Selecting Quasielastic Events at MINERνA

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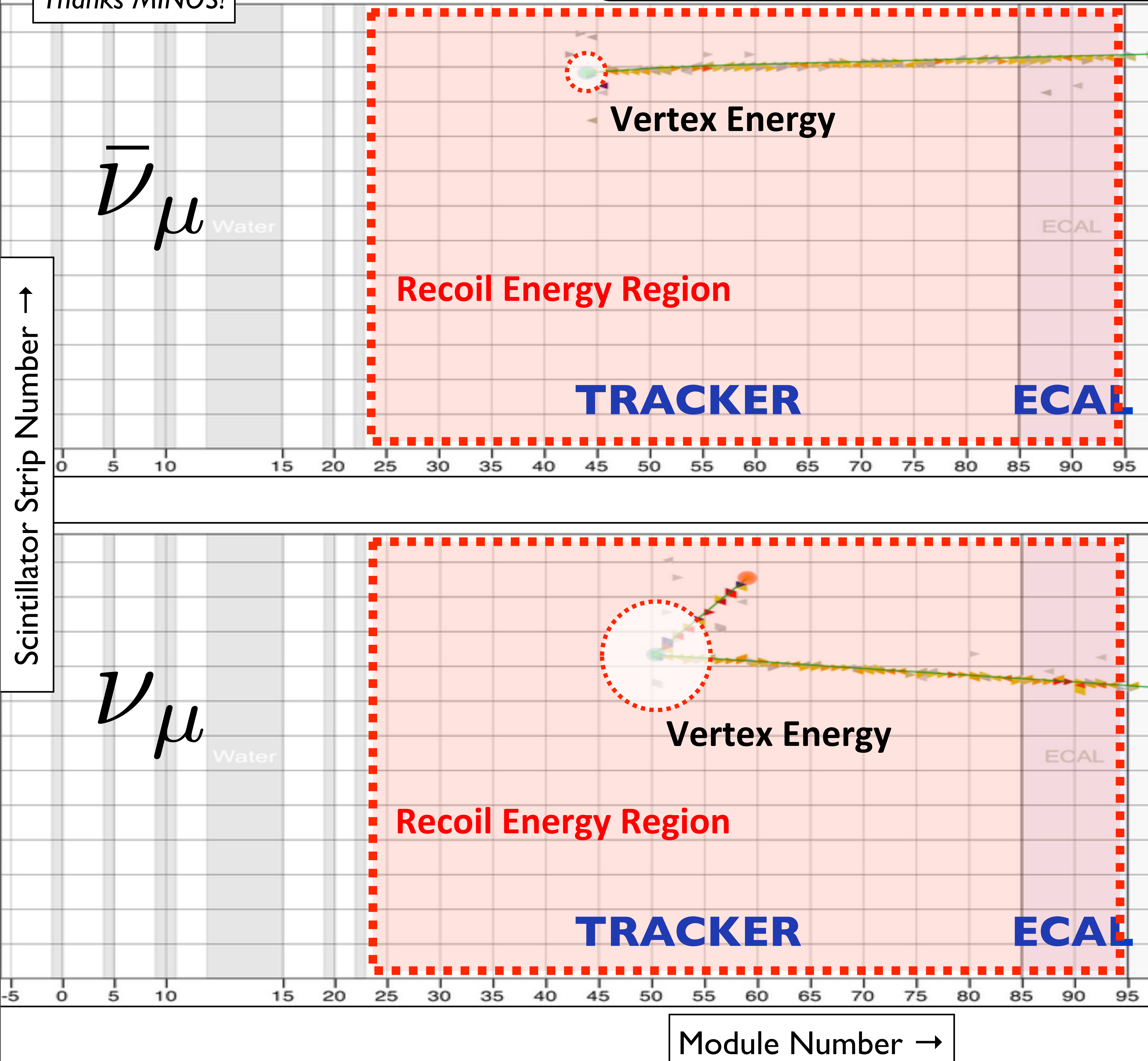
2013.December.3

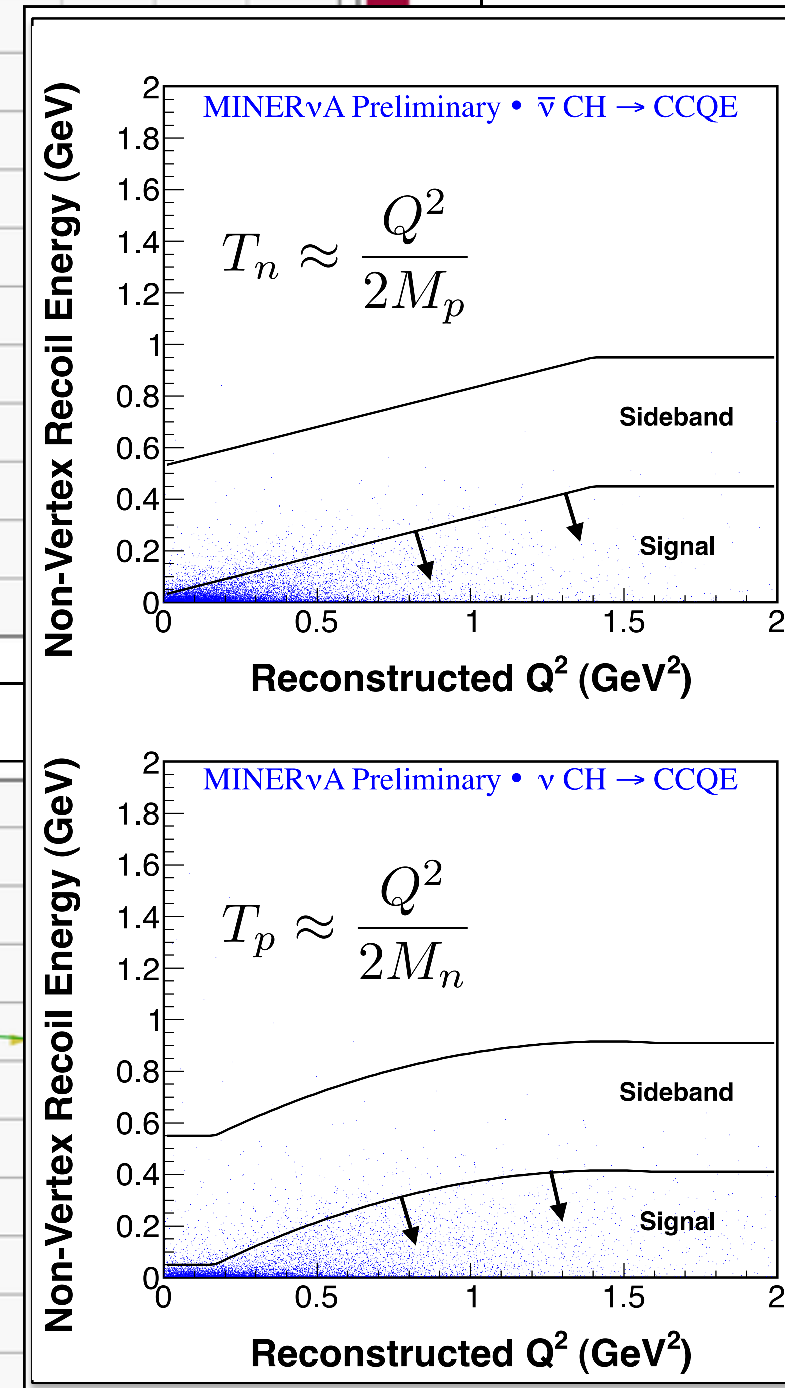
The Five-Slide Version
(It is Four Slides long ;)

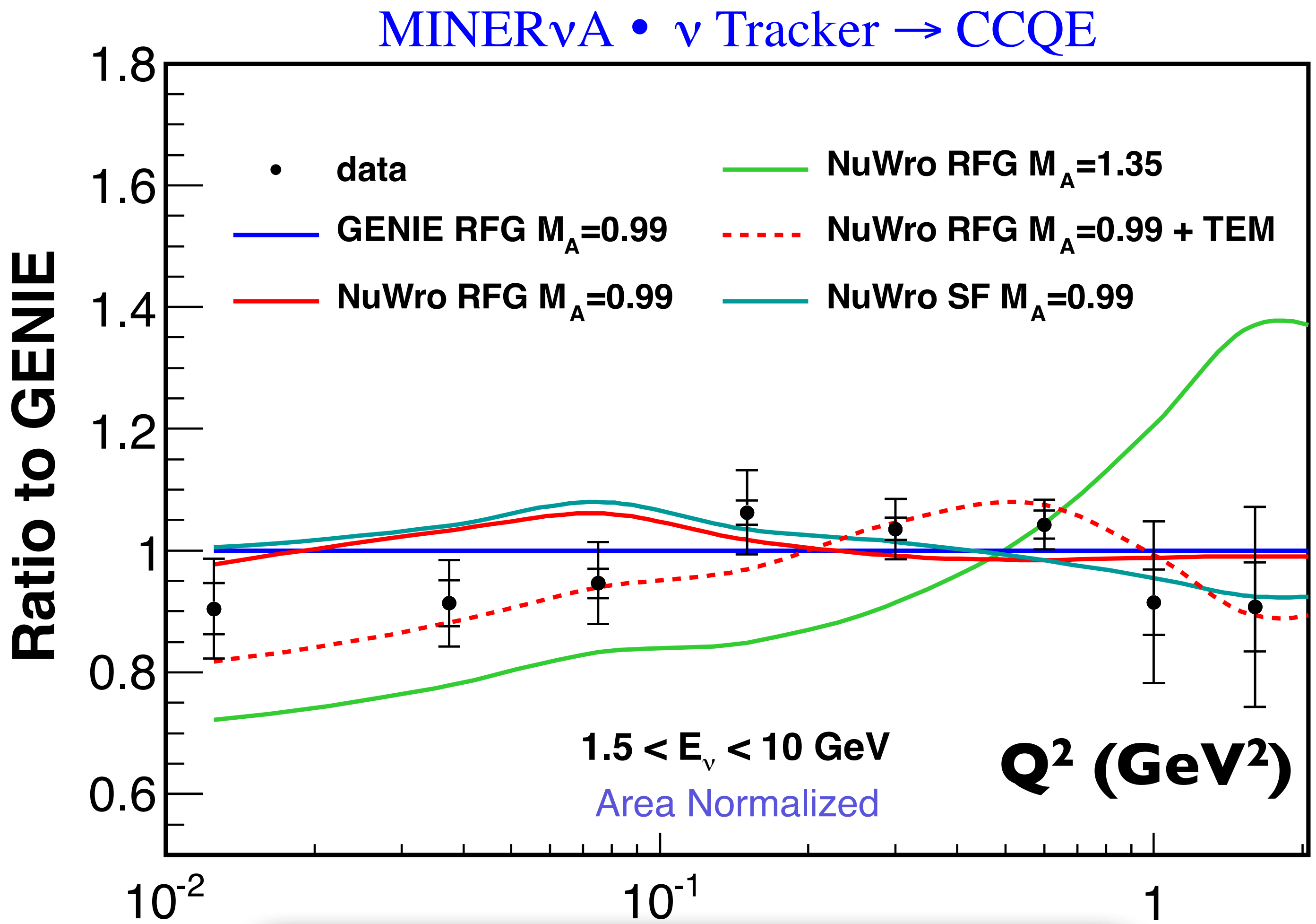
MINOS for Charge!

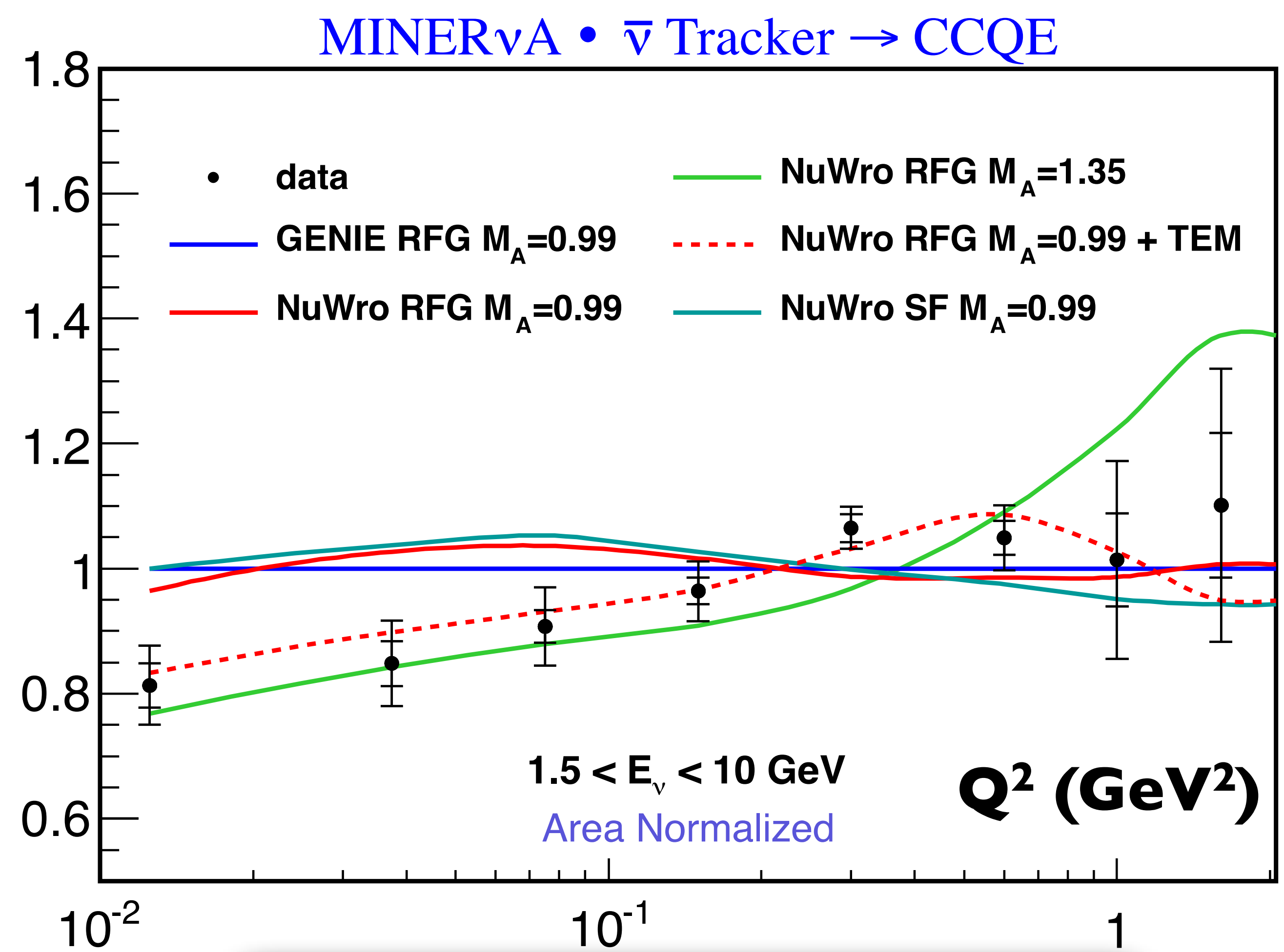
Thanks MINOS!

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







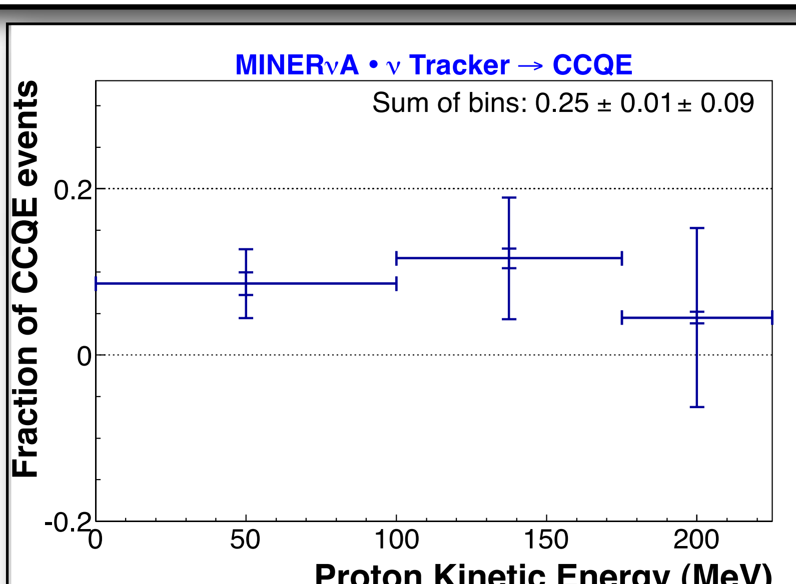


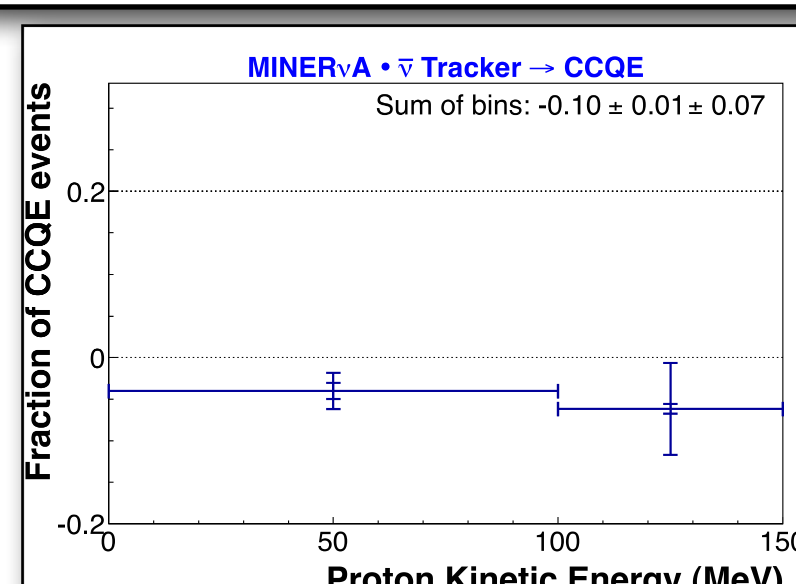
Neutrino

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

Antineutrino

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
Shape χ^2/d.o.f.	2.90	0.66	1.73	2.99





CCQE in the Future

- Low Energy:
  - Two-track $d\sigma/dQ^2$ with Michel veto.
    - Include non-MINOS-matched muons, reconstructing Q^2 via the proton arm.
    - Separate set of ratio measurements in the nuclear targets.
  - $d^2\sigma/dT_\mu d\theta_\mu$ for neutrino and antineutrino.
  - $d^2\sigma/dT_p d\theta_p$ for neutrino? (Statistics are a major challenge.)
- Repeat everything in the Medium Energy beam.
  - Not underway yet...

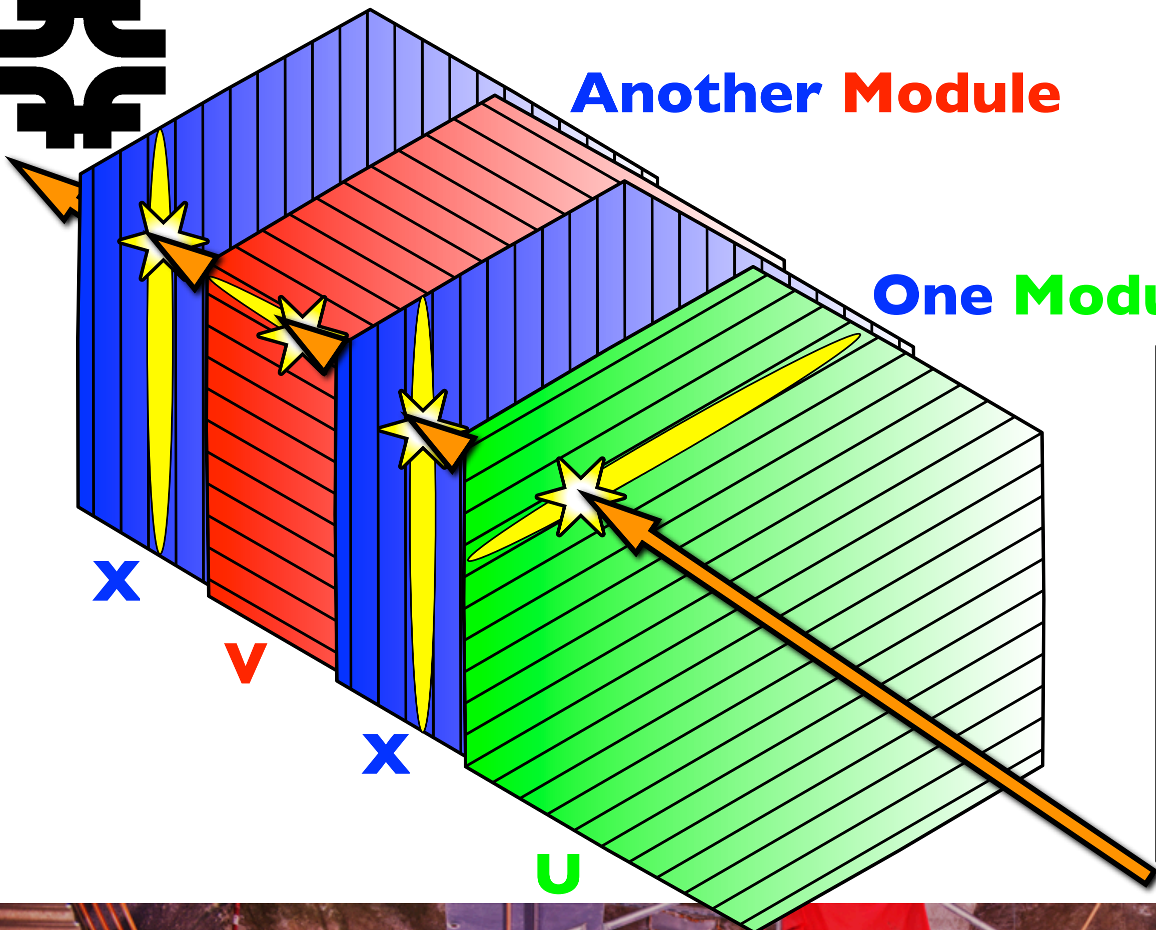
MINERνA Summary

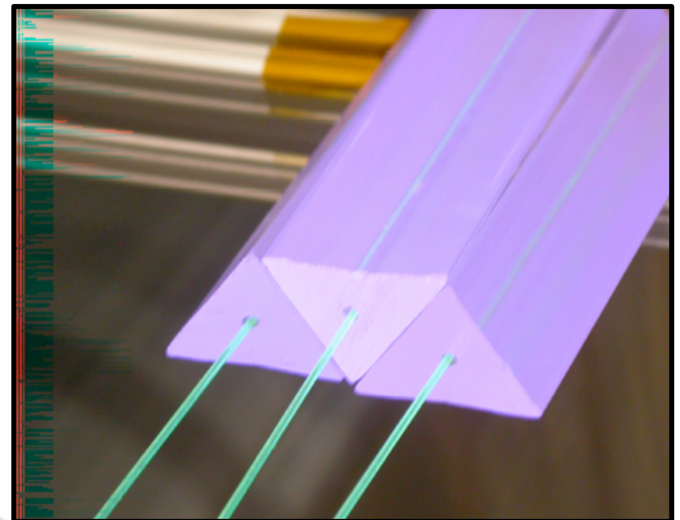
QE Characteristics	Values
Event Selection	1 Muon, Recoil consistent with QE Q^2. The number of tracks and vertex energy are not used in event selection. (No Michel veto in current publication.)
Nuclear Target	Mostly CH.
Neutrino Flux Range	[1.5 GeV, 10 GeV] (Higher energy is possible. Lower energy is accessible via proton-arm reconstruction.)
Sign Selection	Yes.
Muon Angular Range	[0 degrees, ~20 degrees]* (*MINOS-matched sample. [0 degrees, 180 degrees] accessible via proton-arm)
Muon Energy Range	~[1.5 GeV, 10 GeV] (Higher energy is possible. Lower energy is accessible via proton-arm reconstruction.)
Proton Detection Threshold	~80 MeV KE for tracking. ~50 MeV KE for Isolated Shower. ~? to see anything...
Neutrino Energy Determination	QE Formula with RFG assumptions.
Q^2 Determination	QE Formula - unfold to true muon kinematics.
MC Generator	GENIE. (+ some NuWro for specific studies and comparisons at the generator level.)
QE Measurements & Publications	Future: Two-track $d\sigma/dQ^2$, $d^2\sigma/dT_\mu d\theta_\mu$ $d\sigma/dQ^2$: 10.1103/PhysRevLett.111.022501, 10.1103/PhysRevLett.111.022502

Now, with details...

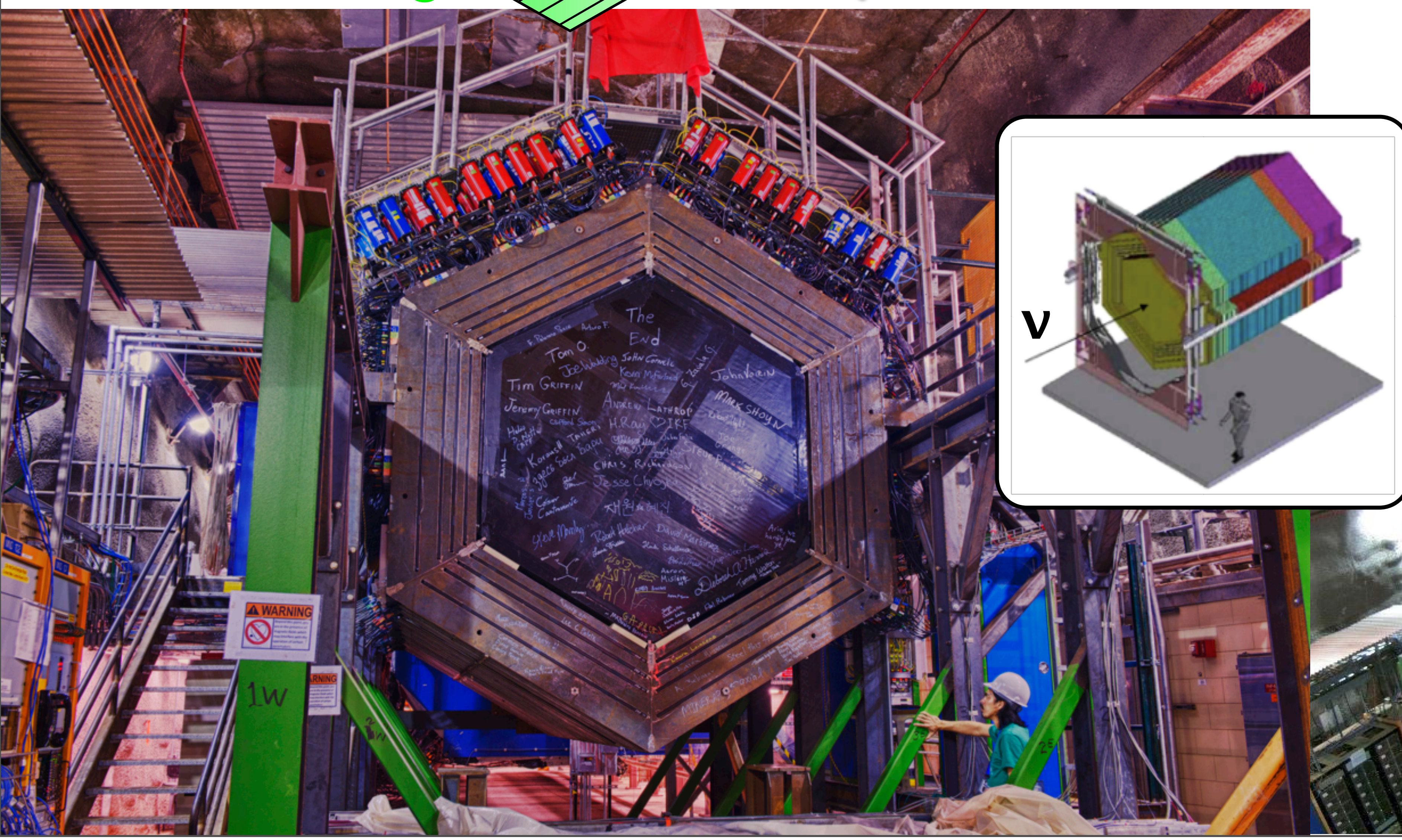
Detector & Event Selection

MINERvA

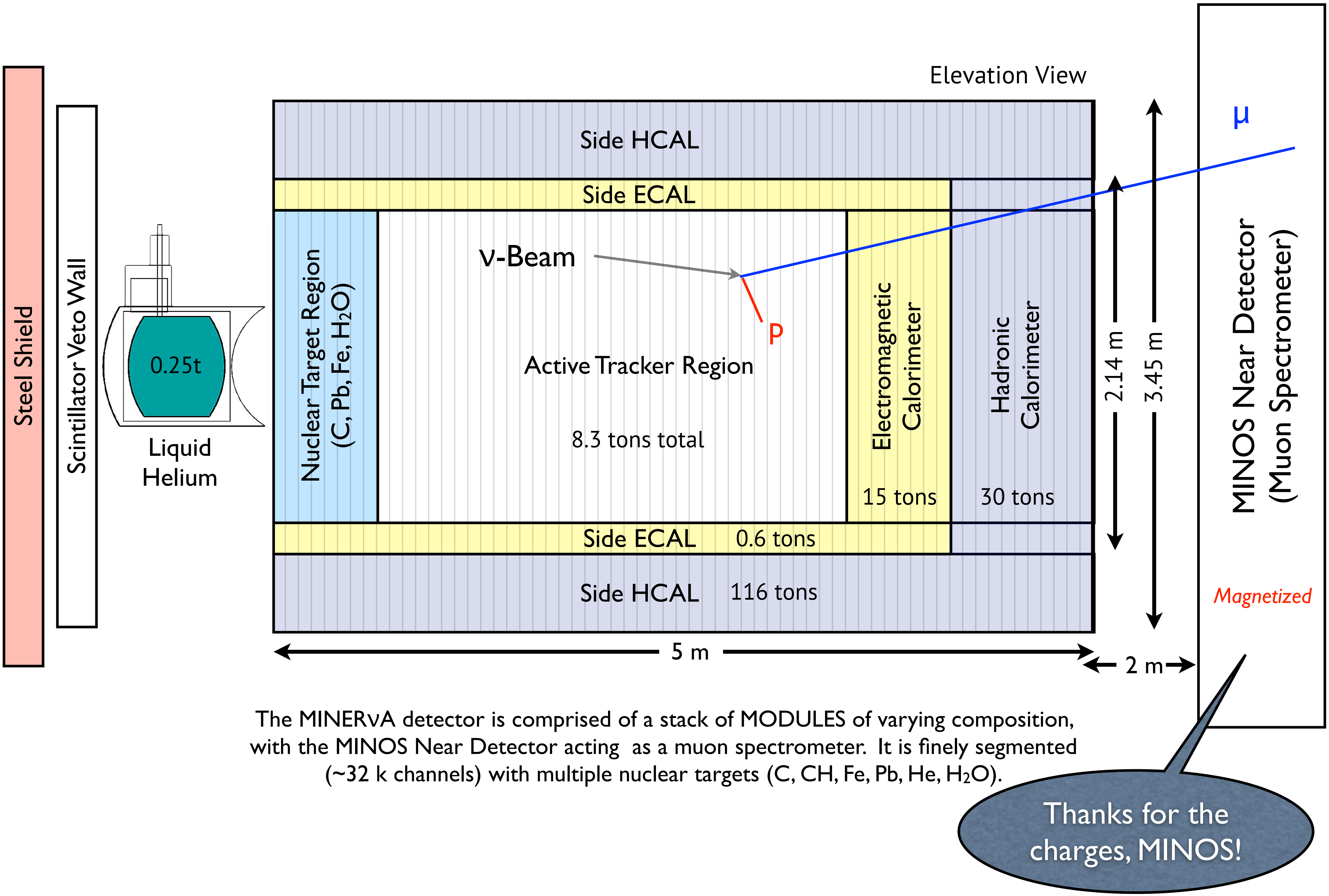




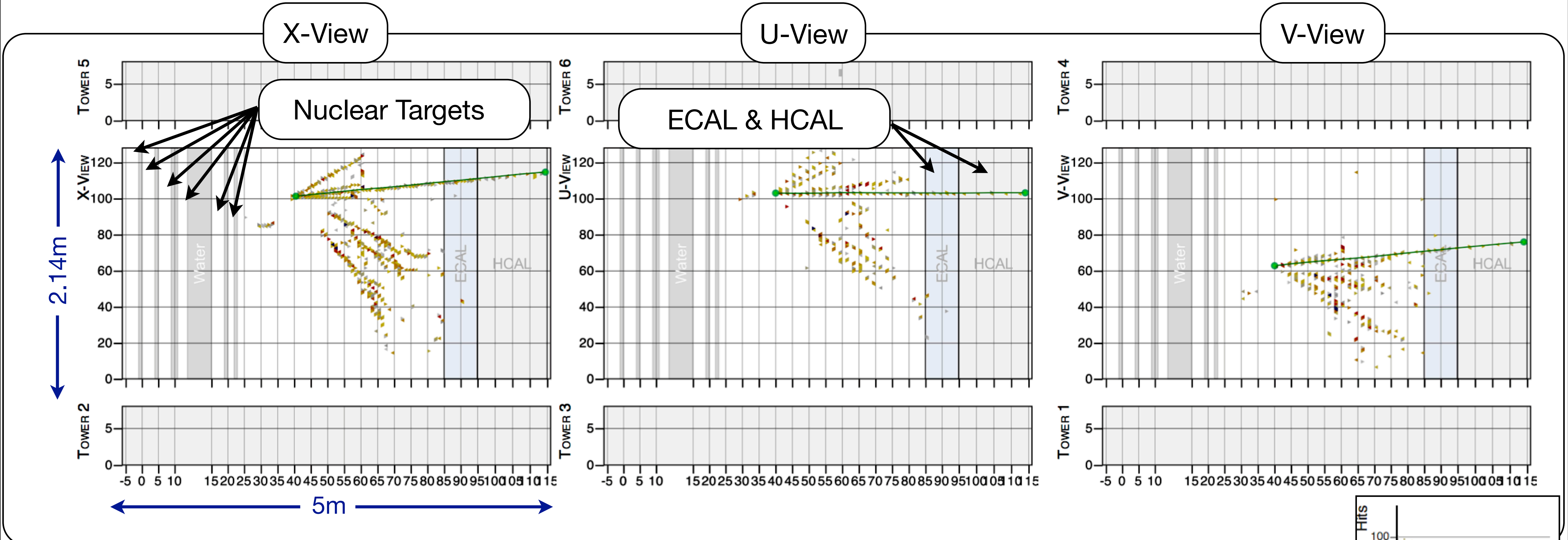
- Fine-grained resolution for excellent kinematic measurements.
- Low-energy cross-section program well-suited to next-generation oscillation experiments.
- Nuclear effects with a variety of target materials ranging from Helium to Lead. Especially important for ME run.

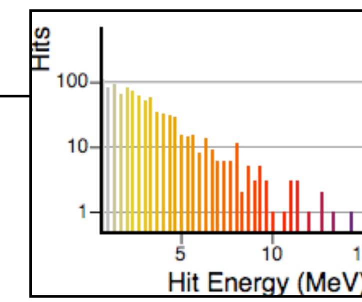


The Best Thing Since Sliced Bread...

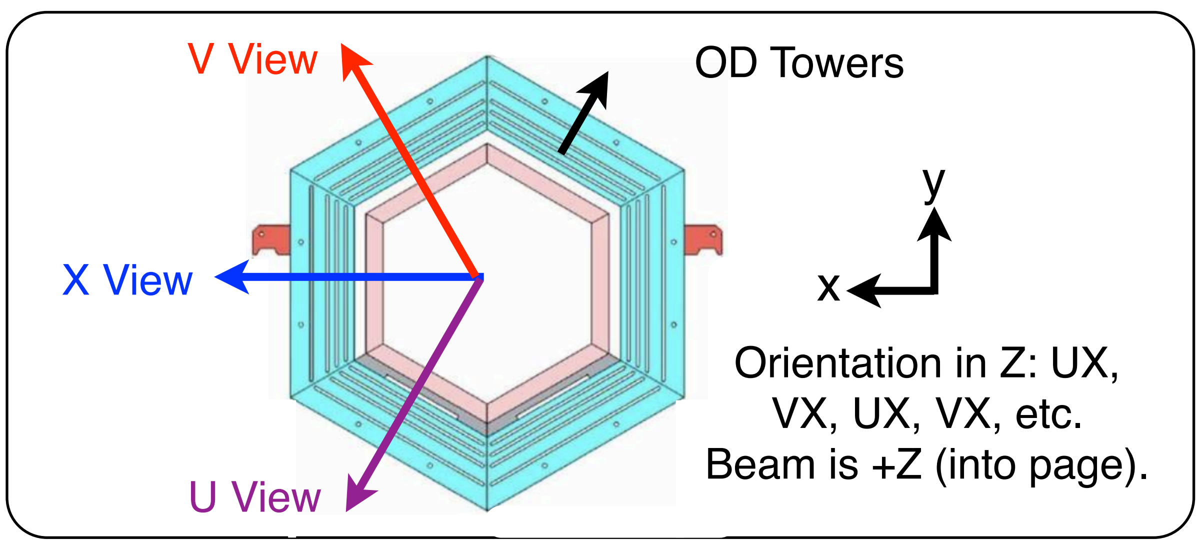


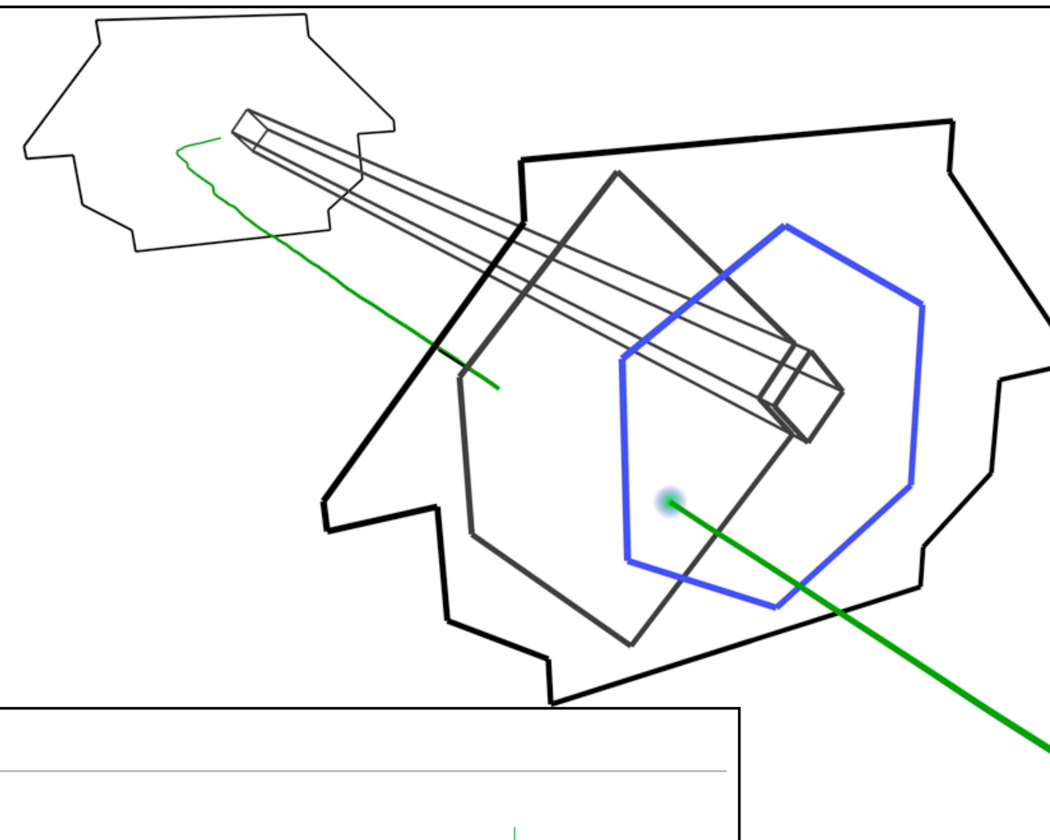
The MINERνA detector is comprised of a stack of MODULES of varying composition, with the MINOS Near Detector acting as a muon spectrometer. It is finely segmented (~32 k channels) with multiple nuclear targets (C, CH, Fe, Pb, He, H_2O).

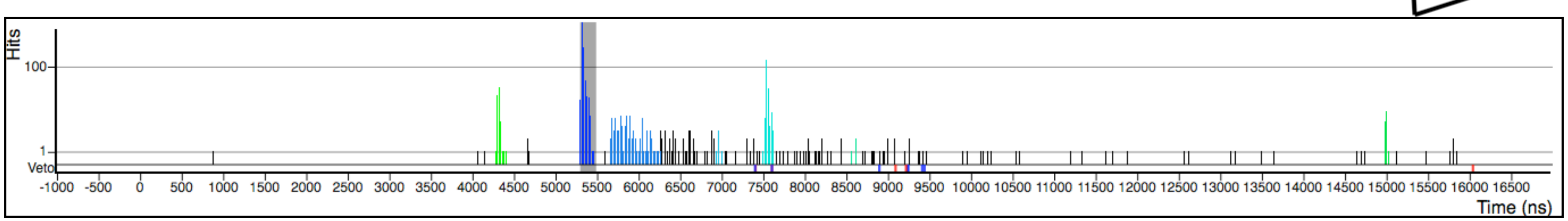


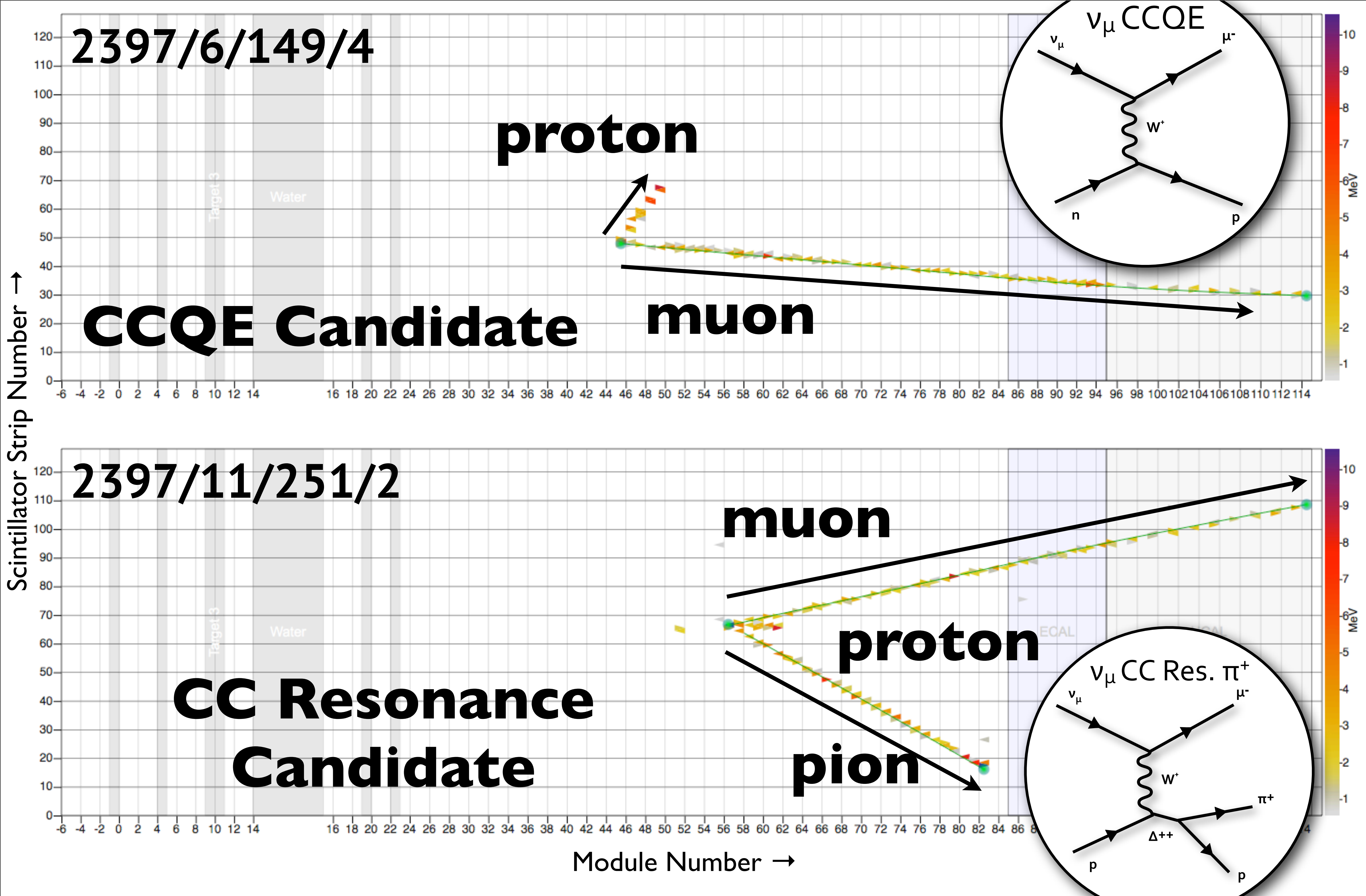


Data: 2397/3/915/3



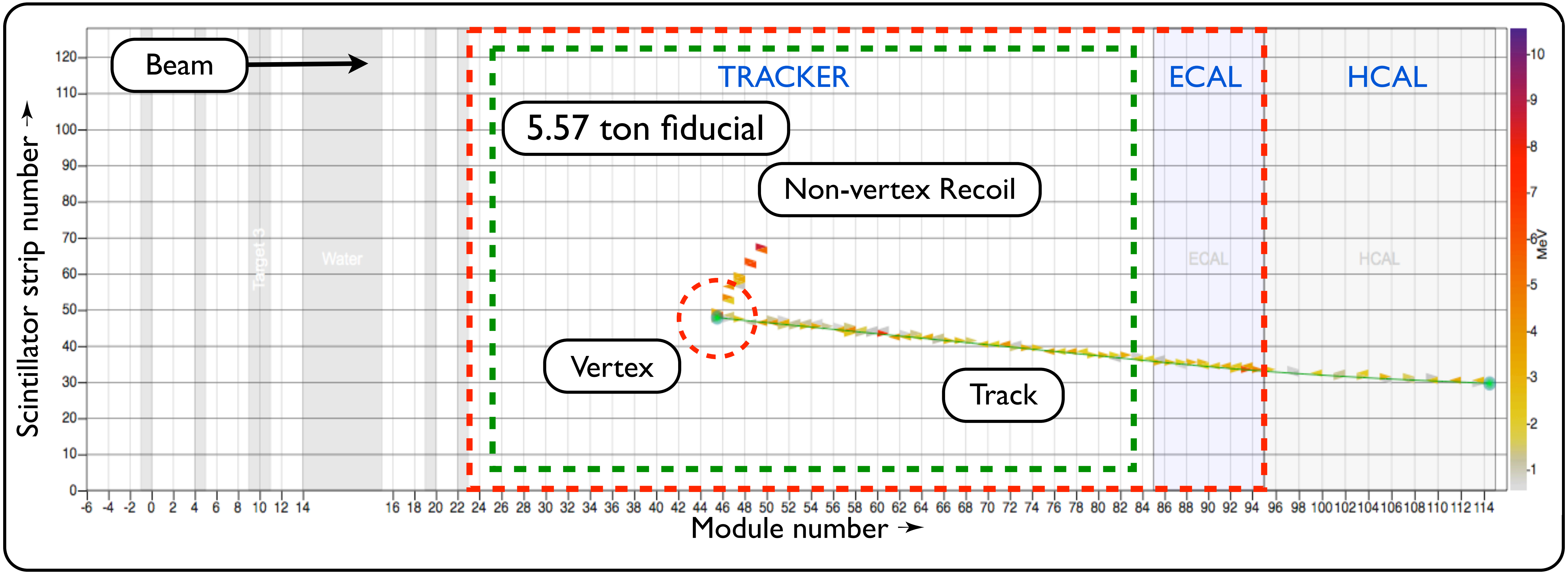






(The CCQE candidate might very well have a pion for its long track - this event was NOT checked with a dE/dX fit when making this slide!

MINERvA CCQE

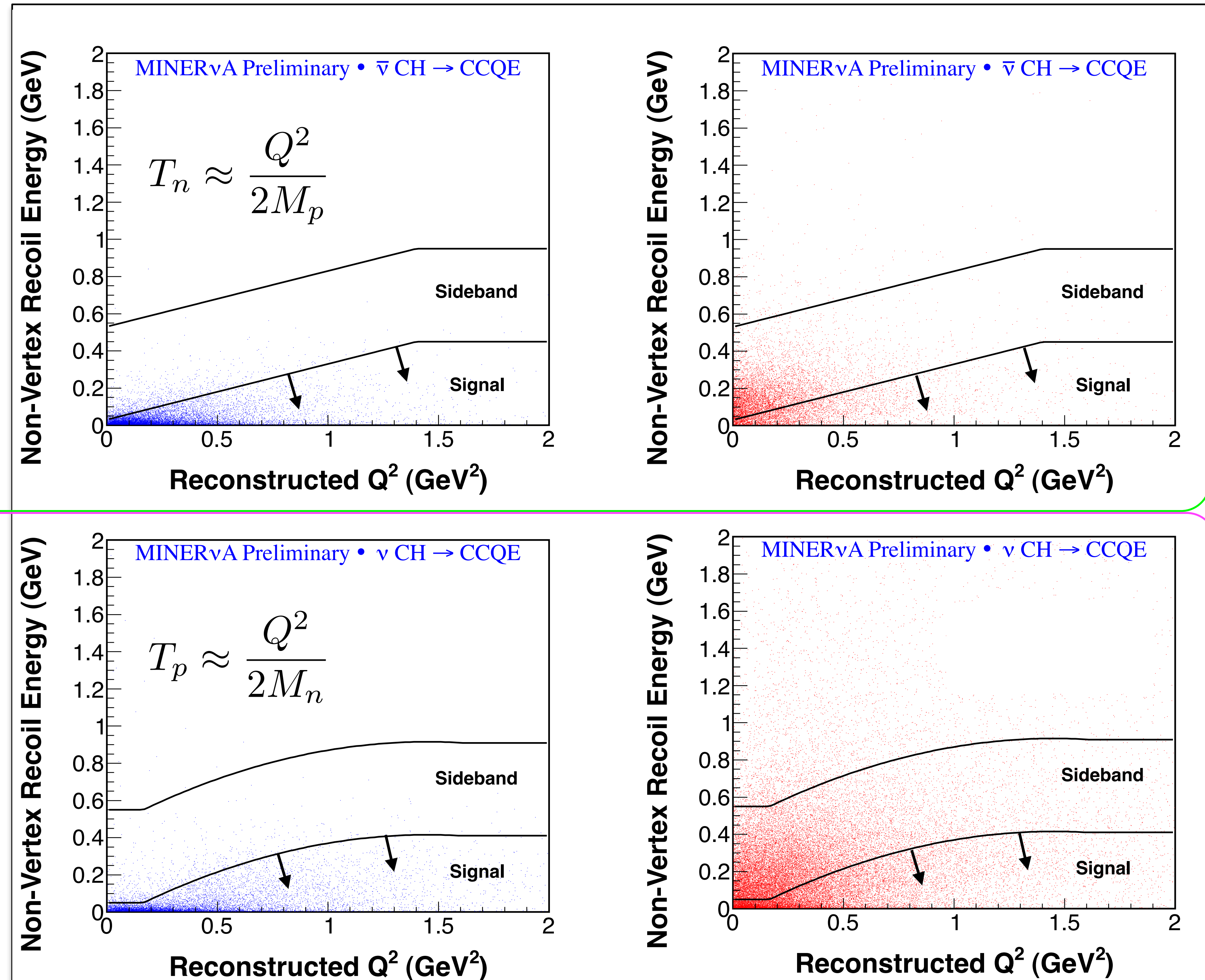


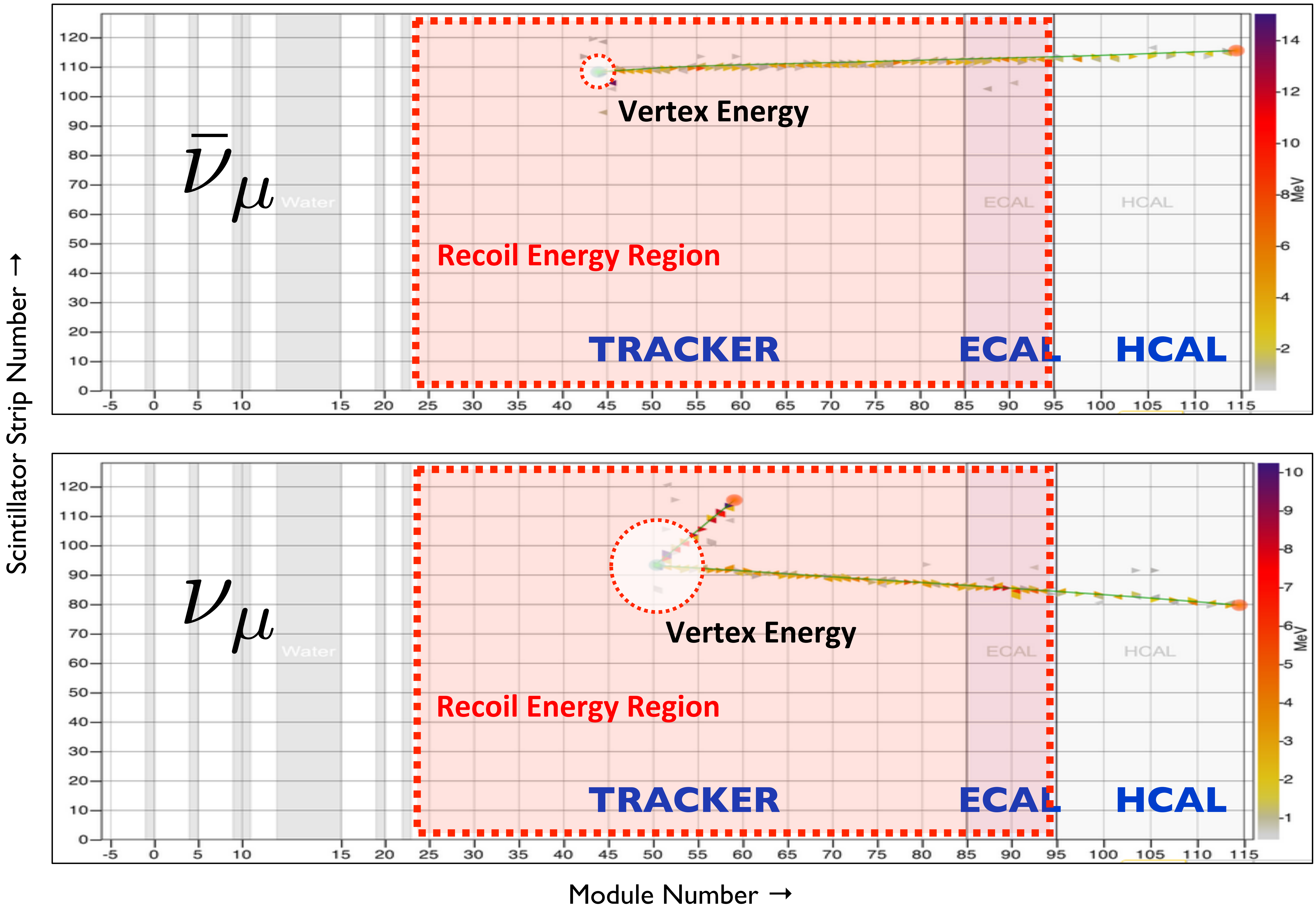
- Single muon/anti-muon momentum and sign analyzed in MINOS.
- Reconstructed topology cuts to remove extra particles.
- Recoil (tracker + E-cal) consistent with CCQE at event Q^2.
  - The region around the vertex is special.

CCQE Selection

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

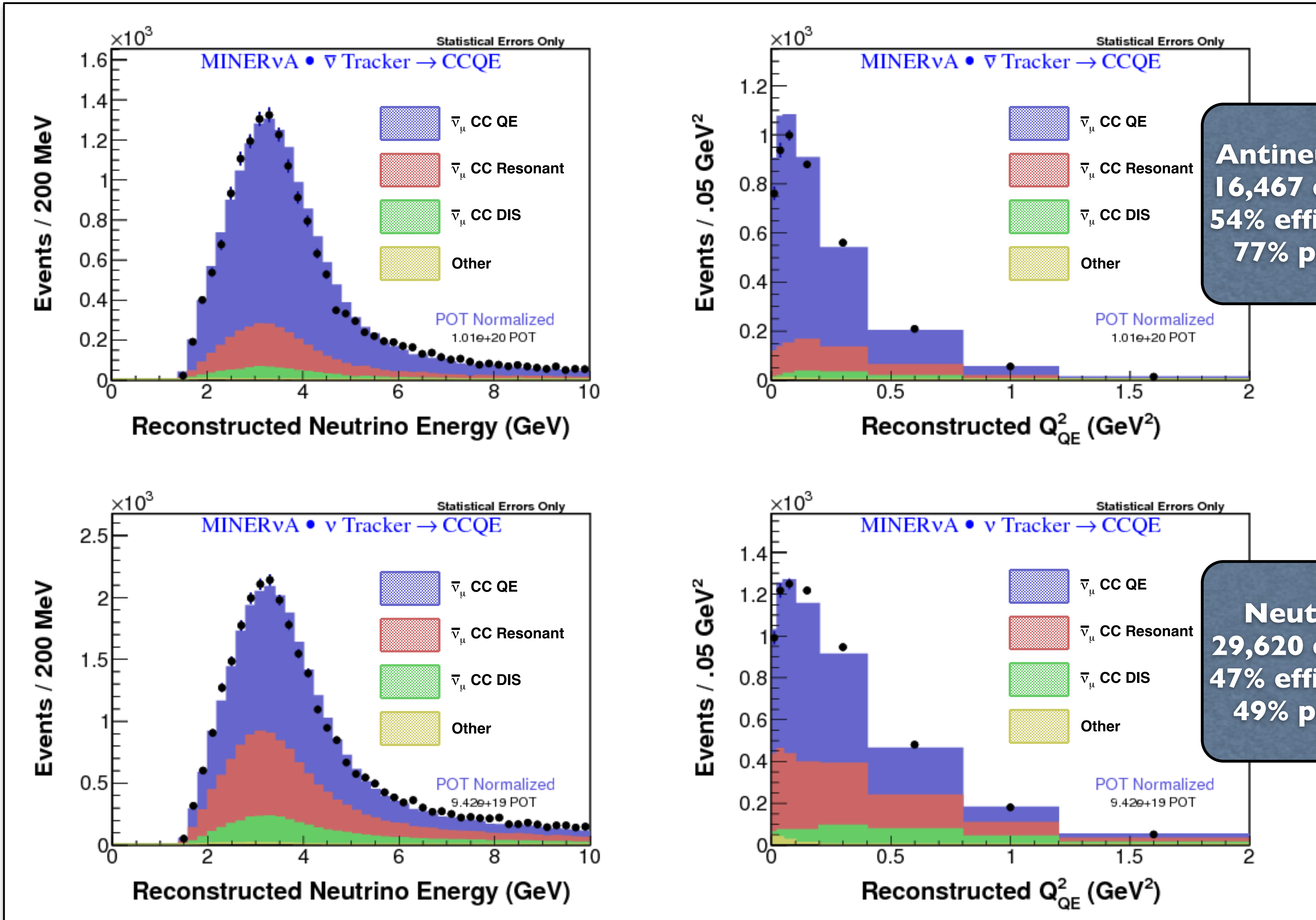
- **Antineutrino**
  - 10 g/cm2 vertex region
    - Contains < 120 MeV KE protons
    - Contains < 65 MeV KE pions
  - ≤ 1 isolated shower outside the vertex.
- **Neutrino**
  - 30 g/cm2 vertex region
    - Contains < 225 MeV KE protons
    - Contains < 100 MeV KE pions
  - ≤ 2 isolated showers outside the vertex.





Scintillator Strip Number →
$\bar{\nu}_\mu$
Vertex Energy
Recoil Energy Region
TRACKER
ECAL
HCAL
Water
MeV
ν_μ
Vertex Energy
Recoil Energy Region
TRACKER
ECAL
HCAL
Water
MeV
Module Number →

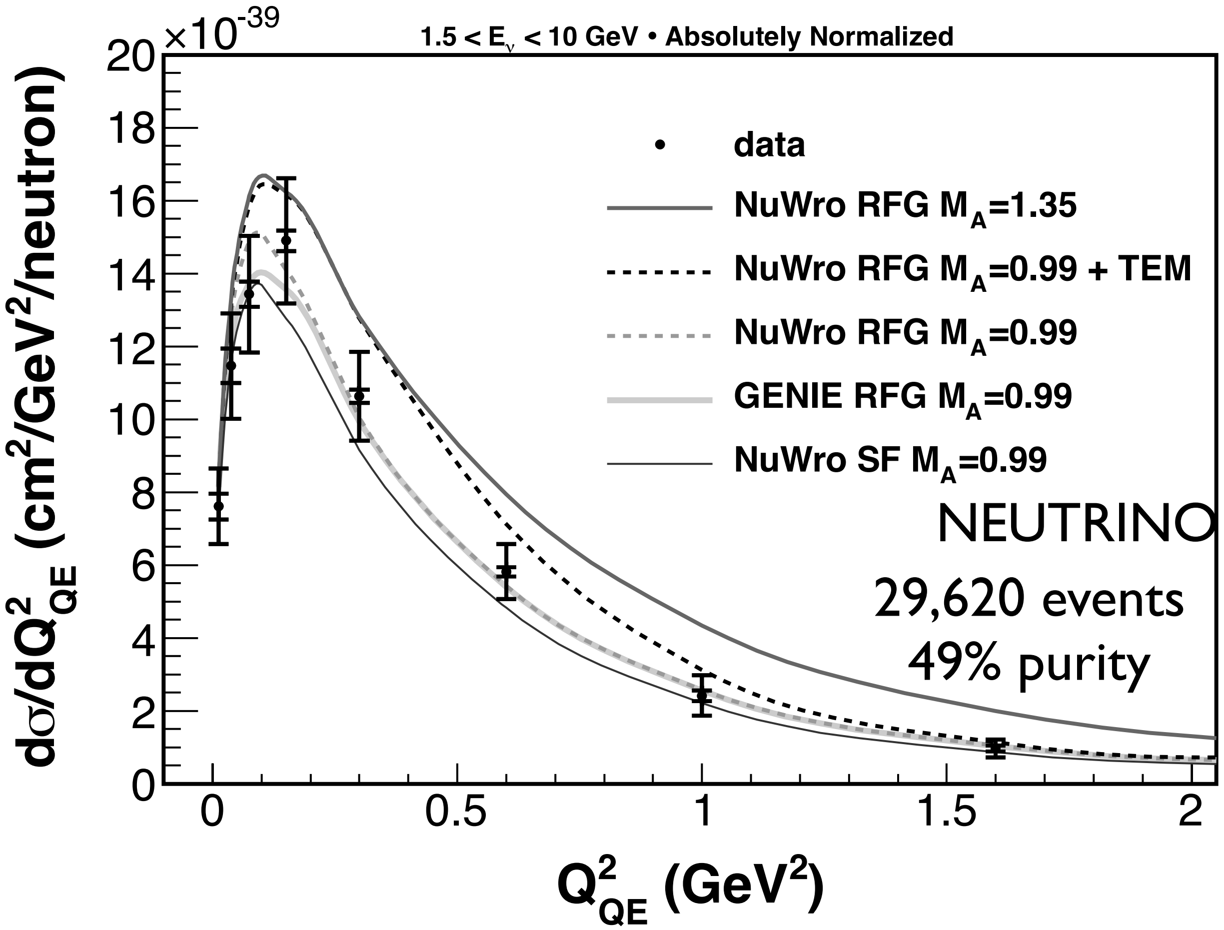
Selection Performance



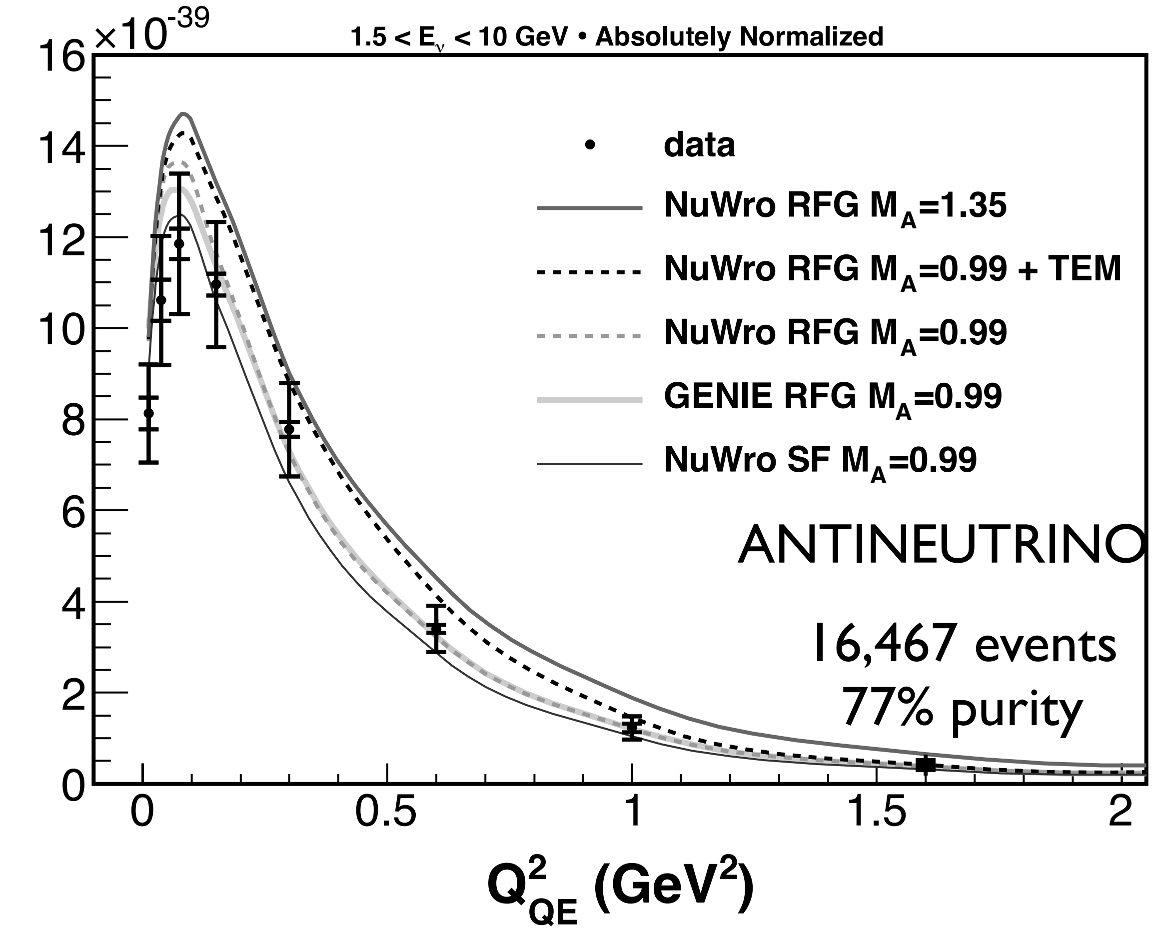
Antineutrino
16,467 events
54% efficiency
77% purity

Neutrino
29,620 events
47% efficiency
49% purity

Results



1.5 < Eν < 10 GeV • Absolutely Normalized
×10^-39
dσ/dQ²QE (cm²/GeV²/neutron)
data
NuWro RFG MA=1.35
NuWro RFG MA=0.99 + TEM
NuWro RFG MA=0.99
GENIE RFG MA=0.99
NuWro SF MA=0.99
NEUTRINO
29,620 events
49% purity
Q²QE (GeV²)



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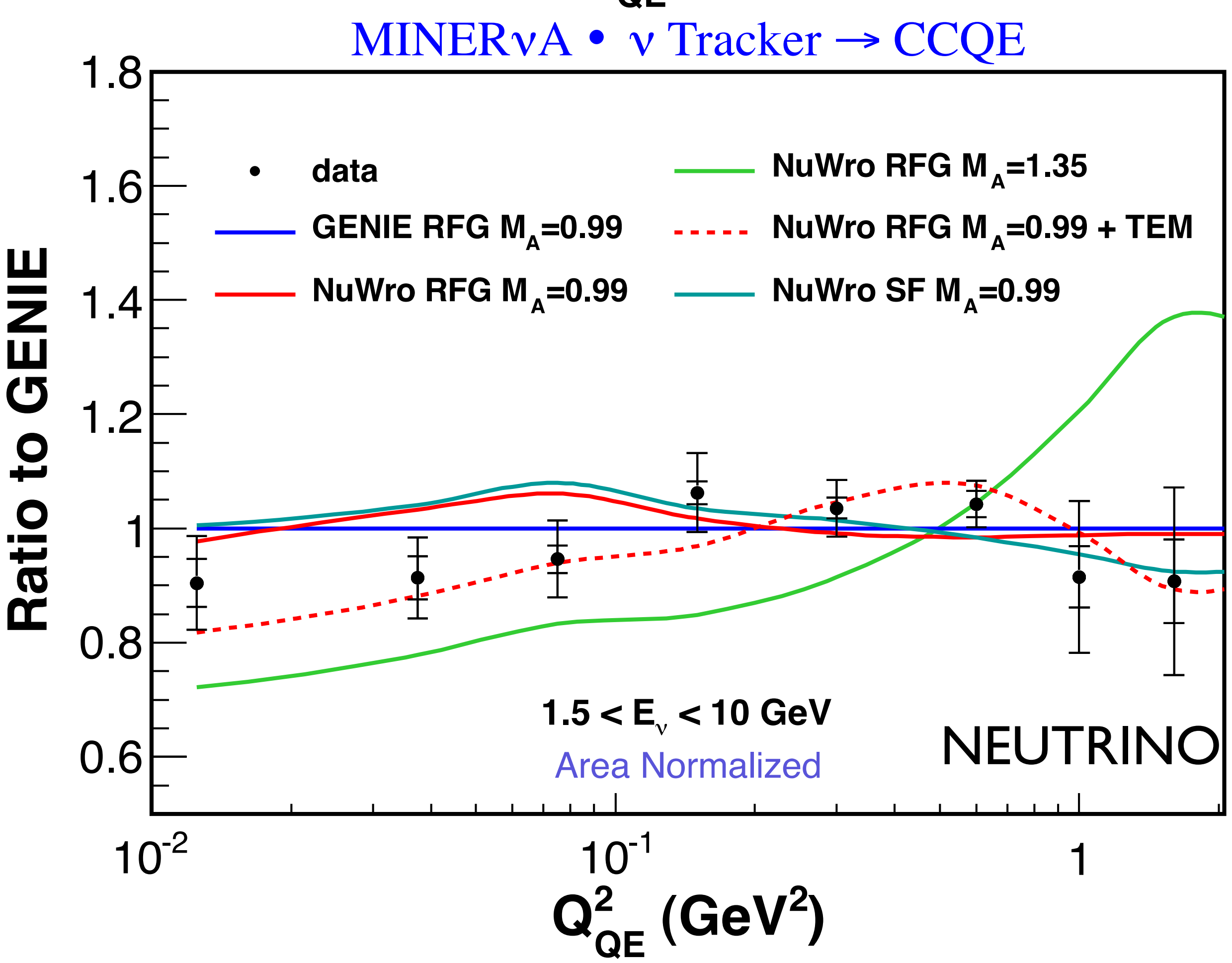
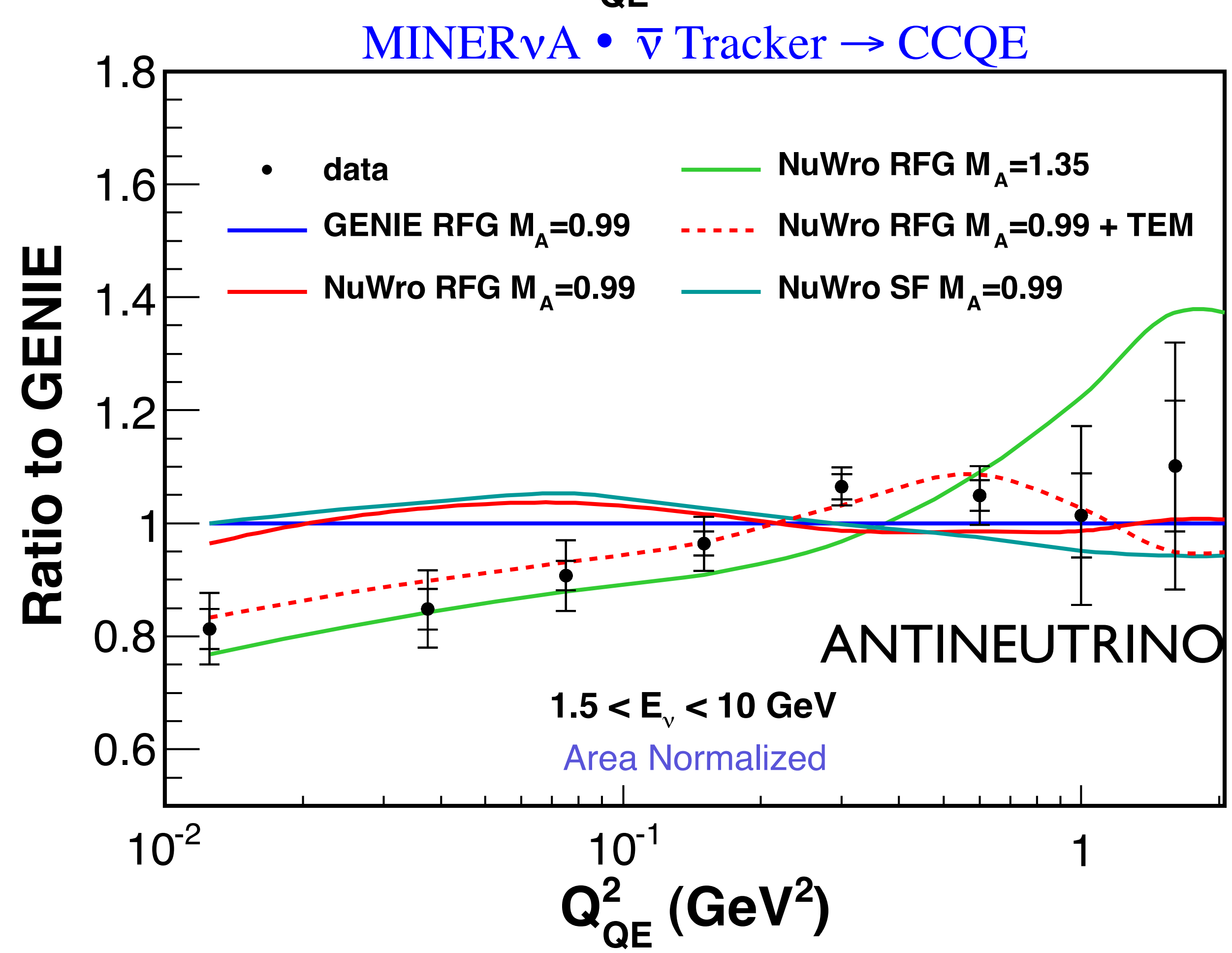
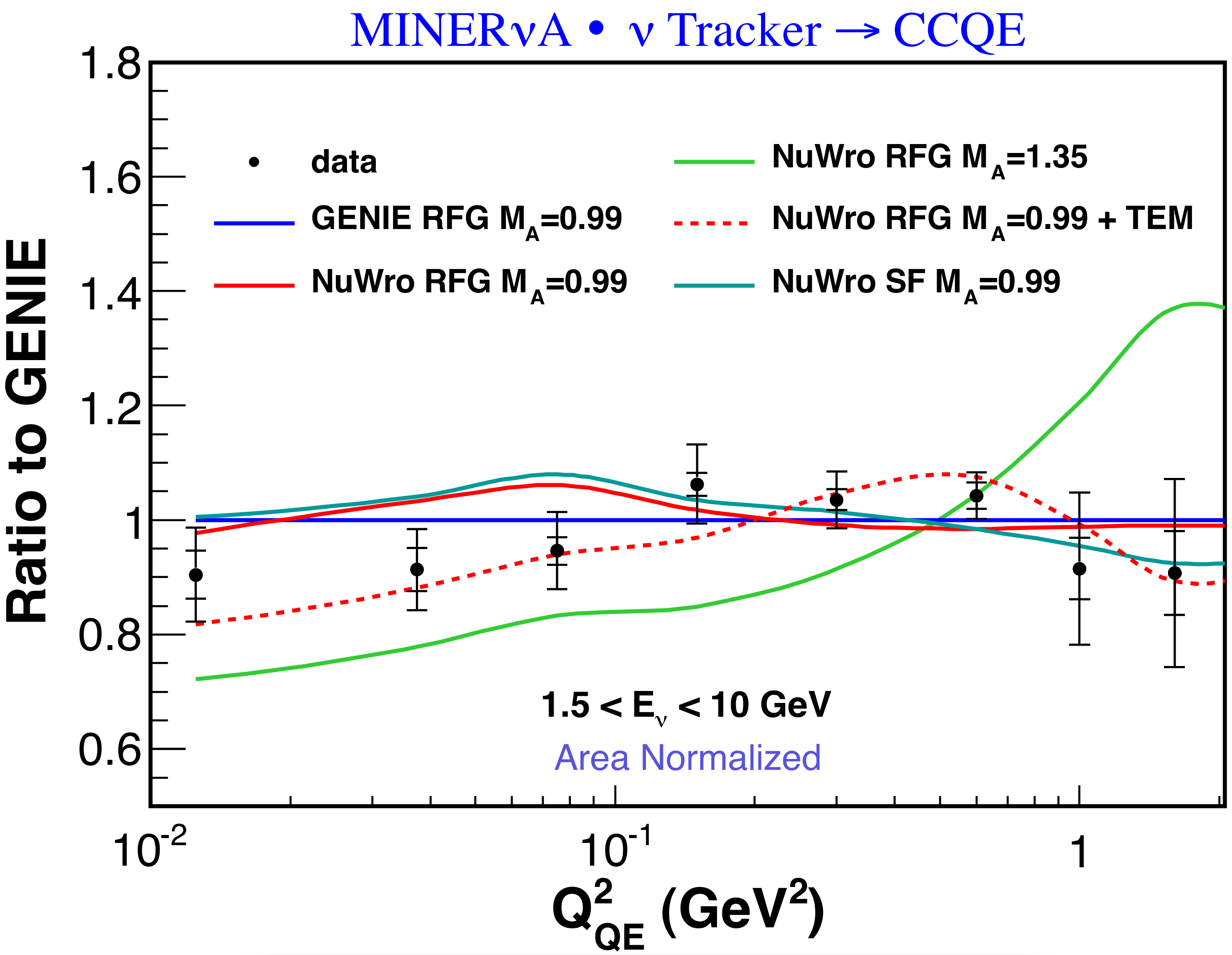


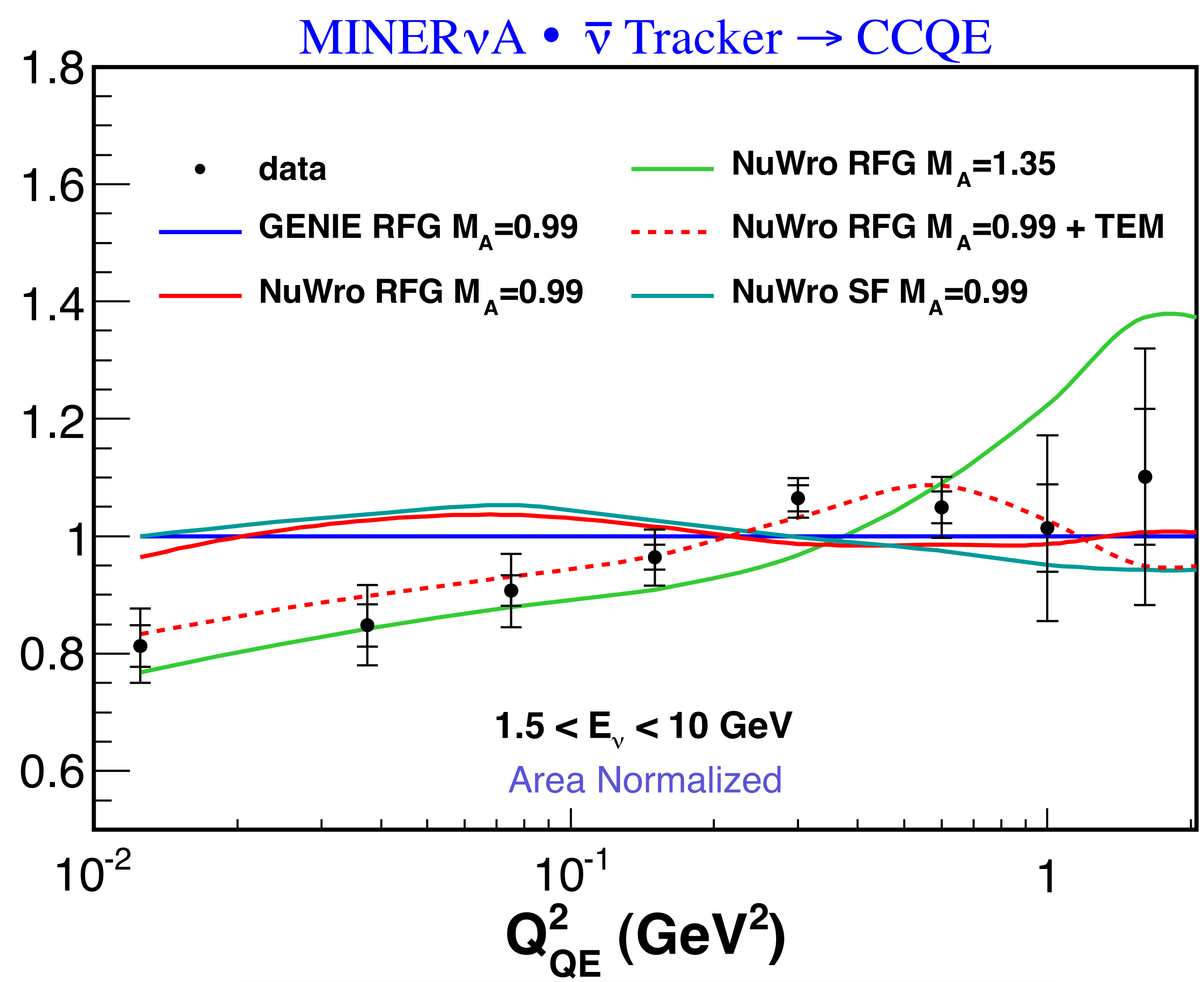
MINERνA • ν Tracker → CCQE
Ratio to GENIE
data
GENIE RFG MA=0.99
NuWro RFG MA=0.99
NuWro RFG MA=1.35
NuWro RFG MA=0.99 + TEM
NuWro SF MA=0.99
1.5 < Eν < 10 GeV
Area Normalized
NEUTRINO
Q²QE (GeV²)



MINERνA • ν̄ Tracker → CCQE
Ratio to GENIE
data
GENIE RFG MA=0.99
NuWro RFG MA=0.99
NuWro RFG MA=1.35
NuWro RFG MA=0.99 + TEM
NuWro SF MA=0.99
ANTINEUTRINO
1.5 < Eν < 10 GeV
Area Normalized
Q²QE (GeV²)

Neutrino (Left), Antineutrino (Right)





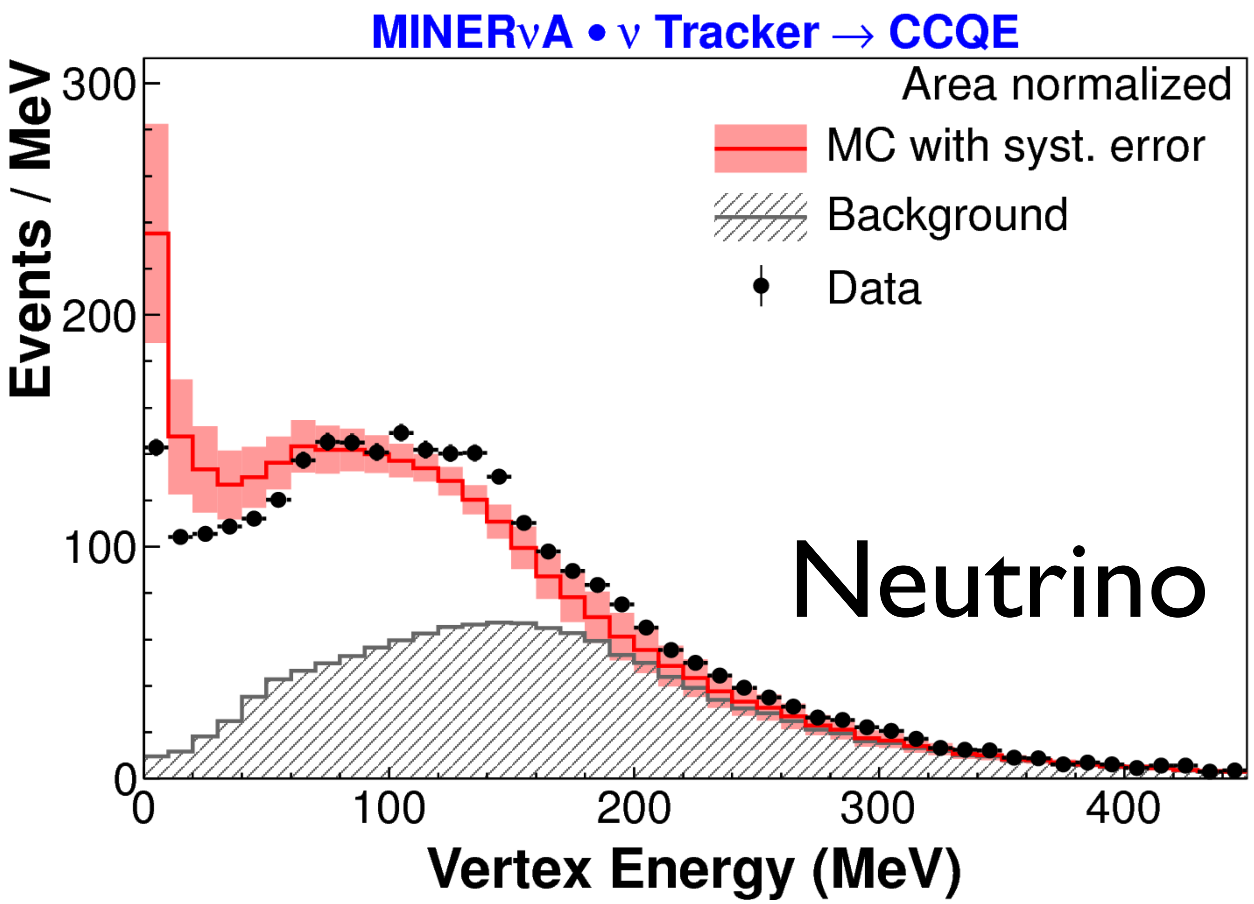
Neutrino

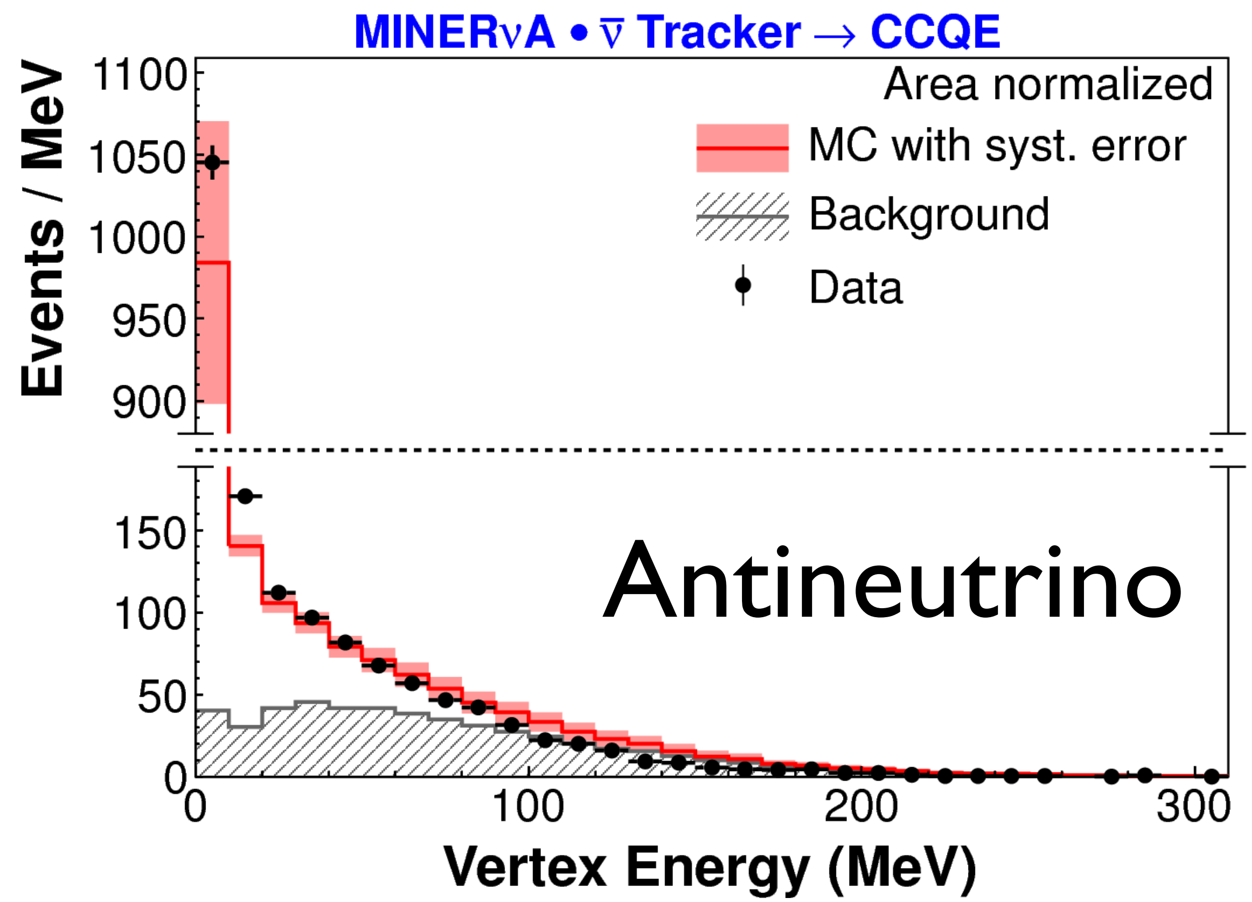
NuWro Model	RFG	RFG +TEM	RFG	SF
M_A (GeV/c^2)	0.99	0.99	1.35	0.99
Rate χ^2/d.o.f.	3.5	2.4	3.7	2.8
Shape χ^2/d.o.f.	4.1	1.7	2.1	3.8

Antineutrino

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
Shape χ^2/d.o.f.	2.90	0.66	1.73	2.99

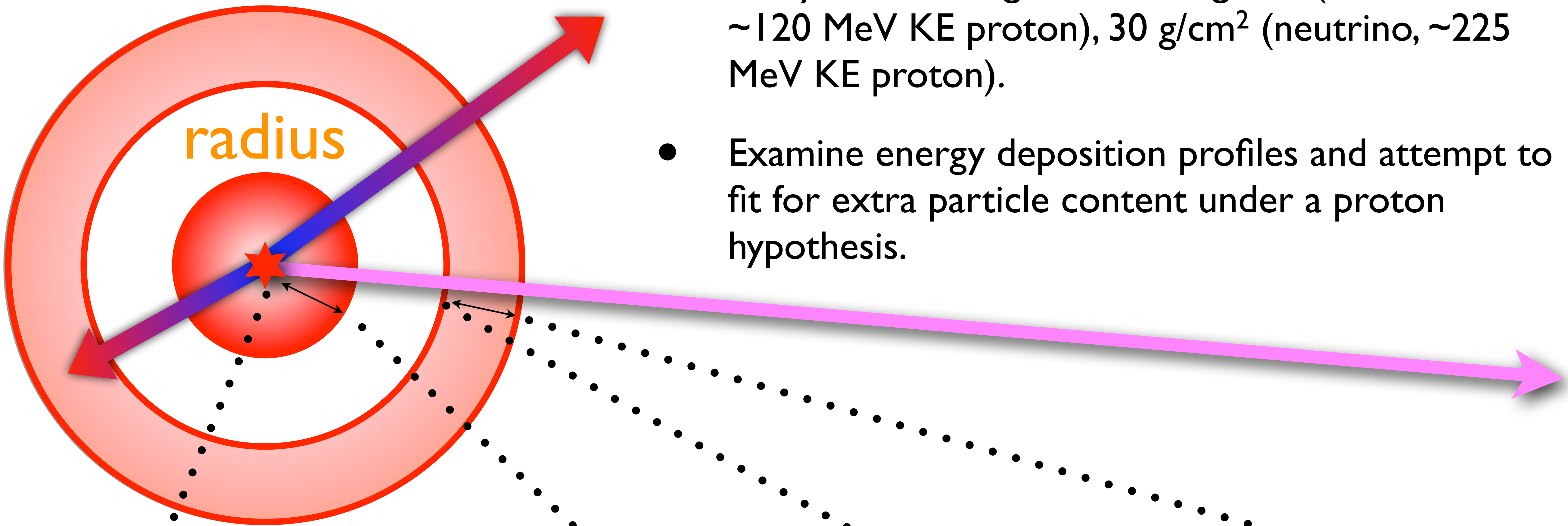
Vertex Energy

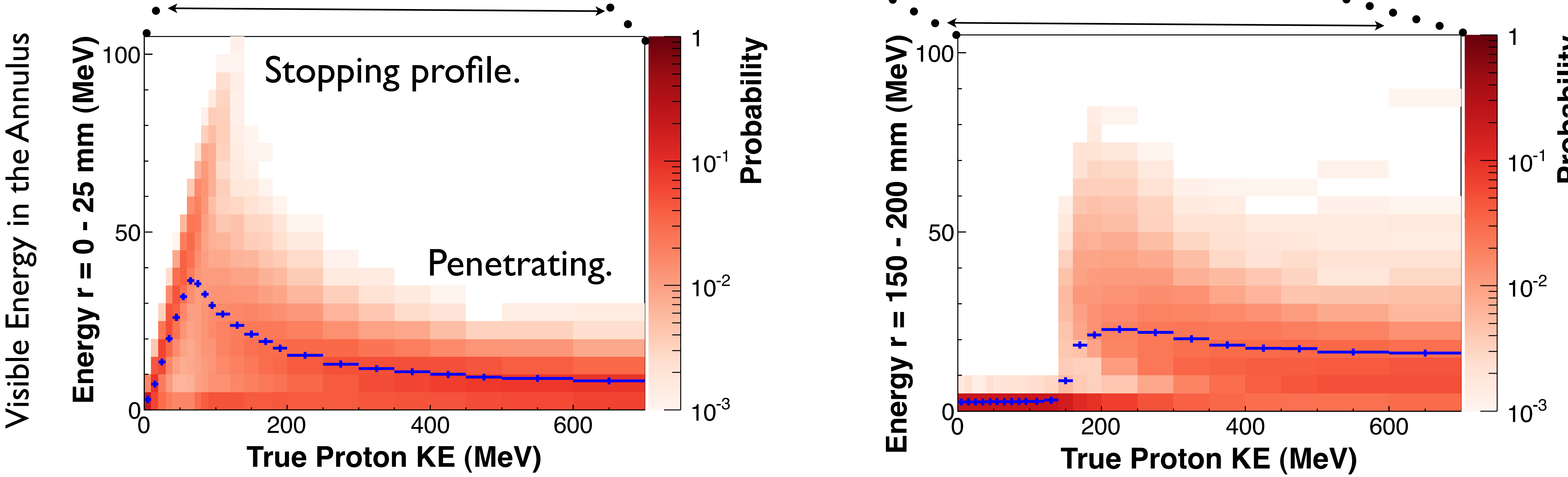


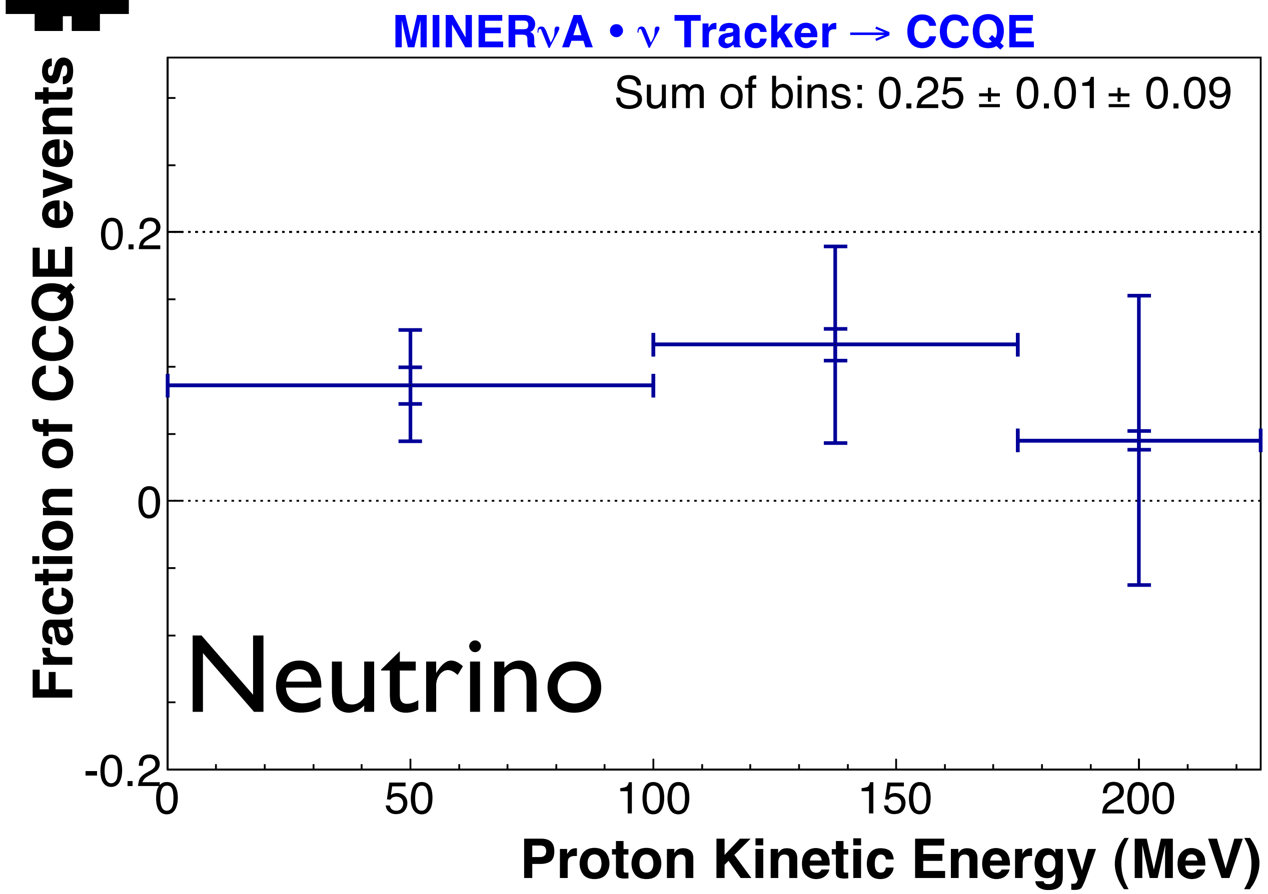


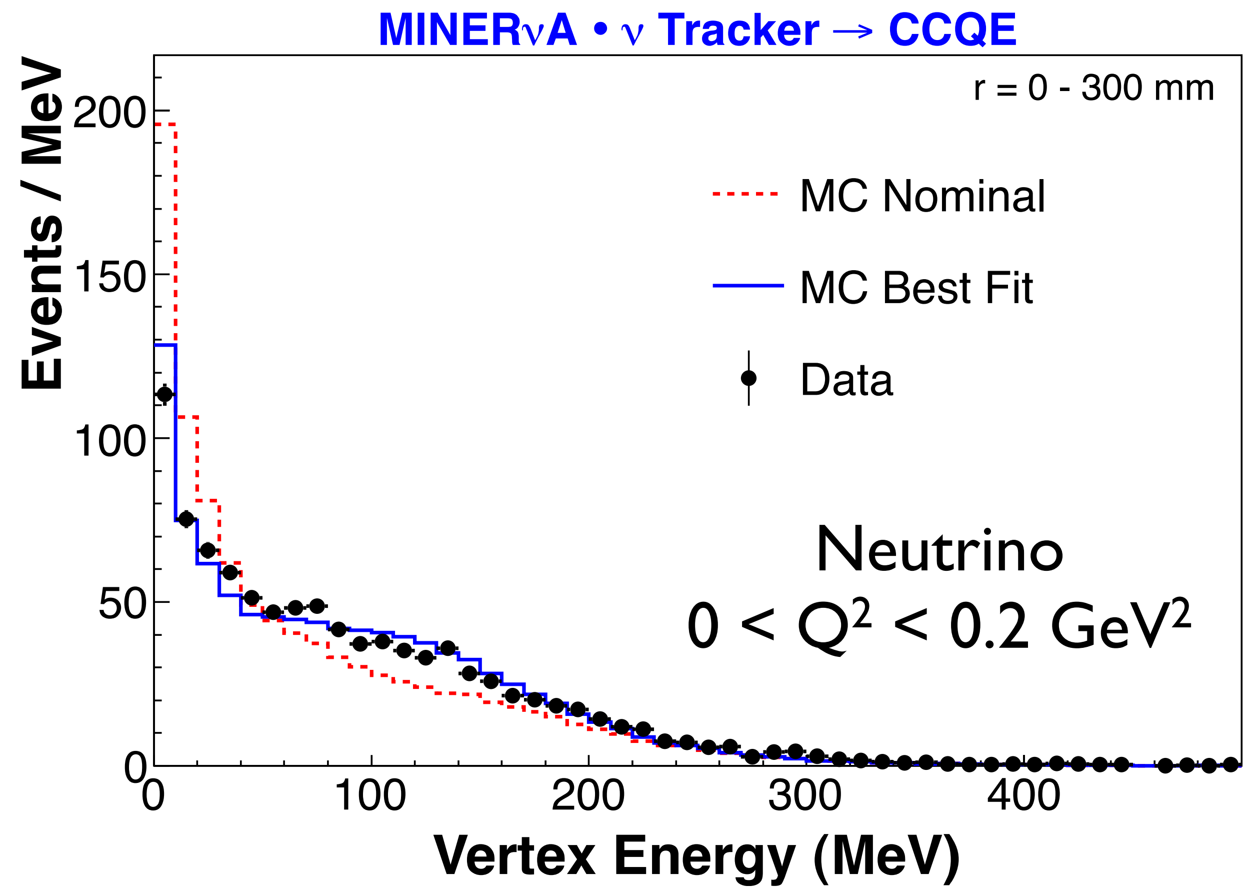
- Energy near the vertex is not used as part of the event selection because we are not confident in our MC to produce a realistic hadron spectrum.
- Indeed, in the data, we see a harder vertex energy distribution for neutrinos, and a slightly softer distribution for antineutrinos.

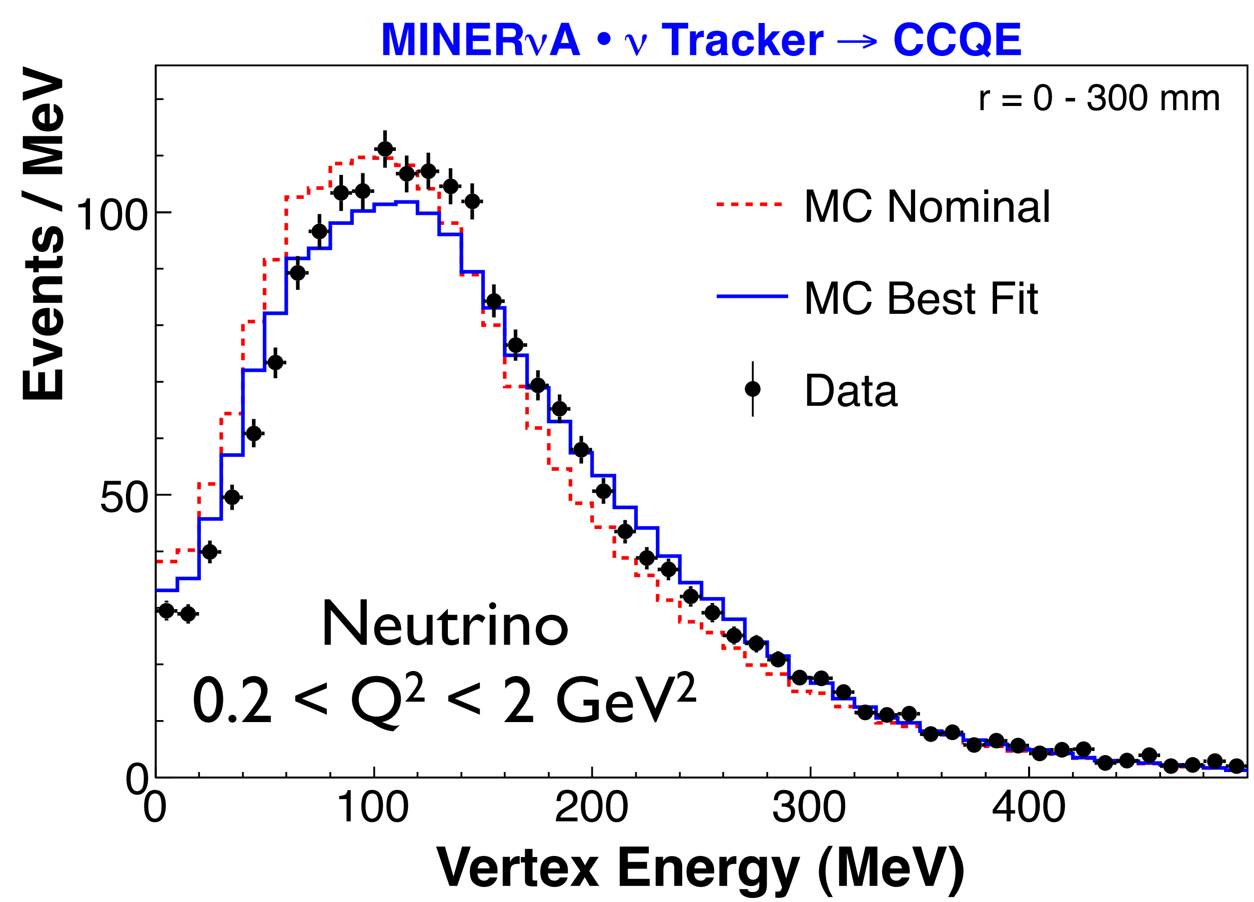
- Study annular rings out to 10 g/cm^2 (antineutrino, ~120 MeV KE proton), 30 g/cm^2 (neutrino, ~225 MeV KE proton).
- Examine energy deposition profiles and attempt to fit for extra particle content under a proton hypothesis.



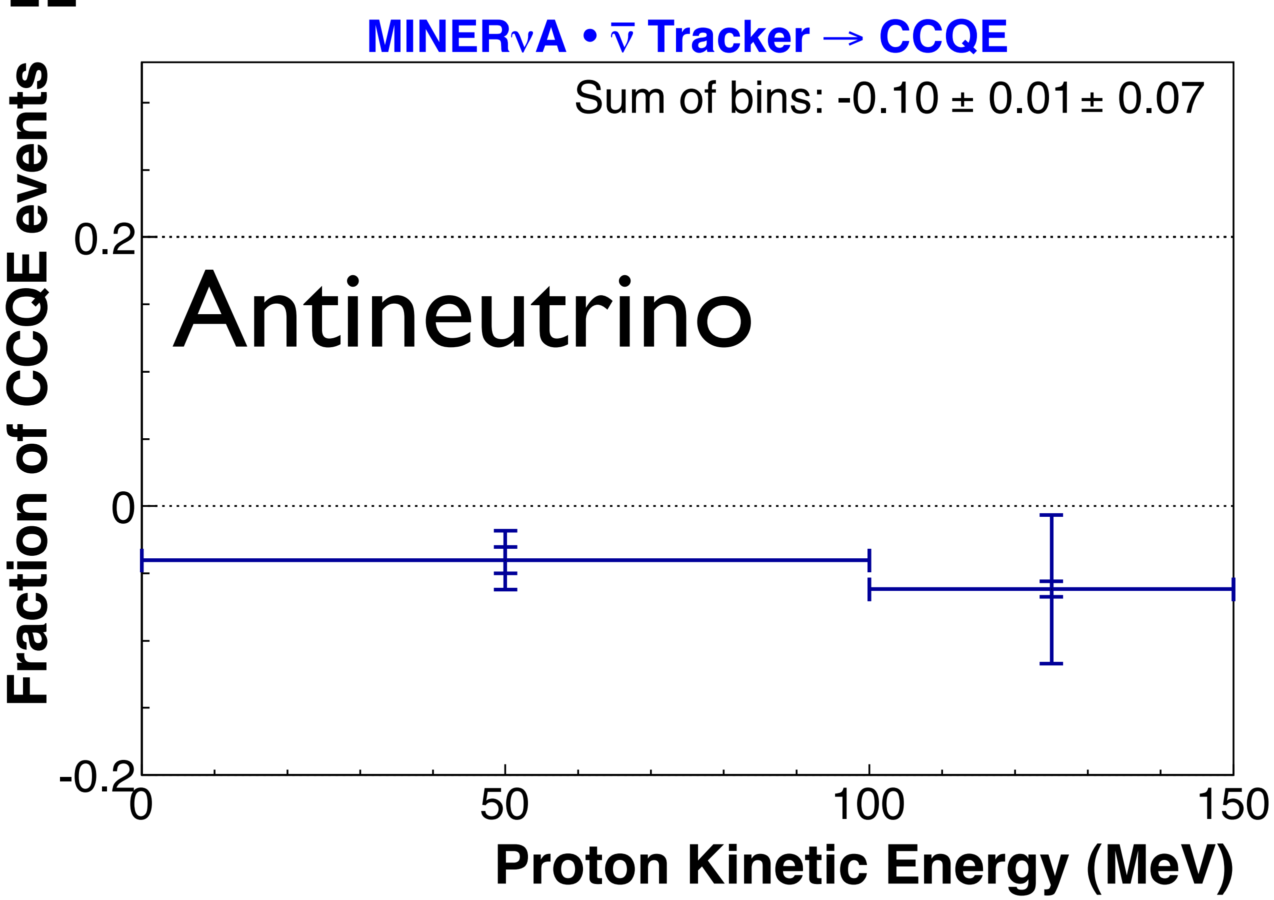


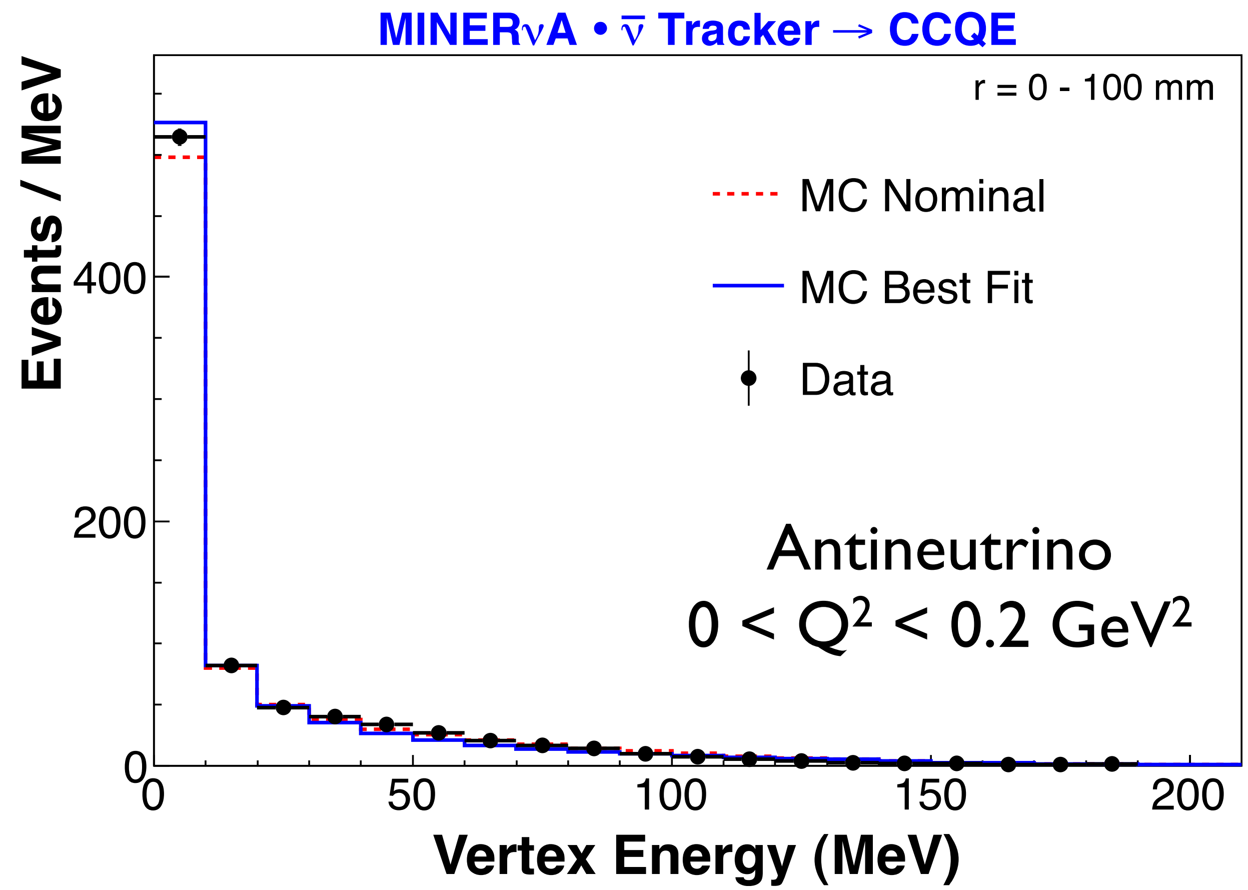




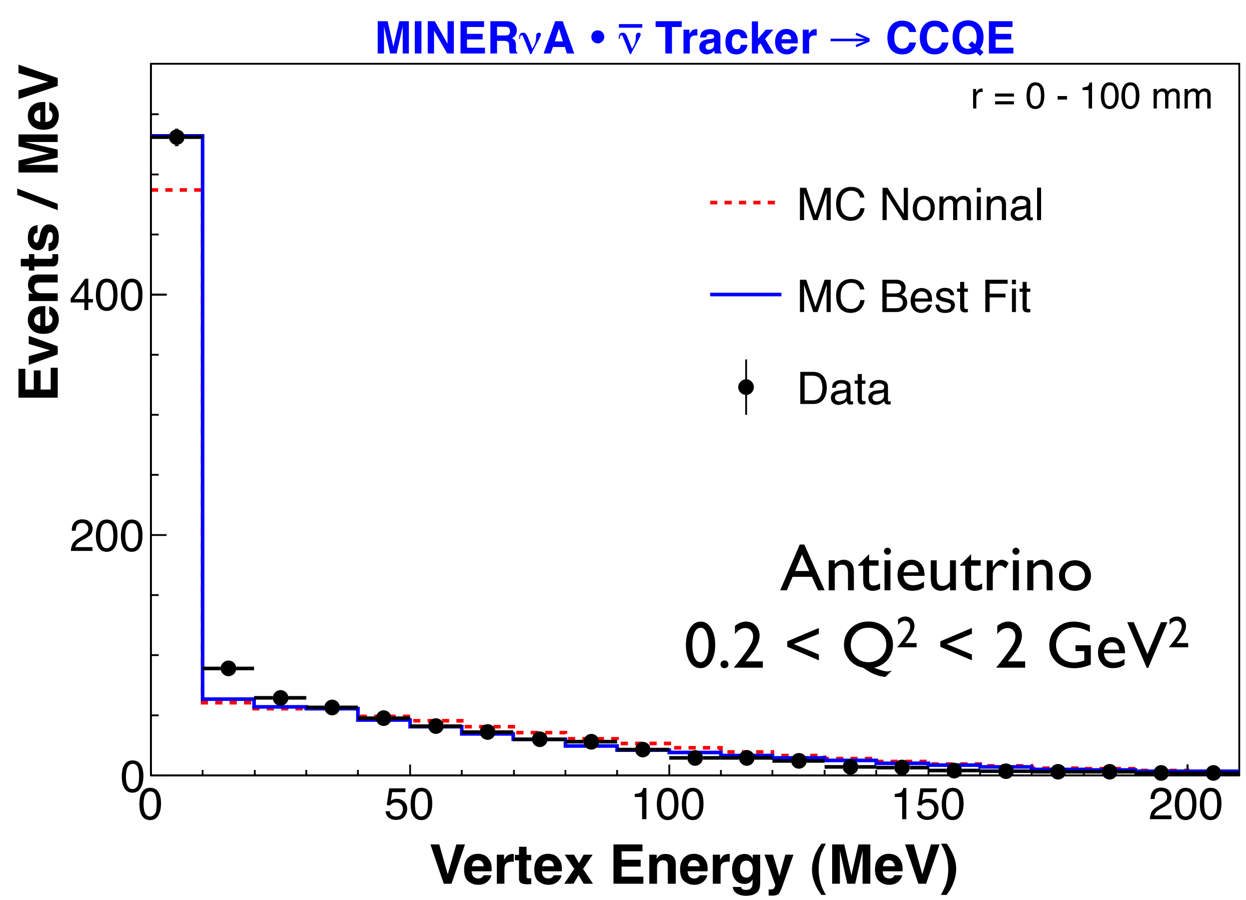


- In our neutrino data, we find that adding an additional low-energy proton (KE < 225 MeV) to (25 ± 9)% of QE events improves agreement.





- In our antineutrino data, we find no such evidence.
- Indeed, there is some evidence of an over-prediction in the number of protons with the data preferring (-10 ± 7)% of QE events to have an extra proton.



Back-Up

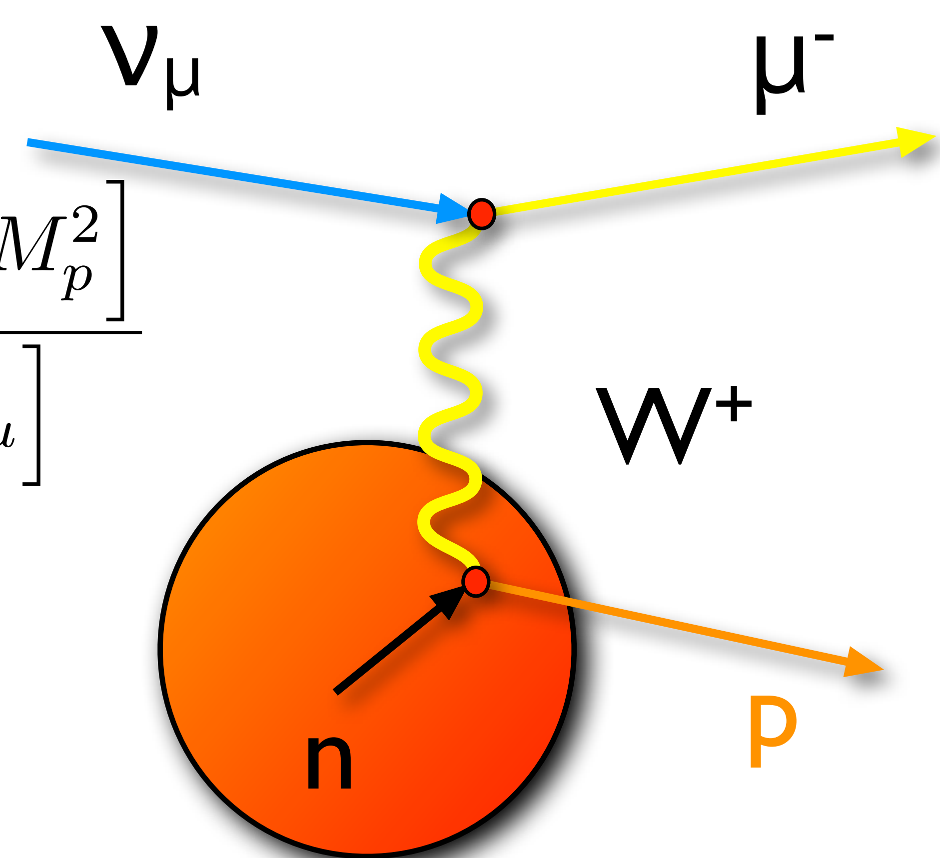
Quasi-Elastic Scattering

(Flip nucleons for antineutrino scattering.)

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

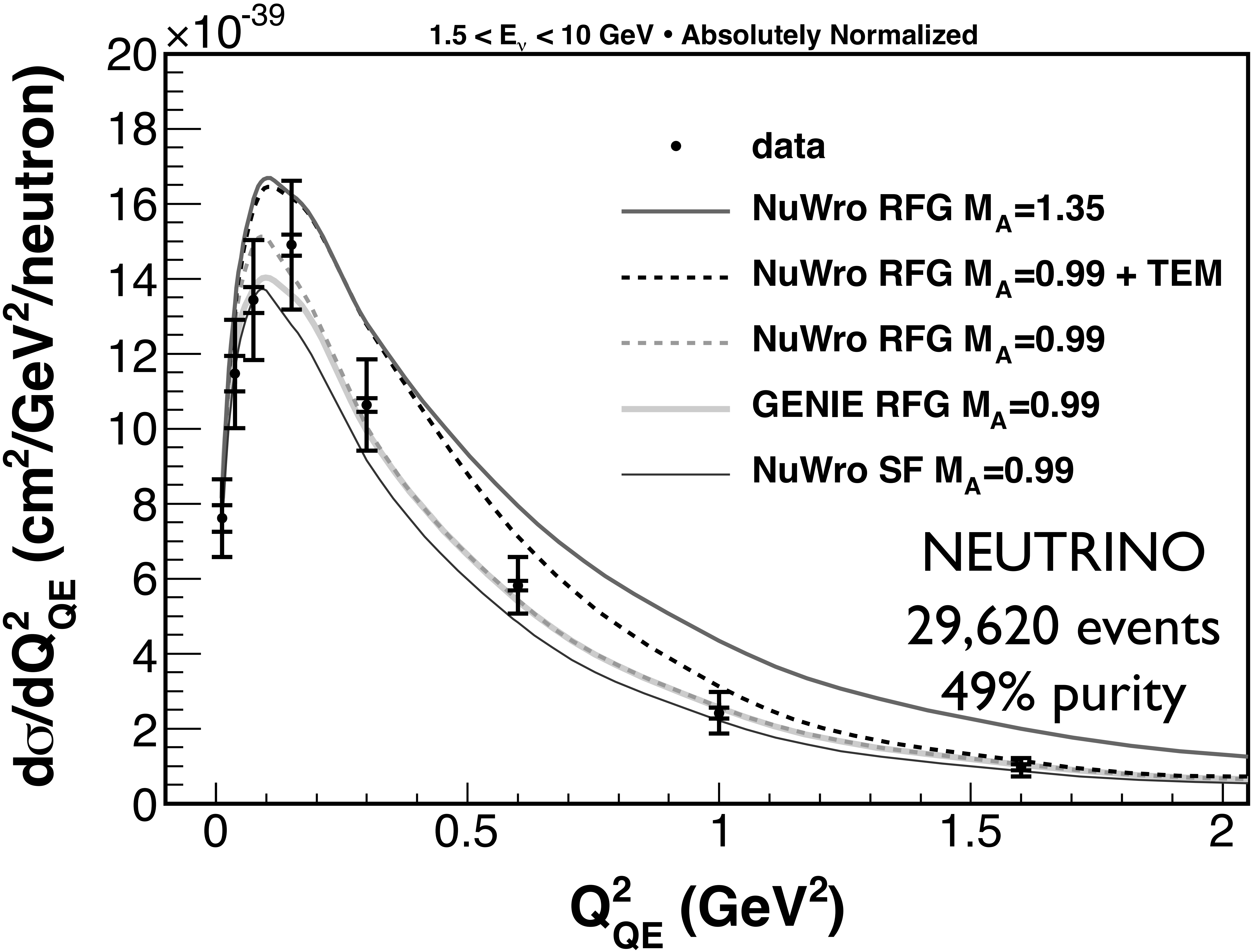
$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE}\left(E_\mu - \sqrt{E_\mu^2 - m_\mu^2}\cos\theta_\mu\right)$$

$E_\mu = T_\mu + m_\mu$	Muon Energy
M_n, M_p, m_μ	Neutron, Proton, Muon Mass
E_B	Binding Energy (~30 MeV)
θ_μ	Muon Angle w.r.t. Neutrino Direction

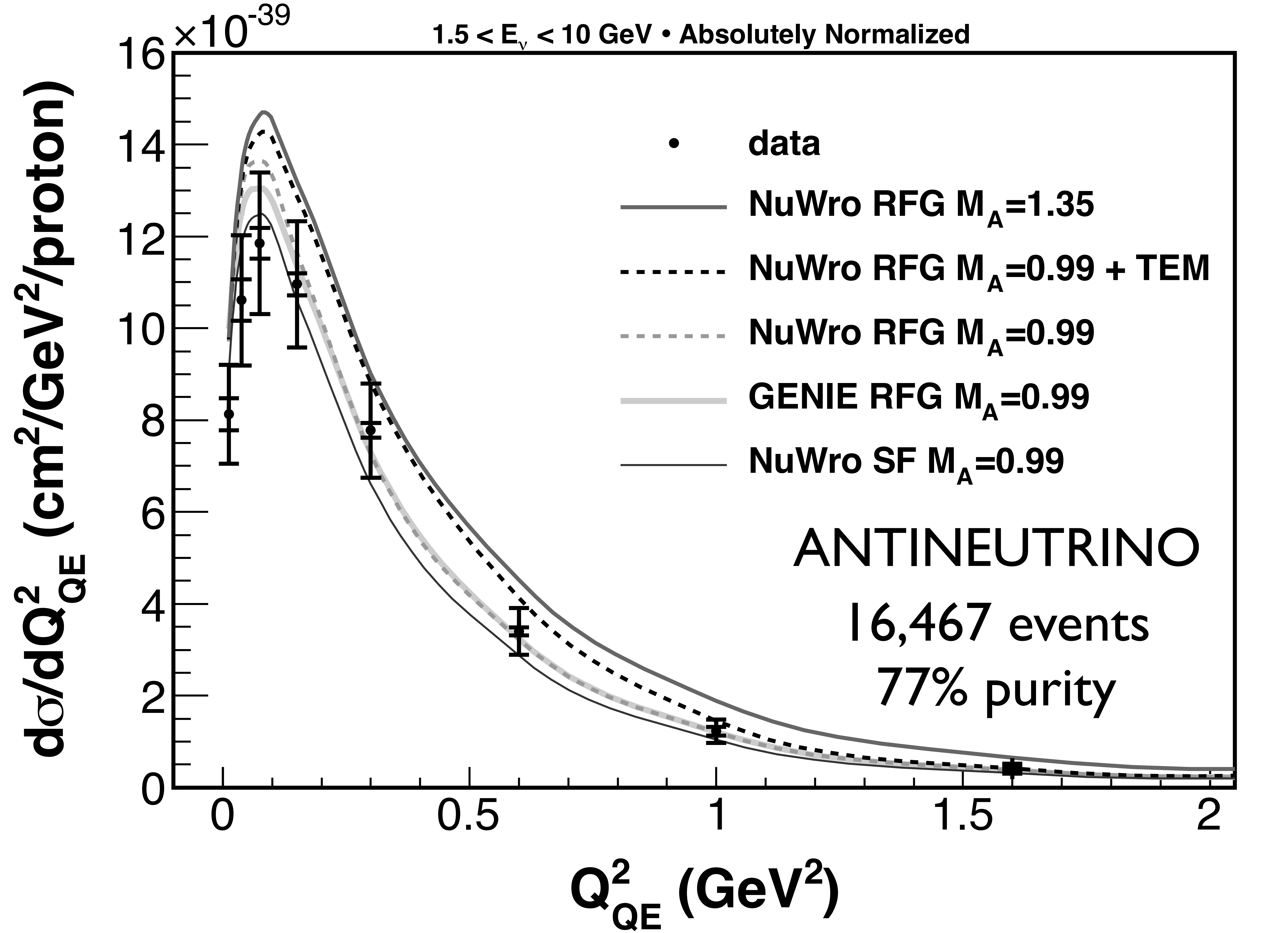


$$\nu_l + n \to l^- + p$$

$$\bar{\nu}_l + p \to l^+ + n$$



1.5 < Eν < 10 GeV • Absolutely Normalized
×10-39
dσ/dQ2QE (cm2/GeV2/neutron)
Q2QE (GeV2)
data
NuWro RFG MA=1.35
NuWro RFG MA=0.99 + TEM
NuWro RFG MA=0.99
GENIE RFG MA=0.99
NuWro SF MA=0.99
NEUTRINO
29,620 events
49% purity



1.5 < E_ν < 10 GeV • Absolutely Normalized
$\times 10^{-39}$
$d\sigma/dQ^2_{QE}$ (cm^2/GeV^2/proton)
Q^2_{QE} (GeV^2)
data
NuWro RFG M_A=1.35
NuWro RFG M_A=0.99 + TEM
NuWro RFG M_A=0.99
GENIE RFG M_A=0.99
NuWro SF M_A=0.99
ANTINEUTRINO
16,467 events
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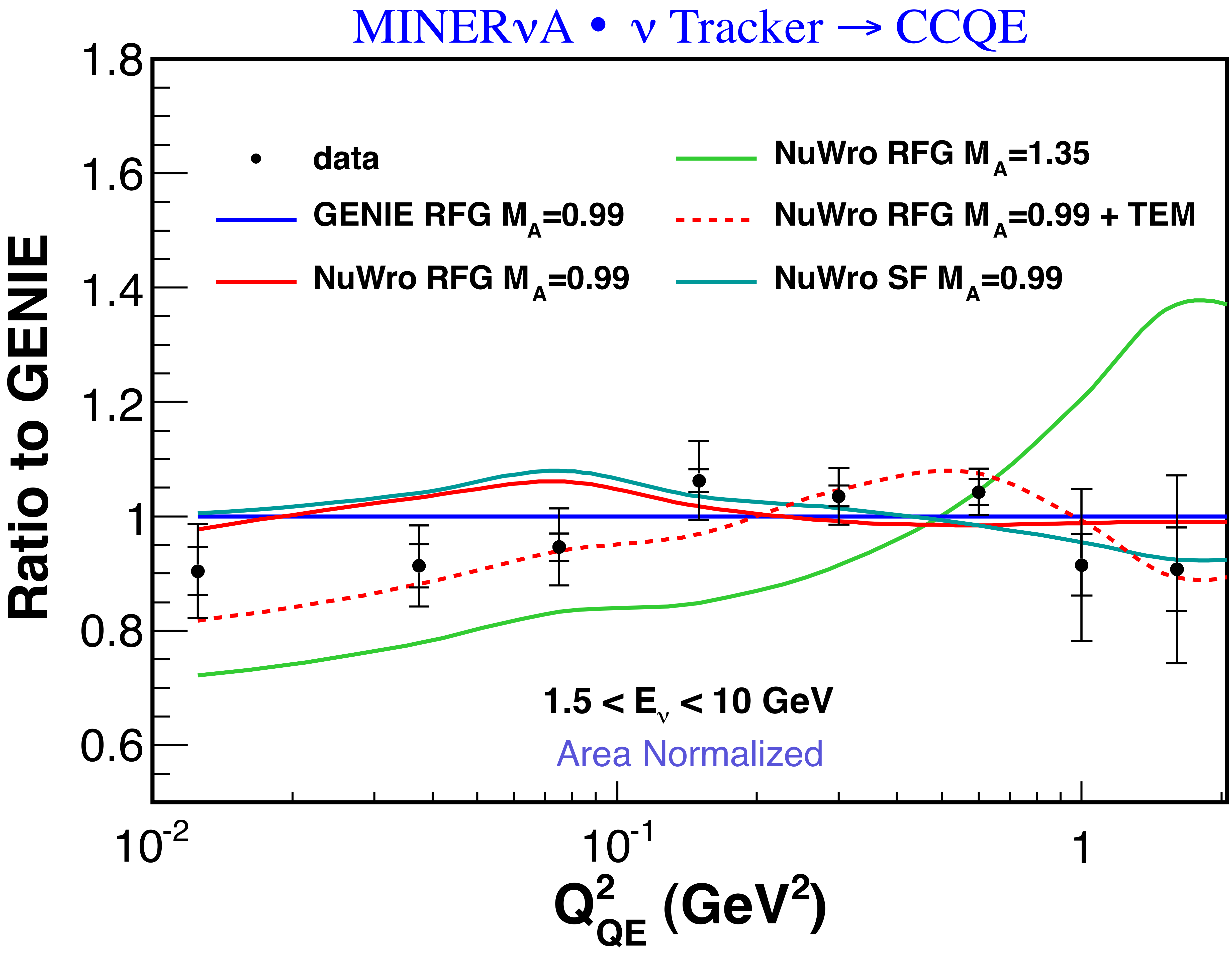
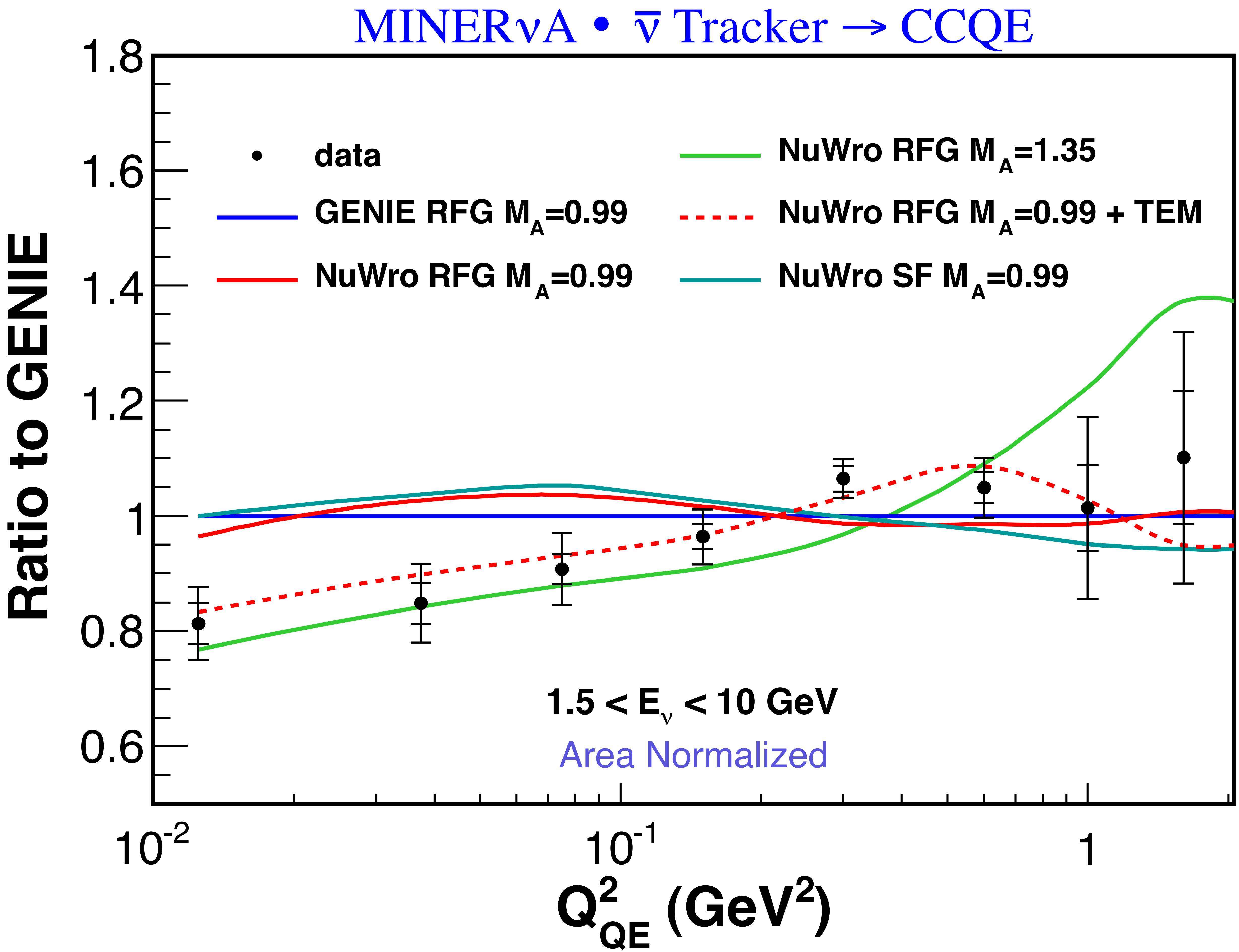
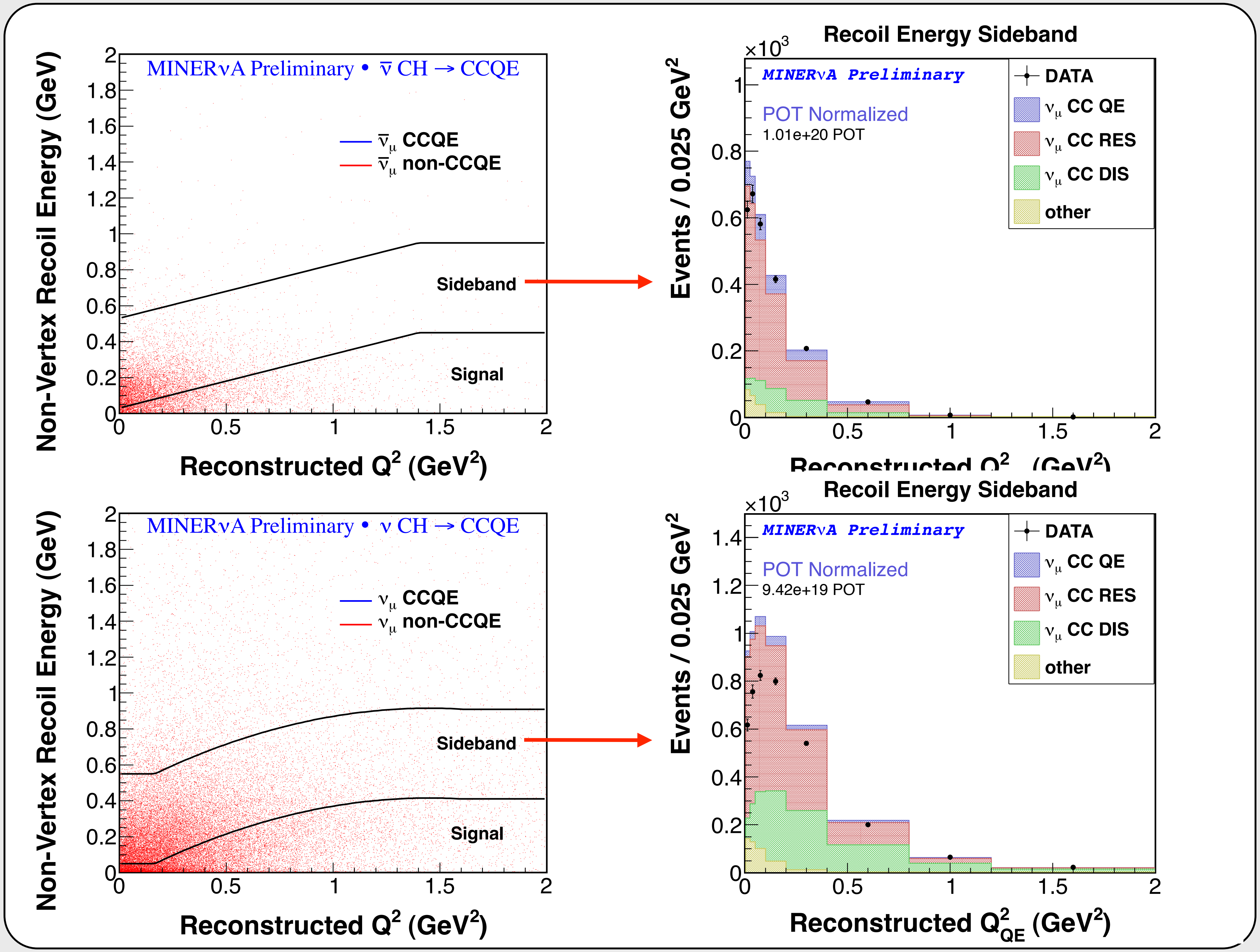

MINERνA • ν Tracker → CCQE
Ratio to GENIE
1.8
1.6
1.4
1.2
1
0.8
0.6
data
GENIE RFG M_A=0.99
NuWro RFG M_A=0.99
NuWro RFG M_A=1.35
NuWro RFG M_A=0.99 + TEM
NuWro SF M_A=0.99
1.5 < E_ν < 10 GeV
Area Normalized
10^-2
10^-1
1
Q²_QE (GeV²)


MINERνA • ν̄ Tracker → CCQE
Ratio to GENIE
data
GENIE RFG M_A=0.99
NuWro RFG M_A=0.99
NuWro RFG M_A=1.35
NuWro RFG M_A=0.99 + TEM
NuWro SF M_A=0.99
1.5 < E_ν < 10 GeV
Area Normalized
1.8
1.6
1.4
1.2
1
0.8
0.6
10^-2
10^-1
1
Q²_QE (GeV²)

Constraining Non-QE Backgrounds

- Given the challenge and large uncertainties on cross-section models and especially FSI, *constraining backgrounds with data* is very valuable



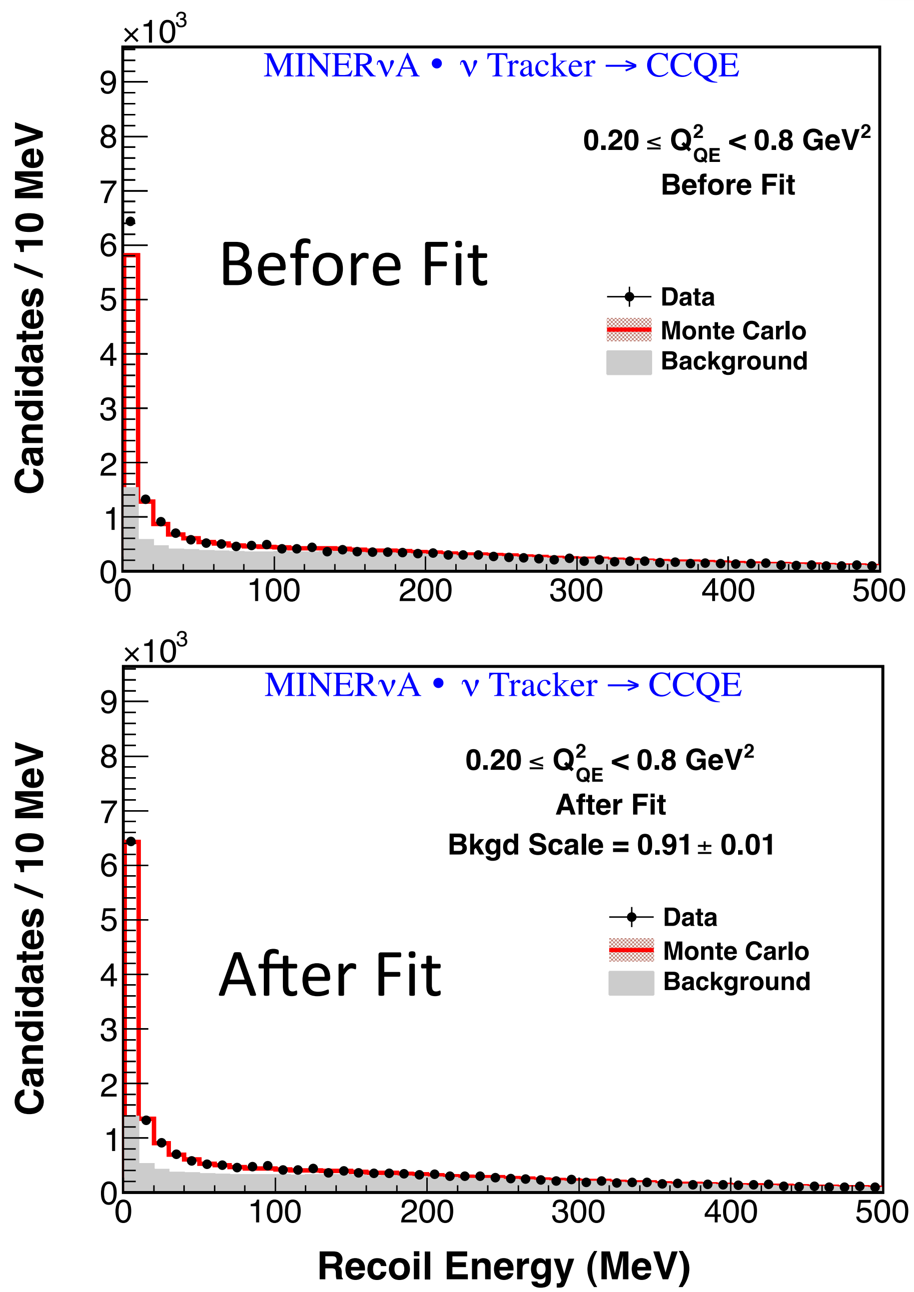
$\bar{\nu}_\mu$

ν_μ

Constraining Non-QE Backgrounds

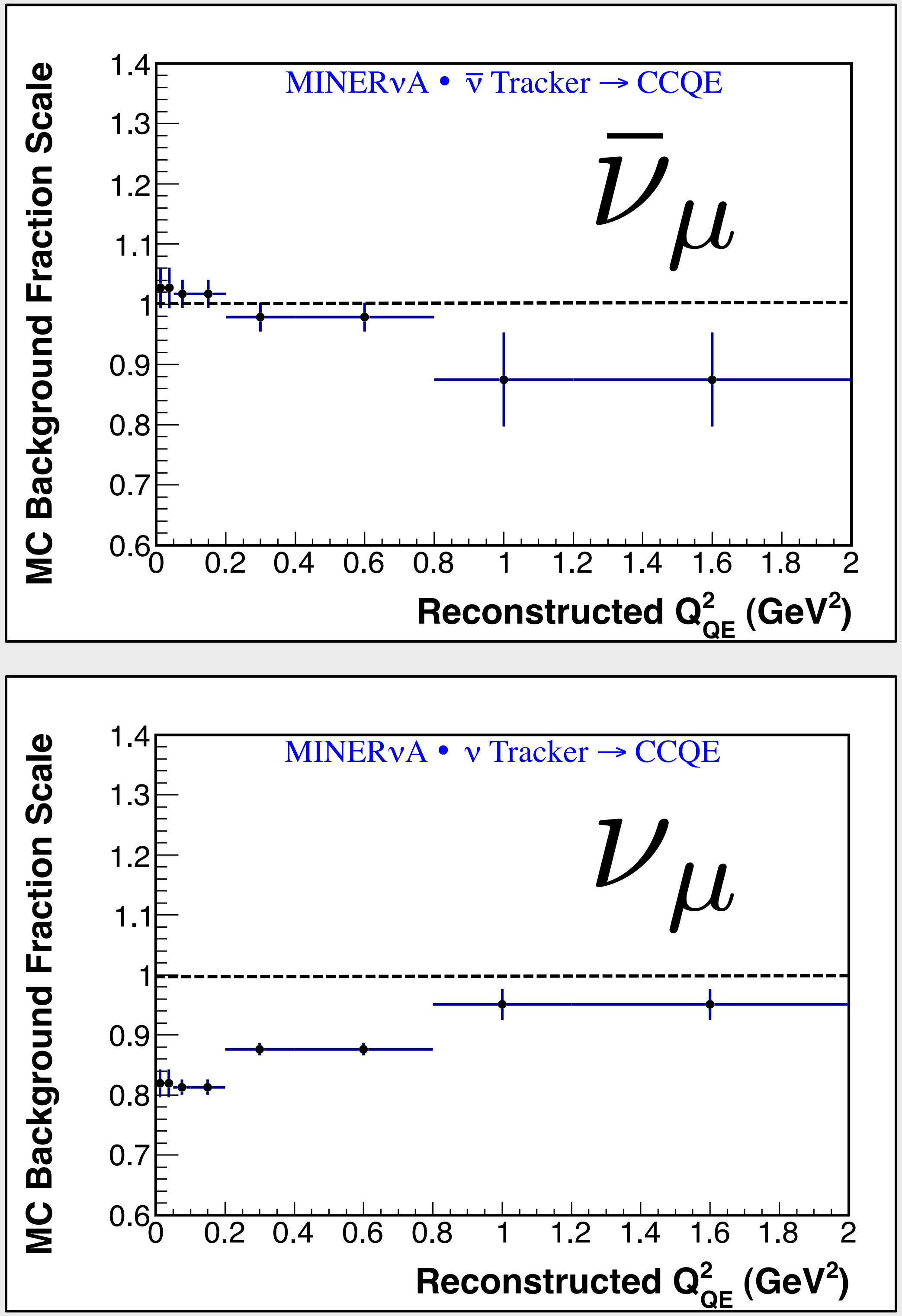
- Perform a fit in bins of Q^2_{QE} to set the relative signal – background fraction

One Sample Q^2_{QE} Bin

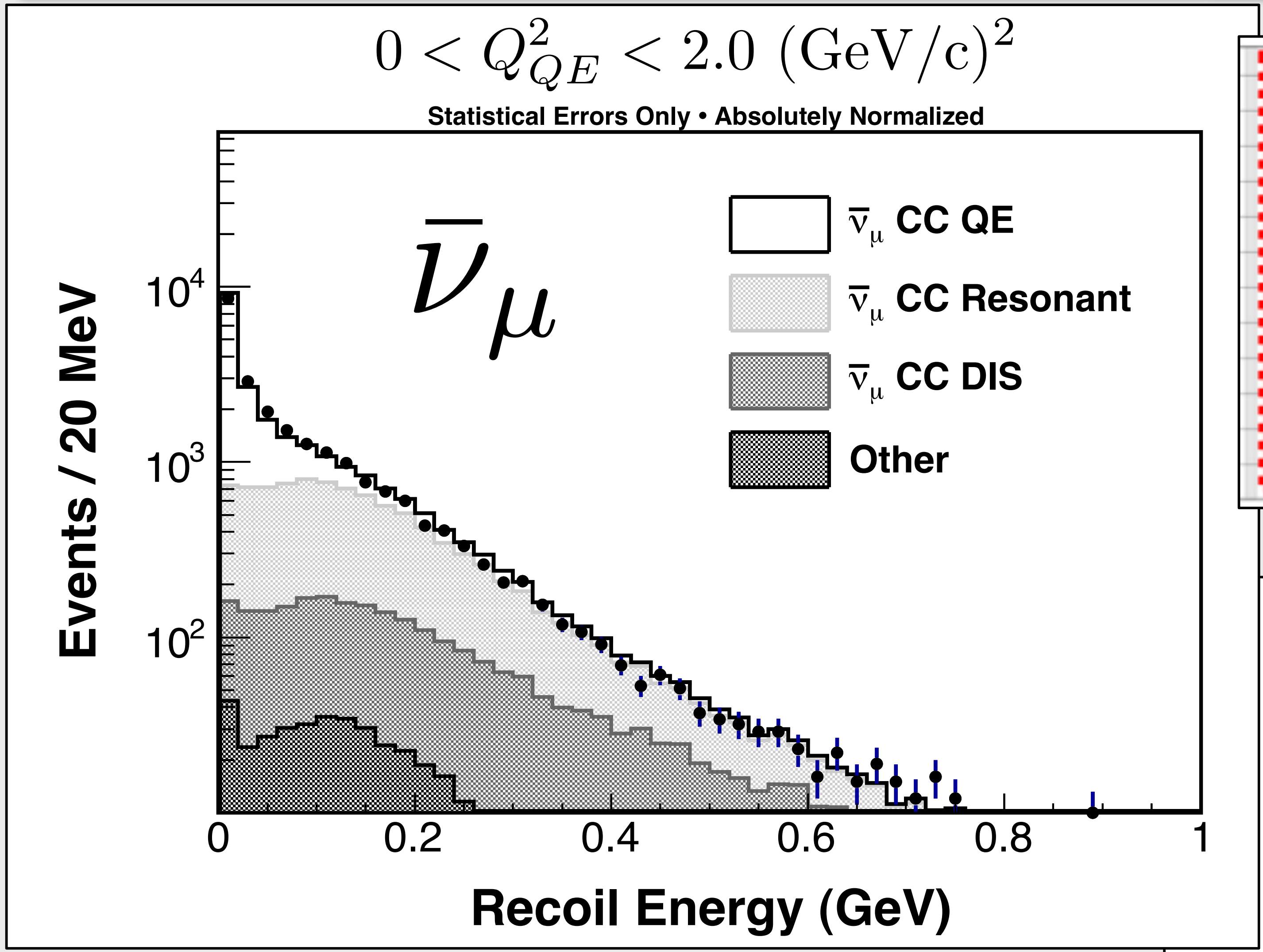


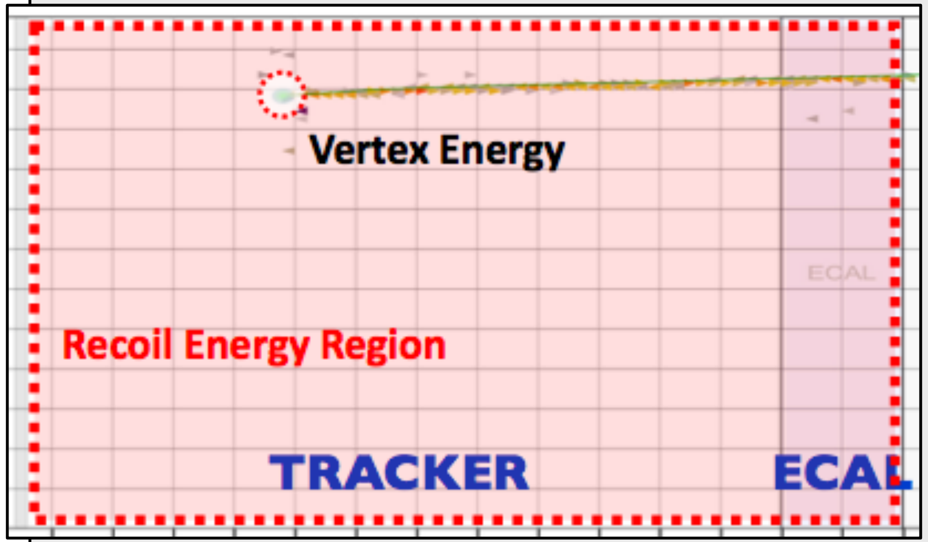
All Bins

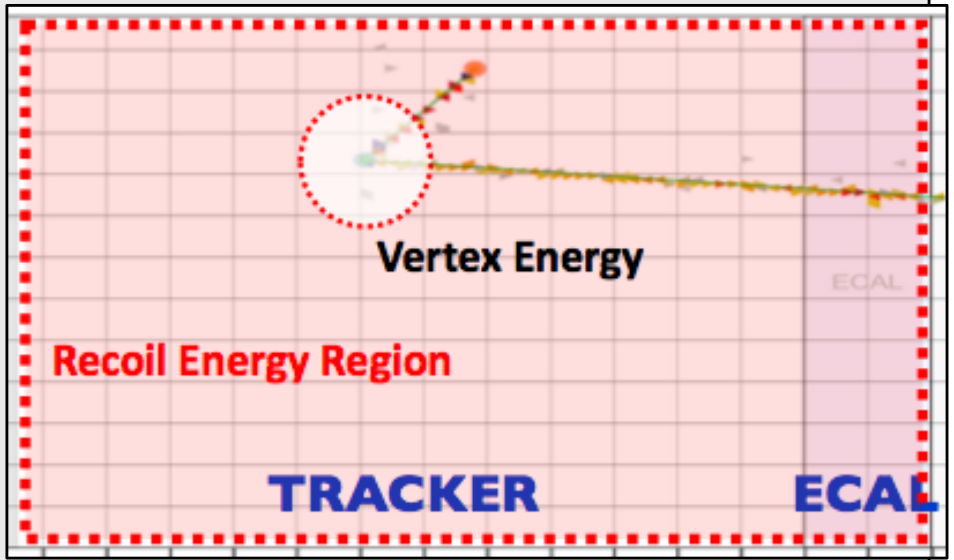
Modify the predicted non-QE background rate by **5-15%**

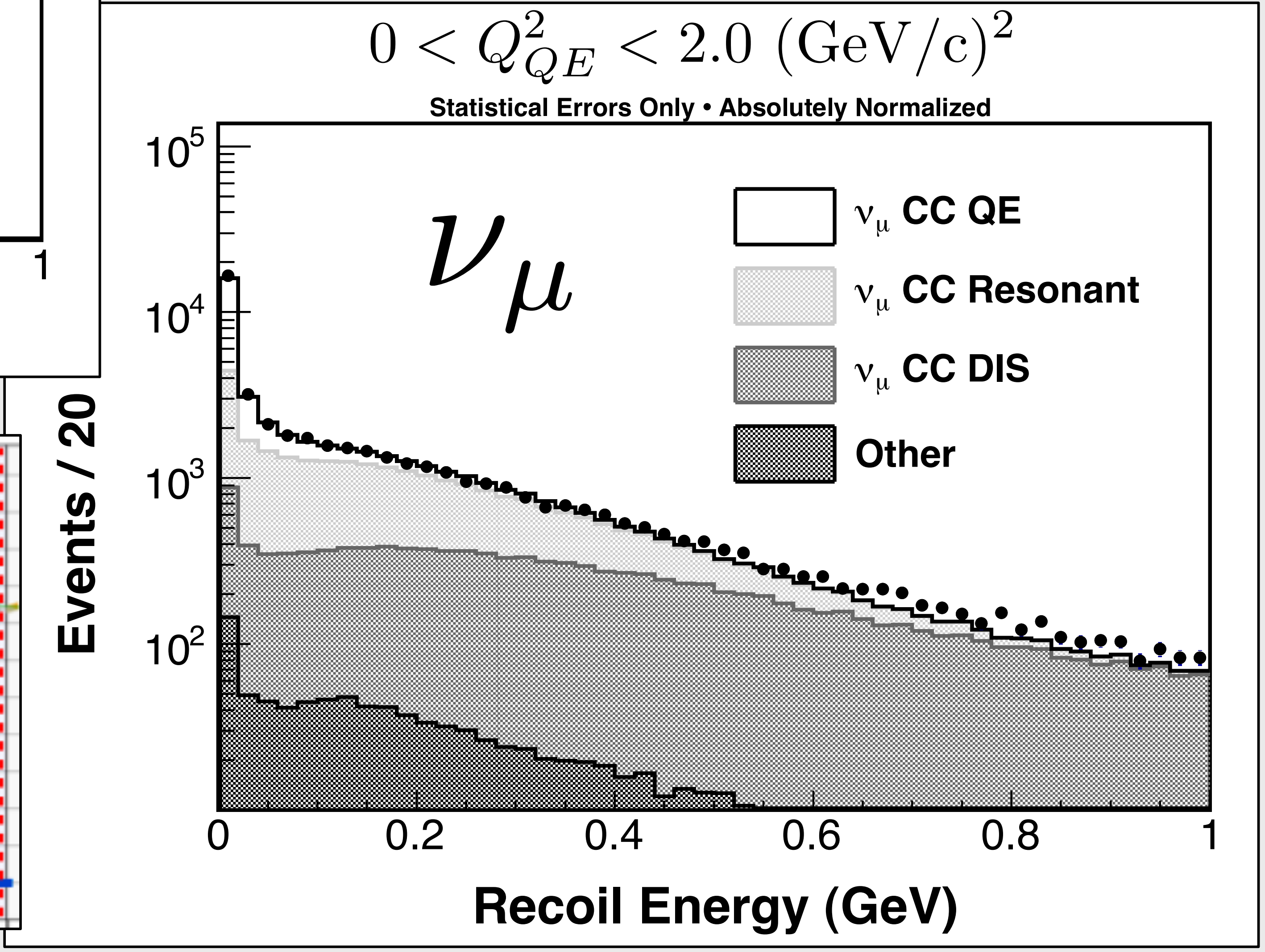


Final Recoil Distributions

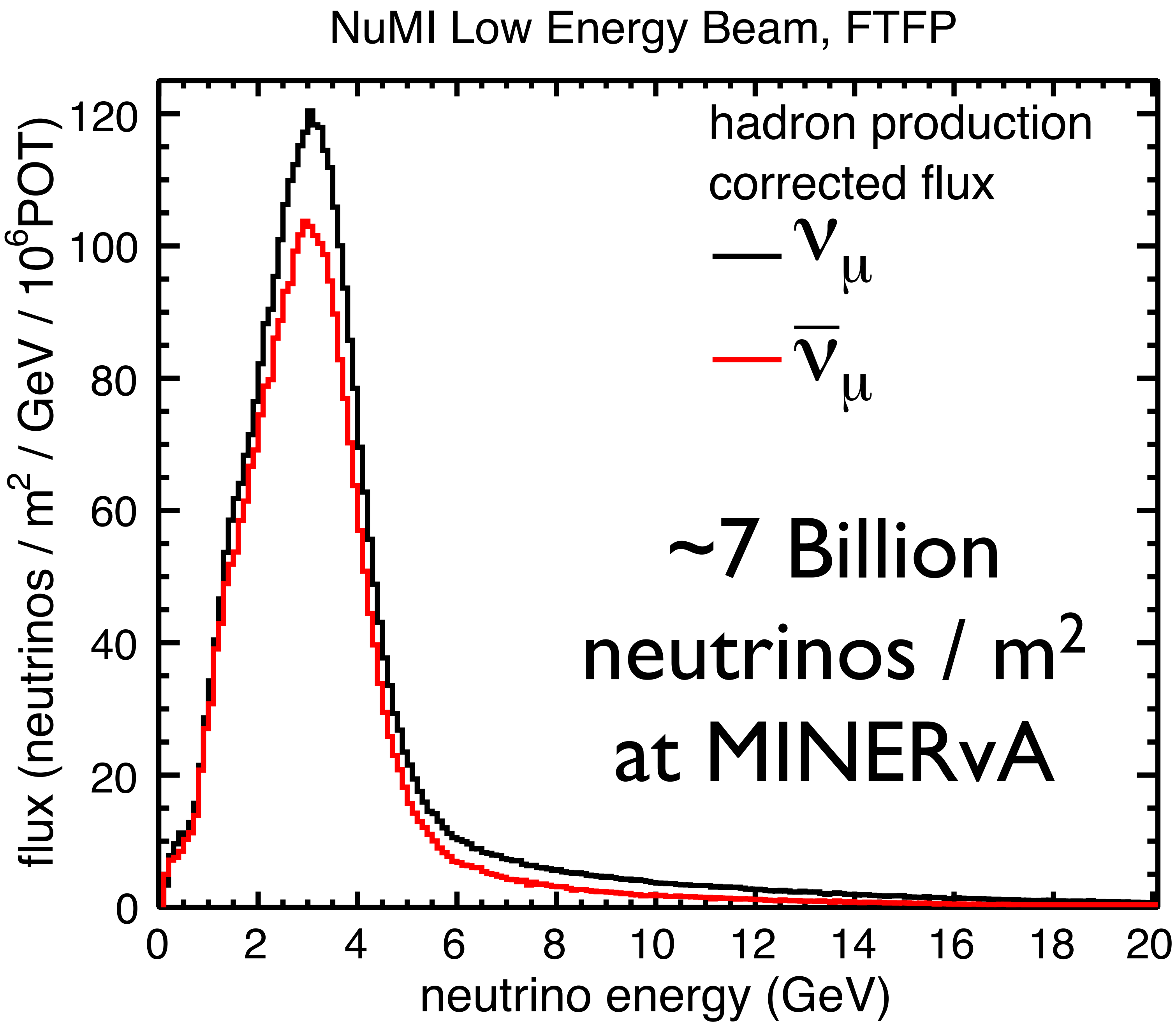


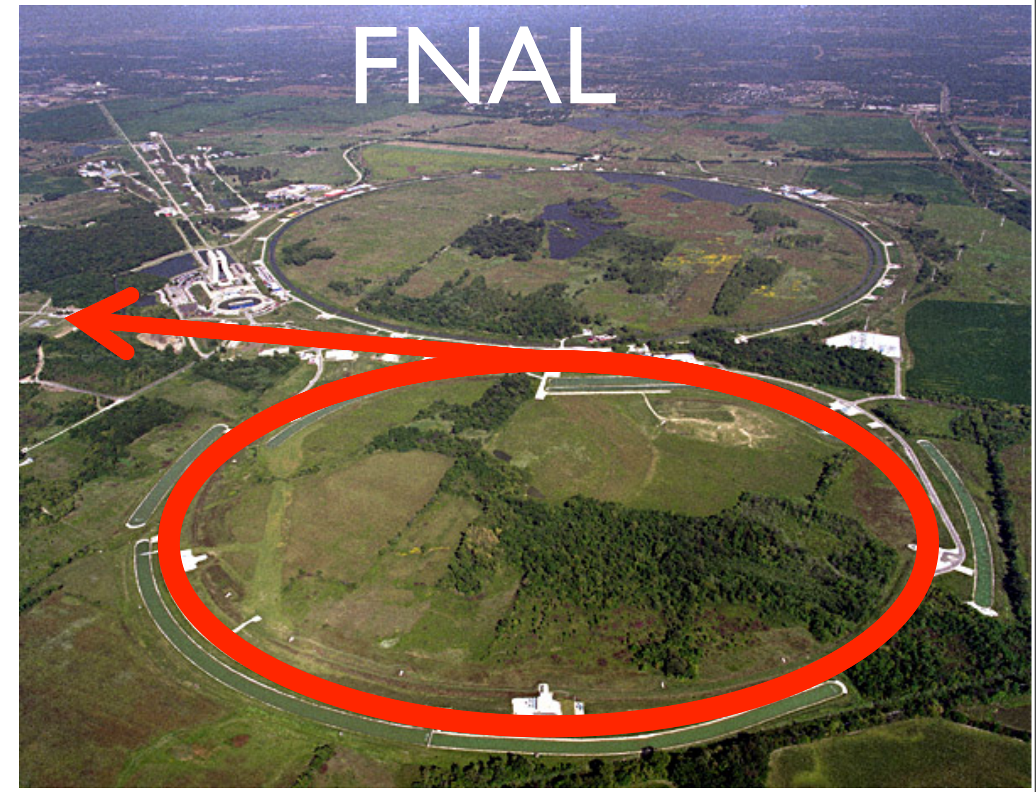






Neutrino Beam





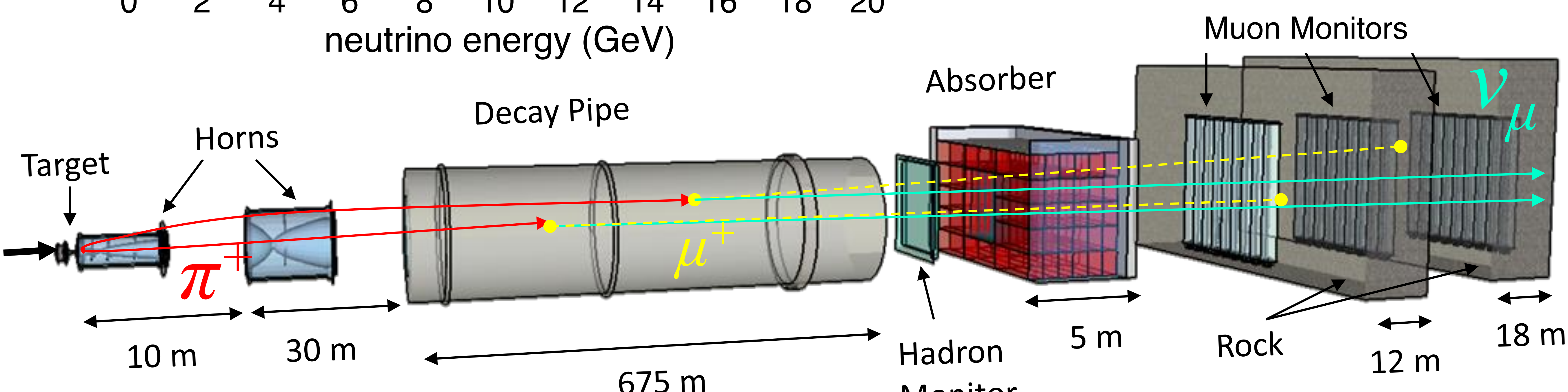
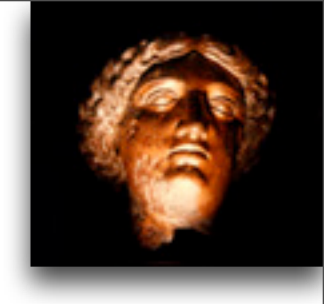
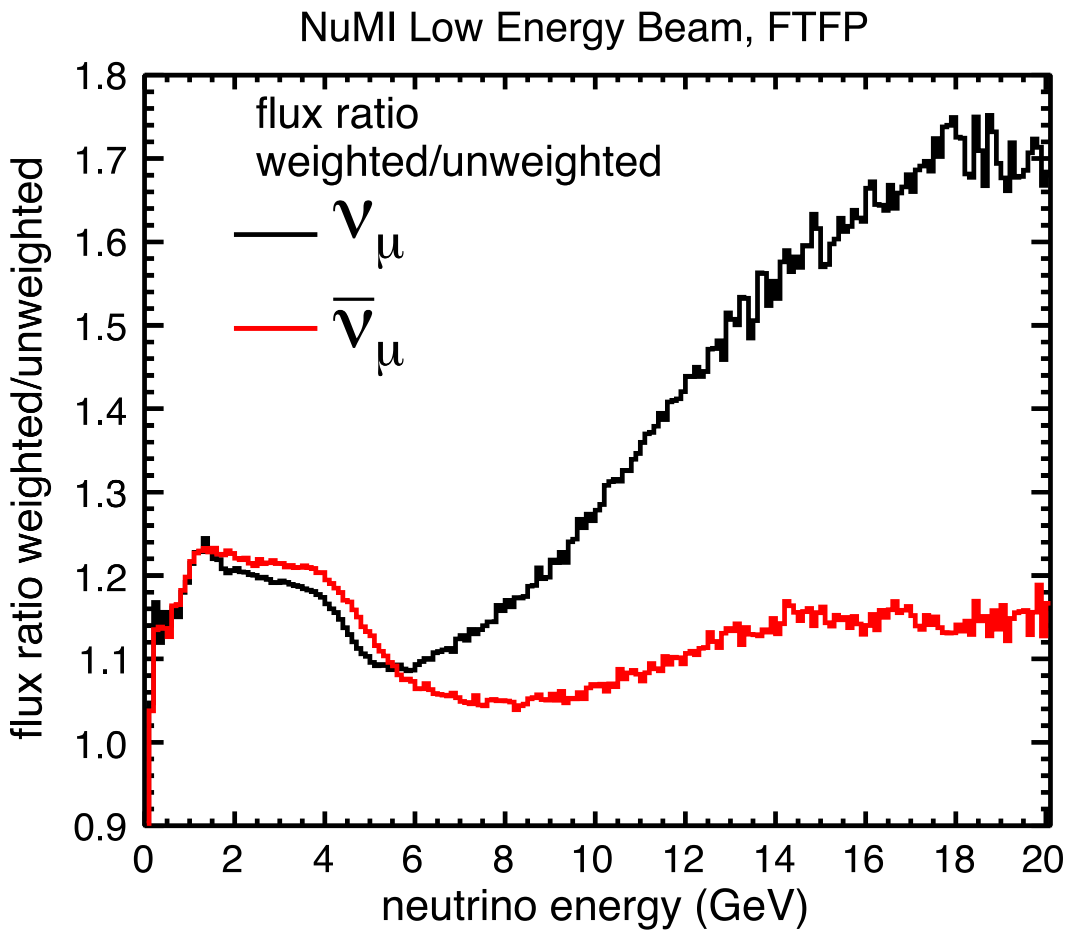


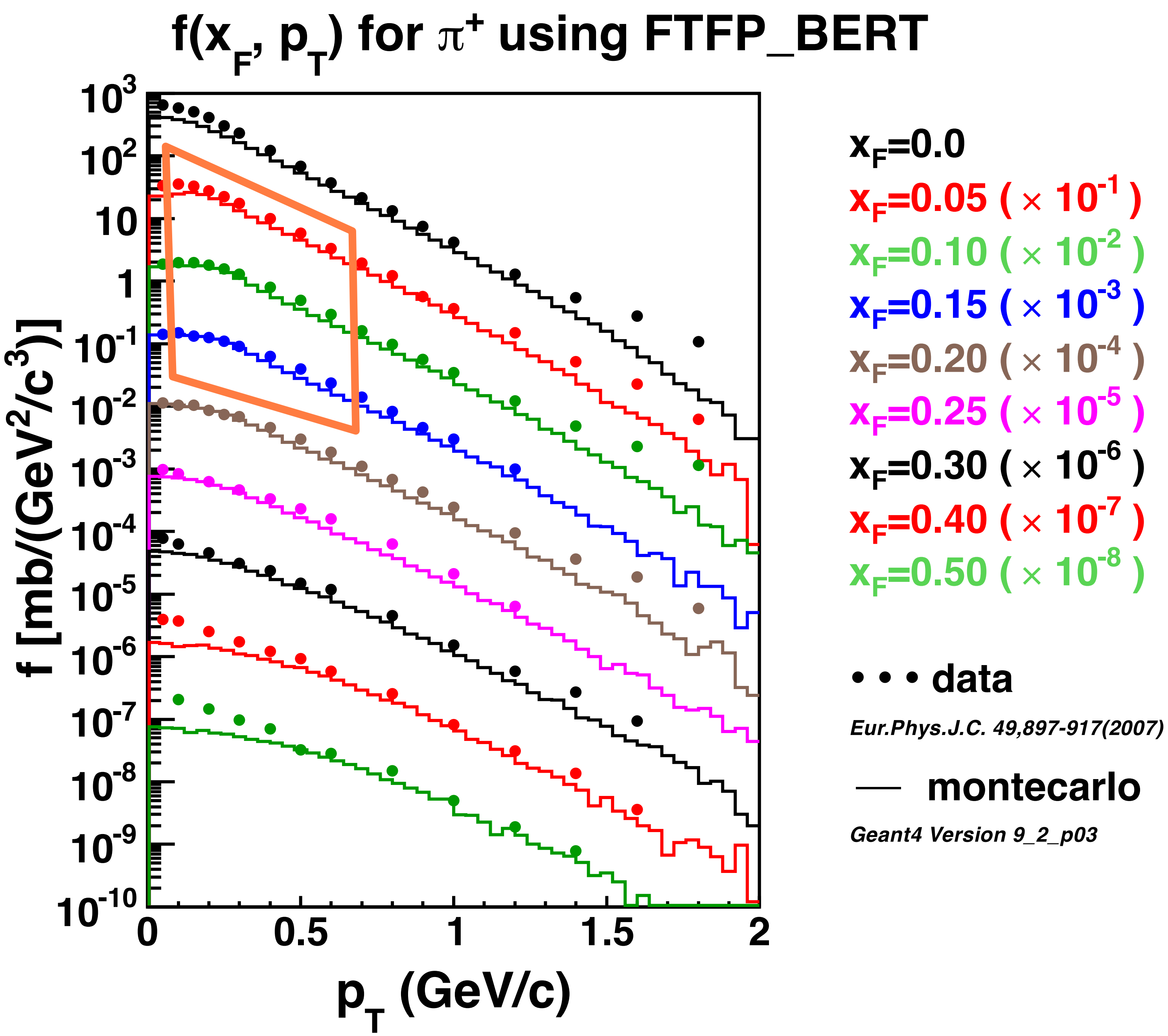
figure courtesy Ž. Pavlović

Beam Flux

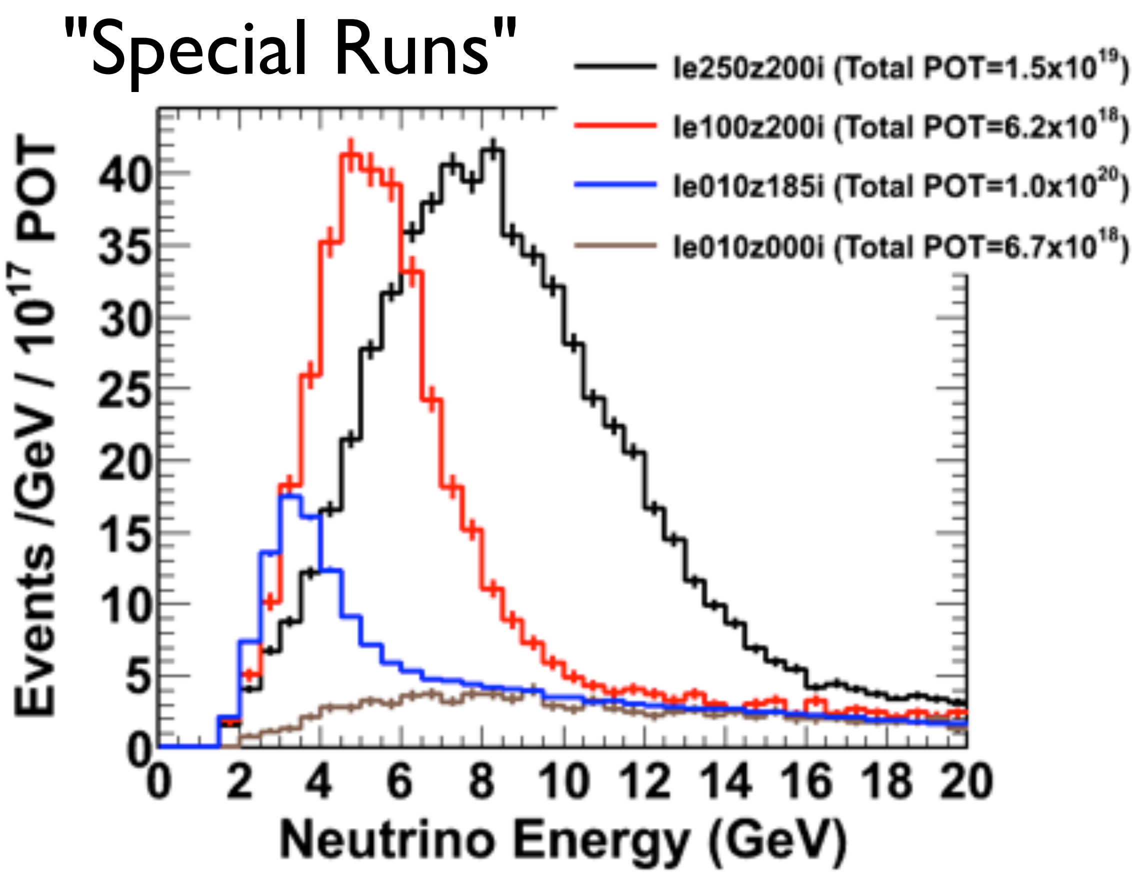


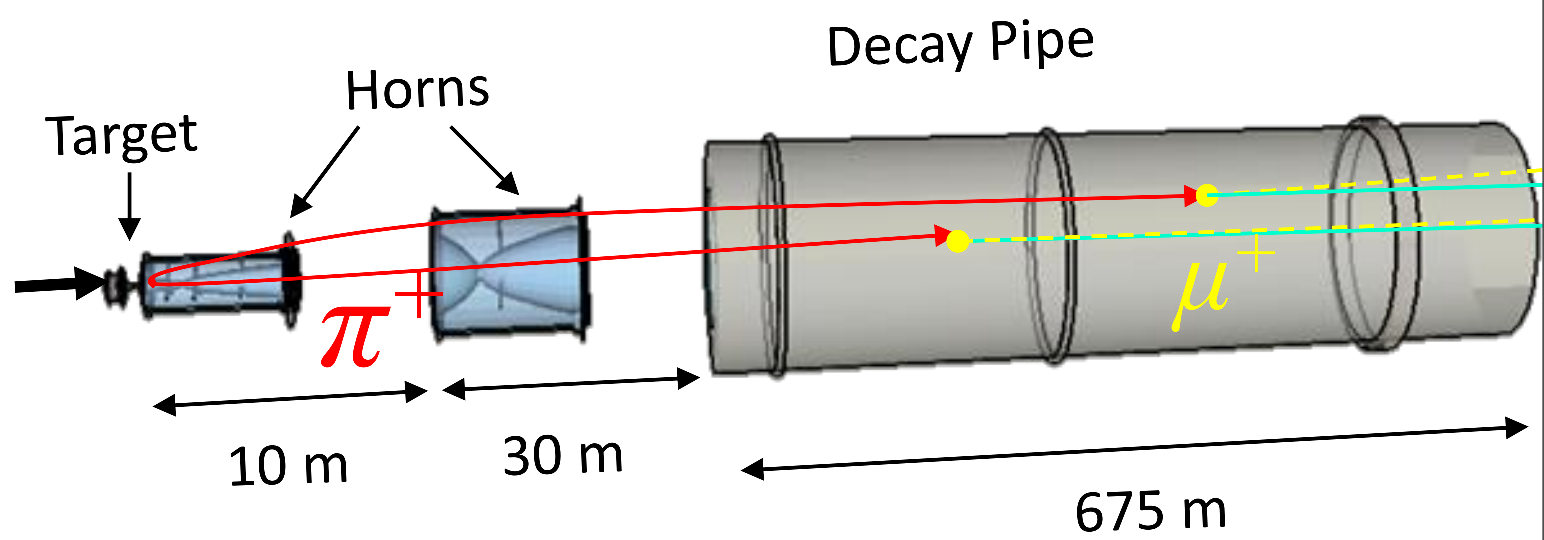
- Tune the hadron production spectrum (FTFP) to world data (mostly NA49 for MINERvA).
- Complicated by relatively sparse data, and the problems associated with thick targets.





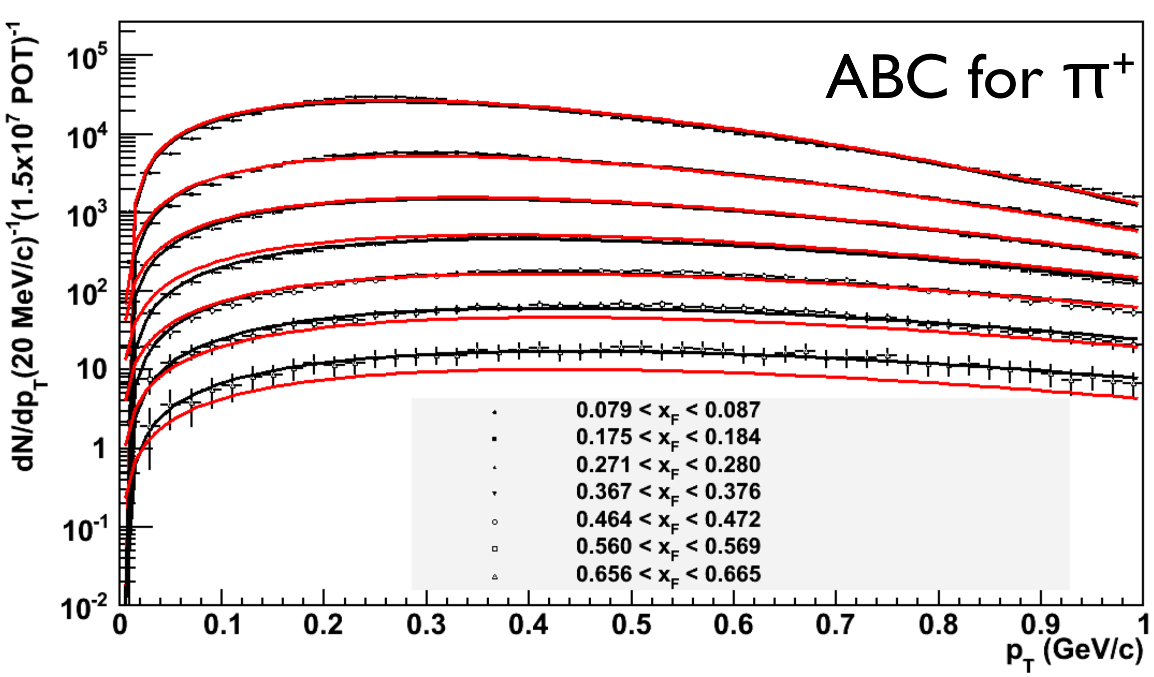
Beam Flux



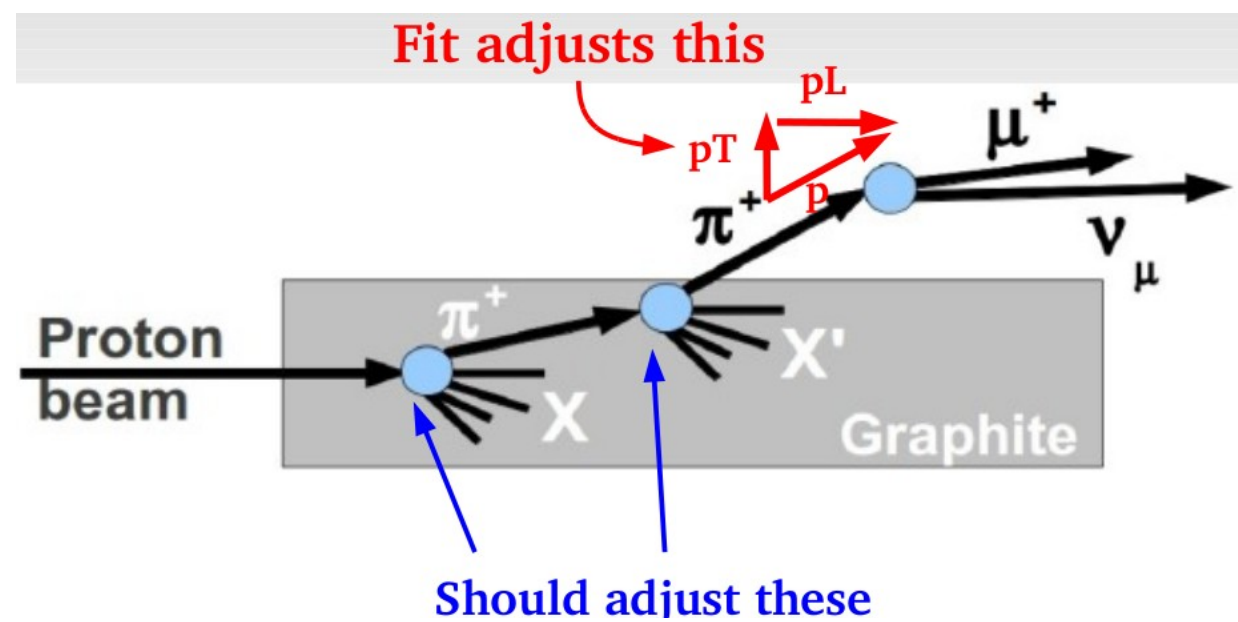


Vary target position and horn current.

$$\frac{d^2 N}{dx_F\, dp T} = [A(x_F) + B(x_F)\, p_T + D(x_F)\, p_T^2]\, e^{-C(x_F)\, p_T^{E(x_F)}}$$

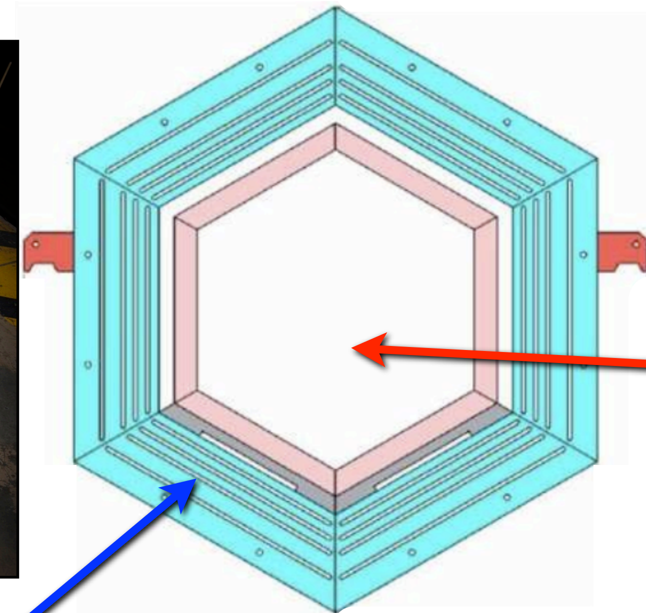


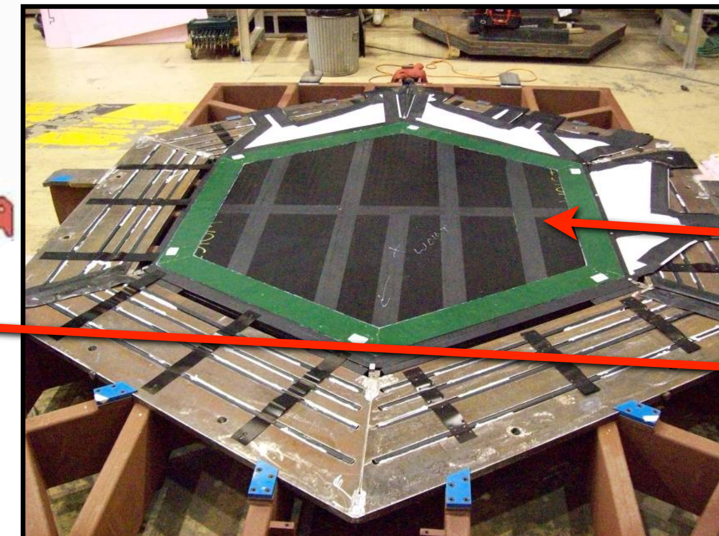
Dots: FTFP
Solid: ABC
Solid: Parameterized ABC



Thick targets!

MINERνA Modules



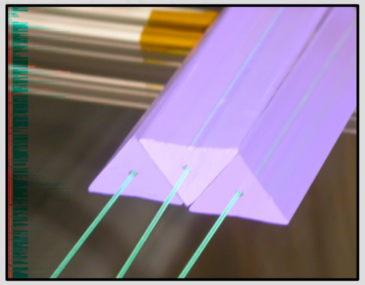


...and an inner detector element of scintillator strips and absorbers/ targets.

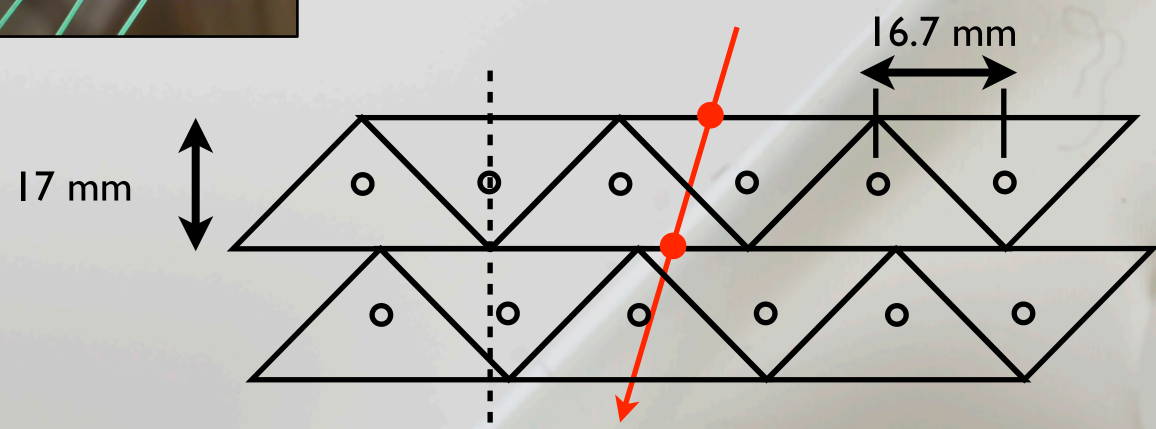
Modules have an outer detector frame of steel and scintillator...

- Four basic module types:
  - *Tracker:* two scintillator planes in stereoscopic orientation.
  - *Hadronic Calorimeter:* one scintillator plane and one 2.54-cm steel absorber.
  - *Electromagnetic Calorimeter:* two scintillator planes and two 2-mm lead absorbers.
  - *Nuclear Targets:* absorber materials (some with scintillator planes).
- Instrumented outer-detector steel frames.
- 120 Total Modules: 84 Tracker, 10 ECAL, 20 HCAL, 6 Nuclear Targets.

Plastic Scintillator Strips: The Active Detector Elements.

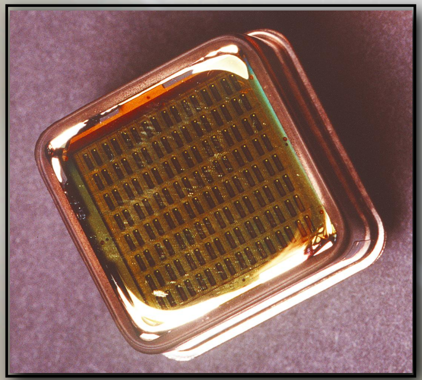


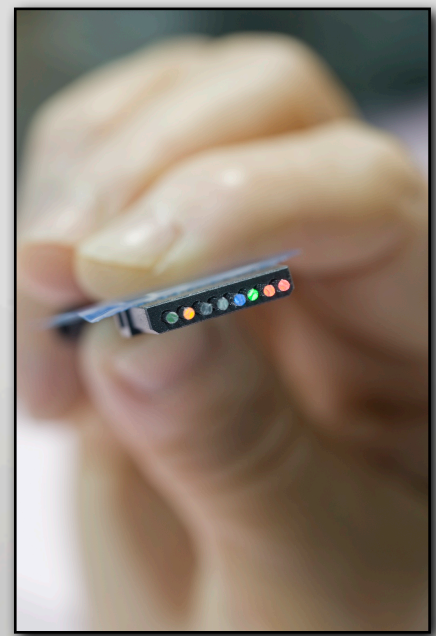
Extruded scintillator & wavelength shifting fibers.



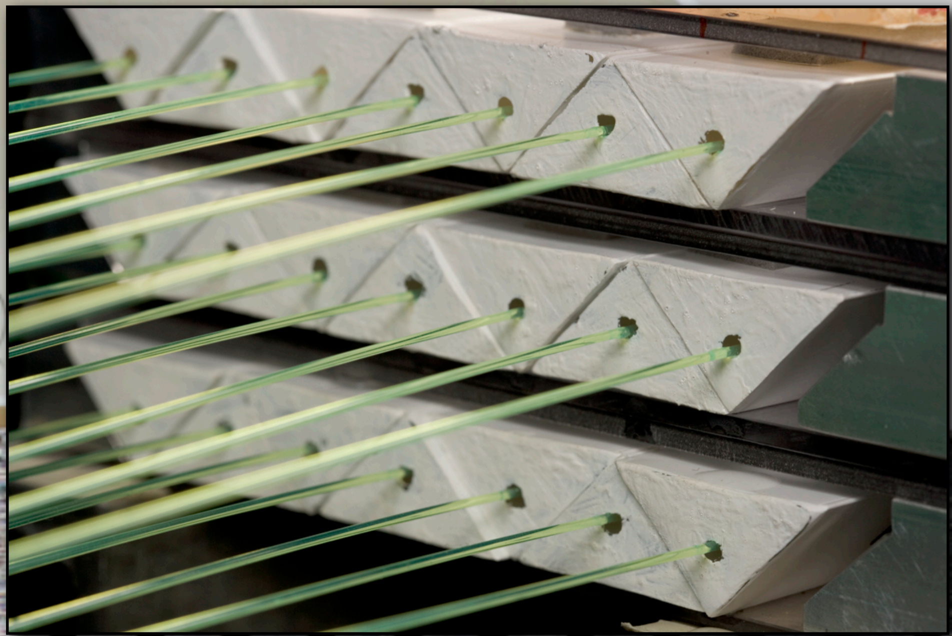
Charge-sharing for improved position resolution (~3 mm) & alignment.

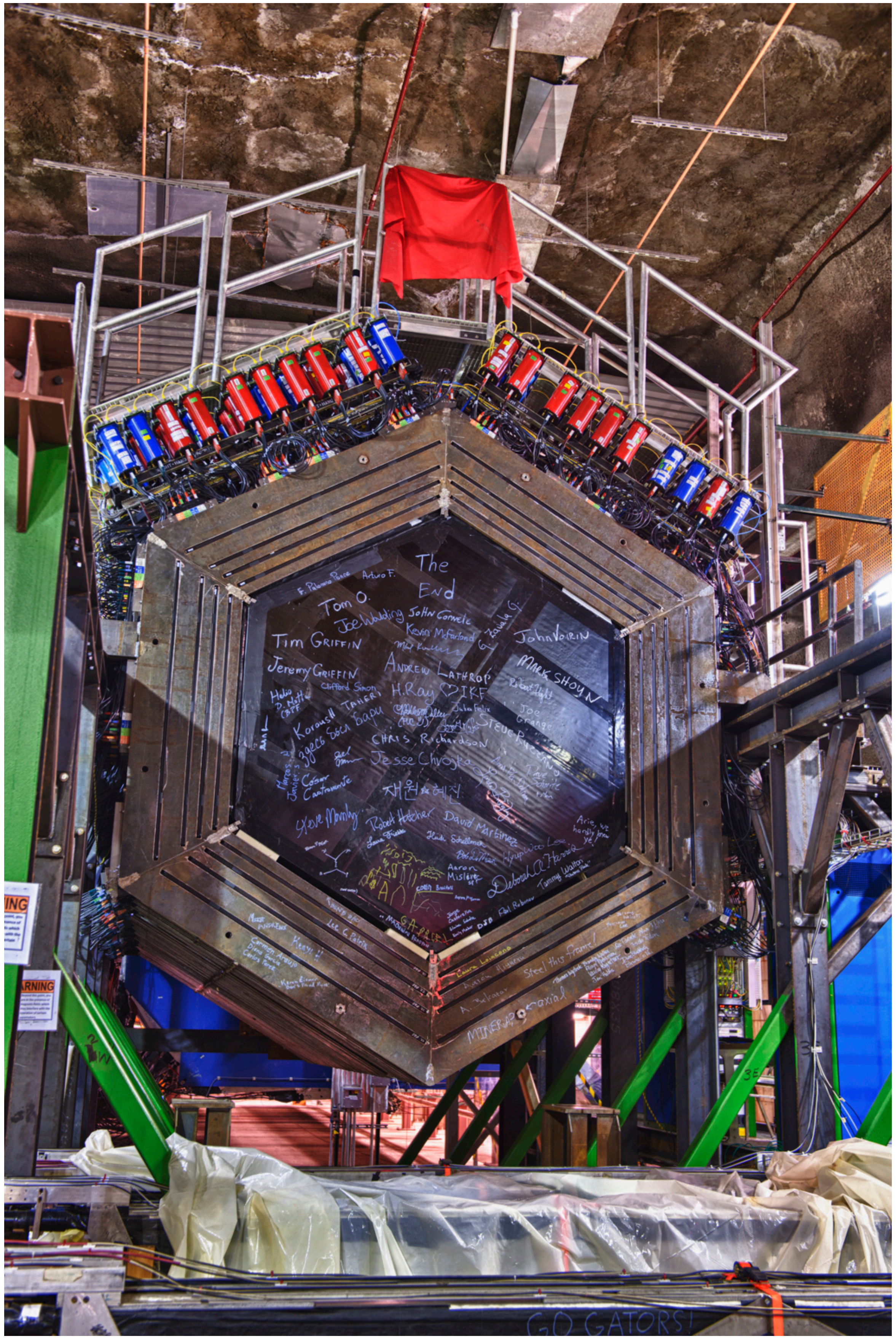
Fibers bundled into cables to interface with 64 channel multi-anode PMTs.

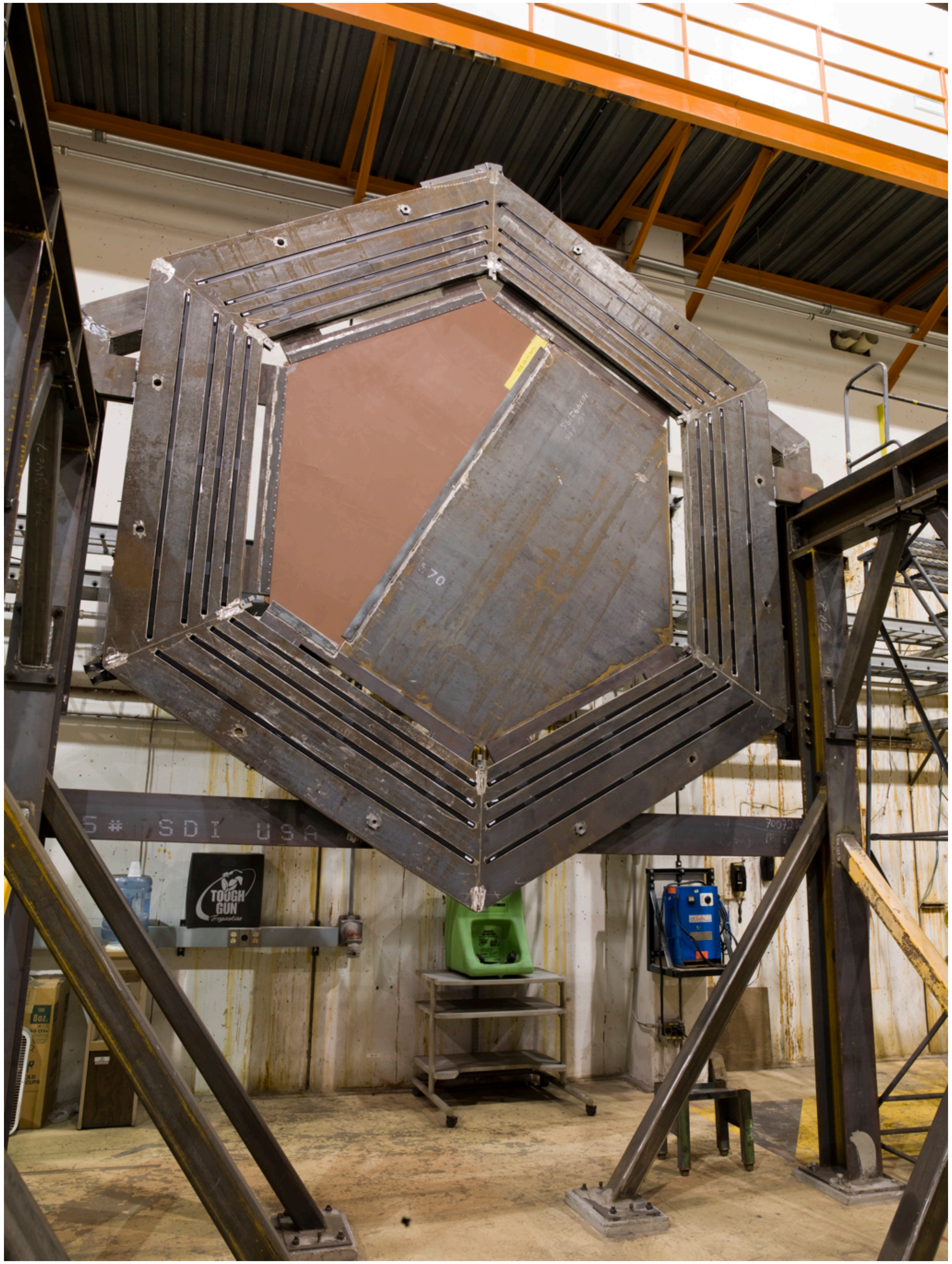




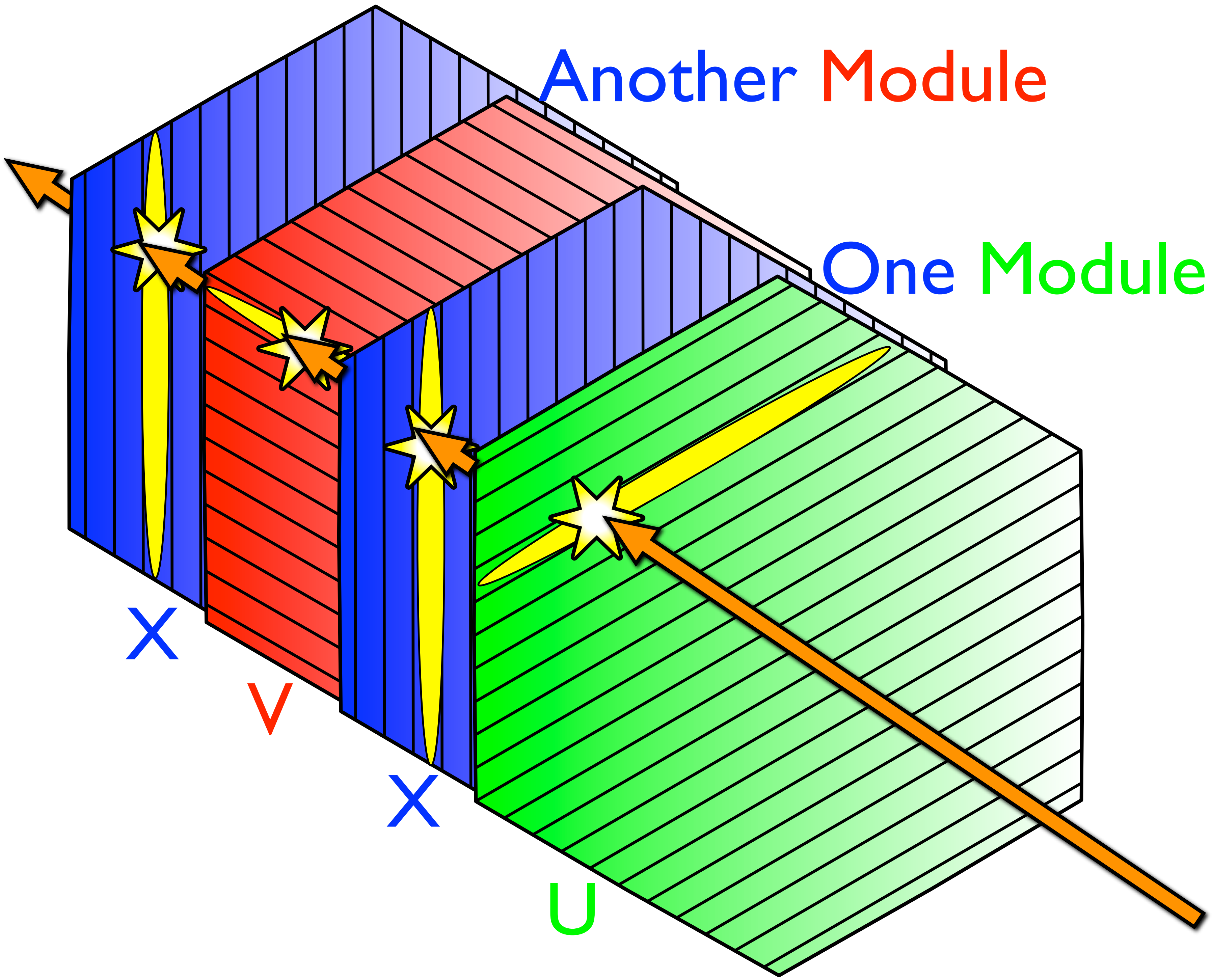
Strips are bundled into PLANES to provide transverse position location across a module.

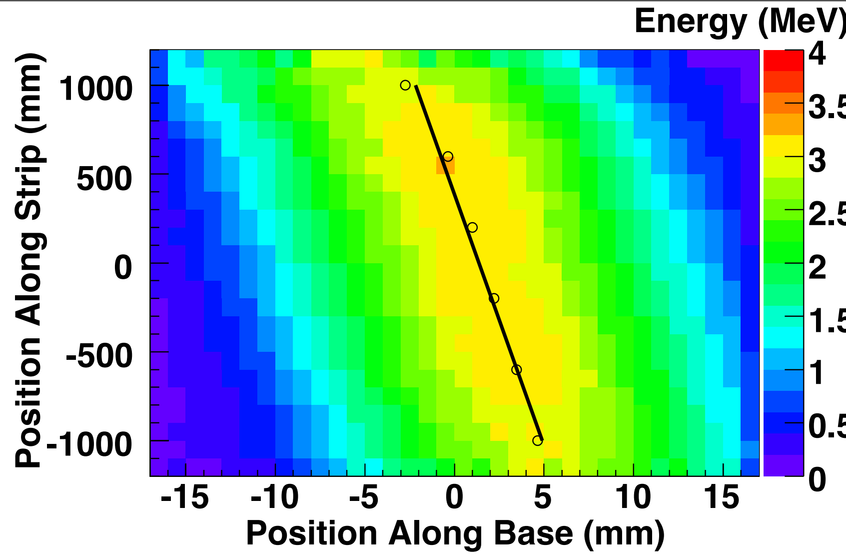


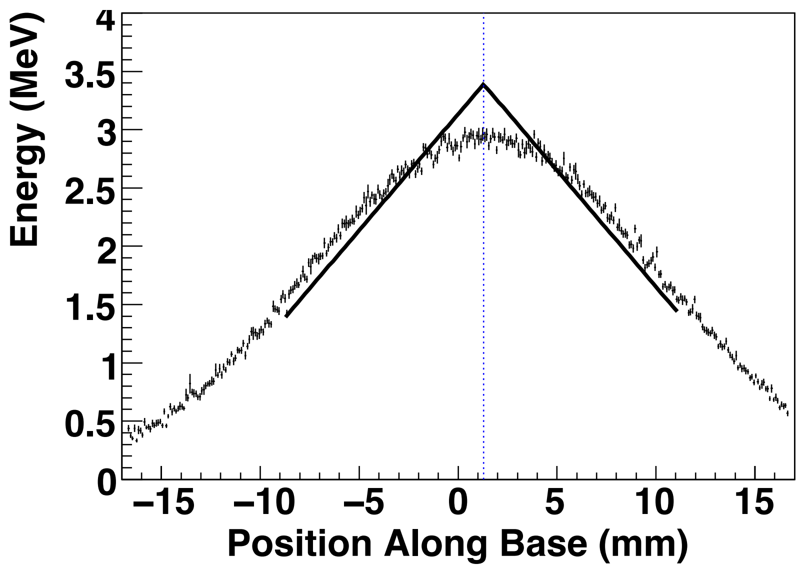

The End
Tim GRIFFIN
Jeremy GRIFFIN
GO GATORS!

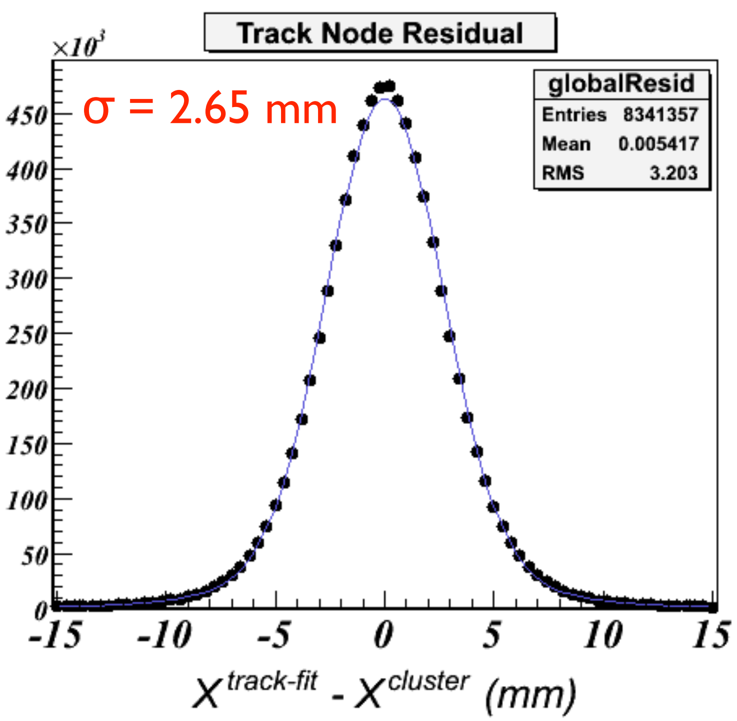

SDI USA
TOUGH GUN

Planes are mounted stereoscopically in UX or VX orientations for 3D tracking. There are typically two planes per module.





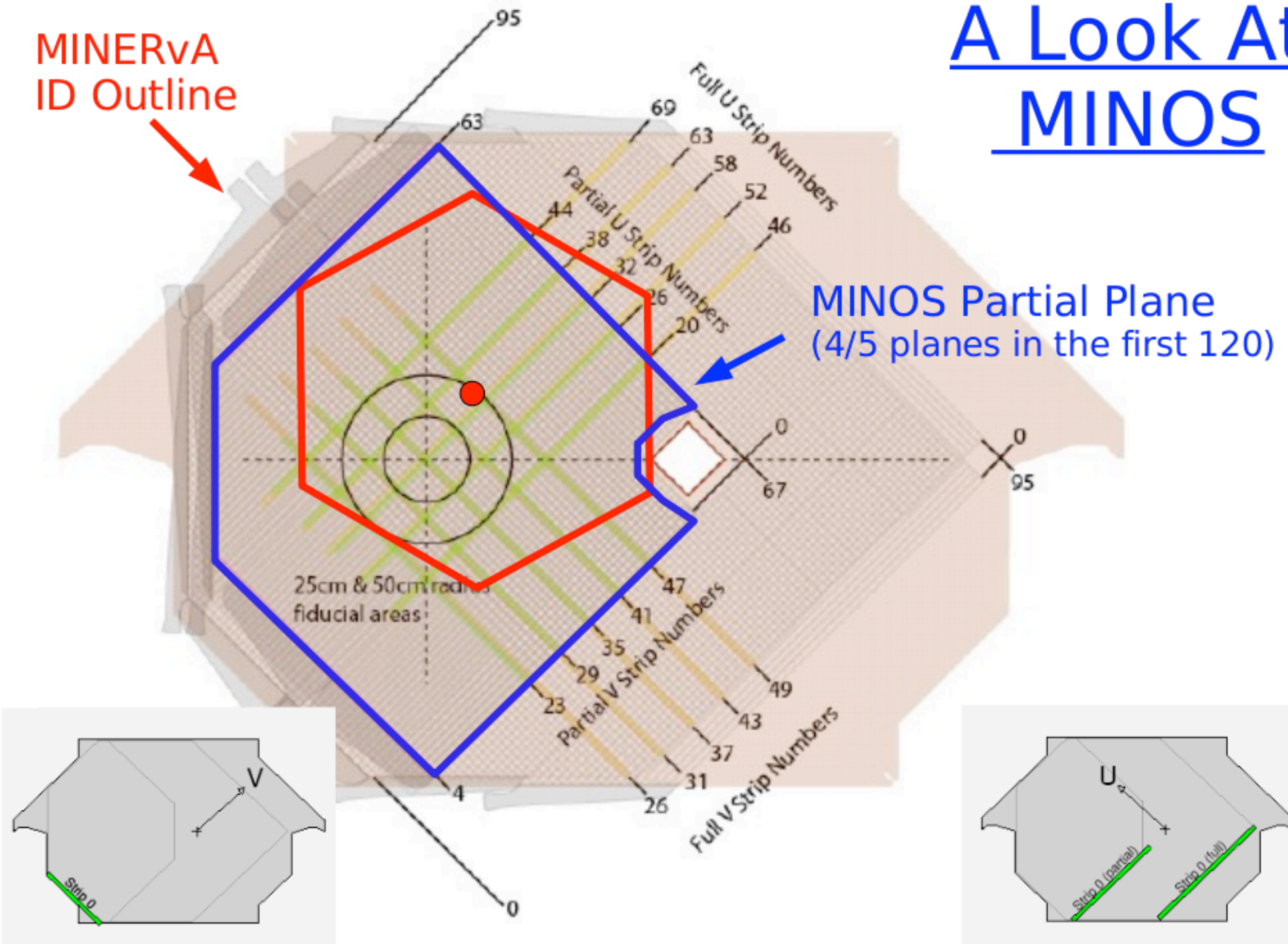




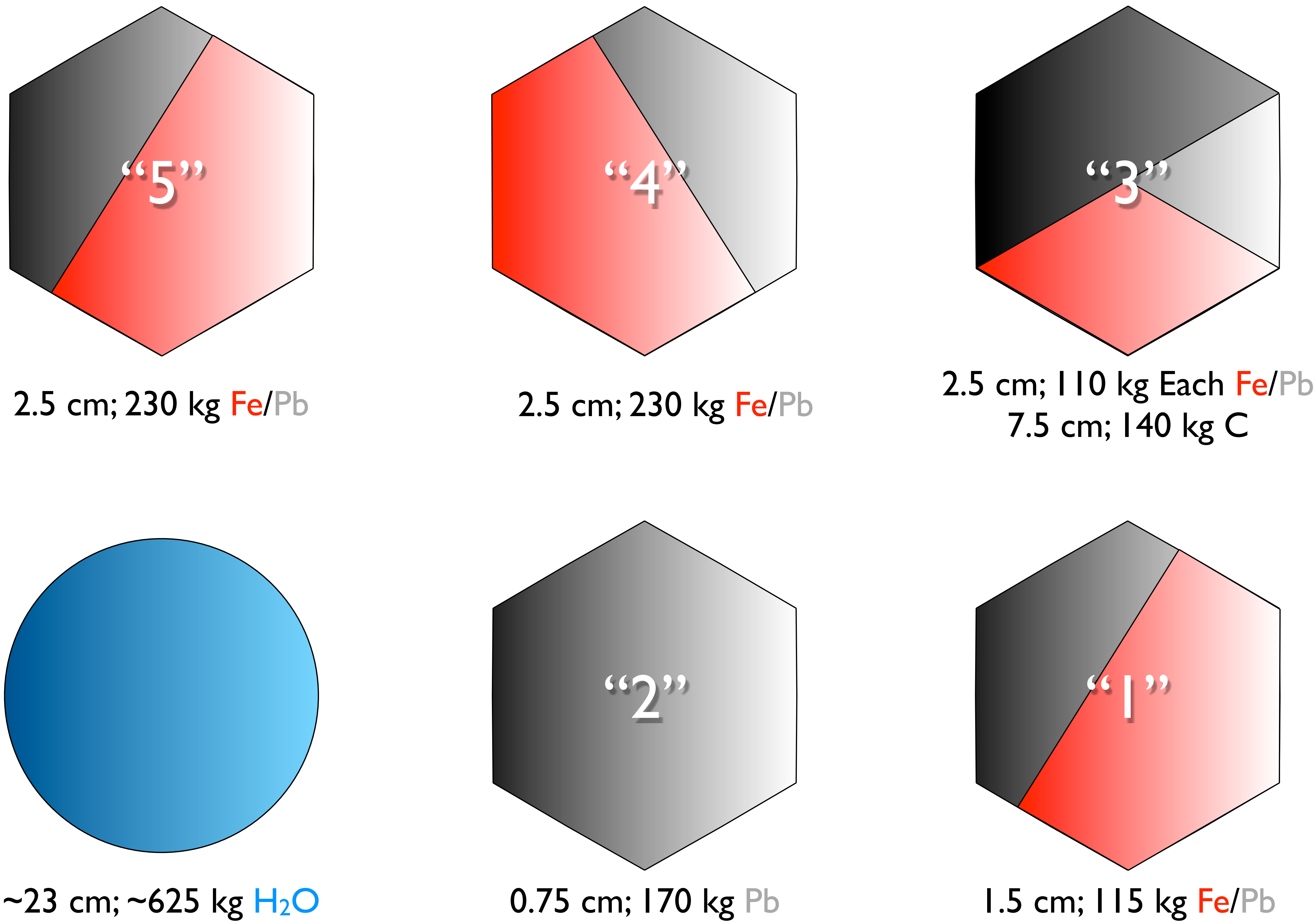
A Look At MINOS

MINERvA ID Outline

MINOS Partial Plane
(4/5 planes in the first 120)

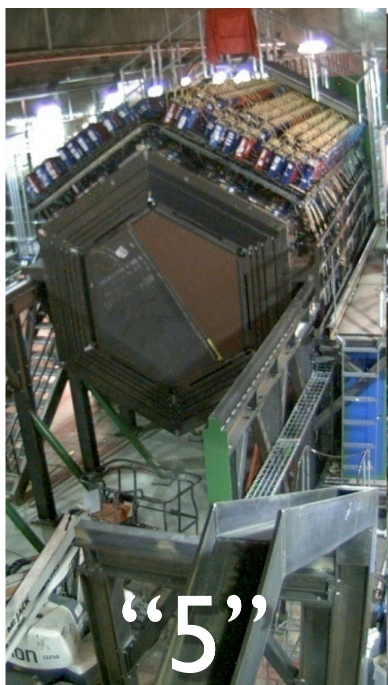


Water Iron Lead Carbon



Target Installation

Iron/Lead



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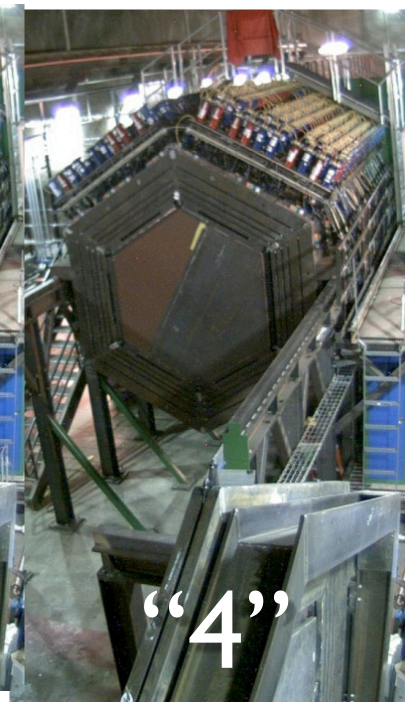
Lead/Iron



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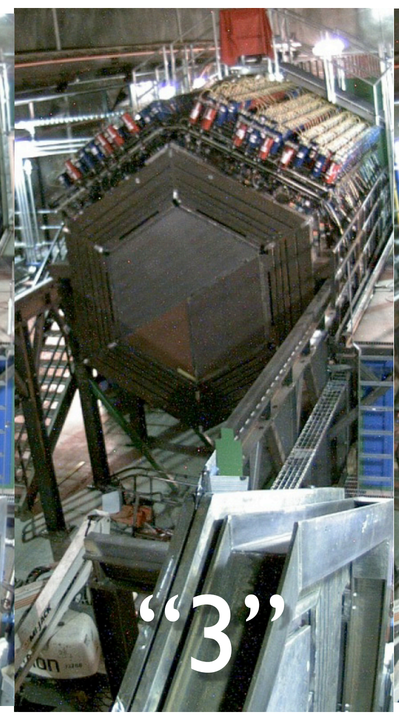
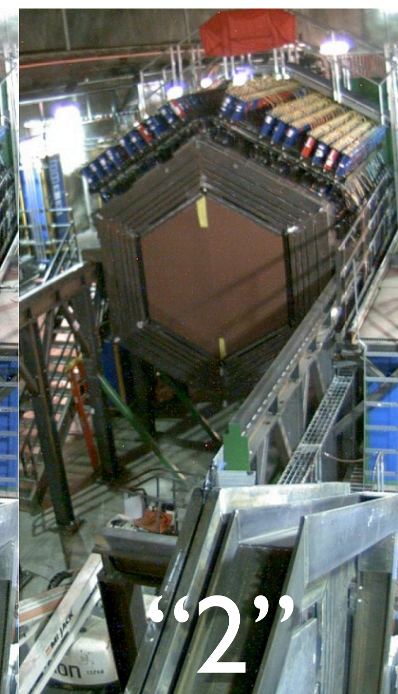
Lead/Iron
Graphite



3/08

Lead



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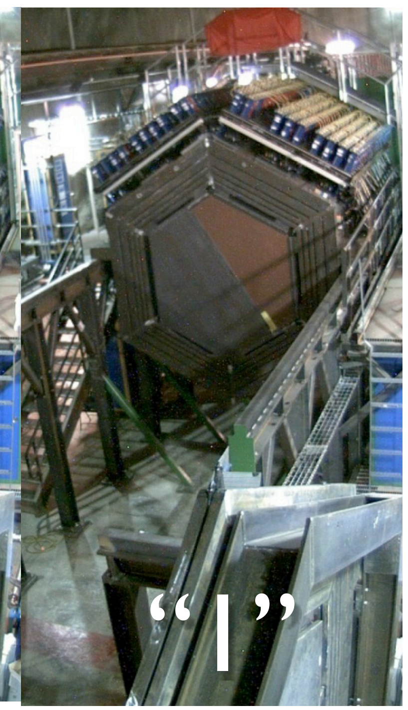
Iron/Lead



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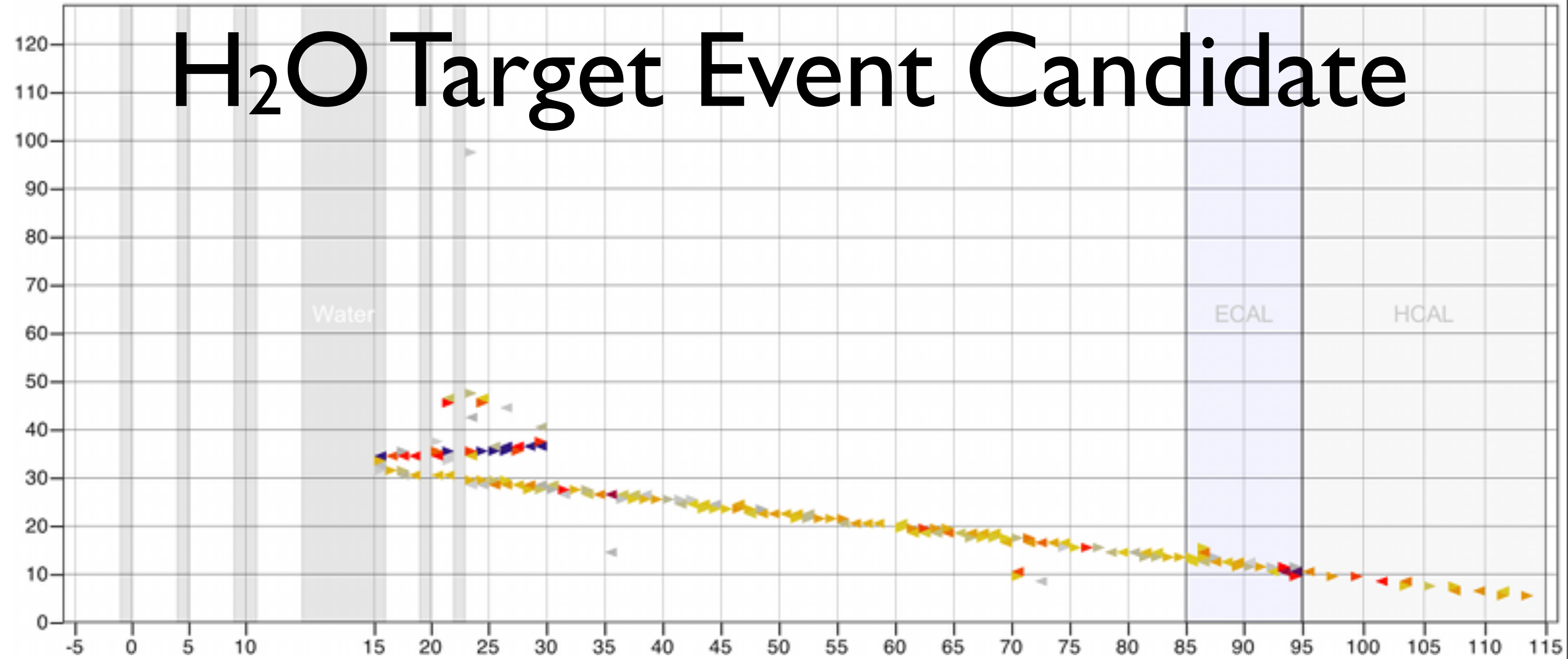
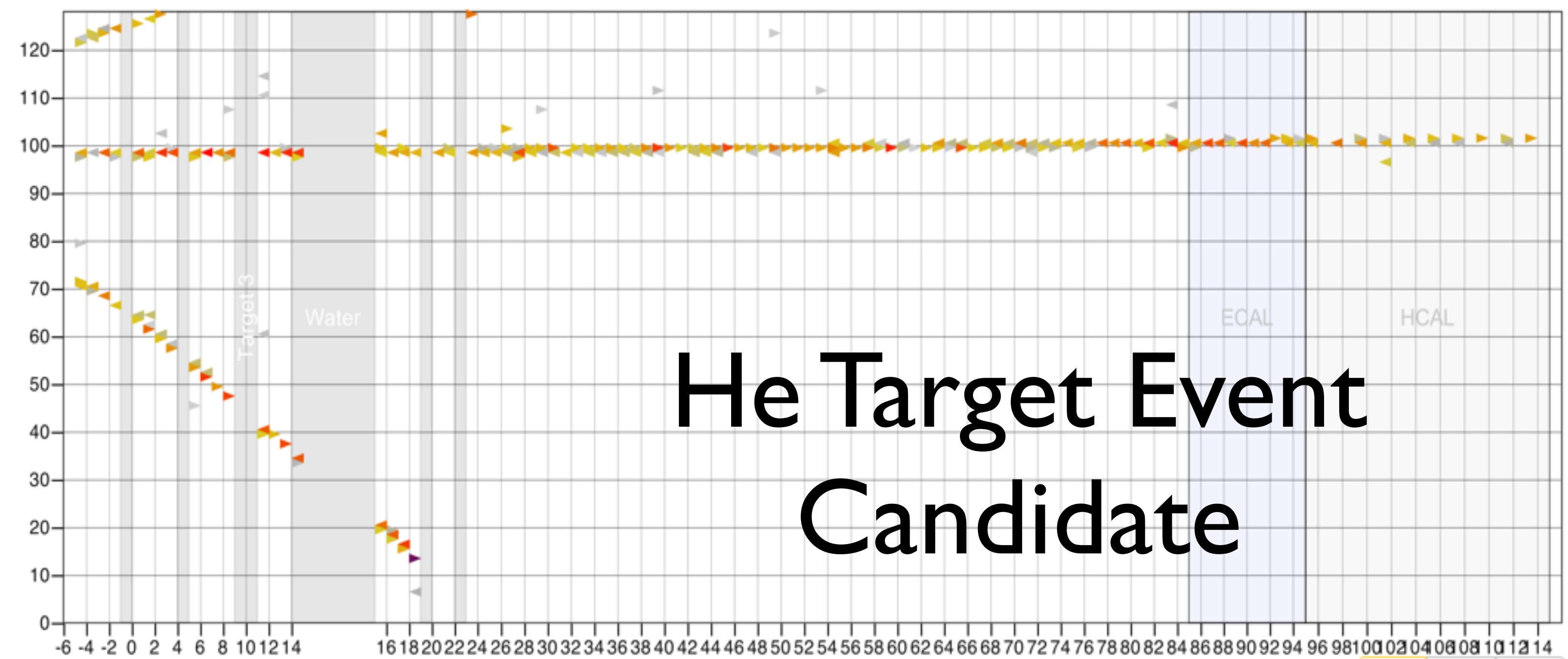
Solid targets installed in Spring 2010

Water target installed in November, 2011.

Liquid Targets





Liquid helium target installed in Spring, '11. Filled Summer '11.

TargetID	TargetZ	Fiducial Area (cm^2)	Areal Mass (g/cm^2)	Mass (kg)	N Protons	N Neutrons	N Nucleons
2	26	1.60E+04	2.01E+01	3.21E+02	9.00E+28	1.03E+29	1.93E+29
2	82	9.03E+03	2.91E+01	2.63E+02	6.27E+28	9.57E+28	1.58E+29
3	6	1.25E+04	1.33E+01	1.66E+02	4.99E+28	5.00E+28	9.99E+28
3	26	8.34E+03	2.02E+01	1.68E+02	4.71E+28	5.41E+28	1.01E+29
3	82	4.17E+03	2.89E+01	1.21E+02	2.88E+28	4.39E+28	7.27E+28
4	82	2.50E+04	8.98E+00	2.25E+02	5.35E+28	8.17E+28	1.35E+29
5	26	1.60E+04	1.01E+01	1.62E+02	4.53E+28	5.20E+28	9.73E+28
5	82	9.03E+03	1.49E+01	1.34E+02	3.20E+28	4.89E+28	8.08E+28