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Observables

Minerba Betancourt, Fermilab

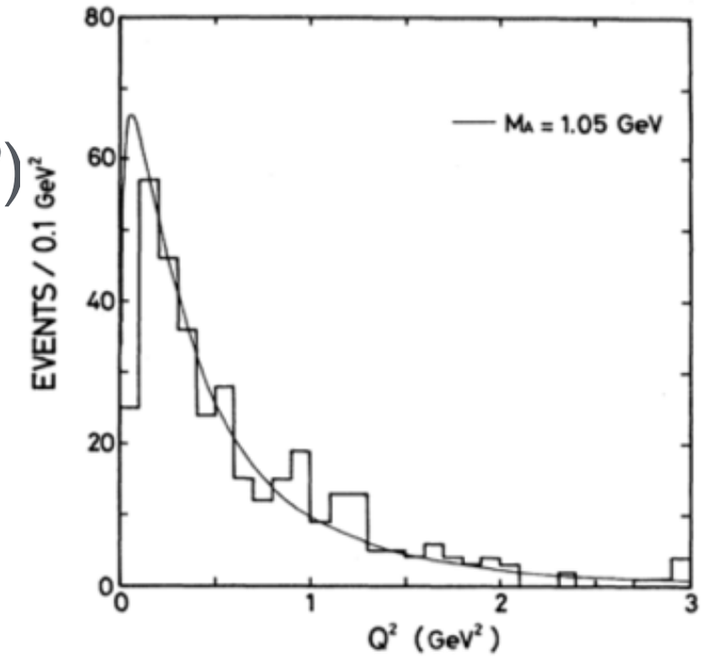
24 June 2017

- CC Low recoil observables
- CC0pi observables

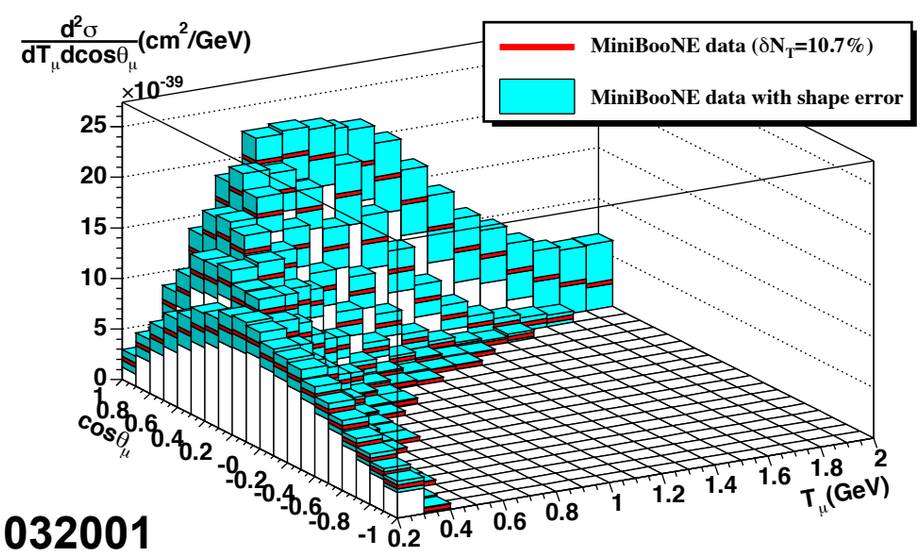
Introduction

Topic: Observables. Describe how you decide what you are going to measure, and how you check you chose the right signal. Give the example of the CCQE recoil analysis vs CC0pi: recoil separates different reactions that are part of CC0pi (CCQE, 2p2h, etc.). Is that valuable? Is it only an irritation? N-dim vs 1-dim issues (with pion analysis or 2 track CCQE)

- Which observables are the best to measure for CCQE?
  - Historically we have been measuring Q^2 (model dependence?)
  - Muon momentum and angle (less model dependence)



Kitagaki, PRD 28, 436 (1983)



Phys.Rev. D88 (2013) no.3, 032001

- We try to find observables that have less model dependence and are useful for theorists

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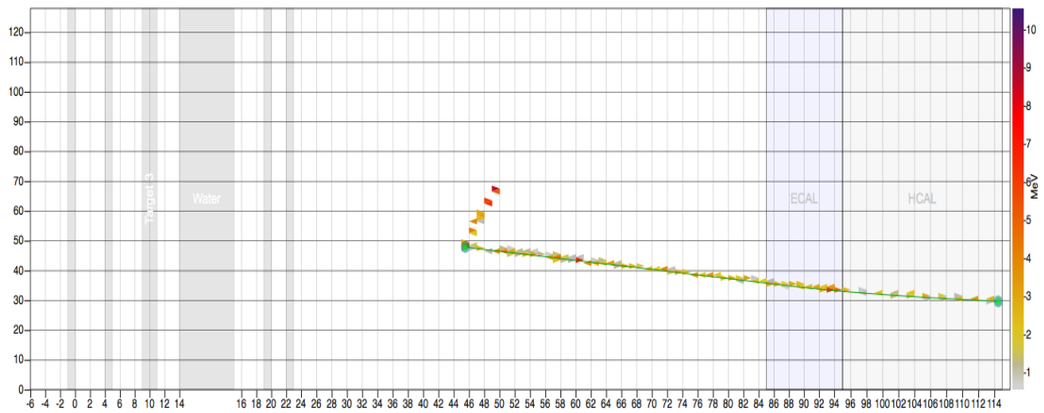
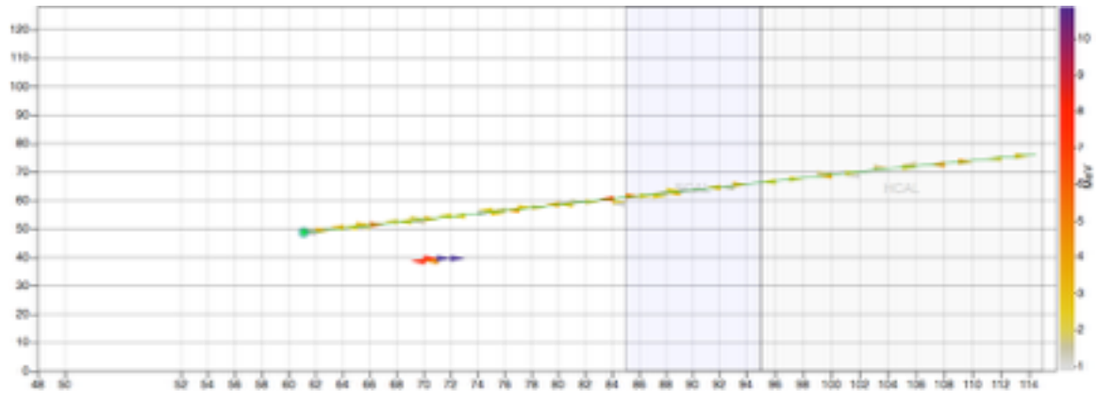
MINERvA Observables

- CC low recoil neutrino and antineutrino
  - Three momentum transfer q_3 and energy transfer q_0 (reconstructed using the event kinematics)
- CC0pi neutrino and antineutrino:
  - Transversal momentum P_T, longitudinal momentum Pz, Q^2 and Eν (reconstructed using information from the muon kinematic)
- CC0pi neutrino (two track):
  - Q^2 reconstructed from proton kinematics

Neutrino



AntiNeutrino



New neutron counting analysis, see Miranda Elkins's poster at Nuint

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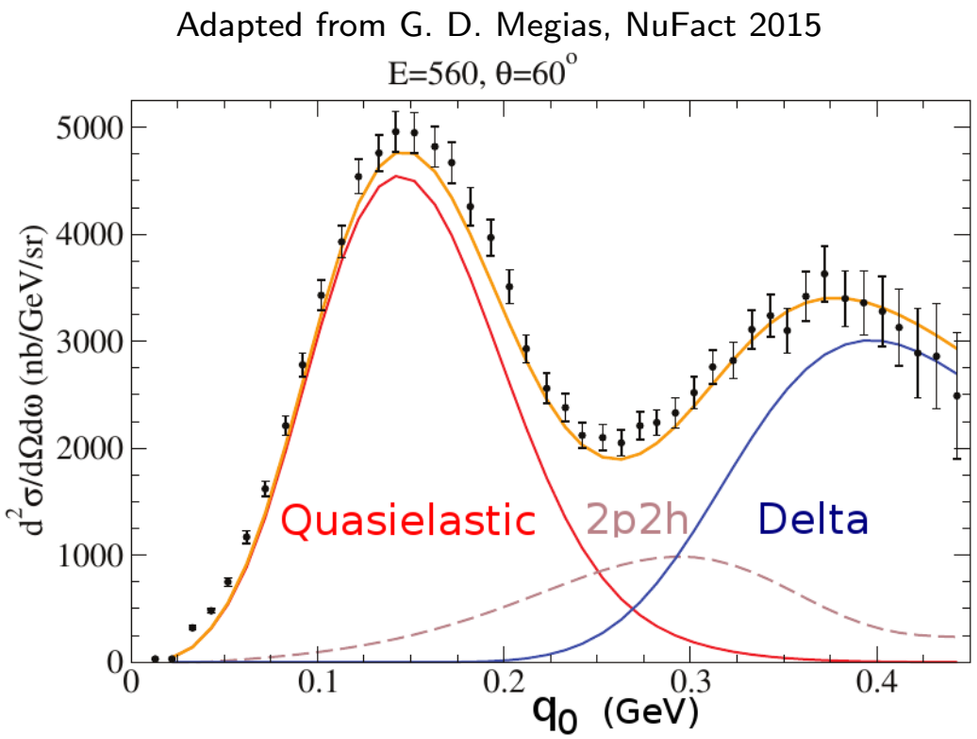
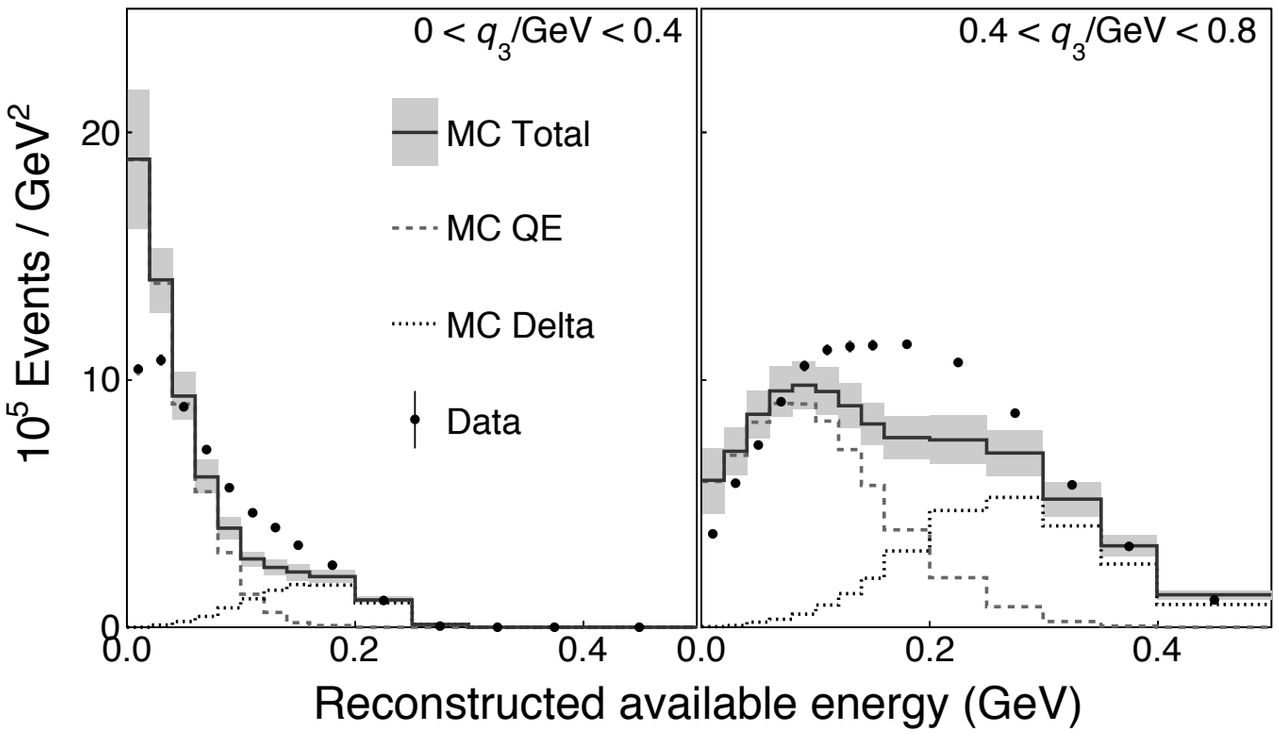
Low Recoil Analysis

From Electron Scattering Data

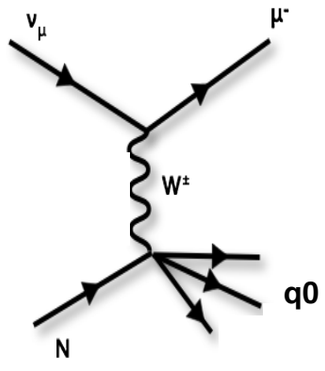


$$q_0 = E_e - E'_e$$

Neutrino Scattering



Phys.Rev.Lett. 116 (2016) 071802



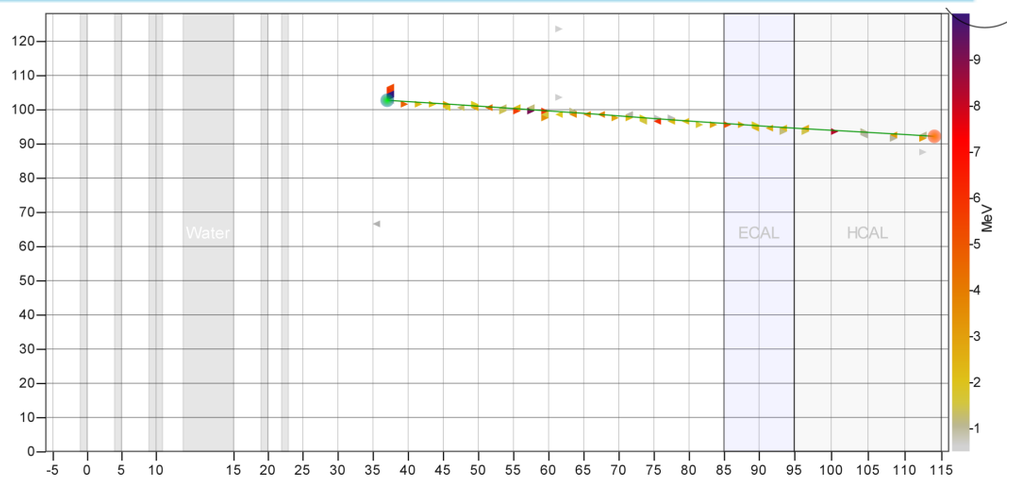
Neutrino energy can be reconstructed using

$$E_\nu = E_\mu + q_0$$

q0==reconstructed available energy

Low Recoil Event Selection and Signal Definition

- Selection:
  - Events in fiducial volumen (tracker)
  - Negative muon matched to MINOS
  - 2<Eν<6 GeV
- Signal: Charged Current, 97% purity
- Observables:
  - **There momentum transfer:** $q_3 \equiv |\mathbf{q}| = \sqrt{Q^2 + q_0^2}$
  - **Energy transfer: q_0 = calorimetry energy**



where neutrino energy and four momentum transfers are reconstructed using

$$E_\nu = E_\mu + q_0 \qquad Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - M_\mu^2$$

- To extract the cross section, unfolding is performed using

$$E_{\text{avail}} = \sum(\text{Proton and } \pi^\pm \text{ KE}) + (\text{Total } E \text{ of other particles except neutrons})$$

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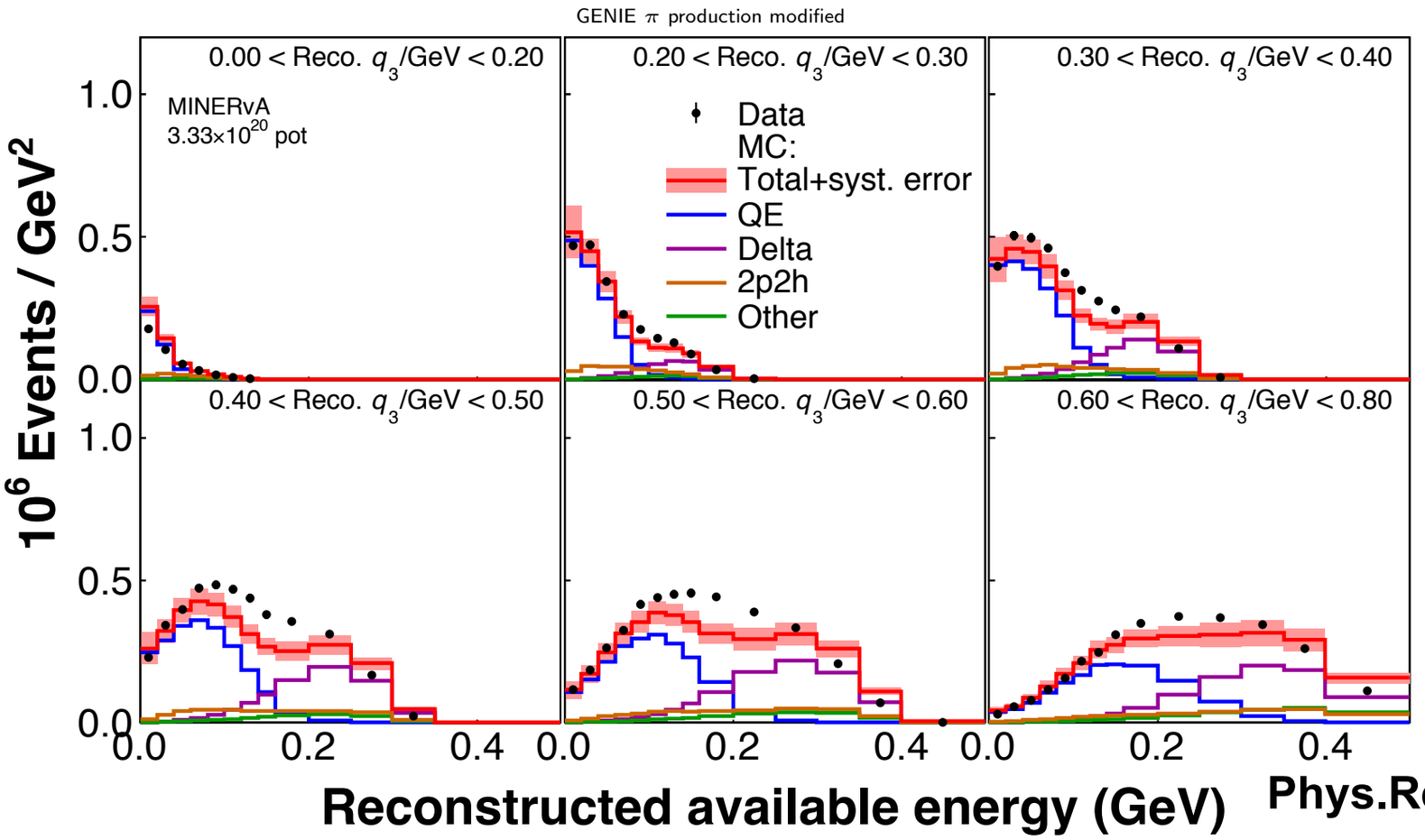
Selected Events Compared with GENIE+2p2h+RPA

- Variables e-scattering like analysis (energy transfer and three momentum transfer)

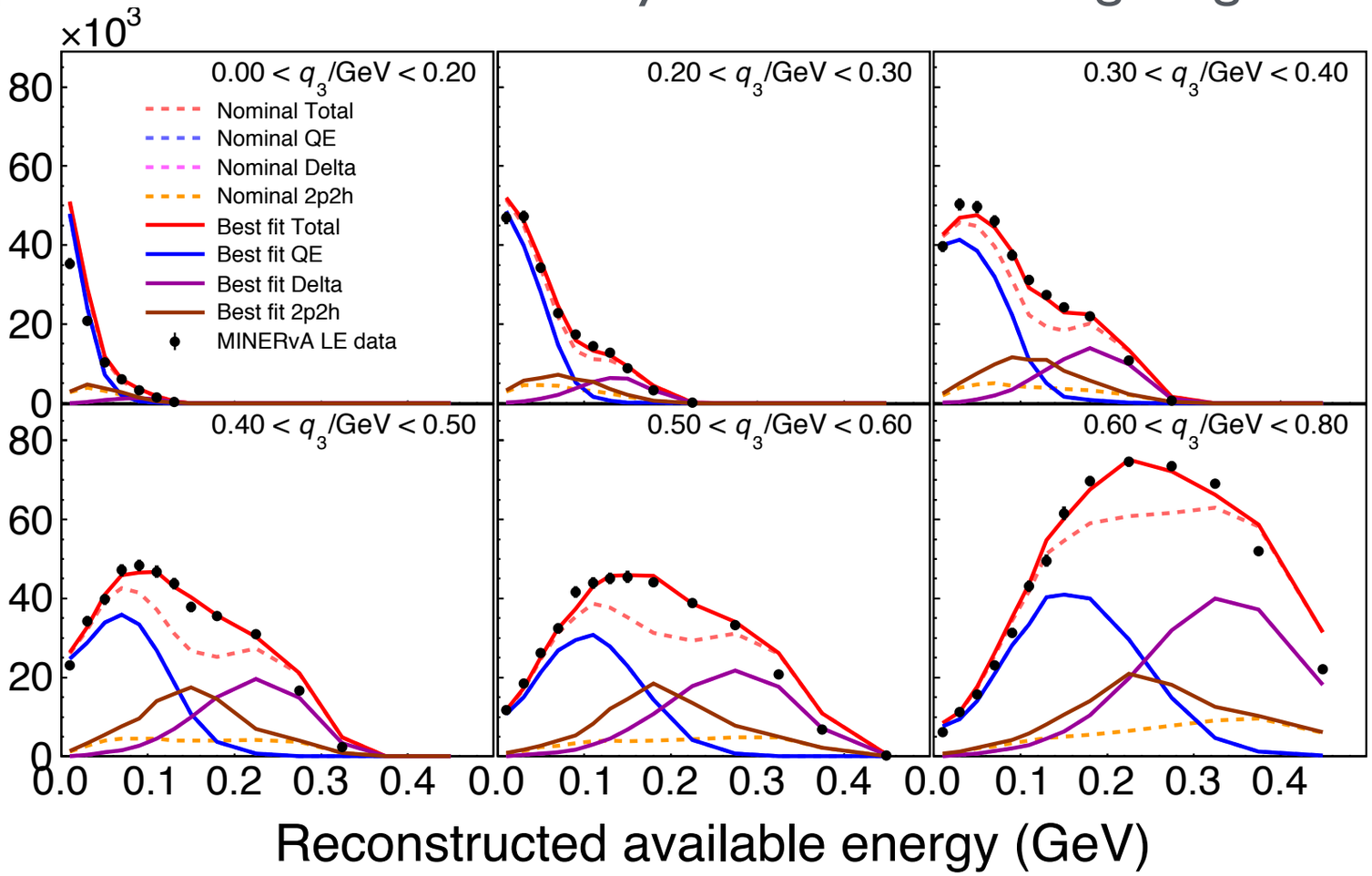


Phys.Rev.Lett. 116 (2016) 071802

- MINERvA found a big data excess in the region where neither 2p2h nor Delta make big contribution, even with the improvements to the model, we don't agree with data where 2p2h effects show up
- See Rik Gran's talk for more details about low recoil analysis and a new analysis for antineutrino!

Including 2p2h model

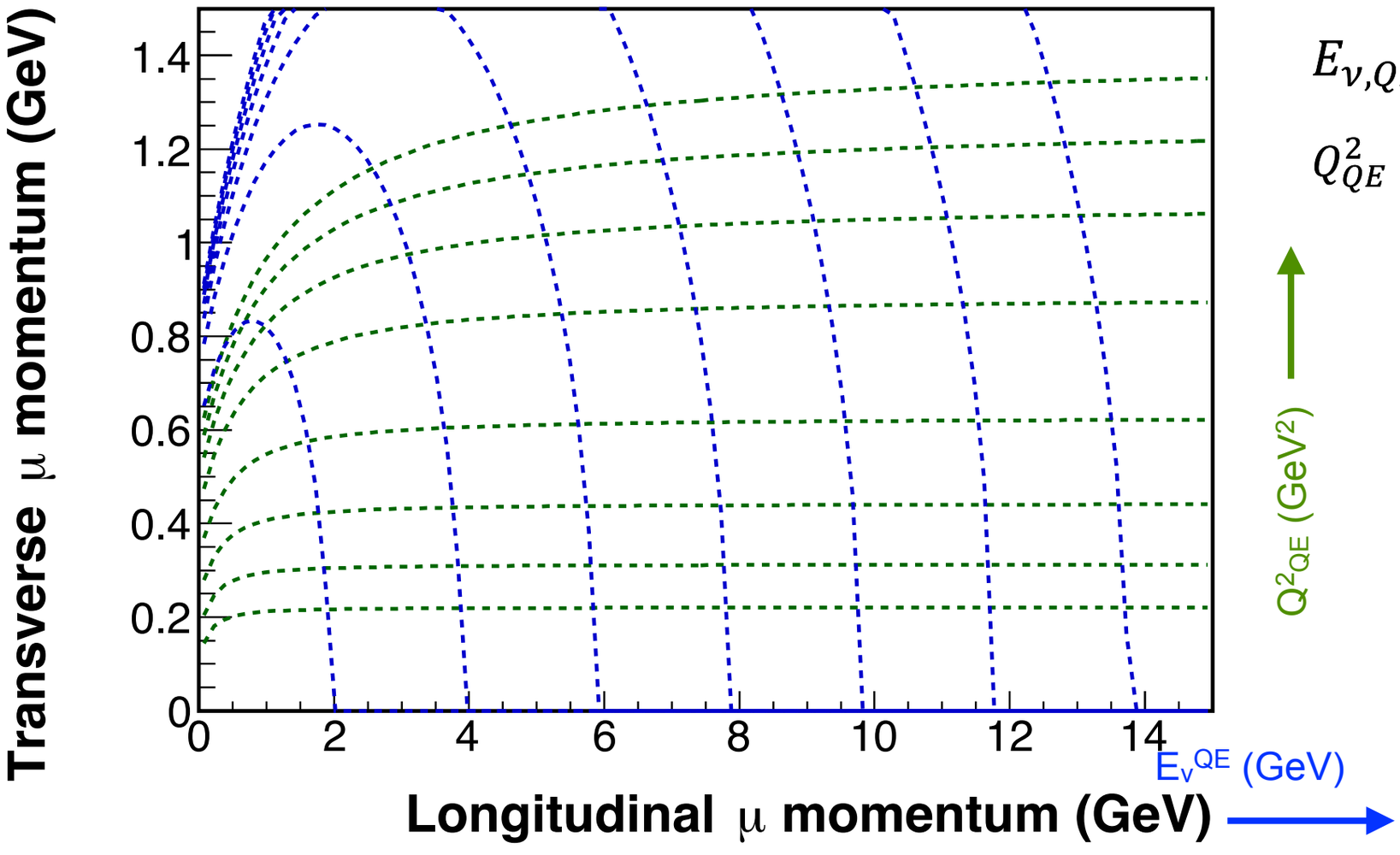
- We use a 2d Gaussian in true variables (q_3,q_0) as a reweighting function applied to the 2p2h events, and fits its parameters to get the best agreement between data and MC (QE and RES are unchanged)
- We include 2p2h in the MC for our analysis with this reweighting



- 2p2h events can involve an initial-state nn or np pair. For a systematic, we take extreme cases of only reweighting events on an nn pair, and only reweighting events on an np pair. We apply these weights to the CCQE analyses

Muon Transverse/Longitudinal Momentum vs Q^2/E_ν

- Decide what to measure:
  - Observables with less model dependence as possible



$$E_{\nu,QE} = \frac{M_n^2 - (M_p - E_b)^2 - M_\mu^2 + 2(M_p - E_b)E_\mu}{2(M_p - E_b - E_\mu + P_\mu \cos(\theta_\mu))}$$

$$Q^2_{QE} = 2E_\nu(E_\mu - P_\mu \cos(\theta_\mu)) - M_\mu^2$$

$Q^2 \sim PT$

$E_\nu \sim Pz$

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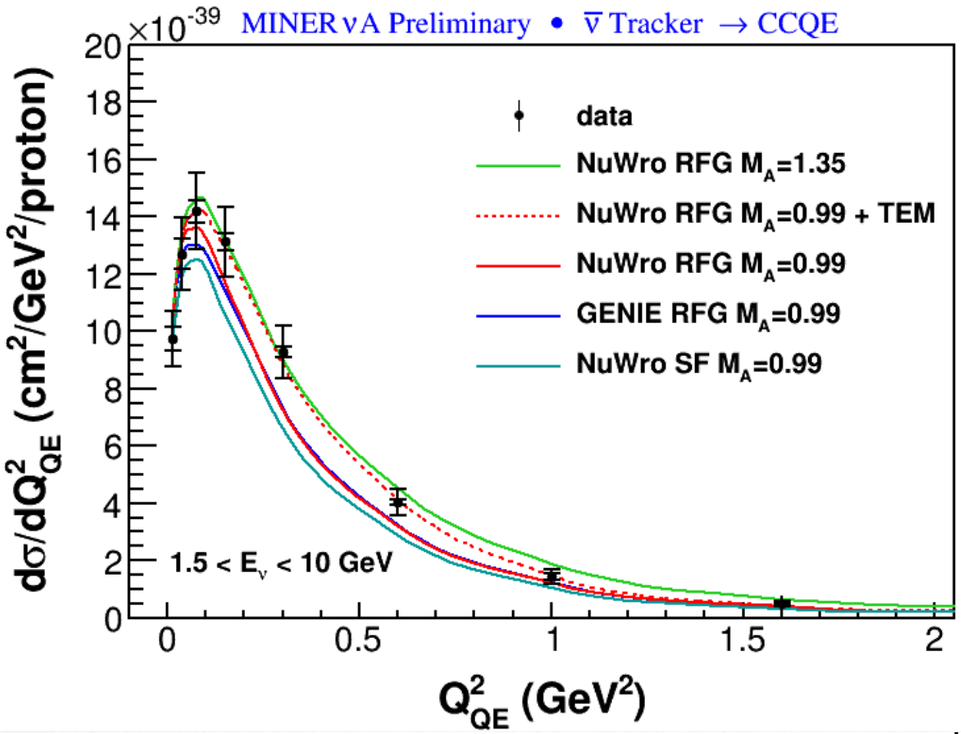
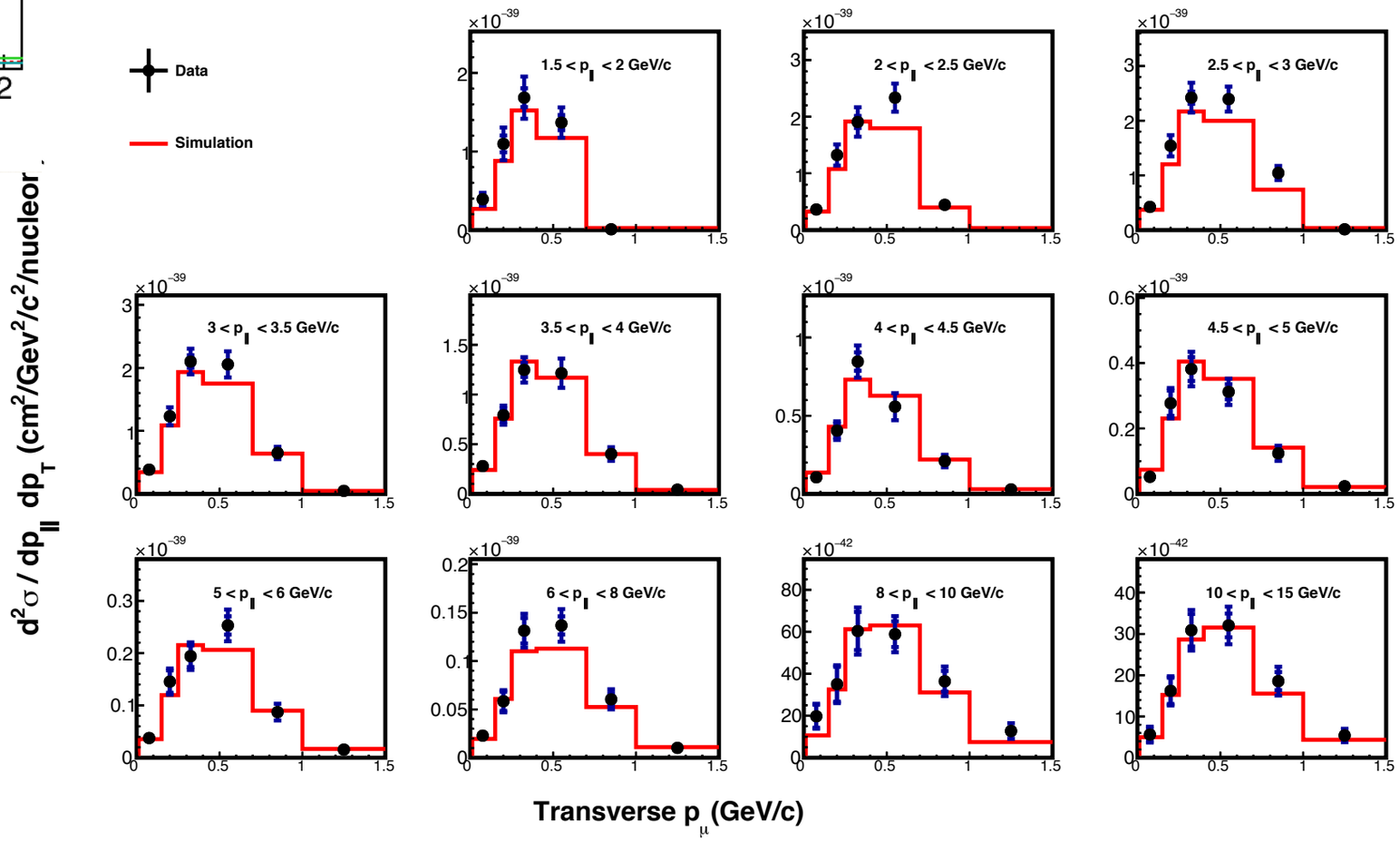
Examples of Measurements with different Signal definition

CCQE



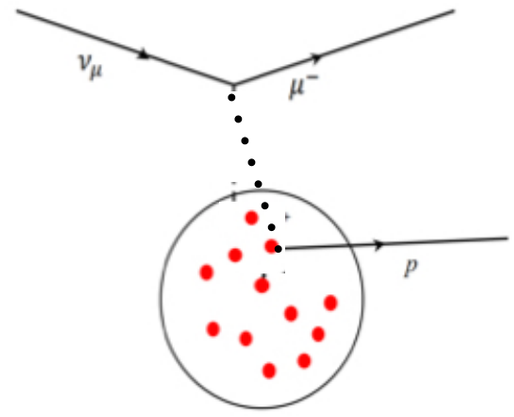
Phys. Rev. Lett. 111, 022502 (2013)

CCQE-like=CC0pi

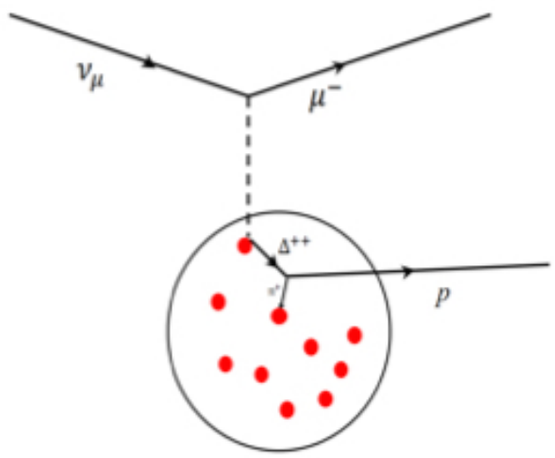


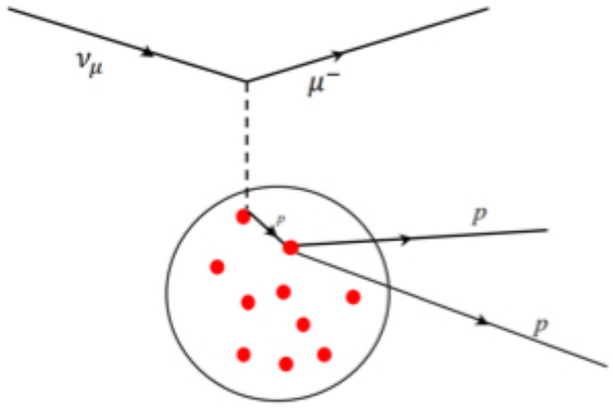
CCQE Signal Definitions

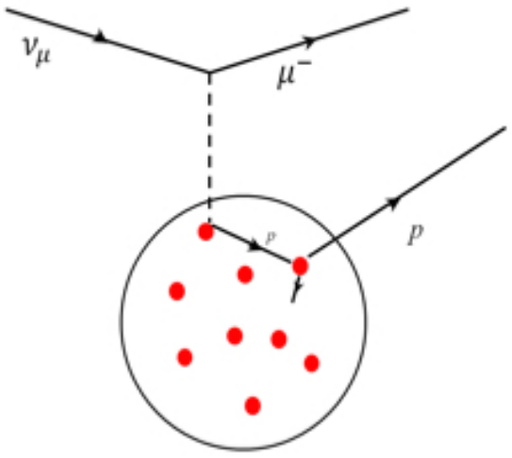
- **CCQE recoil analysis signal:**
  - Signal is defined as an event in which the primary interaction is elastic (regardless of the final state particles)
  - Incoming (anti) neutrino energy between 1.5 and 10 GeV



- **CC0pi analysis signal:**
  - Signal is defined as CCQE-like, no pions in the final state
  - No cut on the neutrino energy

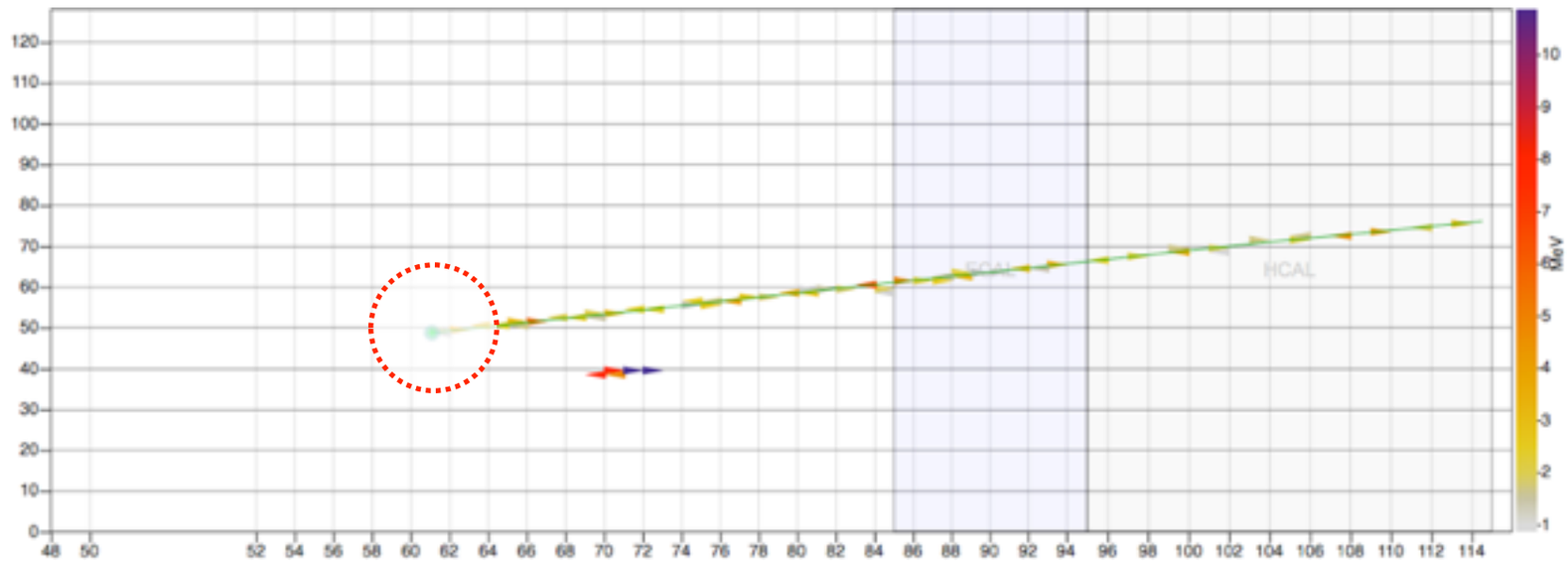






Isolating CCQE Events

- Recoil energy region
  - Sum energy deposited in the recoil region (mostly from pion and proton)
  - Exclude the vertex region where low energy nucleons could come from CCQE events

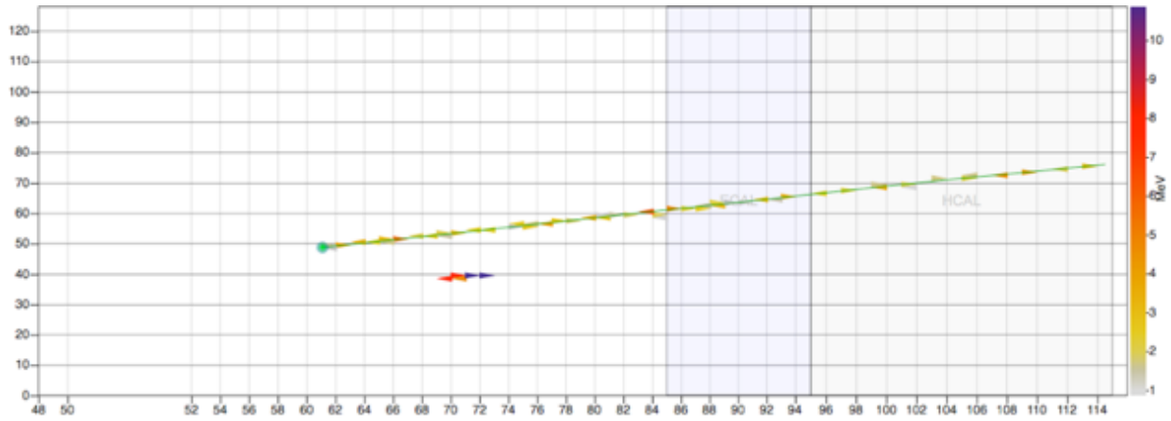


Non-Vertex Recoil Energy

- The non-vertex recoil energy could separate different interaction types, for example
  - 2p2h
  - background events
  - signal events
- Irritation: a recoil cut that gives high efficiency and purity when selecting or rejecting one category will do poorly at selecting or rejecting the others
- Some examples from the neutrino and antineutrino analyzes

CC0pi Antineutrino Event Selection and Signal Definition

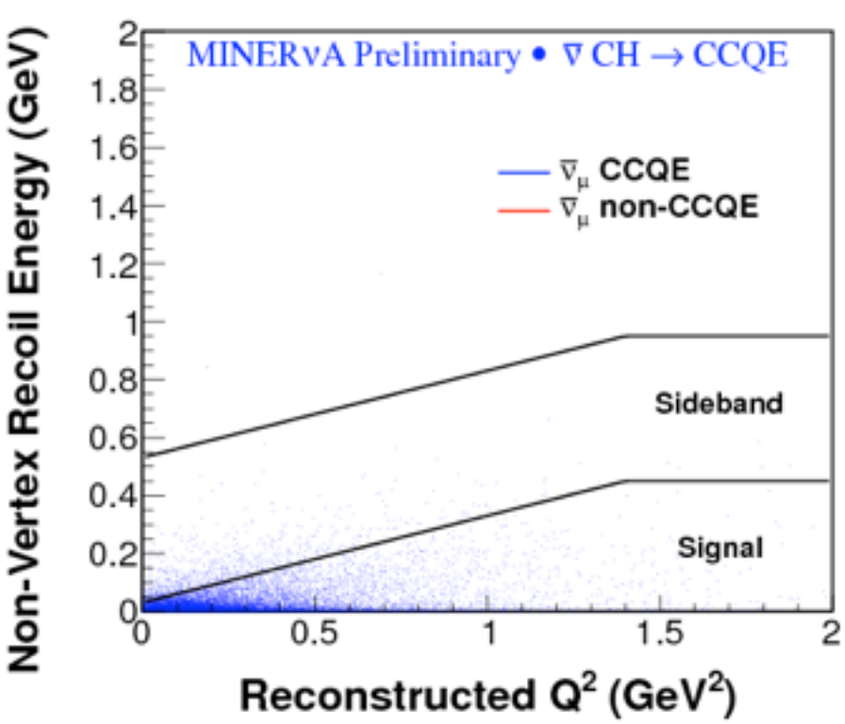
- Muon track charge matched in MINOS as a μ+
- No additional tracks from the vertex
- Low-energy protons are allowed, but are below tracking threshold

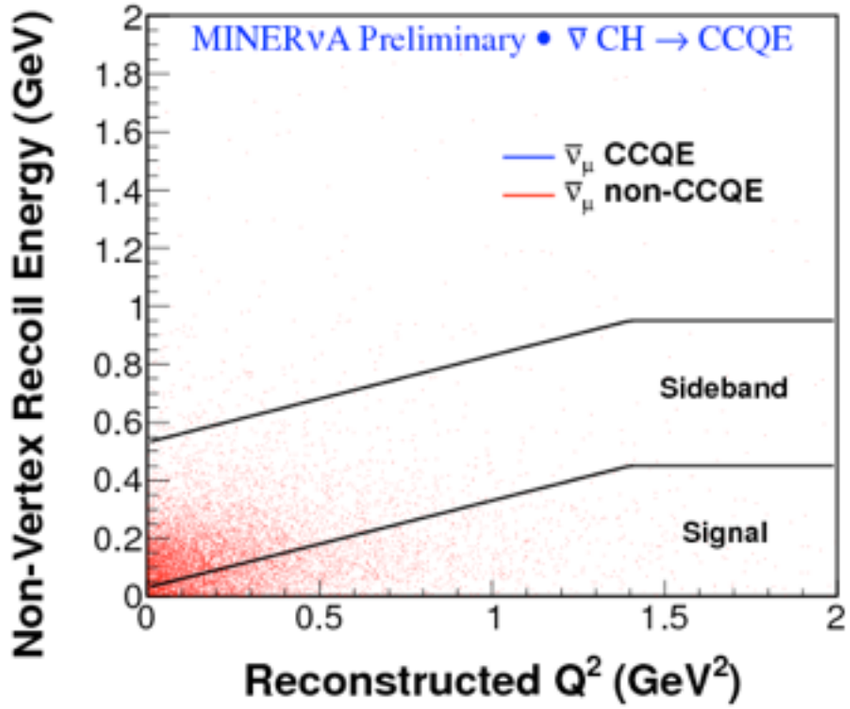


- Signal definition:
  - QE-like: defined by particles exiting the nucleus
  - Any number of neutrons and only low-energy protons (below 120 MeV kinetic energy)
  - No pions, heavy baryons etc
  - Additional constraint: muon angle <20 degrees because of the MINERvA-MINOS acceptance

Non-Vertex Recoil Energy (Antineutrino Measurement)

- Selection requires a cut on non-vertex recoil energy vs Q^2
- This cut optimizes efficiency times purity for true CCQE events

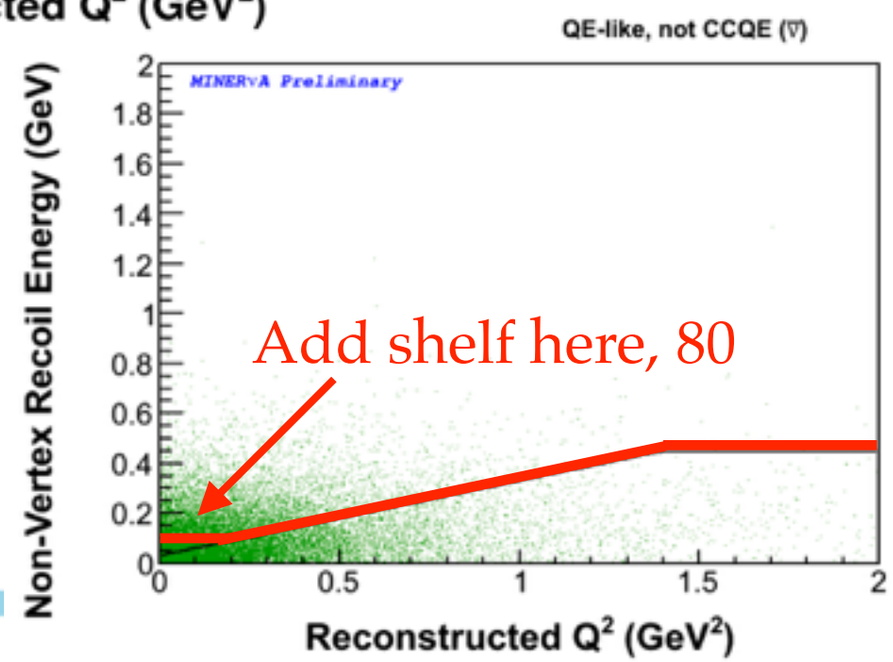




Cut used for the old measurement

$$Q^2_{\mathrm{QE}} = 2E_\nu^{\mathrm{QE}}\left(E_\mu - p_\mu \cos\Theta_\mu\right) - m_\mu^2$$

- In the case of CC0pi, poor efficiency (17%) for accepting CC0pi events that are not CCQE
- Relaxing the cut a low Q^2, efficiency improves

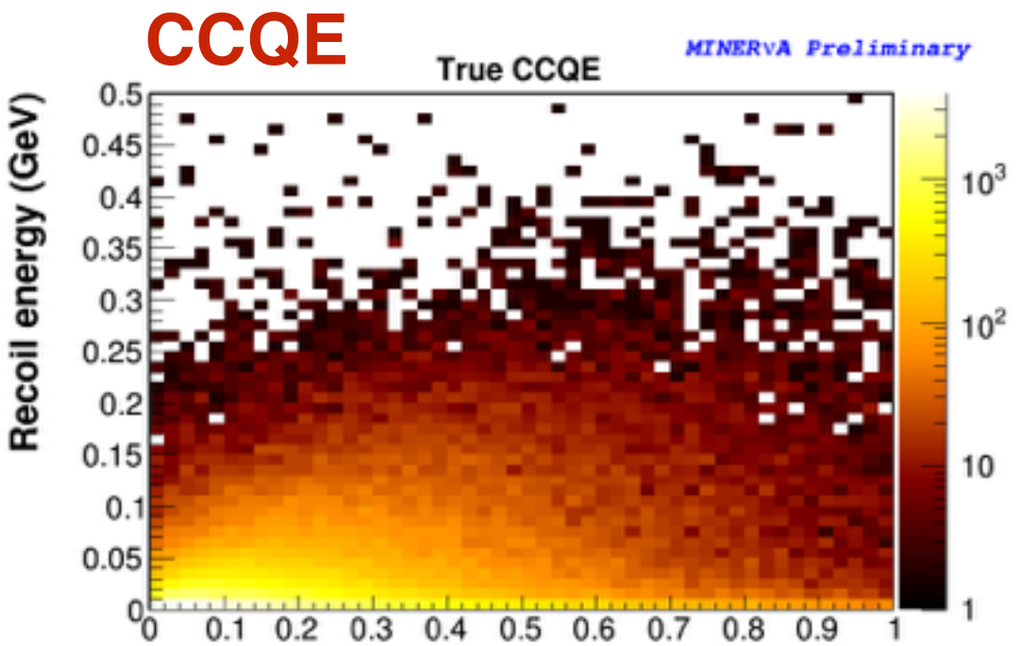


Cut used for the new measurement

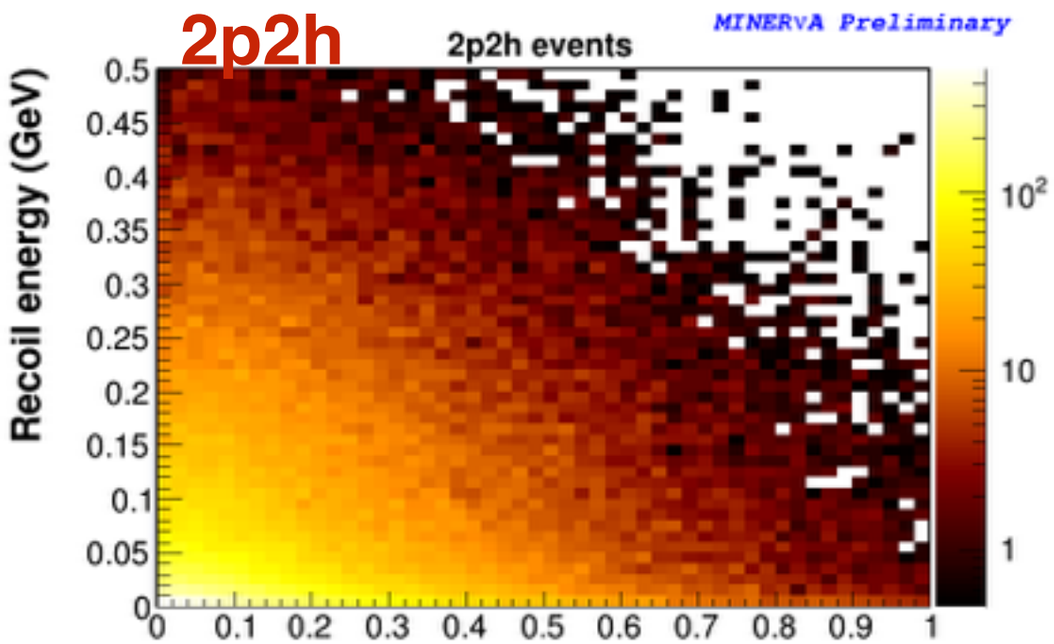
Recoil Distributions for Antineutrino Analysis

- Recoil distributions for interaction types in the antineutrino analysis

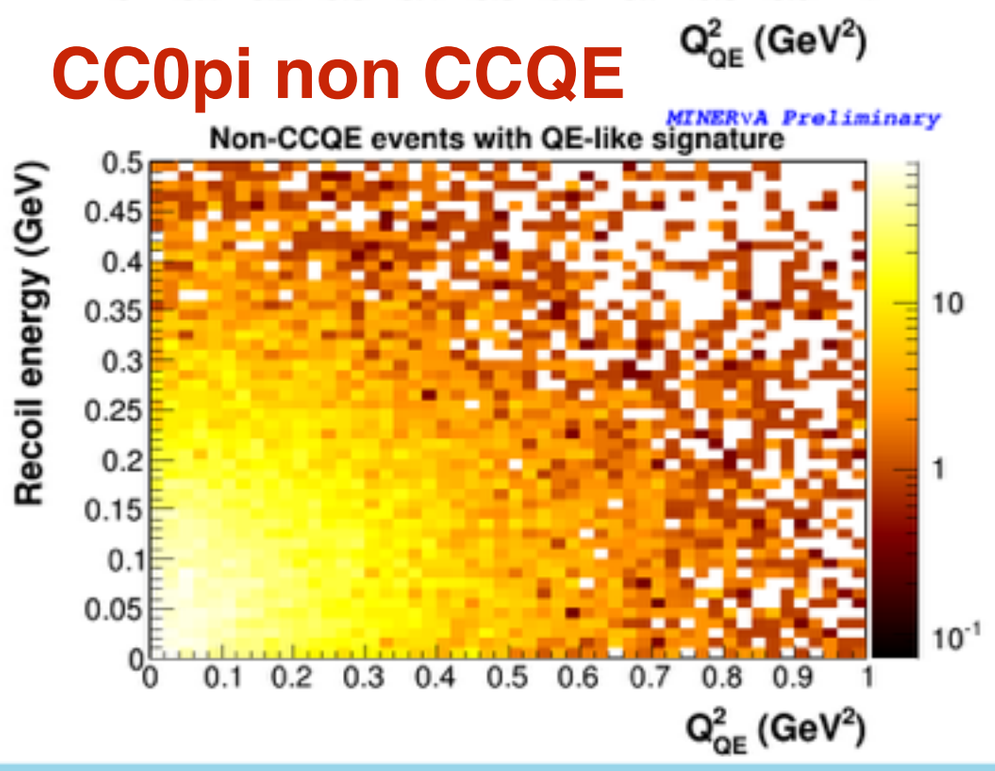
CCQE



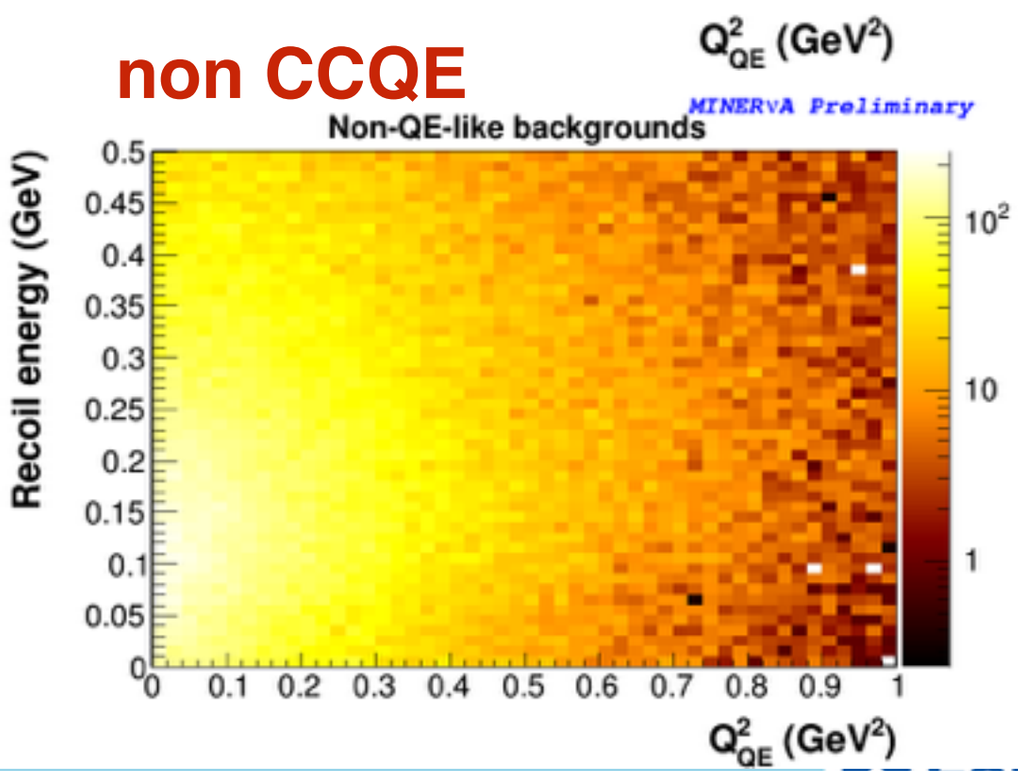
2p2h



CC0pi non CCQE



non CCQE



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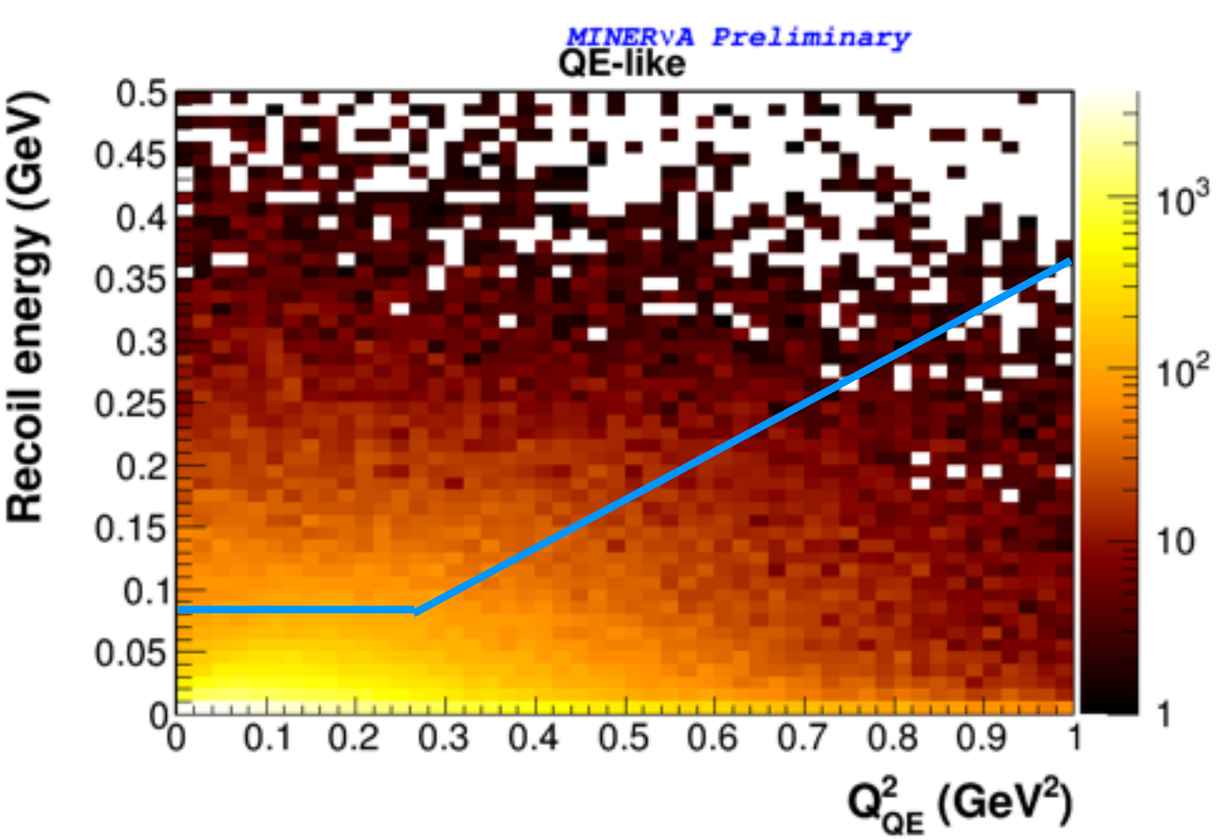
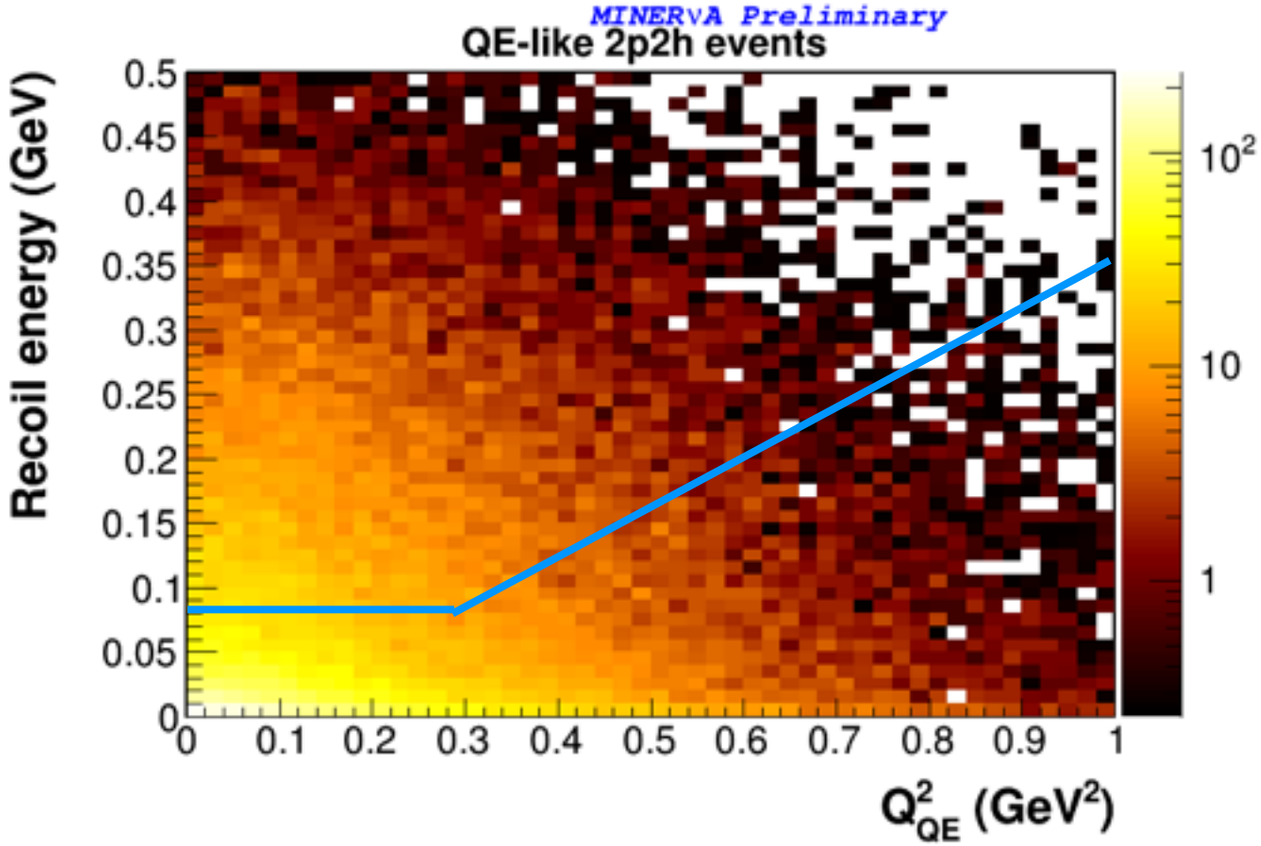
Acceptance for Anti-Neutrino Analysis

Acceptance 54%



Acceptance 43%



- Additional recoil energy from second neutrons (2-particle-2 holes)
- Acceptance is smaller for 2p2h events

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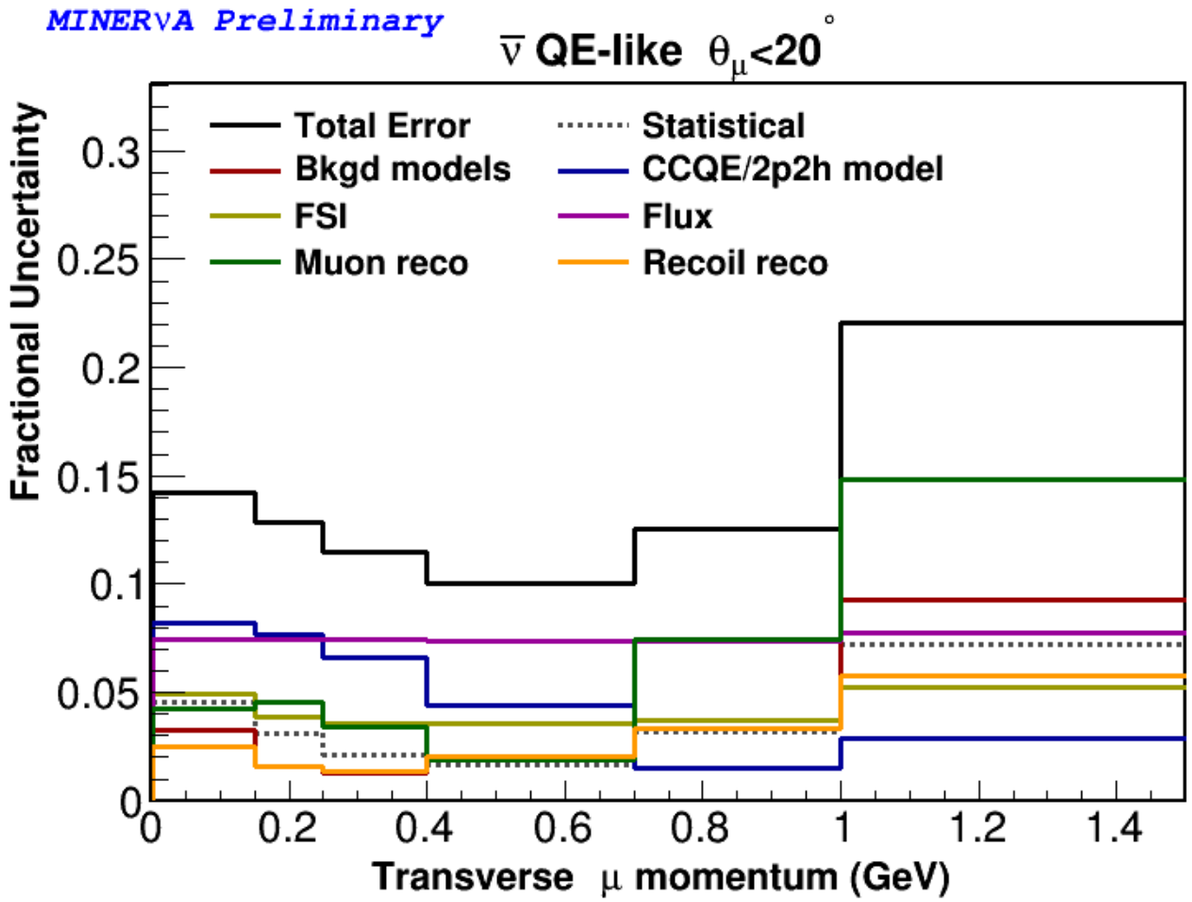
Uncertainties



Fermilab Wine and Cheese Seminar, June 17 2016
Cheryl Patrick's PhD thesis

- Uncertainty from default 2p2h is evaluated using the difference between default genie+2p2h and default genie

- - - Statistical uncertainty

Background models

- **resonant** interactions affect background subtraction

CCQE / 2p2h model

- dominated by uncertainty in **correlation effect strength**

Final-state interactions

- **pion absorption** dominates

Flux

- beam focusing
- tertiary hadron production
- reweight to other experiments

Muon reconstruction

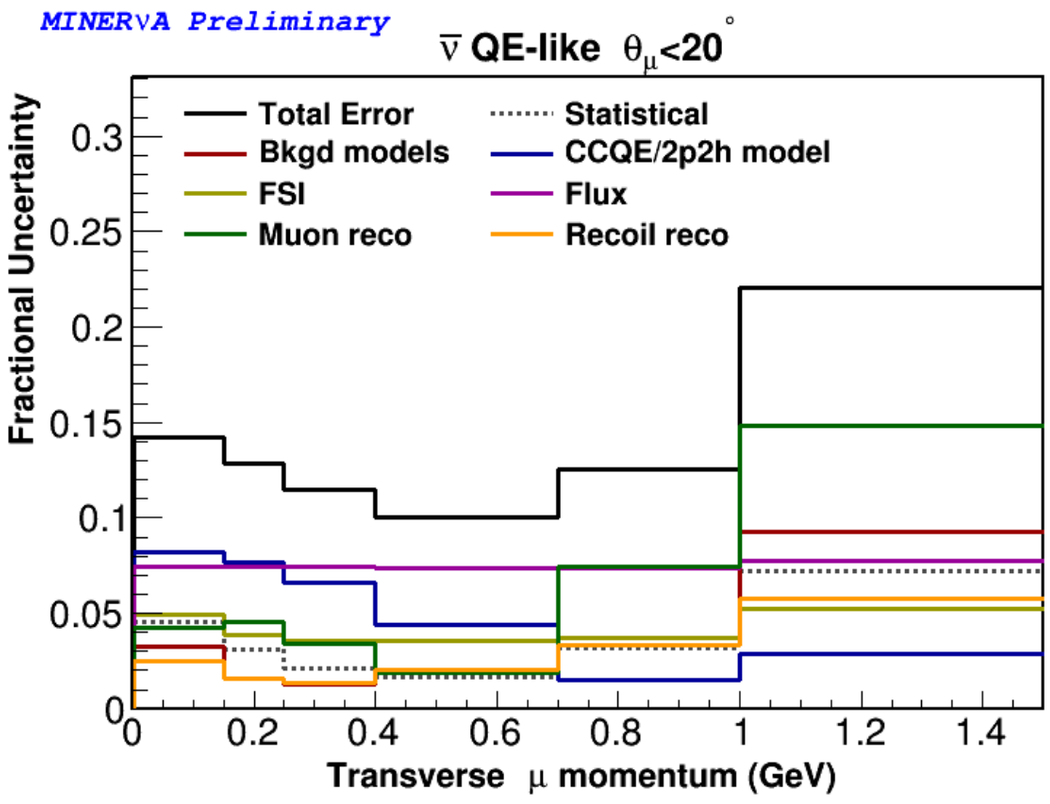
- **muon energy scale** dominates
- tracking efficiency
- muon angle and vertex position

Recoil reconstruction

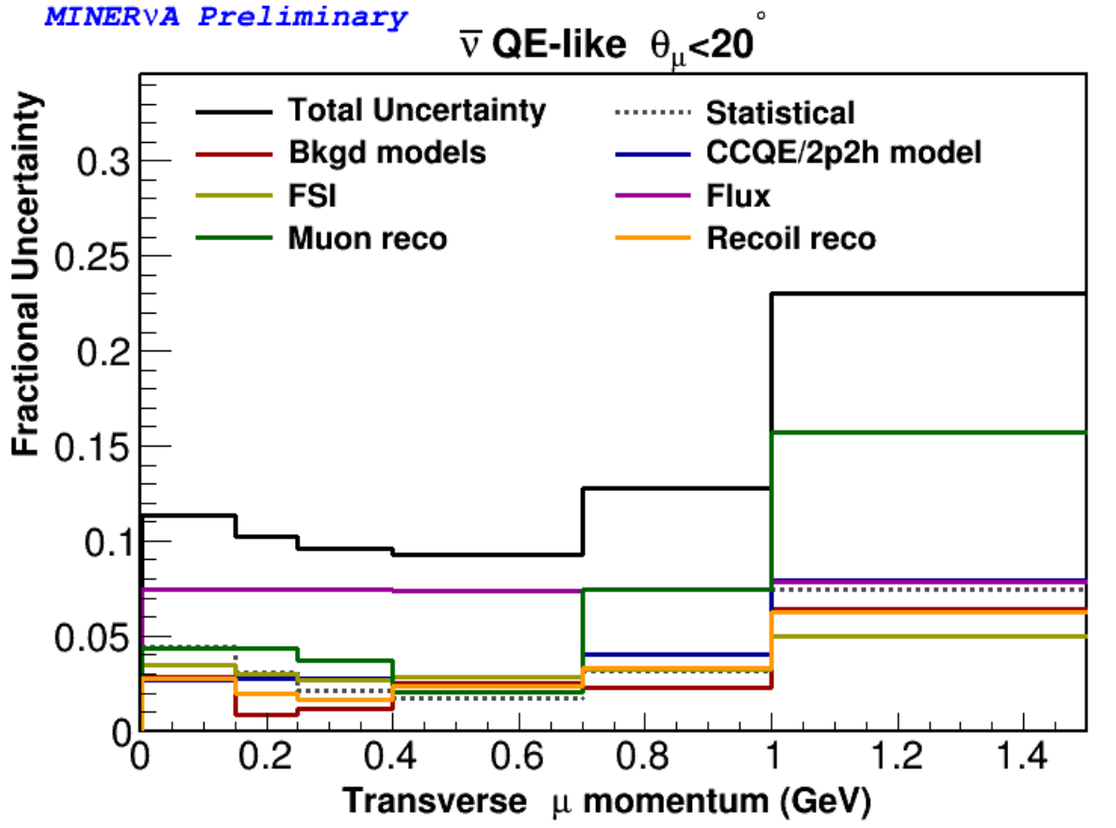
- detector response to different particles - **neutron** dominates

Uncertainties

- The systematics for 2p2h is evaluated using the different initial state tunes; 2p2h np initial state, 2p2h not np initial state and 1p1h QE



Systematics with the default 2p2h



Systematics with tuned 2p2h

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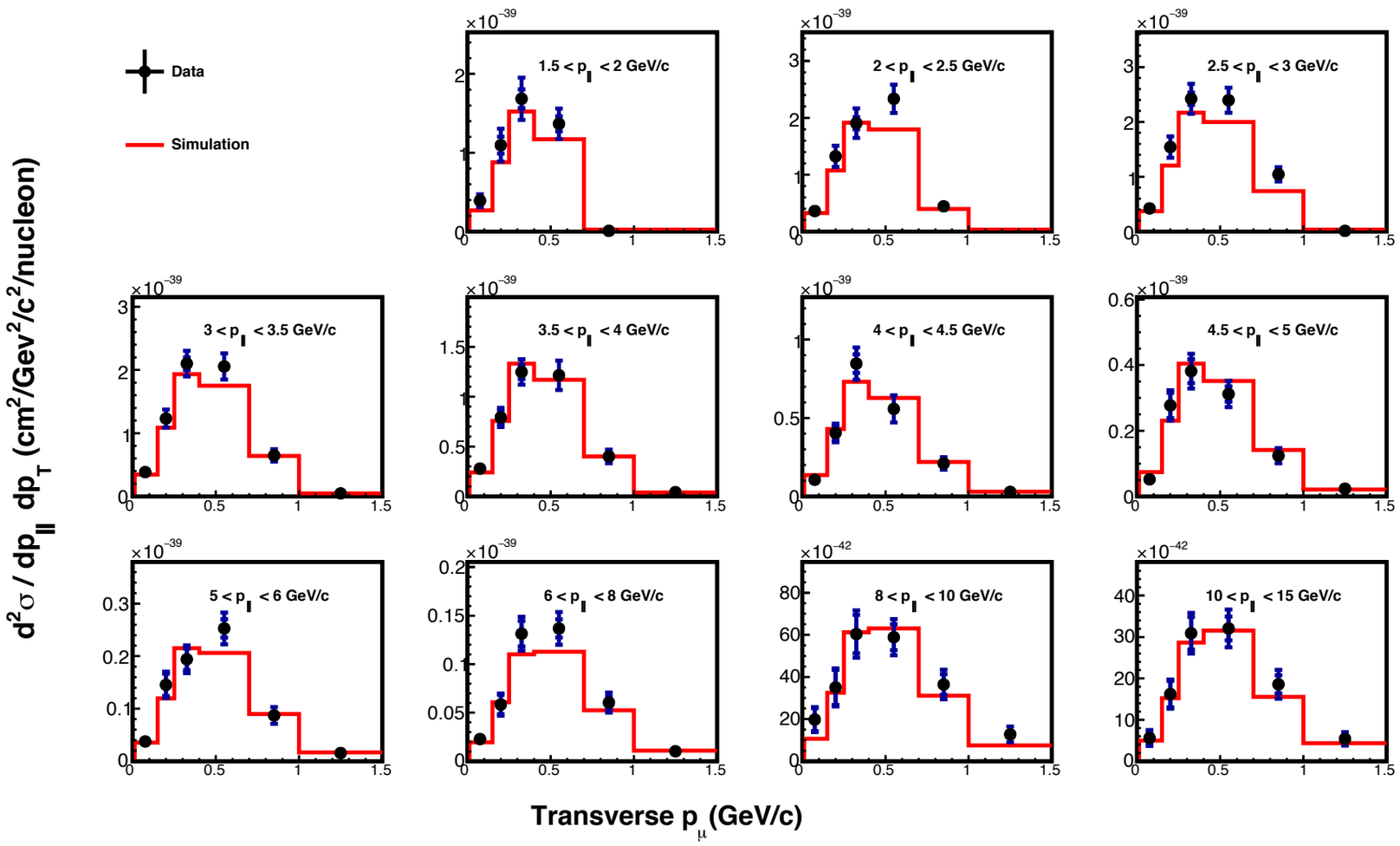
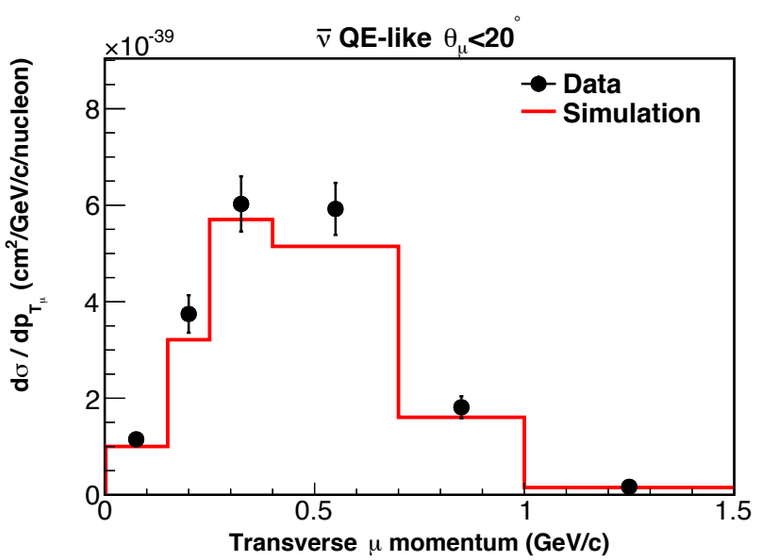
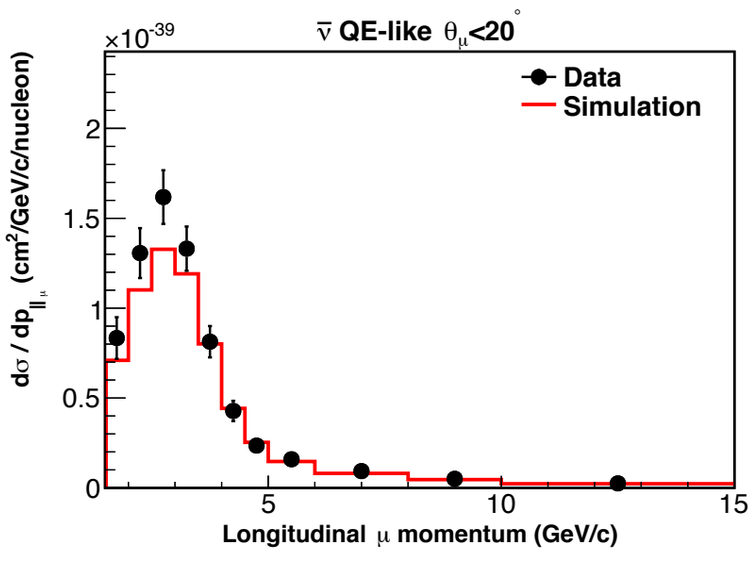
N-dim vs 1-dim Antineutrino CCQE (CC0pi)

2D-dimensional



1-dimensional





Detailed information with the double differential cross sections

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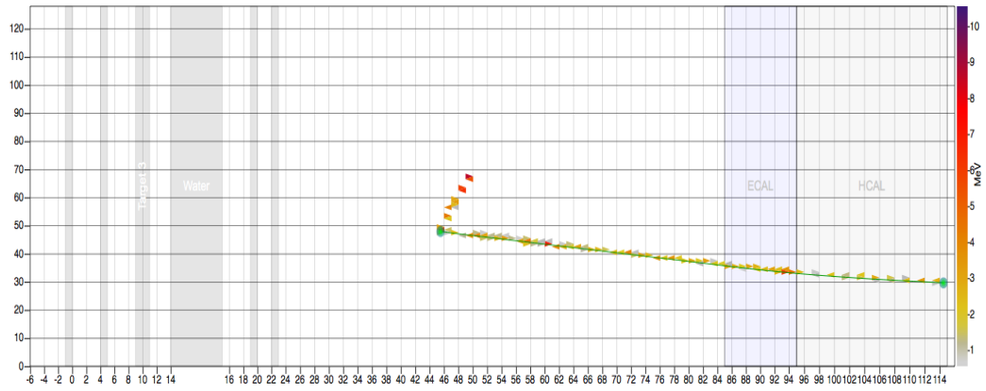
CC0pi Neutrino Event Selection and Signal Definition

- New Selection requires a cut on non-vertex recoil energy, events above 0,5 GeV are removed
- Track pions and protons; select events based on particle identification
- Look for Michel electrons at later time to remove events with pi+



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  - Any number of nucleons of all energy
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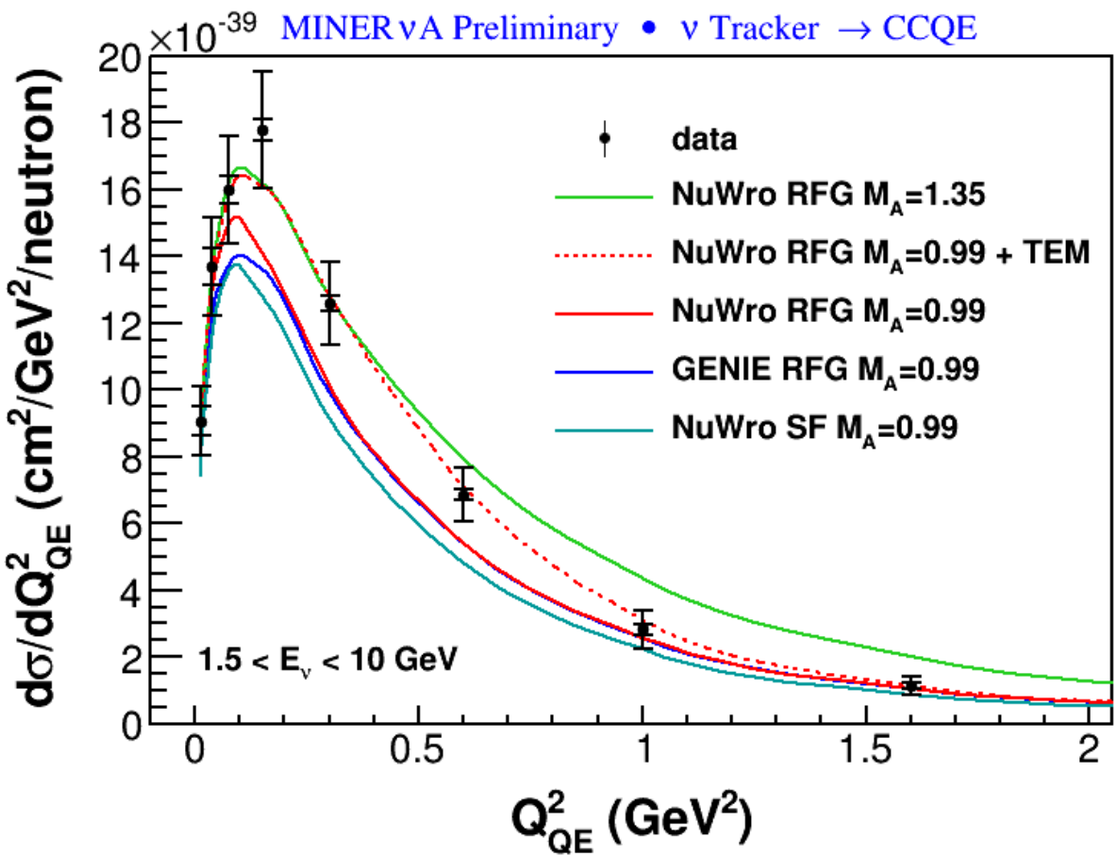
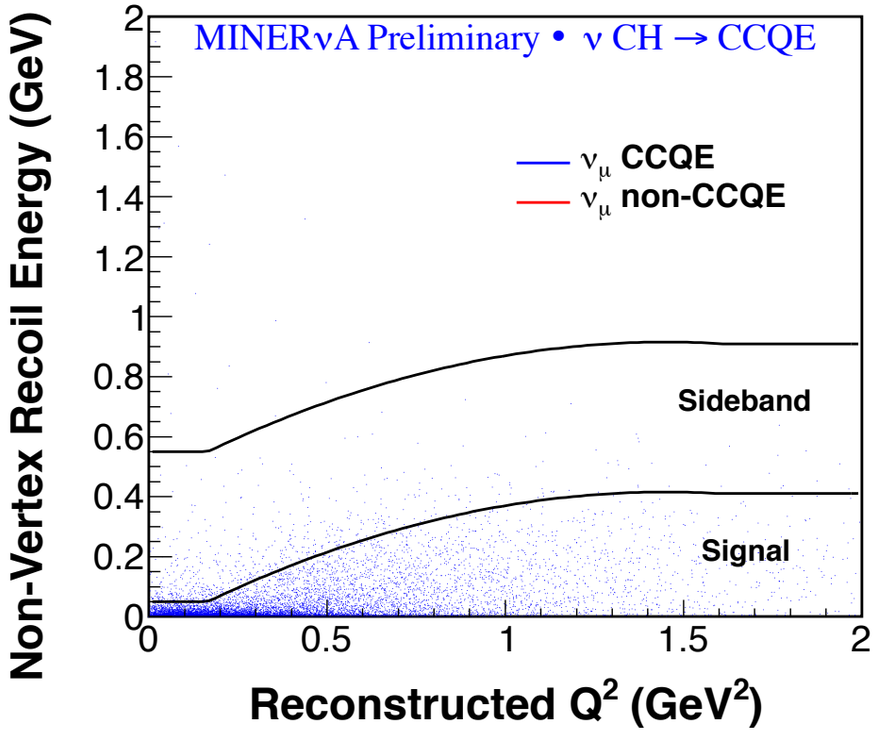
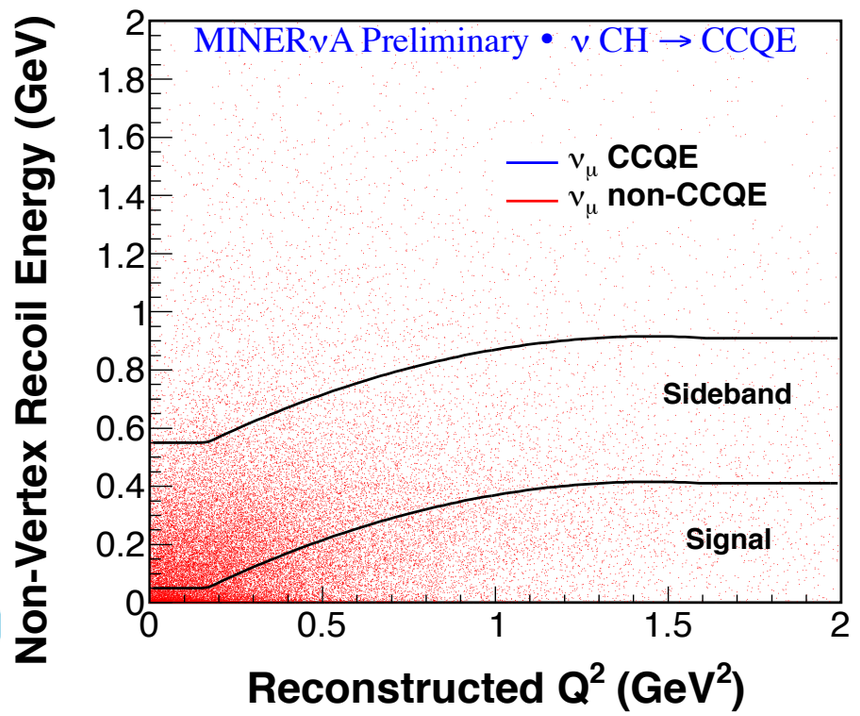
Non-Vertex Recoil Energy (Old Neutrino Measurement)

- Selection requires a cut on non-vertex recoil energy vs Q^2



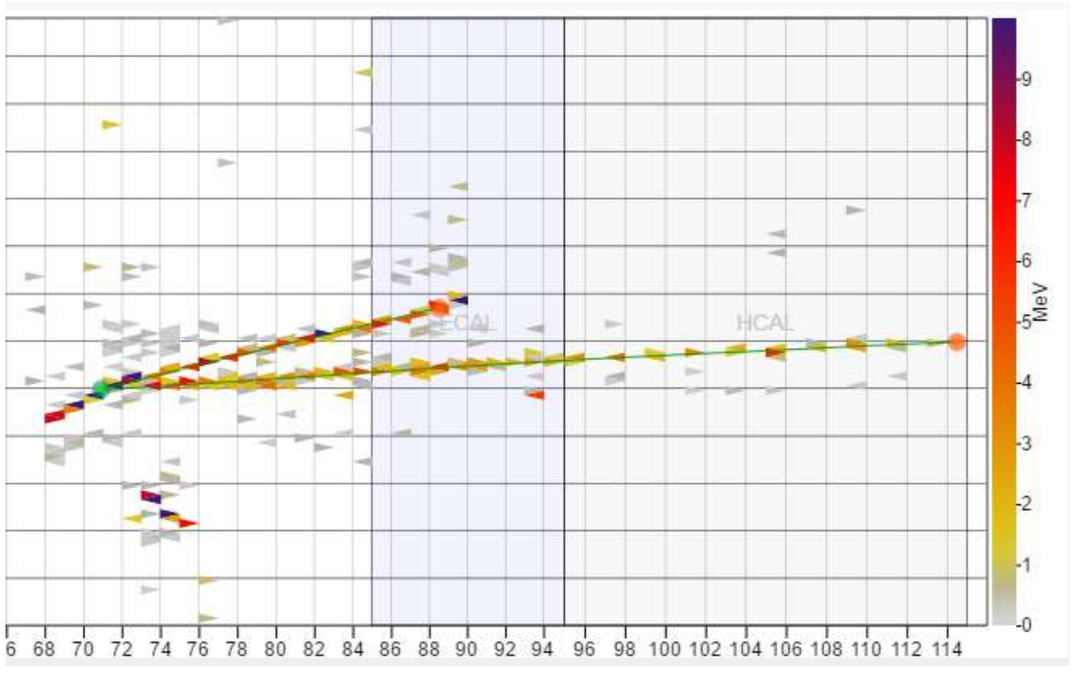
Phys. Rev. Lett. 111, 022501 (2013)

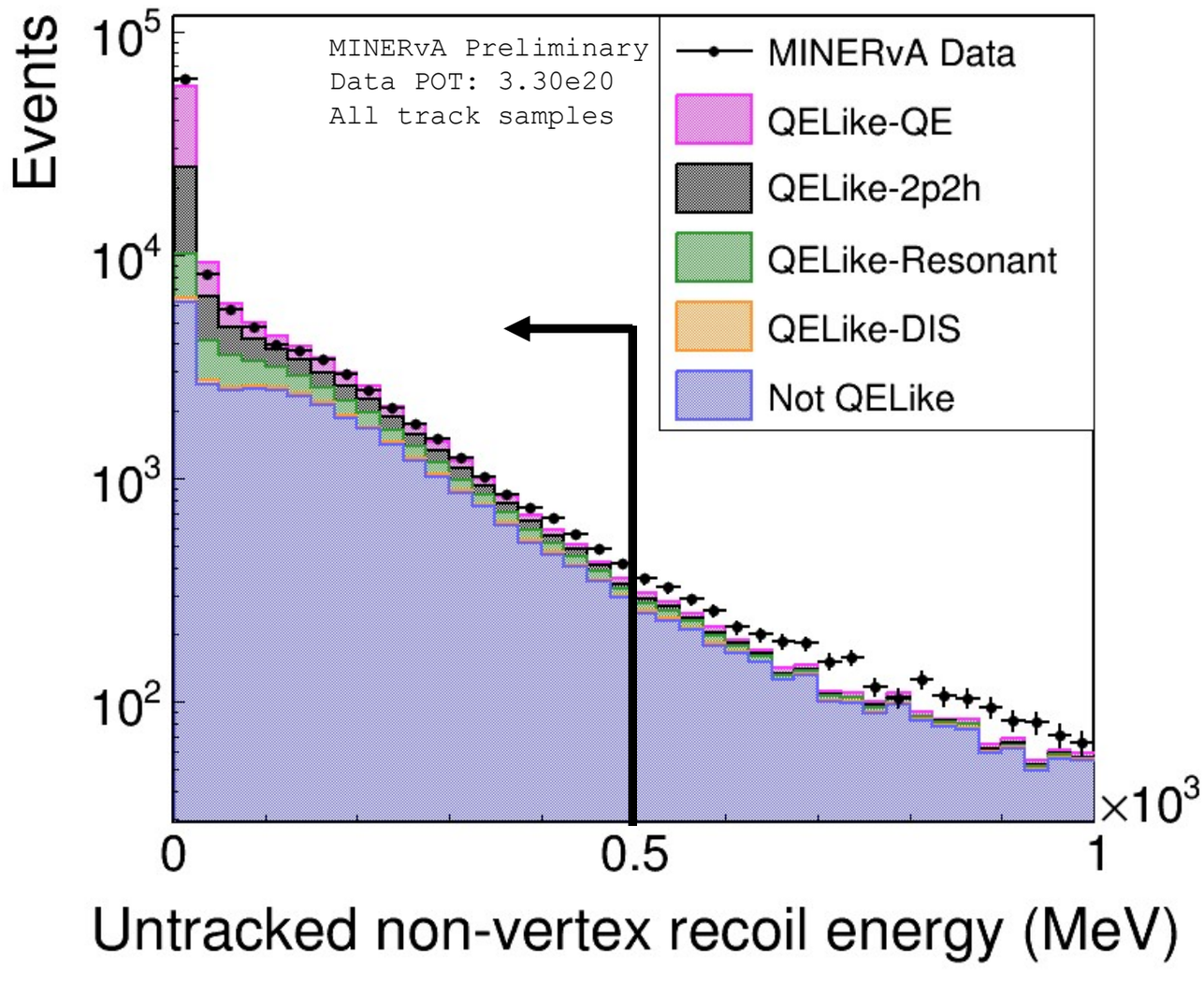




Non-Vertex Recoil Energy (New Neutrino Measurement)

- New Selection requires a cut on non-vertex recoil energy, events above 0,5 GeV are removed

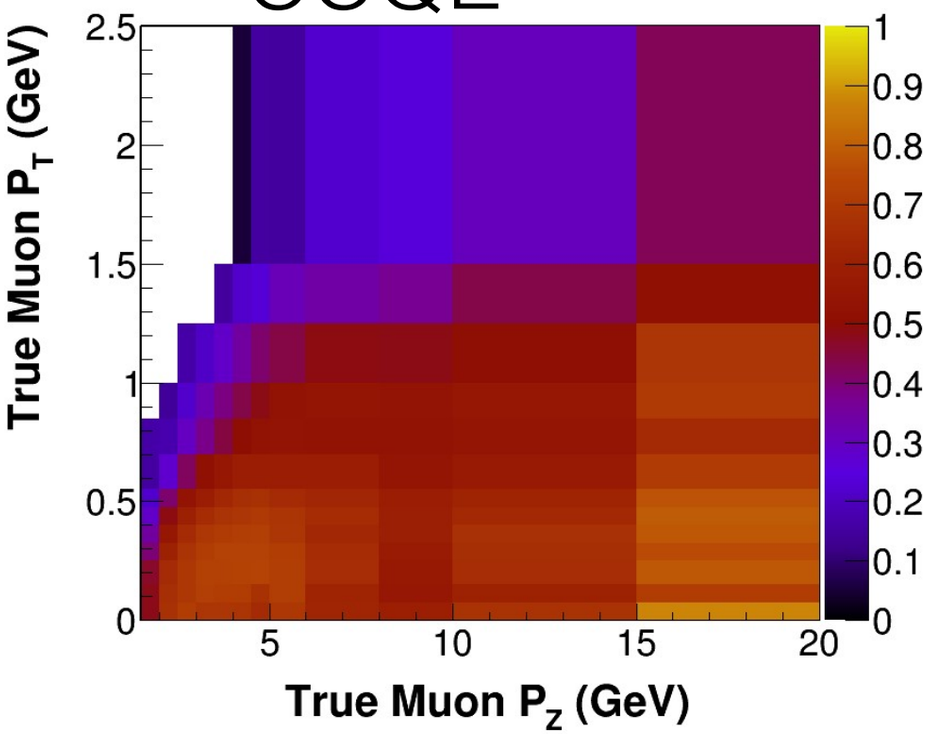




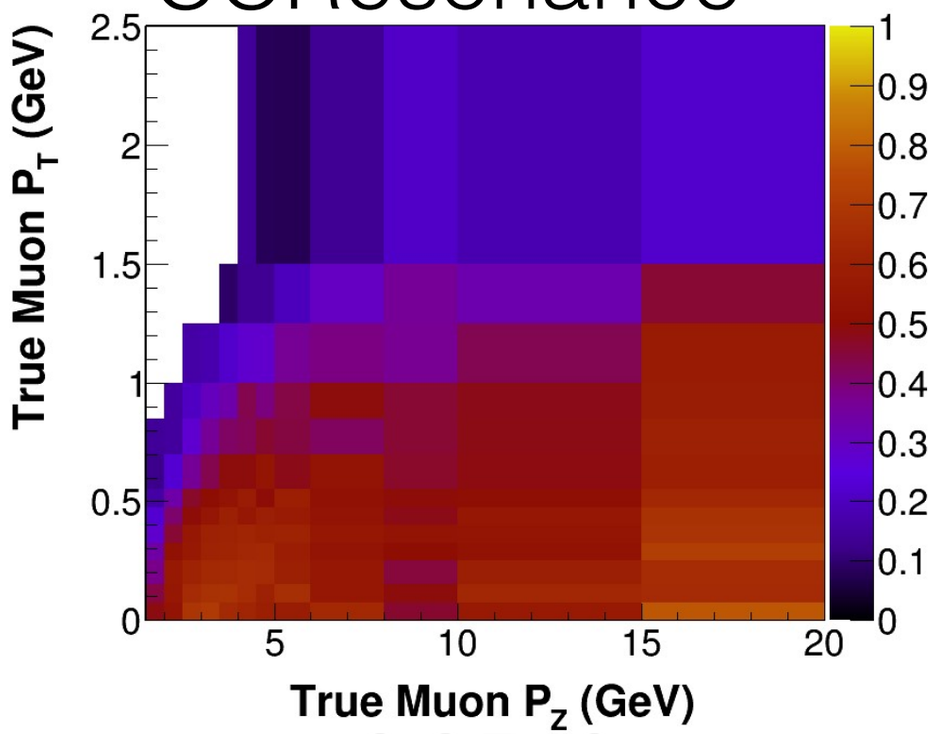
Efficiency for Neutrino Analysis

- For neutrino analysis similar efficiency for signal events and 2p2h events

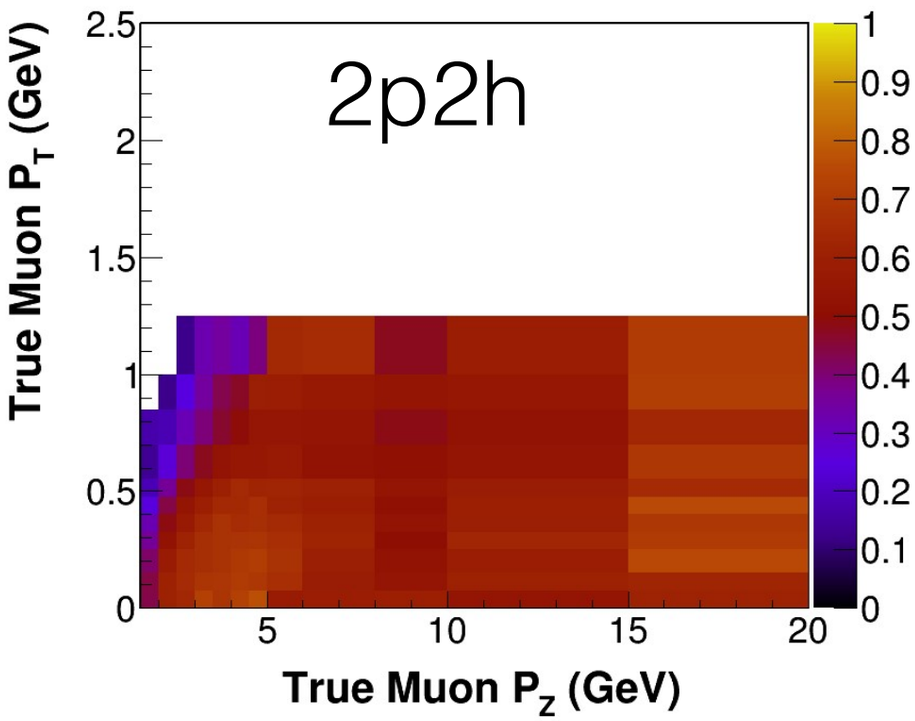
CCQE



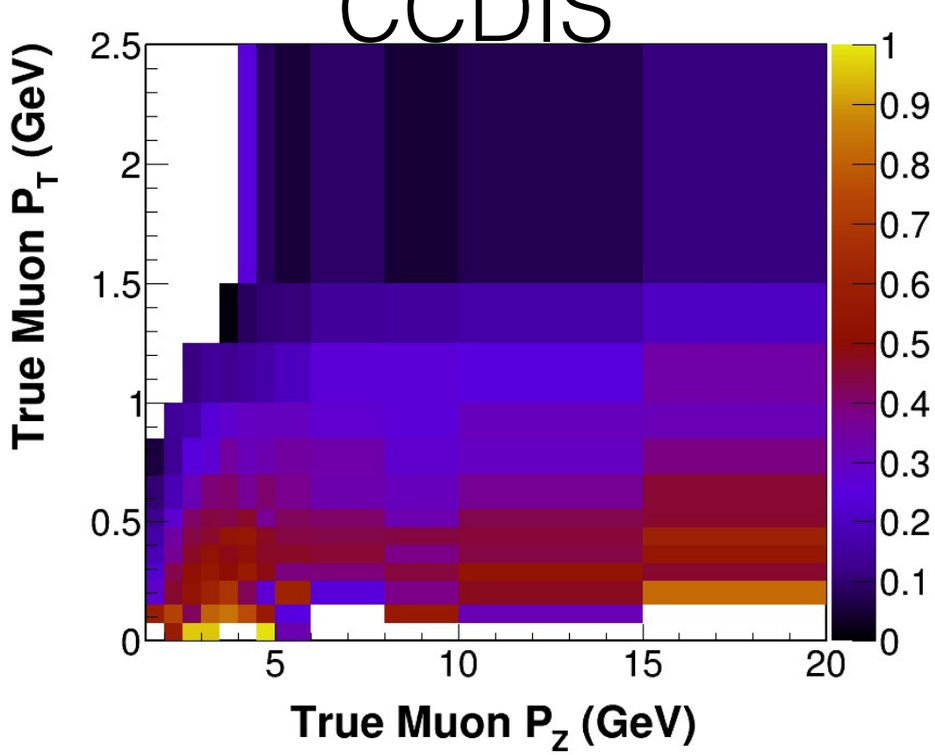
CCResonance



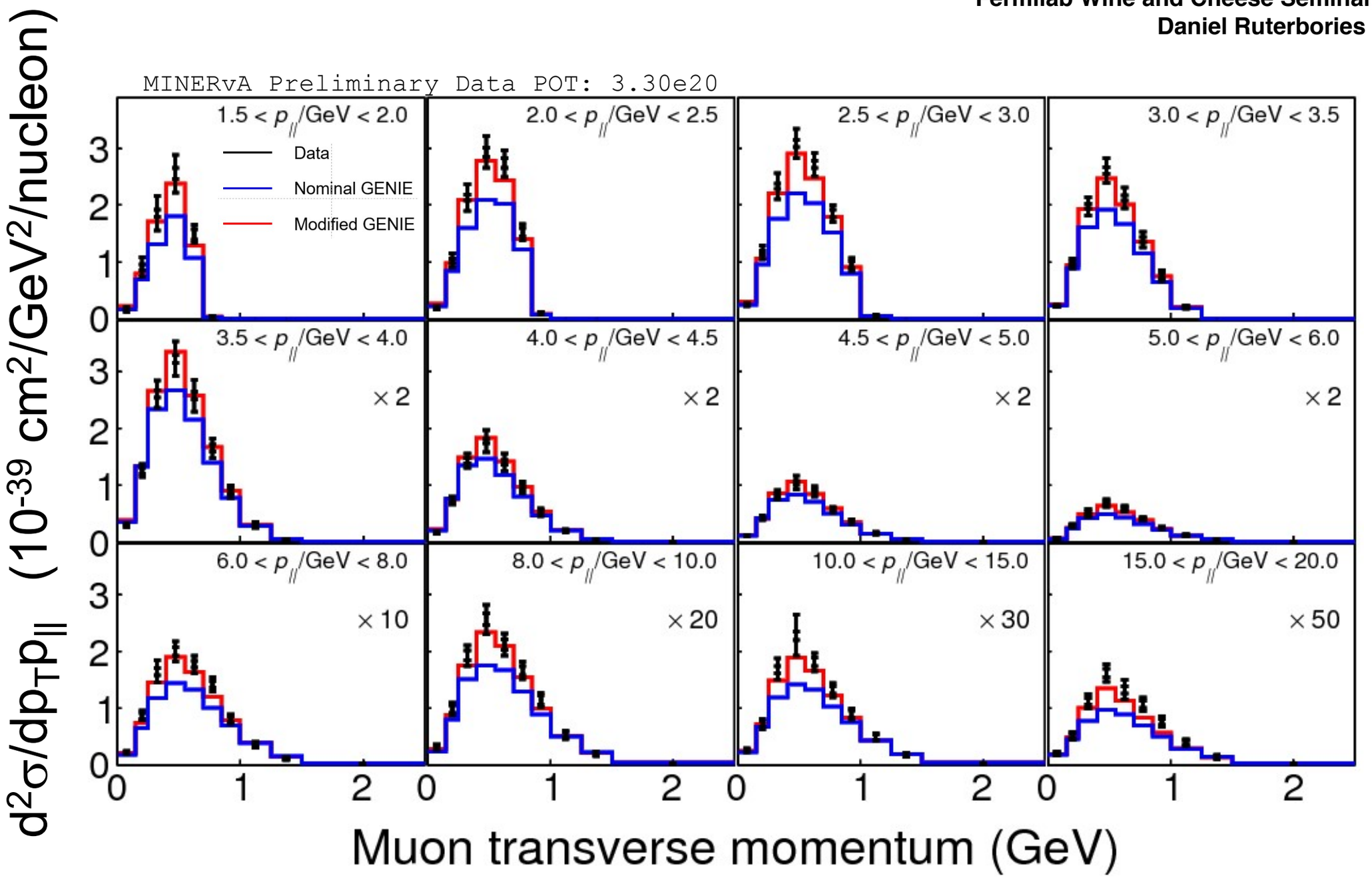
2p2h



CCDIS



Double Differential Cross Section



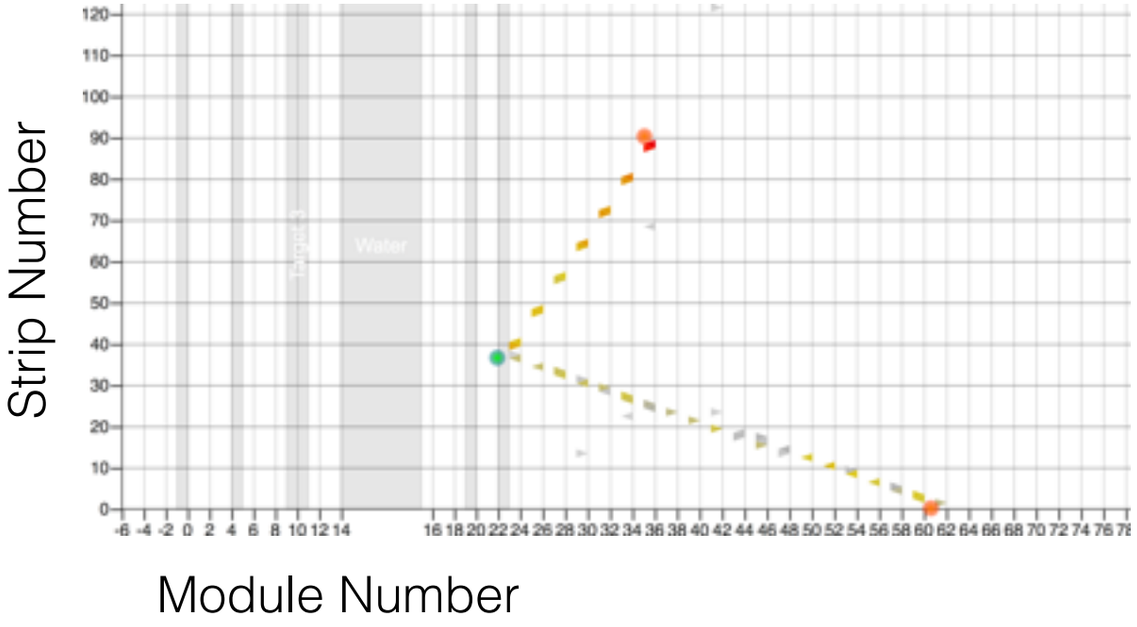
- See Dan Ruterbories's Nuint talk for updated results from neutrino and antineutrino analyses

CC0pi using the Proton Kinematics

- Q^2 is reconstructed using the leading proton from the event (different from the muon kinematic Q^2)
- Using the QE hypothesis and assuming scattering from a free nucleon at rest

$$Q^2 = (M')^2 - M_p^2 + 2M'(T_p + M_p - M')$$

- Measurement: differential cross section as a function of the proton Q^2



Signal (CCQE-like):

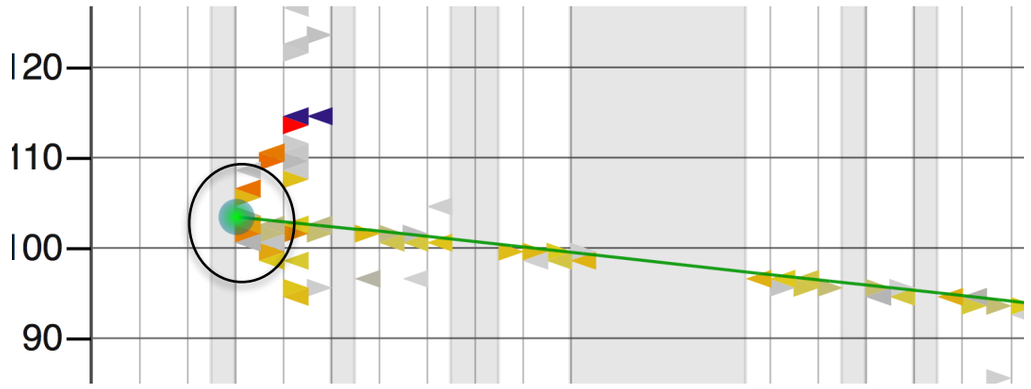
Events with one muon, no pions and at least one proton with momentum> 450 MeV/c

CC0pi measurement on scintillator
Phys. Rev. D. 91, 071301, 2015
CC0pi new measurements on Iron, lead and Carbon
arXiv:1705.03791

- Proton information allows to test FSI models

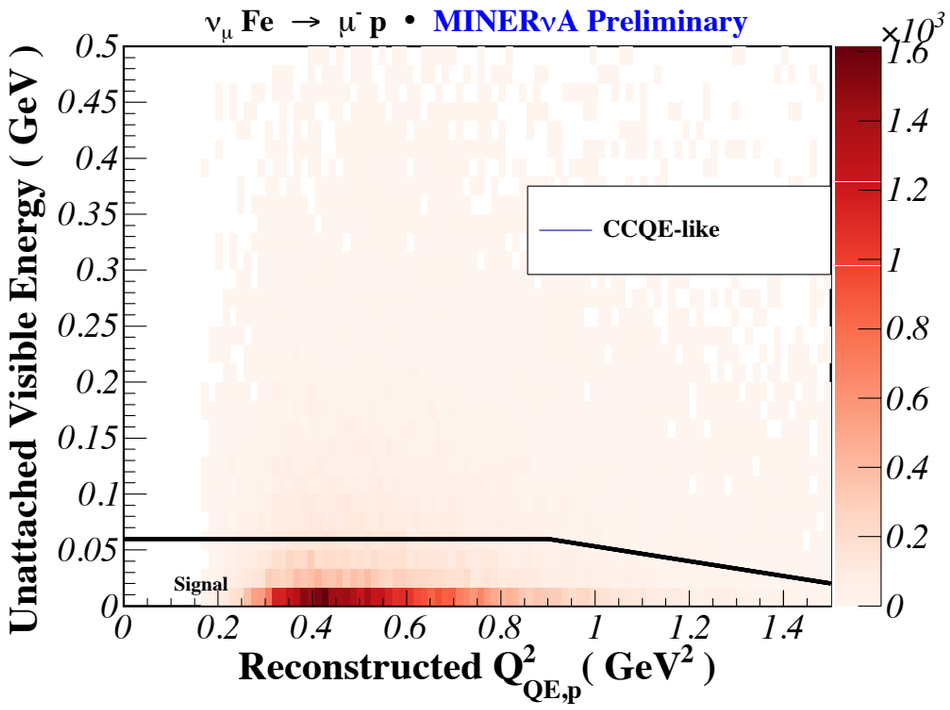
Non-Vertex Recoil Energy for Two Track Events

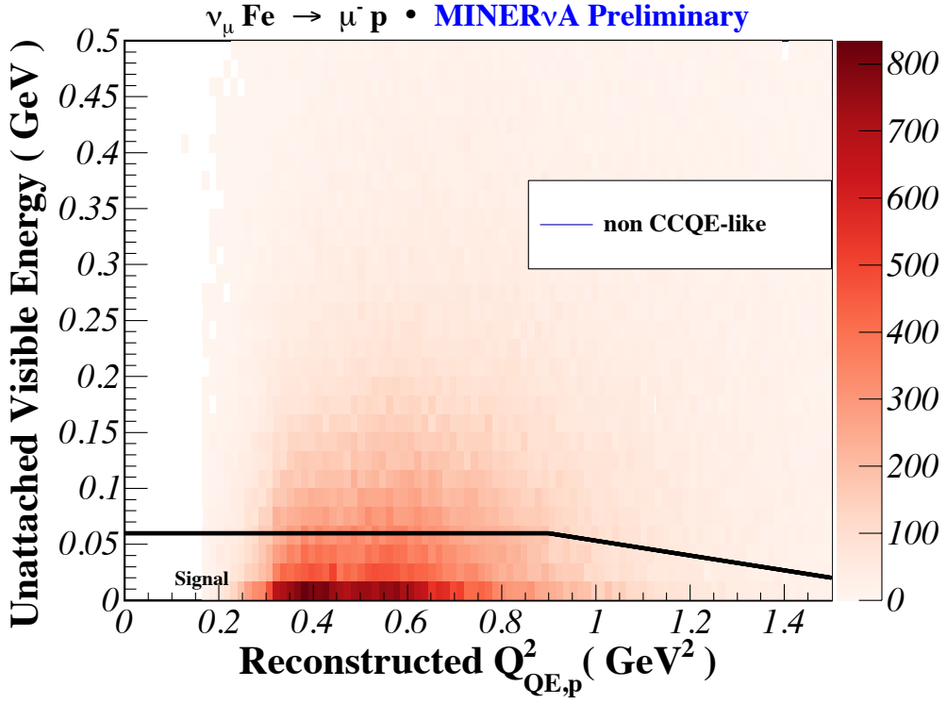
- We define a variable called unattached visible energy, which is the sum of the visible energy that is outside of the sphere (radius=10cm)



Signal

Background





- Efficiency for the selected events and 2p2h events is very similar

Fermilab

Summary

- Observables: we try to make measurements with less model dependence as possible
- Recoil energy separates different processes
- The signal definition is coupled with the acceptance we have in our detectors
- We use a model for 2p2h, thanks to Valencia group!
  - We tune the 2p2h model with the CCInclusive low recoil analysis and use different tunes to evaluate the systematic from 2p2h based on np, nn and QE initial states
- New MINERvA observables:
  - Muon P_T and P_z: less model dependent*
  - Q^2 from proton: allows to test FSI simulations
  - e-scattering like observables: Three momentum transfer q_3 and energy transfer q_0

*New results at Nuint 2017:
Dan Ruterbories (PT, PZ), Rik Grand (q3,q0) and M. Betancourt (proton Q^2)