The MINERvA Experiment - A Status Report

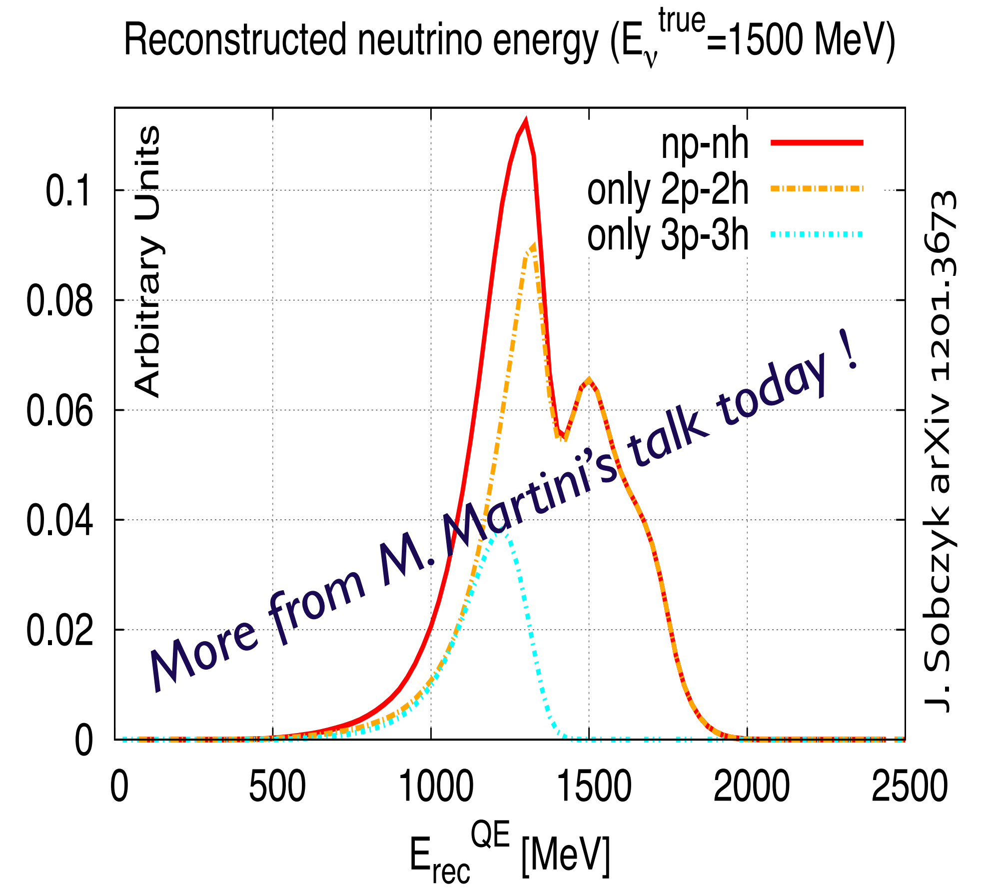
Jyotsna Osta
Fermilab
On behalf of the MINERvA Collaboration

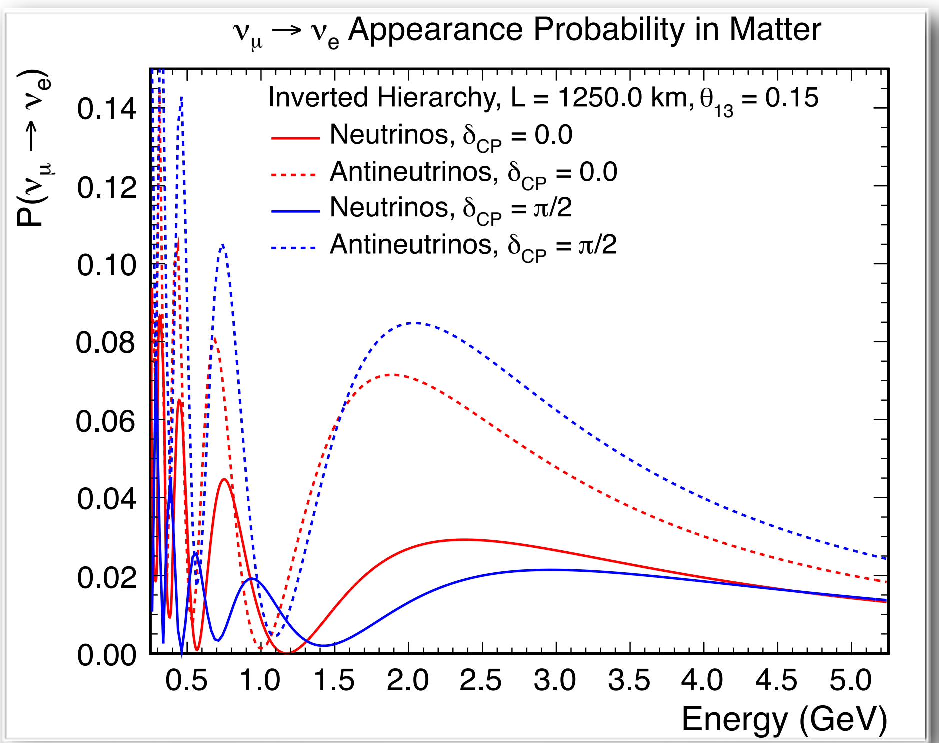
Overview of talk

- Neutrino cross-sections and MINERvA
- MINERvA - the detector design
- The NuMI beam line - neutrinos for MINERvA
- Data analyses in MINERvA
  - The Charged Current Inclusive analysis with neutrinos
  - The cross-sections ratio analysis on the Nuclear Targets (Iron & Lead)
  - The Charged Current Quasi-Elastic analysis with anti-neutrinos
    - MINERvA's first cross-section measurement ! World Premier !
  - The Charged Current Quasi-Elastic analysis with neutrinos
- Conclusions and Outlook

Why study neutrino cross-sections ?

- **Precision neutrino oscillation parameters :**
- Cross-sections are an important systematic, precision measurements of them help nail precise oscillation parameters.
  - Oscillation measurements use dense nuclear targets for statistics. Understanding neutrino-induced interactions in nuclear media crucial.
  - Quasi-elastic interactions provide inputs for neutrino oscillation measurements (neutrino energy & interaction probability).
    - Relationships between observables (E_{lepton}, Θ_{lepton}) and output are modified by nucleus. Dynamics not clear !
  - Searches for CP violation will involve ~% level measurements of oscillation probabilities, both for neutrinos and anti-neutrinos (Schwetz et. al. JHEP 0803 (2008) 021).
    - Relative cross-section error can affect CP sensitivity.





Why study neutrino cross-sections ?

- **Extracting nuclear effects from neutrino interactions :**
- Neutrinos are a Weak, hence unique probe of the nuclear structure.
  - Provide a complimentary and different angle when compared to electro-production.
  - Axial form factors determined via neutrino scattering.
  - The ability of neutrinos and anti-neutrinos to taste different flavors of quarks can help isolate PDFs and structure functions.
  - EMC effects have been studied in detail in electron scattering experiments.
    - use neutrinos as a complimentary probe for these.
  - With theoretical input we may disentangle a challenging mix of multiple nuclear effects e.g. np-nh and Final State Interactions (FSI).

The MINERvA Collaboration

About 70 Nuclear and Particle physicists from 21 institutions

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Centro Brasileiro de Pesquisas Fisicas

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University of Florida

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Hampton University

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Inst. Nucl. Reas. Moscow

G. Niculescu, I. Niculescu
James Madison University

E. Maher
Mass. Col. Lib. Arts

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Northwestern University

N. Tagg
Otterbein College

S. Boyd, I. Danko, S.A. Dytman, B. Eberly, Z. Isvan, D. Naples, V. Paolone
University of Pittsburgh

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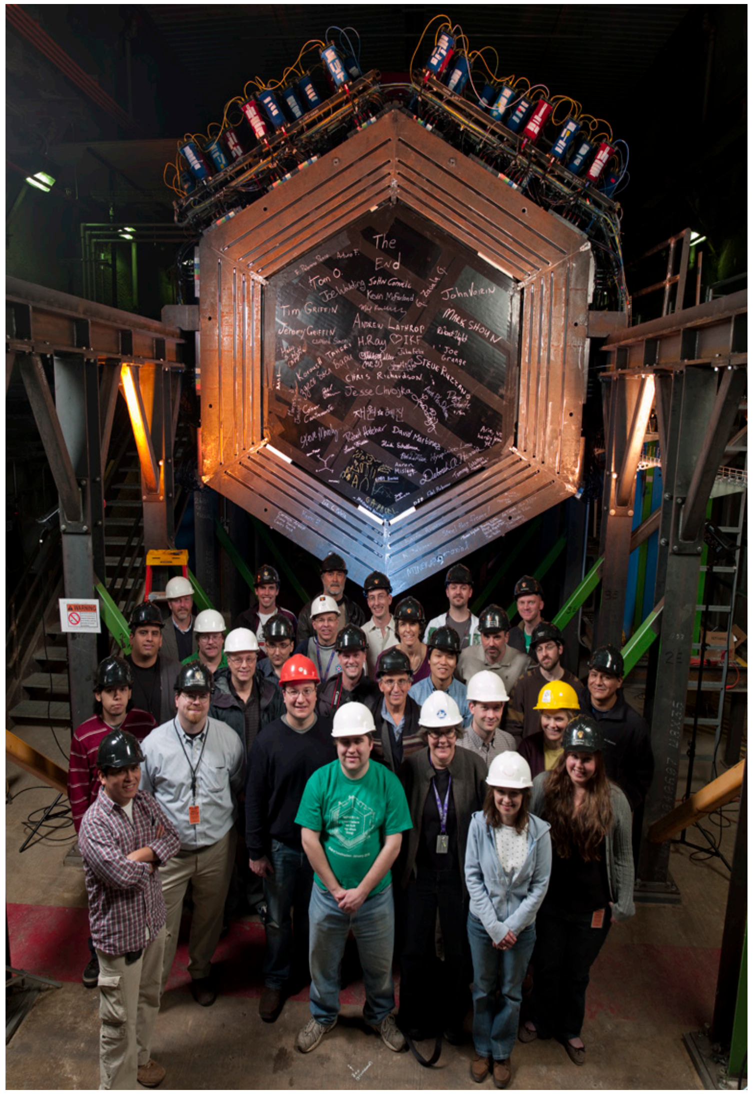
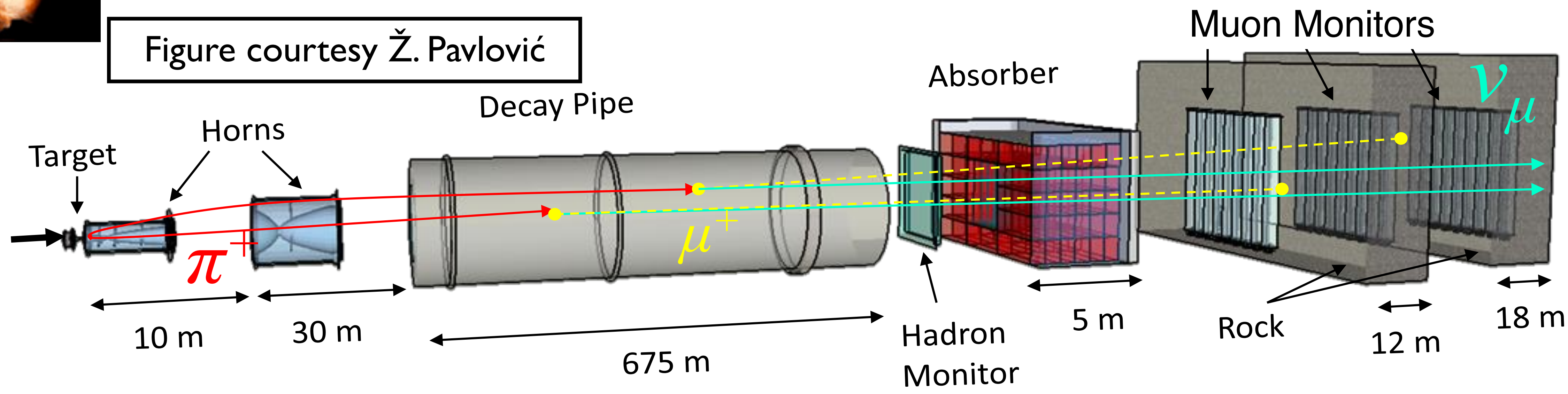
Universidad Tcnica Federico Santa Mara

L. Aliaga, J. Devan, M. Kordosky, J.K. Nelson, J. Walding, D. Zhang
College of William and Mary



The NuMI (Neutrinos at the Main Injector) beam line

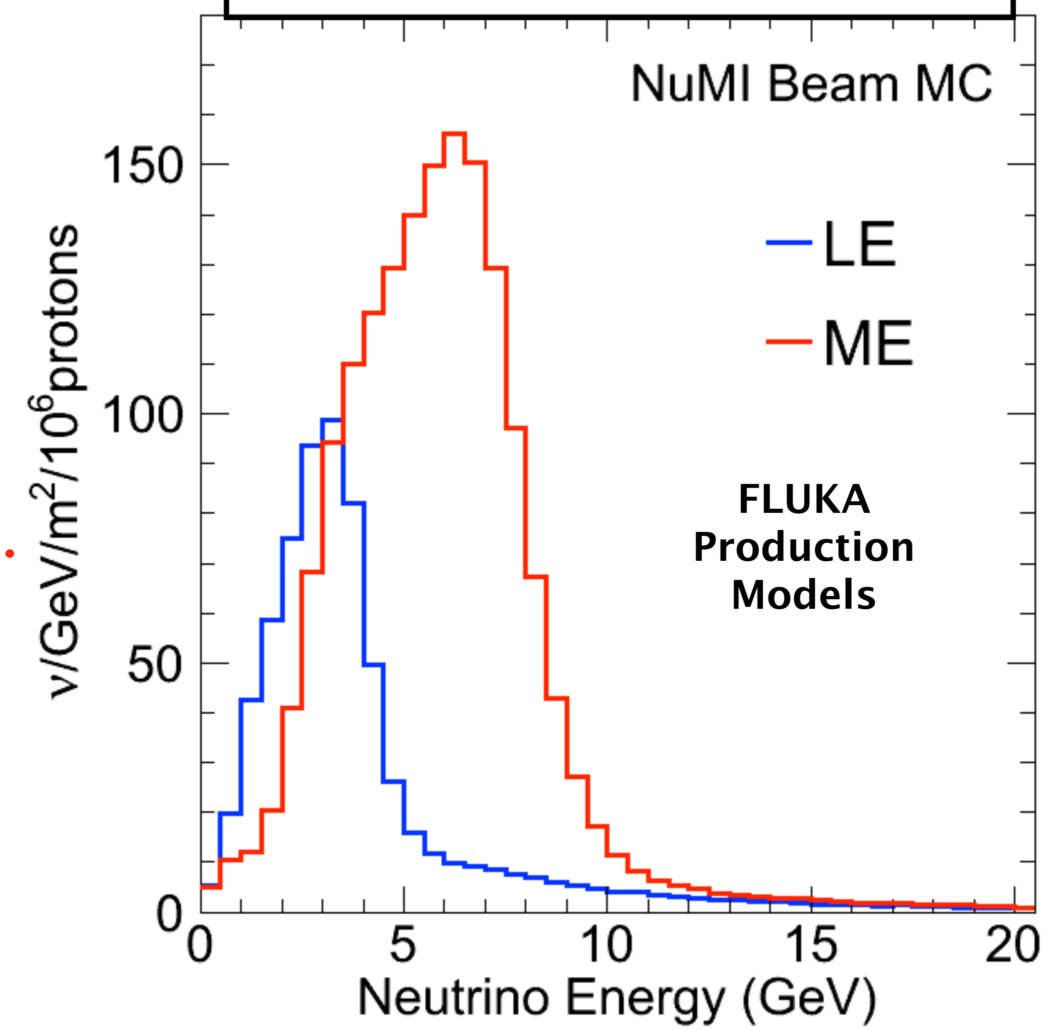


MINERvA

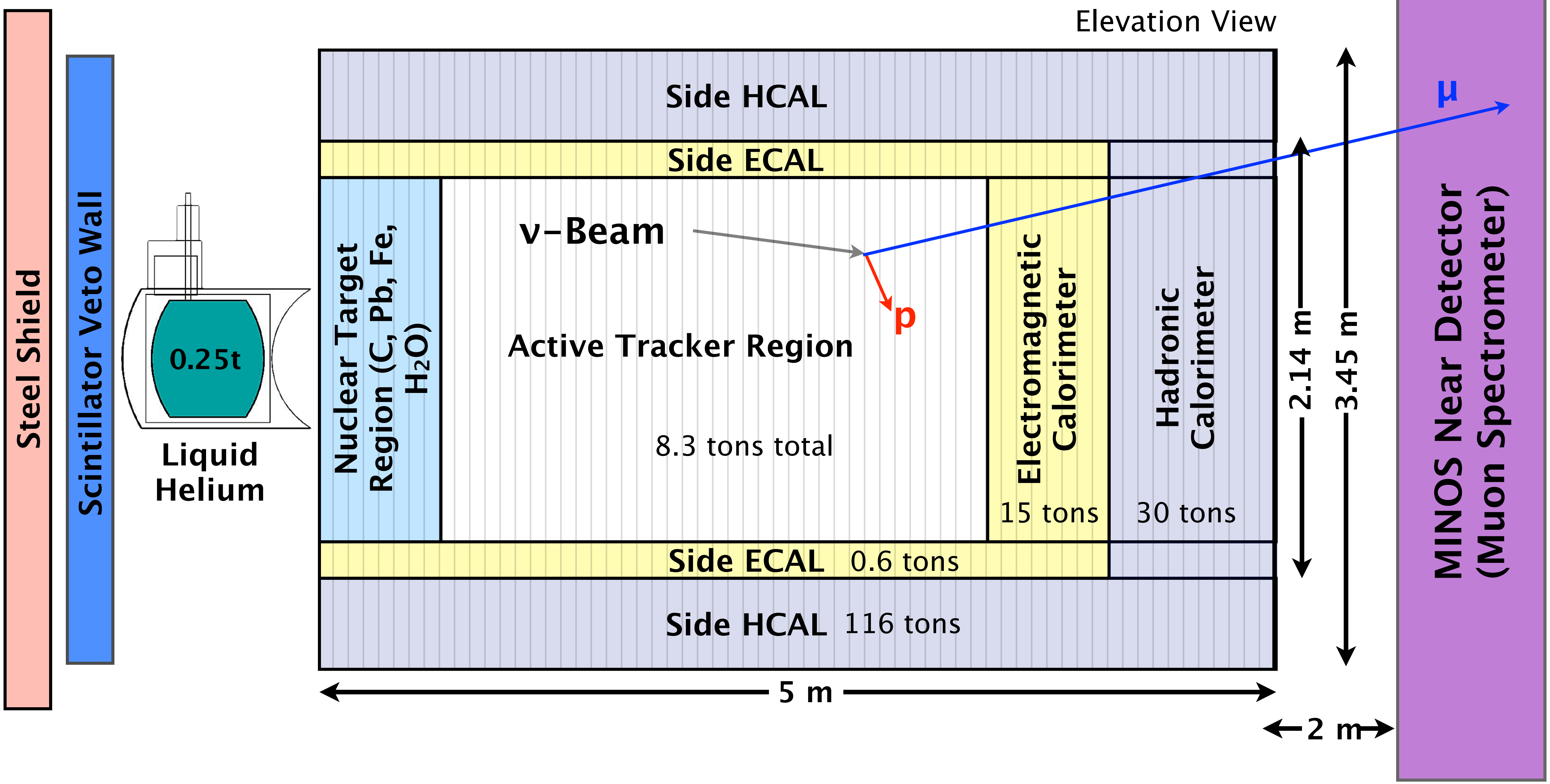
Also see A. Marino's talk from Wednesday !

- Neutrino energy spectrum of the NuMI beam is tunable !
- In the "low energy" configuration, MINERvA has recorded:
  - Neutrinos: 3.98x10^{20} Protons On Target (P.O.T.).
  - Anti-neutrinos: 1.70x10^{20} P.O.T.
- Plans to take data concurrently with NovA starting Spring 2013. NovA plans ➛ 36x10^{20} P.O.T. over 6 years.

Neutrino Mode MC Flux

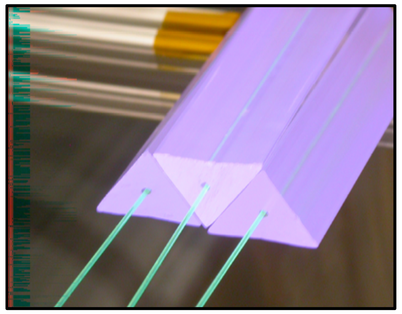


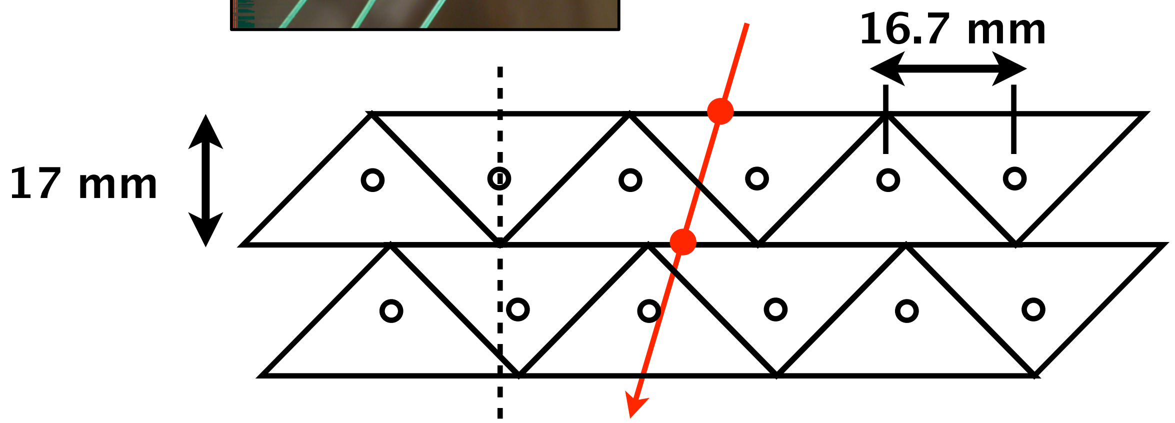
MINERvA - the detector design

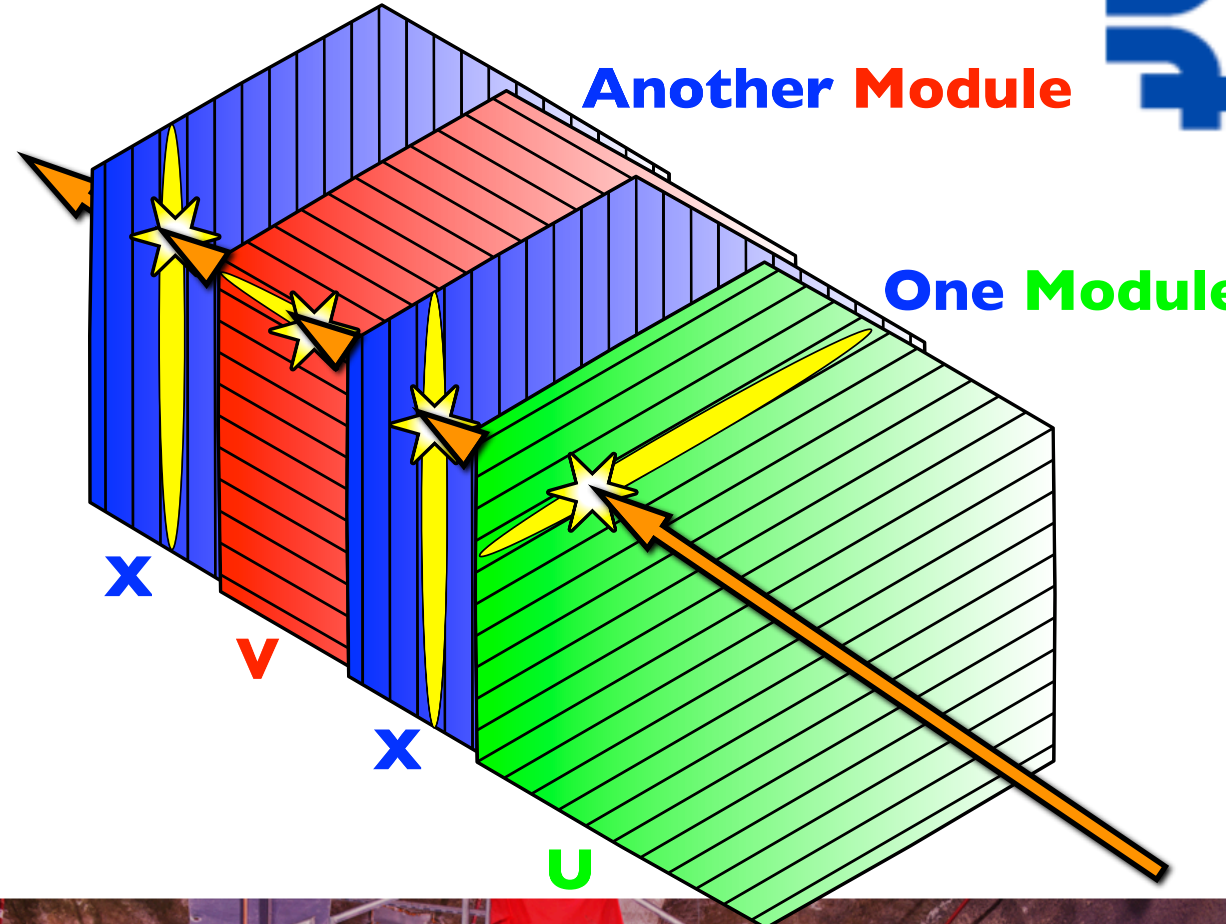


- Detector composed of 120 stacked modules of varying composition.
- Finely segmented (~32 K readout channels), side ECAL & HCAL well instrumented
- MINOS near detector acts as magnetic spectrometer ➛ muon charge and momentum

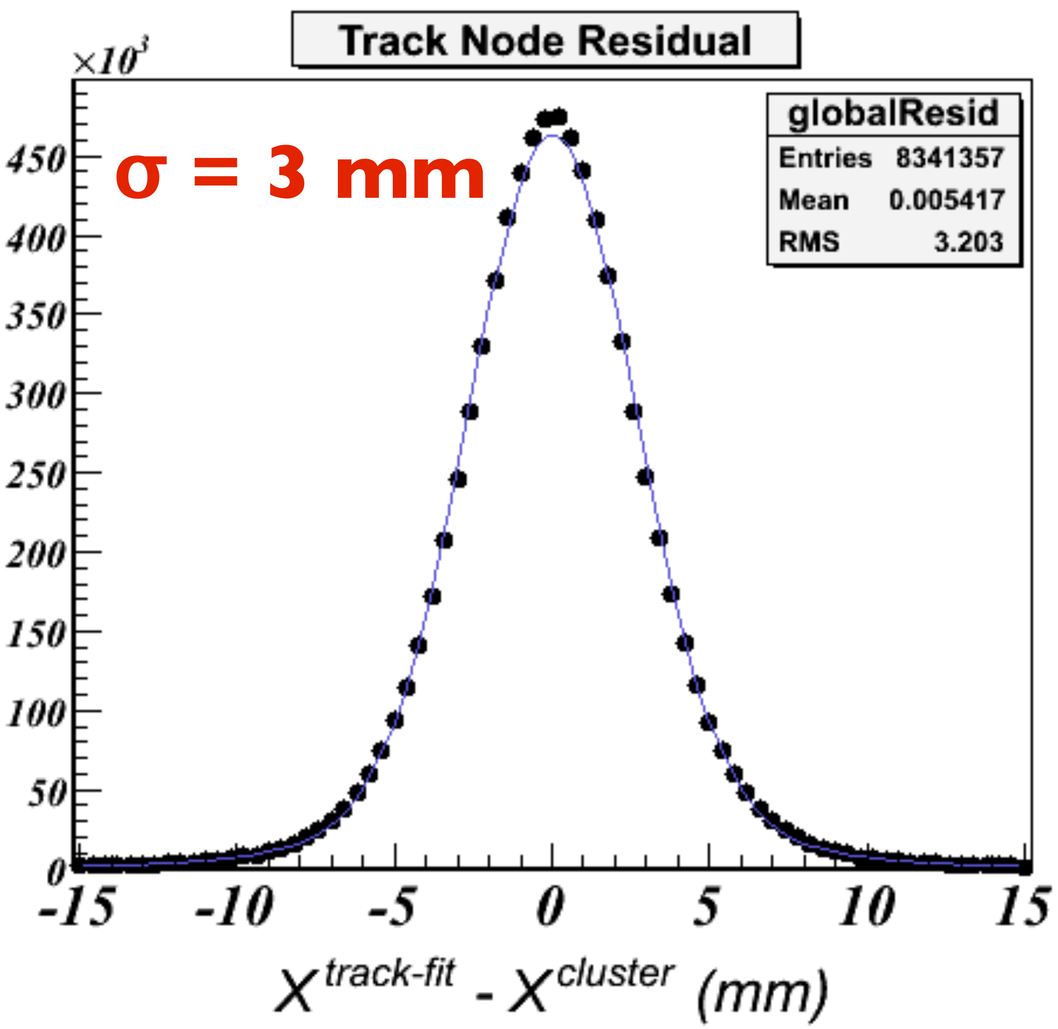
MINERvA - the detector design

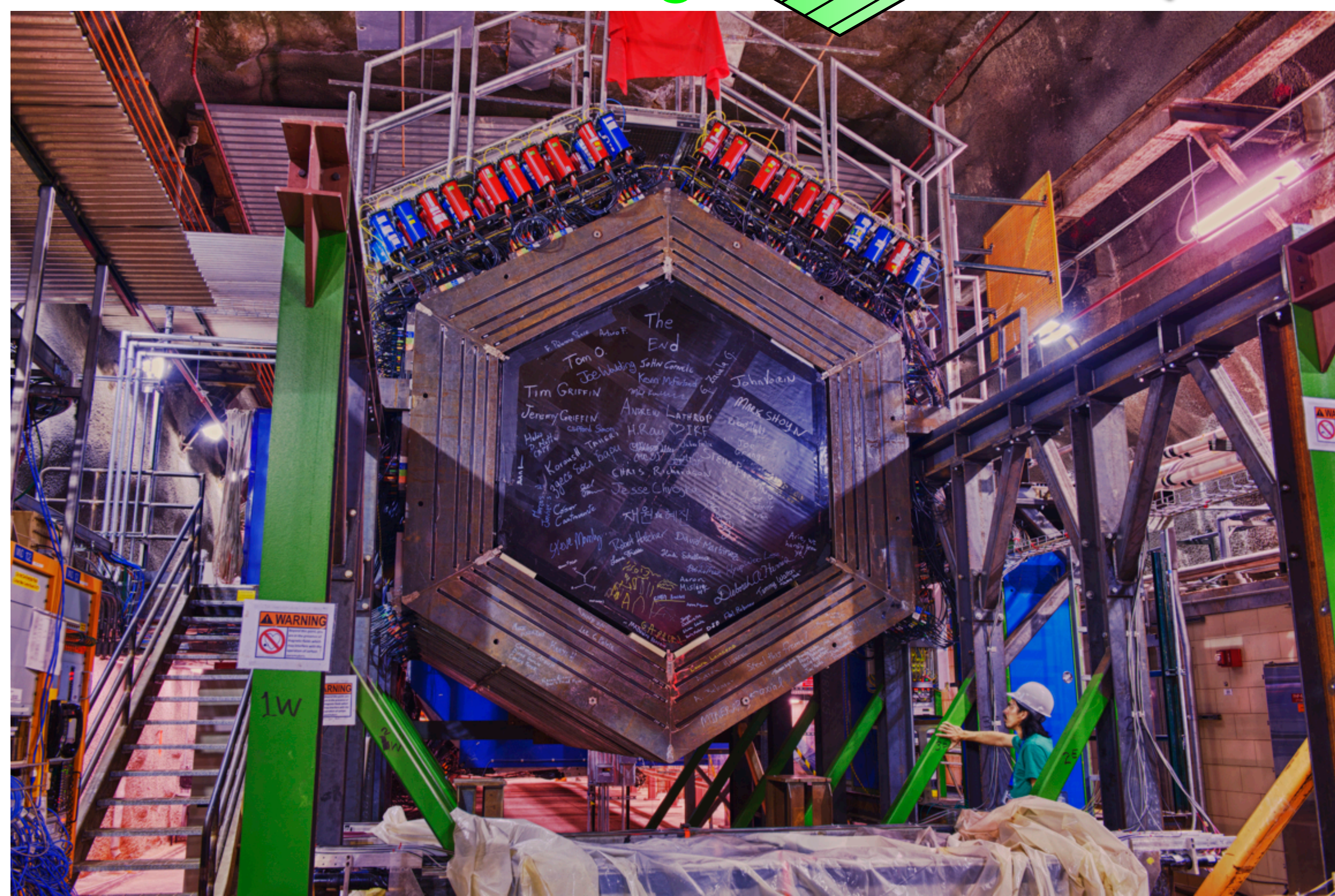




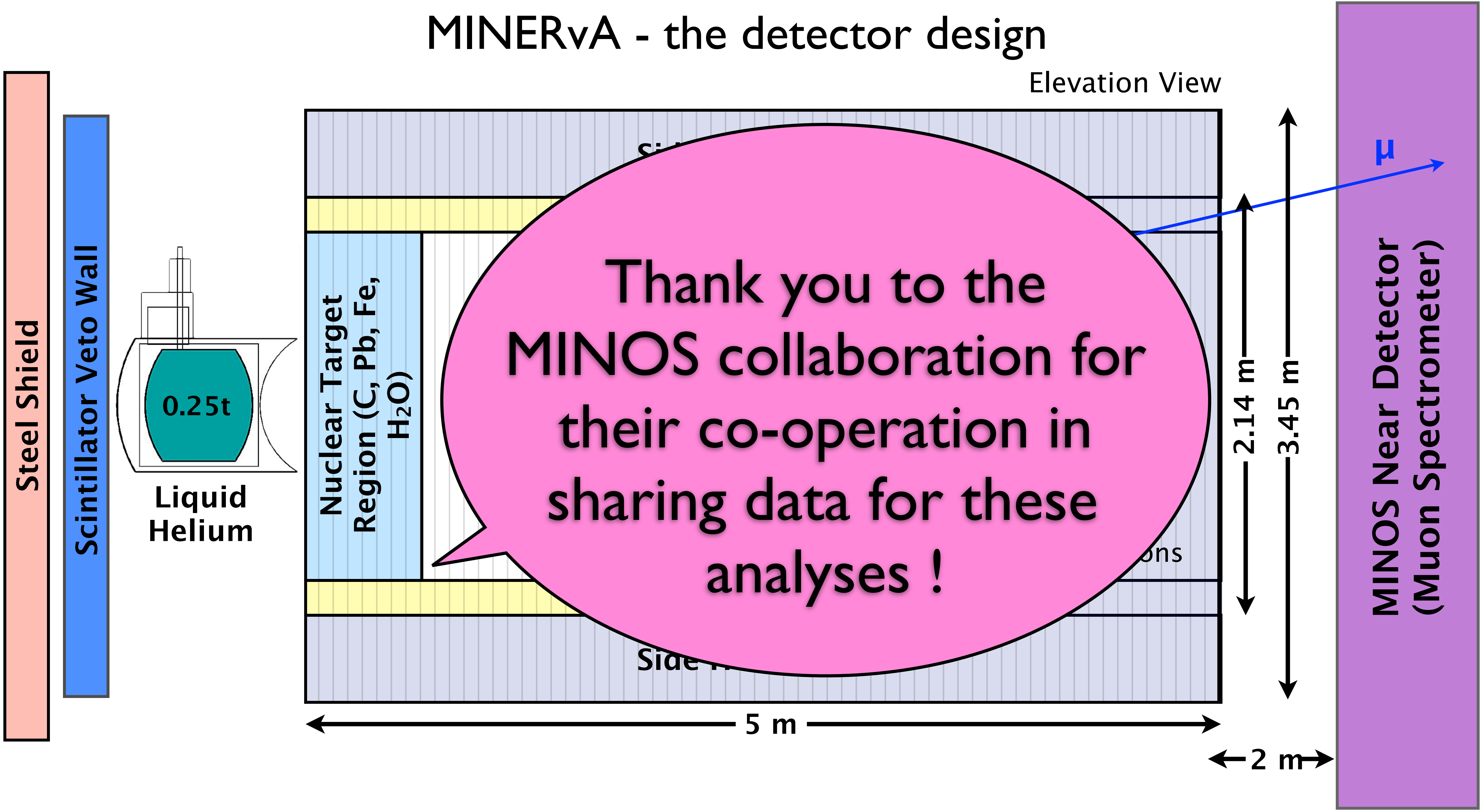


Charge sharing for improved position resolution (~3 mm) and alignment





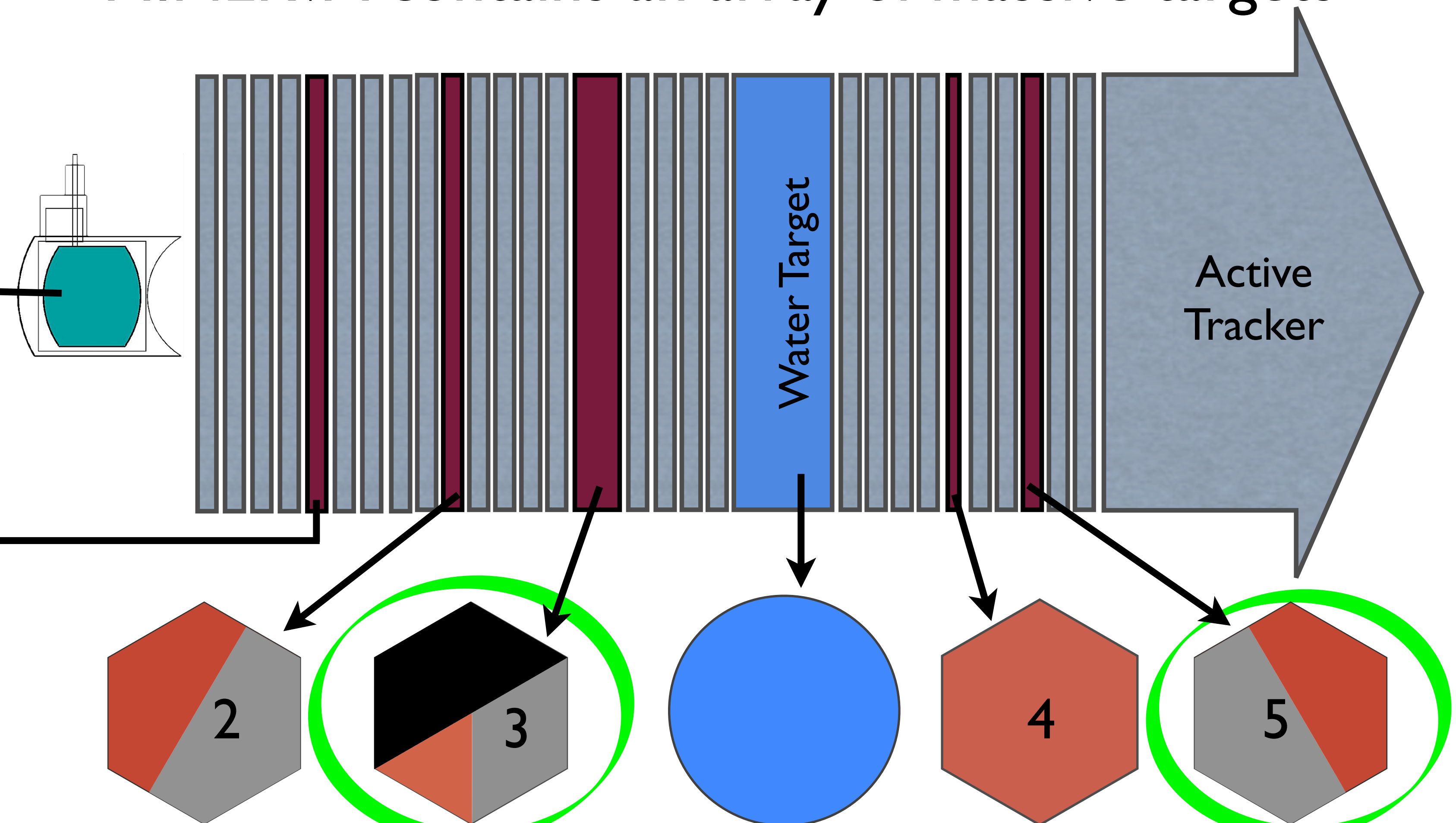
MINERvA - the detector design



- Detector composed of 120 stacked modules of varying composition.
- Finely segmented (~32 K readout channels), side ECAL & HCAL well instrumented
- MINOS near detector acts as magnetic spectrometer ➛ muon charge and momentum

MINERvA contains an array of massive targets

Helium Target
Fiducial Mass :
0.25 tons



WATER TARGET
Fiducial Mass :
625 kg H_20

NUC. TARGET 1
Fiducial Mass :
Fe: 323 kg/
Pb: 264 kg

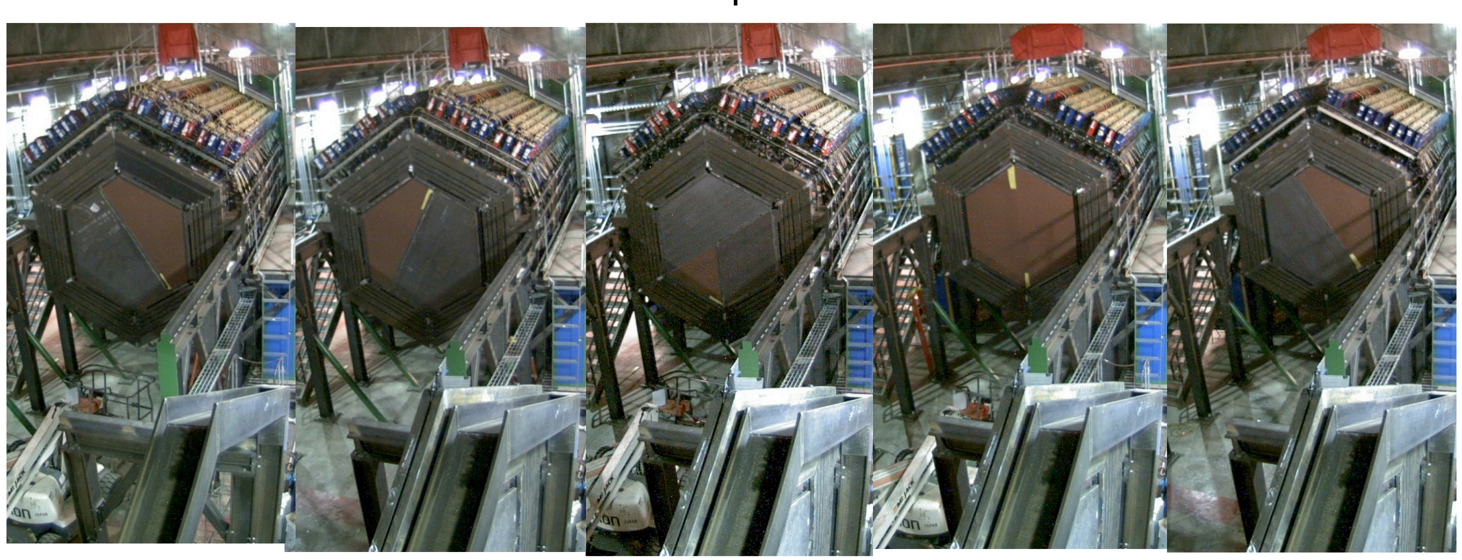
NUC. TARGET 2
Fiducial Mass :
Fe: 323 kg/
Pb: 266 kg

NUC. TARGET 3
Fiducial Mass :
C: 166 kg
Fe: 169 kg/Pb: 121 kg

NUC. TARGET 4
Fiducial Mass :
Pb: 228 kg

NUC. TARGET 5
Fiducial Mass :
Fe: 161 kg/
Pb: 135 kg

Iron/Lead | Lead/Iron | Lead/Iron Graphite | Lead | Iron/Lead



3/15 | 3/10 | 3/08 | 2/19 | 2/16

Today's Subject:
3 & 5

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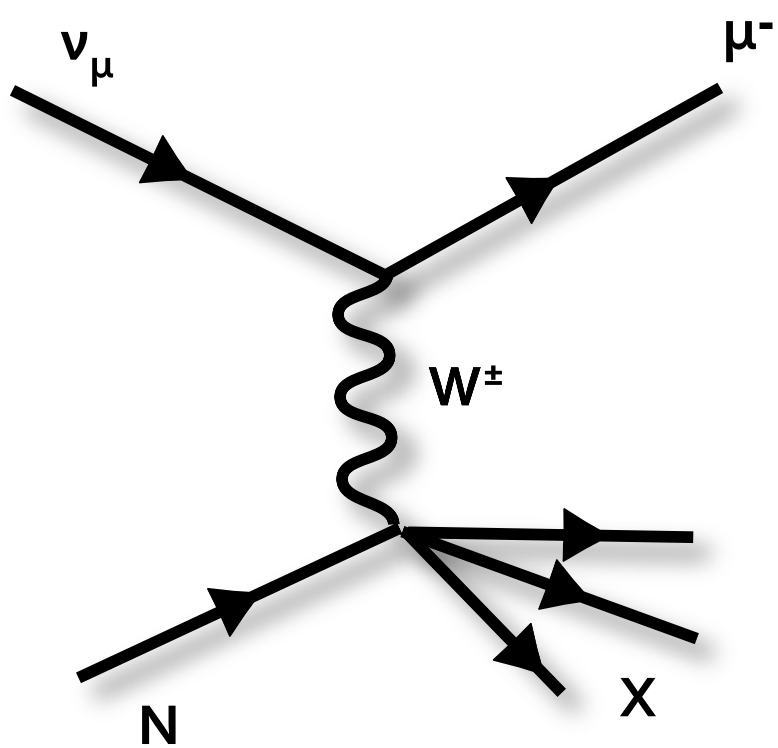
CIPANP, 2012
St. Petersburg, Florida

The Charged Current Inclusive Analysis with neutrinos

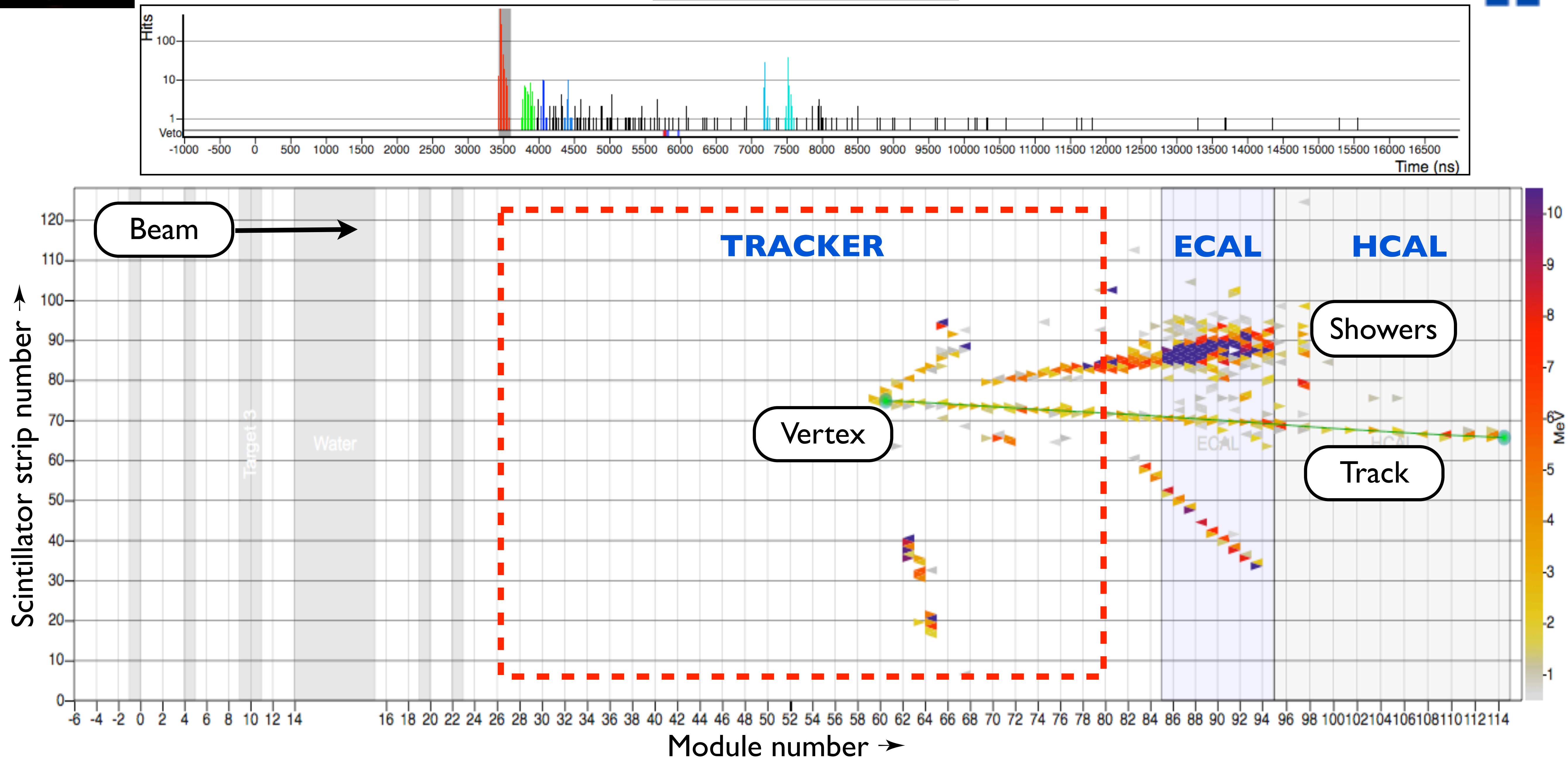
One(+) Track
Plus Recoil !



* using only ~ 25% of the accumulated Protons On Target !

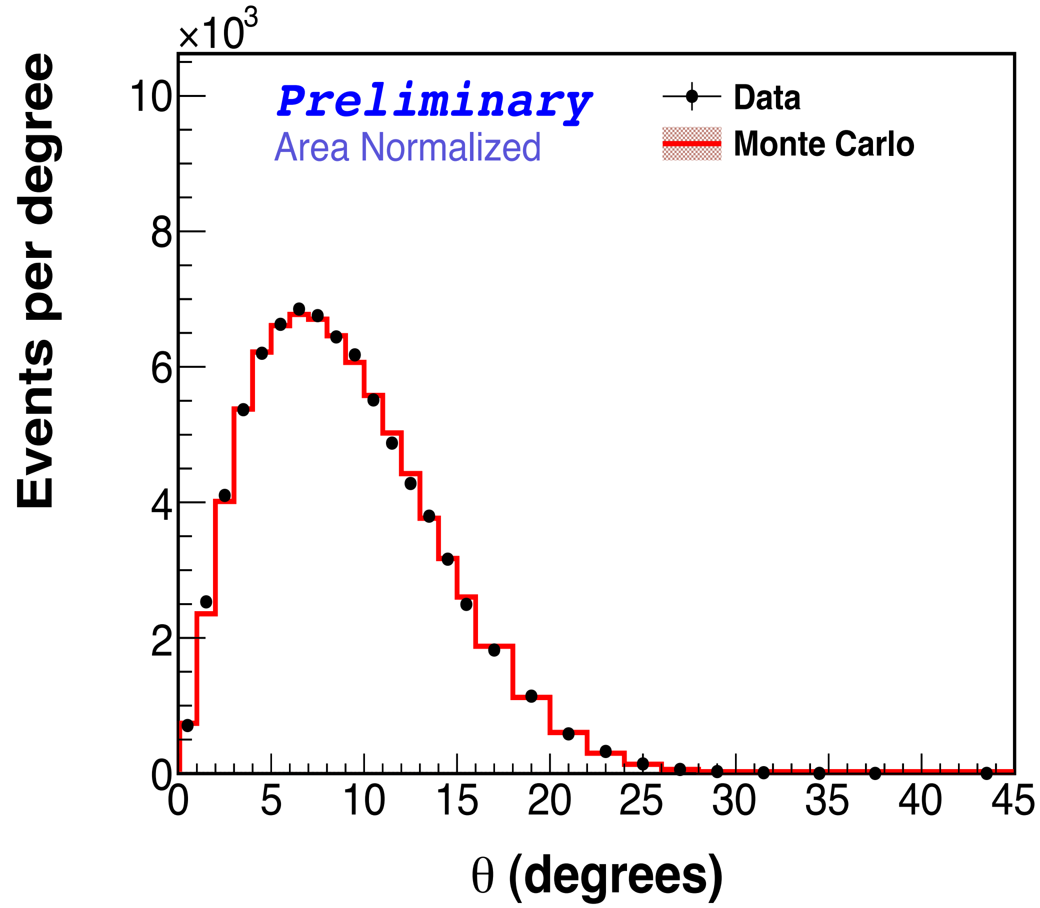
Event Signature & Analysis Technique

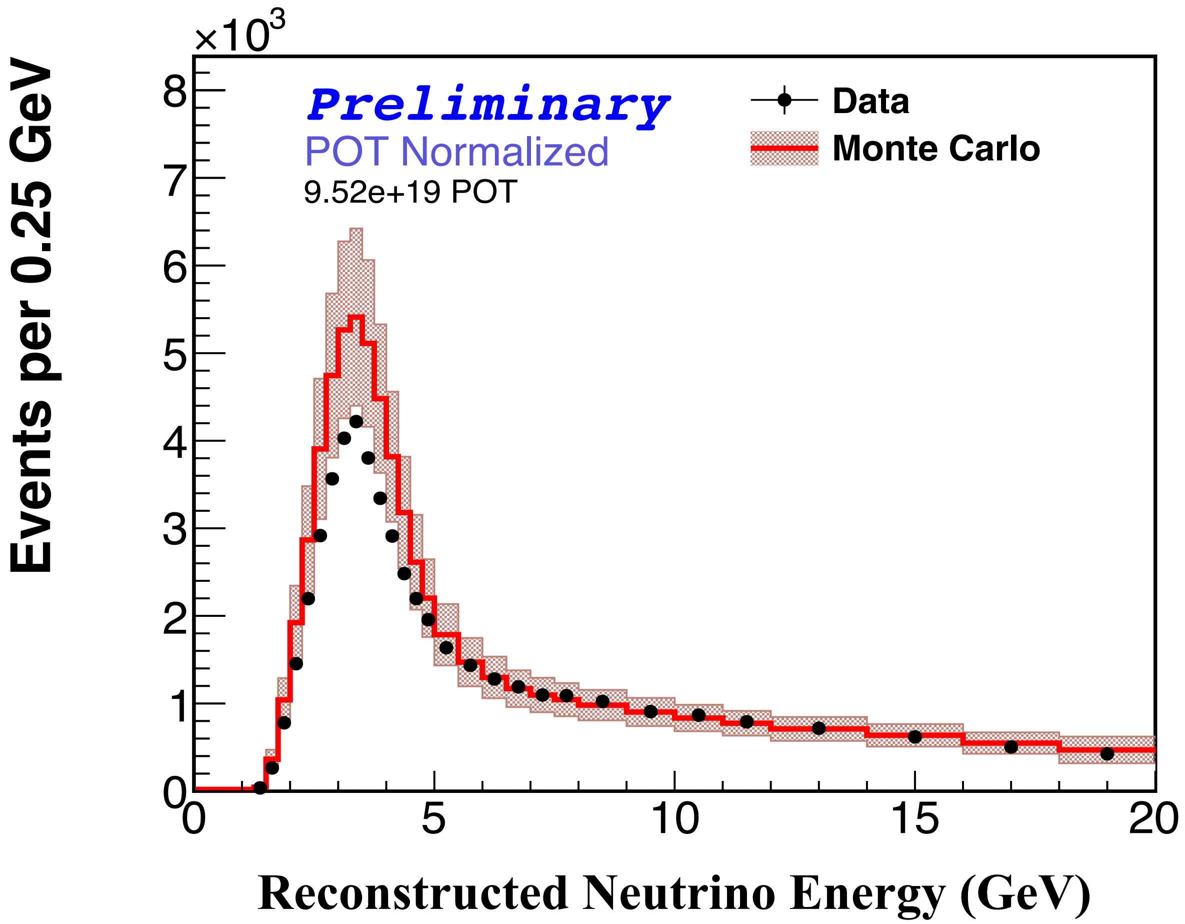
$\nu_\mu + N \rightarrow \mu^- + X$

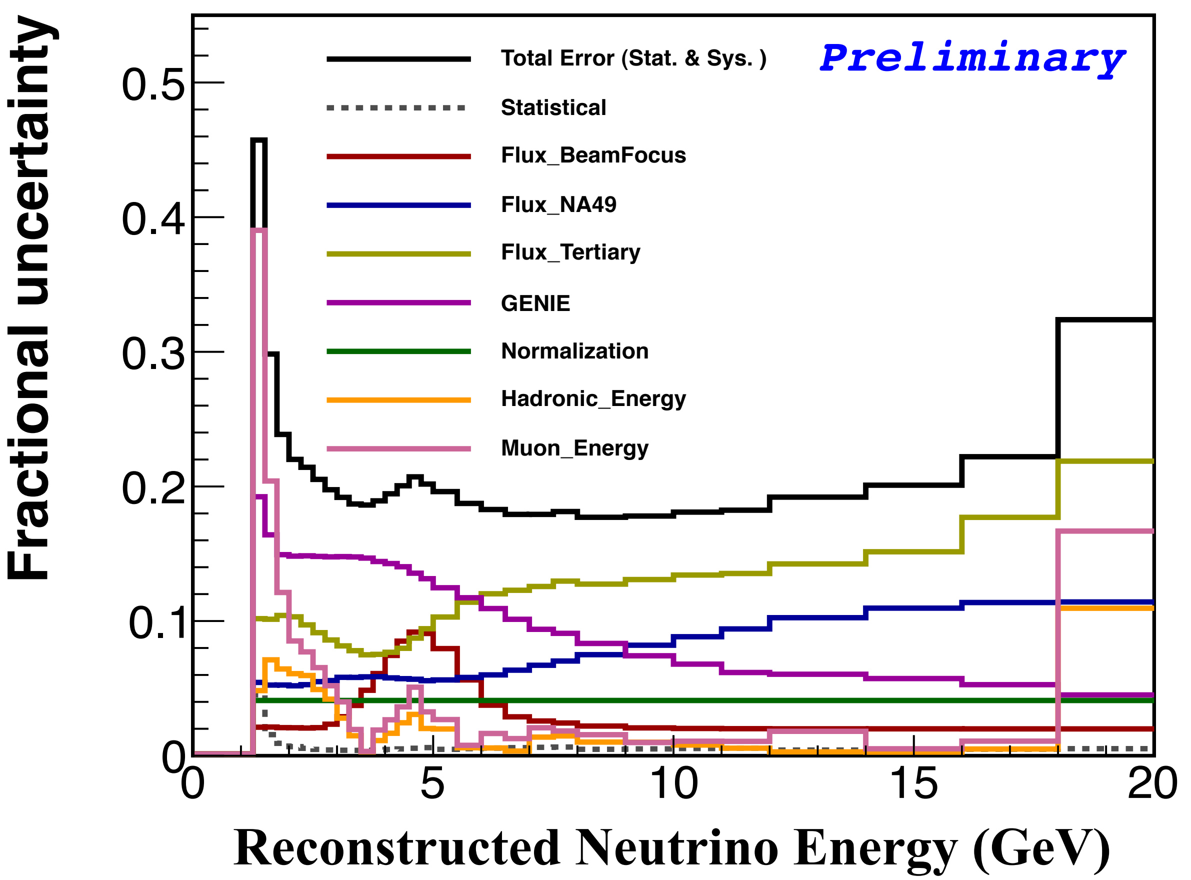


- Event selection criteria :
- Single Muon track in MINERvA, well reconstructed and matched into MINOS detector.
- Reconstructed vertex inside fiducial tracker region of detector (fiducial mass = 5.3 tons).
- Recoil energy computed calorimetrically.

Kinematic variables from CC Inclusive Events

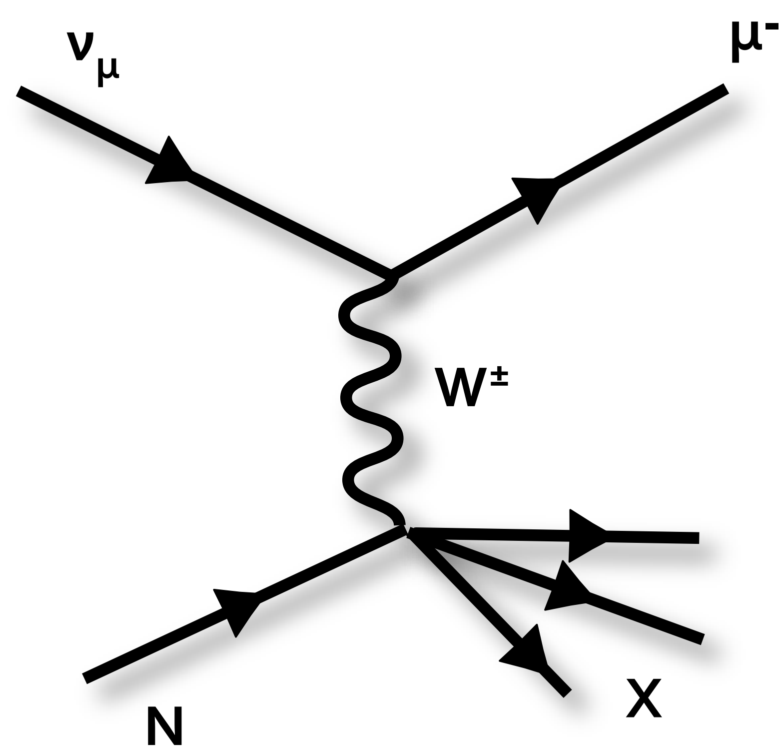






The Cross-sections Ratio Analysis for CC Inclusive Events on the Nuclear Targets

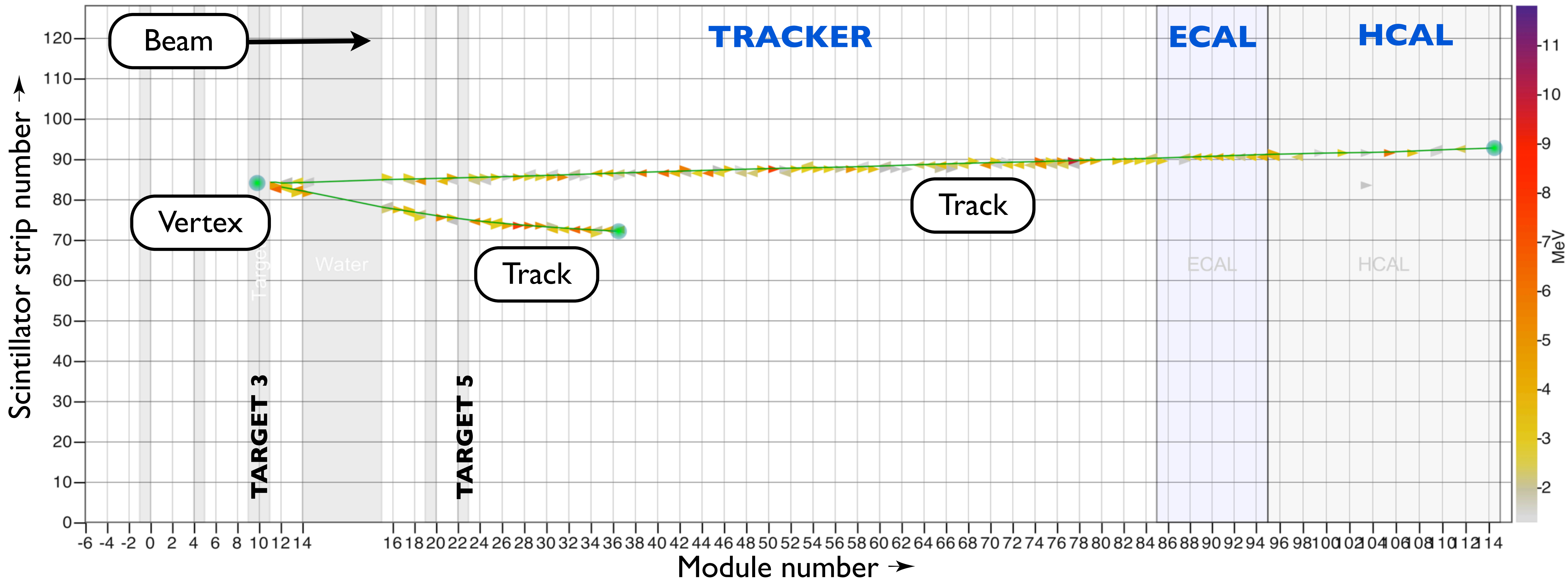
One(+) Track
Plus Recoil !



* using only ~ 25% of the accumulated Protons On Target !
* using only 2 out of the 5 nuclear targets !

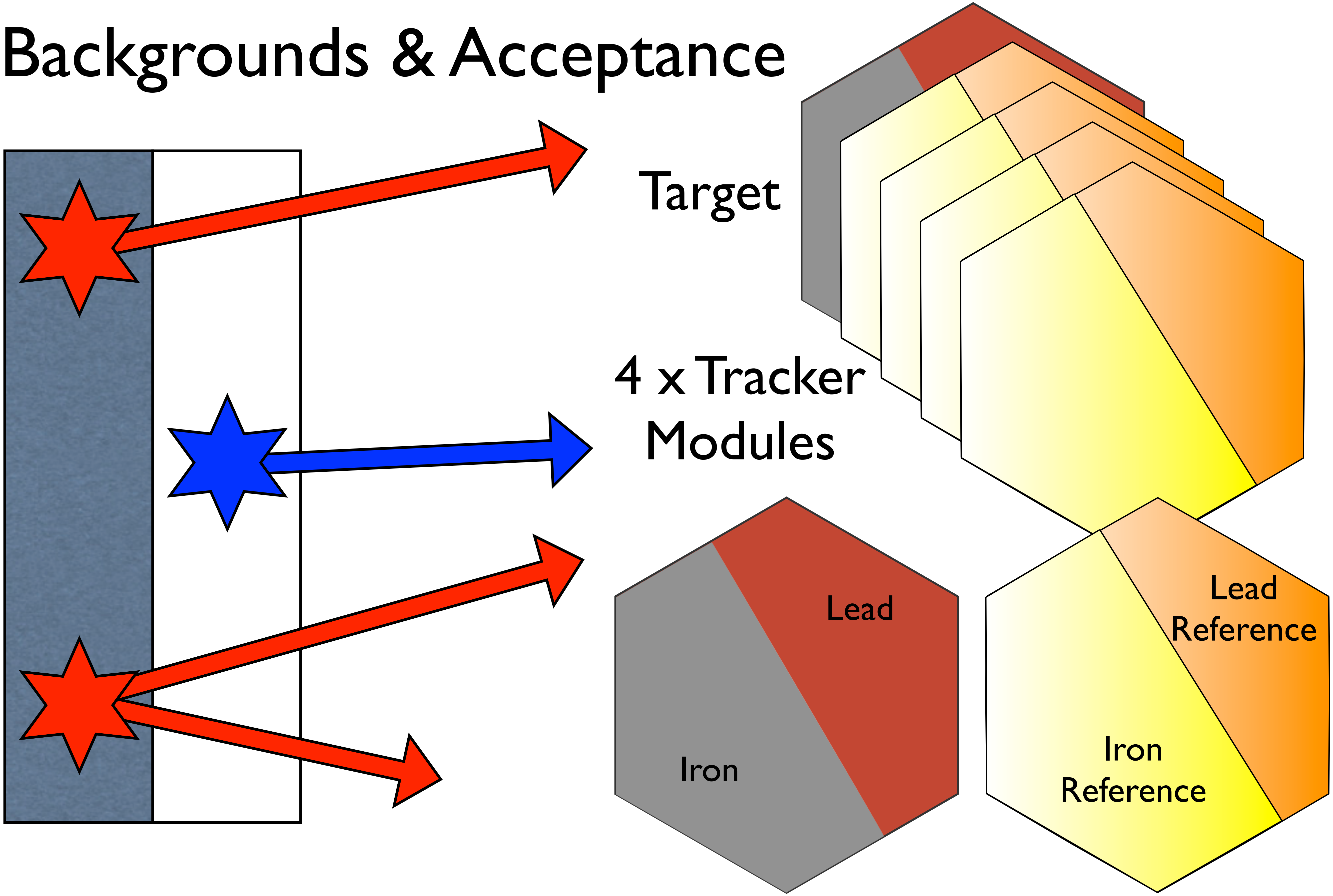
Event Signature & Analysis Technique

$\nu_\mu + N \rightarrow \mu^- + X$



- Event selection criteria:
  - Single Muon track, well reconstructed and matched into MINOS detector.
  - z-position of reconstructed vertex must be near nuclear target.
  - Vertex must be more than 2.5 cm away from materials partition in target.
  - Recoil energy computed calorimetrically.

Backgrounds & Acceptance

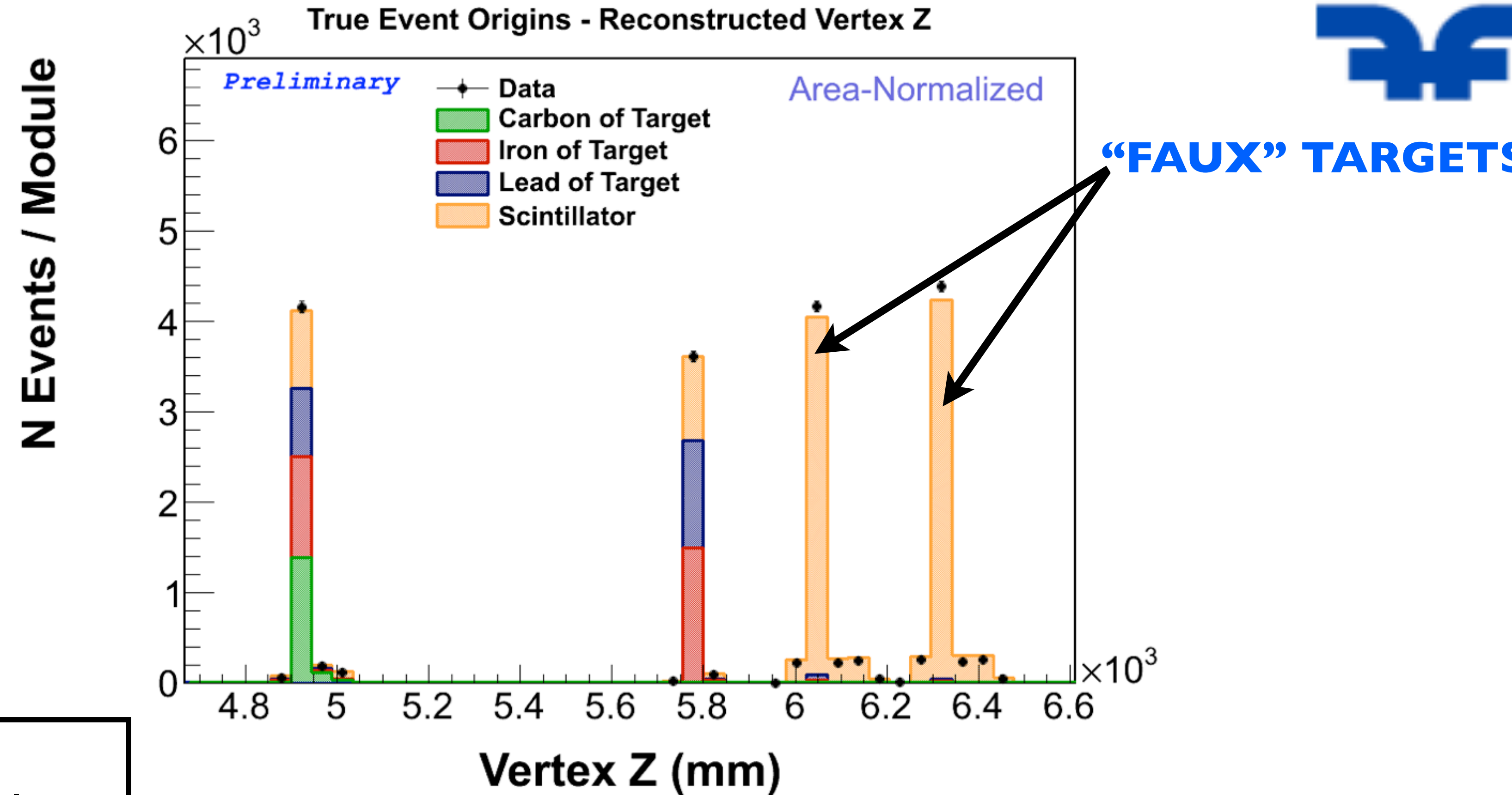


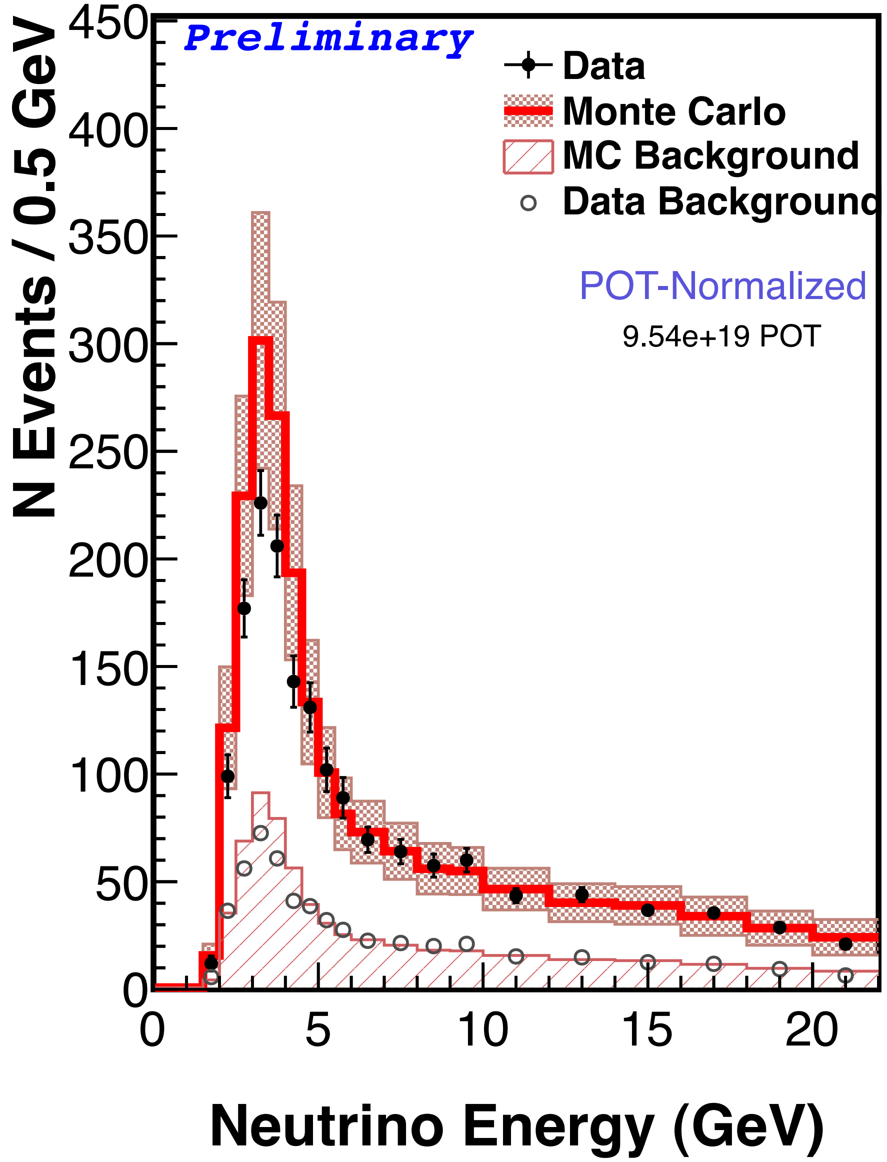
Begin with cross-section ratios to cancel flux and acceptance systematics.

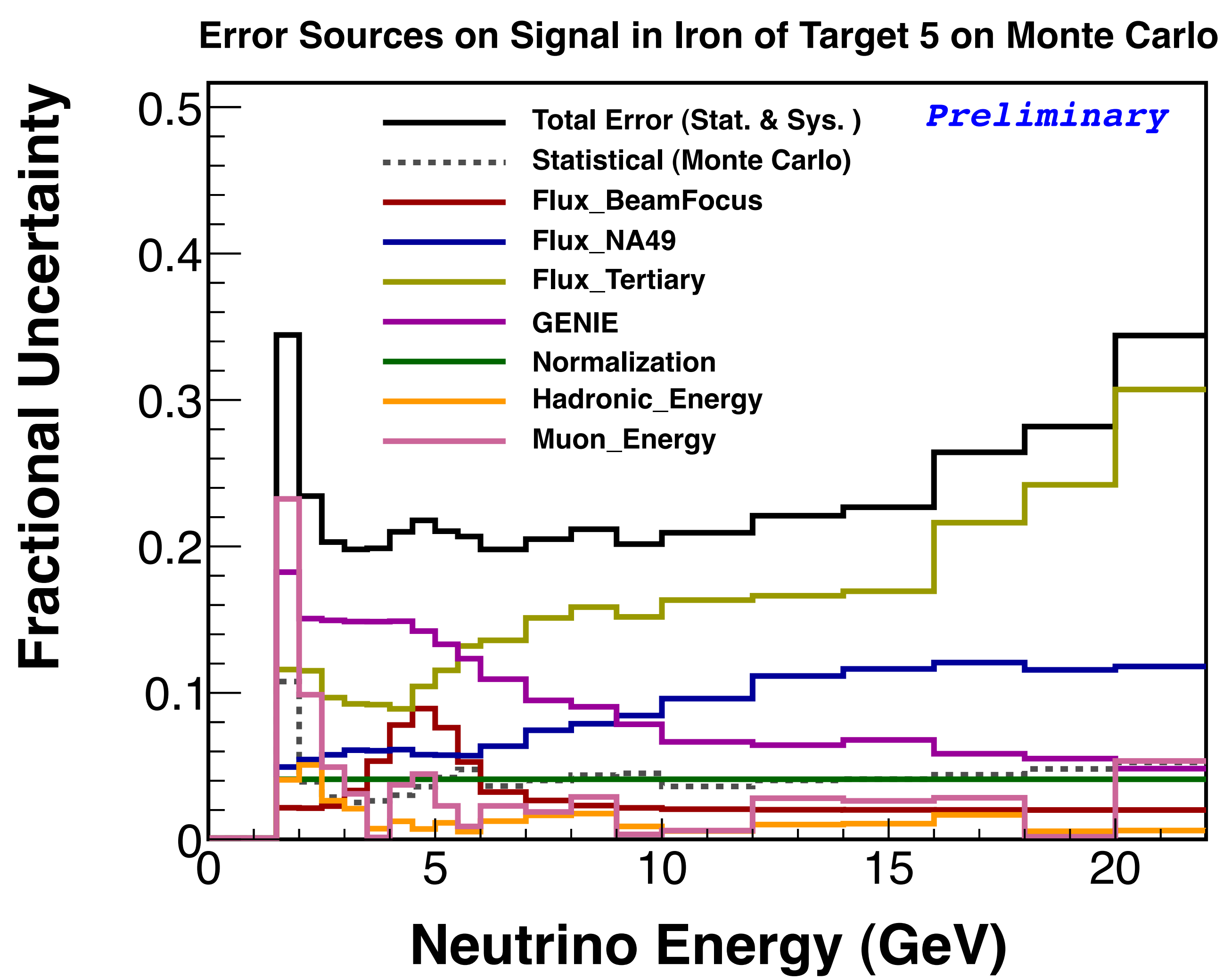
Backgrounds for this analysis

Double ratio of x-sec : (Plastic to cancel x-y, Pb/Fe to cancel z & flux)

$$\frac{\left(\frac{\frac{d\sigma^{Pb}}{dX_i}}{\frac{d\sigma^{CH}}{dX_i}}\right)}{\left(\frac{\frac{d\sigma^{Fe}}{dX_i}}{\frac{d\sigma^{CH}}{dX_i}}\right)}$$







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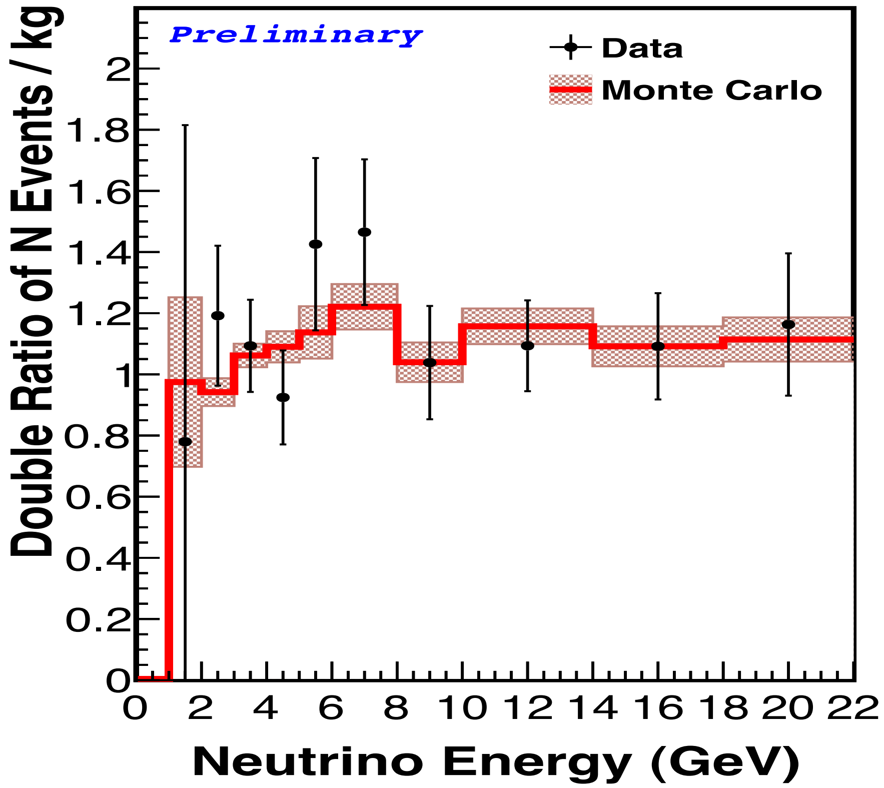
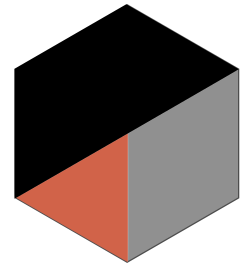
Fermilab

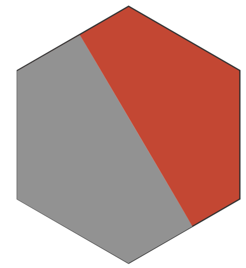
Results - Double Ratios for the nuclear targets

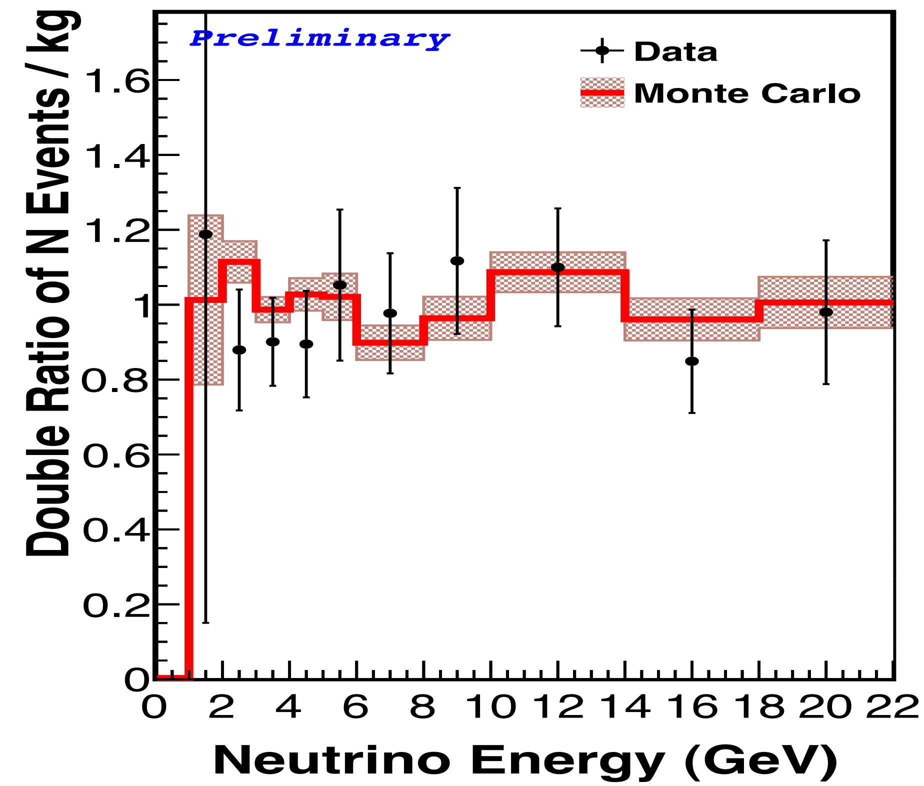
Carbon of Target 3/Iron of Target 3

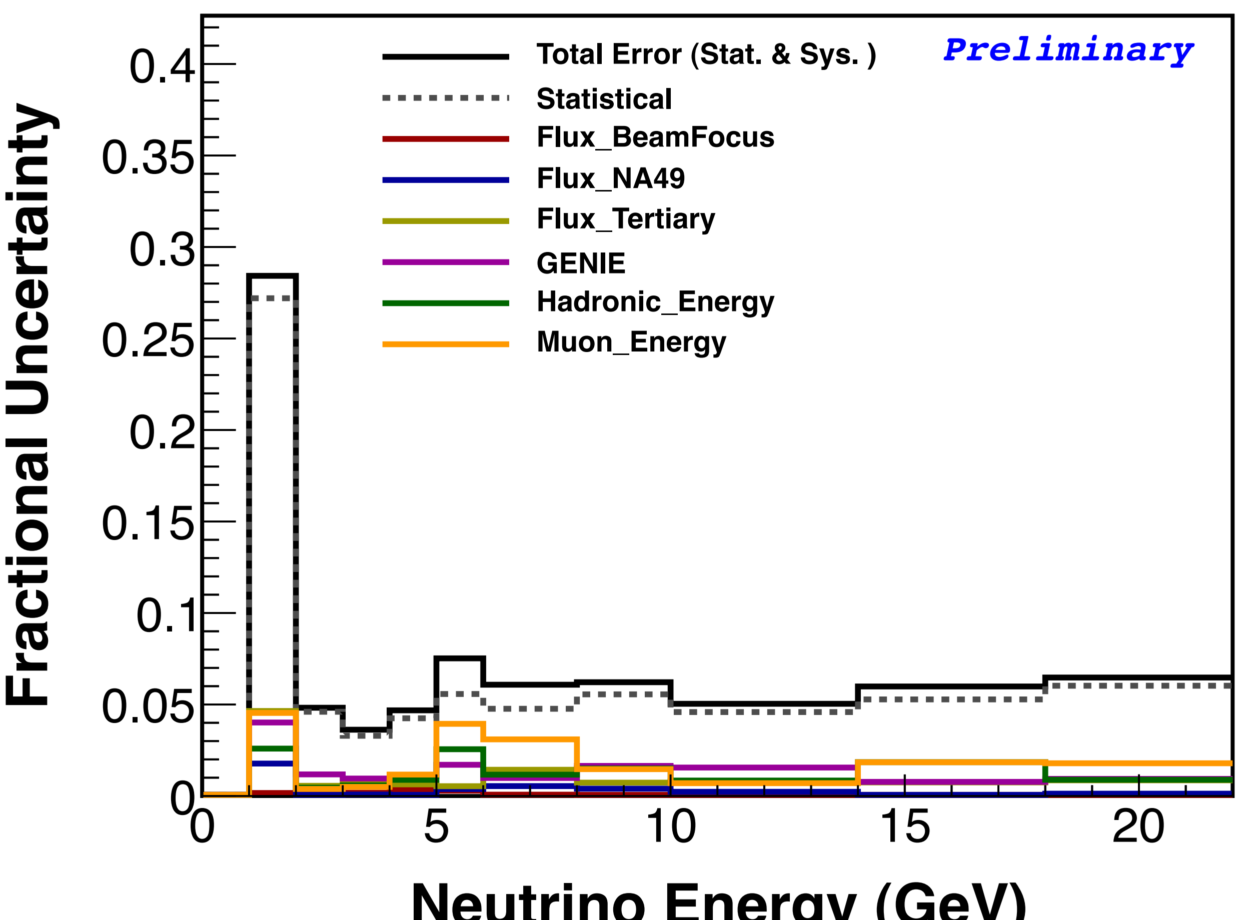


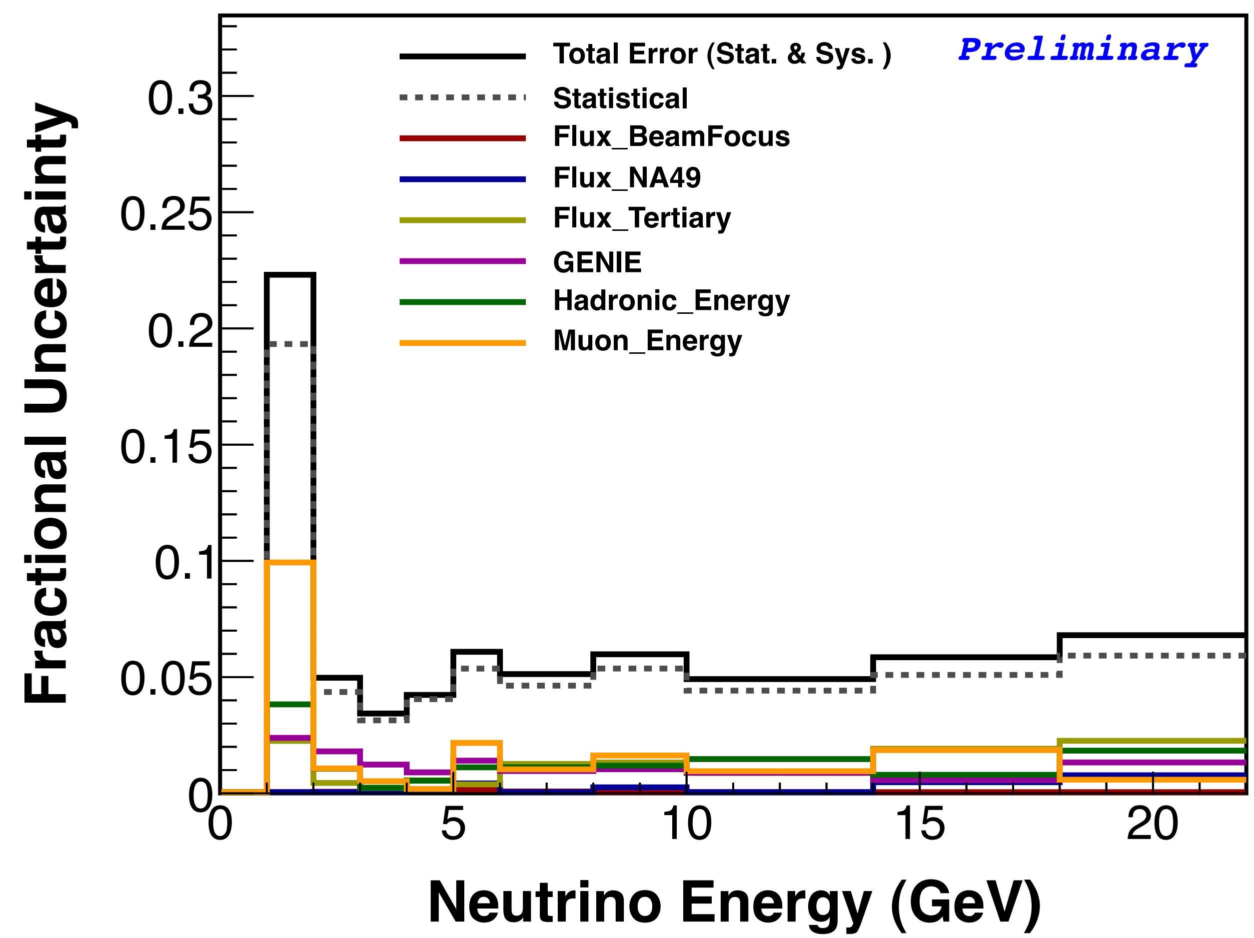


Lead of Target 5/Iron of Target 5

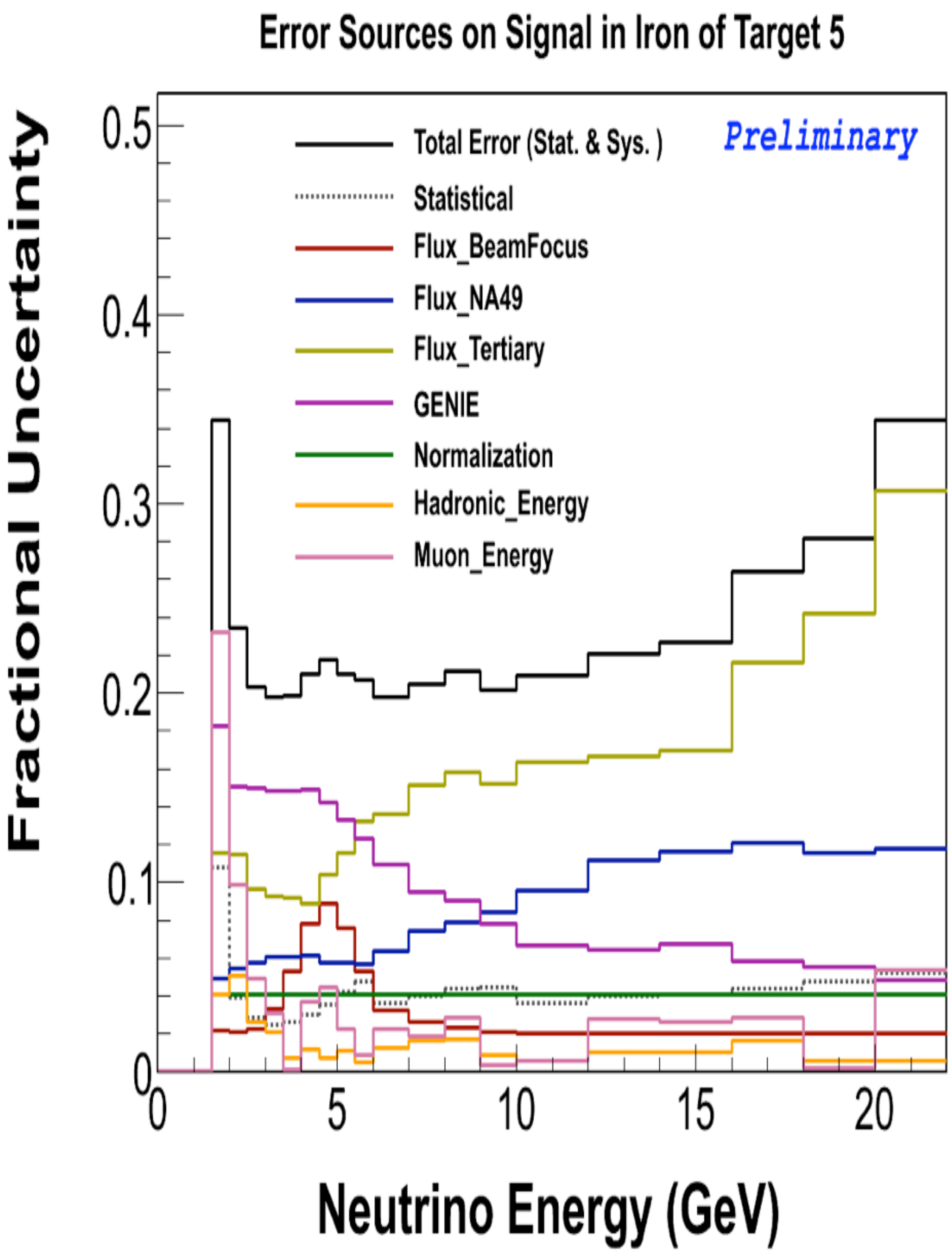


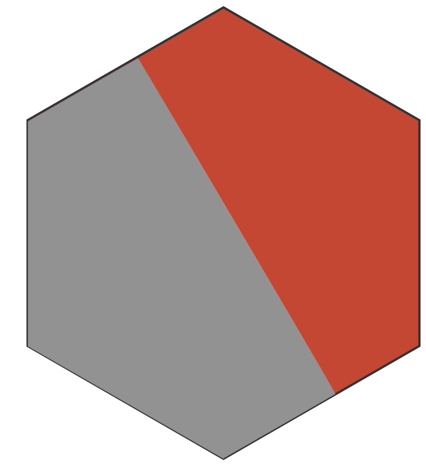




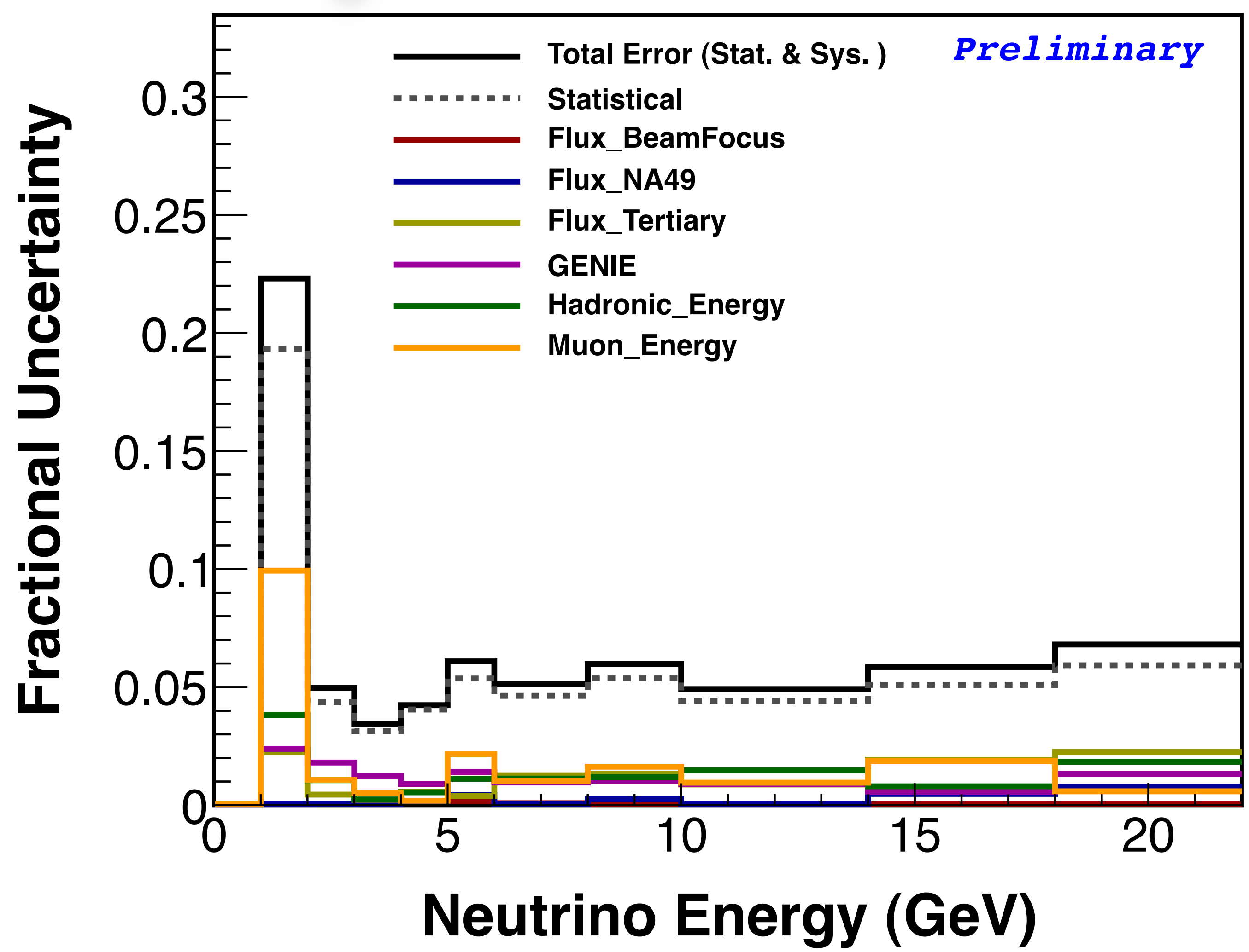


Iron



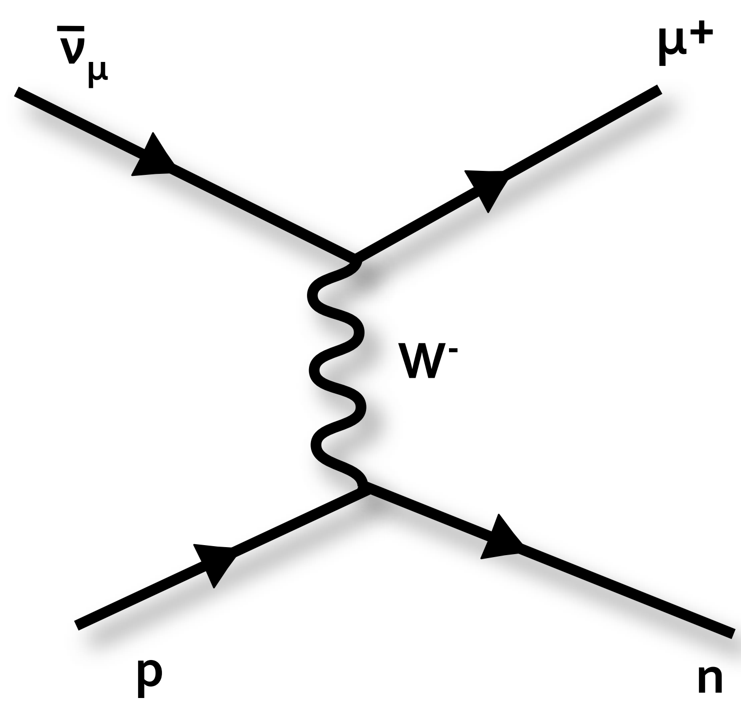


Lead/Iron



The Charged Current Quasi Elastic (CCQE) Analysis with anti-neutrinos

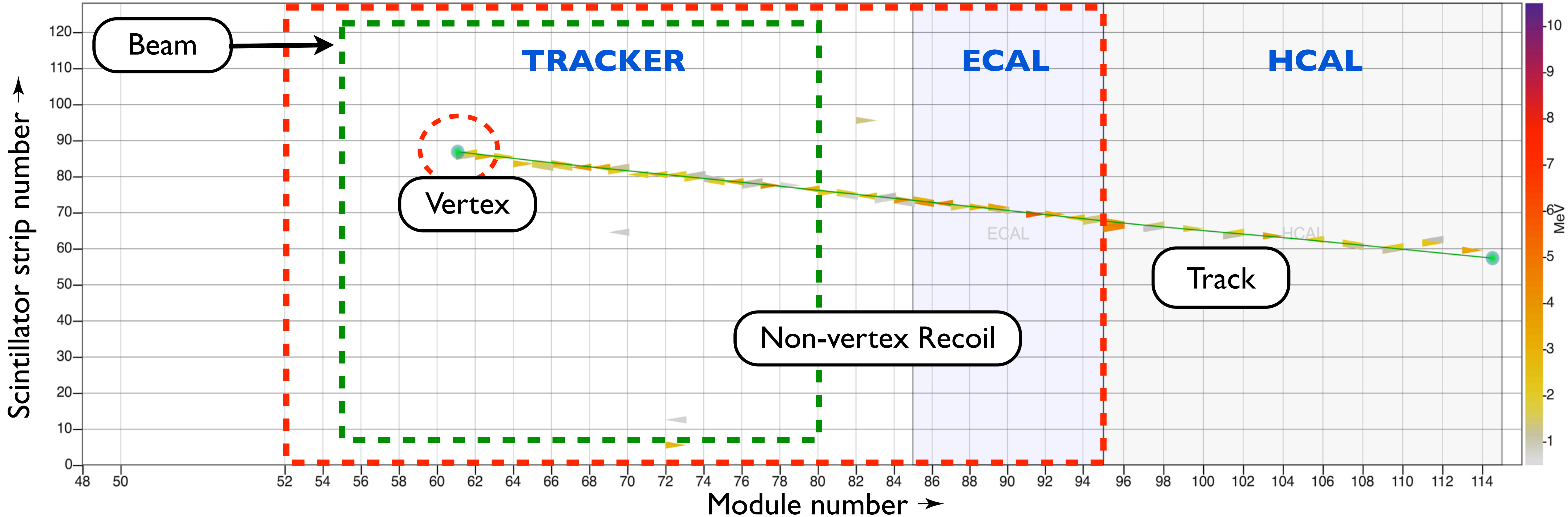
One Track
Plus Nothing !



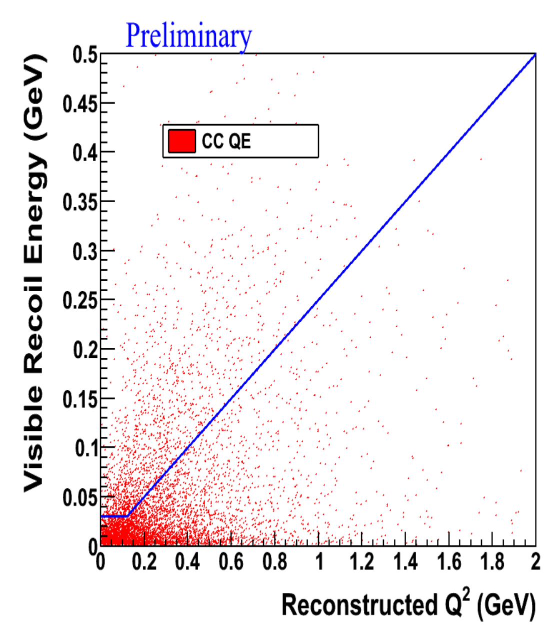
* using only ~ 16% of the accumulated Protons On Target !
* detector partially (55%) built during accumulation of this data

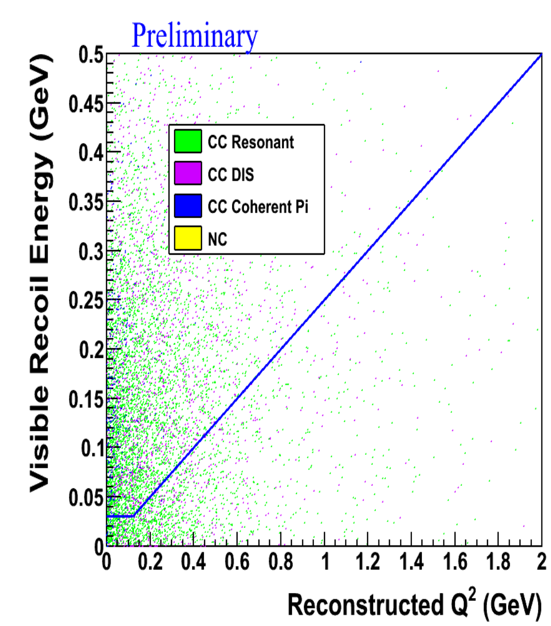
Event Signature & Analysis Technique

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



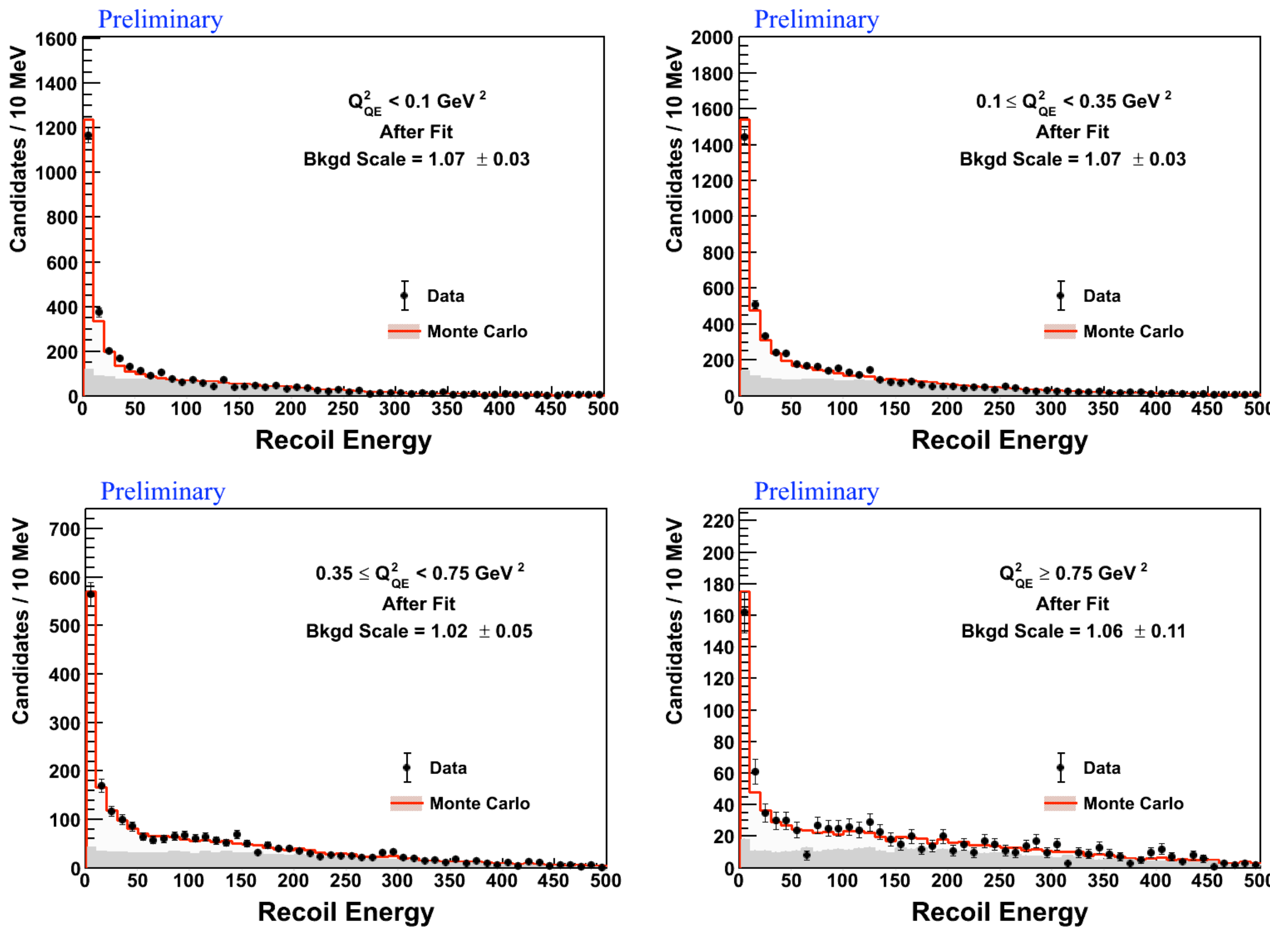
- Event selection criteria :
- Single anti-Muon track, well reconstructed and matched into MINOS detector.
- Reconstructed vertex inside fiducial tracker region of partially-built detector (fiducial mass = 2.6 tons).
- Number of shower-like activity regions <= 1 (neutron may/may not interact).
- Cut on recoil energy away from vertex (10 cm radius) as a function of Q^2.
- Reconstructed neutrino energy < 10 GeV.

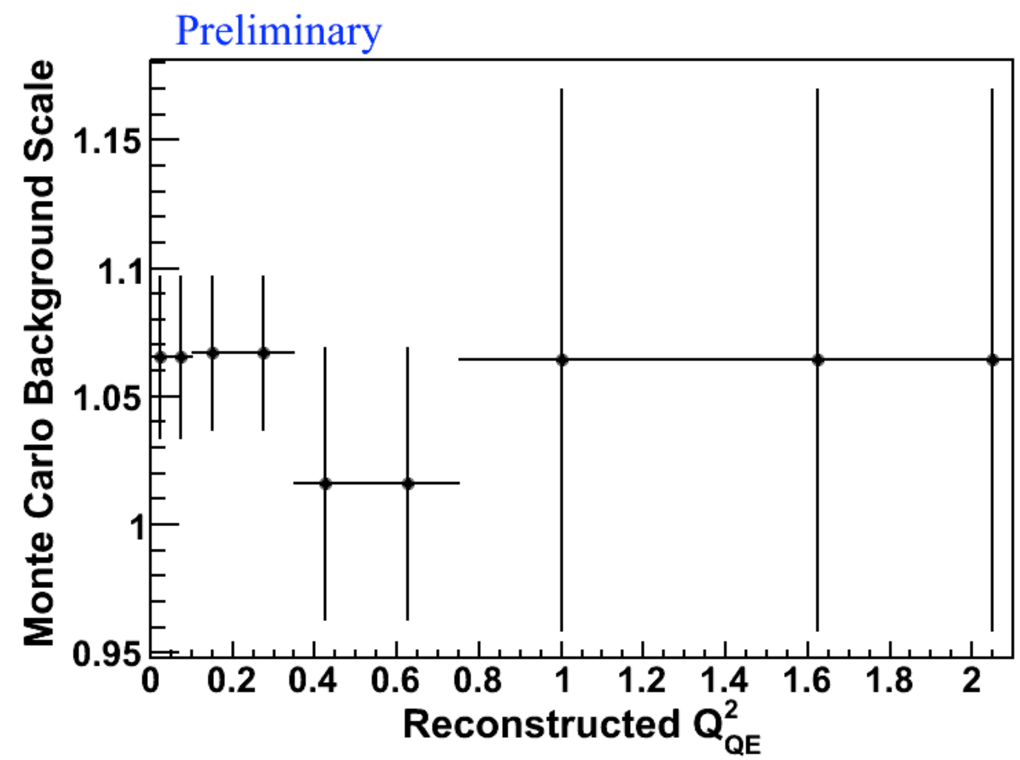


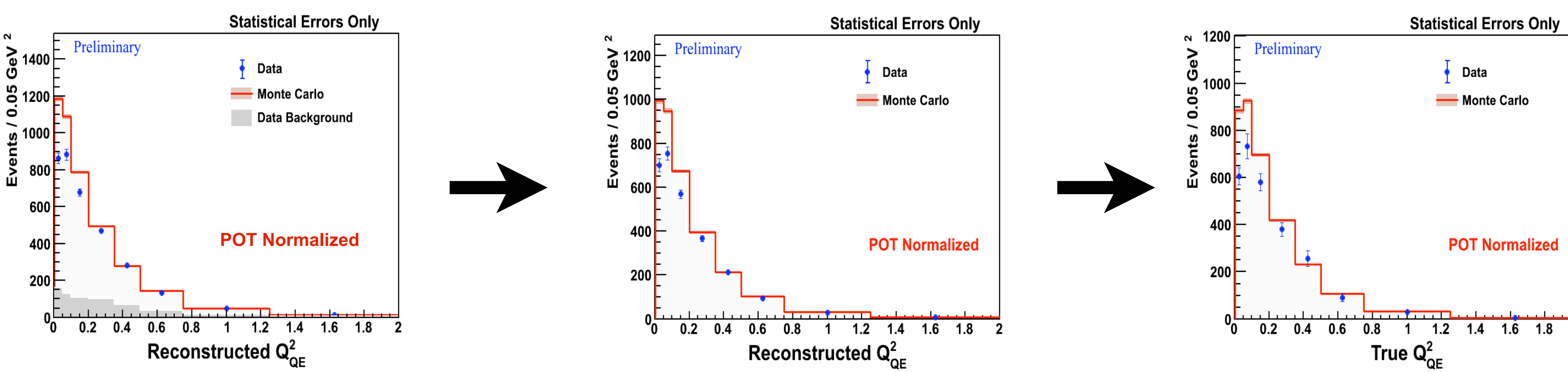


Background estimation technique

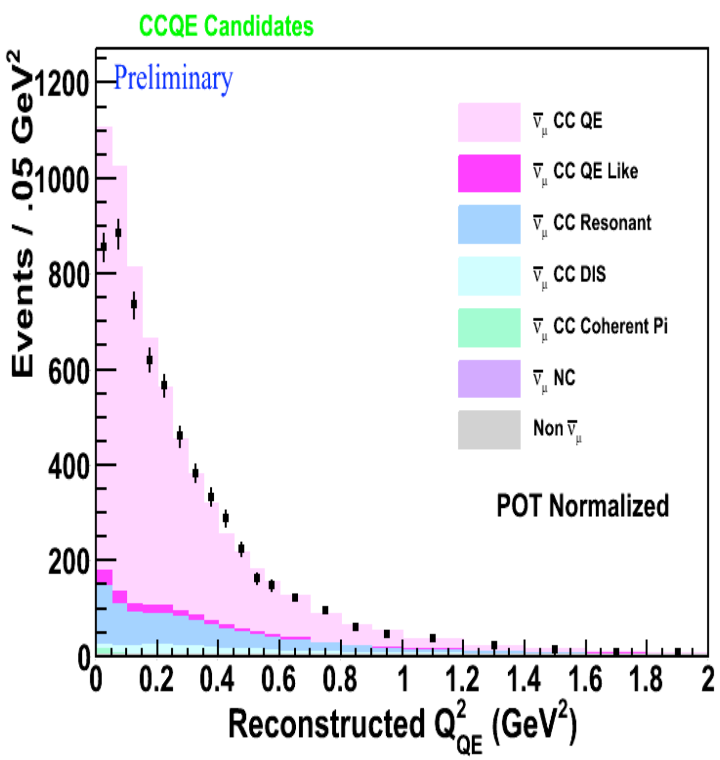
Scale backgrounds in the recoil distributions in MC to match data.

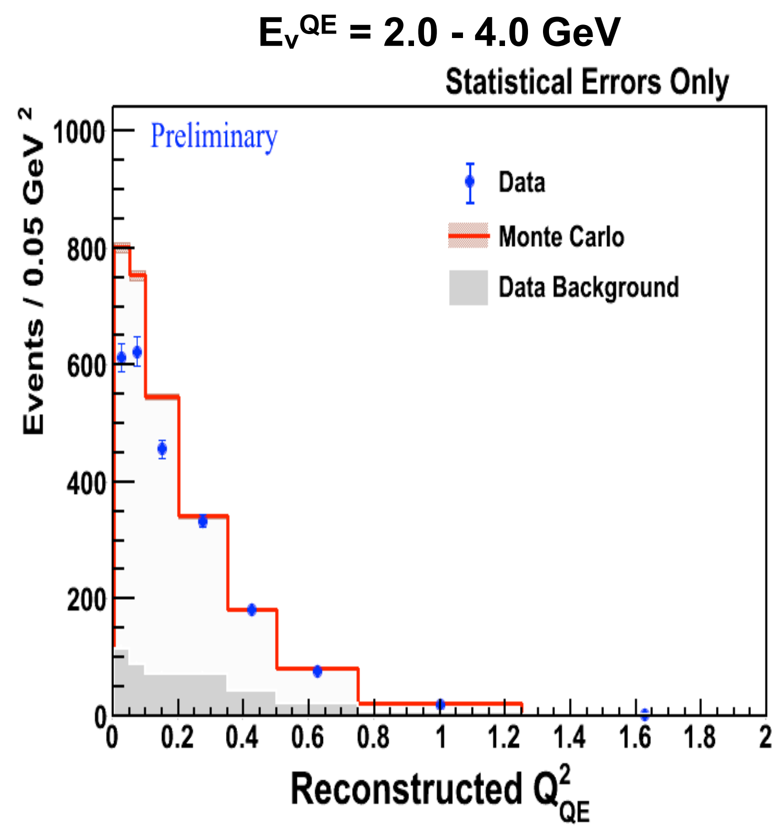


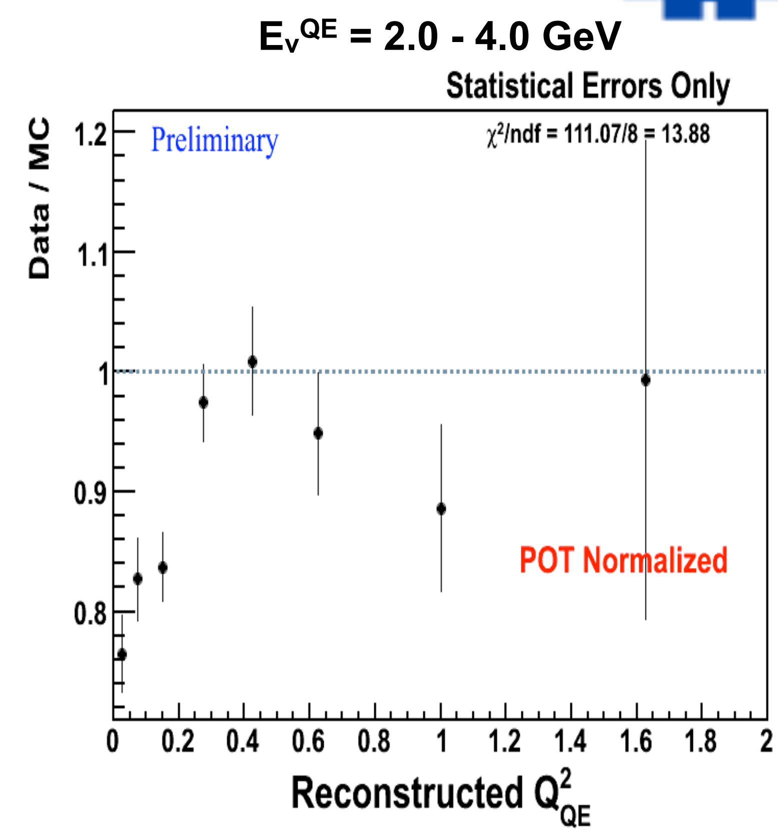


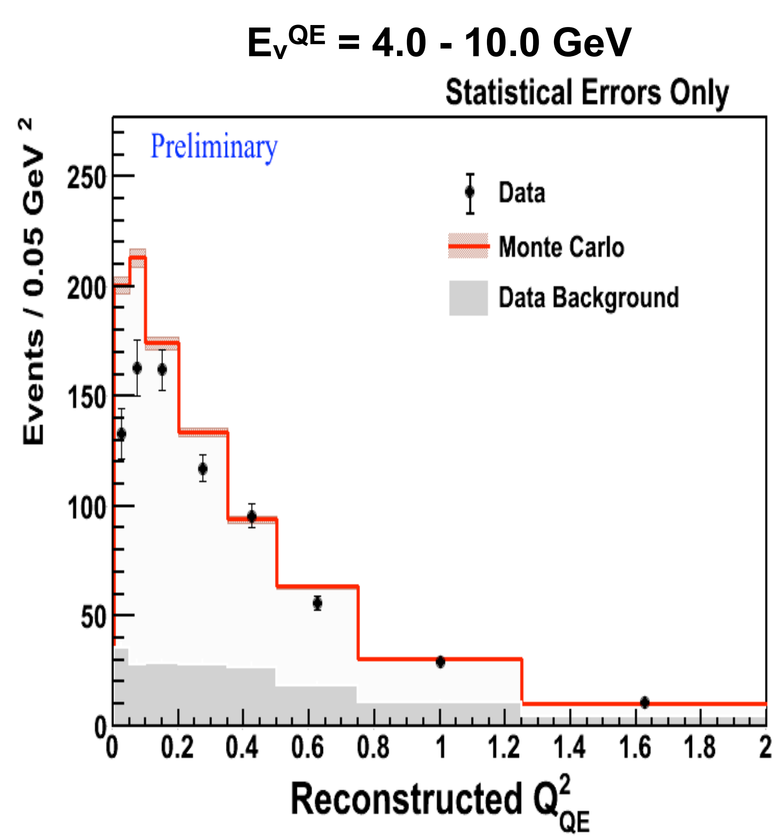


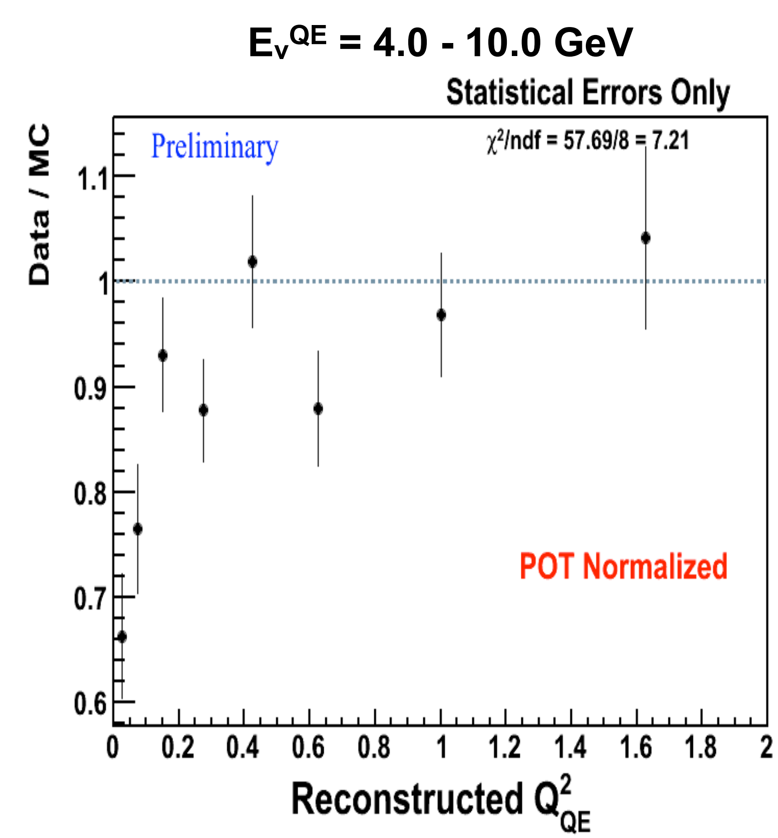
Four-momentum transfer in bins of anti-neutrino energy









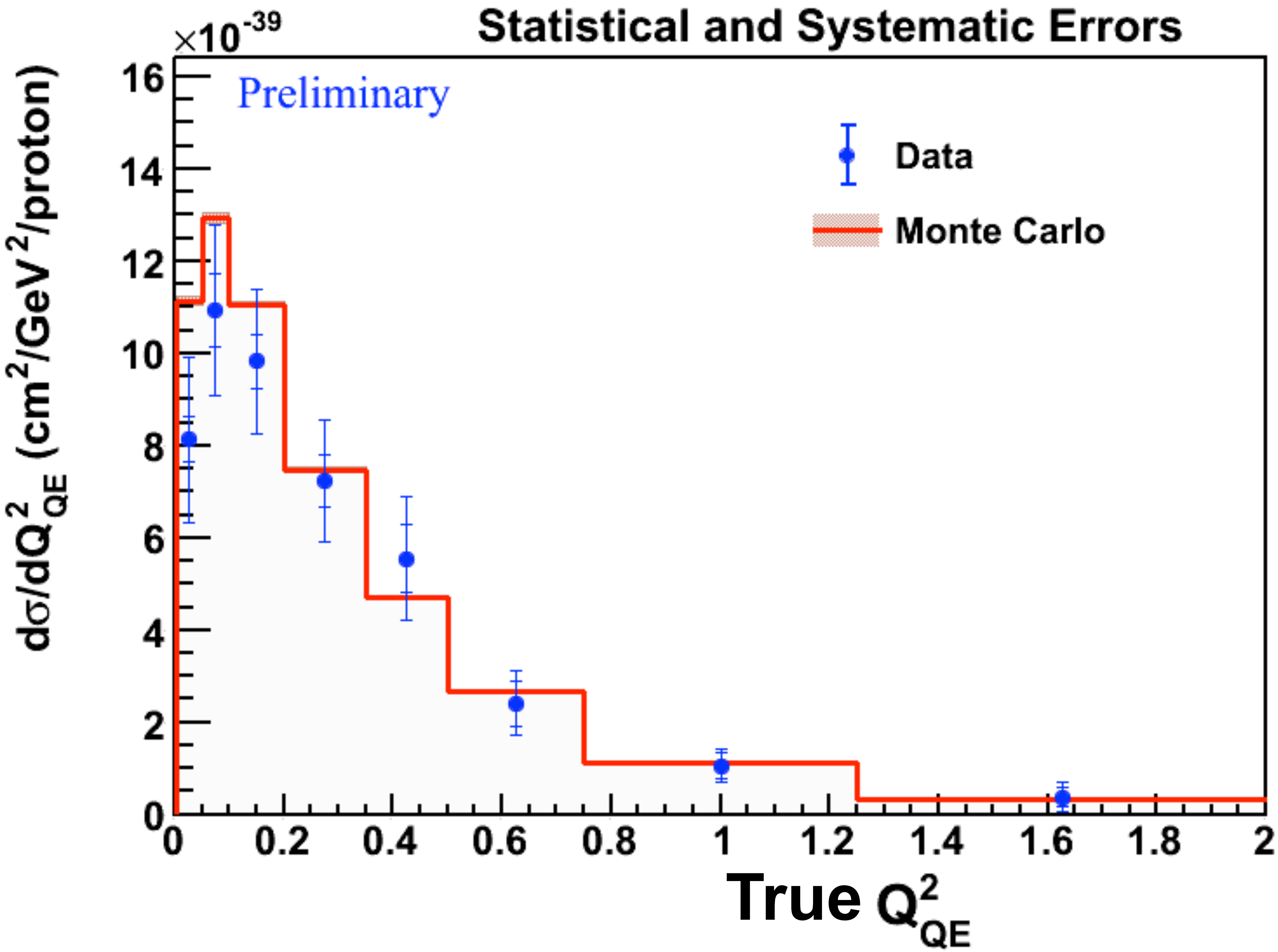


High purity even before background subtraction.

Differential cross-section (dσ/dQ²)

$$\left(\frac{d\sigma}{dQ^2}\right)_i = \frac{1}{\epsilon_i\,(\Phi T)\,\Delta Q_i^2} \times \sum_j \left(M_{ij}\left(N_{\mathrm{data},j} - N^{\mathrm{bkdg}}_{\mathrm{data},j}\right)\right)$$

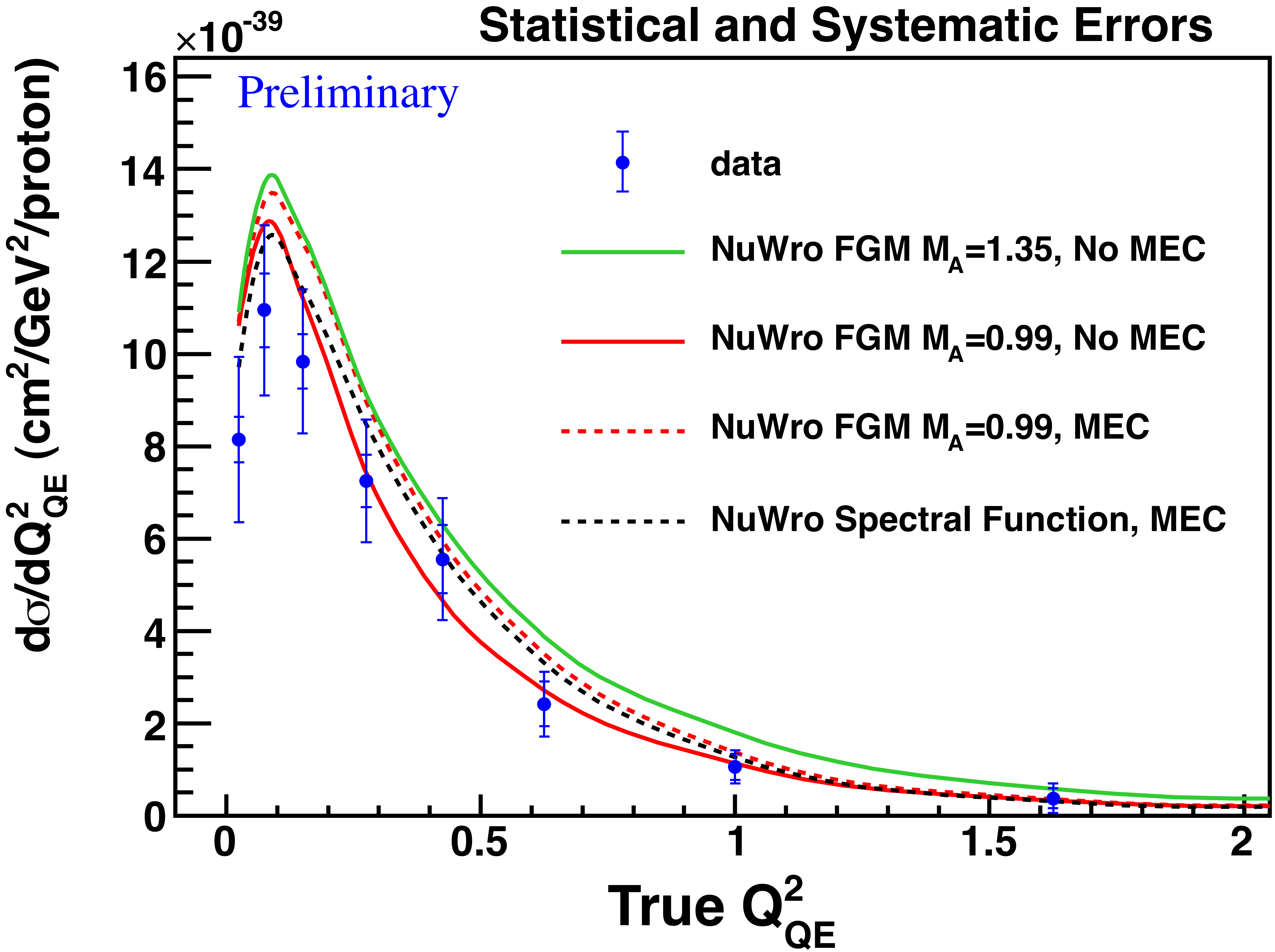
Data compared to GENIE event generator (used by MINERvA)



GENIE 2.6.2; Model M_A = 0.99 GeV

www.genie-mc.org

Data compared to NuWro event generator

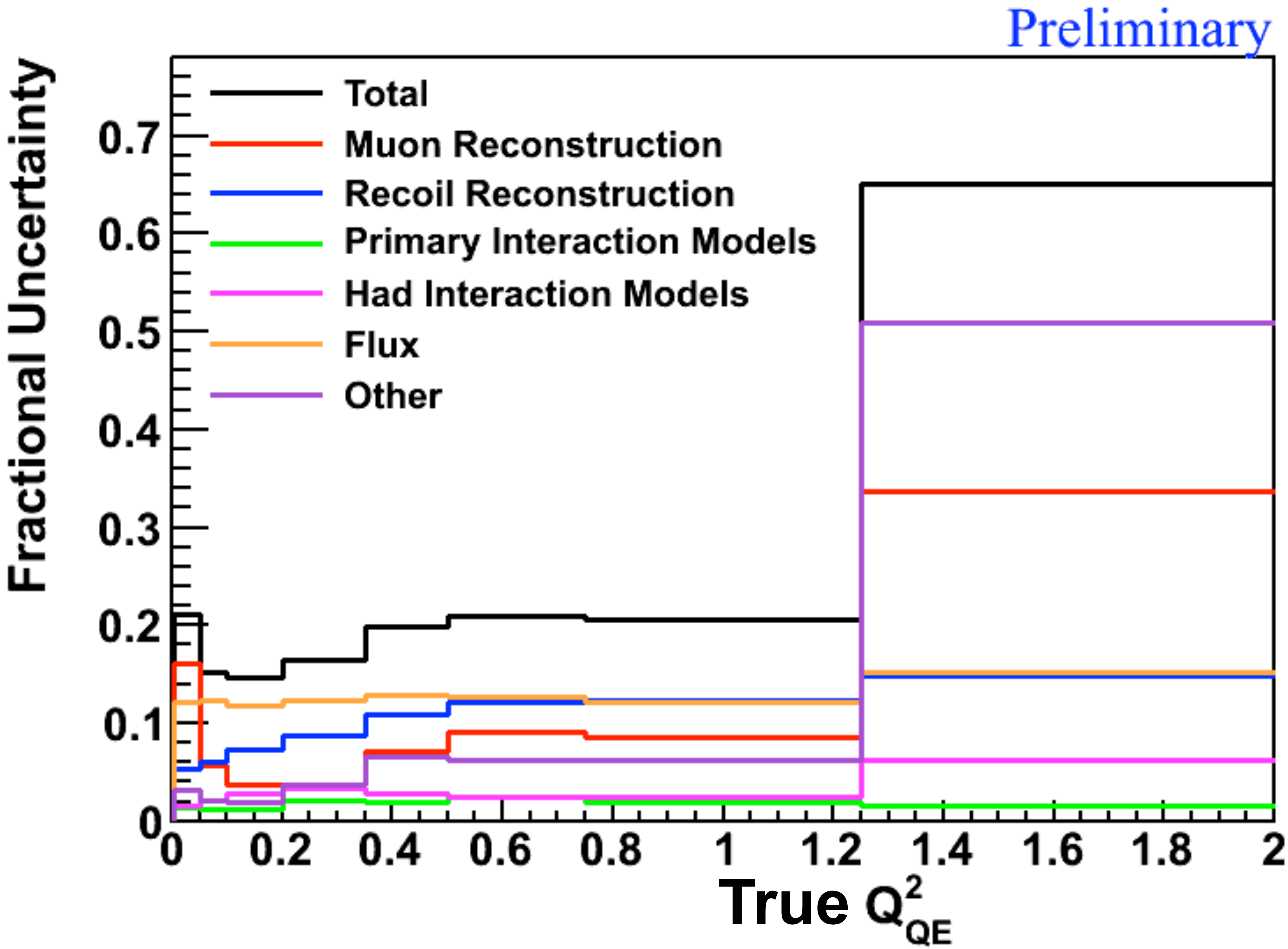


MEC model: Bodek, Budd, Christy. Eur. Phys. J. C(2011) 71:1726

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

Data seems consistent with a Fermi Gas Model with M_A=0.99 and no MEC.

dσ/dQ^2 Systematic Uncertainties on *Data*



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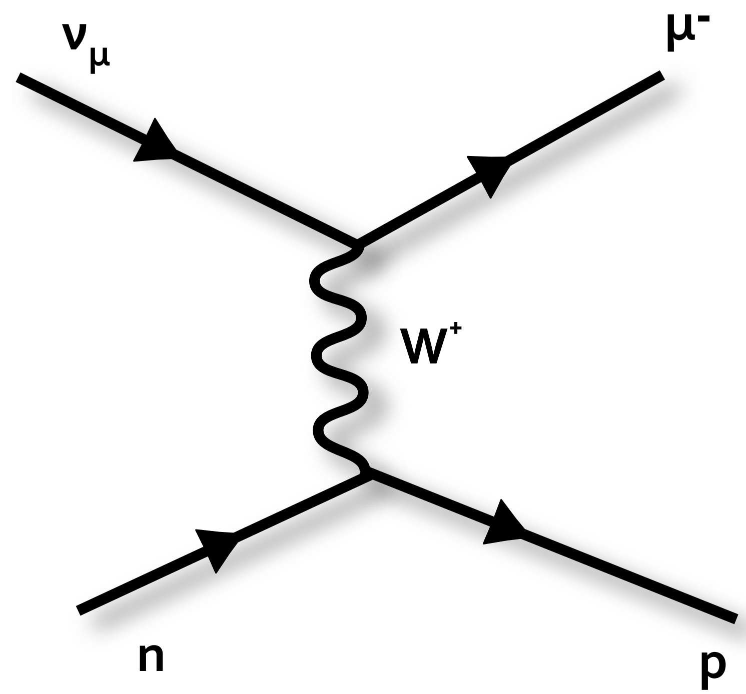
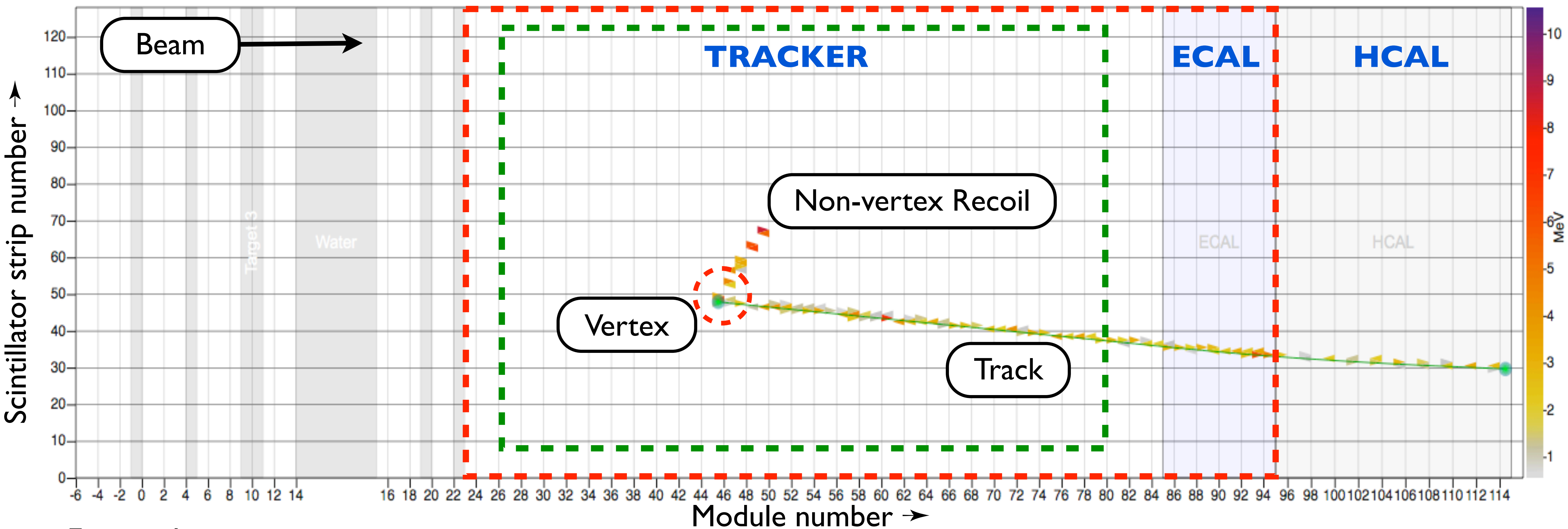


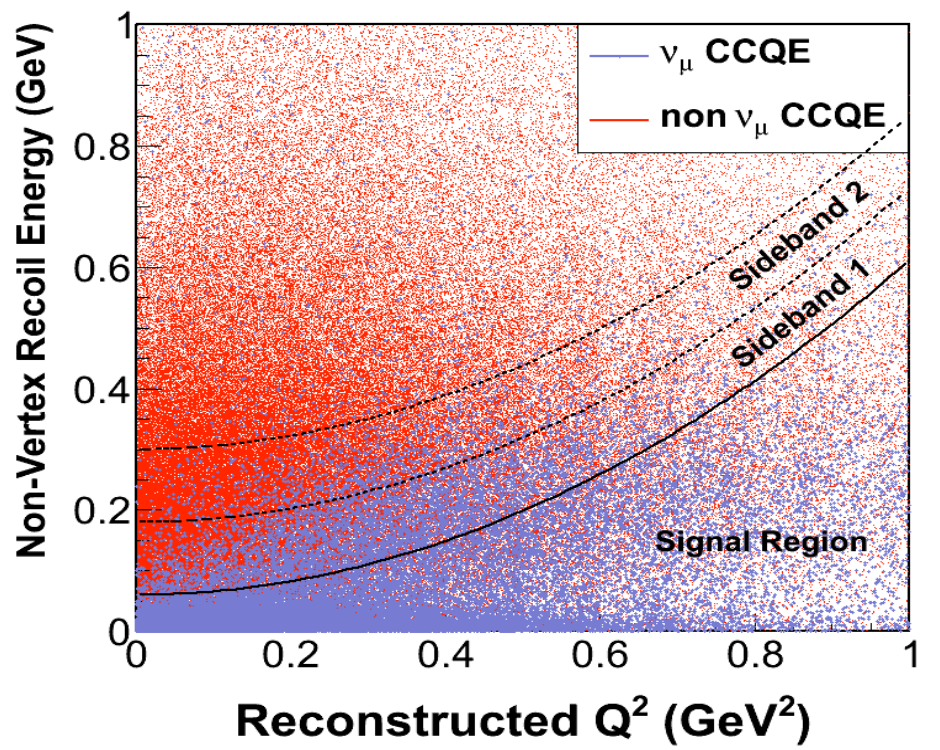
* using only ~ 25% of the accumulated Protons On Target !

Event Signature & Analysis Technique

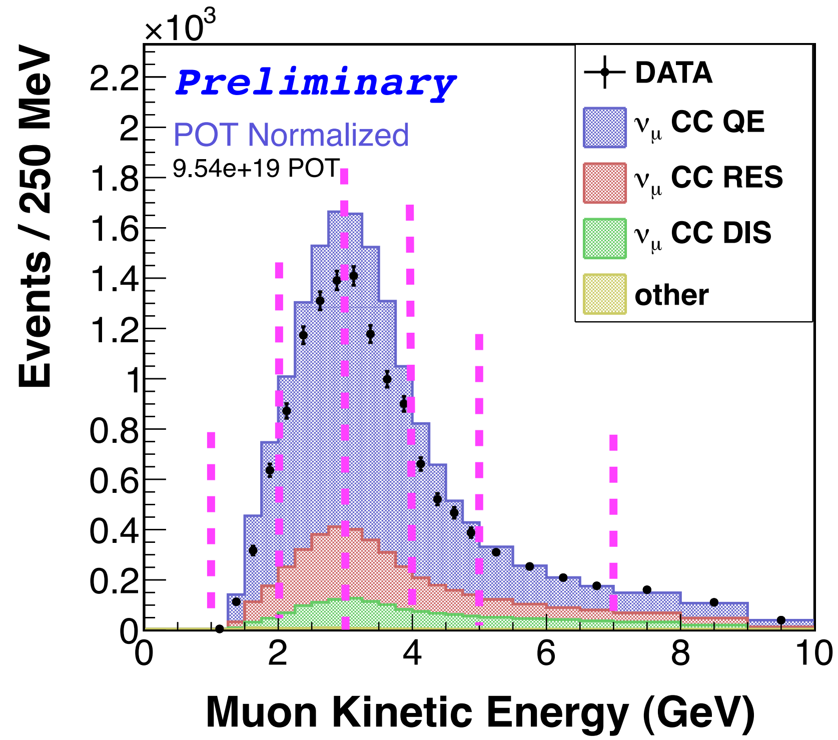
$\nu_\mu + n \rightarrow \mu^- + p$

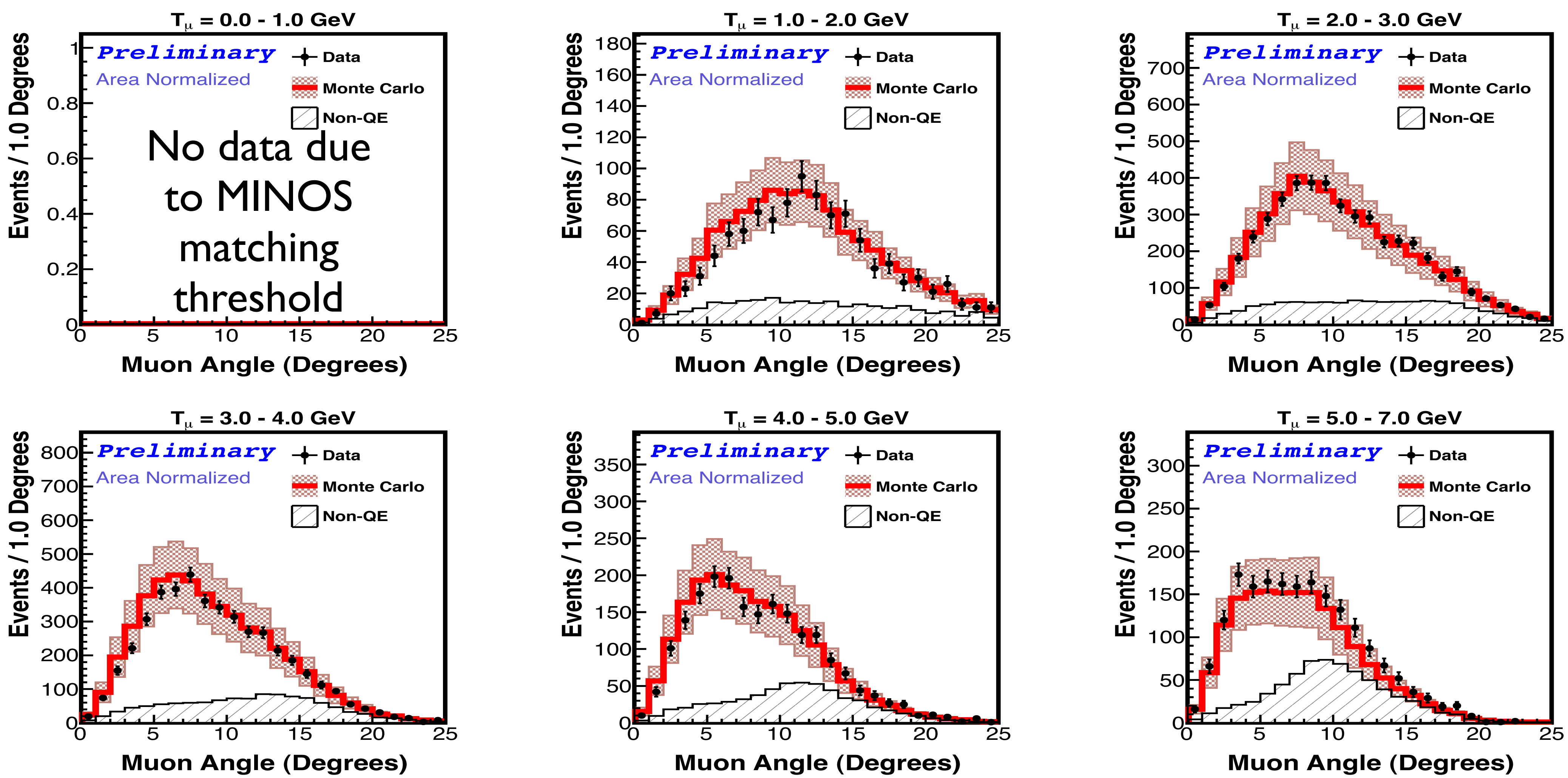


- Event selection criteria :
  - Single Muon track, well reconstructed and matched into MINOS detector.
  - Reconstructed vertex inside fiducial tracker region of detector (fiducial mass = 5.4 tons).
  - Number of shower-like activity regions <= 2.
  - Cut on recoil energy away from vertex (10 cm radius) as a function of Q^2.
  - Reconstructed neutrino energy < 10 GeV.

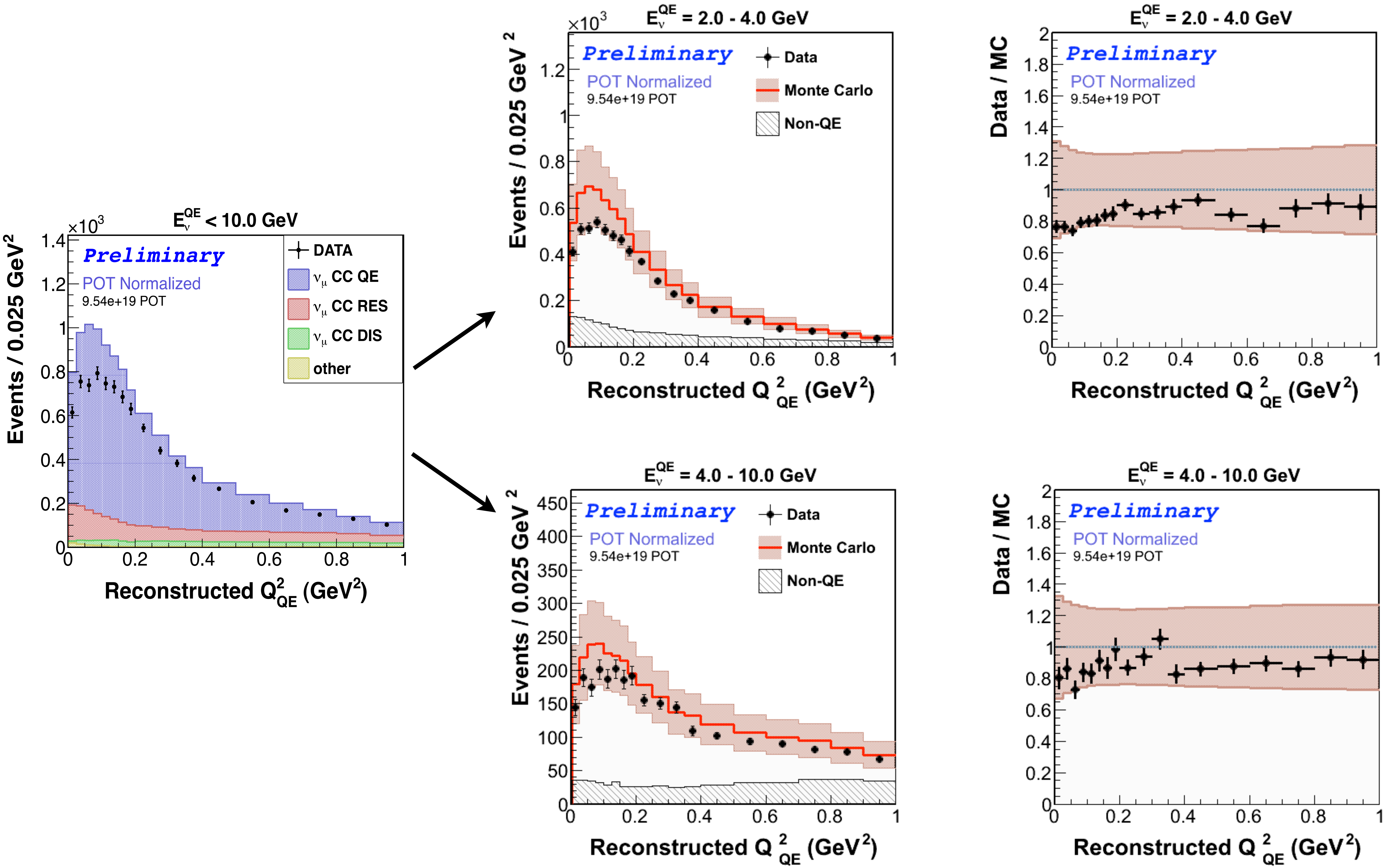


Muon kinematics from CCQE events

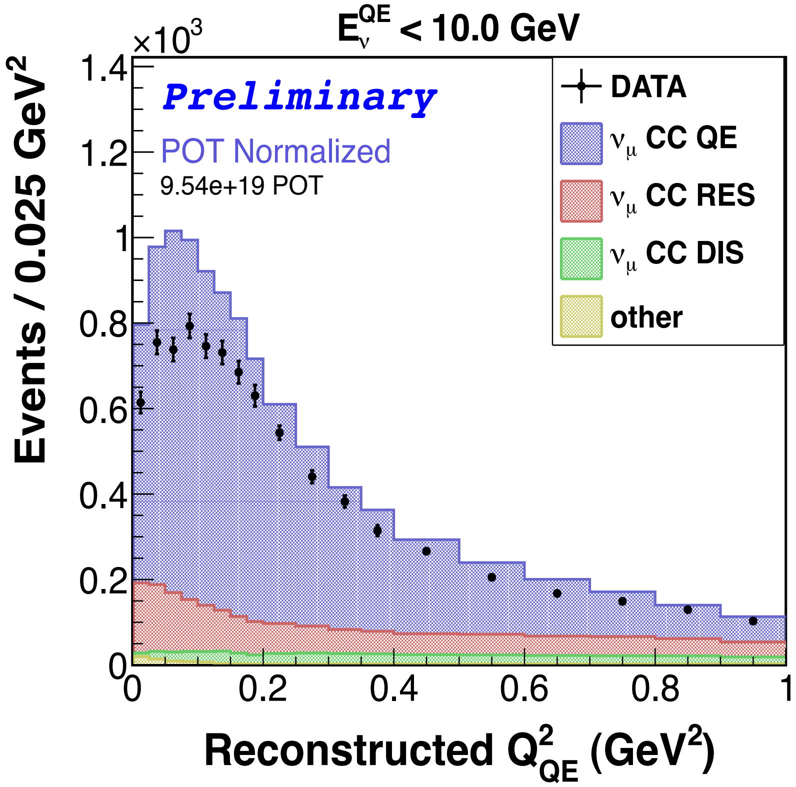


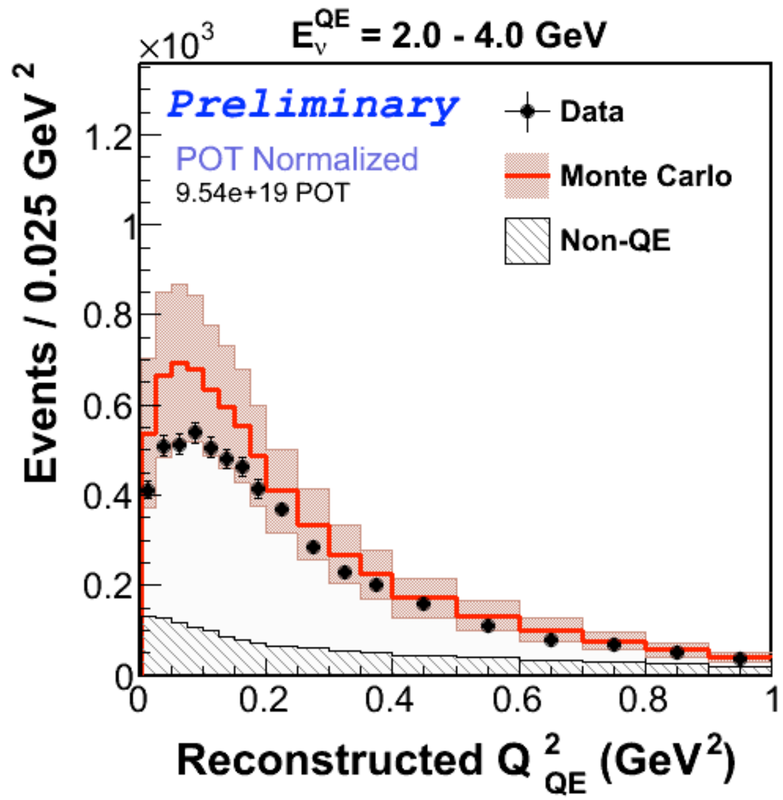


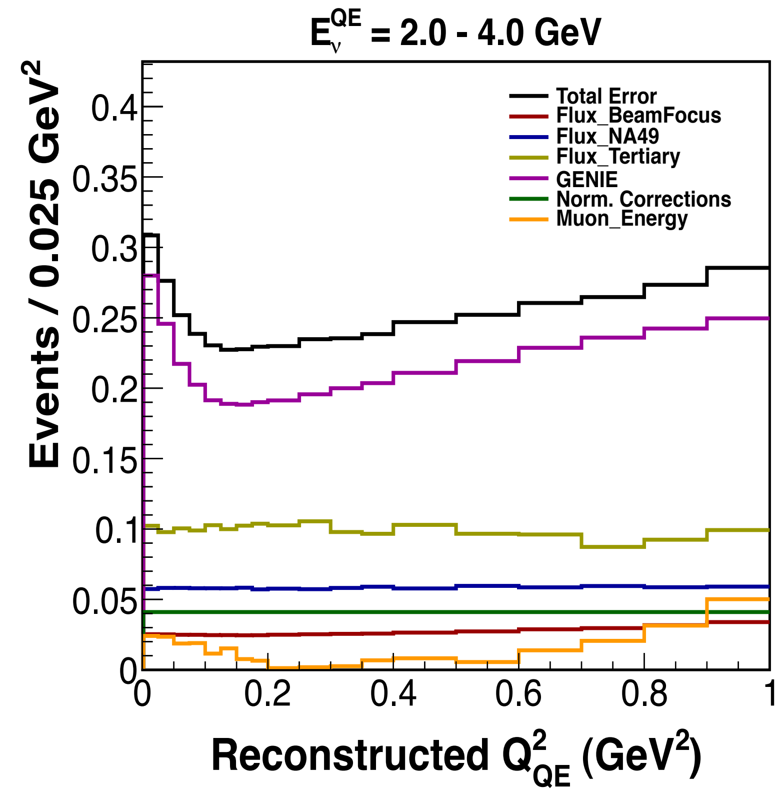
Four-momentum transfer in bins of neutrino energy

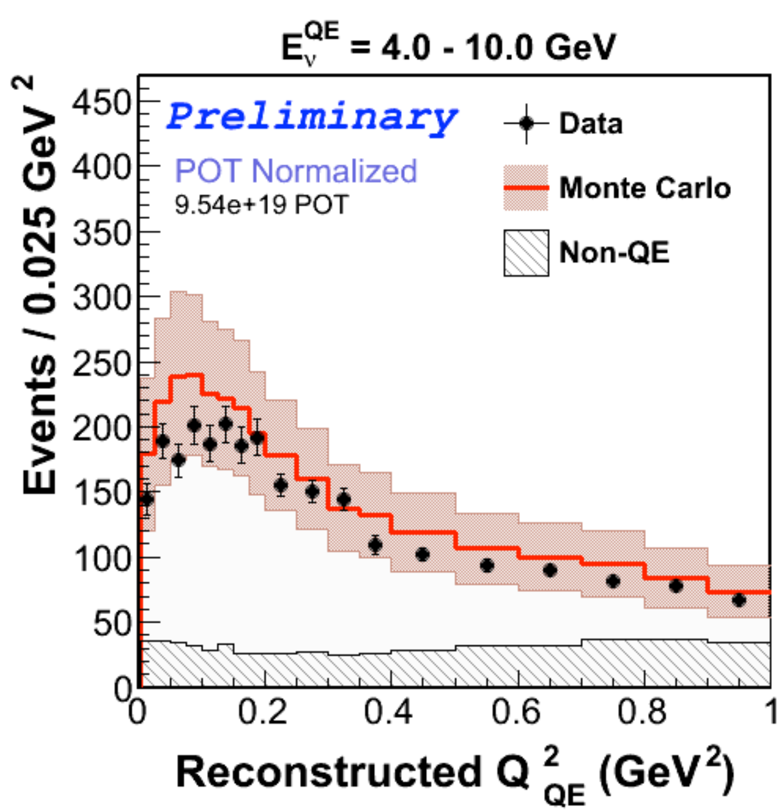


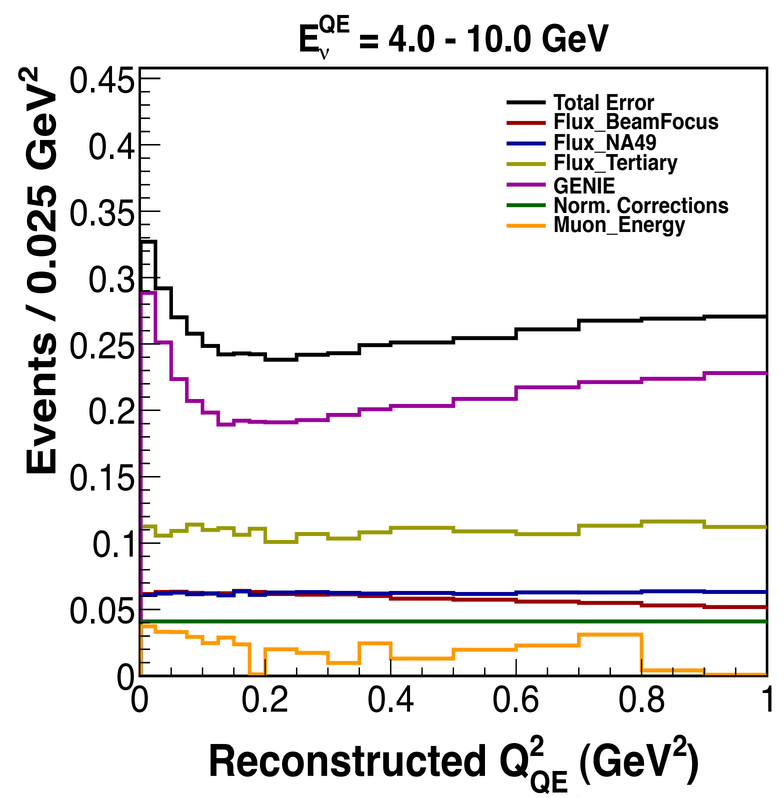
Four-momentum transfer - systematic uncertainties











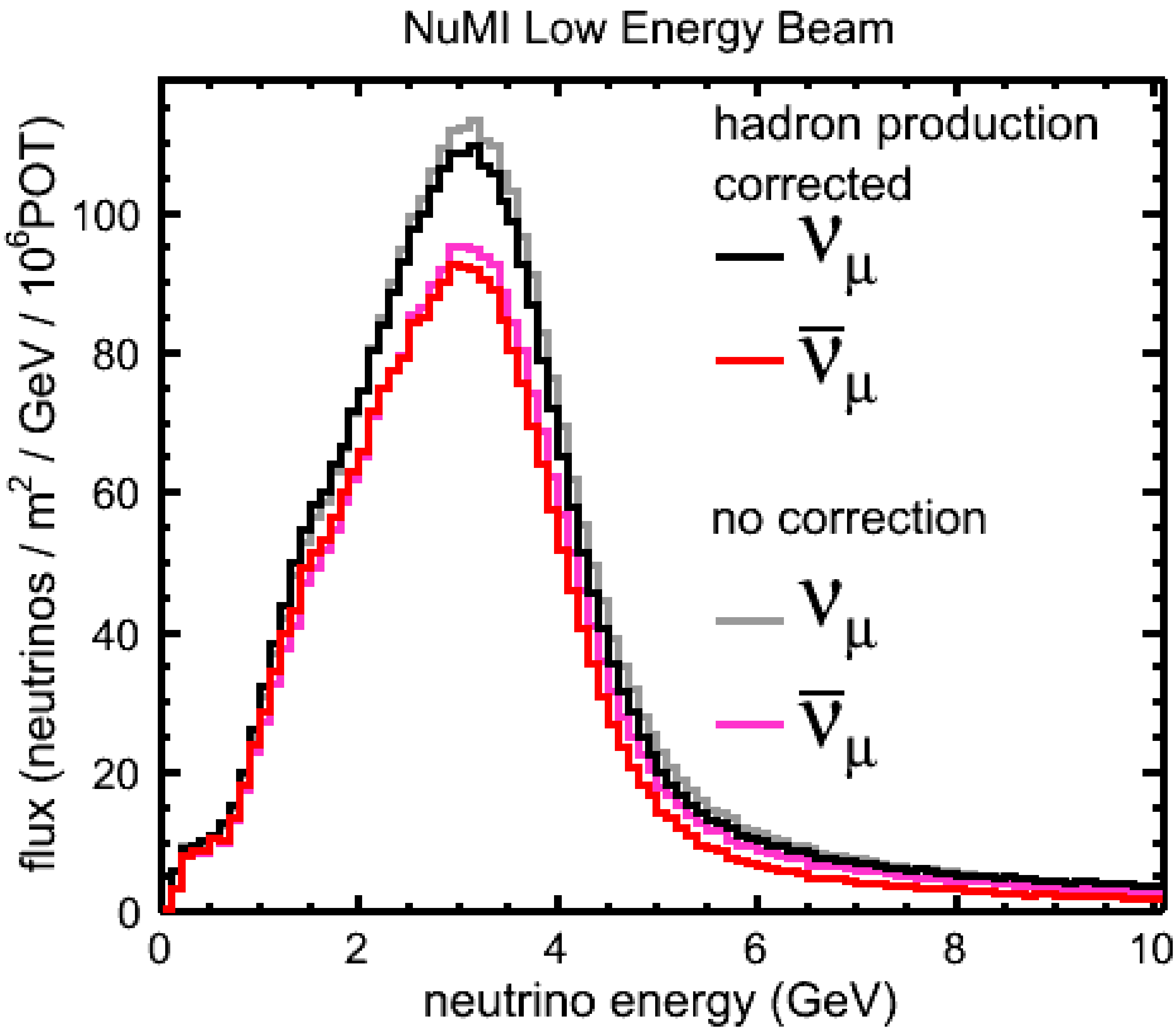
Conclusions and Outlook

- MINERvA has gotten off to a good start via its first Physics analyses results
  - First iteration for these analyses are almost complete. Future iterations involve re-optimizations, reductions of systematic uncertainties.
    - Analyze with more data (next anti-neutrino data set is for complete detector).
  - Initiate a virtuous loop by providing feedback to theoretical community.
    - Better theoretical models for neutrino interactions expected from the first round of MINERvA analyses, will be used broadly.
  - A large array of MINERvA analyses are currently in the offing :
    - CC quasi-elastic where proton is tracked (higher Q^2).
    - Electromagnetic final states.
    - Pion production channels.
    - Look at vertex activity in CC quasi-elastic analyses - np-nh models.
- So this is only the beginning - stay tuned and glued to http://minerva.fnal.gov !

Thank you for your time !

BACKUP SLIDES

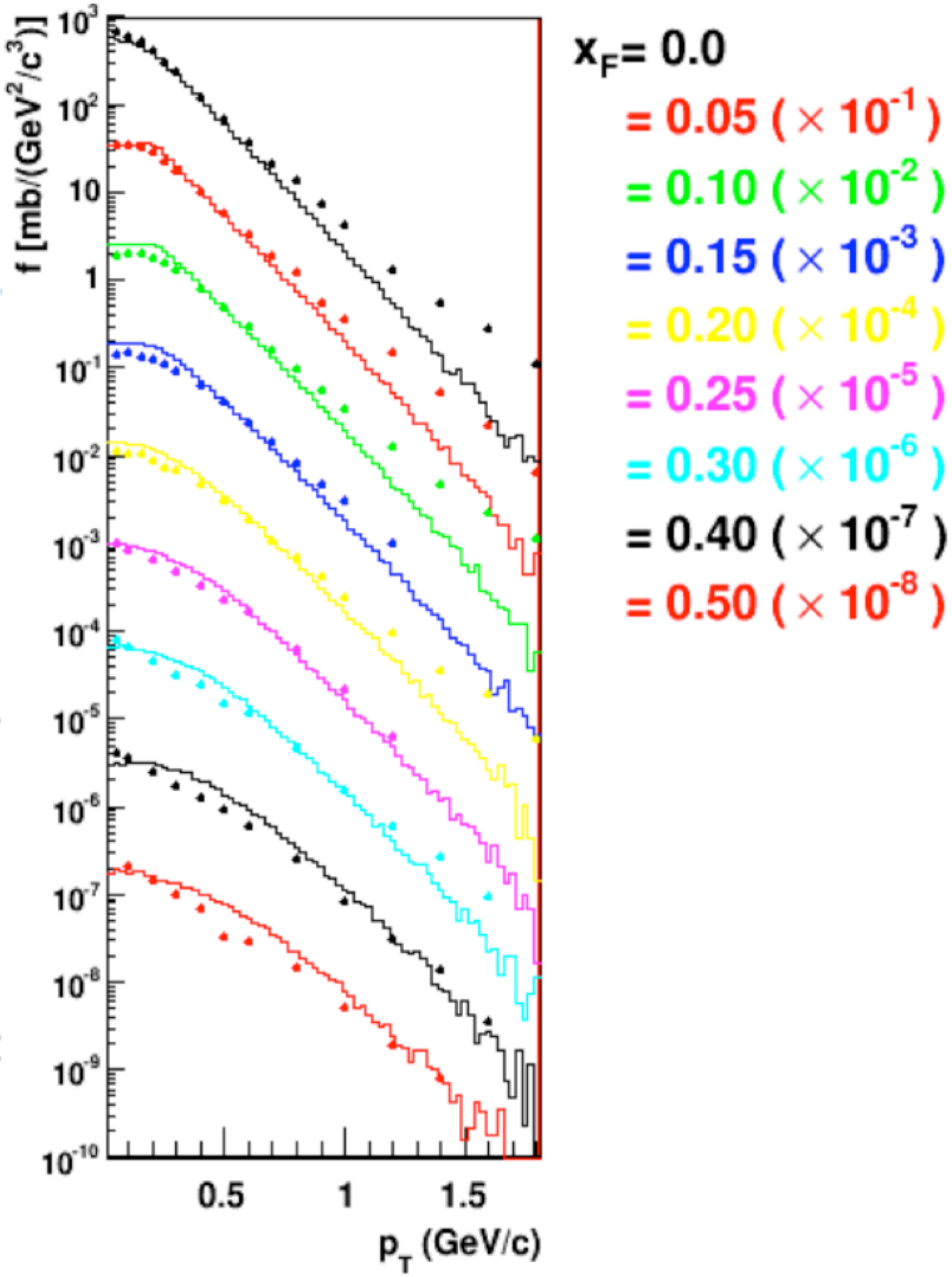
NuMI Low Energy Flux



Here is where MINERvA steps in !

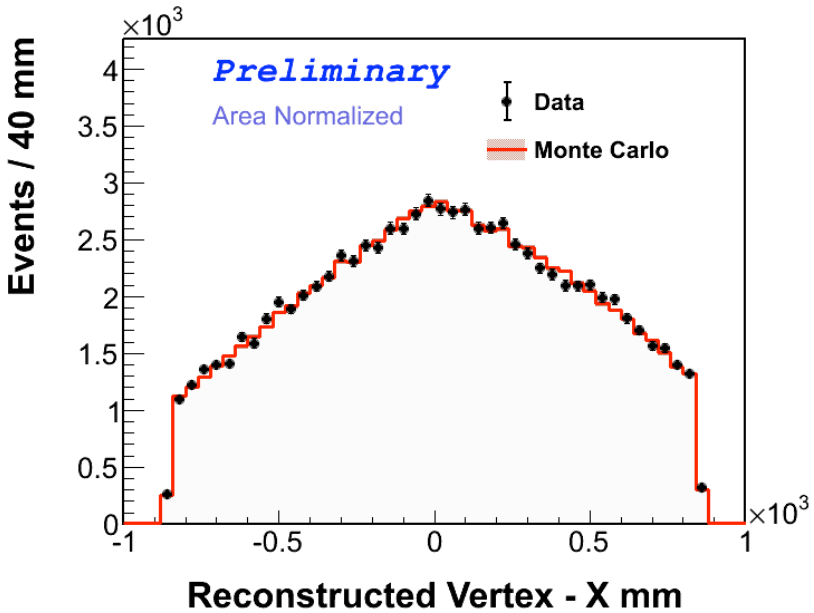
- MINERvA sits in a very intense neutrino beam -
  - Will provide exclusive and inclusive cross-sections across a wide range of neutrino energies (1-20 GeV) and Q^2.
- Fine-grained detector -
  - Study the underlying mechanisms of the quasi-elastic process for this range, measure its A-dependence so that results are consistent across experiments.
    - Understanding the energy reconstruction and kinematics will provide insight into some of the outstanding issues in the understanding of this process.
- Possesses a suite of nuclear targets -
  - Probe EMC-effects with neutrino as a probe.
  - Measure muon + n nucleon effects off of different nuclear targets (e.g. He, H_20, C, Fe, Pb) in the same beam conditions, thus minimizing flux uncertainties.
- Sensitive detector -
  - Exclusive cross-section measurements will shed light on the final state interaction models.

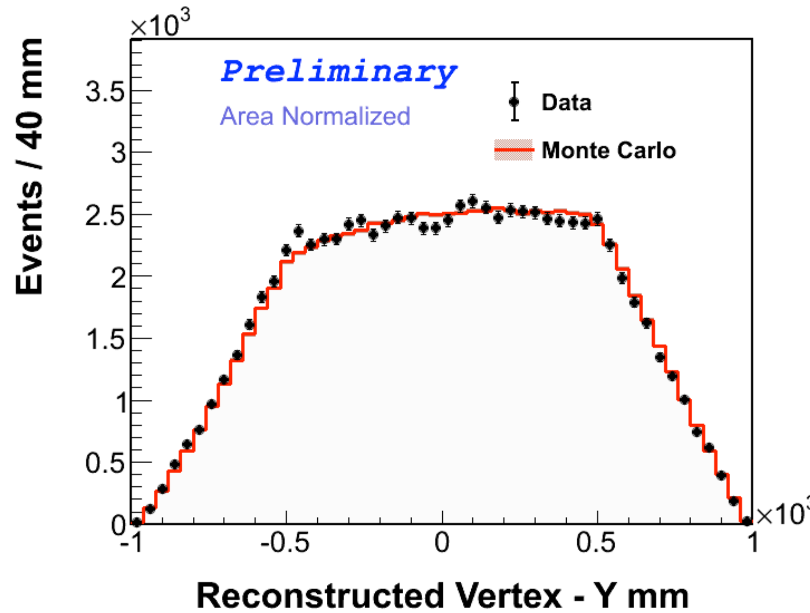
Measuring the flux in MINERvA - very important

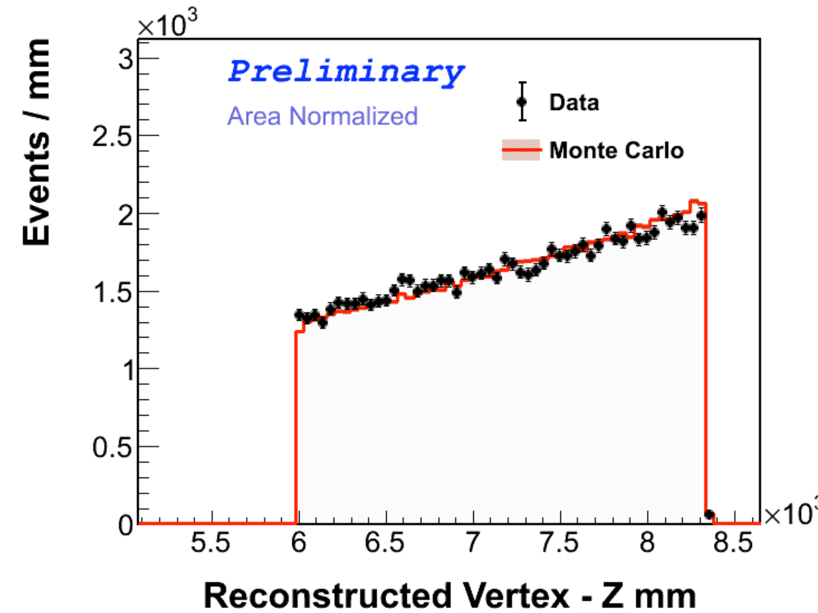


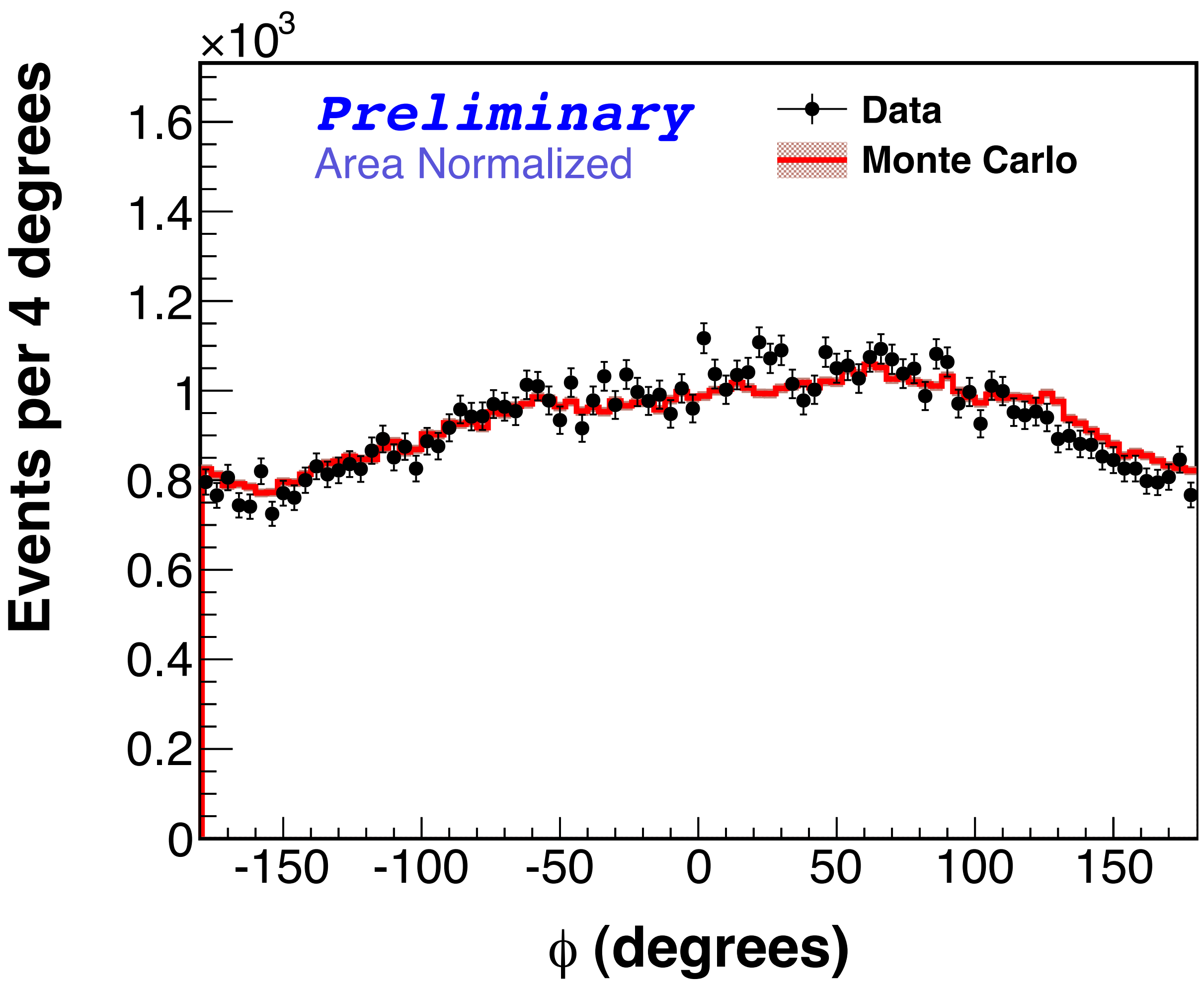
- Flux determination : Leveraging existing hadron production data from NA49 (hadron prod. expt.)
  - Use NA49 data to tune hadron production model predictions at the NuMI target
  - Use these tunings to re-weight flux.
- NA49: 158 GeV/c protons on thin target.
- NuMI: 120 GeV/c protons on thick target ($\sim 2\lambda_{int}$).
- Re-interactions are a 20-30% effect.
- NuMI pions in the focussing peak have x_F ranging from 0 - 0.15.

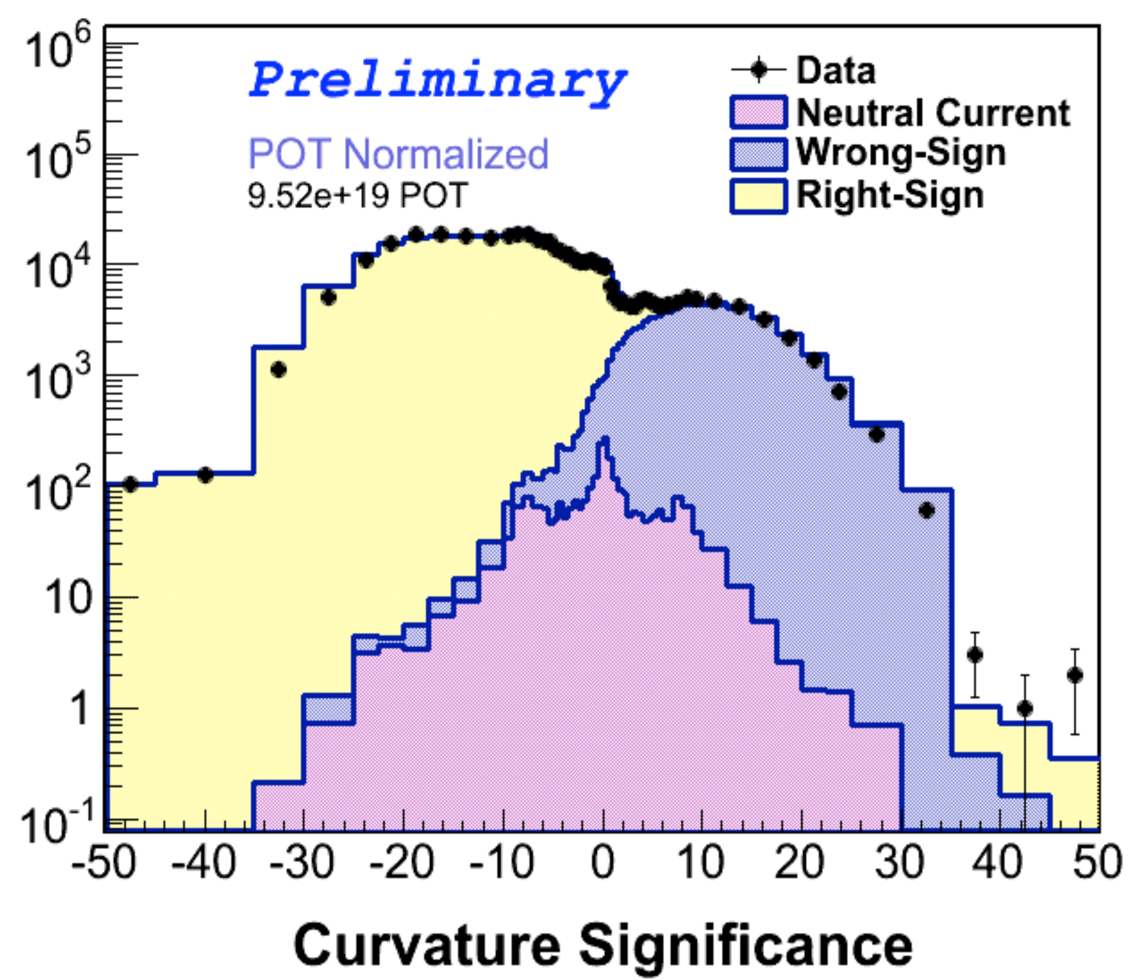
CC Inclusive Neutrino Vertex & Lepton Angles
Area Normalized & Statistical Uncertainties Only











What are we measuring here ?

We're measuring a double ratio of cross-sections here !

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

- **Plastic cross-sections** are the same
- Assuming that **flux** is the same for all the targets
- **Bin sizes** of the variable are the same
- **Target mass** in MINERvA is known rather precisely (~2%)

$$N^{Pb}(X_i) = \frac{N^{Pb}_{\text{measured}} - N^{Pb}_{\text{background}}}{\epsilon^{Pb}_{\text{XY}} * \epsilon^{Pb}_{\text{Z}} * \epsilon^{Pb}_{\text{other}}}$$

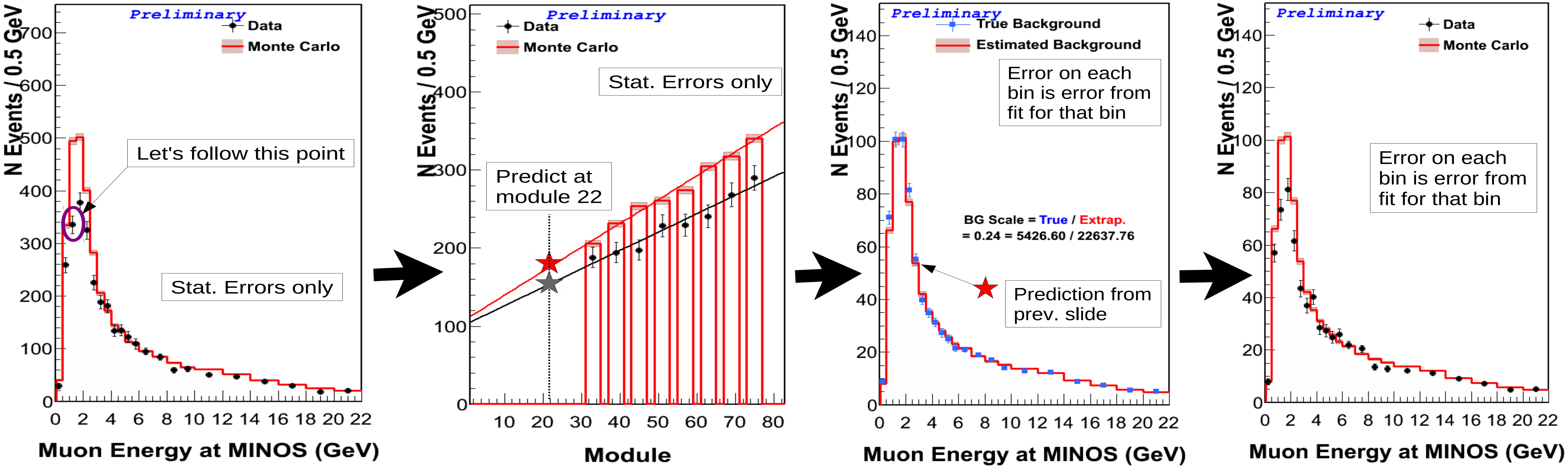
Acceptance correction based on XY position
Acceptance correction based on Z position
Other effects dependent on nuclear target

$$\frac{\frac{d\sigma^{Pb}}{dX_i}}{\frac{d\sigma^{Fe}}{dX_i}} = \frac{\frac{T^{CH}_{nuc}}{T^{Pb}_{nuc}}}{\frac{T^{CH}_{nuc}}{T^{Fe}_{nuc}}} * \frac{\frac{\epsilon^{CH}_{other}}{\epsilon^{Pb}_{other}}}{\frac{\epsilon^{CH}_{other}}{\epsilon^{Fe}_{other}}} * \frac{\frac{N^{Pb}_{meas.} - N^{Pb}_{bg}}{N^{CH}_{meas.} - N^{CH}_{bg}}}{\frac{N^{Fe}_{meas.} - N^{Fe}_{bg}}{N^{CH}_{meas.} - N^{CH}_{bg}}}$$

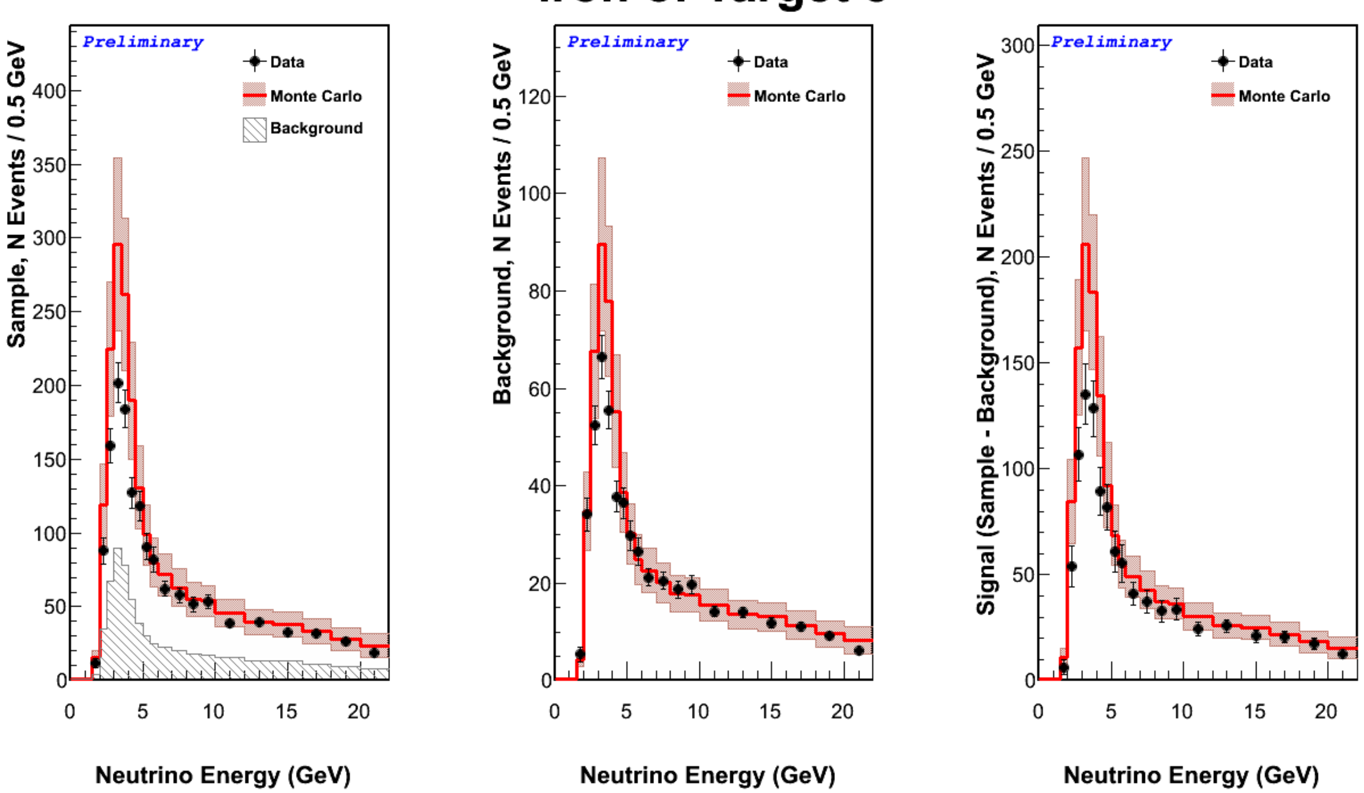
- MINERvA's advantage : this analysis minimizes flux uncertainties since all the targets sit in the same beam !

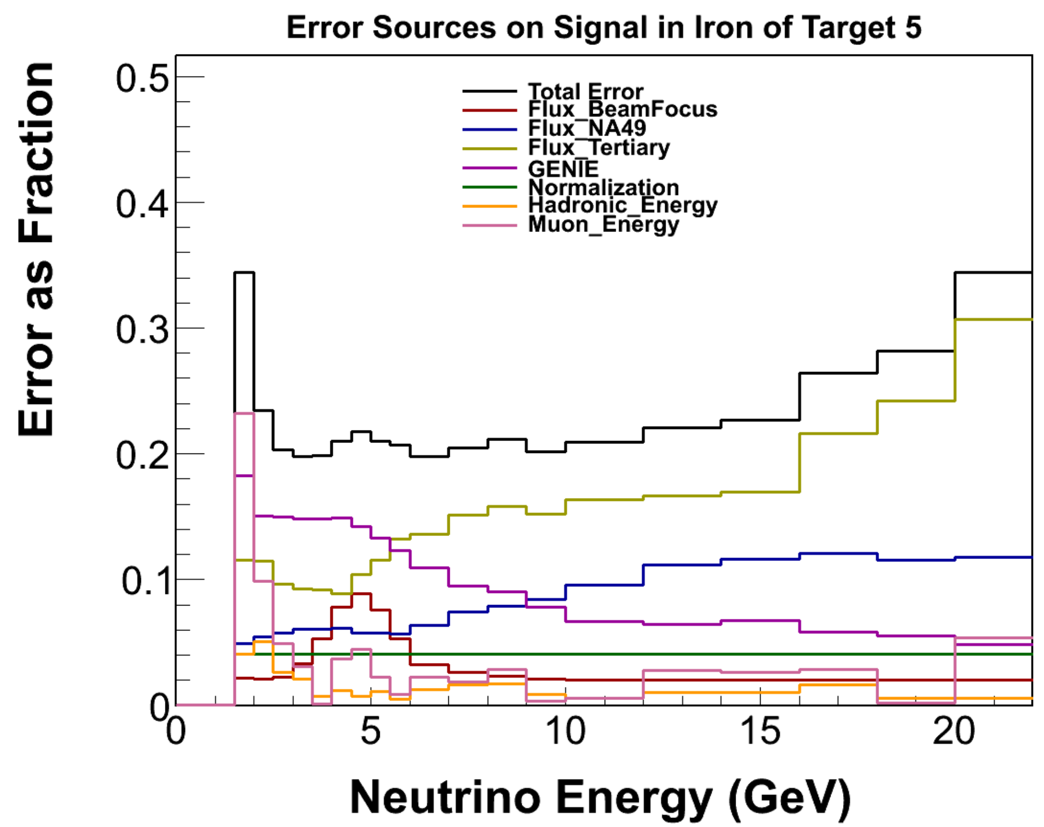
Background estimation technique

Speciality of this technique: background estimates are derived from Data, not from Monte Carlo predictions of cross-sections

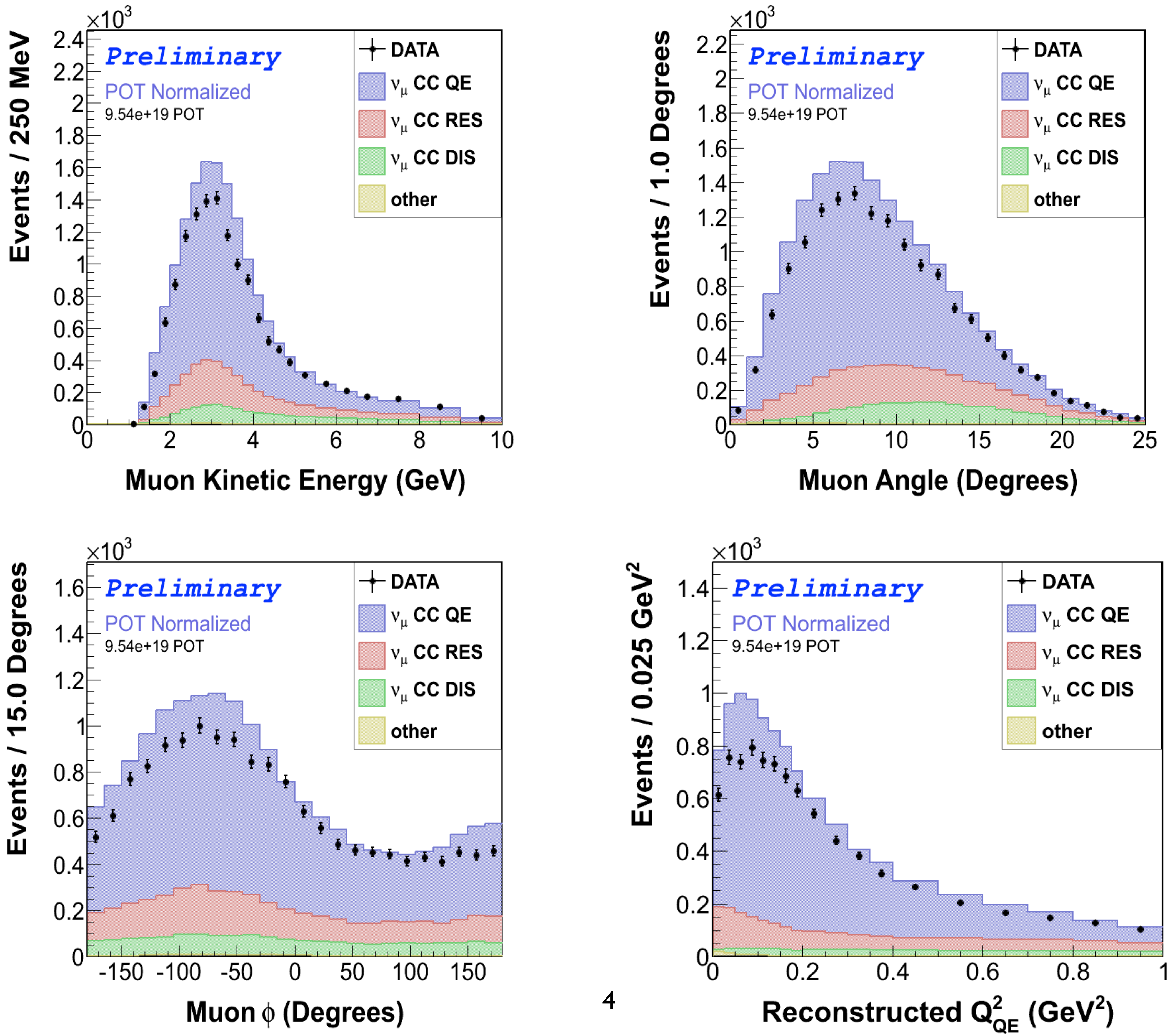


Iron of Target 5

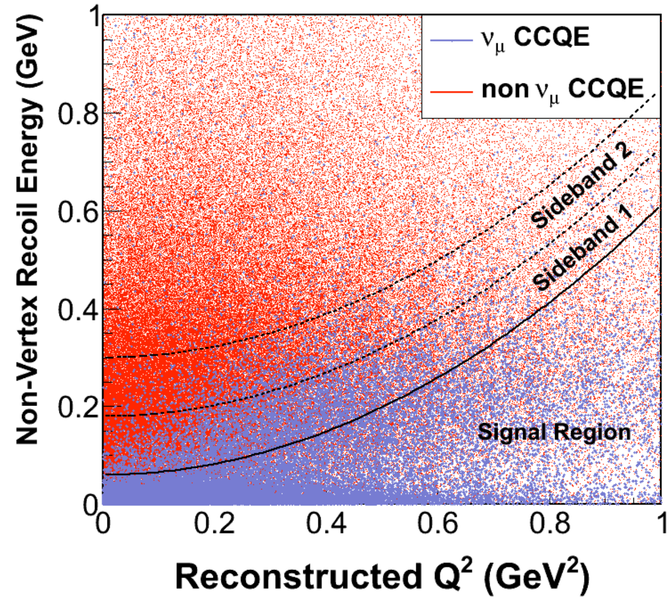


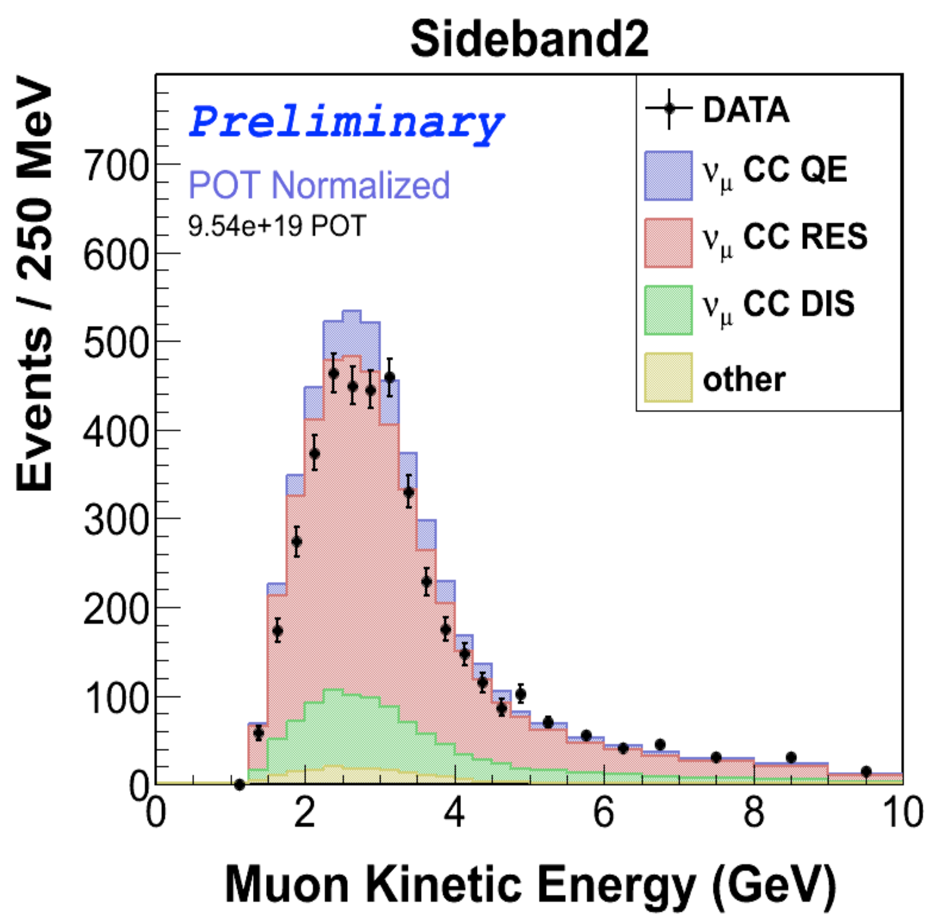


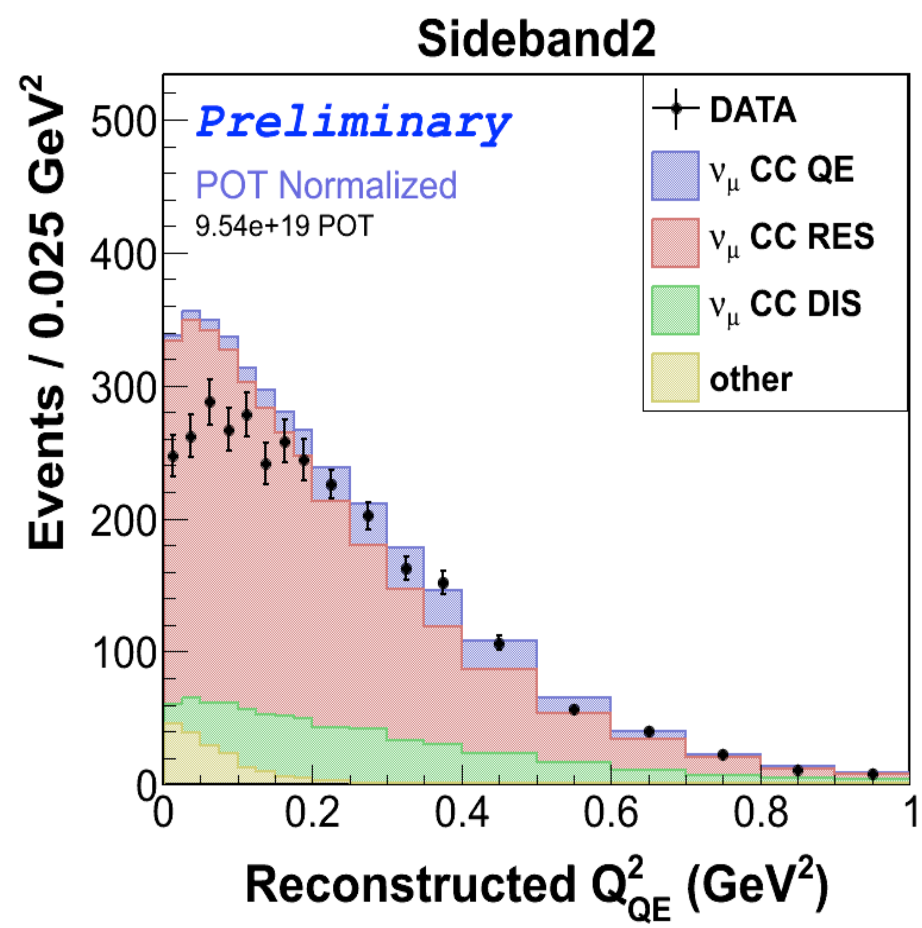
Kinematic variables for ν-induced CCQE events



Side Band Plots - for background adjustment



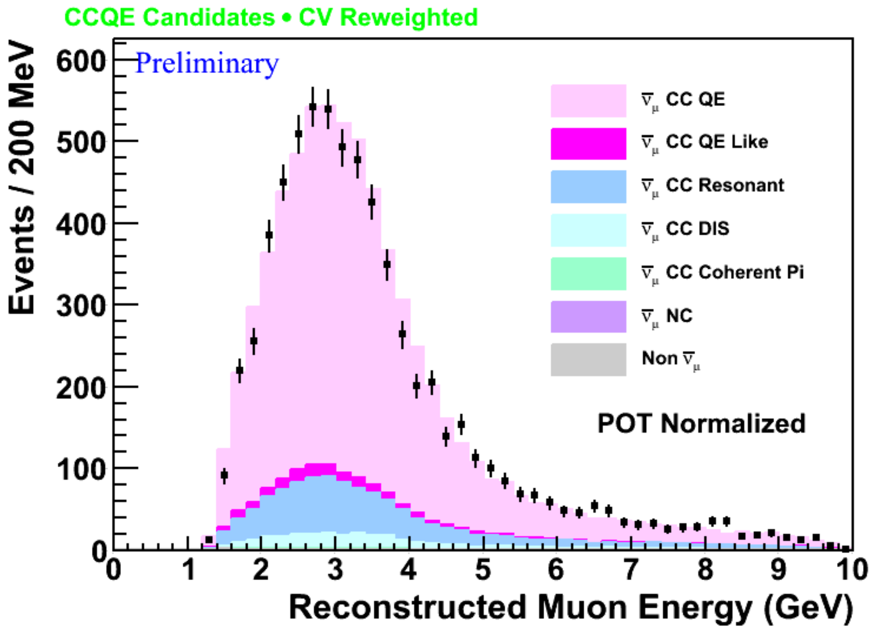




- Substantial bleed-in from Resonance channel.
- Currently in the process of understanding these, then tune backgrounds using this info.

Kinematic variables for $\bar{\nu}$-induced CCQE events

▶ Muon Energy - POT:



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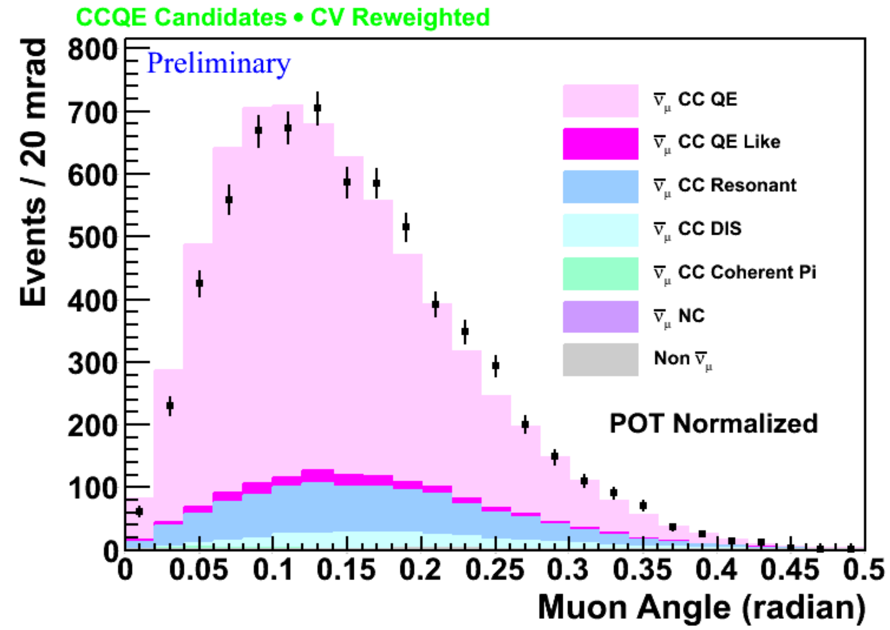
▶ Muon Angle - POT:



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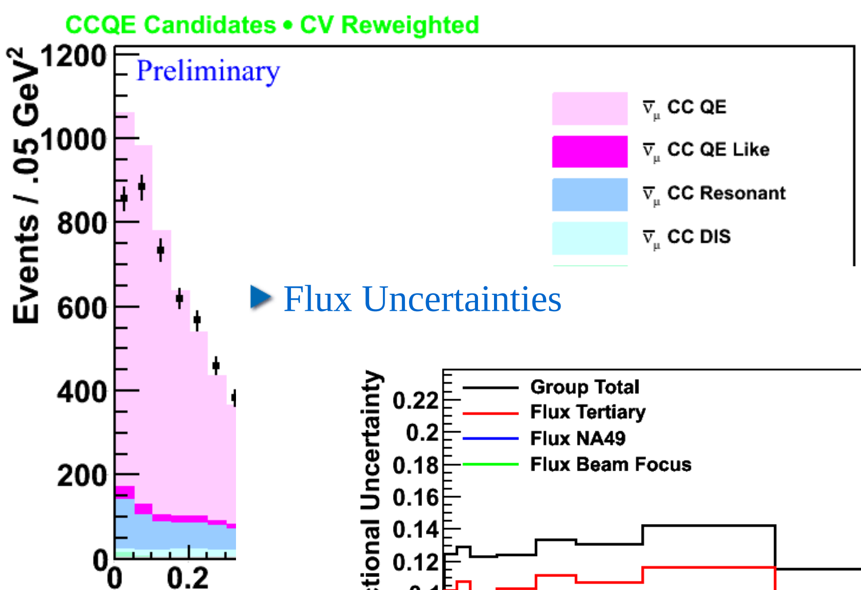
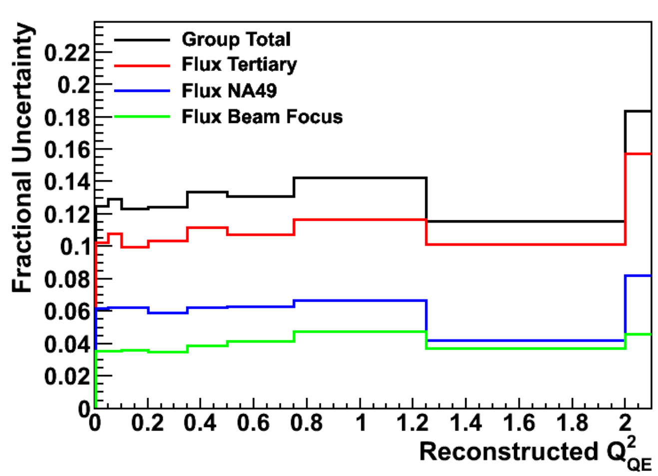
, both by itself and when compared and contrasted to the anti-nu results !

▶ Q2 - POT:



▶ Flux Uncertainties



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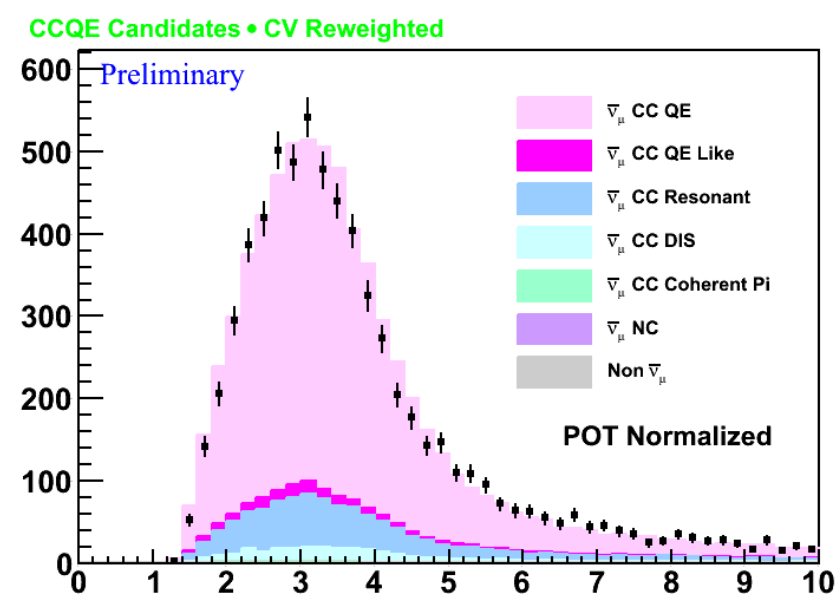
▶ Neutrino Energy - POT:



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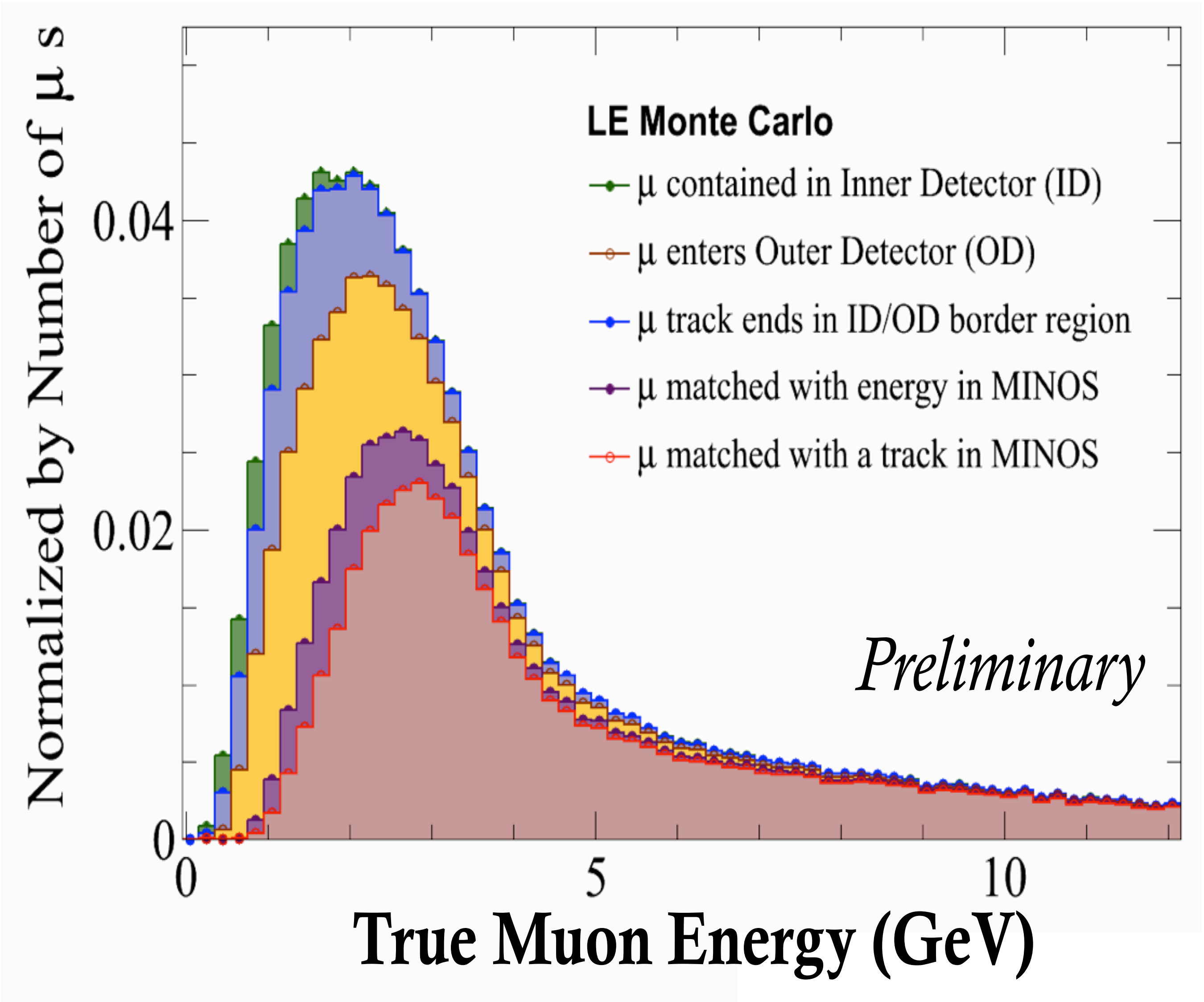
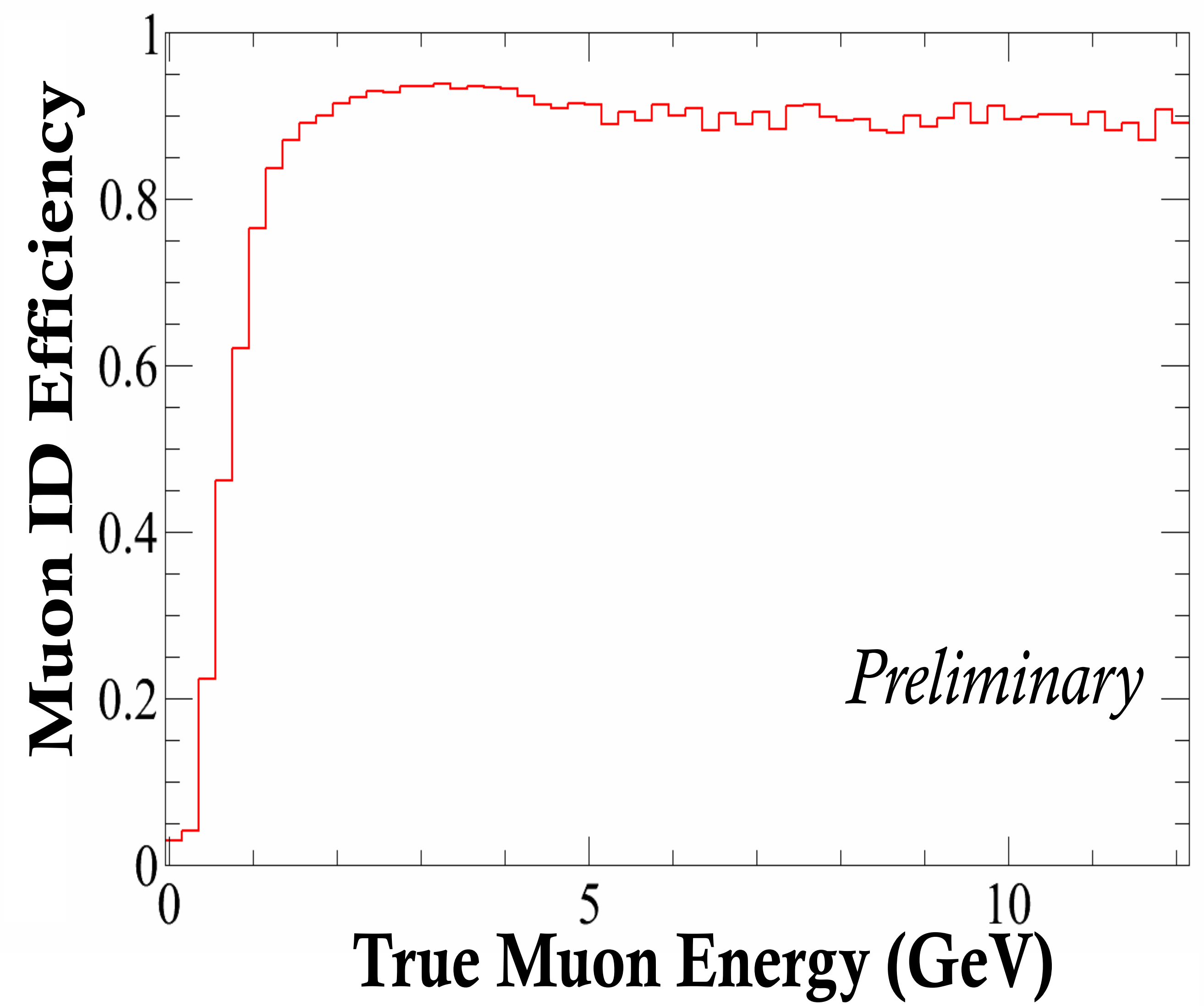
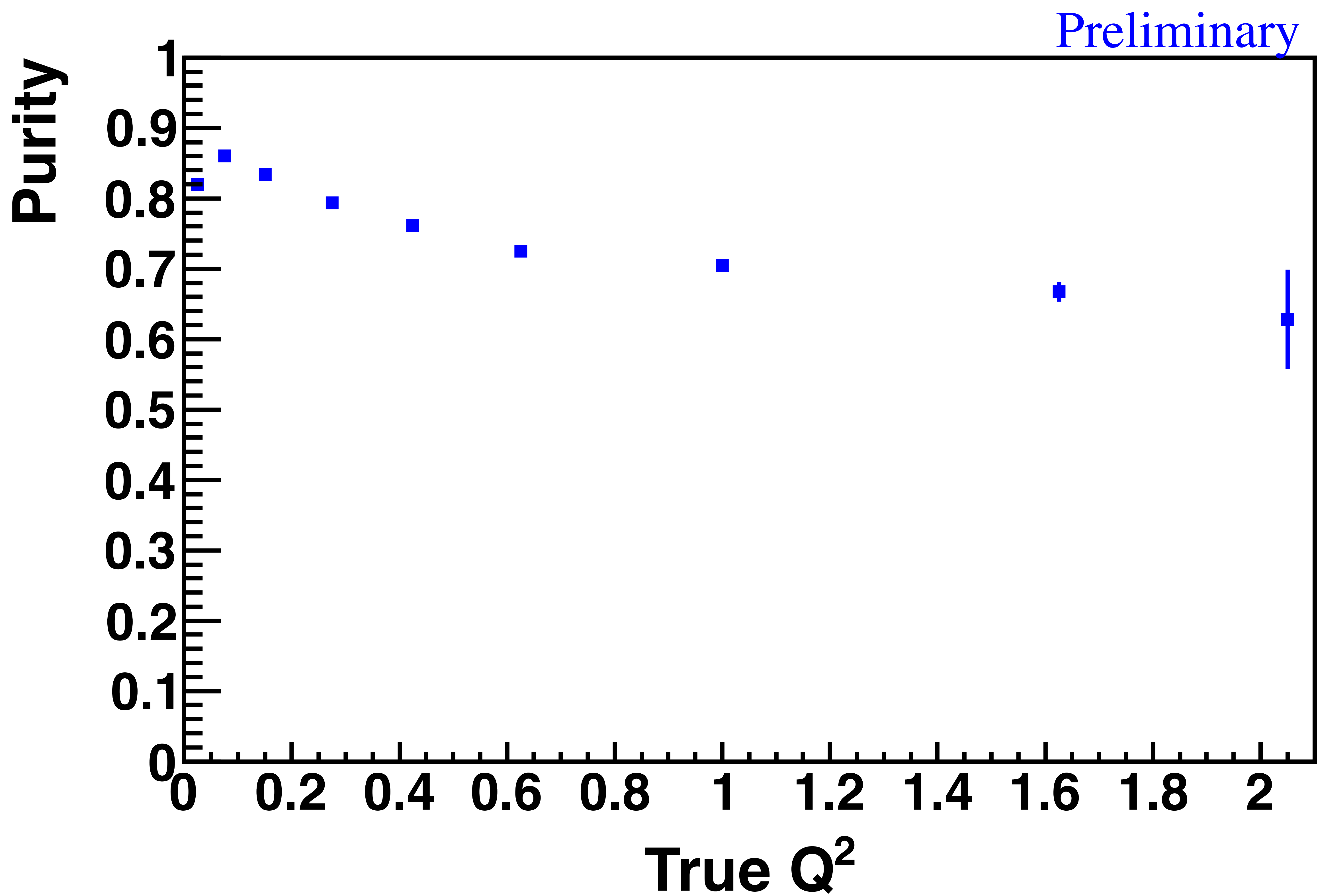
Muon Categories

Muon Type & Efficiency by Energy





Purity of Q^2 for CCQE anti-nu events



Reductions in Systematics for future

For future round of analyses :

- Muon reco uncertainties :
  - Data studies of muons reaching MINOS
  - Adding muons that range out in MINERvA

- Hadronic uncertainties :
  - Test beam data studies