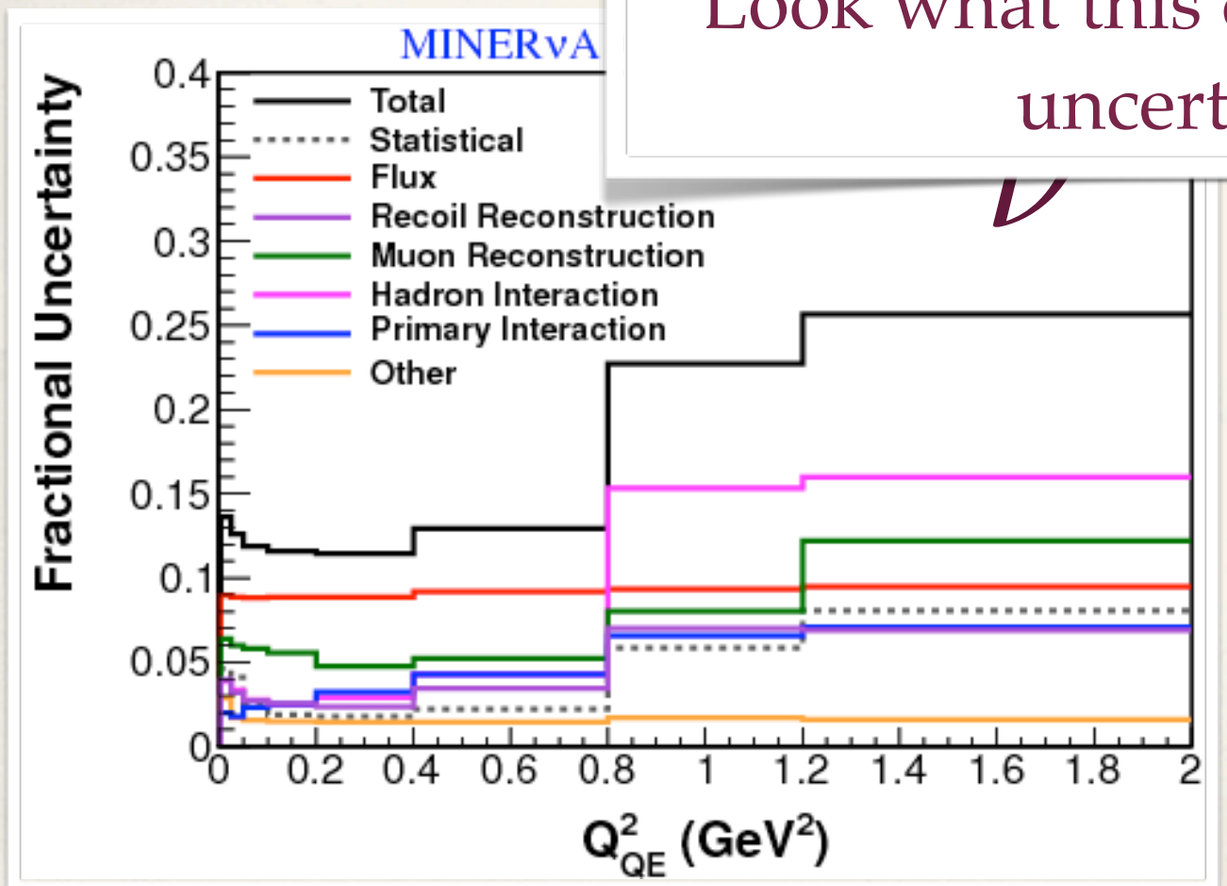
Flux uncertainty dominates, especially at low Q^2

Uncertainties

- Flux uncertainty
- Statistical uncertainty
- Hadron interaction model
- Total u

Area normalizing allows shape-only comparisons.
Look what this does to the flux uncertainty:

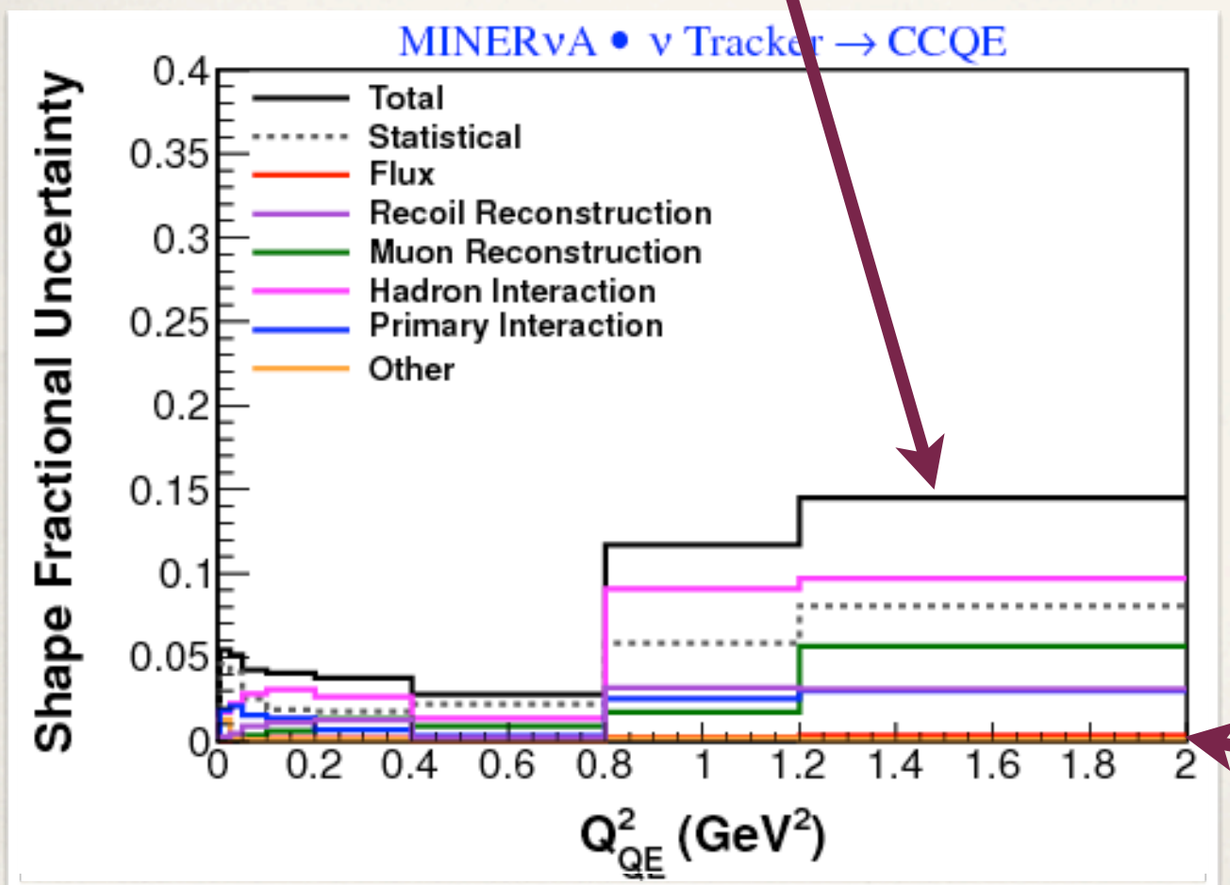


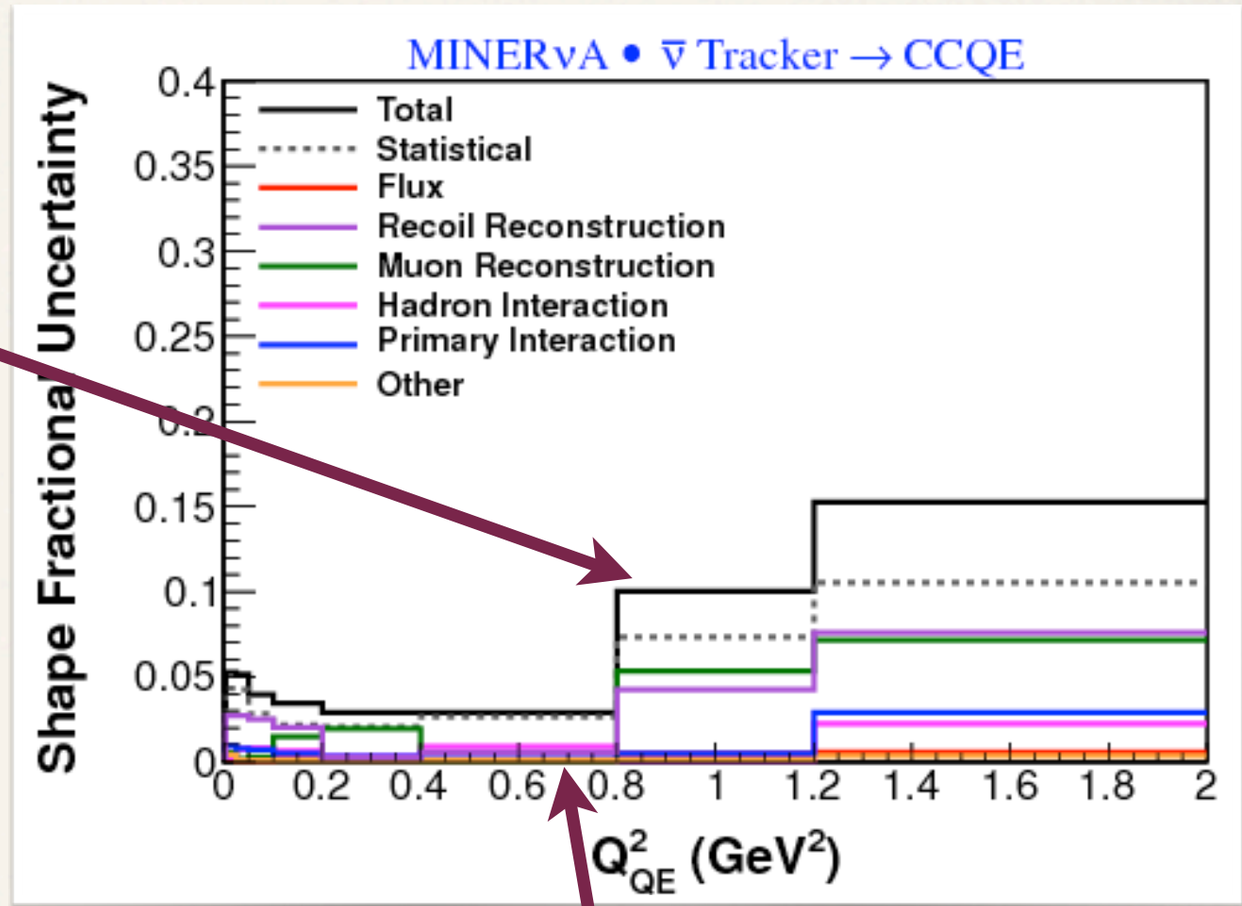


Uncertainties

- Flux uncertainty
- Statistical uncertainty
- Had… mo…
- Total uncertainty

Total uncertainty reduced





Area normalization reduces flux uncertainty

Compare shape to models

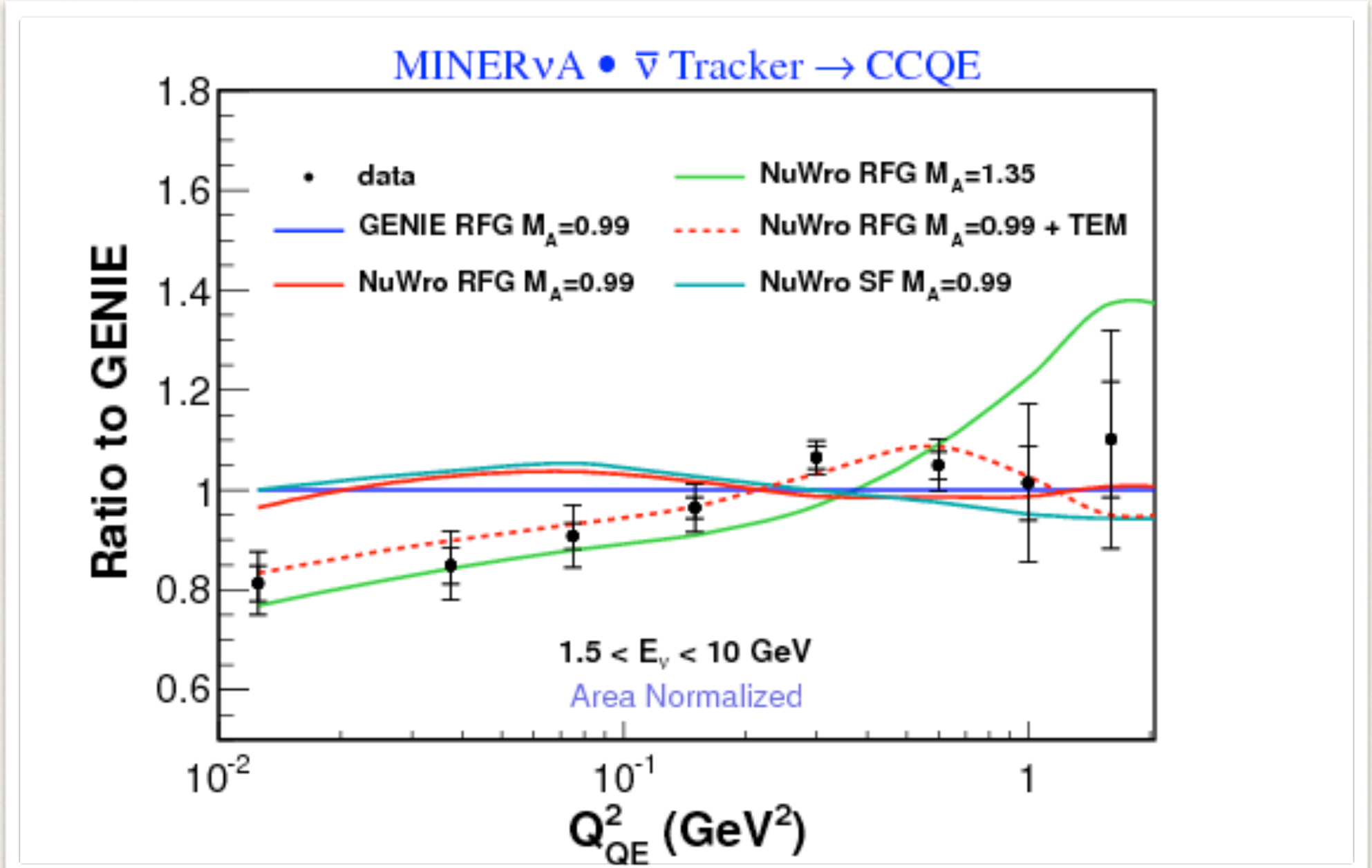
Two frameworks for modeling cross-sections:

GENIE *C. Andreopoulos, et al., NIM 288A, 614, 87 (2010)*

NuWro *K. M. Graczyk and J. T. Sobczyk, Eur.Phys.J. C31, 177 (2003)*

- RFG with $M_A = 0.99$ GeV: as predicted by neutrino-deuterium scattering; used in our Monte Carlo, GENIE
  - *R. Smith and E. Moniz, Nucl.Phys. B43, 605 (1972); A. Bodek, S. Avvakumov, R. Bradford, and H. S. Budd, J.Phys.Conf.Ser. 110, 082004 (2008) ; K. S. Kuzmin, V. V. Lyubushkin, and V. A. Naumov, Eur.Phys.J. C54, 517 (2008)*
- RFG with $M_A = 1.35$ GeV: best-fit M_A from MiniBooNE, SciBooNE
- Spectral functions: more sophisticated nuclear momentum model
  - *O. Benhar, A. Fabrocini, S. Fantoni, and I. Sick, Nucl.Phys. A579, 493 (1994)*
- Transverse enhancement: as seen in electron scattering data, parameterizing effects possibly caused by correlations
  - *A. Bodek, H. Budd, and M. Christy, Eur.Phys.J. C71, 1726 (2011)*

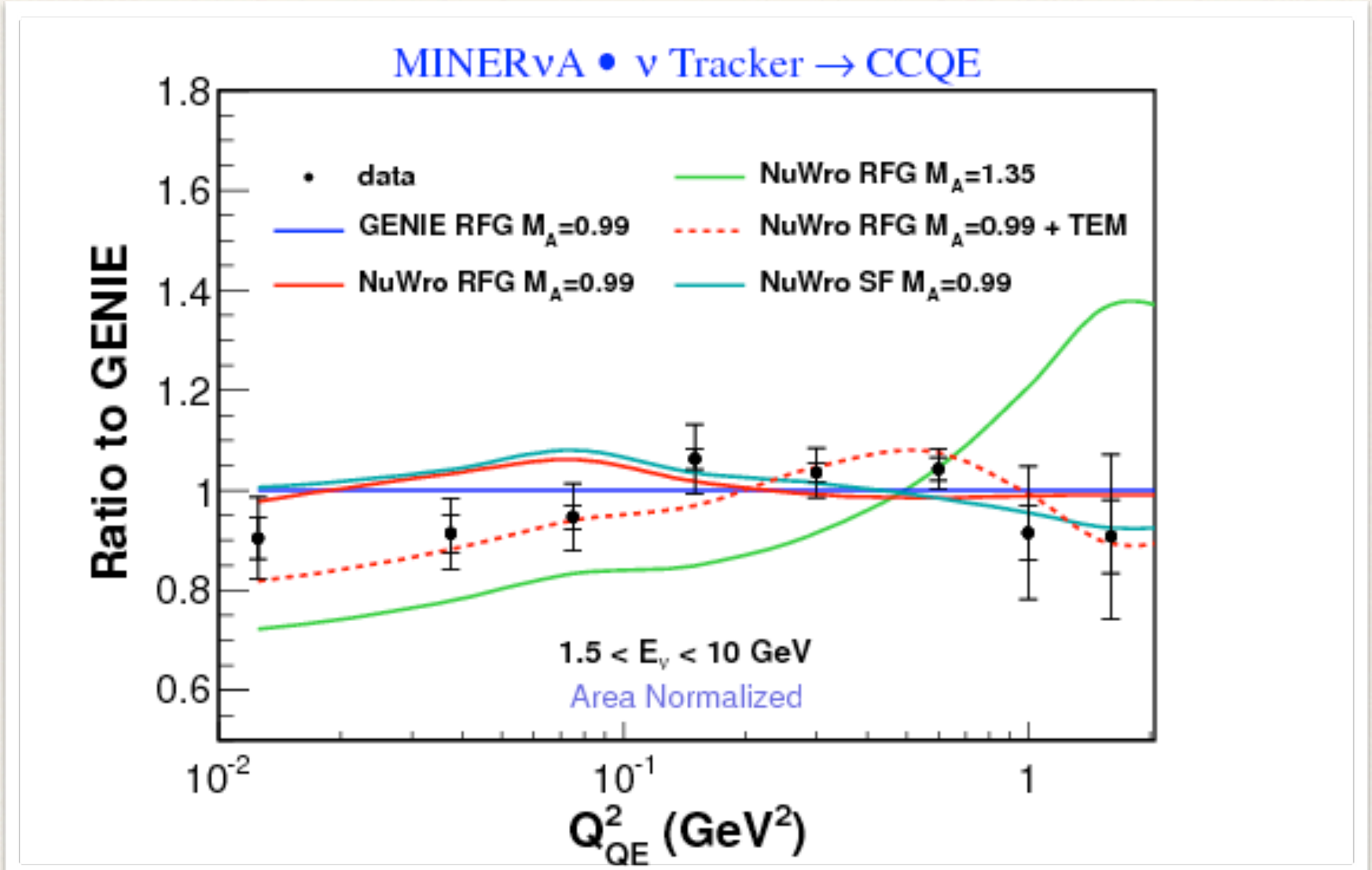
Antineutrino results



Data favors TEM, suggesting initial-state correlations

L. Fields, J. Chvojka et al. (MINERvA Collaboration), Measurement of Muon Antineutrino Quasielastic Scattering on a Hydrocarbon Target at Ev~3.5 GeV, Phys. Rev. Lett. 111, 022501 (2013)

Neutrino results

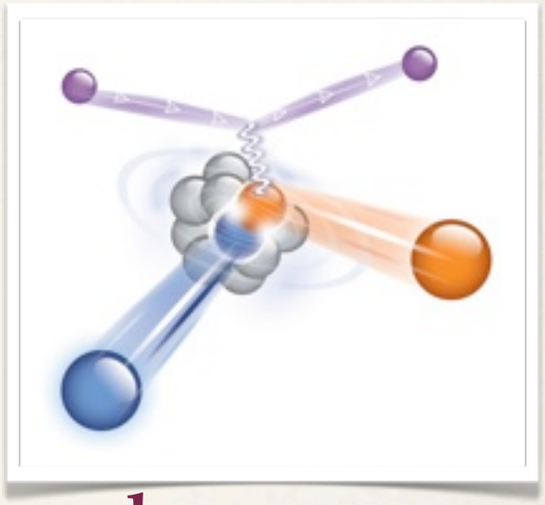


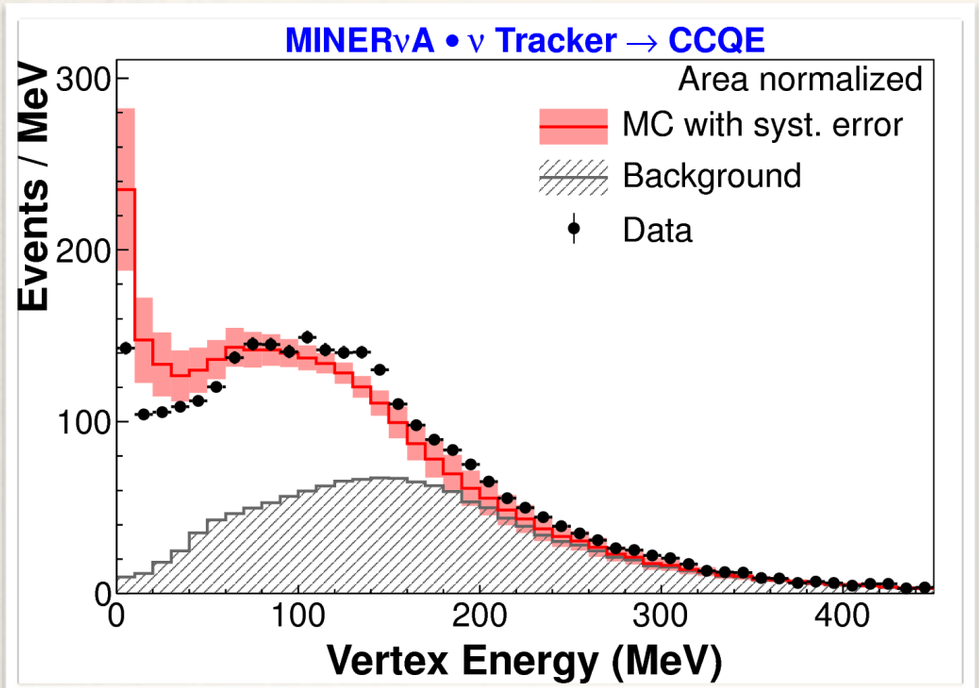
Data favors TEM, suggesting initial-state correlations

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

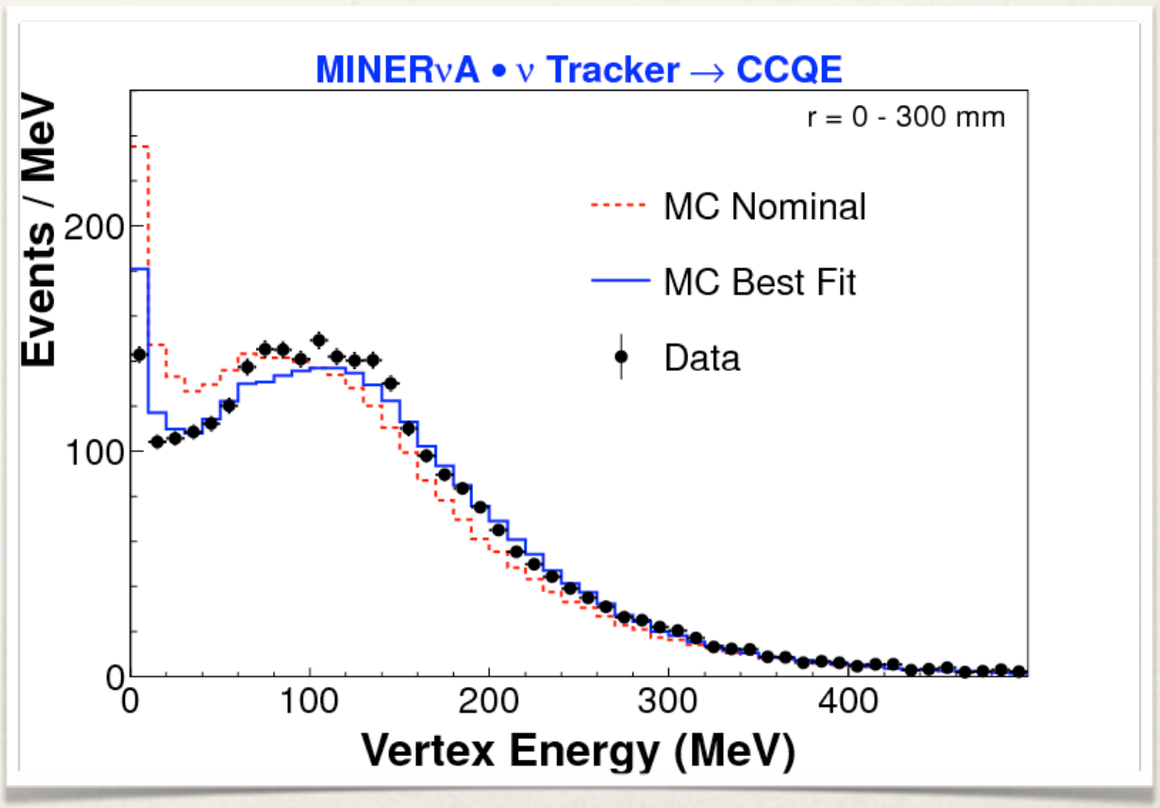
Vertex energy - extra protons

- The TEM predicts additional low-energy nucleons
- Our recoil cuts neglected the vertex region
- We can examine this for evidence of extra nucleons



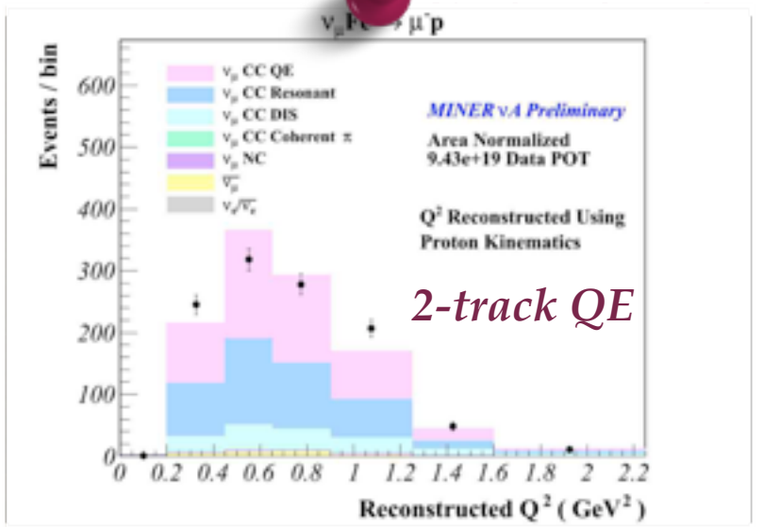


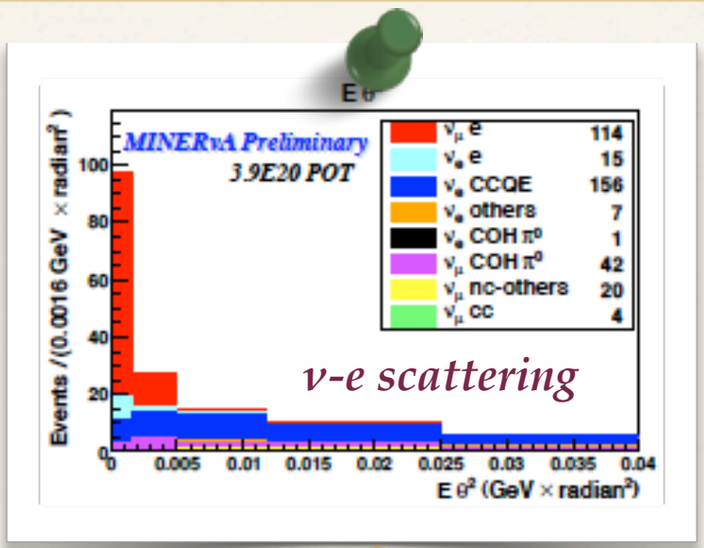
- A **harder neutrino-mode energy spectrum** is seen in data than MC
- It is not seen in antineutrino mode

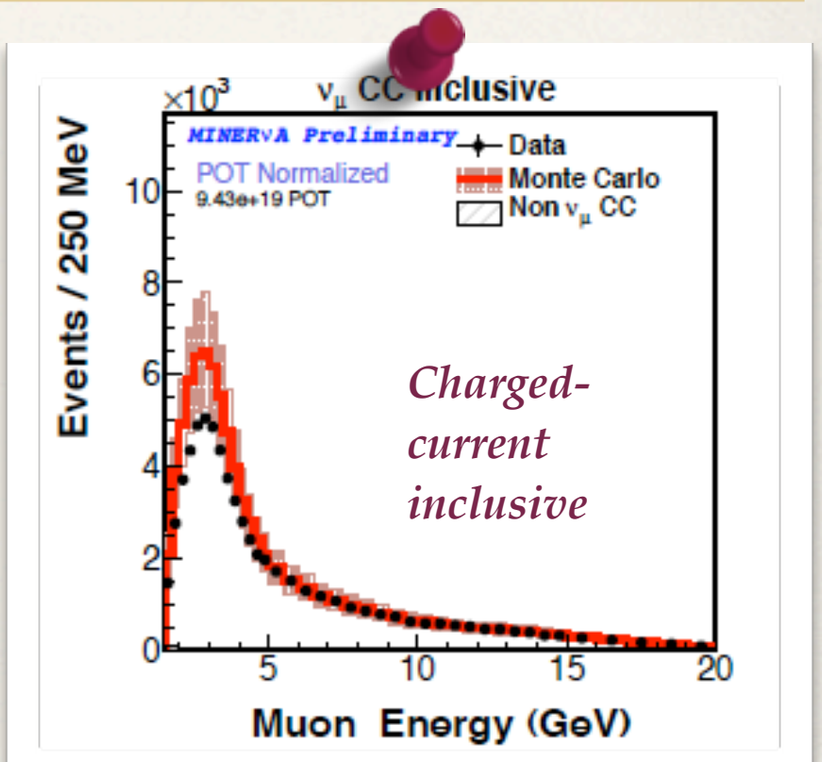


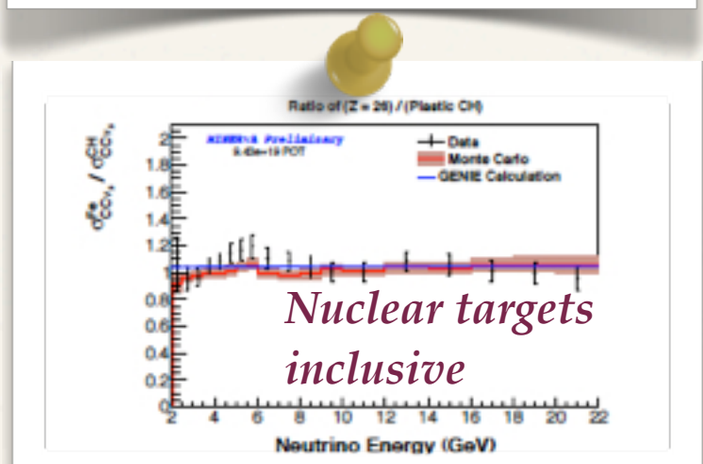
- Modeling an additional proton 25±9% of the time makes the MC fit better to the data
- This suggests **p-n correlations**

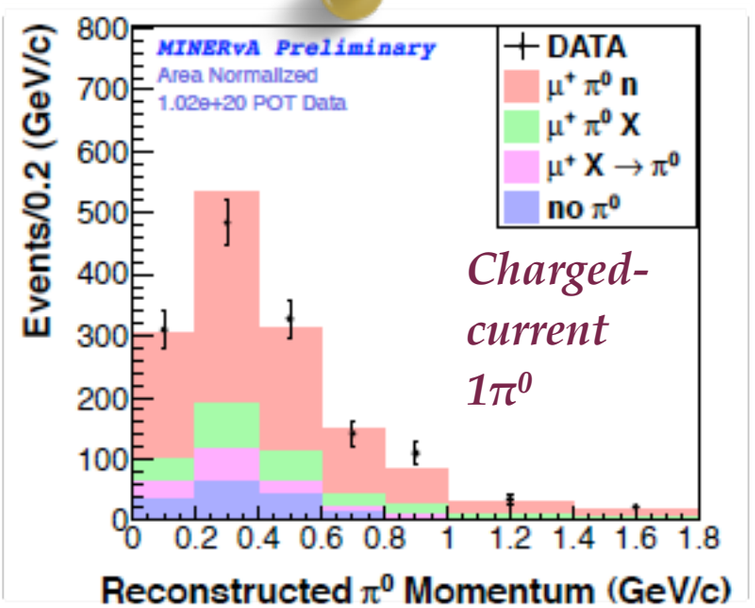
Stay tuned for more results!

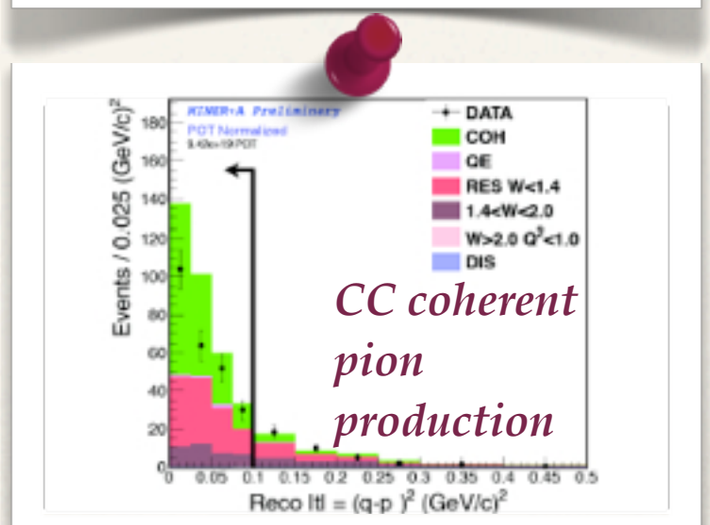


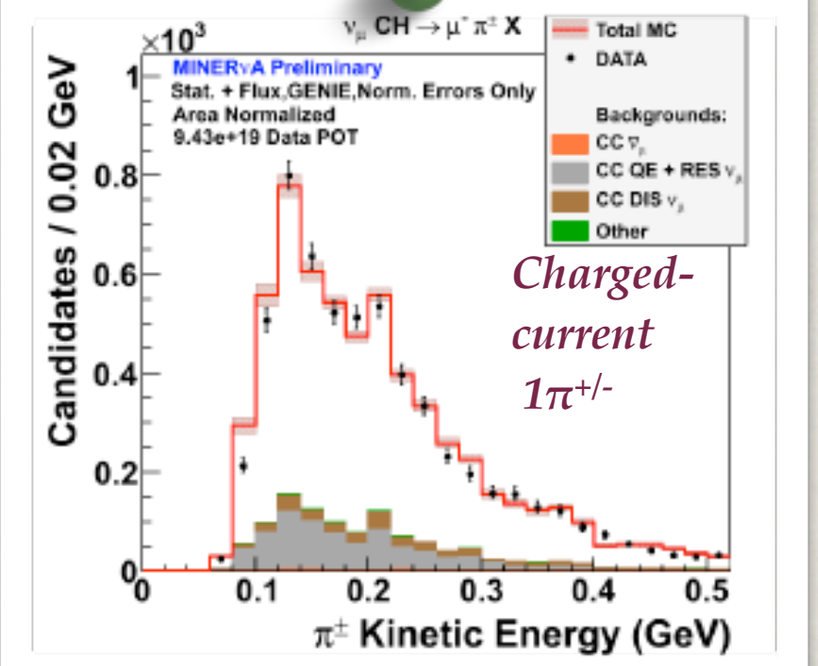




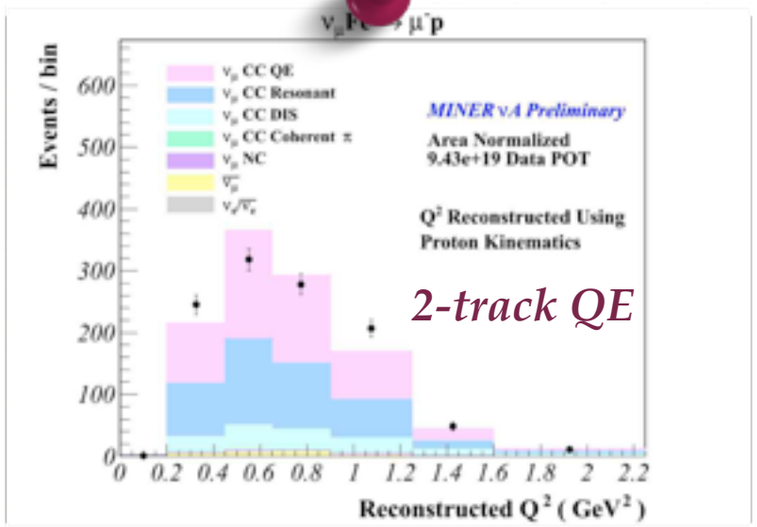




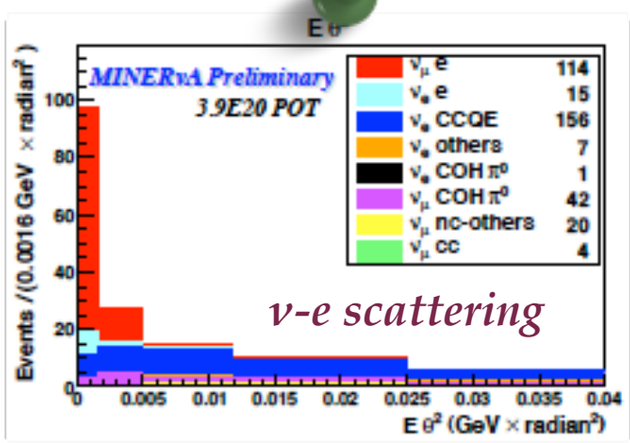




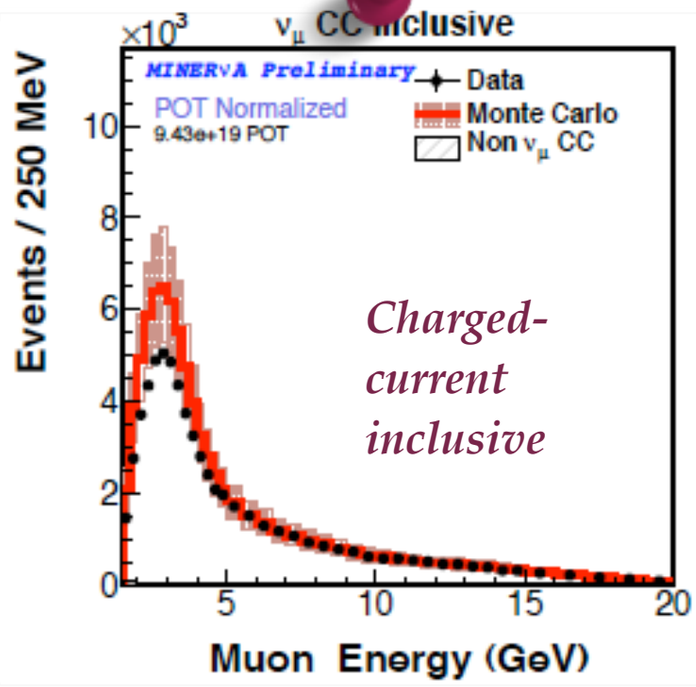
Stay tuned for more results!



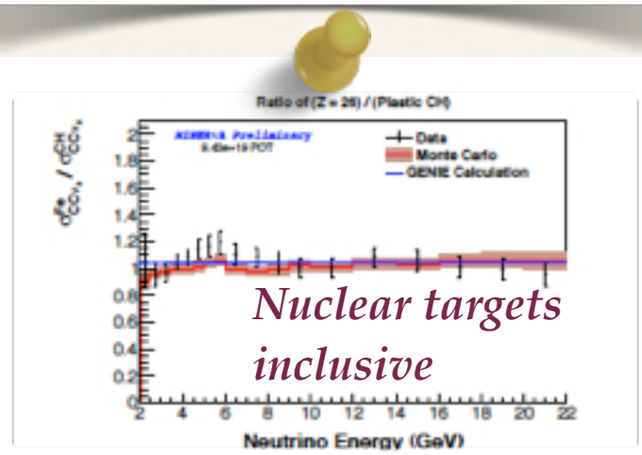
2-track QE



ν-e scattering

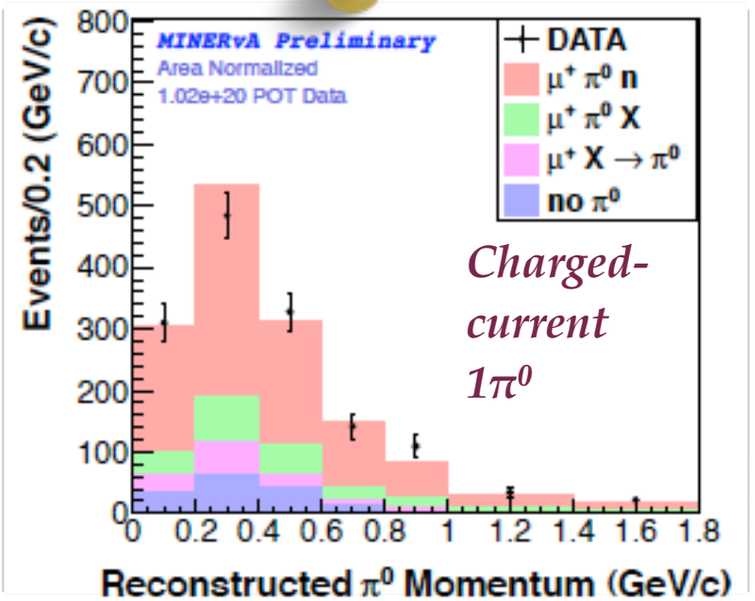


Charged-current inclusive

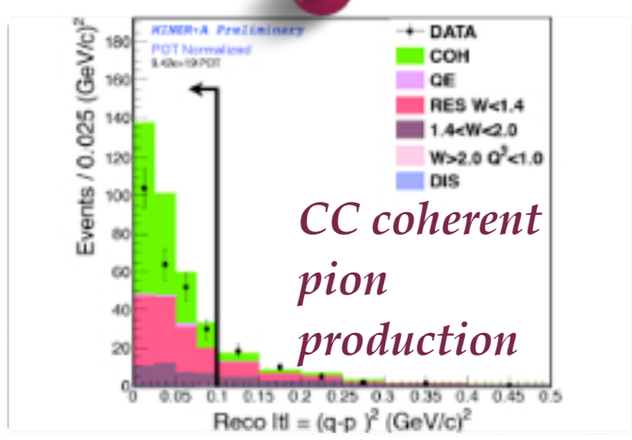


Nuclear targets inclusive

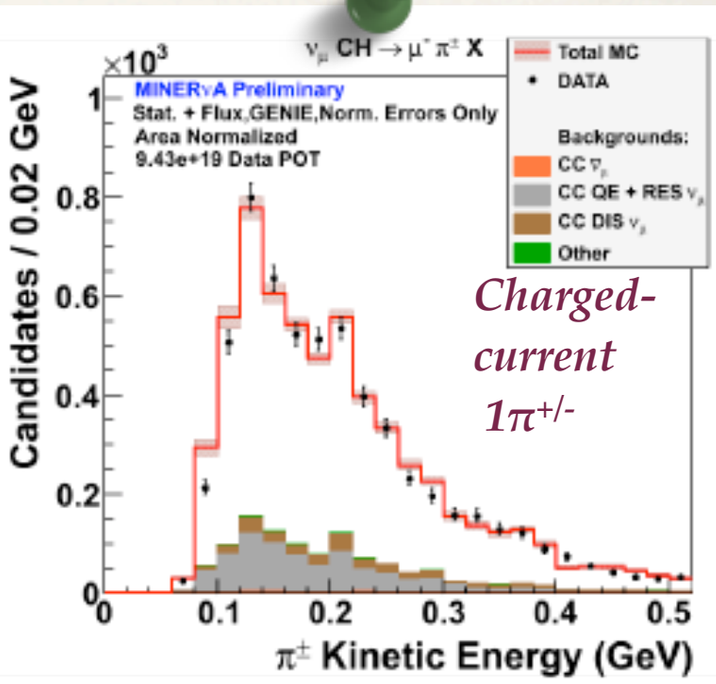
Tusen tack!



Charged-current 1π⁰



CC coherent pion production

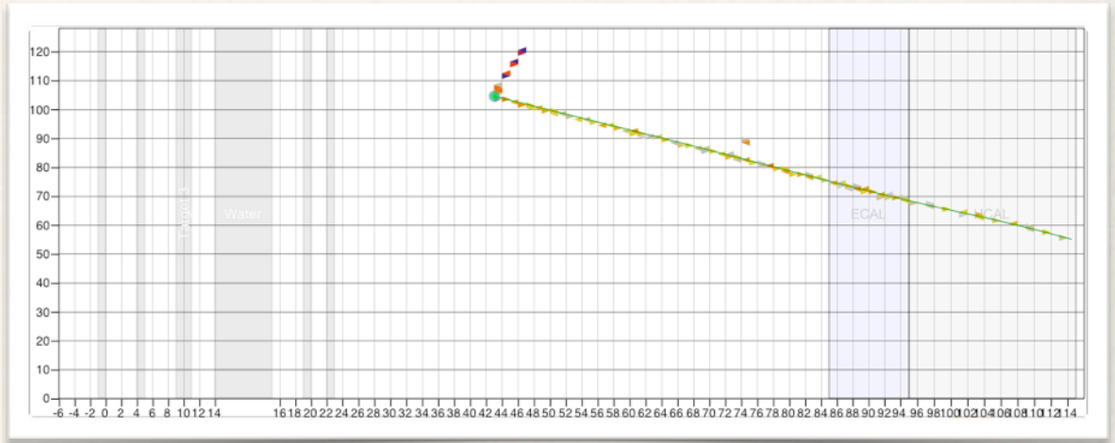


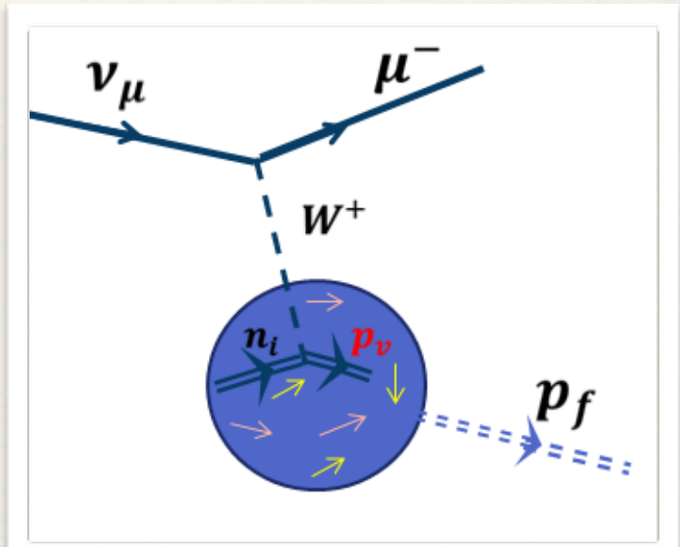
Charged-current 1π+/-

Backup slides

Two-track study

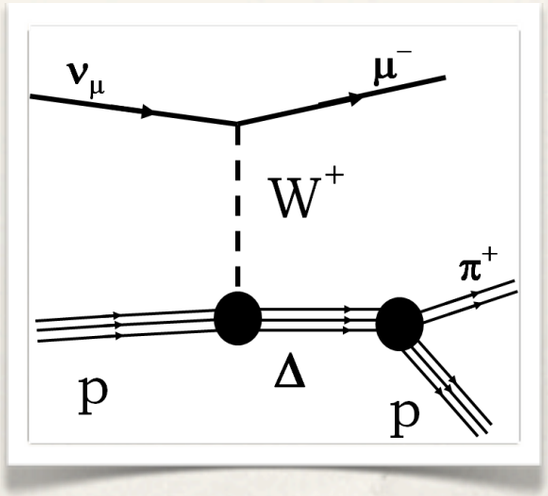
- This study only uses muon track
  - MINOS-matched muons
- Another study will include proton track in neutrino mode
  - Increased angular acceptance
  - Cross-check on results
  - Examine final-state interactions ("QE-like")
  - Study interactions in nuclear targets





Final-state proton could re-interact within nucleus

Pions produced and re-absorbed could fake a QE signal



Study in progress!

χ^2 for fits to antineutrino data

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

χ^2 for fits to neutrino data

NuWro model	RFG	RFG +TEM	RFG	SF
M_A (GeV)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f	3.5	2.4	3.7	2.8
Rate χ^2/d.o.f	4.1	**1.7**	2.1	3.8