The MINERvA Experiment

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Rutgers, The State University of New Jersey

On behalf of the
MINERvA collaboration

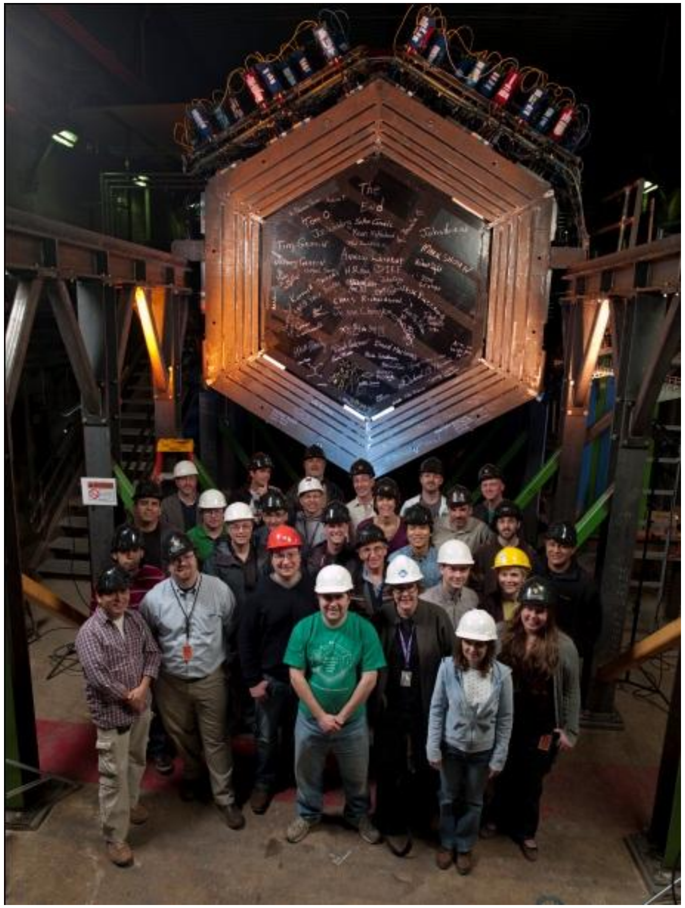
Workshop on Electron-Nucleus Scattering XII
Marciana Marina, Isola d'Elba
June 25-29, 2012

Outline

- Meet MINERvA
- The NuMI beam
- The MINERvA Detector
- First results
  - ν_μ inclusive charged current
  - ν_μ inclusive charged current ratios of nuclear targets
  - $\bar{\nu}_\mu$ charged current quasi elastic
  - ν_μ charged current quasi elastic

MINERvA
Main INjector ExpeRiment v-A

- MINERvA is a neutrino scattering experiment at Fermilab in Batavia, IL, USA.
- Collaboration of 80 nuclear and particle physicists.



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

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

NuMI Beamline

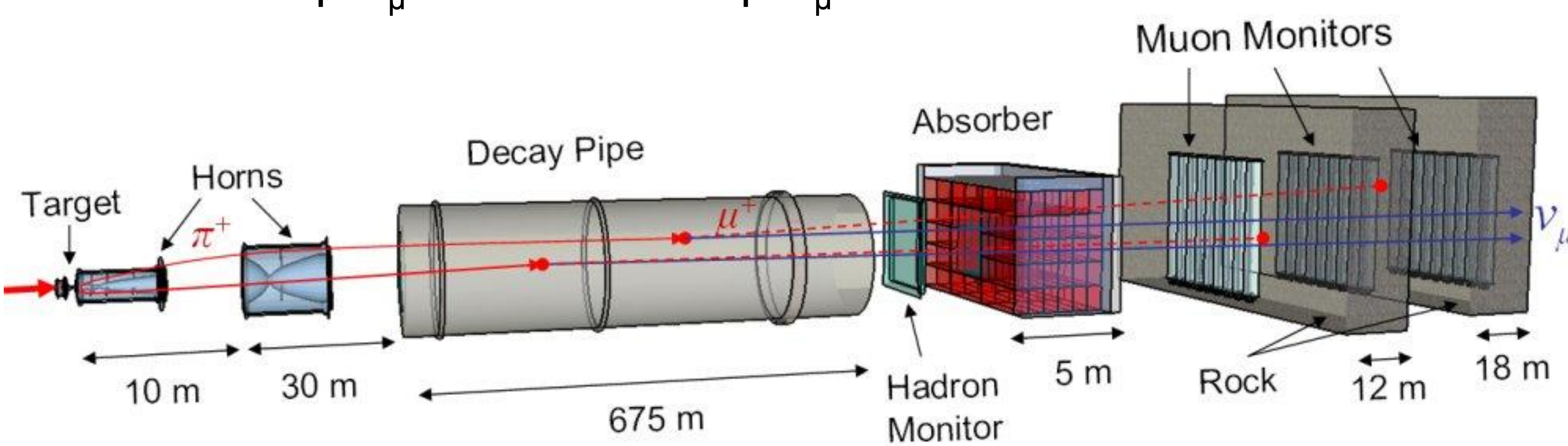
Delivers ~35×10^{12} protons on target (POT) per spill at ~0.5 Hz, a beam power of 300-350 kW.

120 GeV proton → Carbon target

$pC \rightarrow \pi^{\pm}$ and $K^{\pm}$

Magnetic horns focus + or -

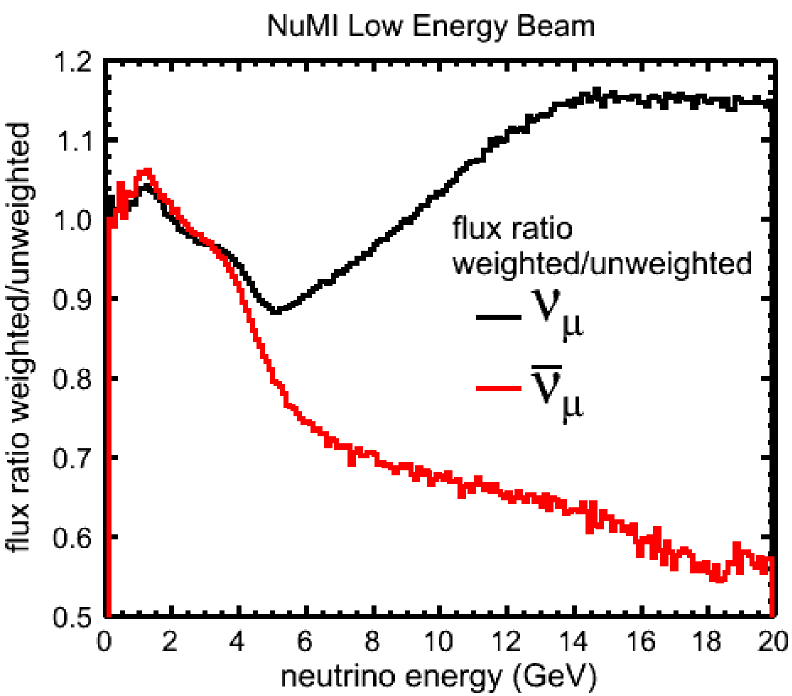
$\pi^+ / K^+ \rightarrow \mu^+ \nu_\mu$ or $\pi^- / K^- \rightarrow \mu^- \bar{\nu}_\mu$

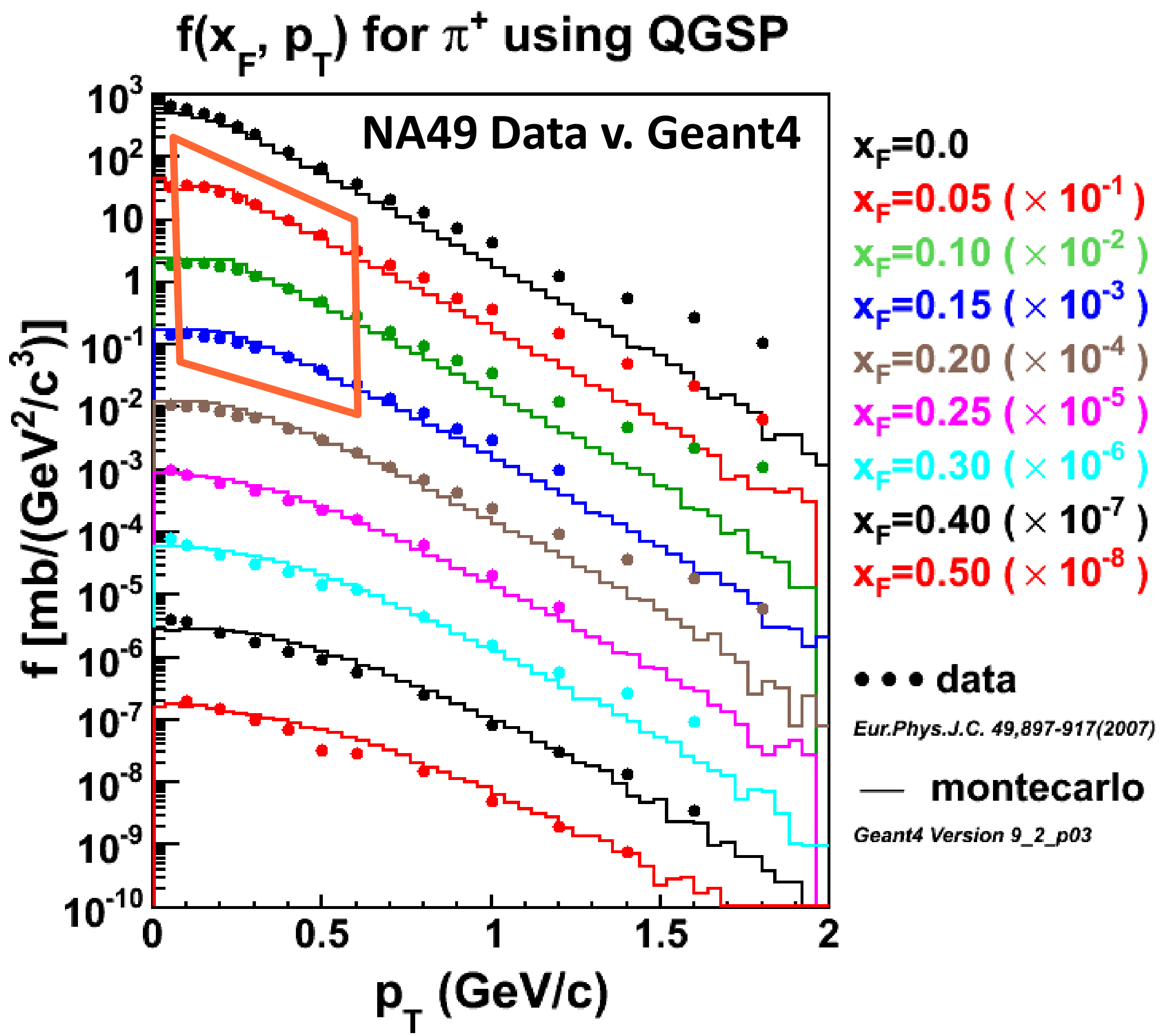


MINERvA

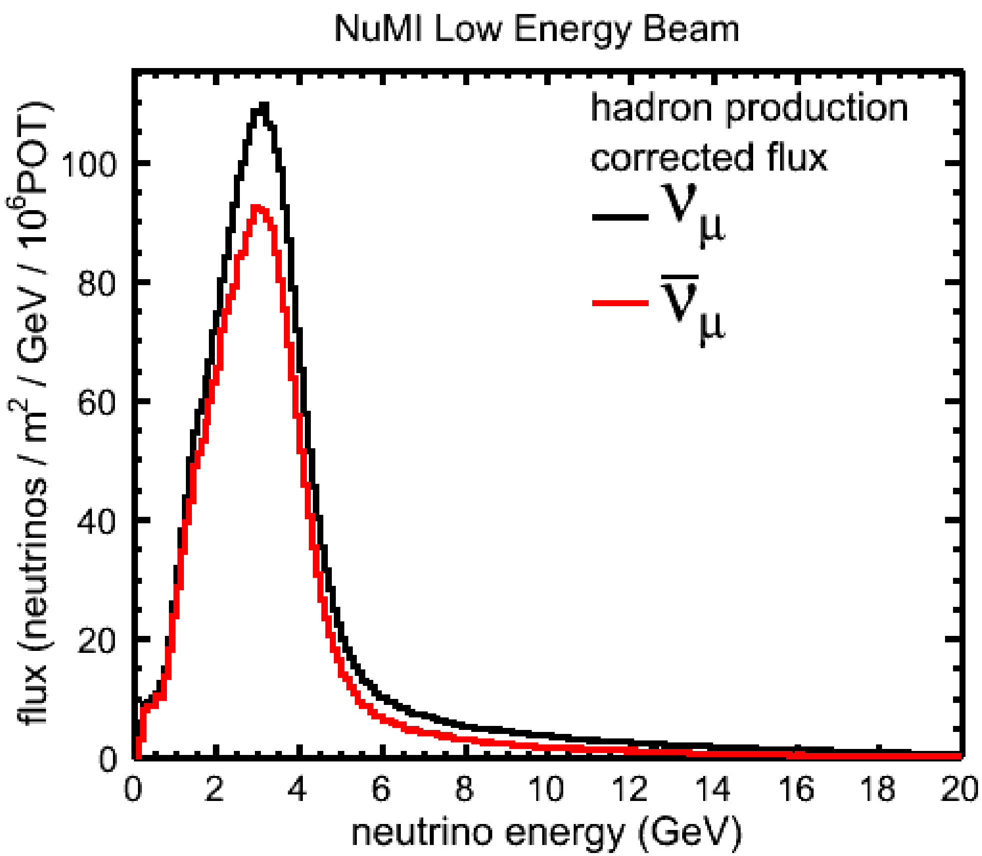
Tuning to Hadron Production Data

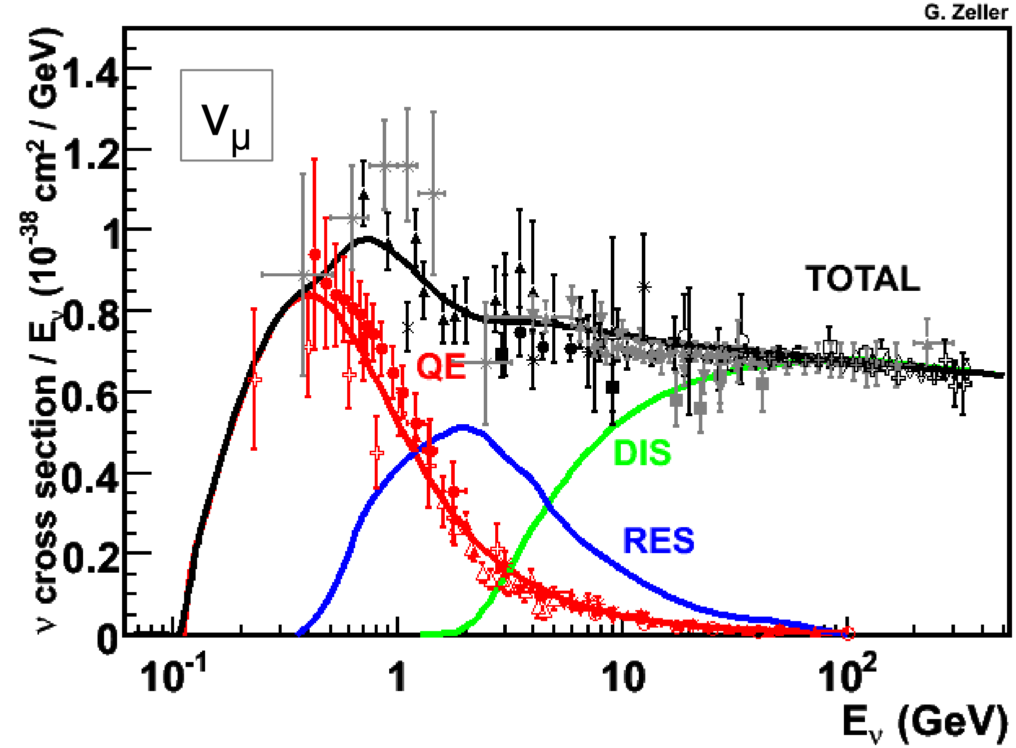
- Hadron production simulated with Geant4 to predict flux.
- Flux is reweighted based on hadron production data compared to Geant4.

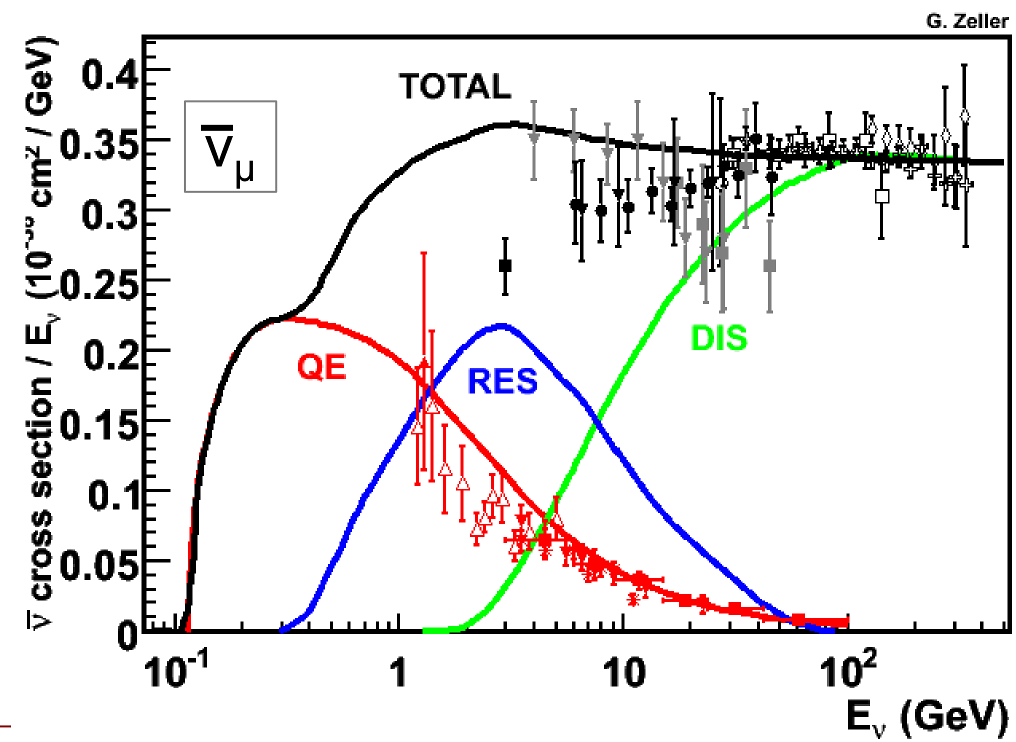




Neutrinos Seen





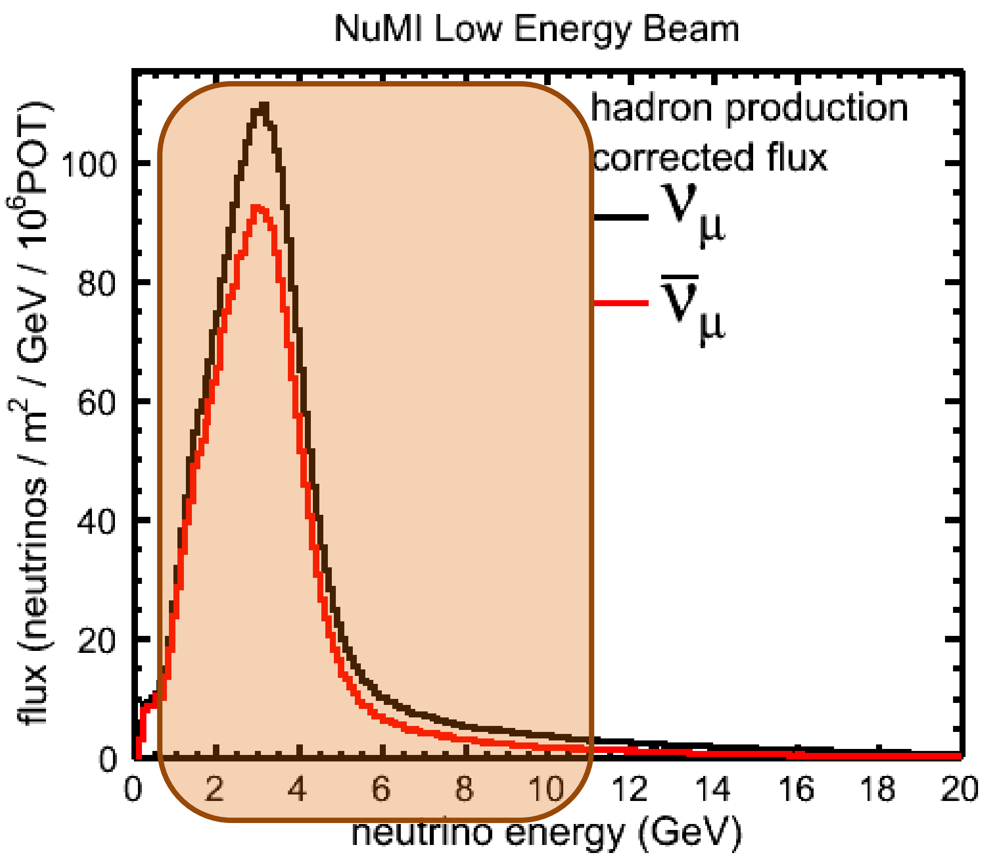


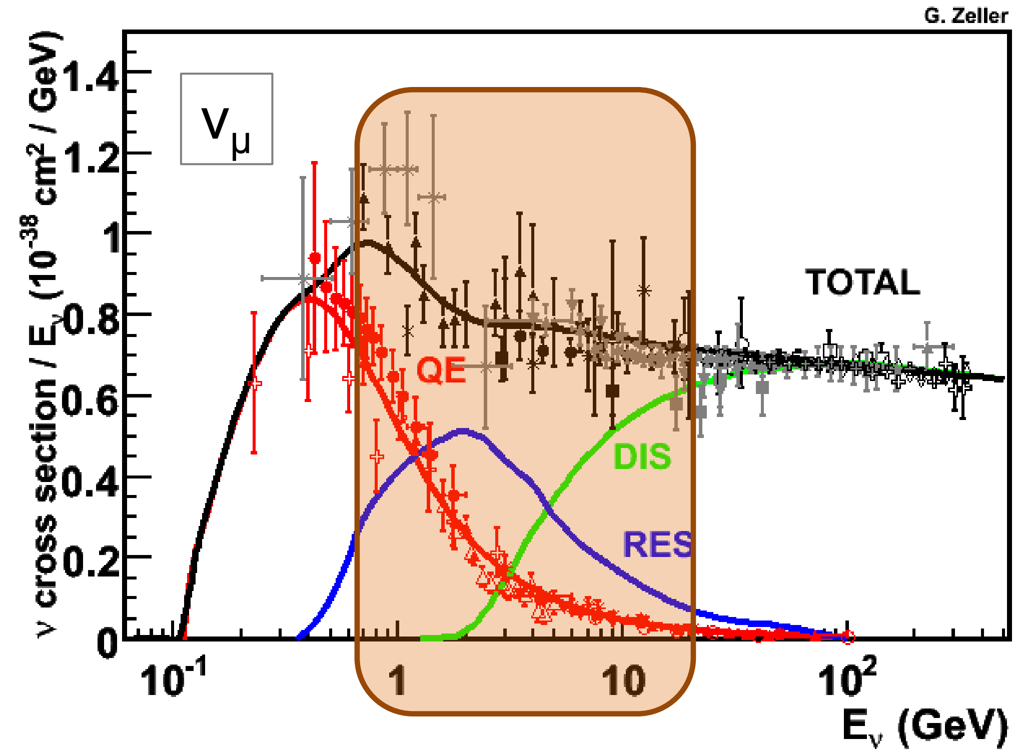
Data collected:

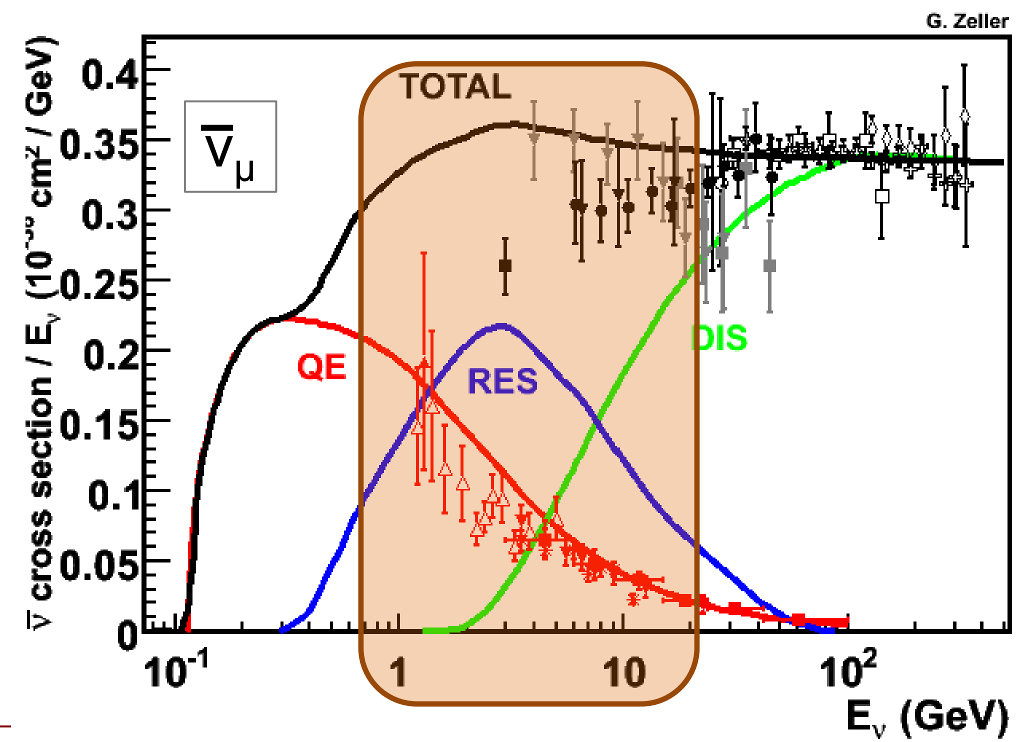
ν_μ **LE** 3.98×10^{20} POT

$\bar{\nu}_\mu$ **LE** 1.7×10^{20} POT

Neutrinos Seen







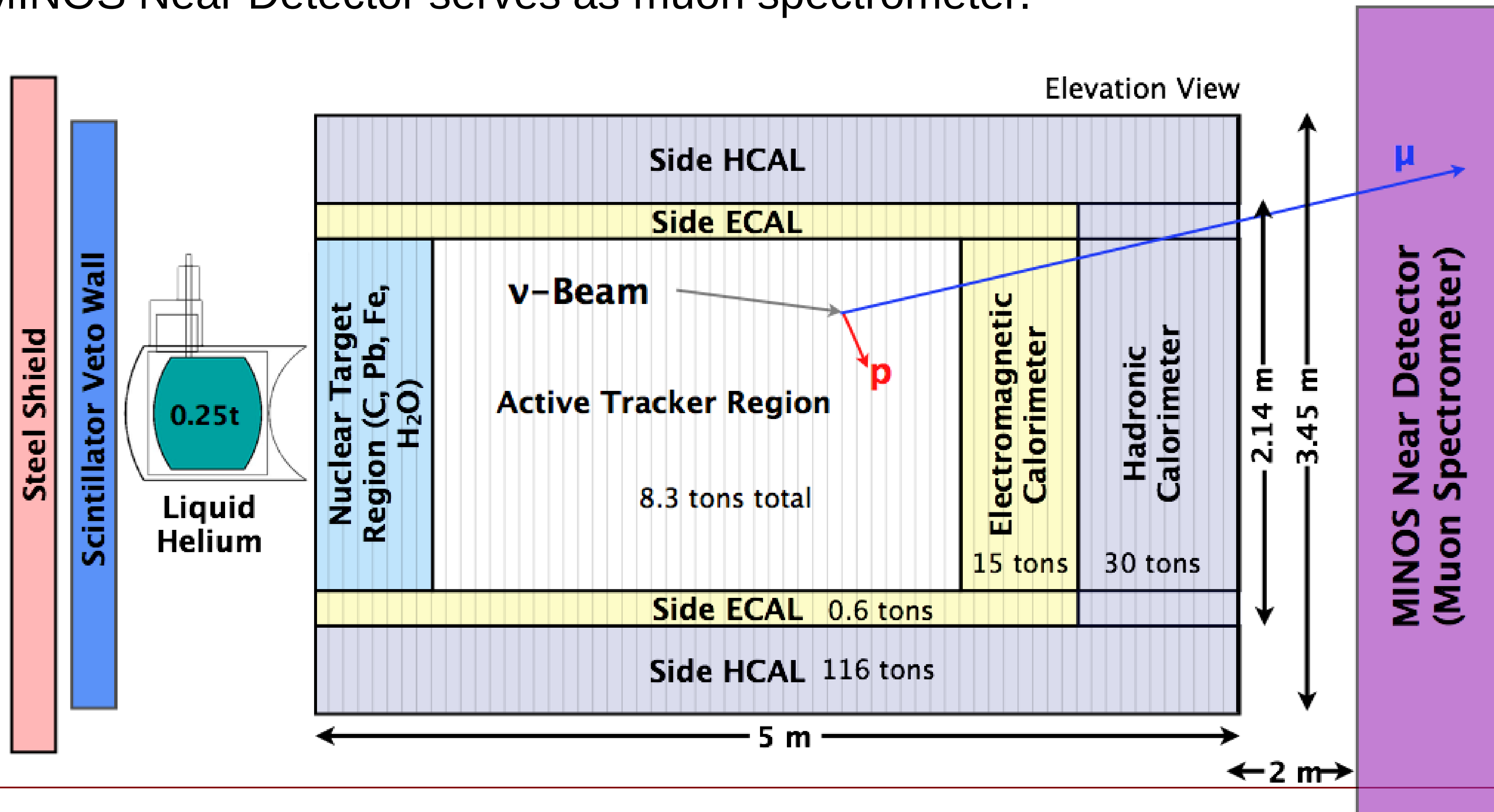
Data collected:

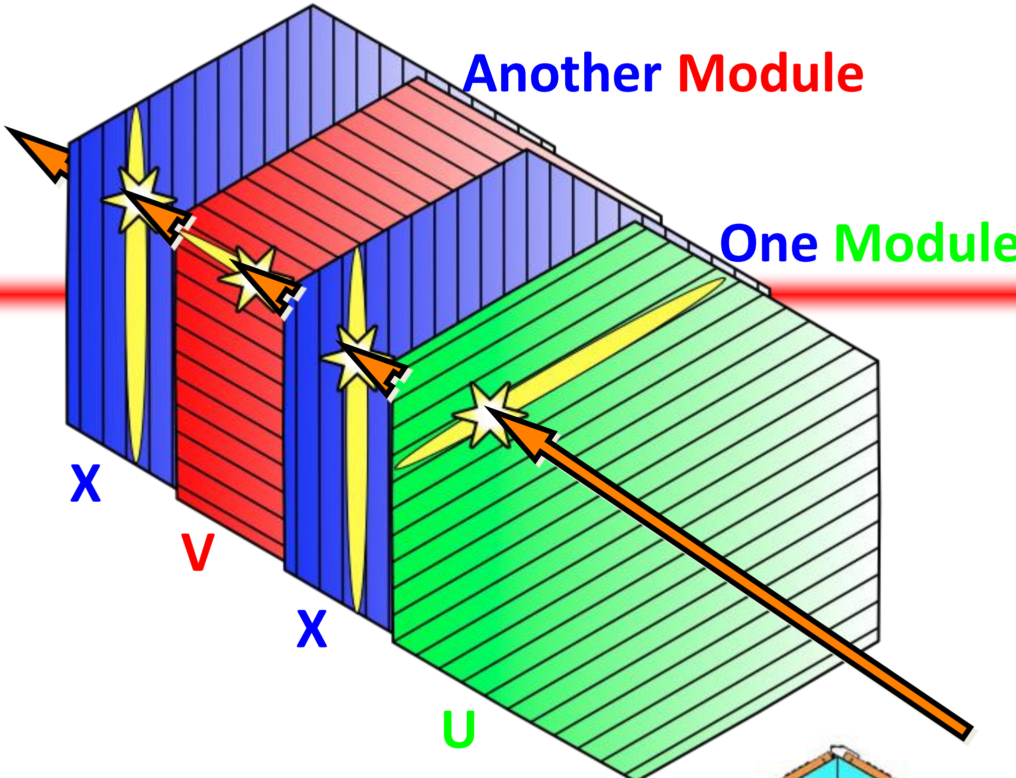
ν_μ **LE** 3.98x10^{20} POT

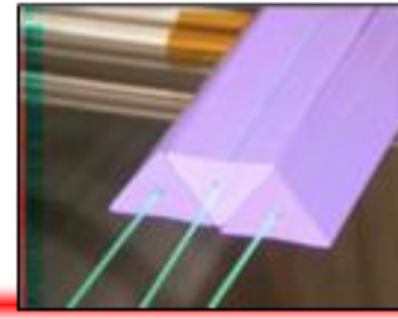
$\bar{\nu}_\mu$ **LE** 1.7x10^{20} POT

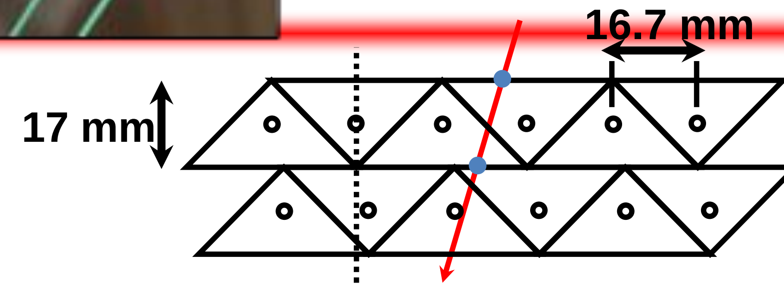
MINERvA Detector

- 120 scintillator modules for tracking and calorimetry (~32k readout channels).
- Construction completed Spring 2010. He and Water added in 2011.
- MINOS Near Detector serves as muon spectrometer.

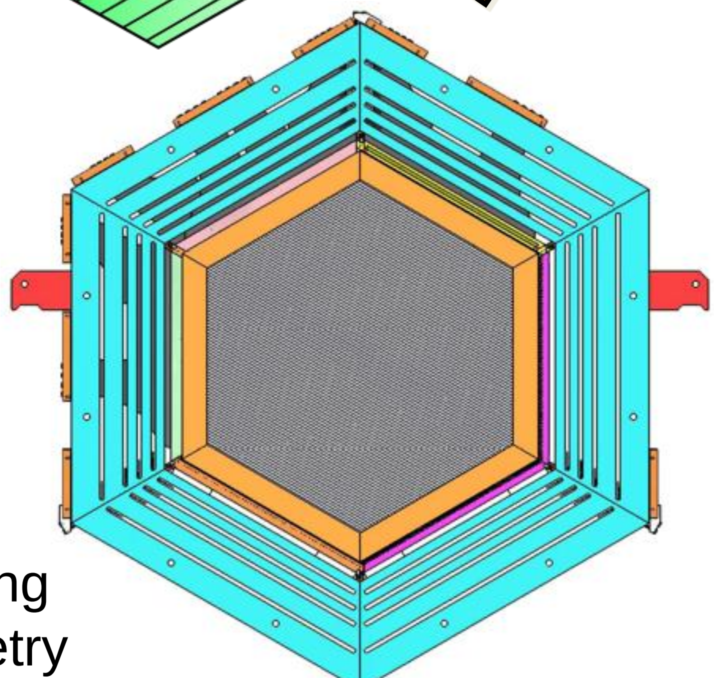




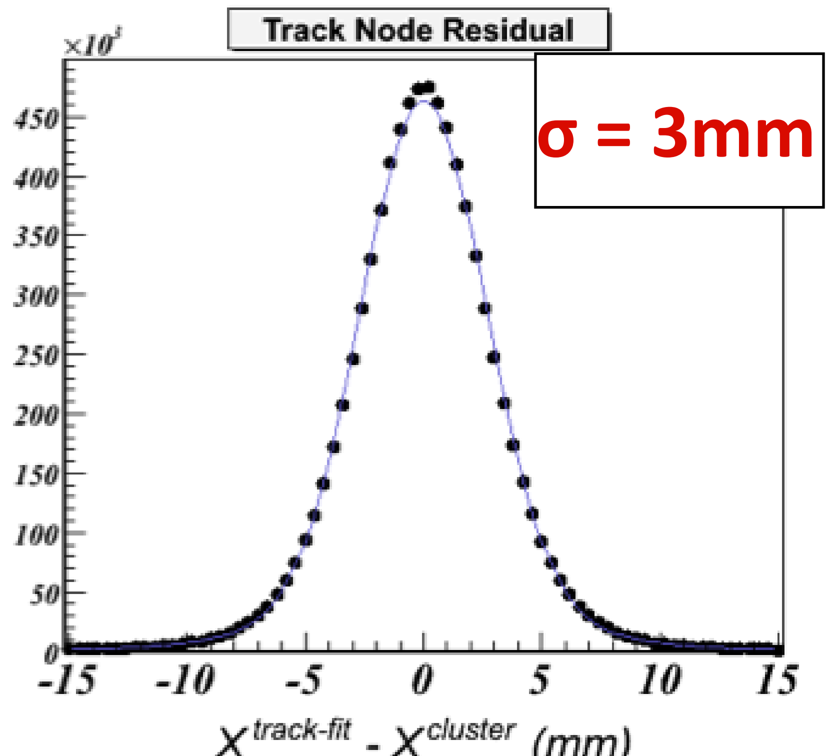




Charge sharing for improved position resolution (~3 mm) and alignment

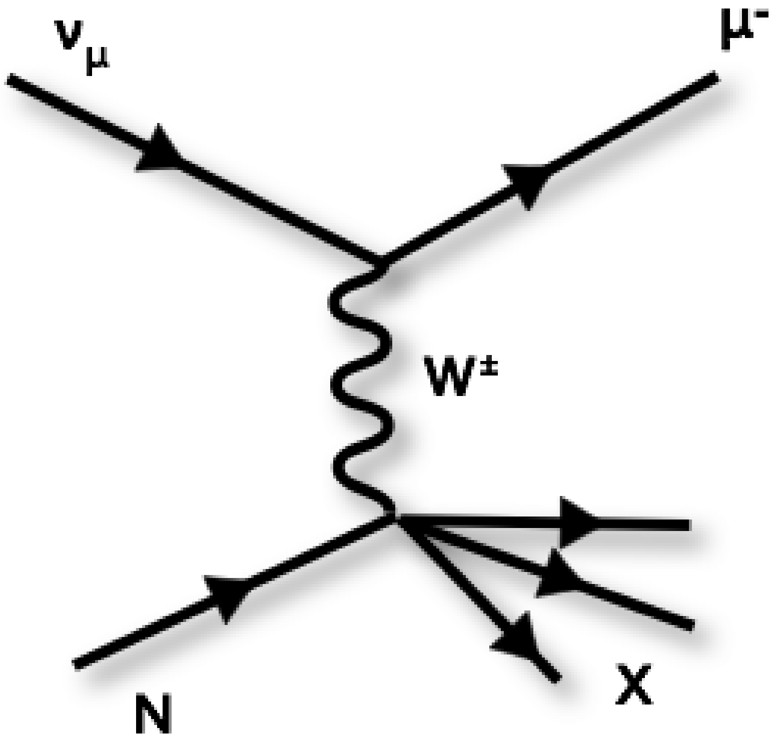


Scintillator - tracking
Lead - EM calorimetry
Steel - hadronic calorimetry

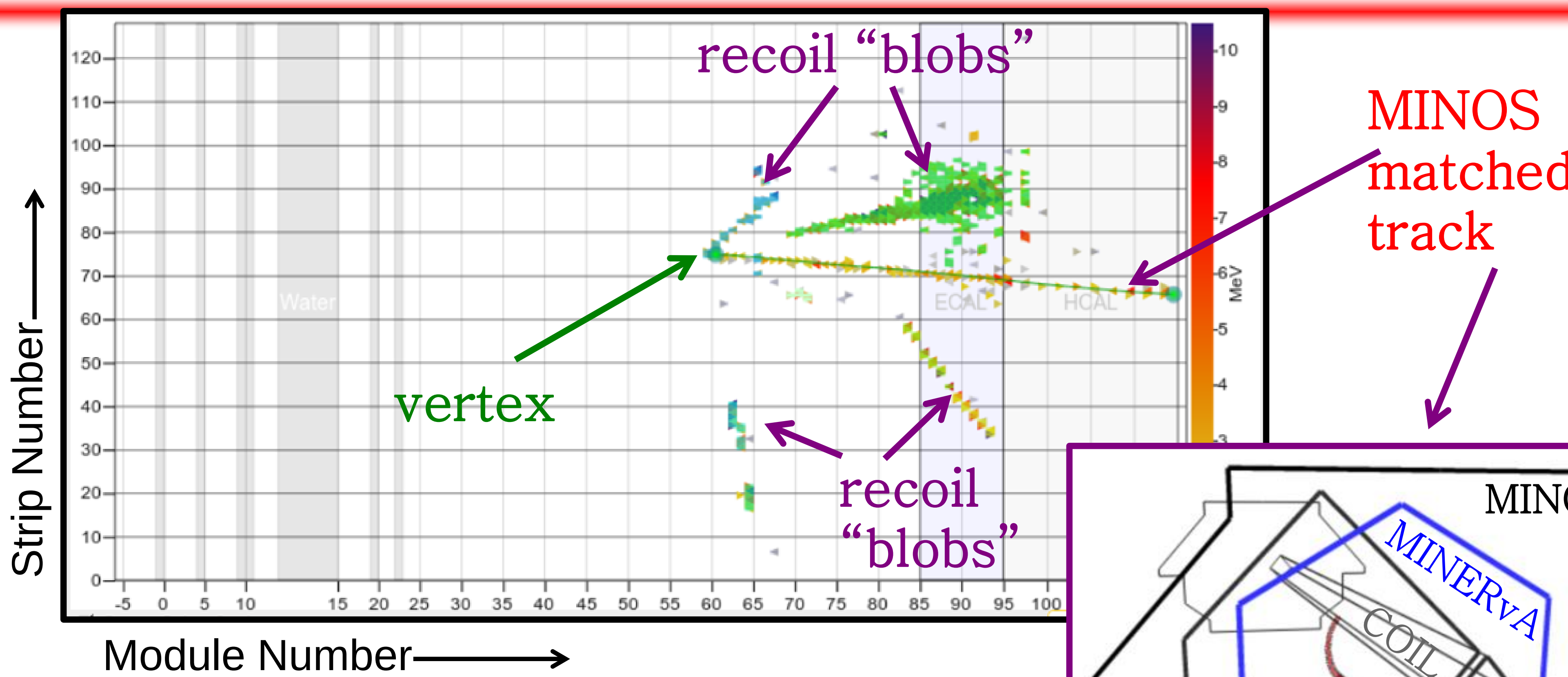


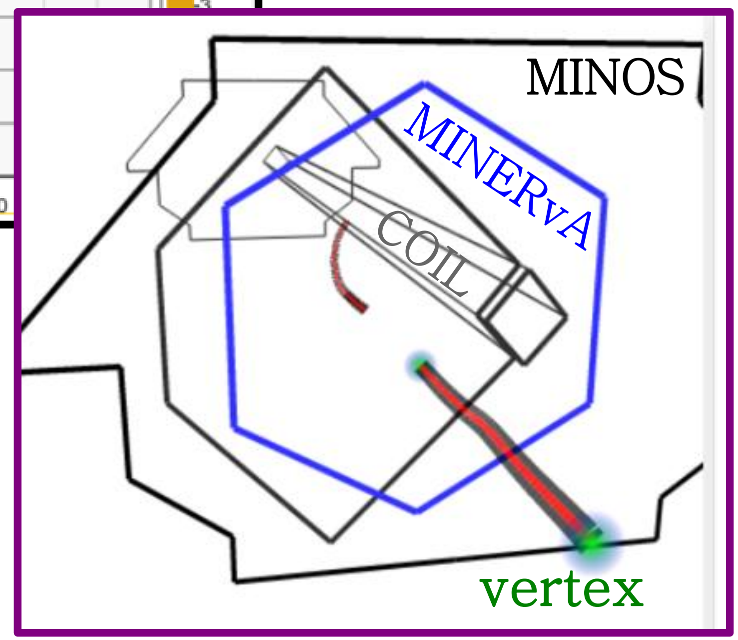
Inclusive Charged Current Scattering

$CC\nu_\mu$



Event Reconstruction

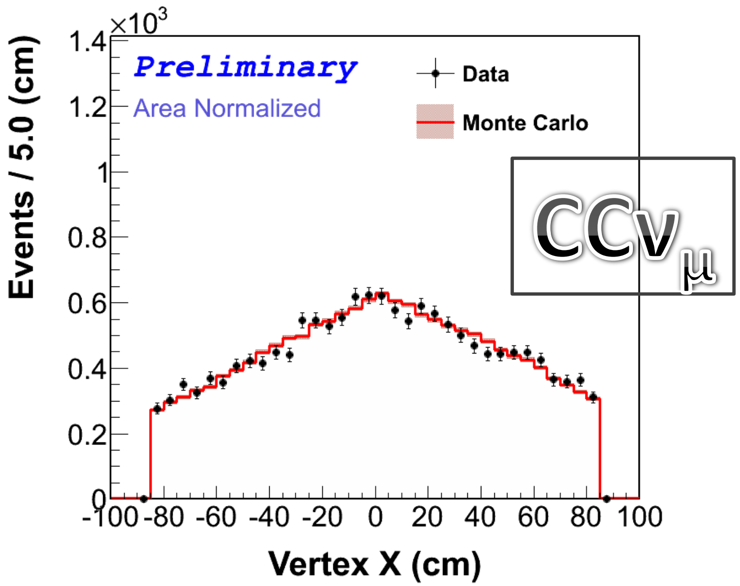


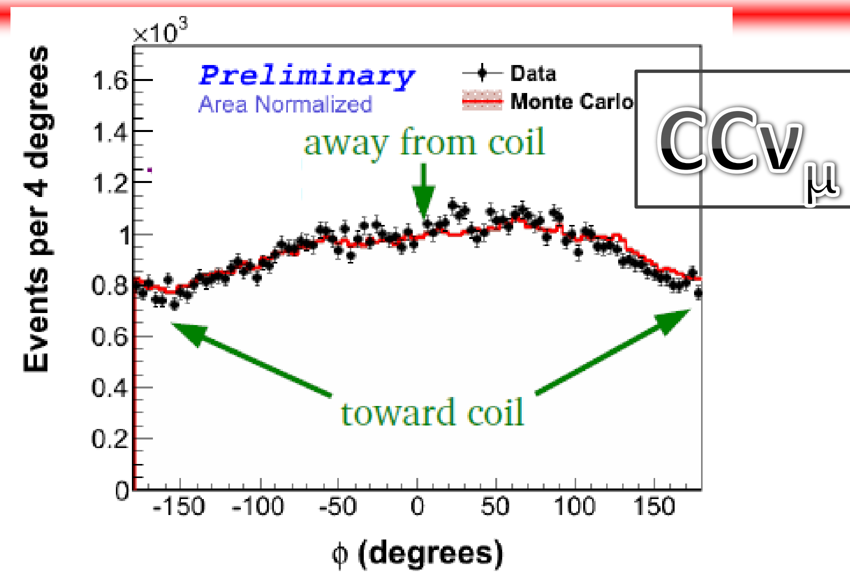


<u>Reconstructed objects</u>

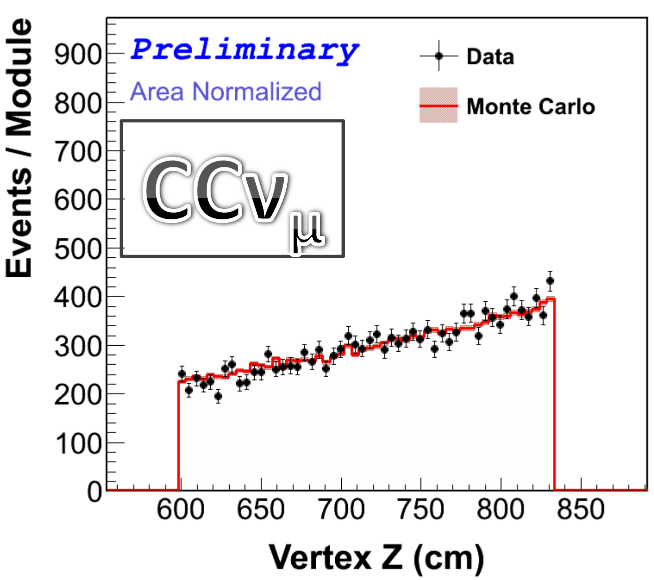
MINOS tracks, other tracks, vertices, endpoints, blobs

Vertex Distributions - Acceptance

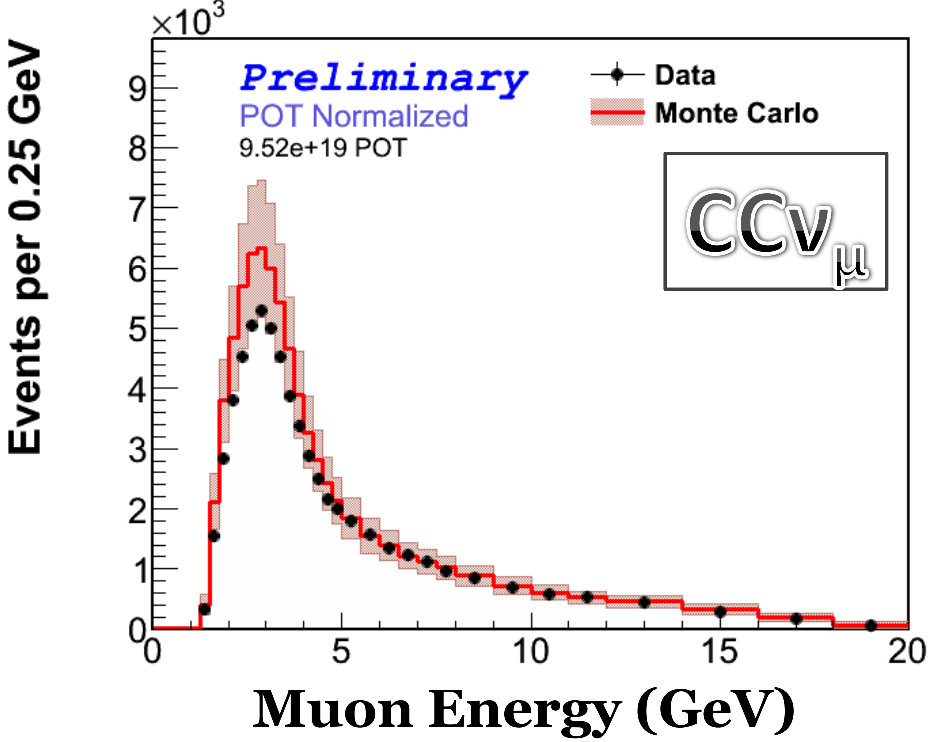


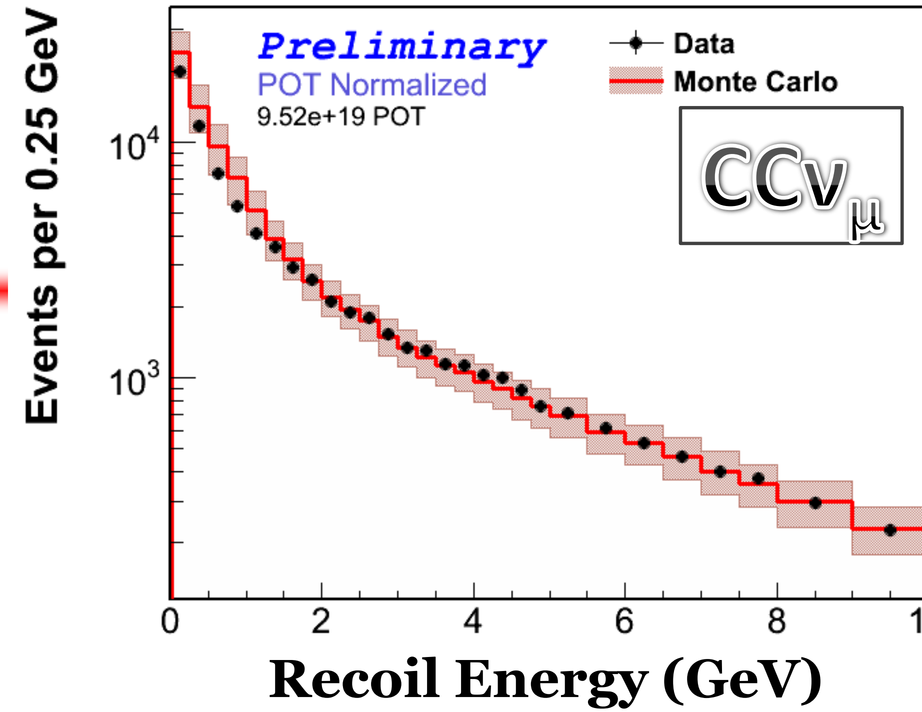


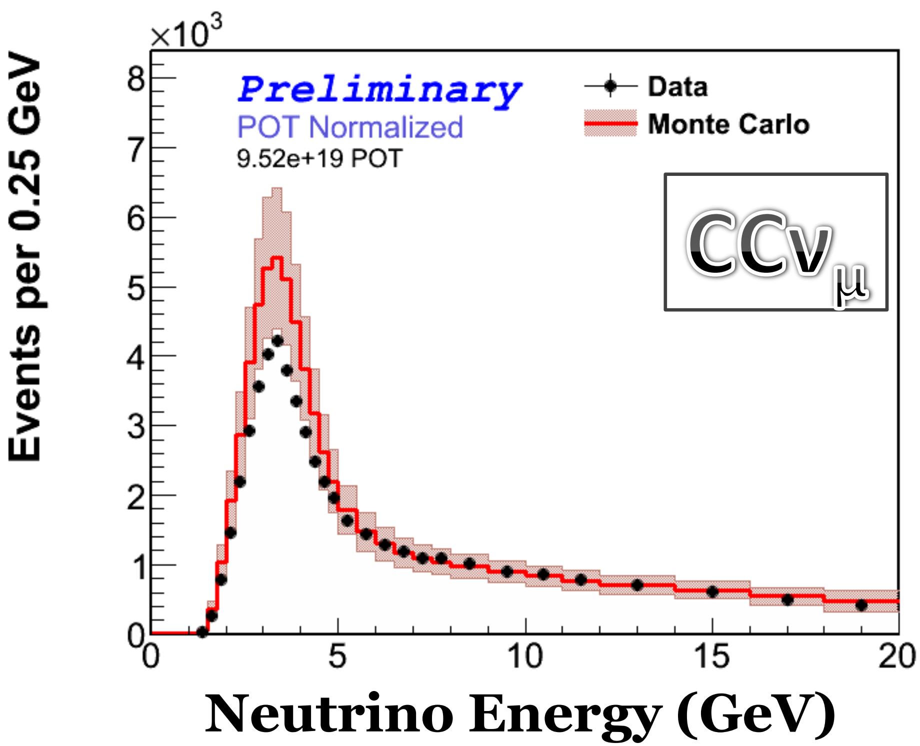
"MINOS-matched" muons
(for CC ν_μ inclusives sample)

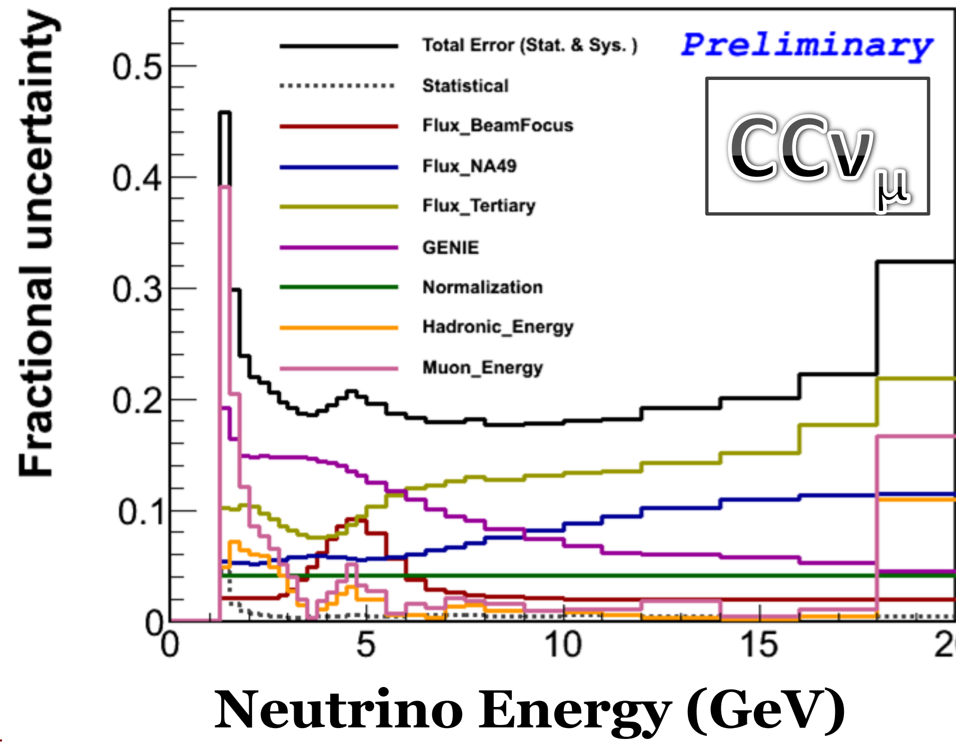


- Energy threshold ~2 GeV.
- Good angular acceptance up to scattering angles of about 10 degrees, with limit of about 20 degrees.
- Bias is complex but well understood.

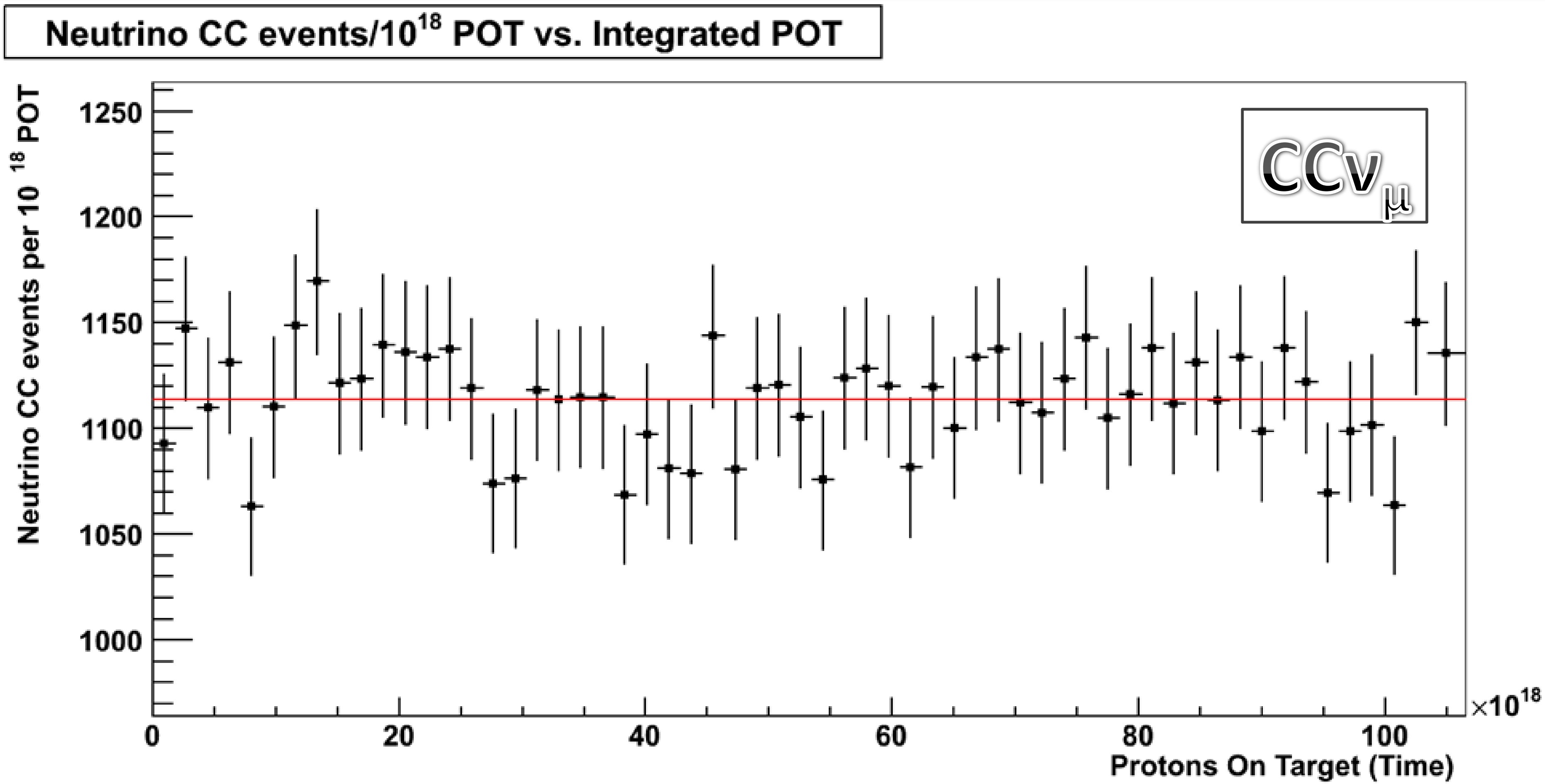

Preliminary
POT Normalized
9.52e+19 POT
Data
Monte Carlo
$CC\nu_\mu$
Events per 0.25 GeV
$\times 10^3$
Muon Energy (GeV)


Preliminary
POT Normalized
9.52e+19 POT
Data
Monte Carlo
$CC\nu_\mu$
Events per 0.25 GeV
Recoil Energy (GeV)


Preliminary
POT Normalized
9.52e+19 POT
Data
Monte Carlo
$CC\nu_\mu$
Events per 0.25 GeV
$\times 10^3$
Neutrino Energy (GeV)


Total Error (Stat. & Sys.)
Statistical
Flux_BeamFocus
Flux_NA49
Flux_Tertiary
GENIE
Normalization
Hadronic_Energy
Muon_Energy
Preliminary
$CC\nu_\mu$
Fractional uncertainty
Neutrino Energy (GeV)

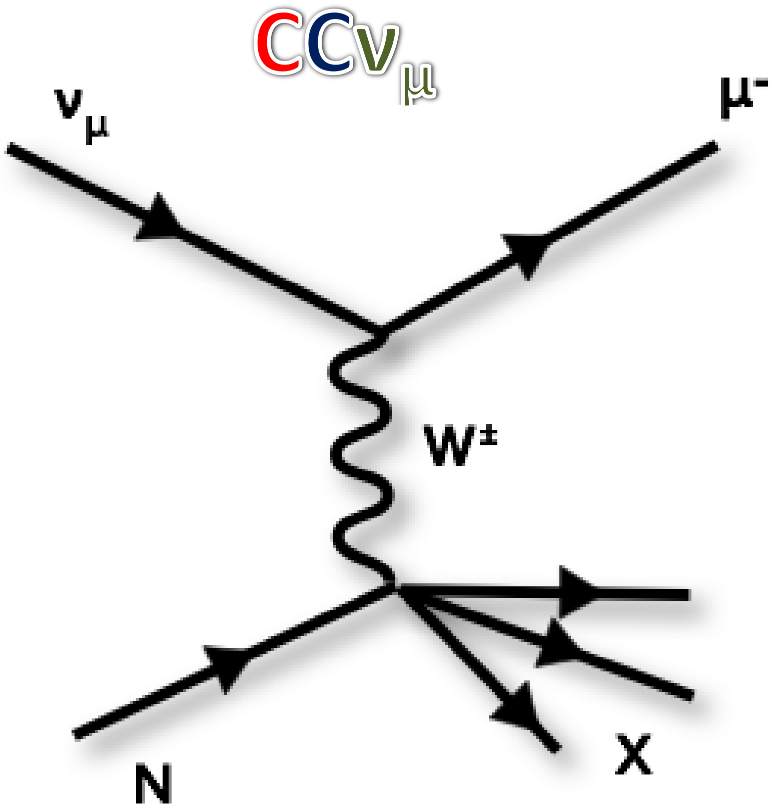
Stability

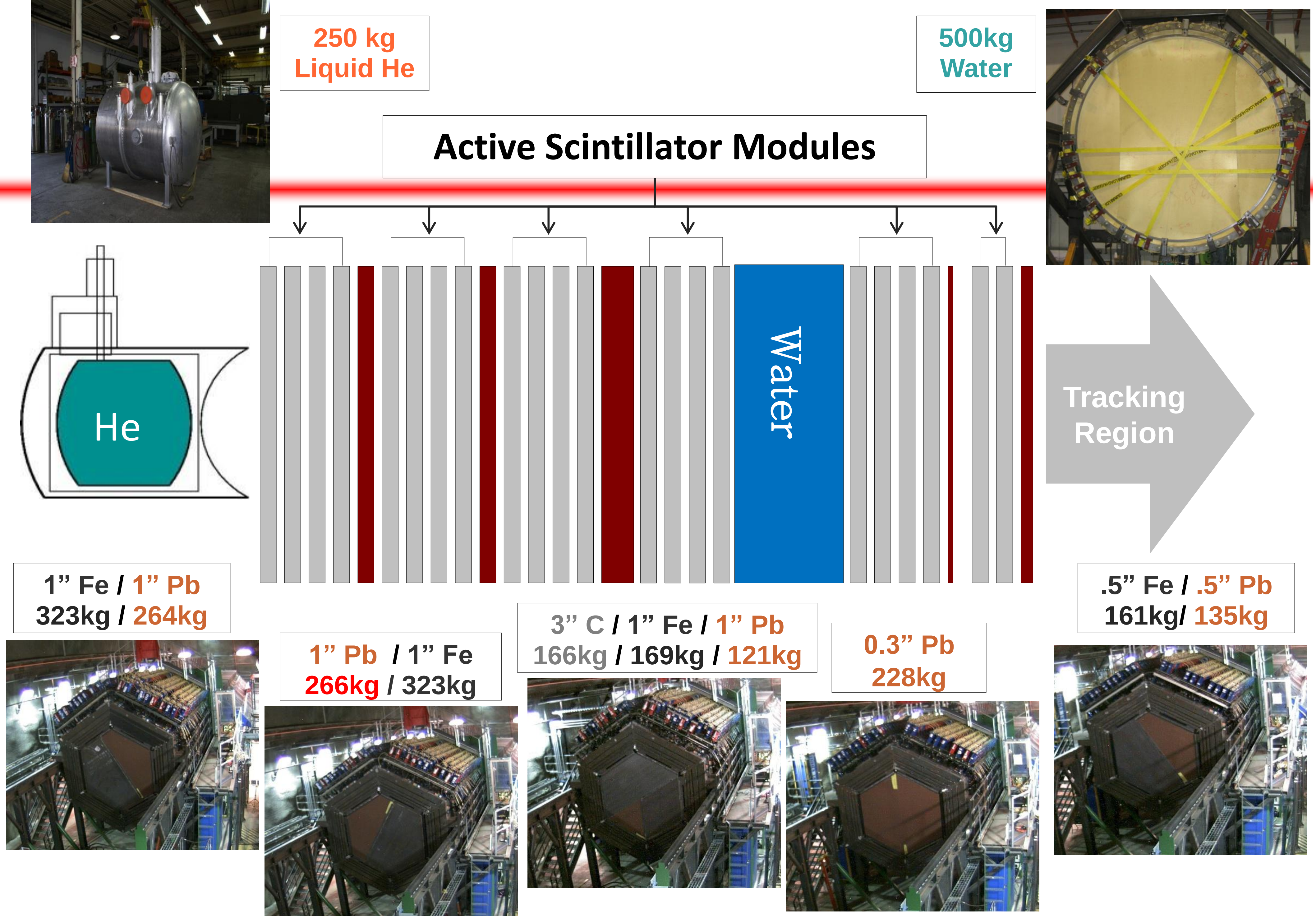


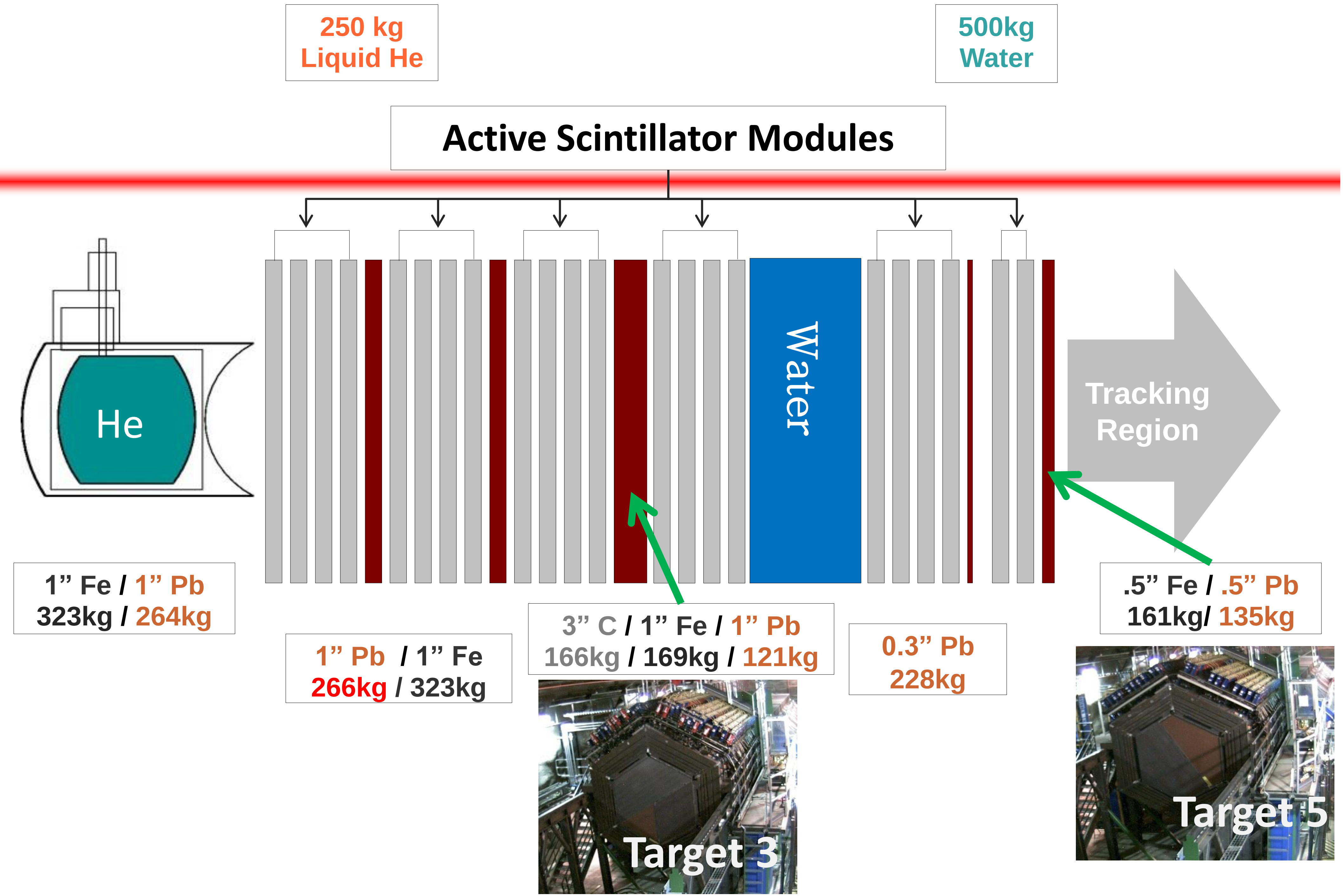
March 22, 2010

July 12, 2010

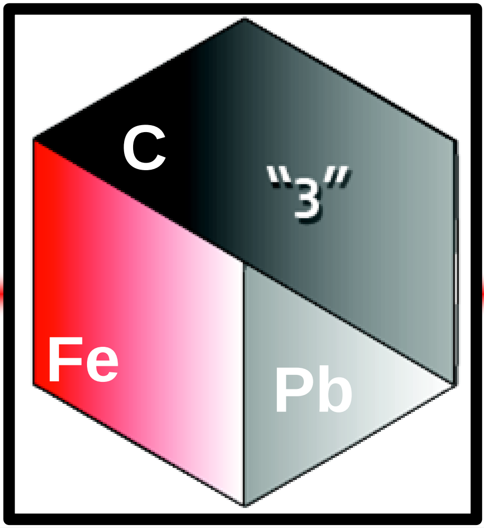
Nuclear Target Ratios Analysis



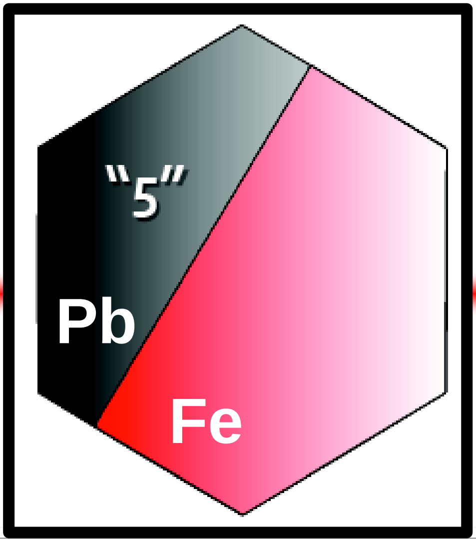

250 kg
Liquid He
500kg
Water
Active Scintillator Modules
He
Water
Tracking
Region
1” Fe / 1” Pb
323kg / 264kg
1” Pb / 1” Fe
266kg / 323kg
3” C / 1” Fe / 1” Pb
166kg / 169kg / 121kg
0.3” Pb
228kg
.5” Fe / .5” Pb
161kg/ 135kg

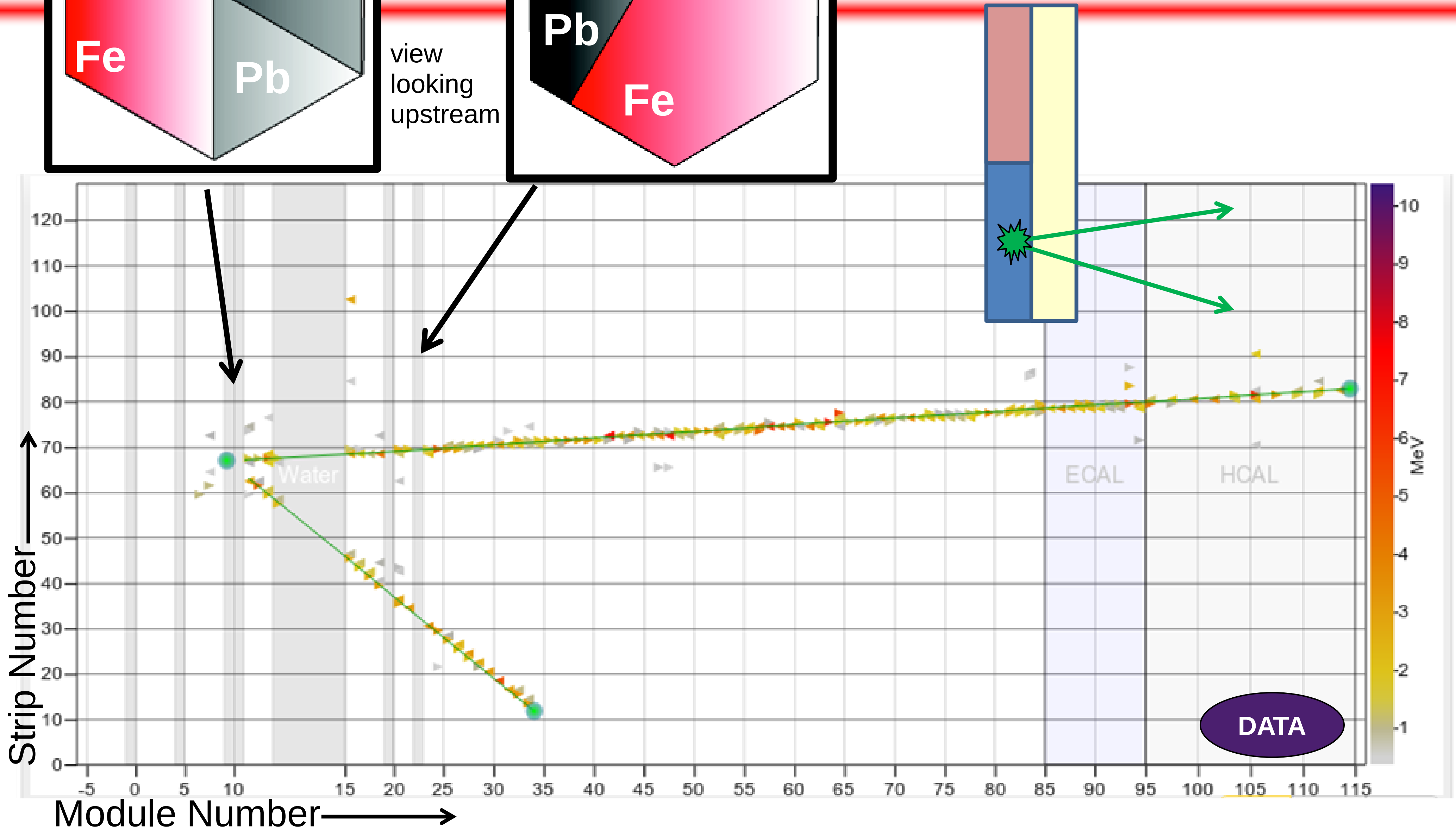

250 kg
Liquid He
500kg
Water
Active Scintillator Modules
He
Water
Tracking
Region
1” Fe / 1” Pb
323kg / 264kg
1” Pb / 1” Fe
266kg / 323kg
3” C / 1” Fe / 1” Pb
166kg / 169kg / 121kg
0.3” Pb
228kg
.5” Fe / .5” Pb
161kg/ 135kg
Target 3
Target 5

An event from target 3

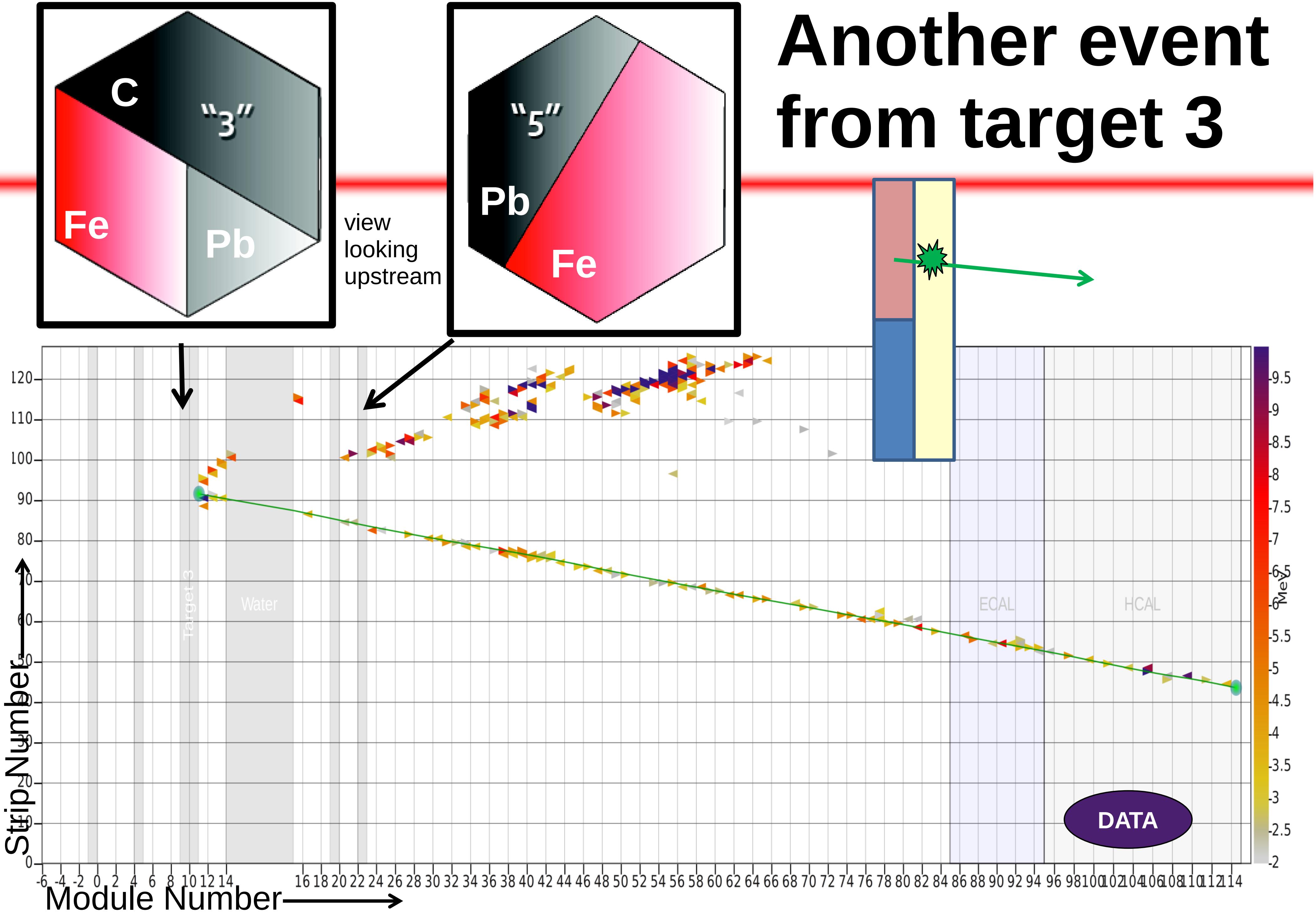


view looking upstream

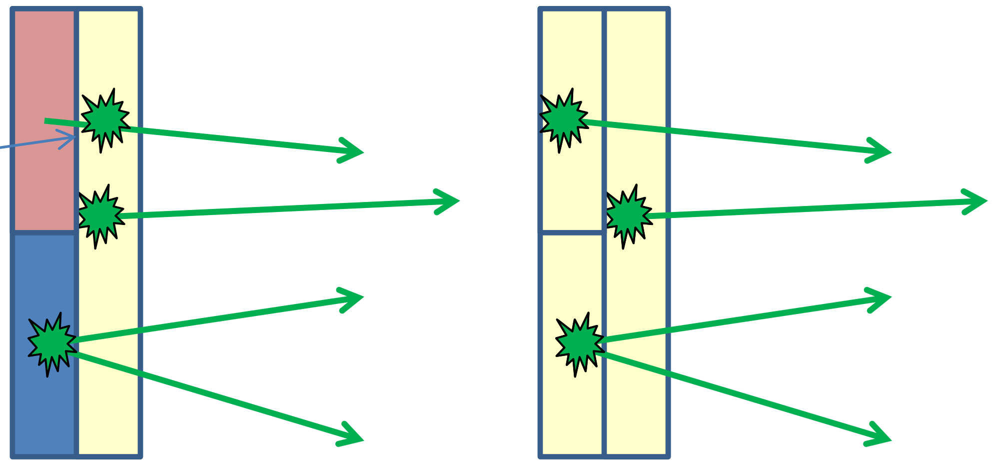


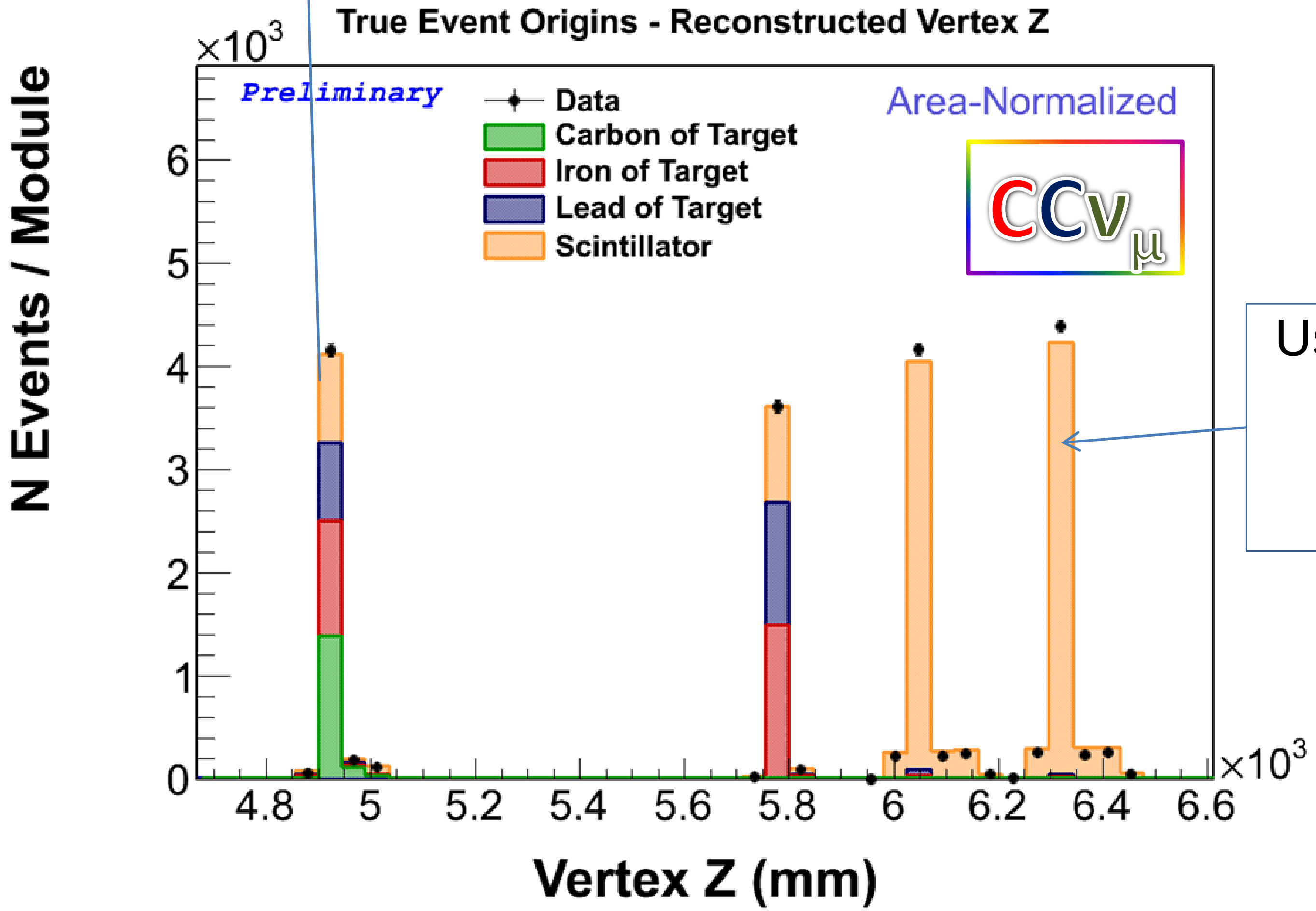


Another event from target 3



Vertices reconstructed wrongly into scintillator are background.

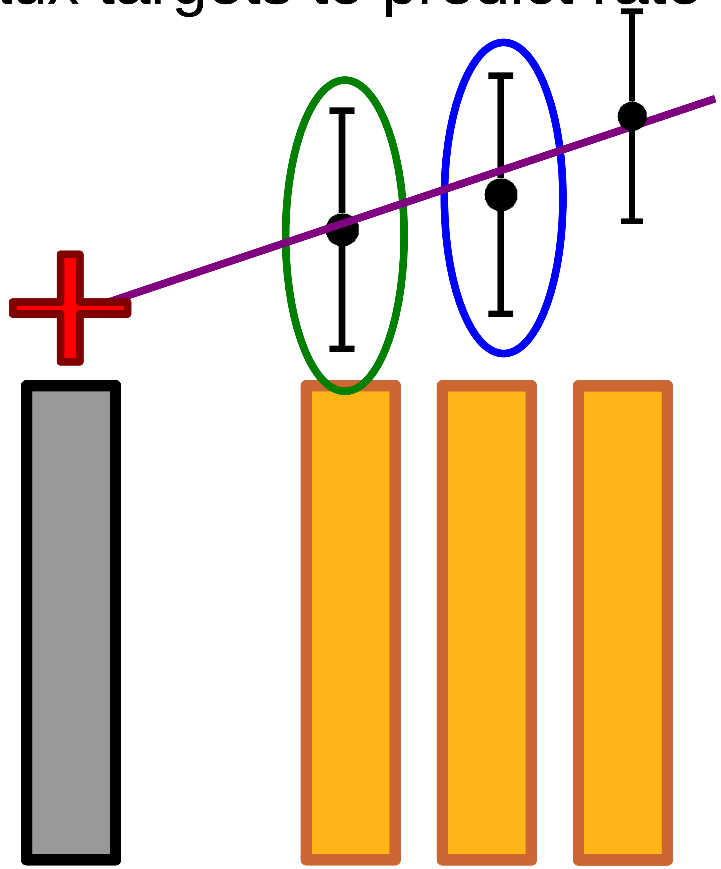


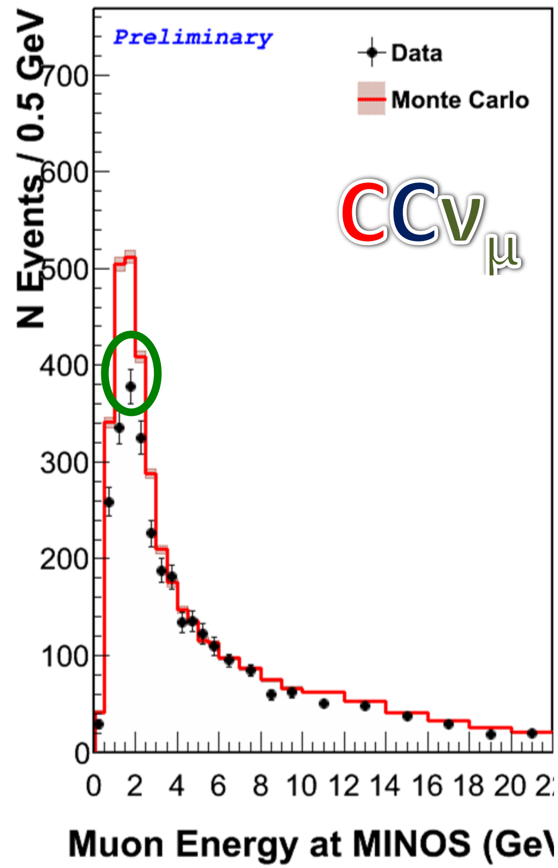


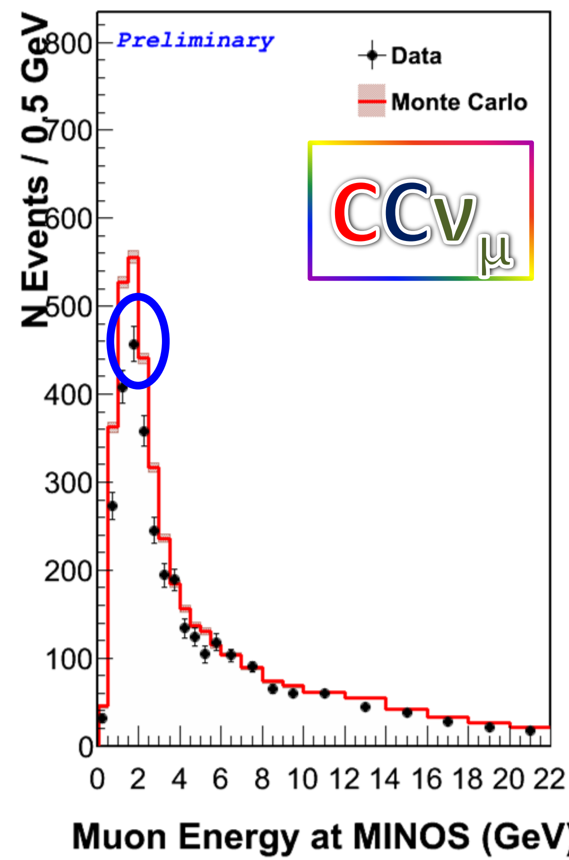
Use upstream tracker modules as “faux” targets to subtract the plastic background.

Background Subtraction

Use faux targets to predict rate if passive target were CH.



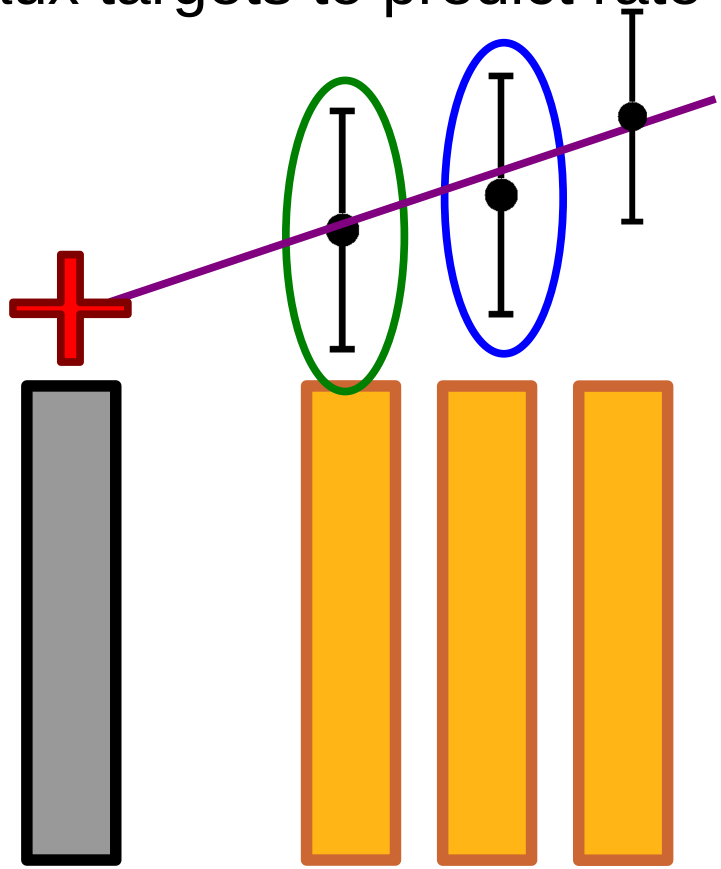


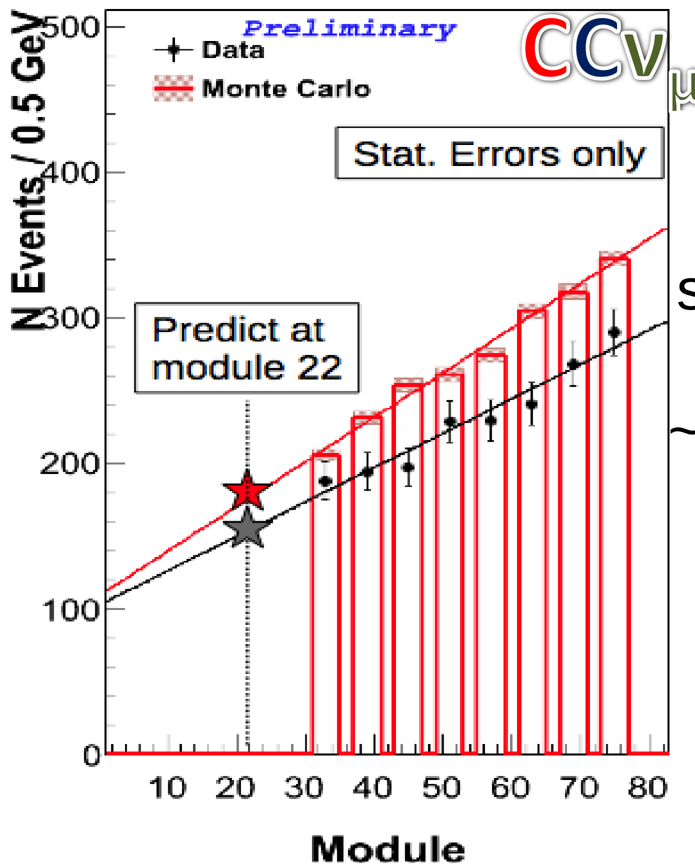


Prediction done in bins of muon momentum.

Background Subtraction

Use faux targets to predict rate if passive target were CH.



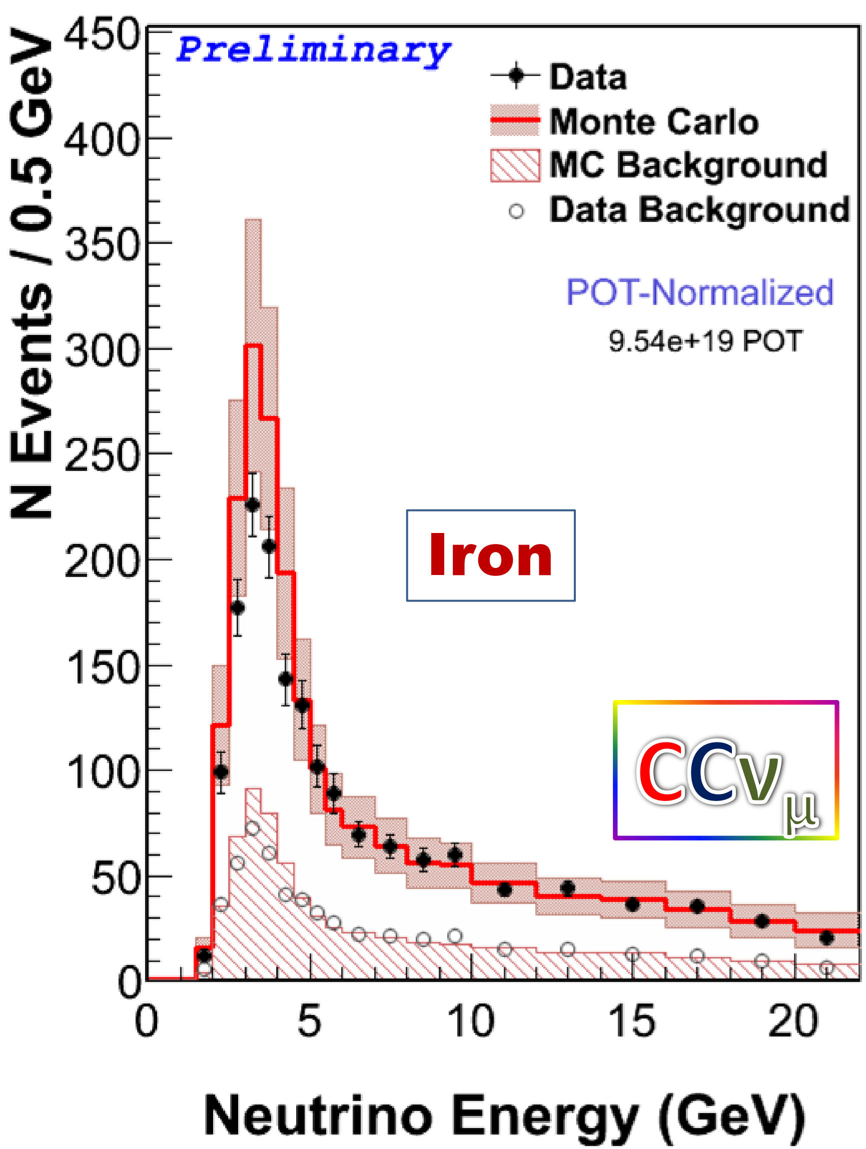


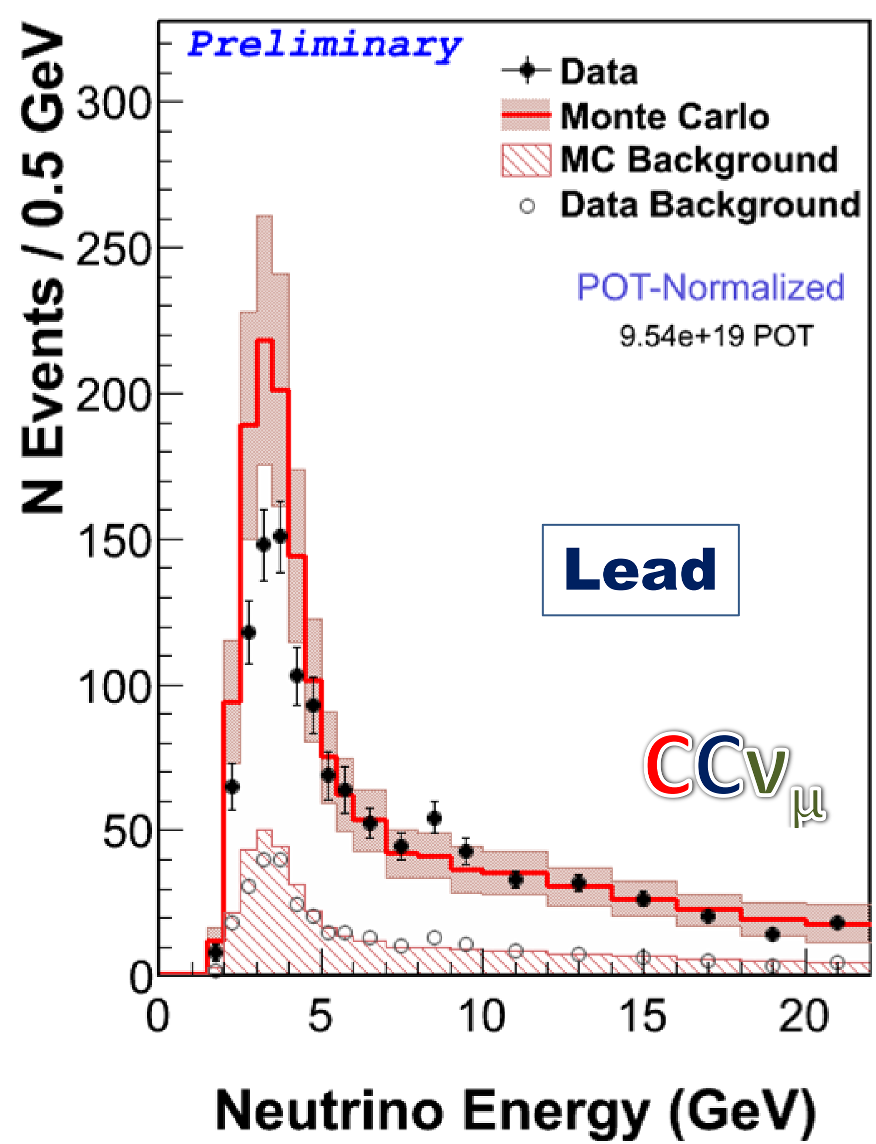
Background subtracted in both MC and data ~without using MC cross section model.

$$B(\text{data}) = P(\text{data})\frac{B(\text{MC})}{P(\text{MC})}$$

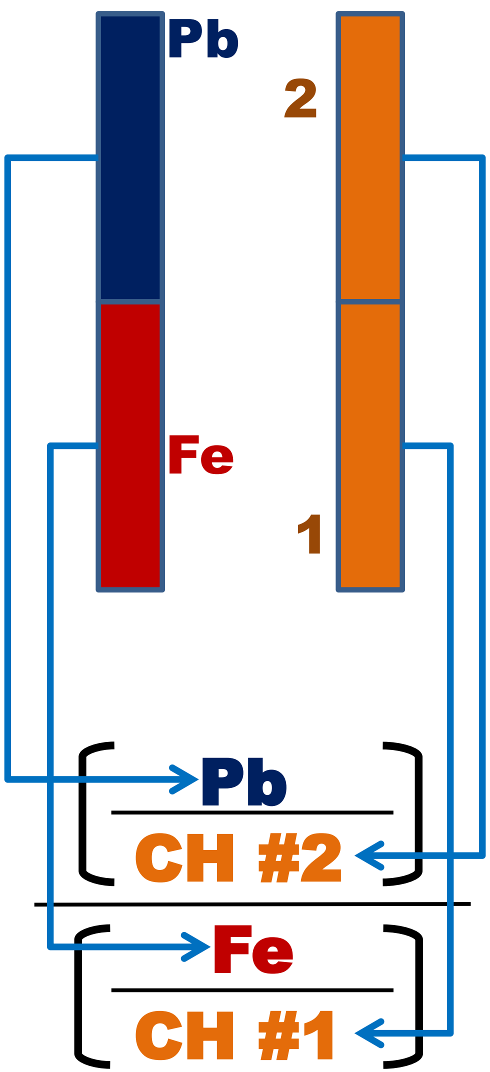
Target 5 Results

Uses ~25% neutrino data recorded and~20% of target mass.





Use a Ratio to Mitigate Errors



Pb(Fe) and 2(1) have ~same efficiency related to XY position.

Pb(2) and Fe(1) have ~same efficiency related to Z position.

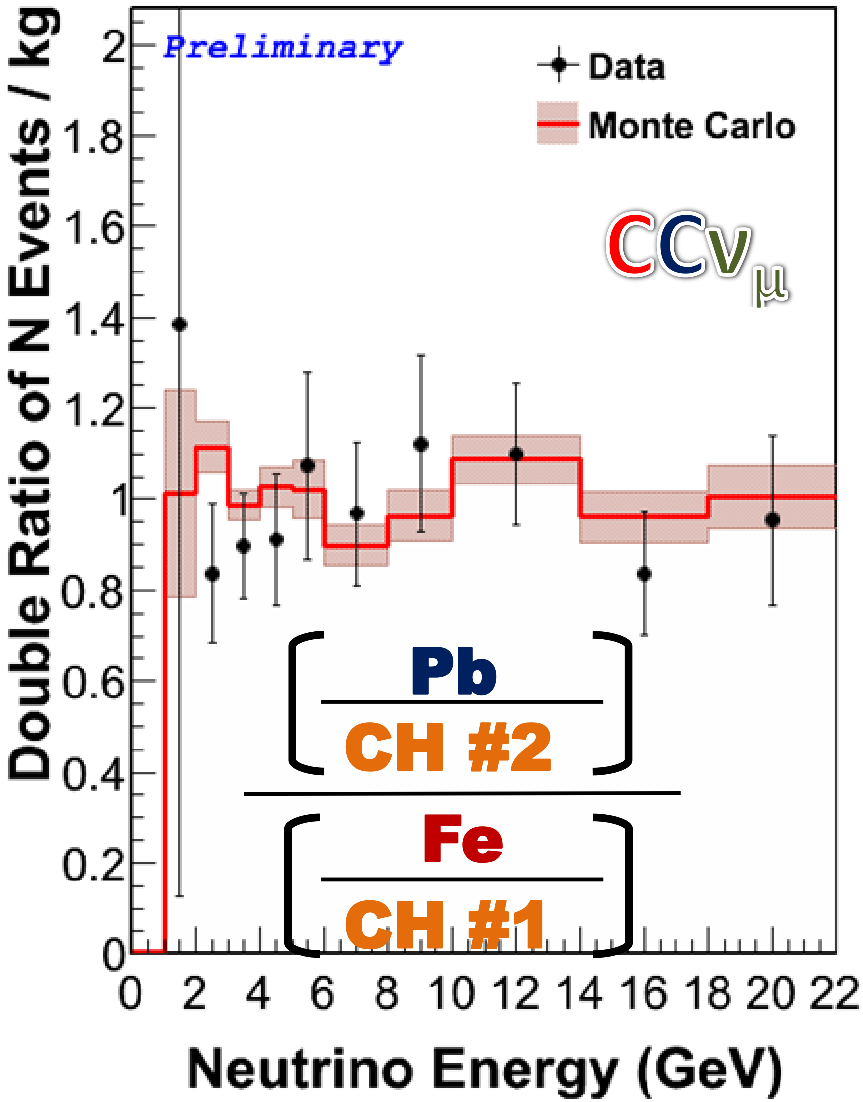
$$\frac{\left[\dfrac{\varepsilon^{xy}\varepsilon^{z}}{\varepsilon^{xy}\varepsilon^{z}}\right]}{\left[\dfrac{\varepsilon^{xy}\varepsilon^{z}}{\varepsilon^{xy}\varepsilon^{z}}\right]} \sim 1$$

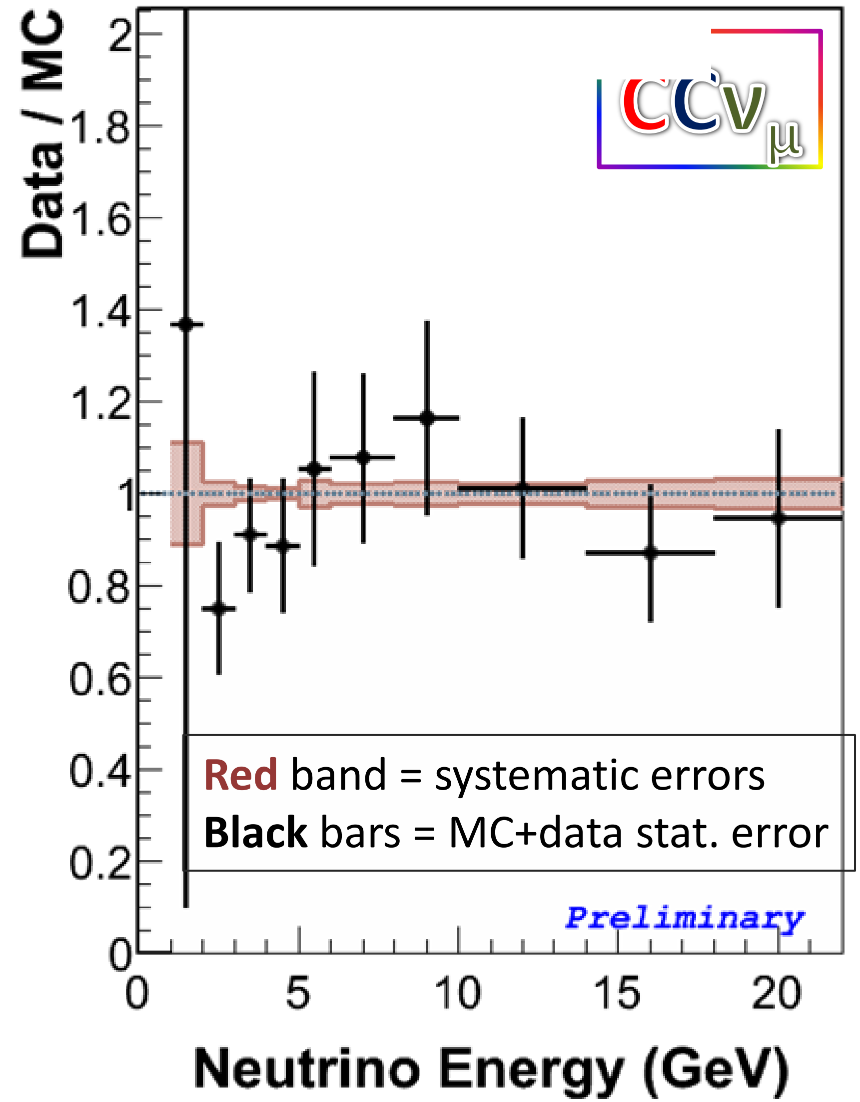
All targets in same beam → flux largely cancels

All targets in same detector → similar reconstruction

Target 5 Results - Ratio

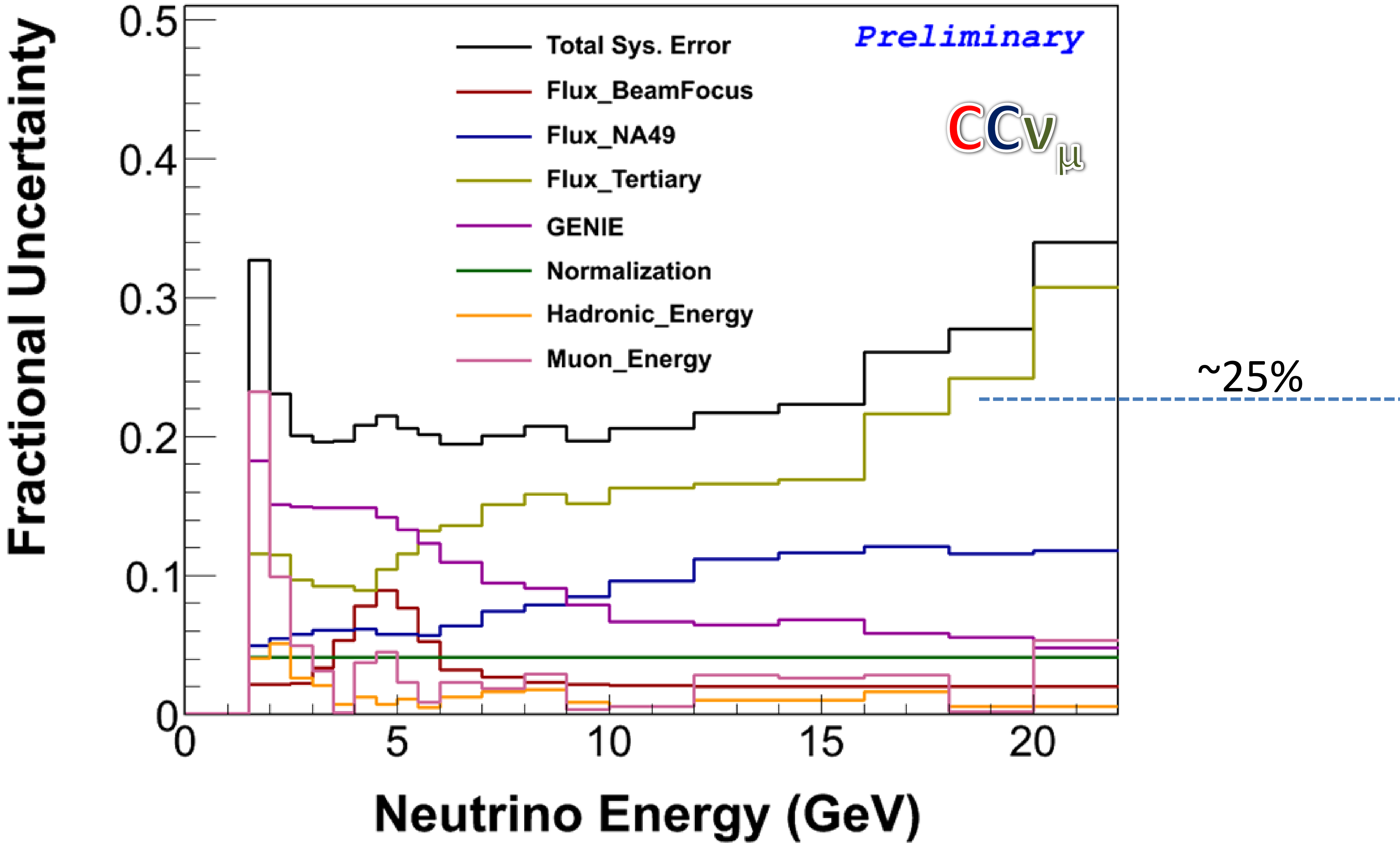
Uses ~25% neutrino data recorded and~20% of target mass.



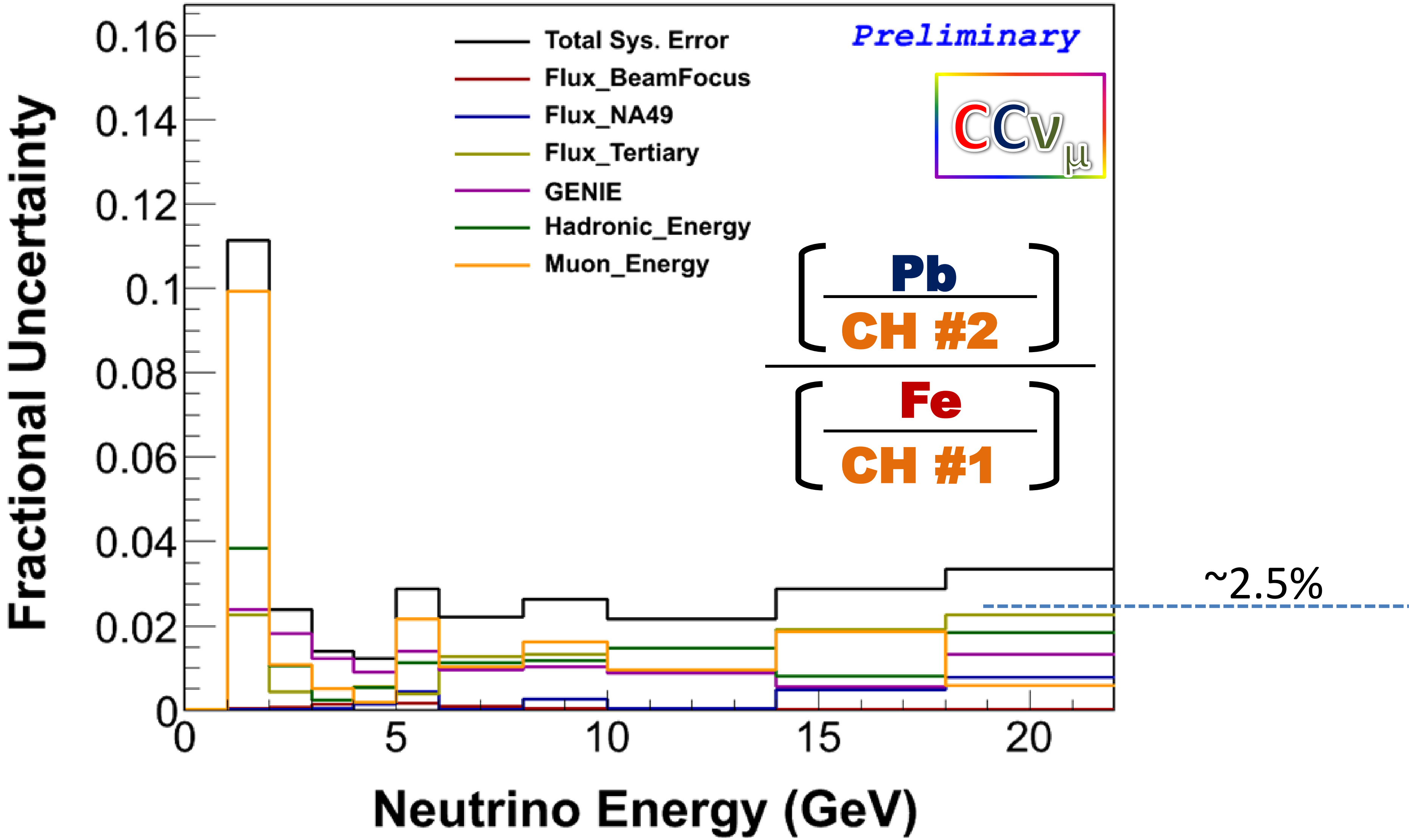


Higher statistics → Plot X, Q^2 in bins of neutrino energy

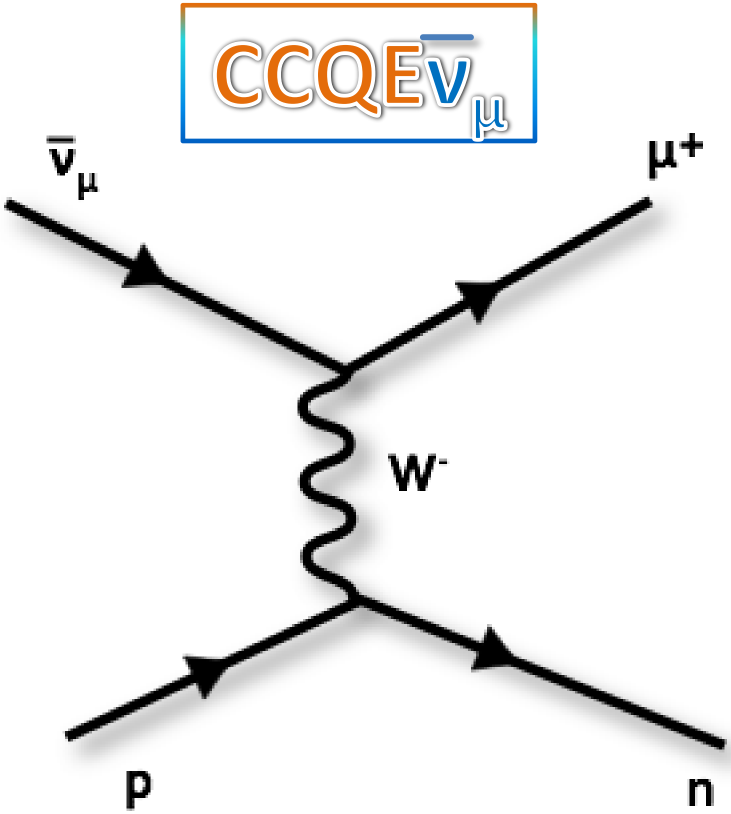
Systematic Error - Iron of Target 5

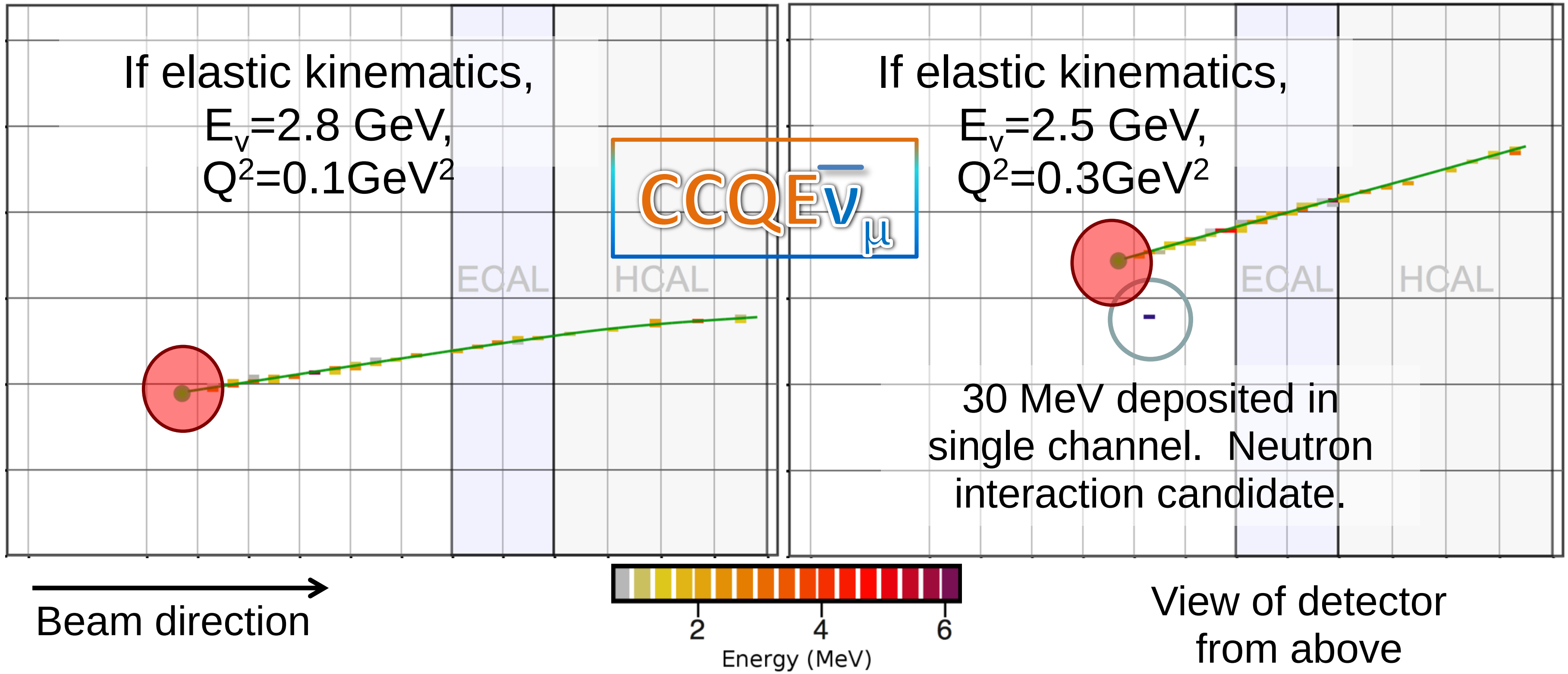


Systematic Error - Ratio



Antineutrino Quasi Elastic Scattering

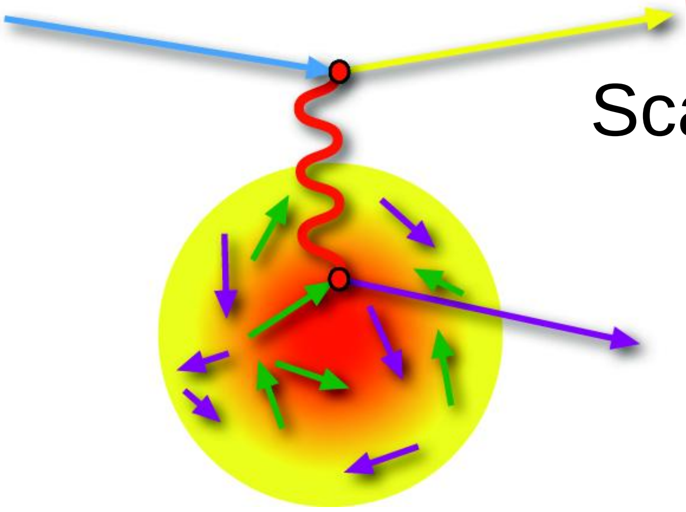




- Require a μ^+ matched into MINOS.
- Require no other tracks.
- Require 0 or 1 clumps of energy deposition (neutron candidate).

- Sum recoil energy (excluding 10cm around vertex).

Why don't we cut on vertex activity? We want to measure it!



Scattering off a nucleus can be messy.

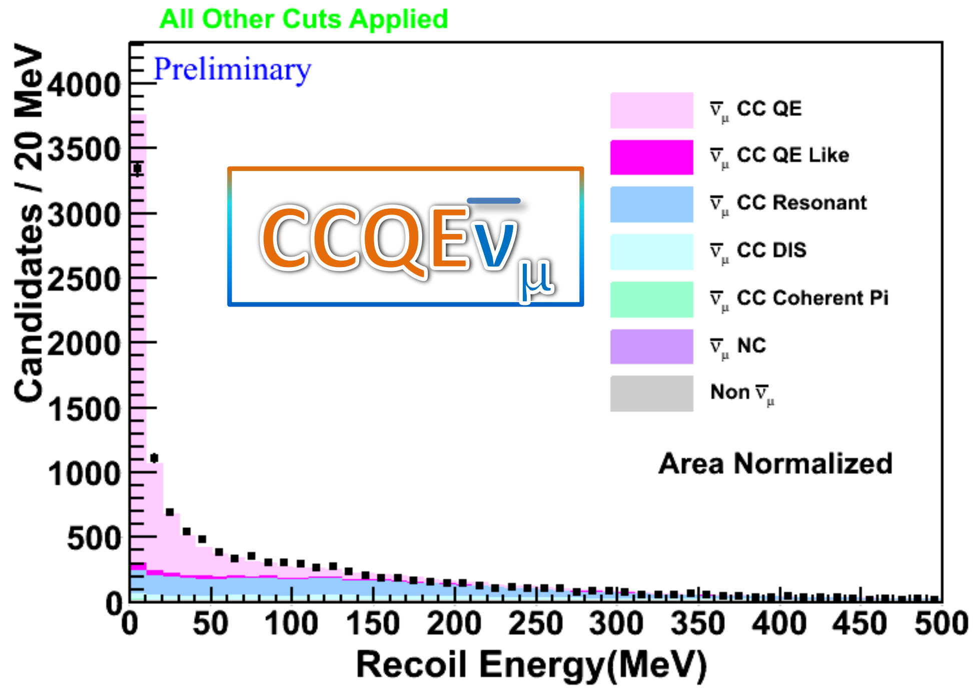
We must interrogate the final state products to allow testing of MEC and FSI models.

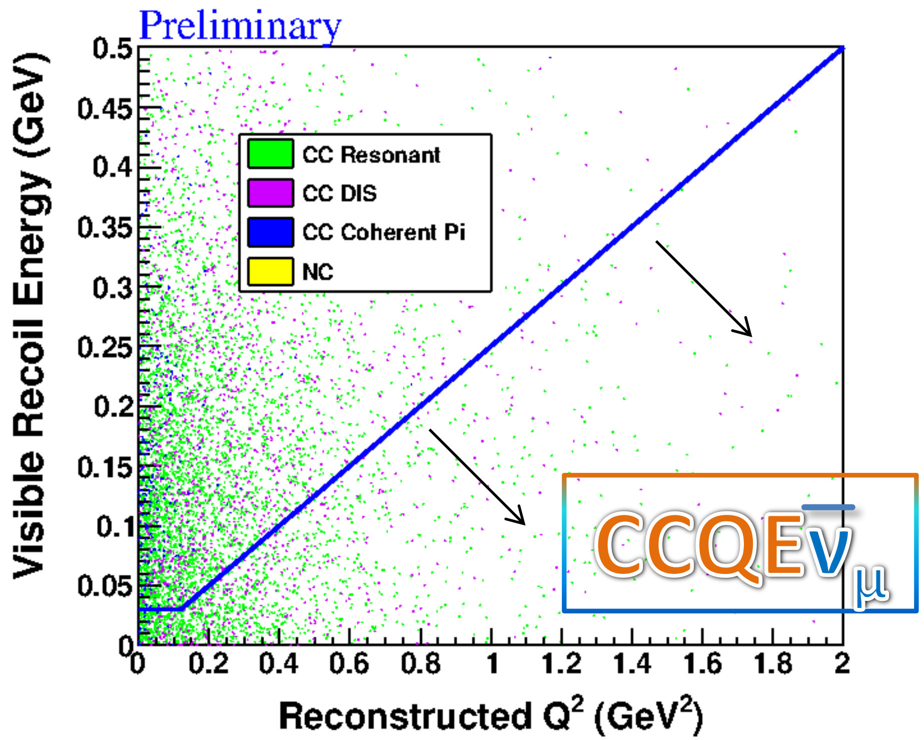
Illustration: Fermilab/Diana Canzone

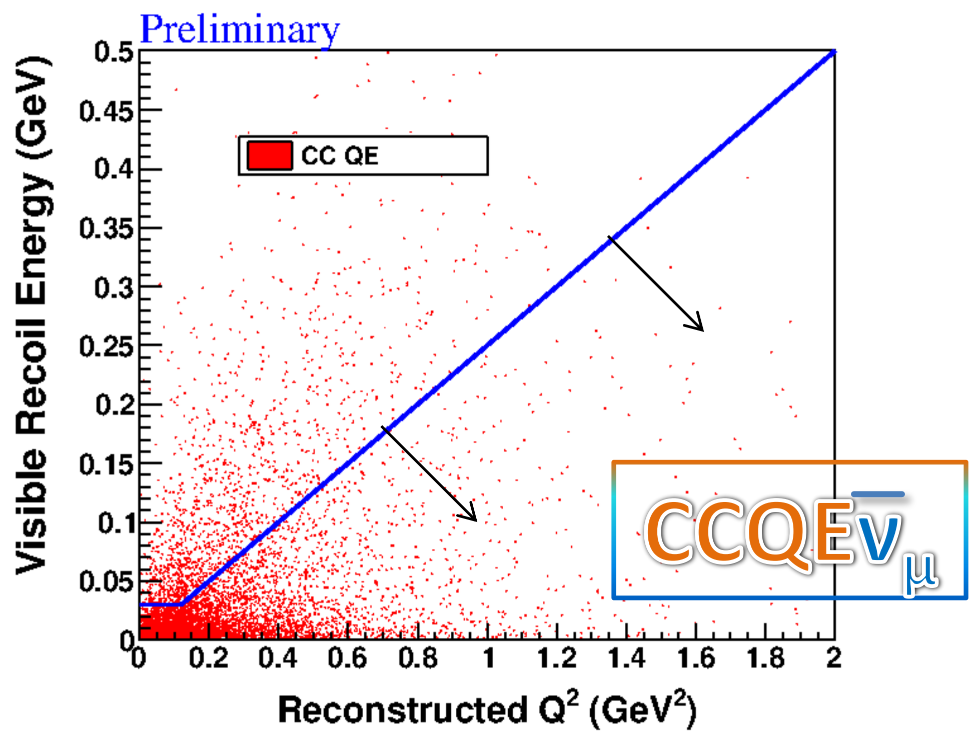
Recoil Energy Cut

Expect higher Q^2_{QE} events to have more recoil energy.

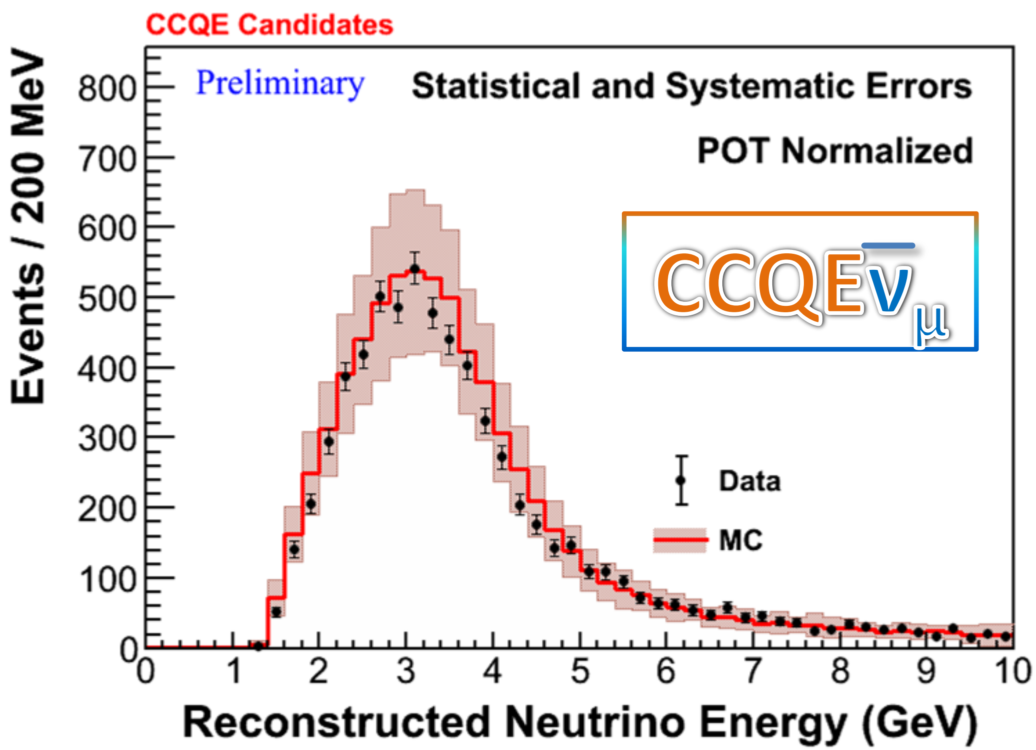
Recoil cut scales with Q^2_{QE}.
Total selection purity is ~80%.

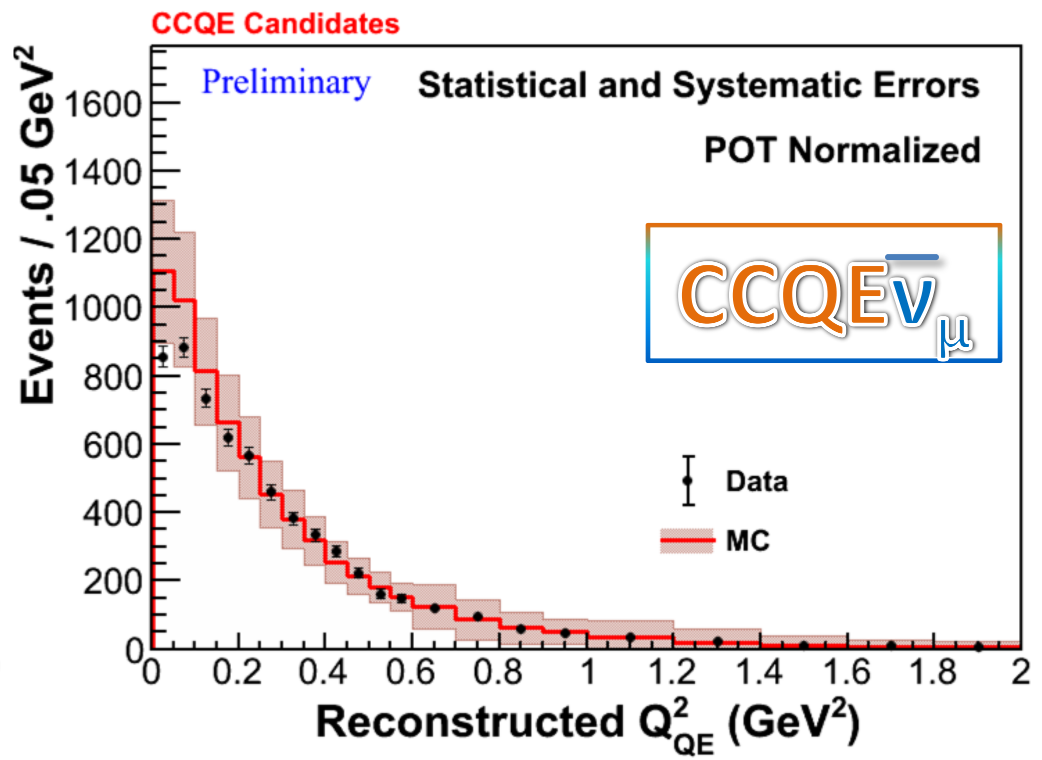






Kinematic Distribution



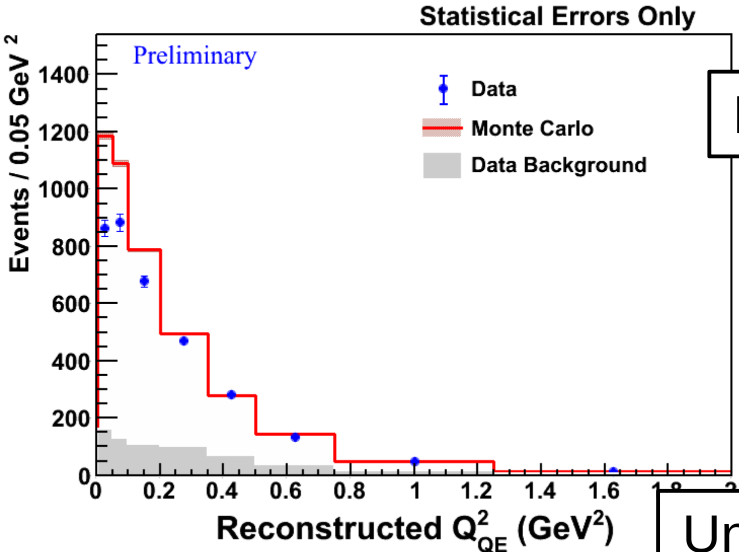


$$E_\nu = \frac{m_\mu^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

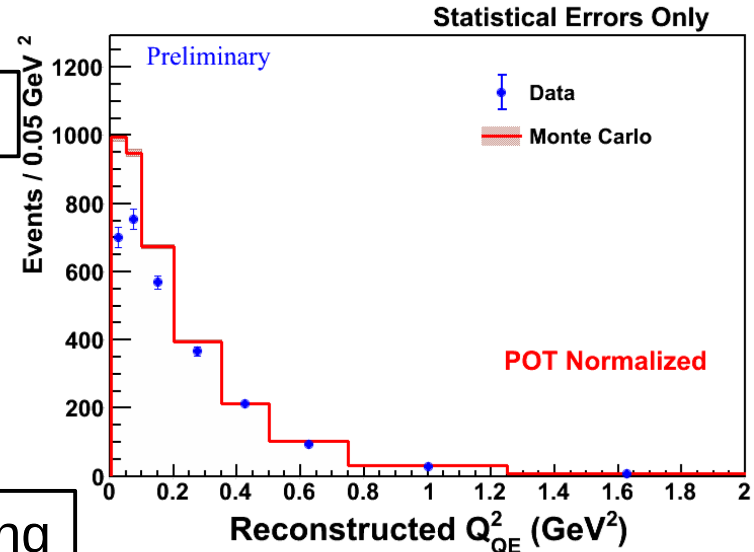
$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

Getting to $d\sigma/dQ^2_{QE}$

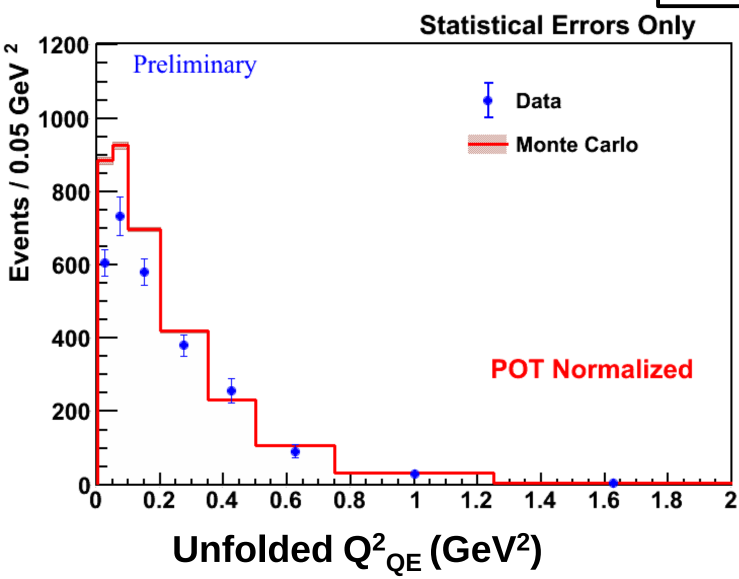
CCQE $\bar{\nu}_\mu$



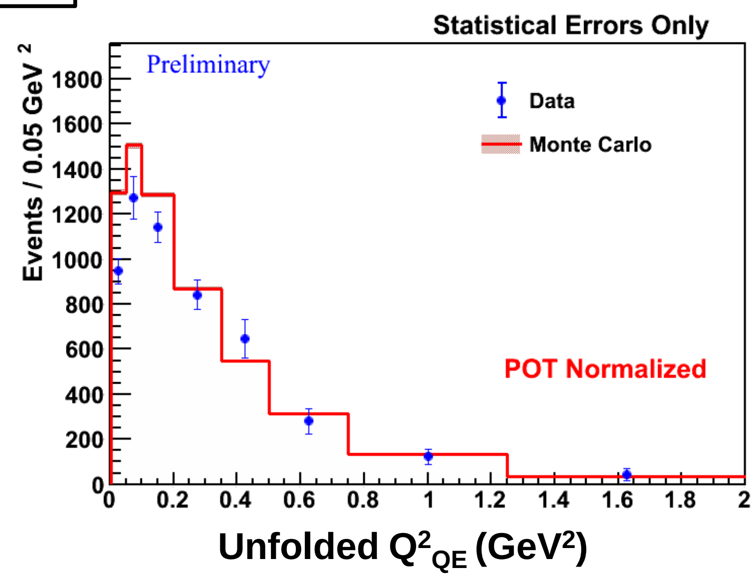
Background subtraction



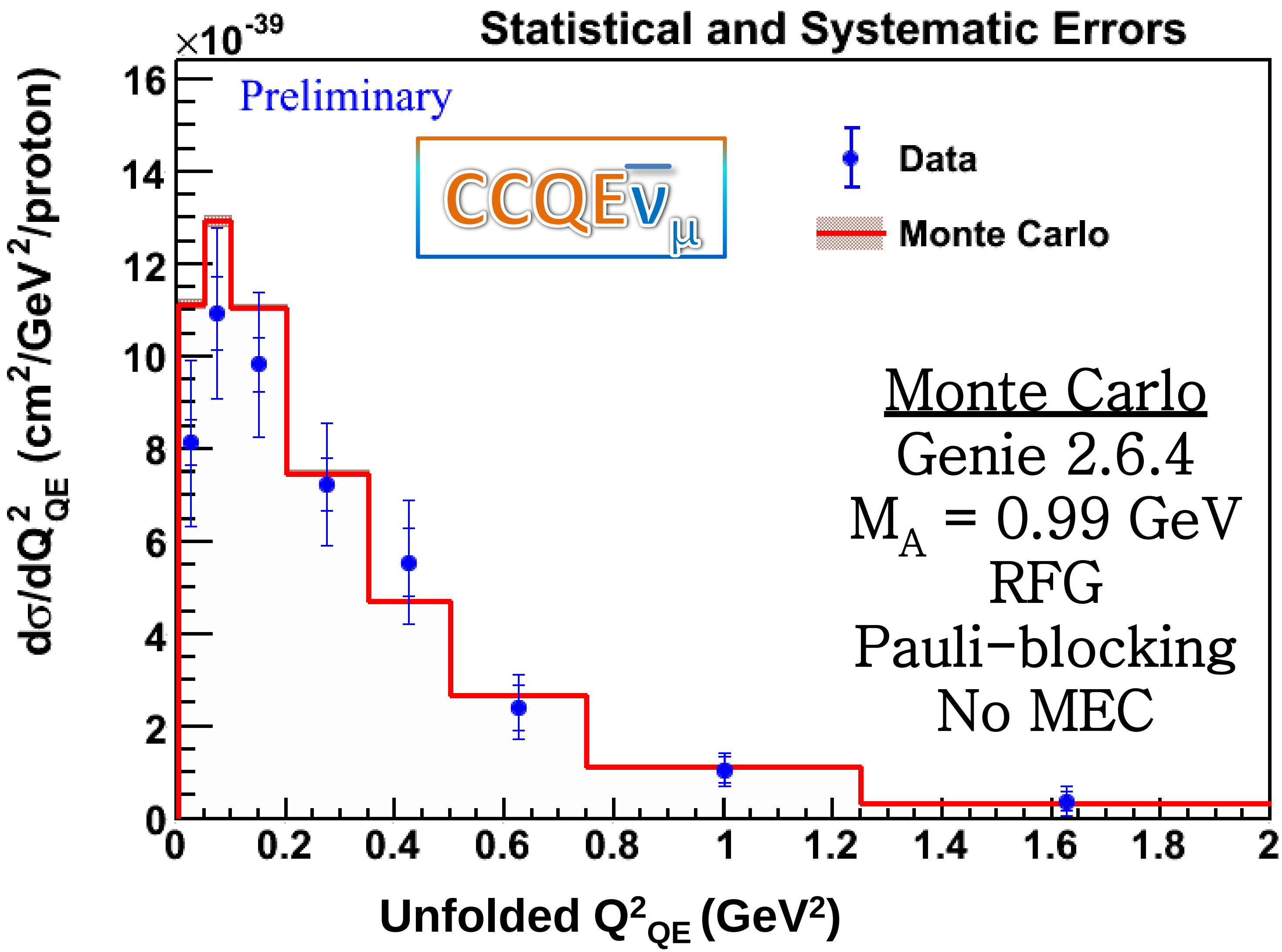
Unfolding detector smearing



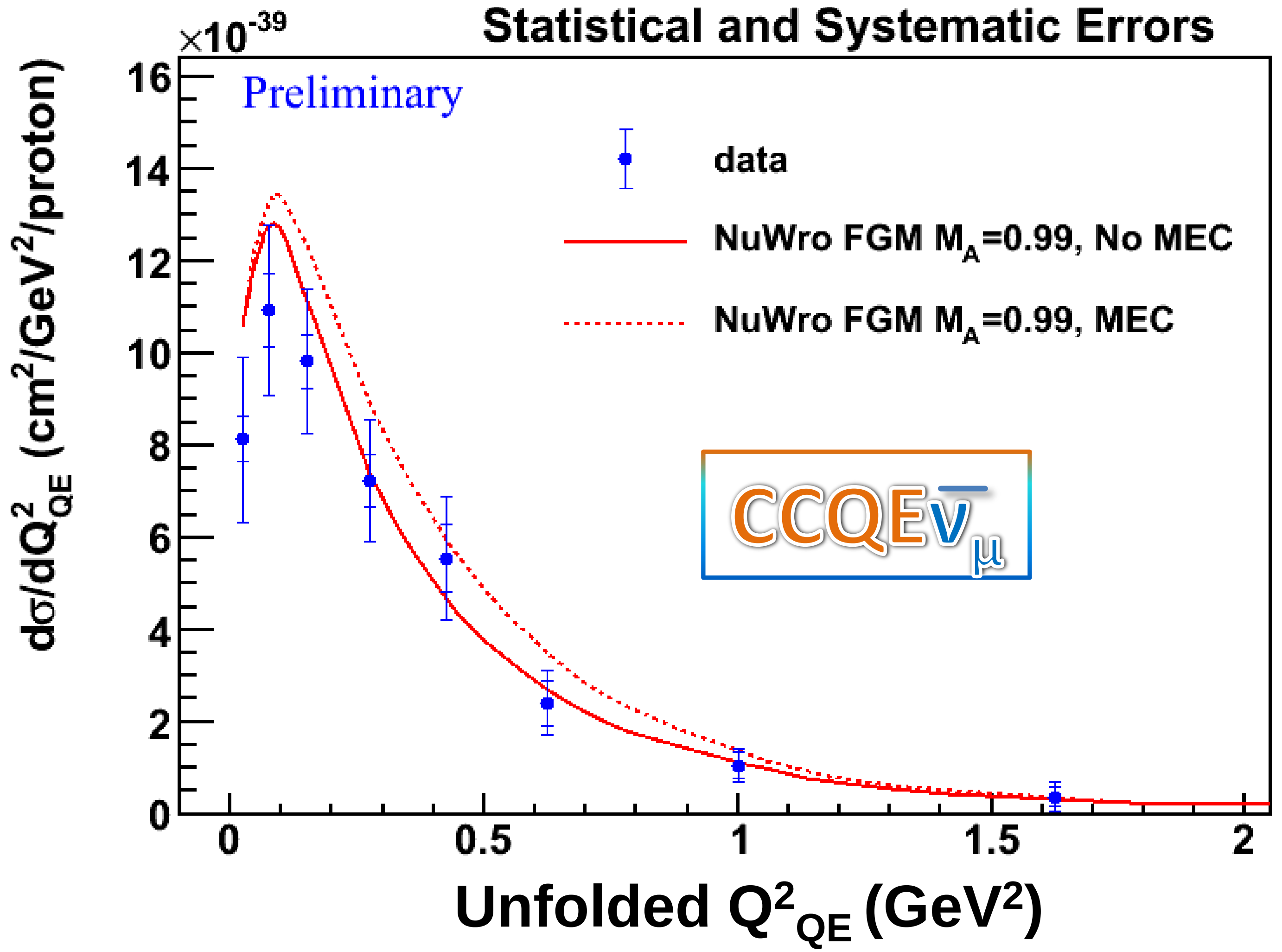
Efficiency correction



$d\sigma/dQ^2_{QE}$



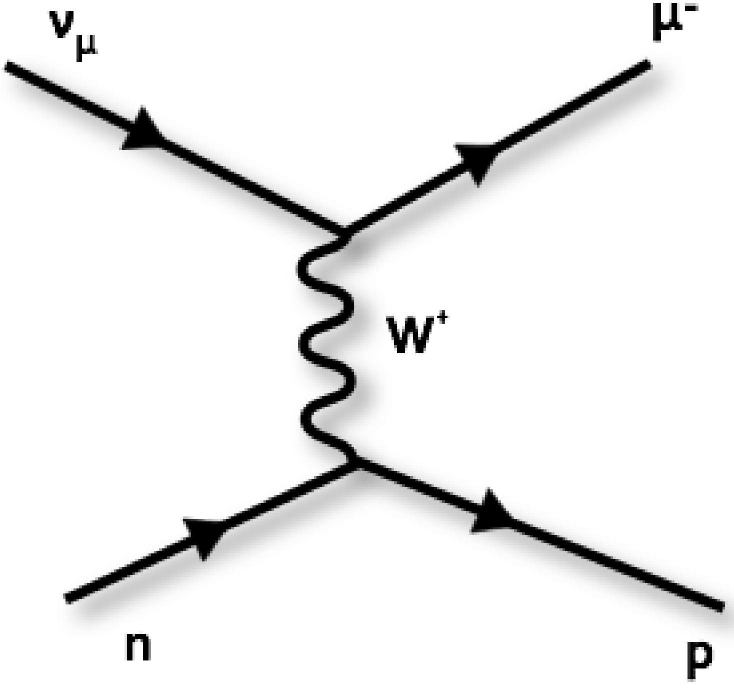
$d\sigma/dQ^2_{QE}$

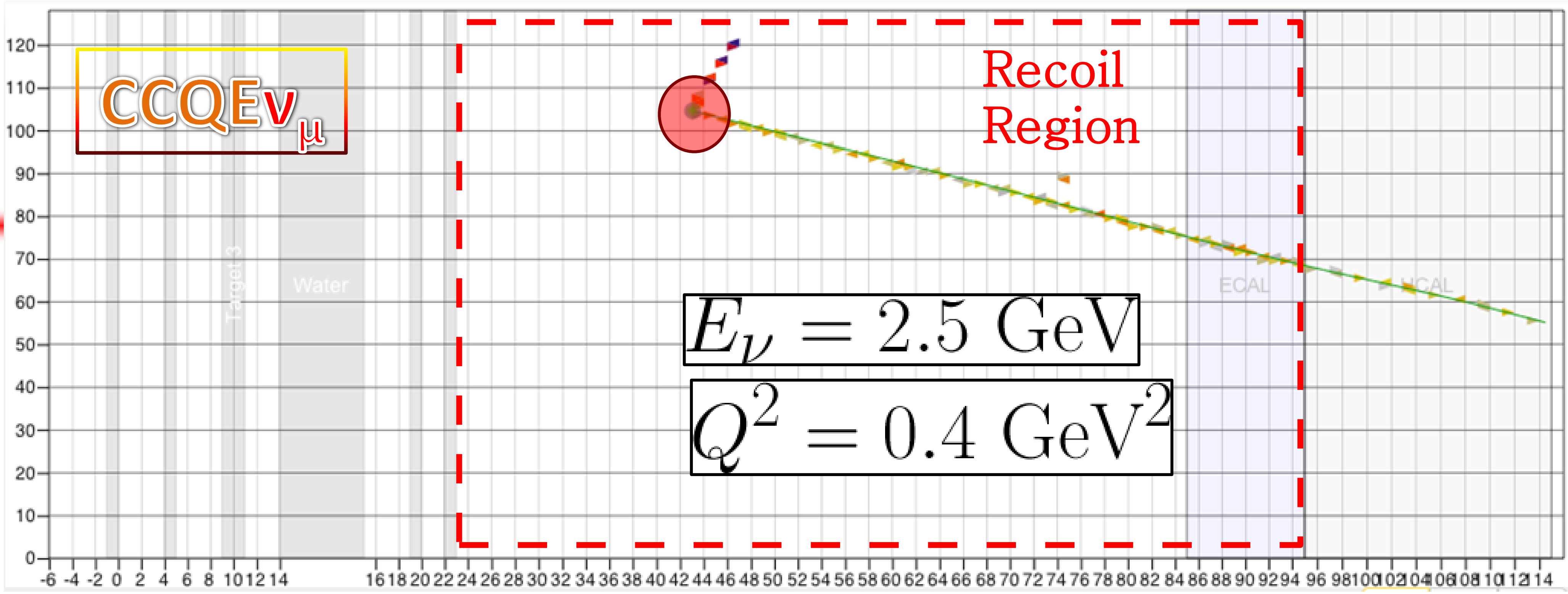


NuWro: Golan, Juszczak, Sobczyk. arXiv: 1202.4197 [nucl-th]

Neutrino Charged Current Quasi Elastic Scattering

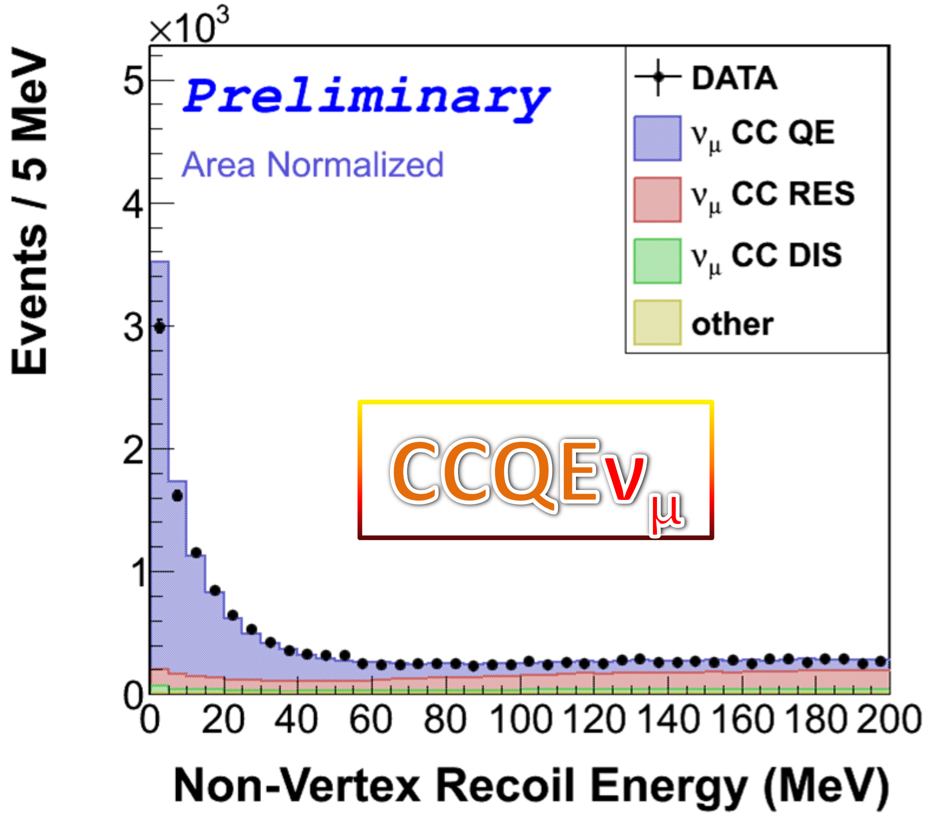
$CCQE\nu_\mu$

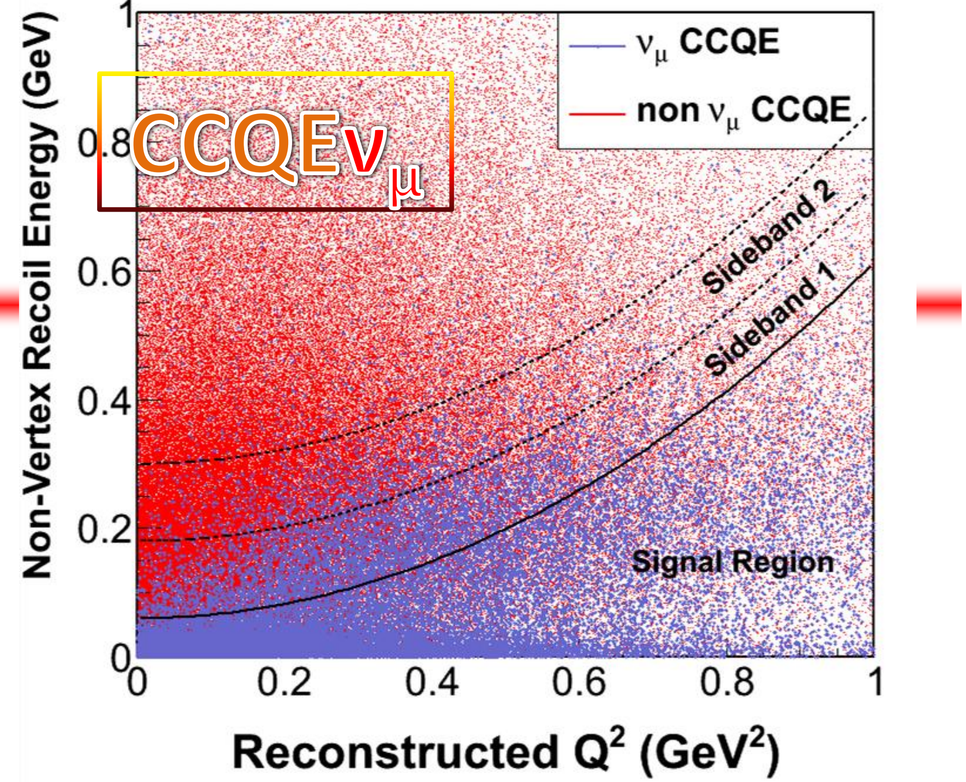




- Require a μ^- matched into MINOS.
- Require 0 or 1 other tracks (proton candidate).
- Require 0 or 1 clumps of energy deposition (proton candidate).

- Sum recoil energy (excluding 10cm around vertex).

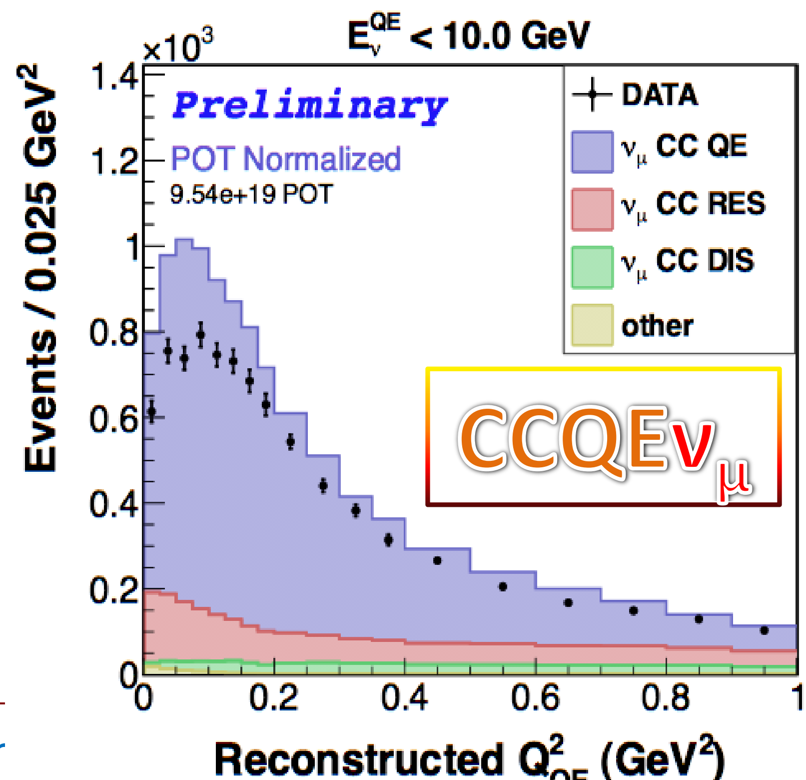


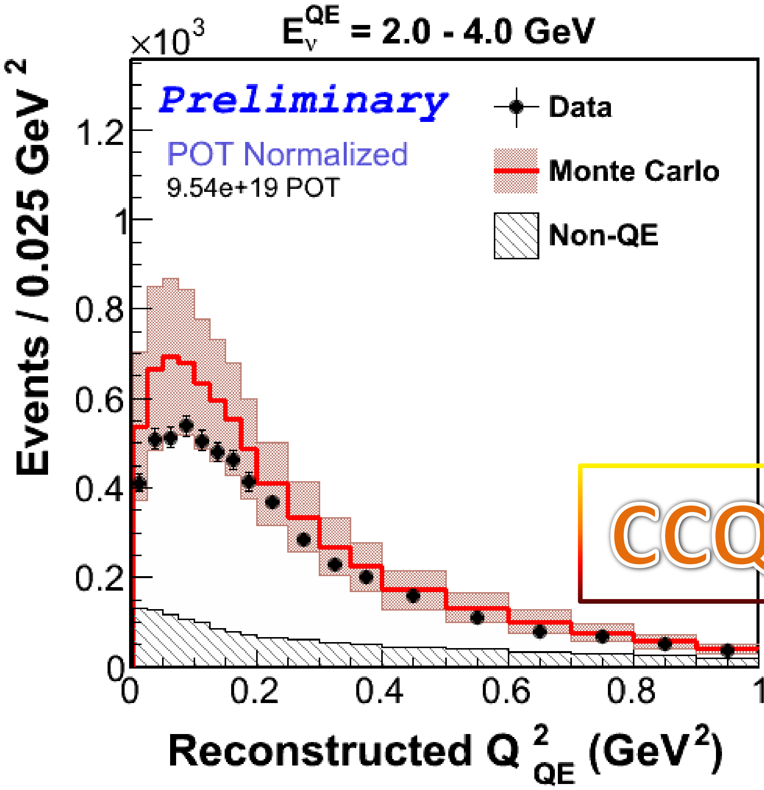


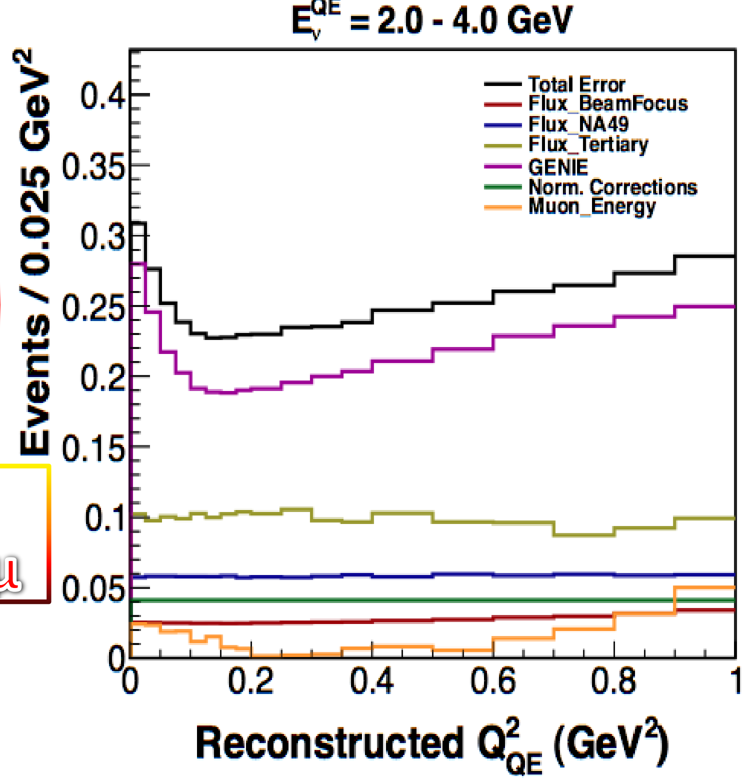
$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

Sideband regions will be used to understand background in data.

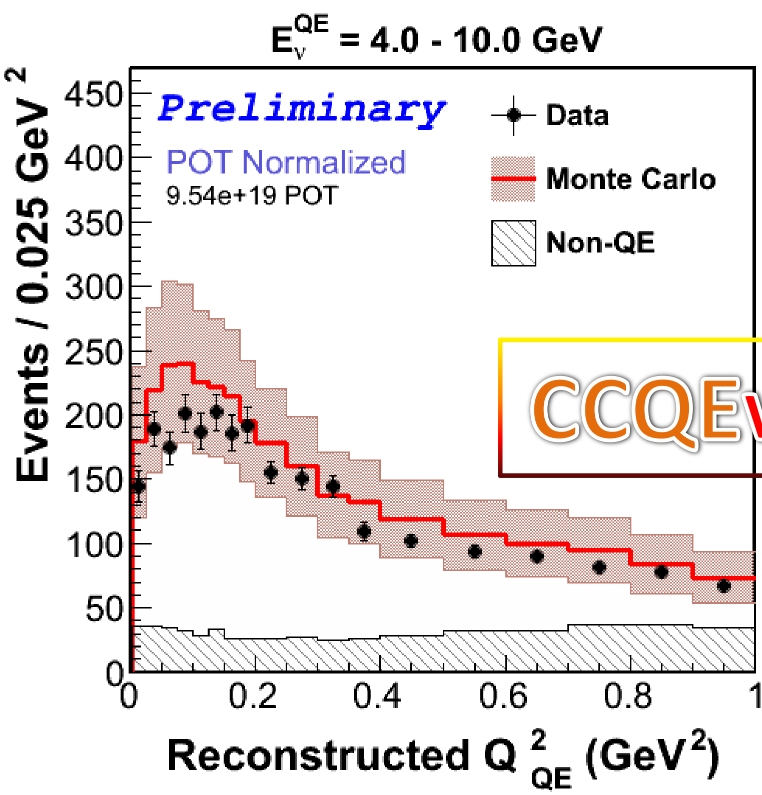
Proton reconstruction not yet used in Q^2, E_ν calculations.

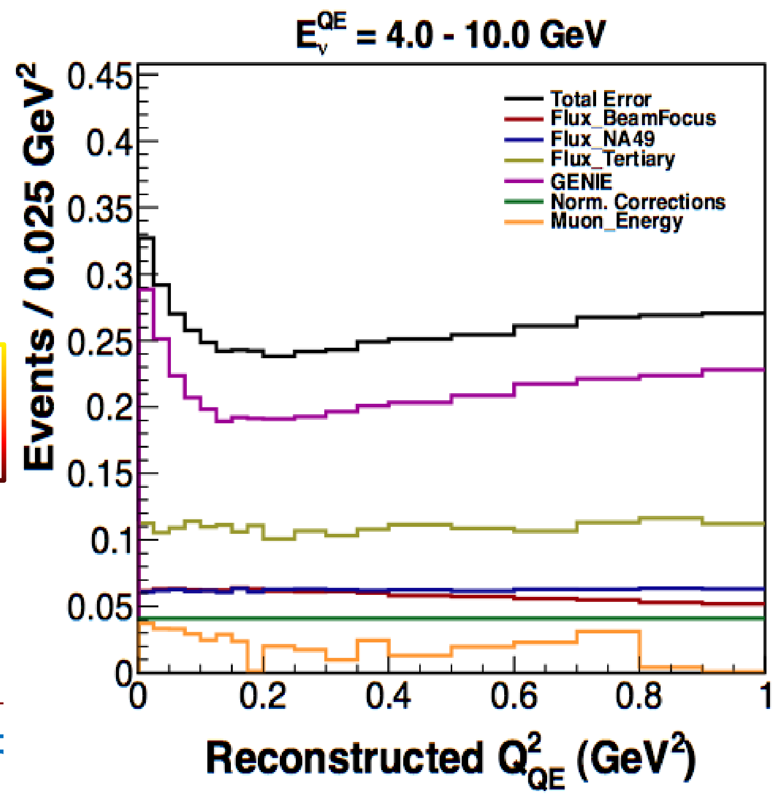






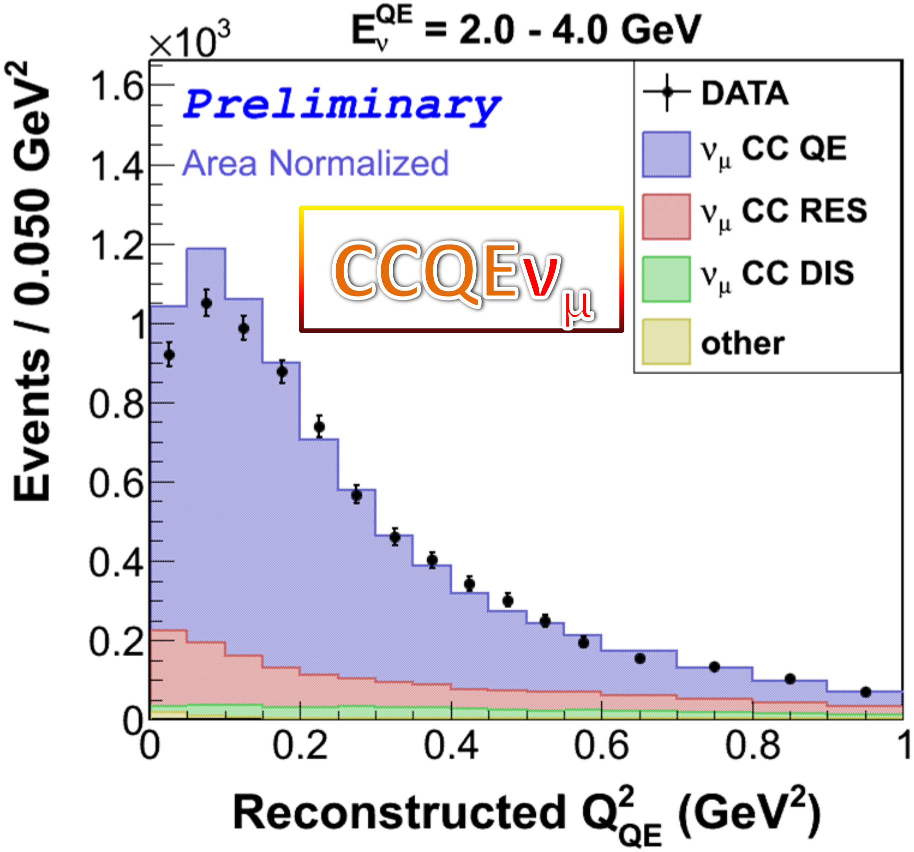
CCQEν_μ

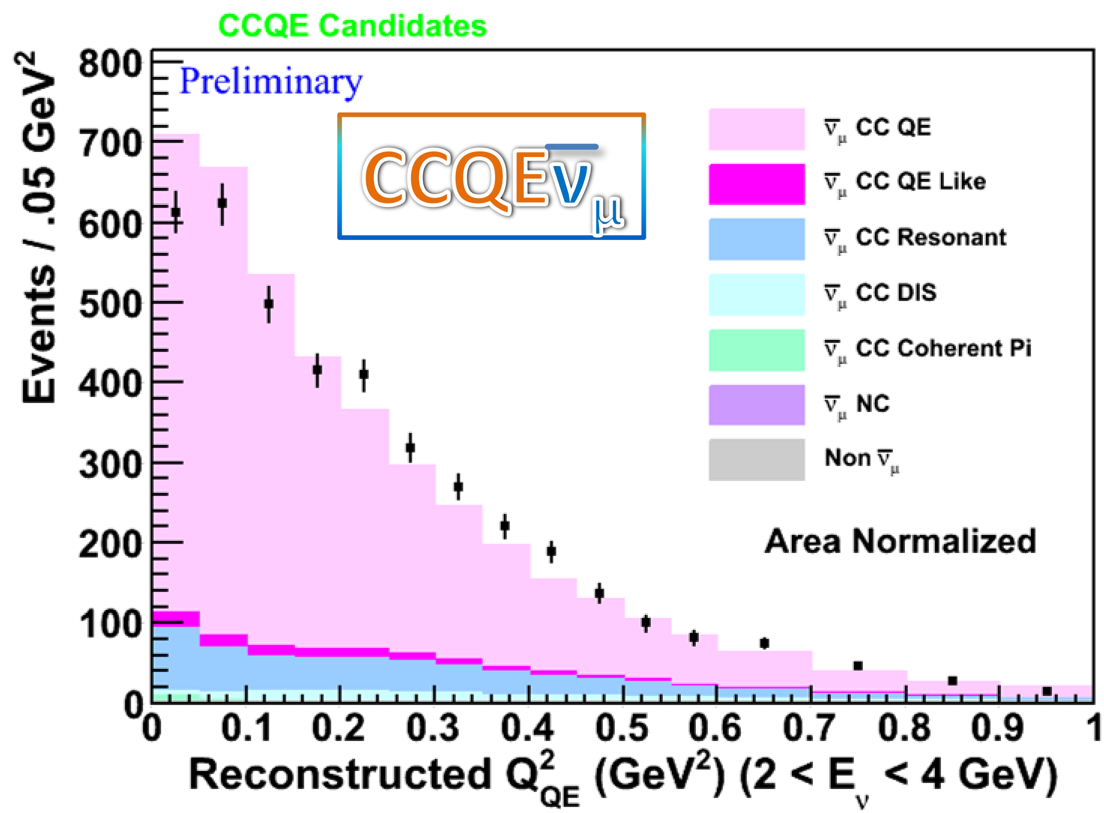




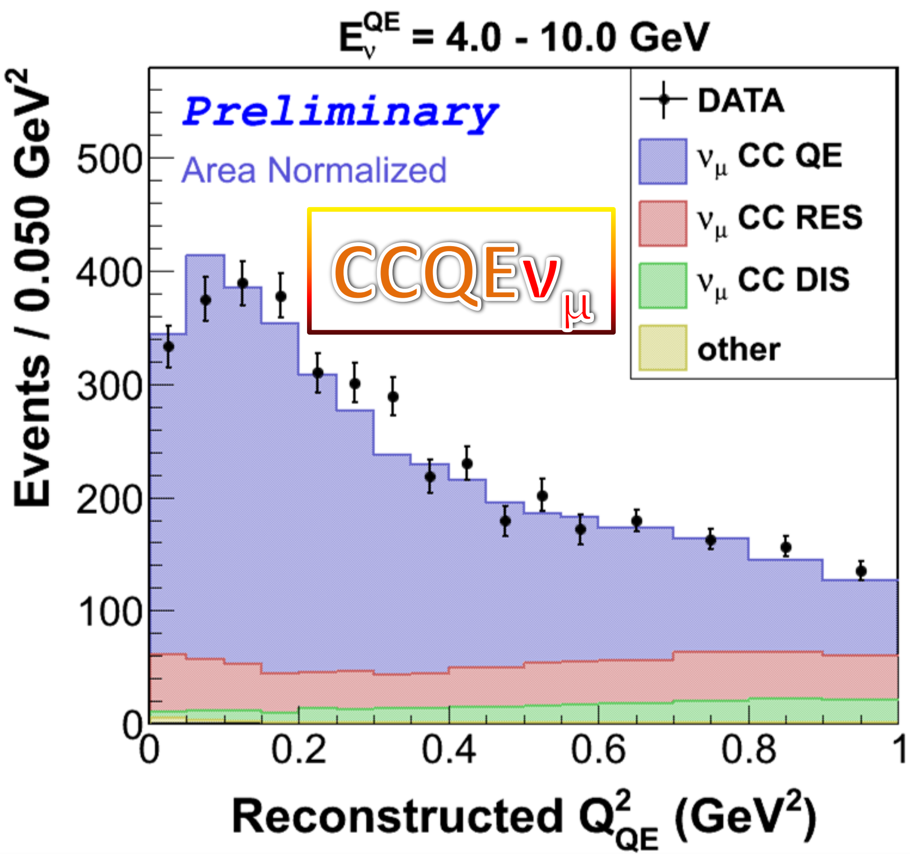
CCQEν_μ

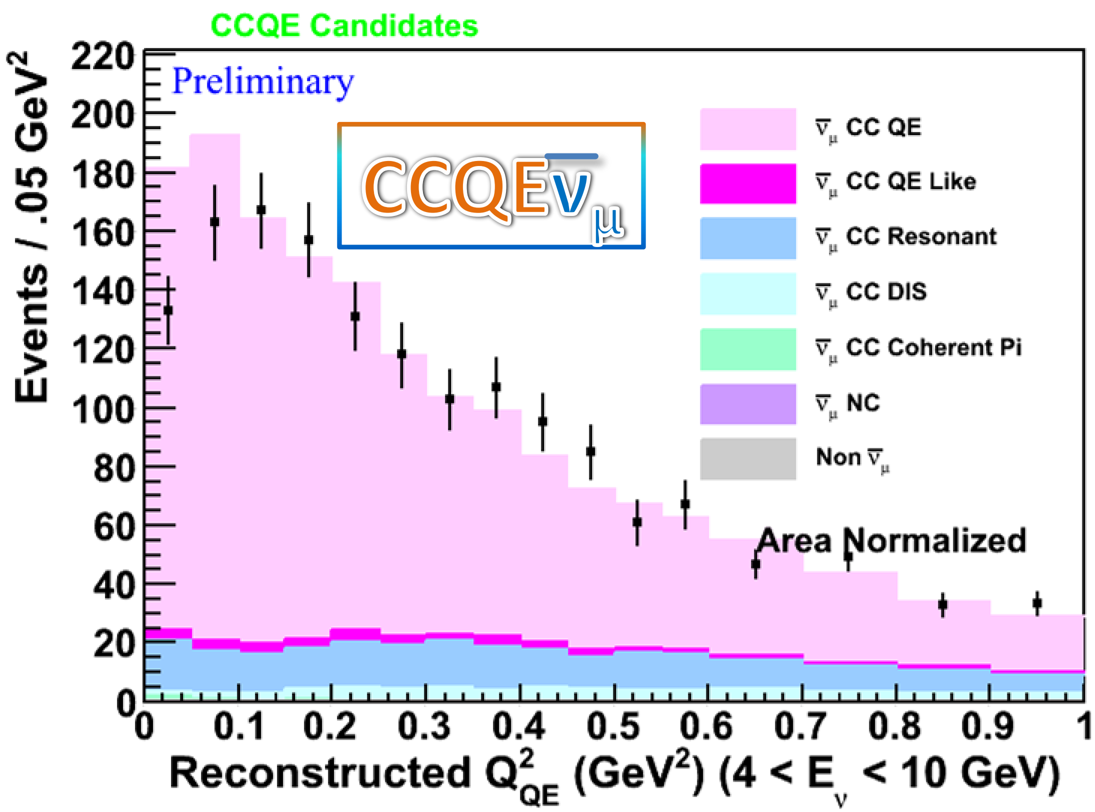
Neutrino and Antineutrino CCQE 2-4 GeV





Neutrino and Antineutrino CCQE 4-10 GeV



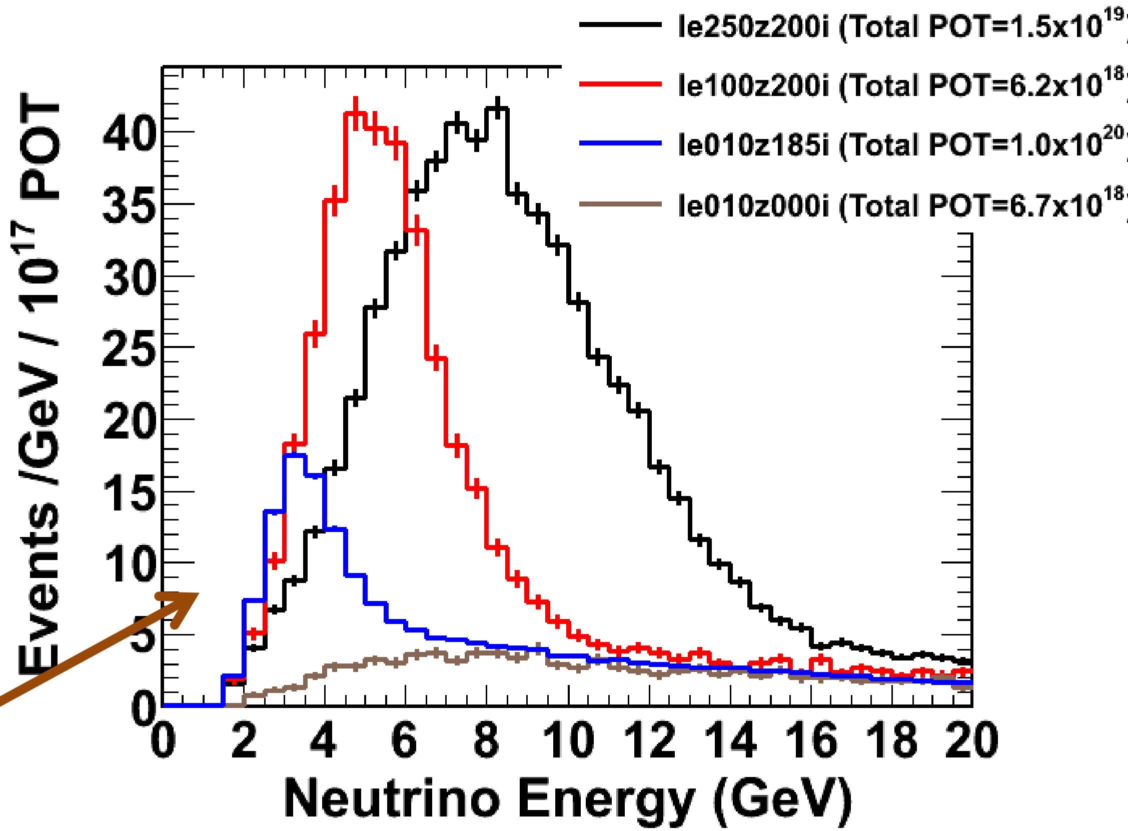


Conclusions

- MINERvA is performing well and is producing results. $CC\nu_\mu$
  - Systematic errors have been explored. Improvements possible.
- Nuclear target ratios analysis method works well. $CC\nu_\mu$
  - Needs to use full statistics in hand. Wait for more data.
- Our first antineutrino $d\sigma/dQ^2_{QE}$ is public. $CCQE\bar{\nu}_\mu$
  - Neutrino $d\sigma/dQ^2_{QE}$ is coming soon.
  - …and more exclusive analyses are in progress! $CCQE\nu_\mu$

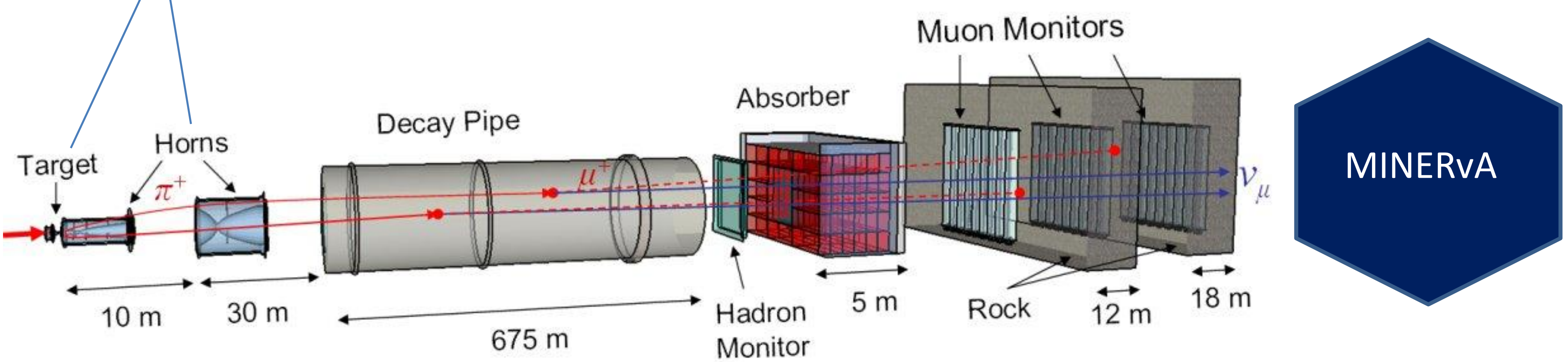
Backup

Understanding Our Flux



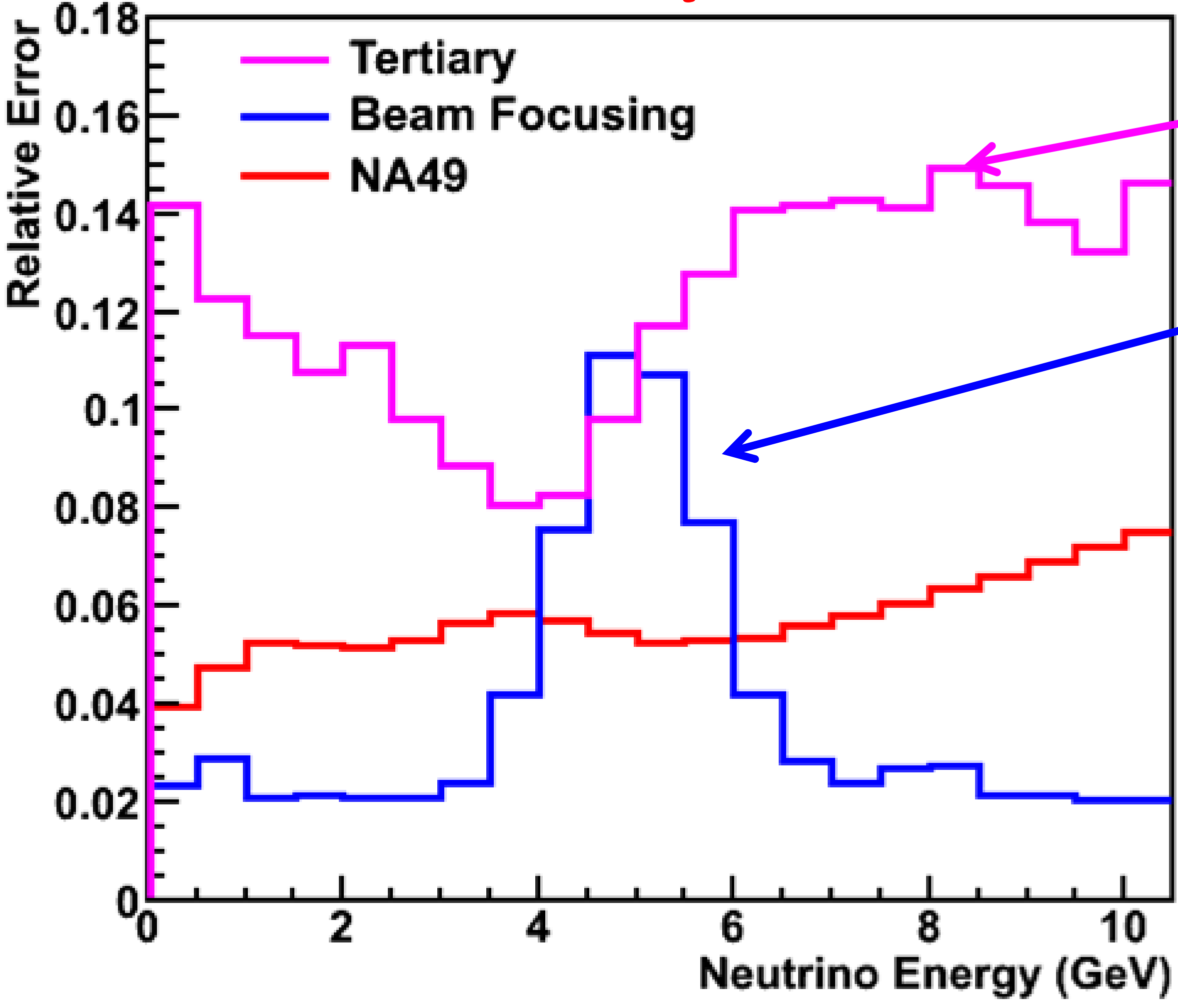
Vary the target position and the horn current to change the flux spectrum.

Monitor spread of $\mu^{\pm}$ from $\pi^{\pm}$ decay



Current Flux Uncertainties

Preliminary!

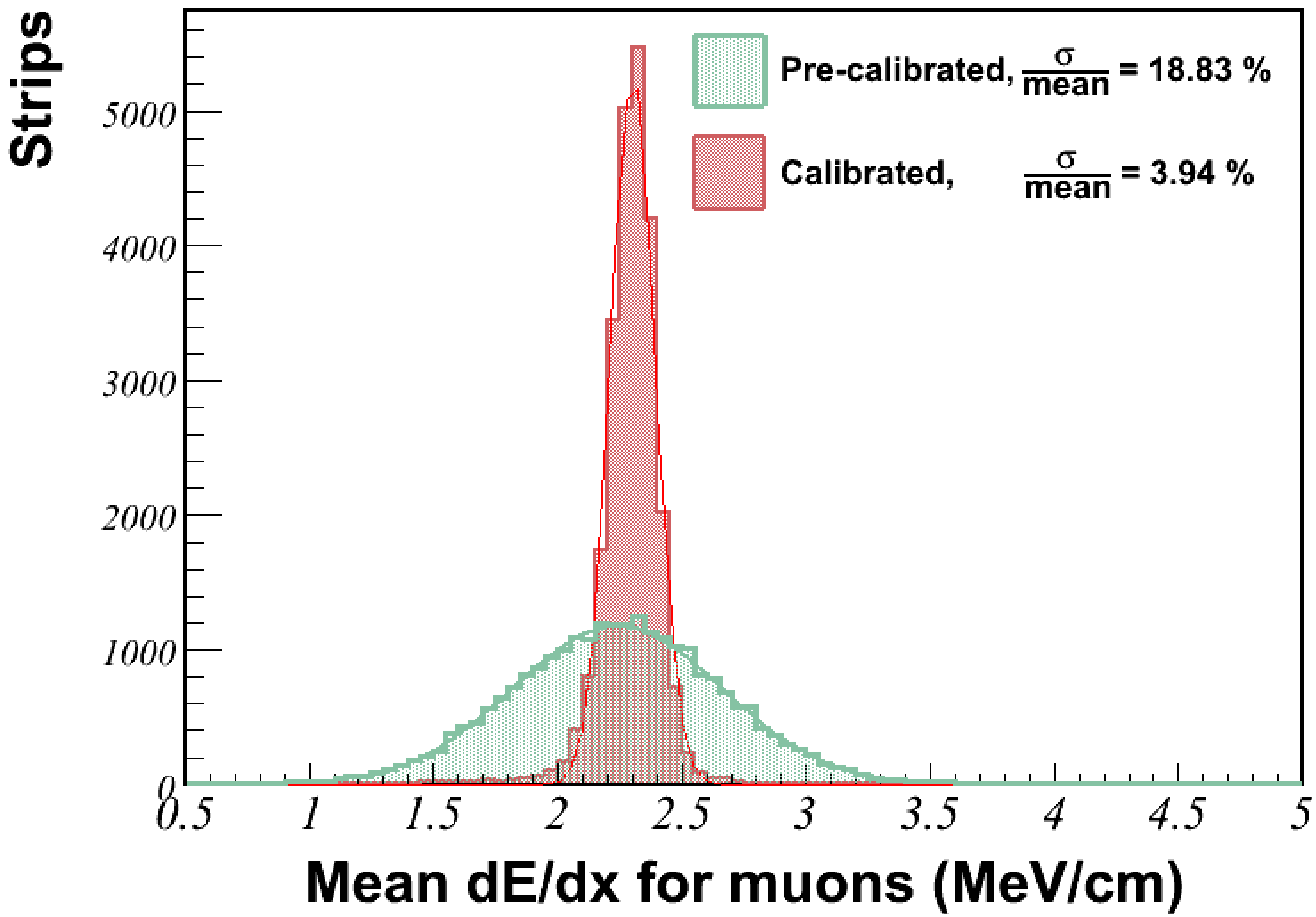


"Tertiary" = non-NA49

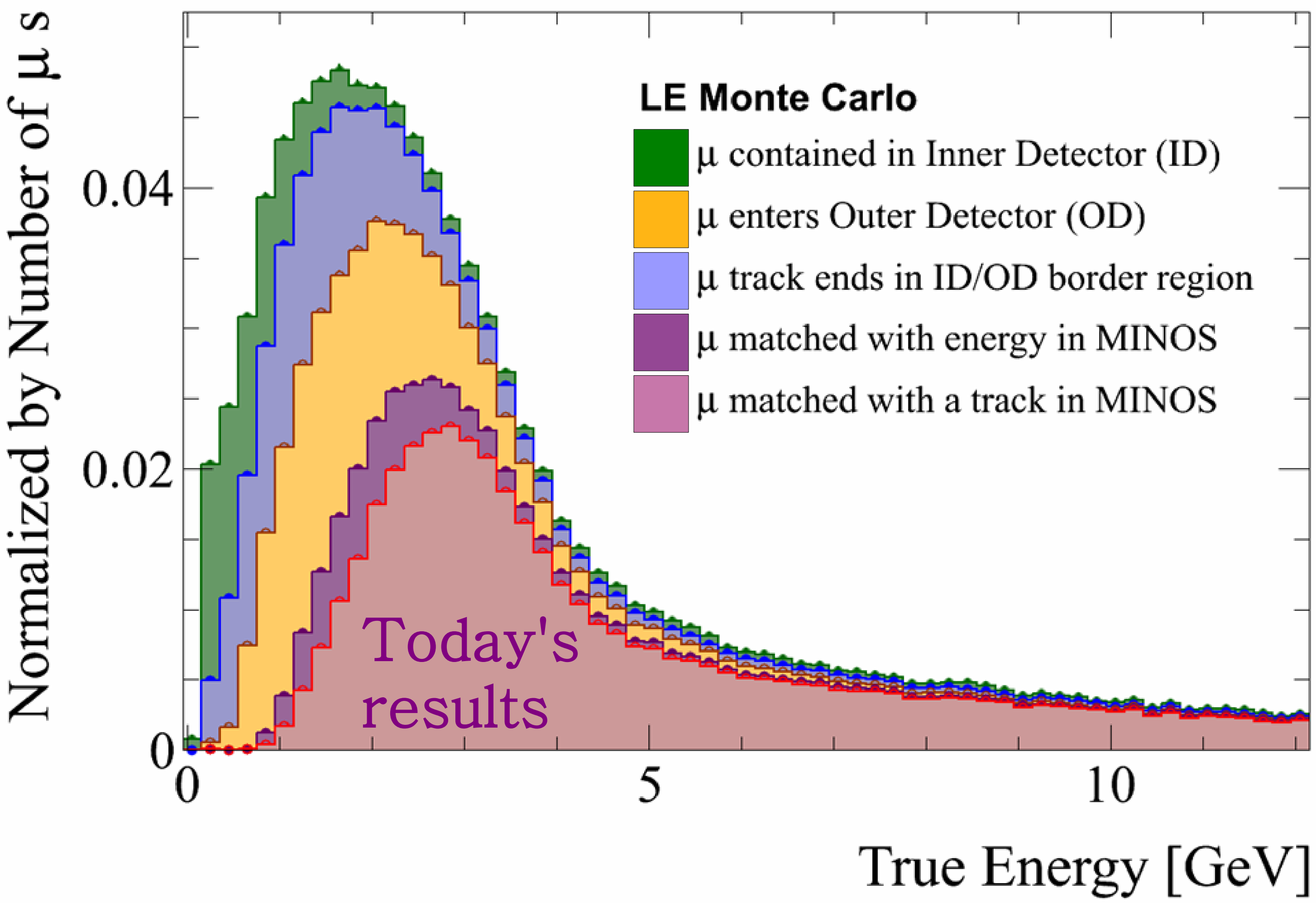
Z. Pavlovic, PhD Thesis, Texas (2008)

Can be improved with work!

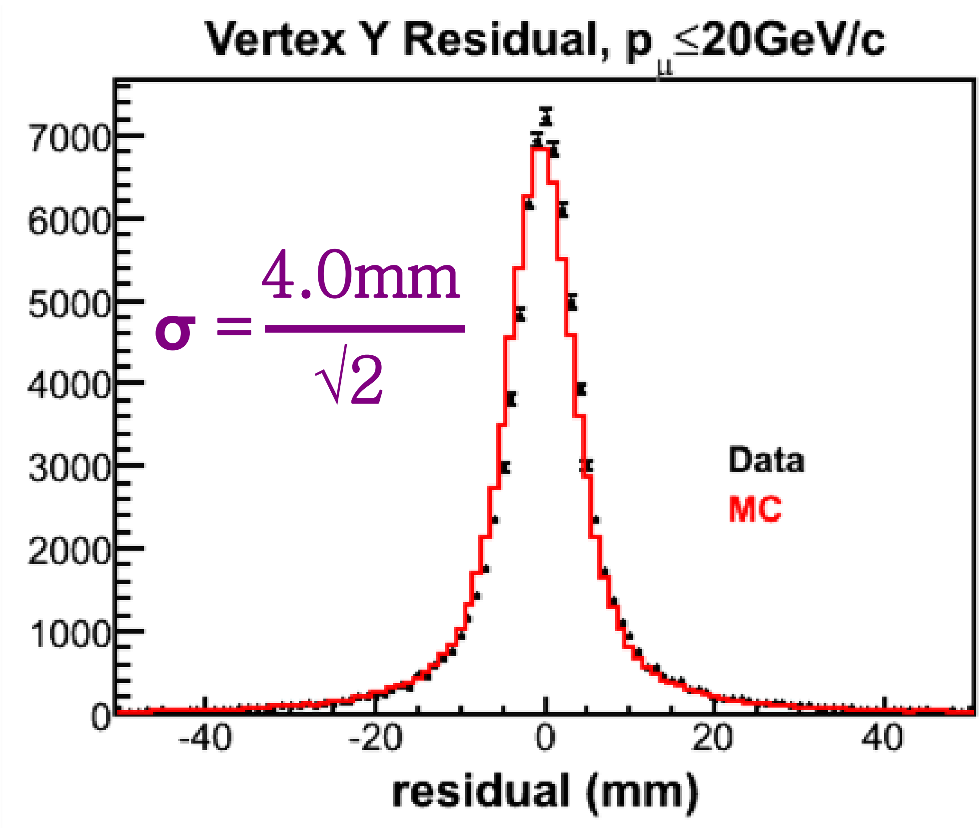
Alignment and Strip Response

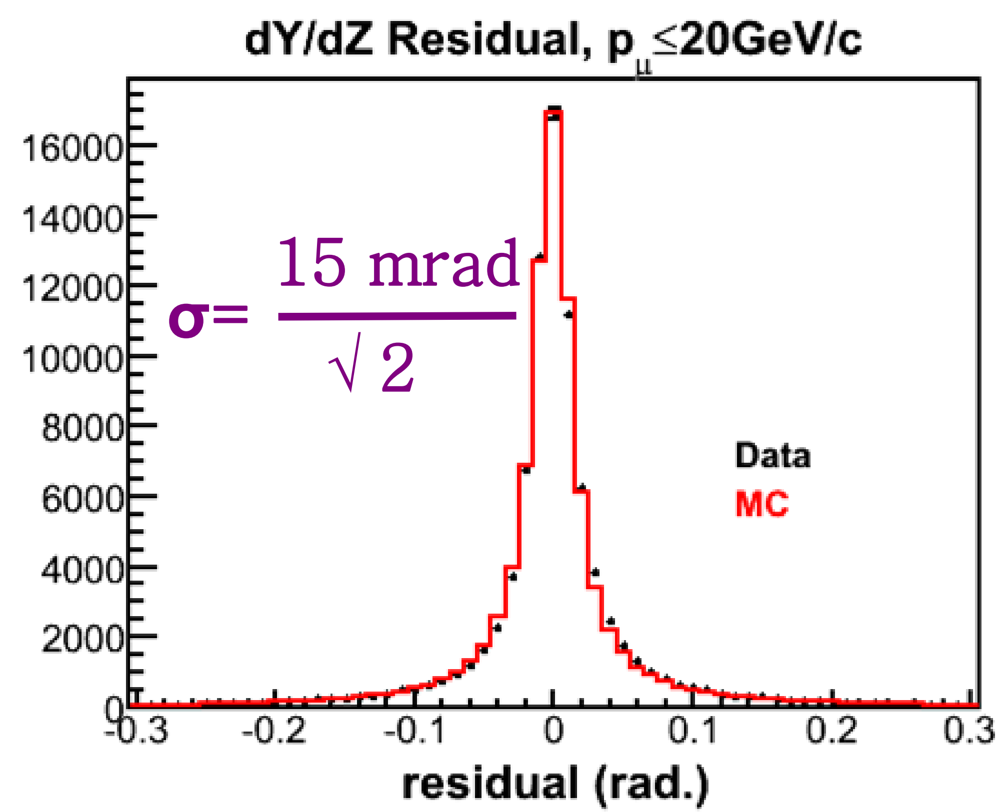


Where do the muons go?

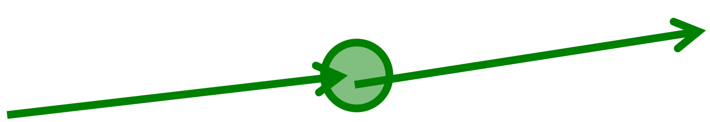


Tracking Resolutions

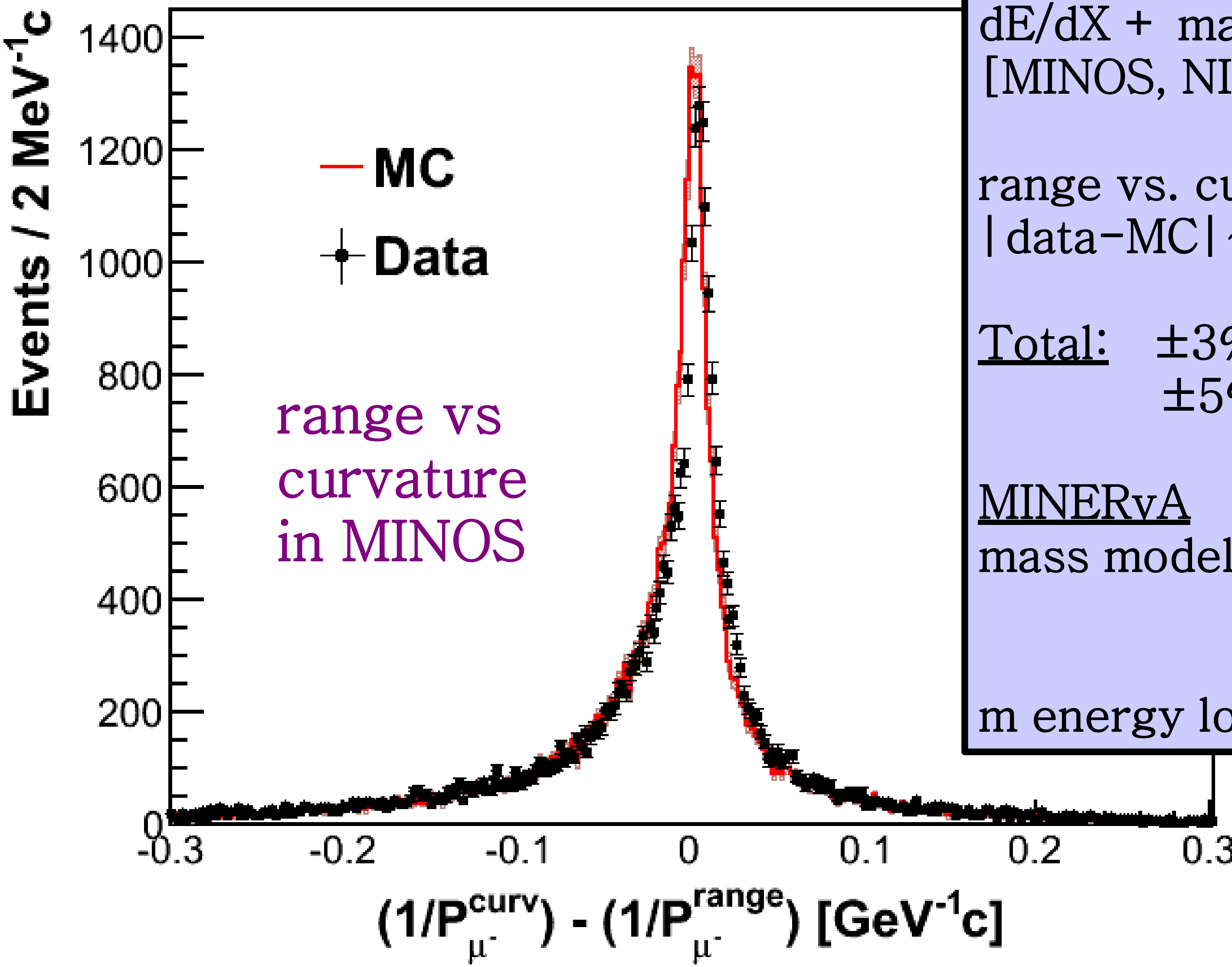




Split-track study of rock m
in tracker region



Muon Energy Uncertainty



<u>MINOS</u>
dE/dX + mass model = 2%
[MINOS, NIM A 596, 190 (2008)]

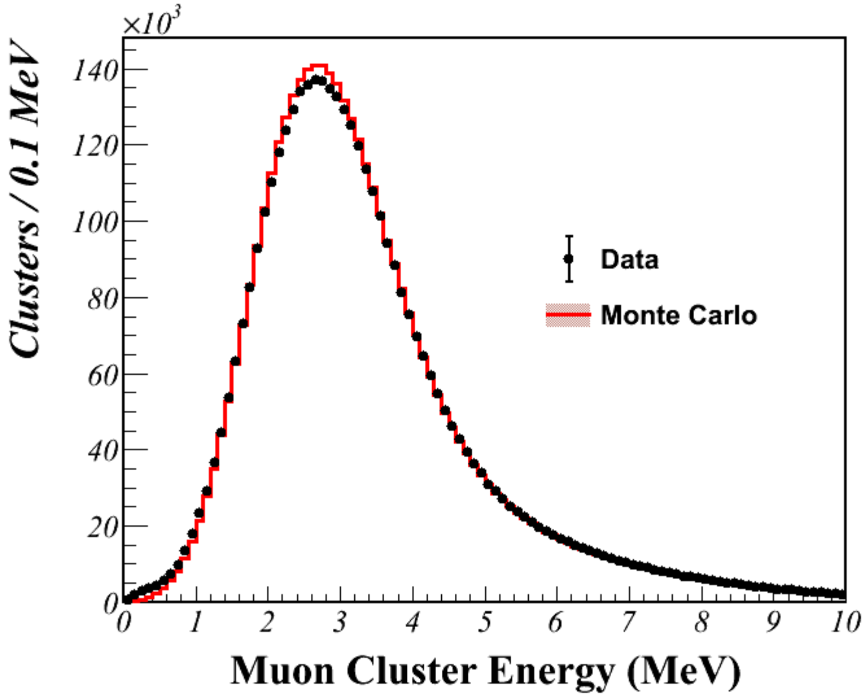
range vs. curvature
|data−MC|~25 MeV

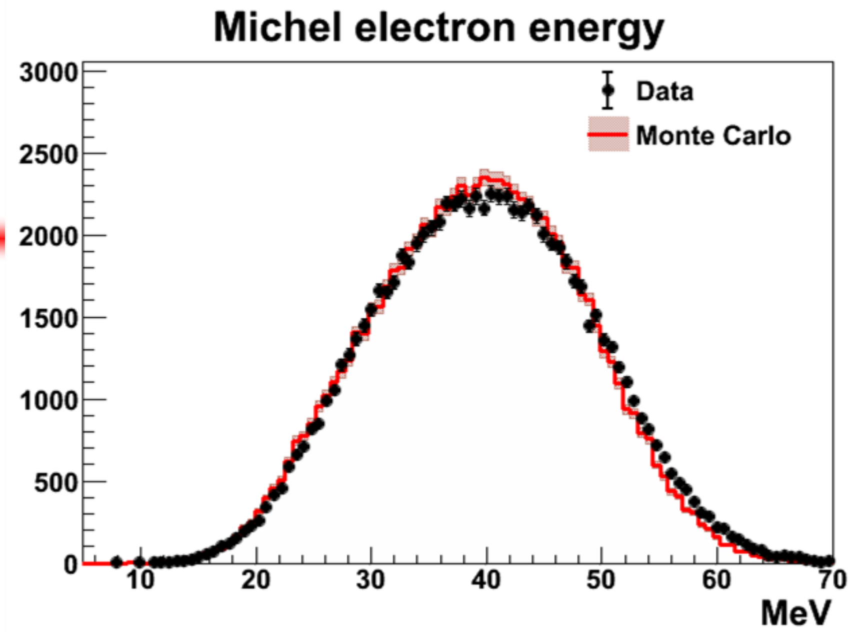
<u>Total:</u> ±3% p> 1.5 GeV
±5% P<1.5 GeV

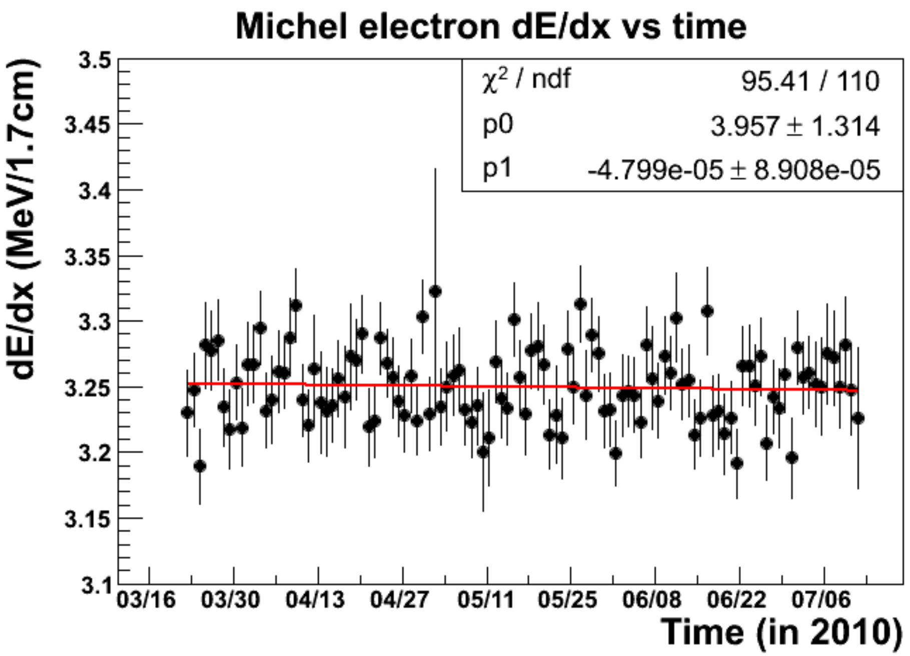
<u>MINERvA</u>
mass model = 11 MeV tracker
= 17 MeV Nucl.Tgts.

m energy loss = 30 MeV

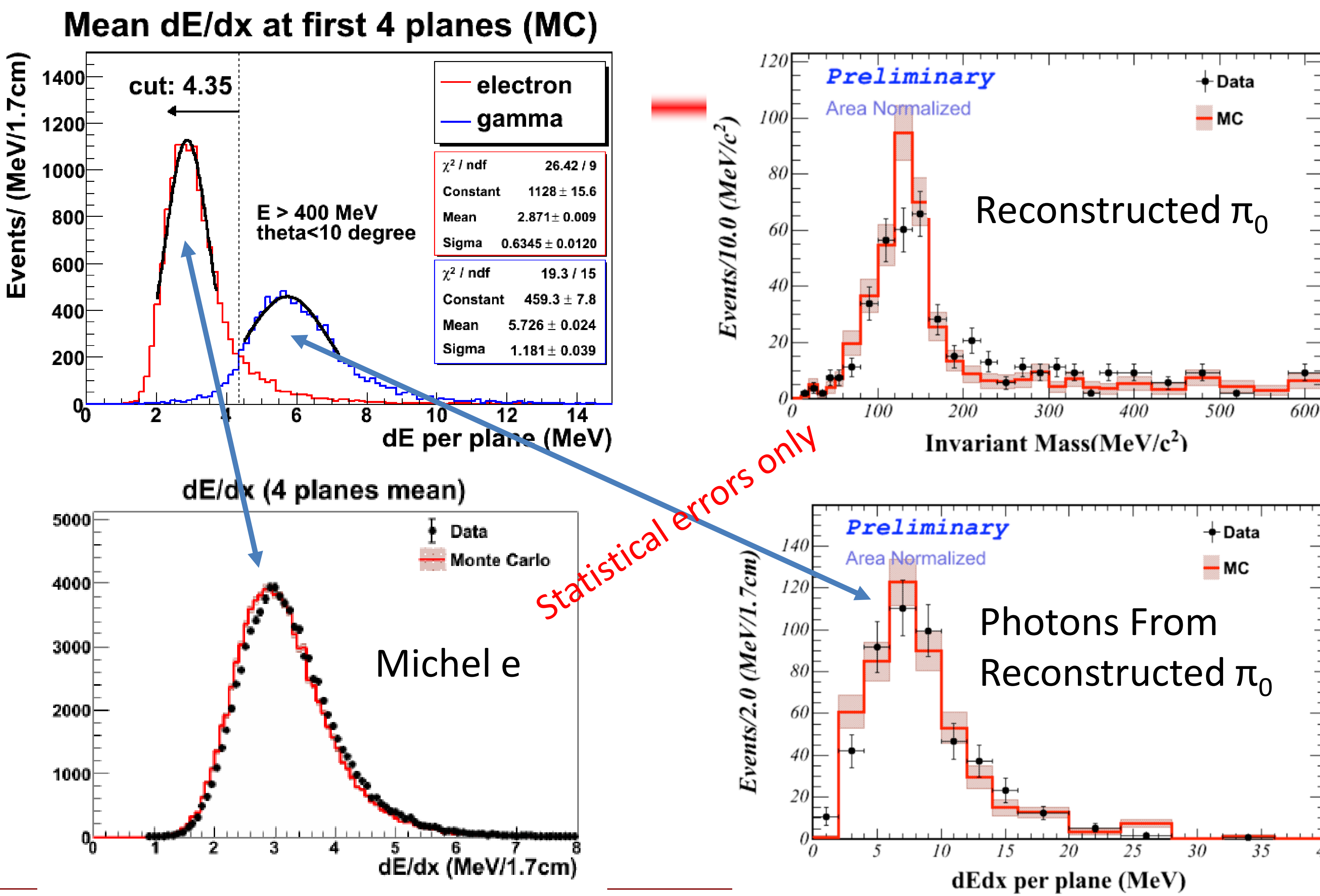
Energy Scale and Stability



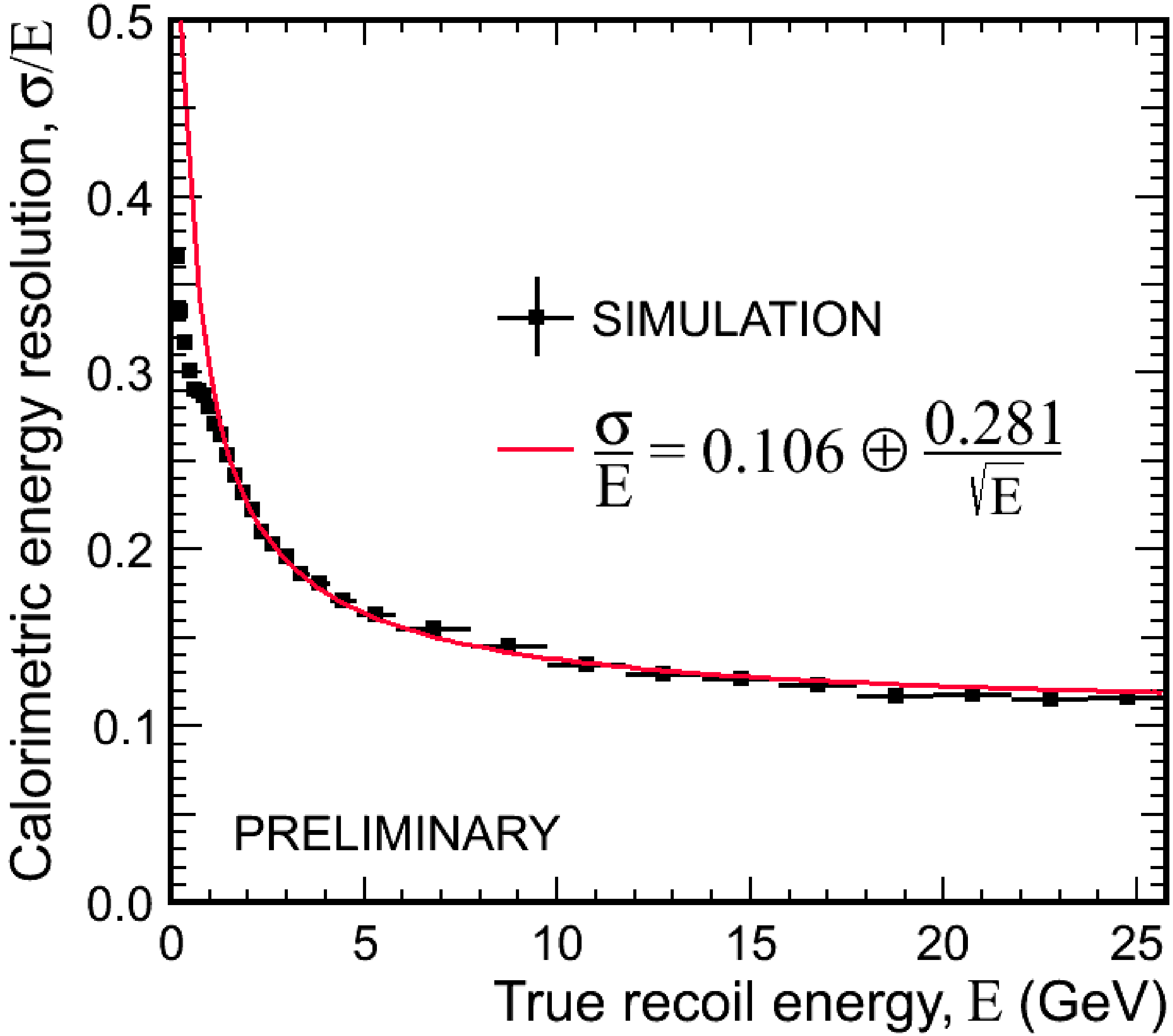




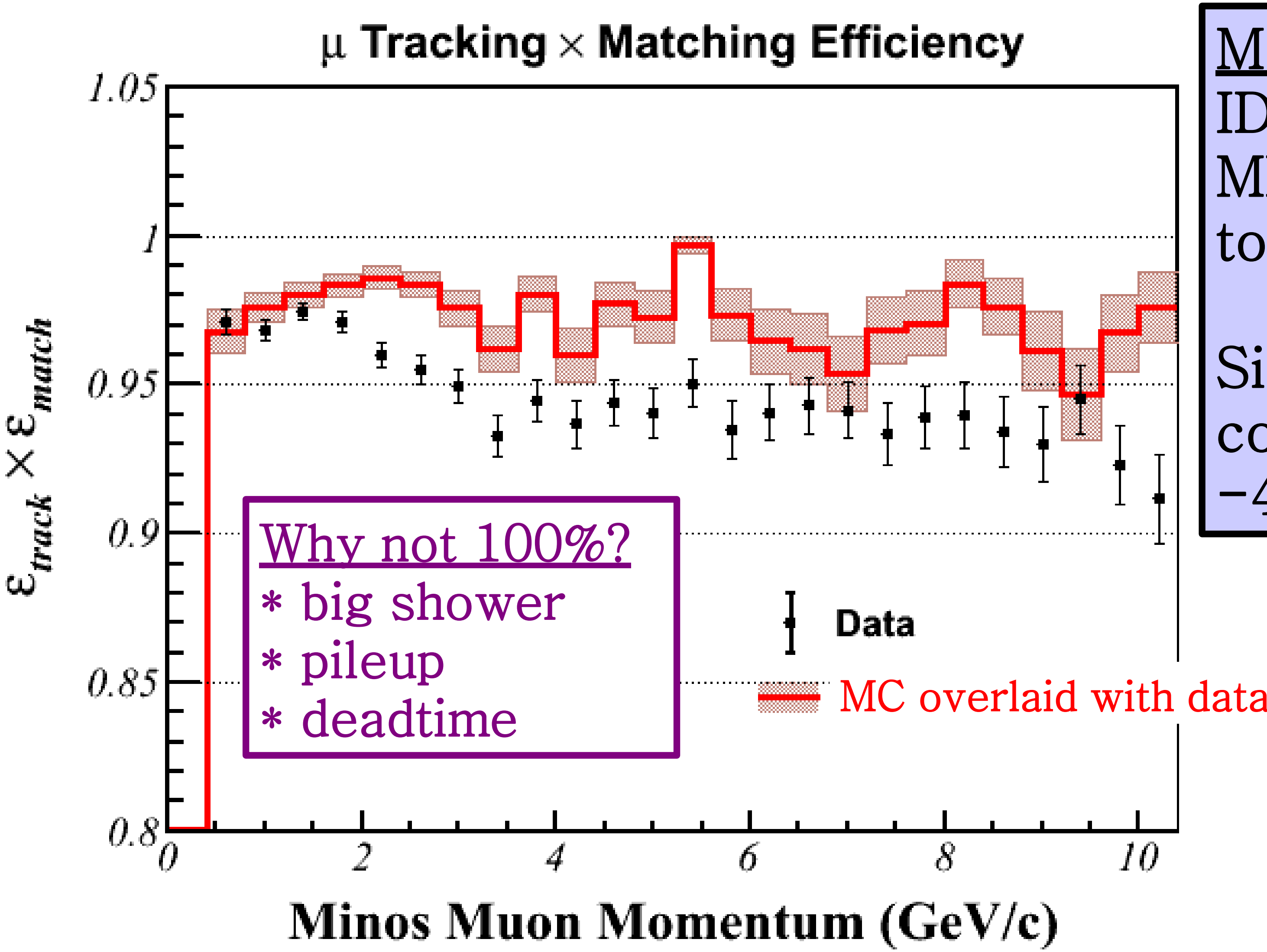
Michels, π_0 and e/γ Separation



shower energy resolution



Tracking x Matching Efficiency

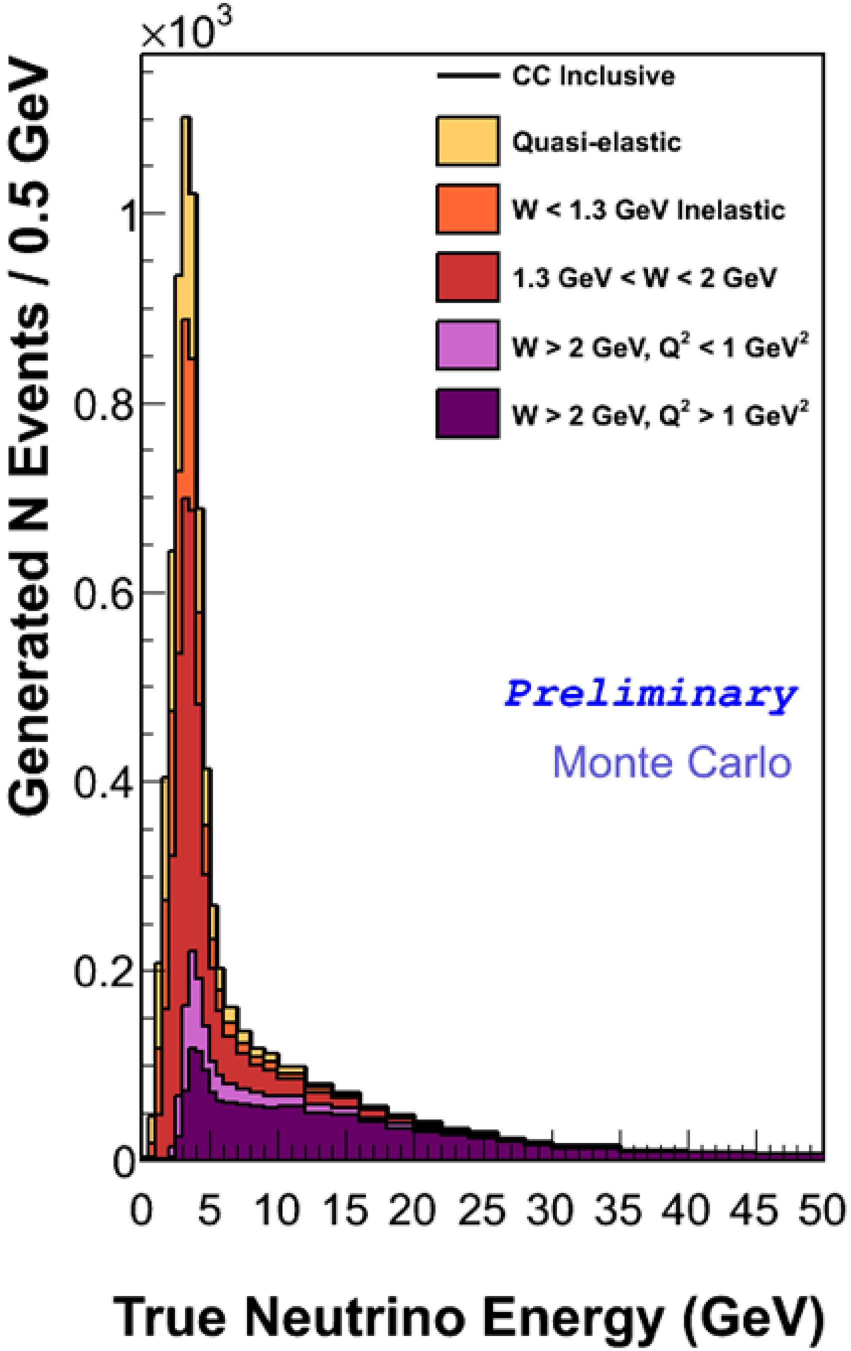


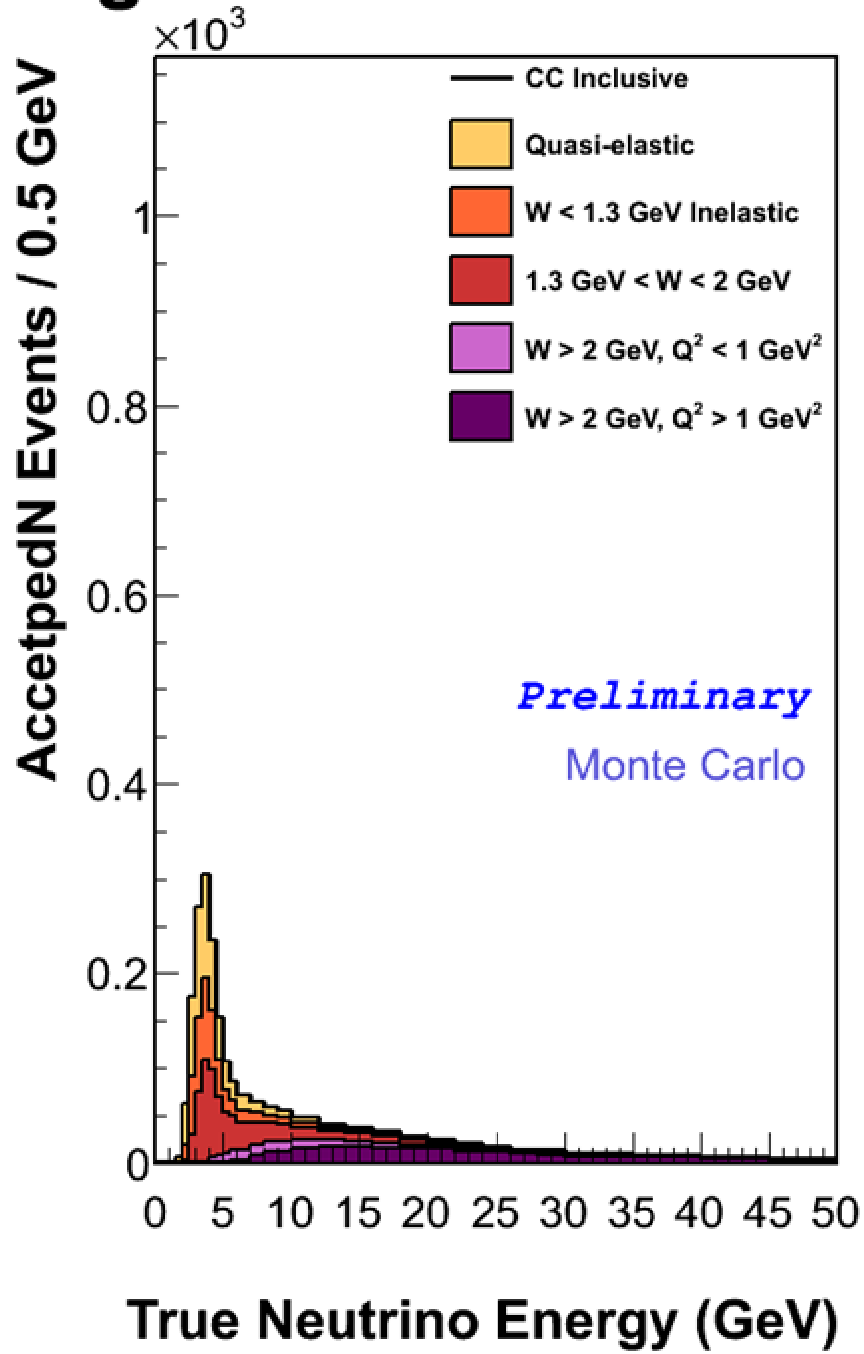
Why not 100%?
* big shower
* pileup
* deadtime

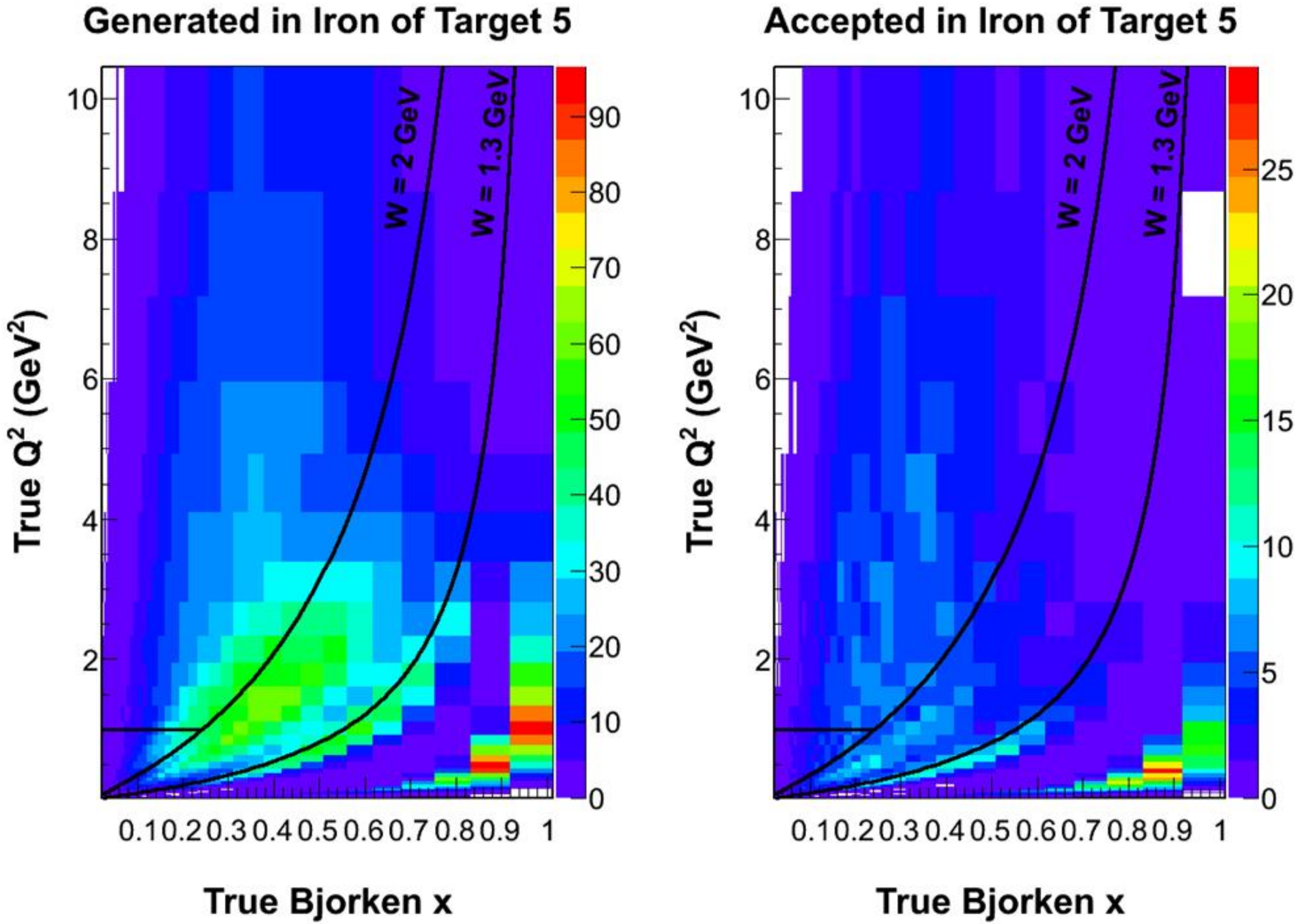
Method
ID clean μ in MINOS, point back to MINERvA

Single event MC correction
−4.6±2.5%

Iron of Target 5






Generated in Iron of Target 5
Accepted in Iron of Target 5
True Q^2 (GeV^2)
True Bjorken x
W = 2 GeV
W = 1.3 GeV
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
2
4
6
8
10
0
10
20
30
40
50
60
70
80
90
5
15
25

Double ratio of cross sections

What cancels?

$$\frac{\left(\frac{\frac{d\sigma^{Pb}}{dX_i}}{\frac{d\sigma^{CH}}{dX_i}}\right)}{\left(\frac{\frac{d\sigma^{Fe}}{dX_i}}{\frac{d\sigma^{CH}}{dX_i}}\right)} = \frac{\left(\frac{\frac{1}{\Phi_\nu^{Pb} T_{nuc}^{Pb}} \frac{1}{\Delta X_i} N^{Pb}(X_i)}{\frac{1}{\Phi_\nu^{CH} T_{nuc}^{CH}} \frac{1}{\Delta X_i} N^{CH}(X_i)}\right)}{\left(\frac{\frac{1}{\Phi_\nu^{Fe} T_{nuc}^{Fe}} \frac{1}{\Delta X_i} N^{Fe}(X_i)}{\frac{1}{\Phi_\nu^{CH} T_{nuc}^{CH}} \frac{1}{\Delta X_i} N^{CH}(X_i)}\right)}$$

- **Plastic cross sections** are the same
- Assume that **flux** is the same for all targets
- **Bin sizes** are the same

Double ratio of cross sections
reduced

- Double ratio gives us the ratio of lead to iron cross section, and with more cancellations to come...

$$\frac{\frac{d\sigma^{Pb}}{dX_i}}{\frac{d\sigma^{Fe}}{dX_i}} = \frac{\left(\frac{\frac{N^{Pb}(X_i)}{\boxed{T^{Pb}_{nuc}}}}{\frac{N^{CH}(X_i)}{\boxed{T^{CH}_{nuc}}}}\right)}{\left(\frac{\frac{N^{Fe}(X_i)}{\boxed{T^{Fe}_{nuc}}}}{\frac{N^{CH}(X_i)}{\boxed{T^{CH}_{nuc}}}}\right)}$$

- We know how many **nucleons** were used to build MINERvA (to ~2%)

Separable Efficiency/Acceptance

Measured to true number of events

$$N^{Fe} = \frac{N^{Fe}_{meas.} - N^{Fe}_{bg}}{\epsilon^{Fe}_{xy} * \epsilon^{Fe}_{z} * \epsilon^{Fe}_{other}}$$

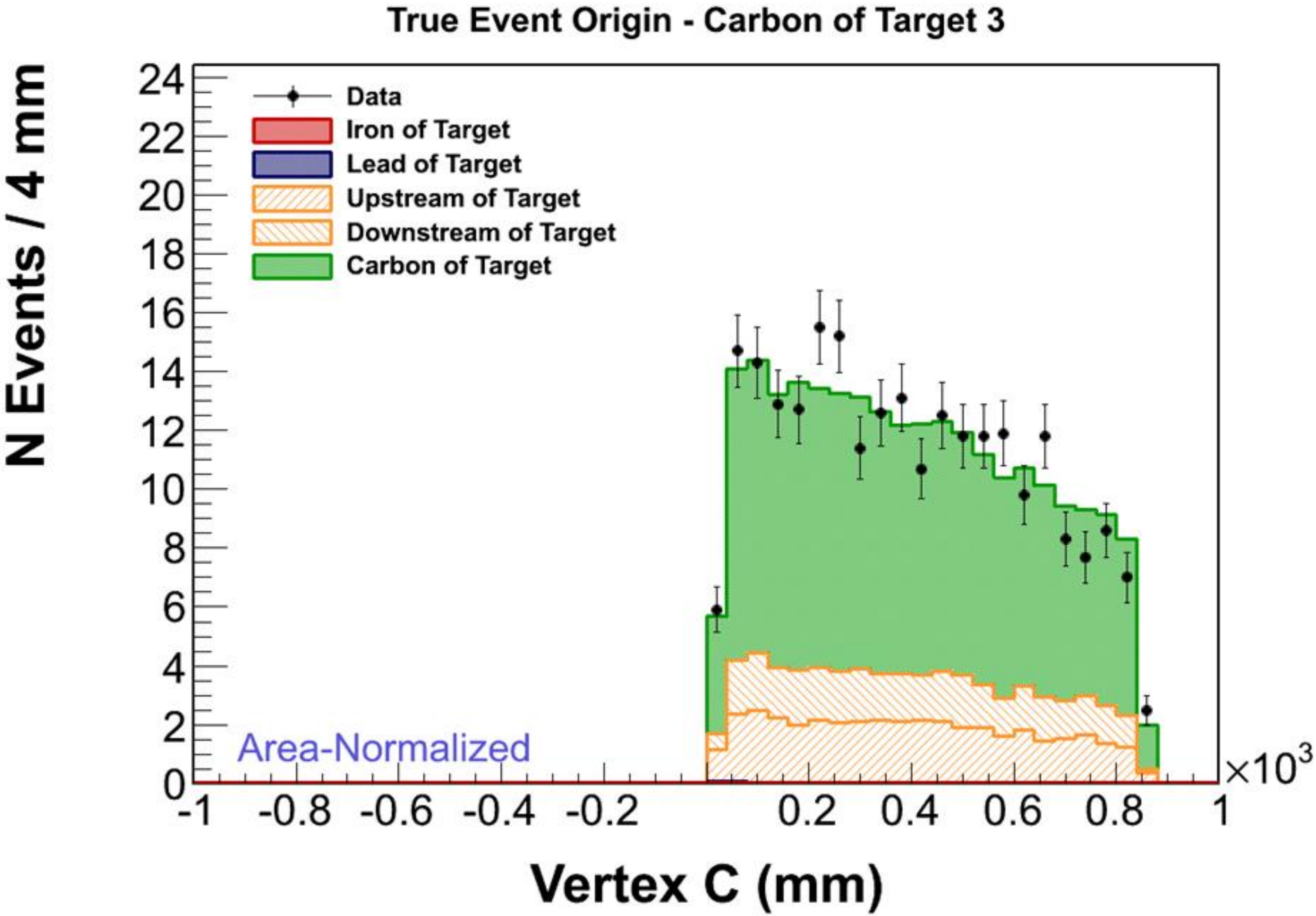
- Separate event selection efficiency into:
  - Acceptance dependent on XY position
  - Acceptance dependent of Z position
  - Other effects specific to the nuclear target

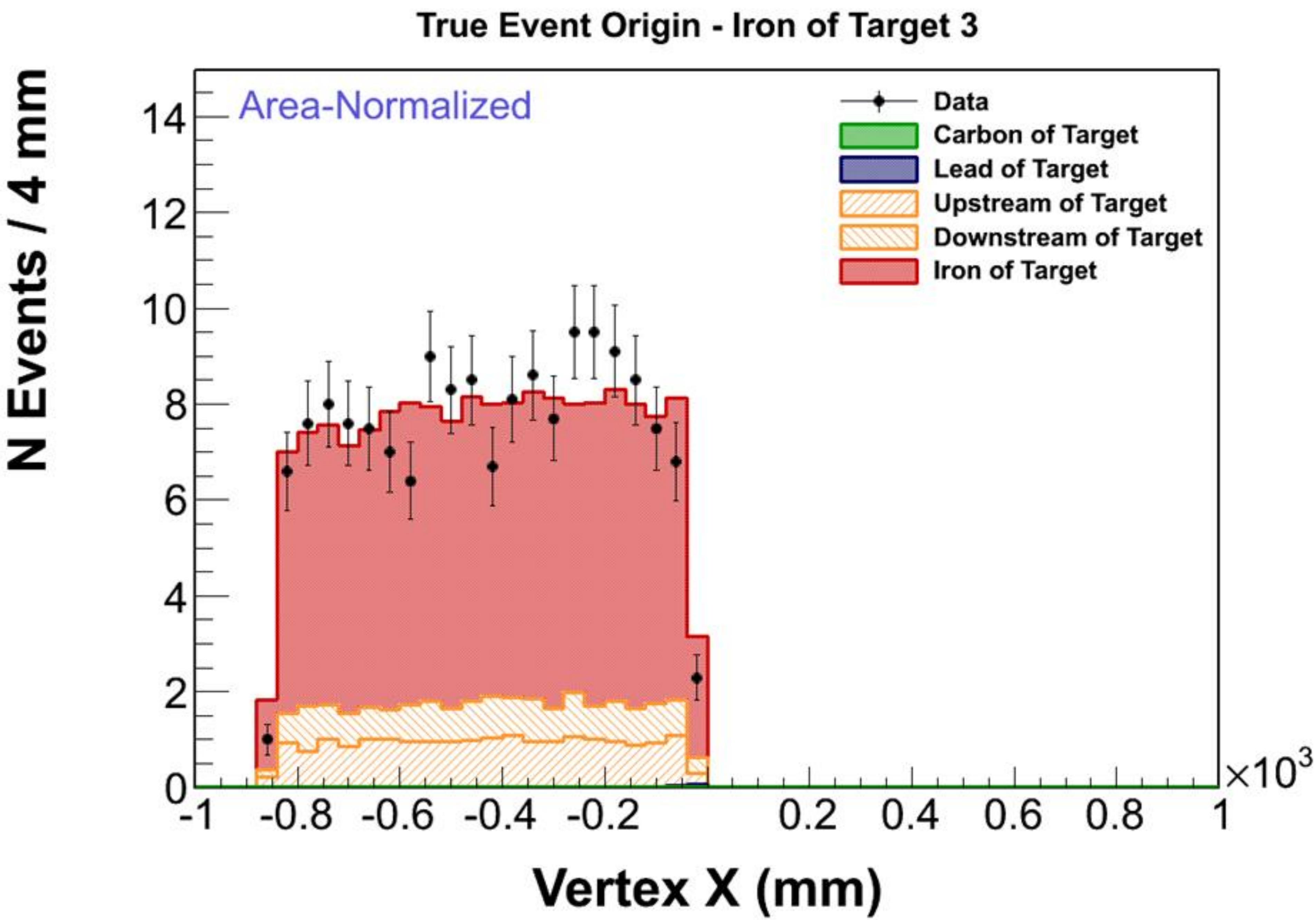
Separable Efficiency/Acceptance

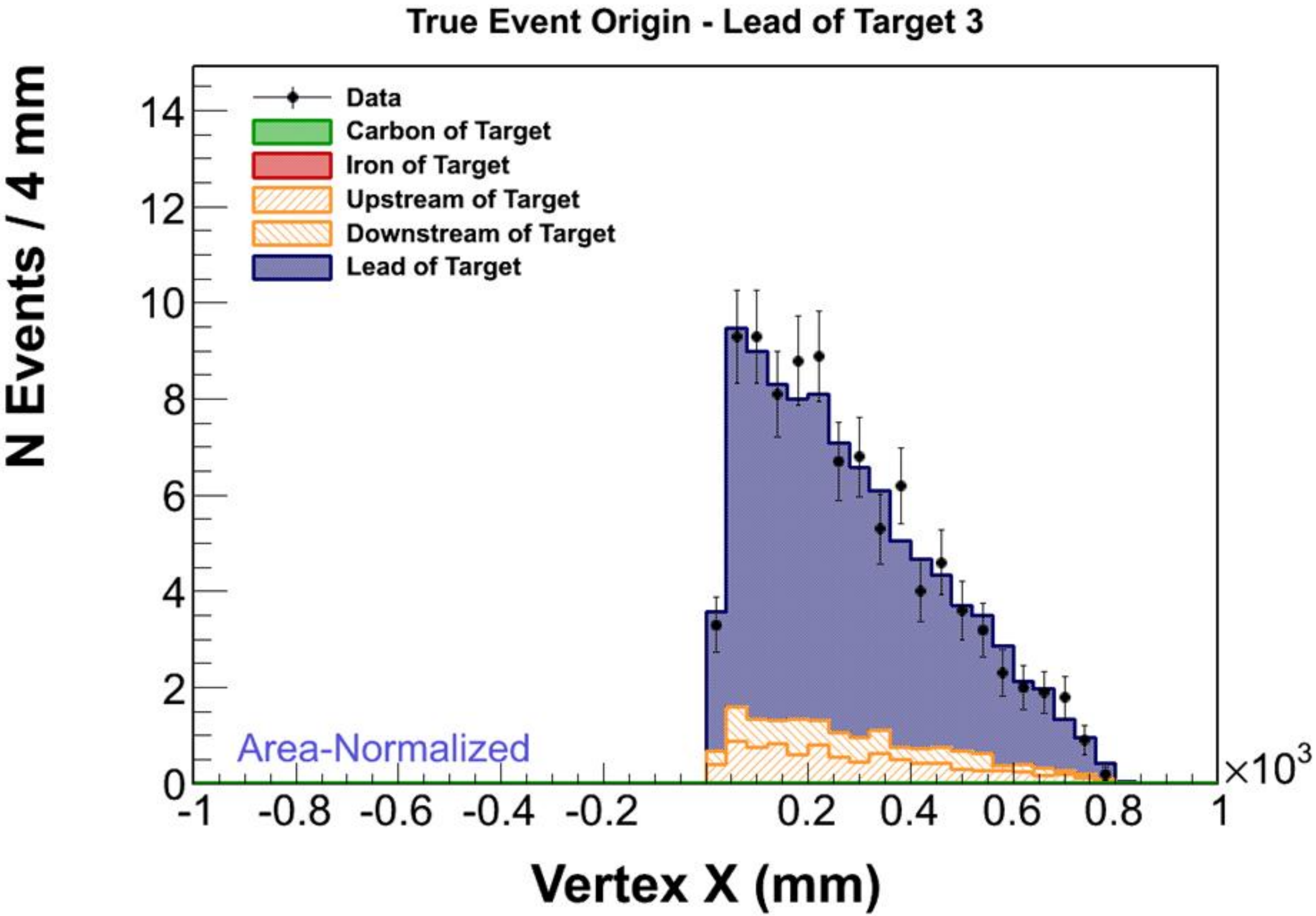
- Comparing samples with different acceptances

$$\frac{\dfrac{\boxed{\epsilon_{xy}^{CH}} * \boxed{\epsilon_{z}^{CH}} * \epsilon_{other}^{CH}}{\boxed{\epsilon_{xy}^{Pb}} * \boxed{\epsilon_{z}^{Pb}} * \epsilon_{other}^{Pb}}}{\dfrac{\boxed{\epsilon_{xy}^{CH}} * \boxed{\epsilon_{z}^{CH}} * \epsilon_{other}^{CH}}{\boxed{\epsilon_{xy}^{Fe}} * \boxed{\epsilon_{z}^{Fe}} * \epsilon_{other}^{Fe}}} \approx \frac{\dfrac{\epsilon_{other}^{CH}}{\epsilon_{other}^{Pb}}}{\dfrac{\epsilon_{other}^{CH}}{\epsilon_{other}^{Fe}}}$$

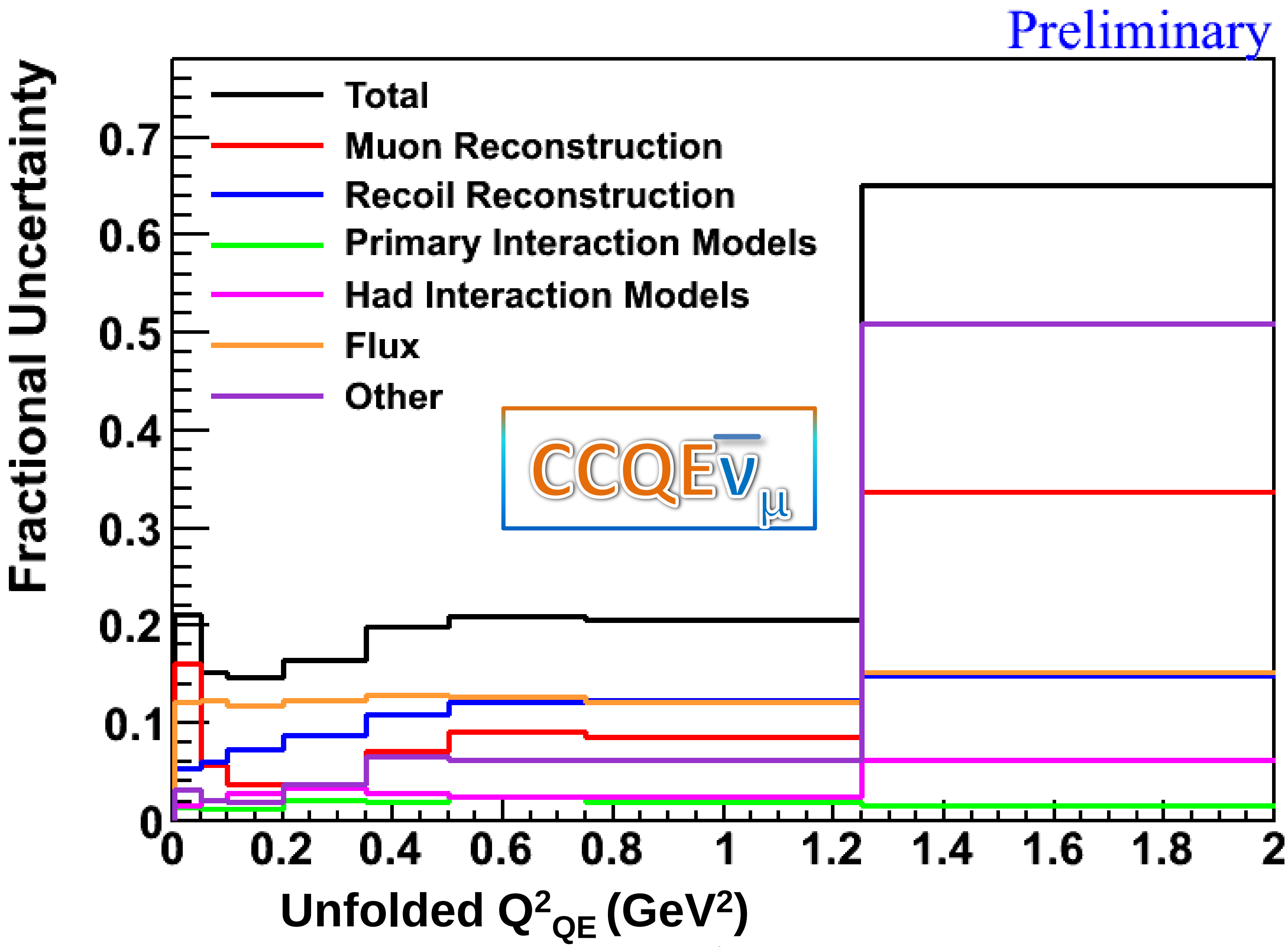
- Plastic reference target in the **same region in Z**
- Iron and Lead target are in the **same region in Z**
- Iron and its plastic reference occupy the same **XY region**
- Lead and its plastic reference occupy the same **XY region**


True Event Origin - Carbon of Target 3
N Events / 4 mm
Data
Iron of Target
Lead of Target
Upstream of Target
Downstream of Target
Carbon of Target
Area-Normalized
Vertex C (mm)
$\times 10^3$
0
2
4
6
8
10
12
14
16
18
20
22
24
-1
-0.8
-0.6
-0.4
-0.2
0.2
0.4
0.6
0.8
1

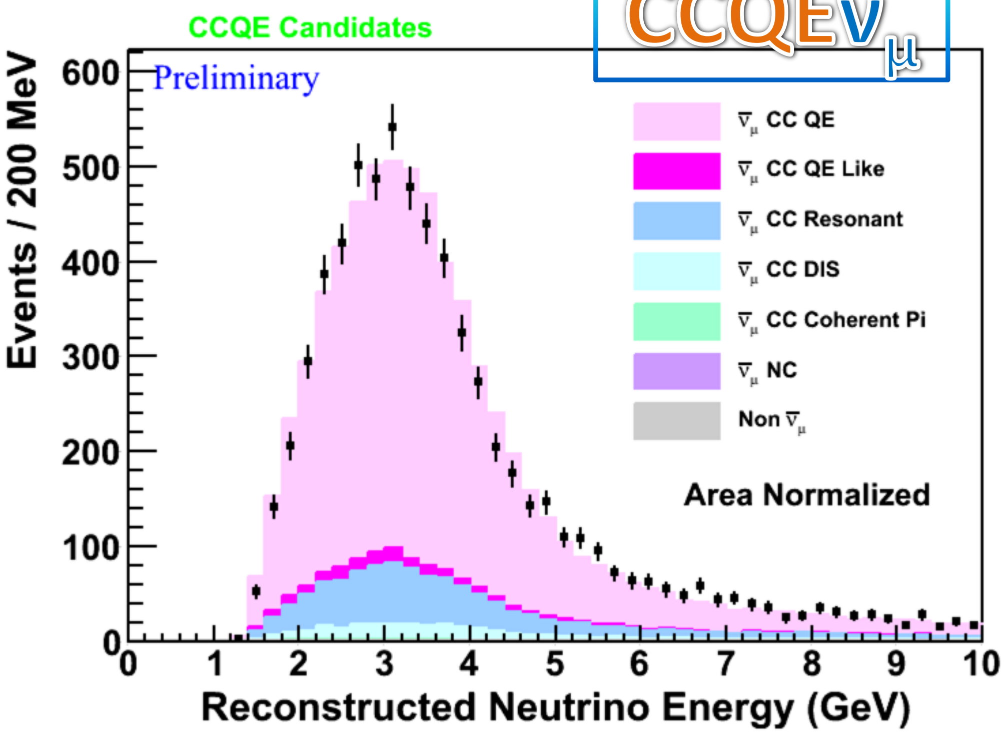

True Event Origin - Iron of Target 3
Area-Normalized
Data
Carbon of Target
Lead of Target
Upstream of Target
Downstream of Target
Iron of Target
N Events / 4 mm
0
2
4
6
8
10
12
14
-1
-0.8
-0.6
-0.4
-0.2
0.2
0.4
0.6
0.8
1
$\times 10^3$
Vertex X (mm)

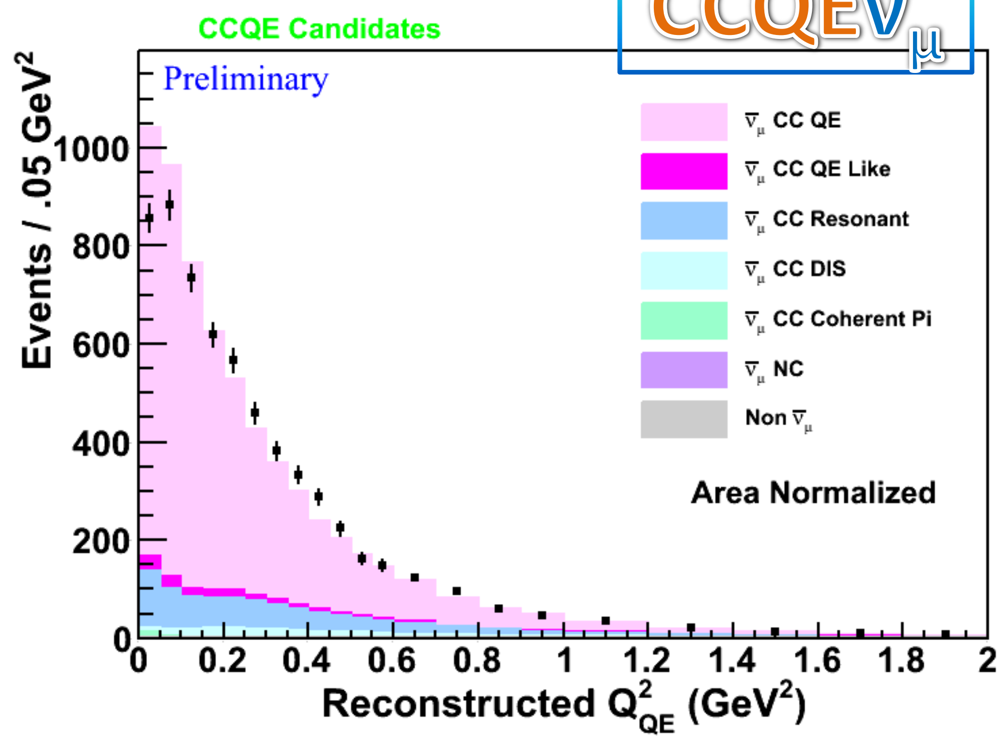

True Event Origin - Lead of Target 3
Data
Carbon of Target
Iron of Target
Upstream of Target
Downstream of Target
Lead of Target
Area-Normalized
N Events / 4 mm
Vertex X (mm)
×10^3
0
2
4
6
8
10
12
14
-1
-0.8
-0.6
-0.4
-0.2
0.2
0.4
0.6
0.8
1

Systematic Errors on $d\sigma/dQ^2_{QE}$



Neutrino Energy & Q^2 Area Normalization

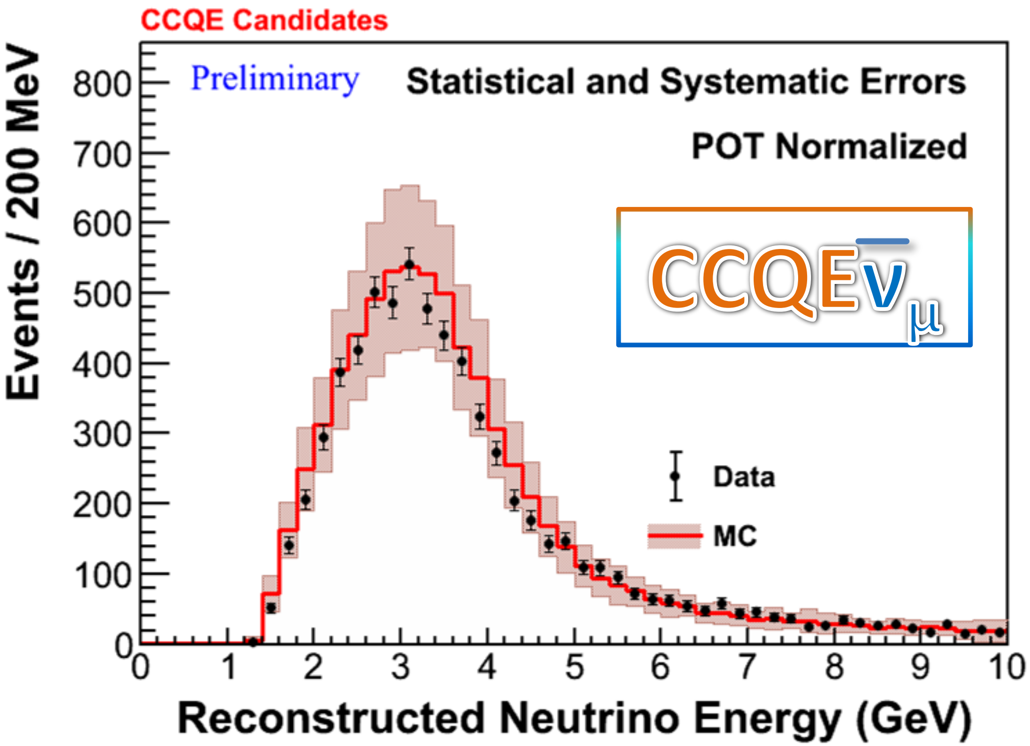


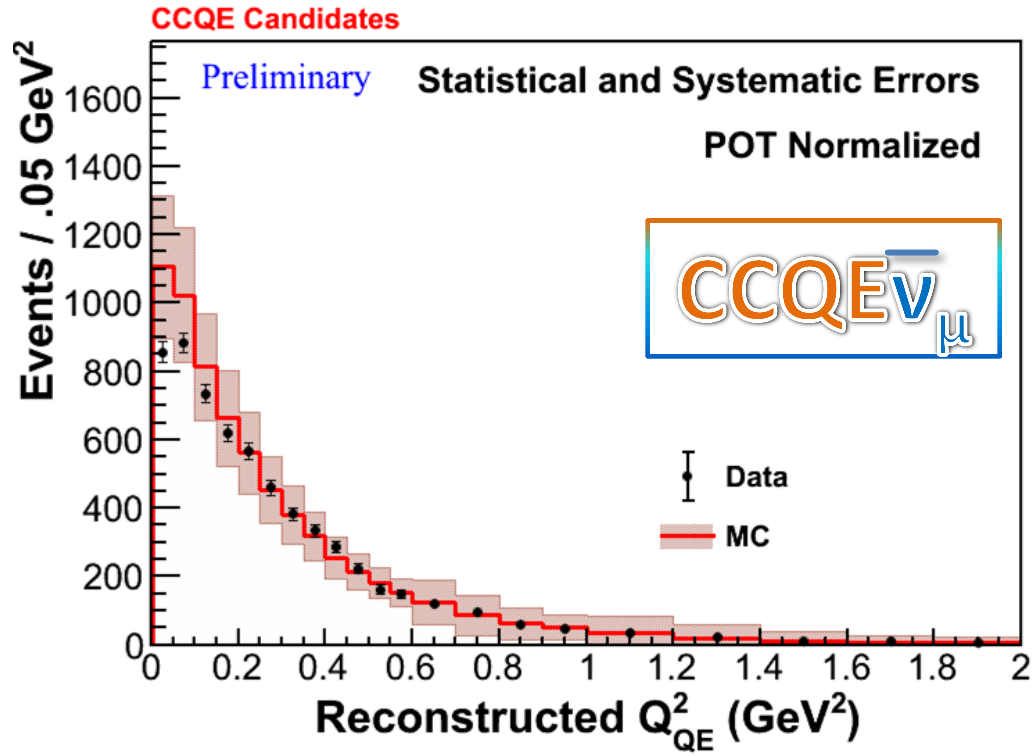


$$E_\nu = \frac{m_\mu^2 - (m_p - E_b)^2 - m_\mu^2 + 2(m_p - E_b)E_\mu}{2(m_p - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

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

Neutrino Energy & Q^2 Absolute Normalization





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

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