Progress in measuring neutrino QE interactions
Summary, Prospects, Challenges, Discussion

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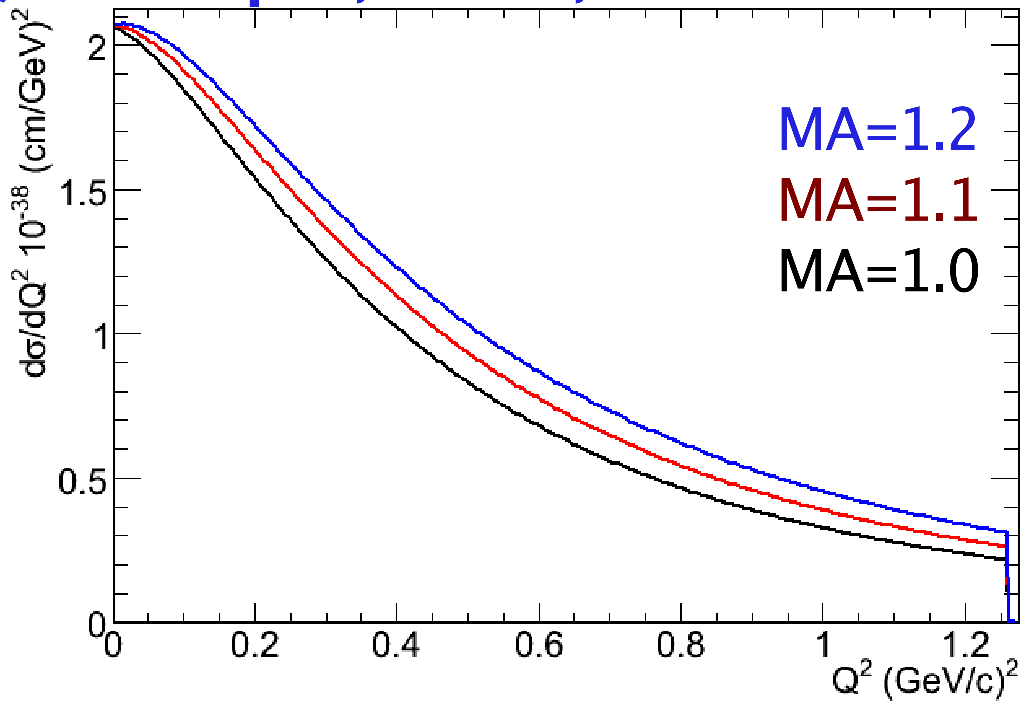
Three ways to see: Q2 shape, rate, or both

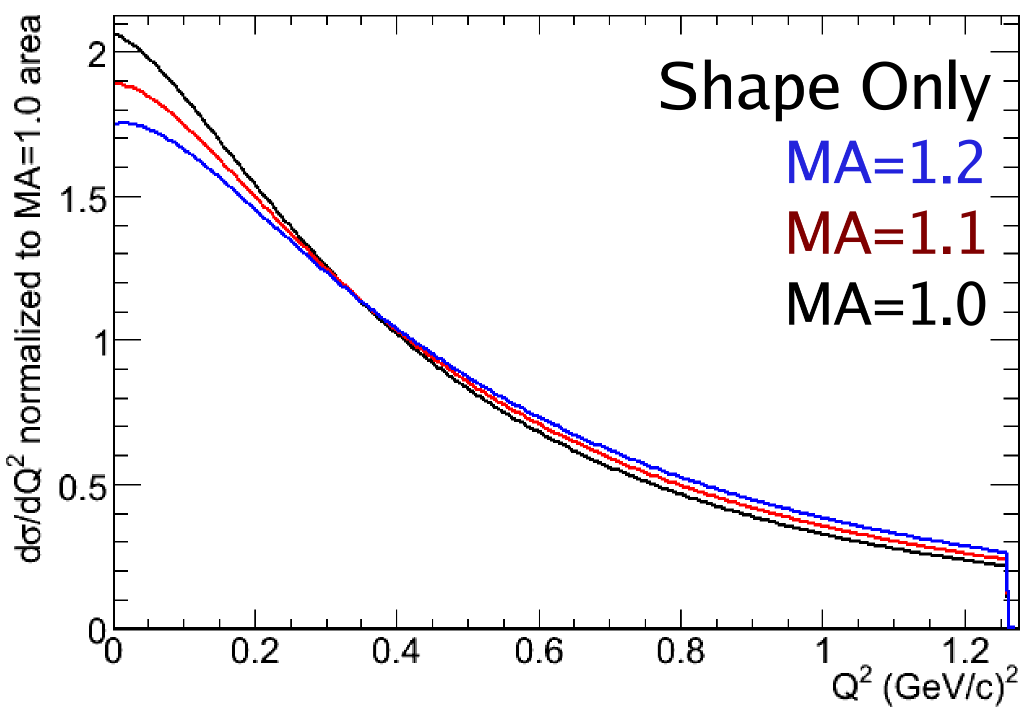
Absolute Quasi-elastic
Cross section
1.0 GeV $\nu_\mu + n \rightarrow \mu^- + p$

(requires flux information)
This is particularly relevant
for a neutrino oscillation analyses

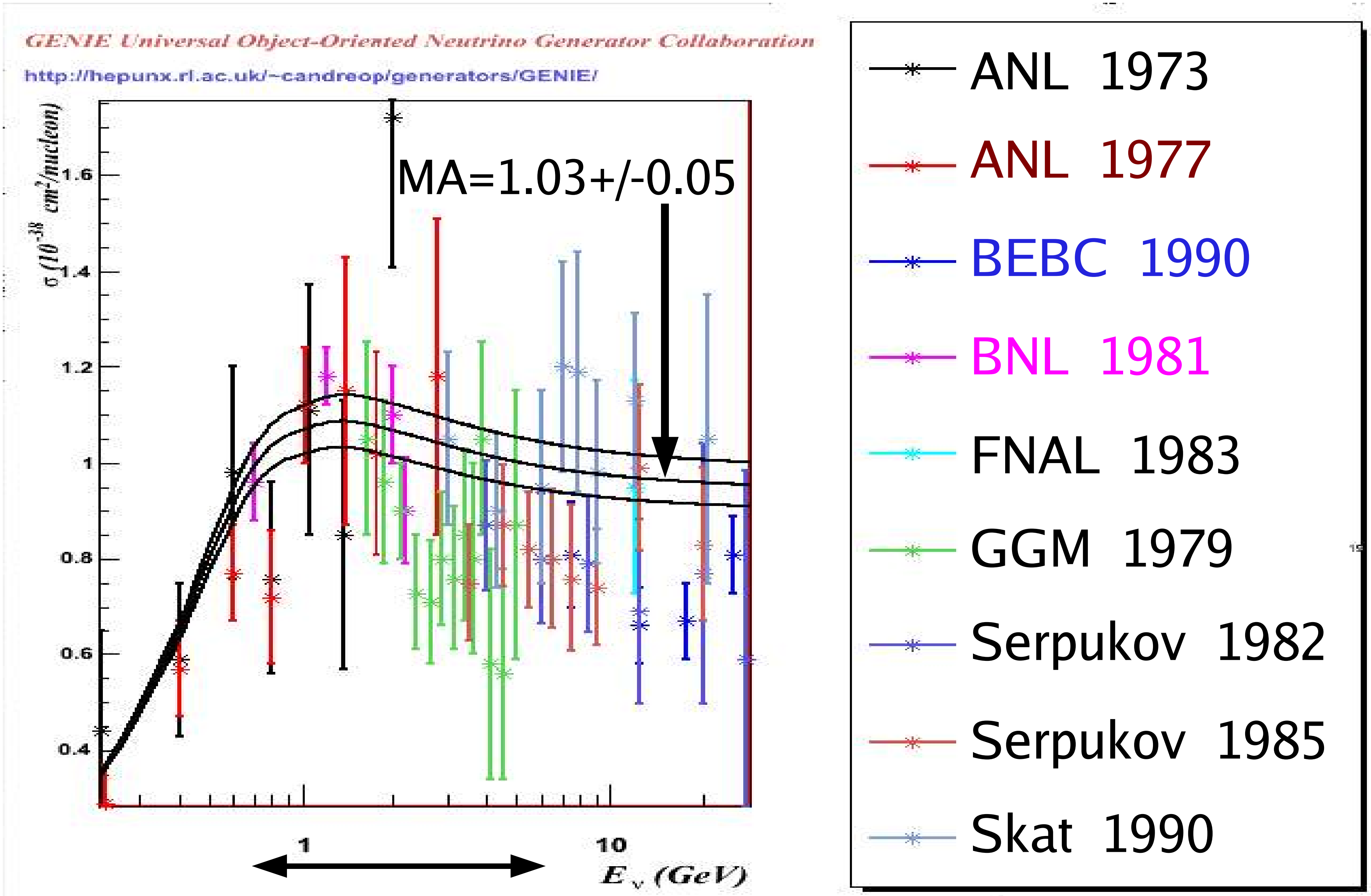


Shape fit
(can be flux independent)
a good way to extract dipole MA

"World Average c. 2001"
was MA = 1.03 +/- 0.03
Olssen vector form factors
mostly from shape fits

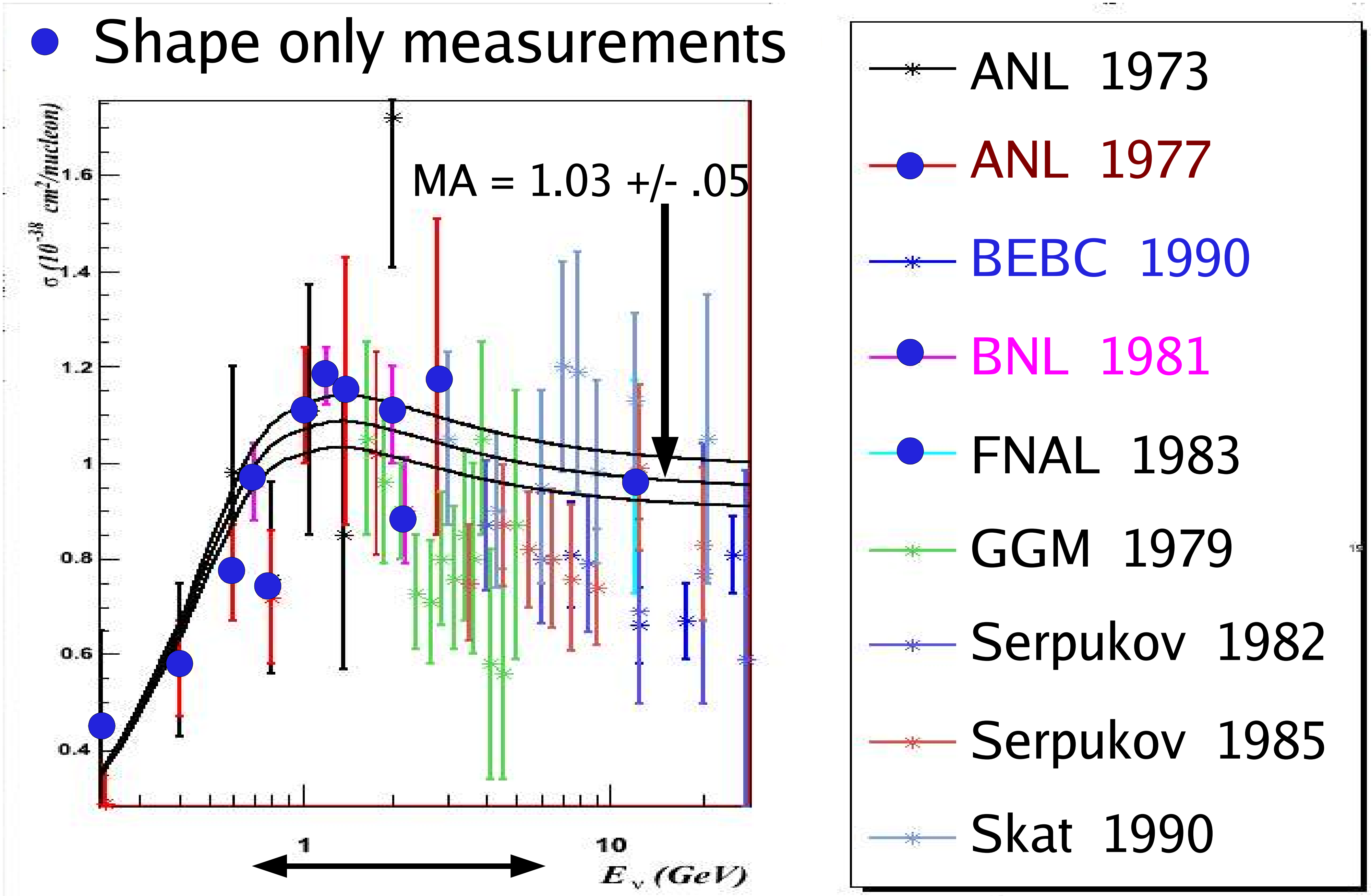


Oscillation experiments need to know QE rate



Region of interest for oscillation experiments

Oscillation experiments need to know QE rate



Region of interest for oscillation experiments

The state of the MA art at NuInt01 conference

Experiment	Target	Shape	Rate (and shape)
ANL 1982	D2	1.00 +/- 0.05	0.74 +/- 0.12
BNL 1990	D2	1.07 +/- 0.06	not given
FNAL 1983	D2	1.05 +/- 0.12	not given
GGM 1979	Pr-Fr	0.94 +/- 0.05	0.84 +/- 0.08
BEBC 1990	D2	1.08	0.94
BNL 1987	Al	1.06	not given
Serpukov 1985	Al		1.00 +/- ?
SKAT 1990	Freon	1.05 +/- 0.07	1.08 +/- 0.14

Some measurements combine rate and shape.
It is not clear whether shape or statistics dominates

K2K at NuInt01: all near detectors have discrepancy with very low Q^2 model and also harder Q^2 spectrum

The state of the art at NuInt07 conference

Several authors provide alternate fits to pre-2000 data

"Effective MA" and Use of updated vector form-factors.

Experiment	Target	Shape	Rate (and shape)
K2K-SciFi '06	H2O	1.20 +/- 0.12	
K2K-SciBar	CH	1.14 +/- 0.11	
MiniBooNE	CH2	1.23 +/- 0.20	? 15% flux error
NOMAD	CH	soon	soon
MINOS	Fe	in progress	in progress
SciBooNE	CH	taking anti-neutrino data	
MINERvA	CH,C,Pb,Fe	construction	construction
T2K near detectors		construction	Several likely One Million QE event samples
NOvA near detectors		proposed	
Liquid Argon detectors		prototypes and proposed	

SciBooNE

SciBar detector in Booster Neutrino Beam
First data in anti-neutrino beam

Several talks already – even more posters!
Please go see and talk with them

NOMAD

Preliminary results at NuInt05

Lots of work on systematics since then.

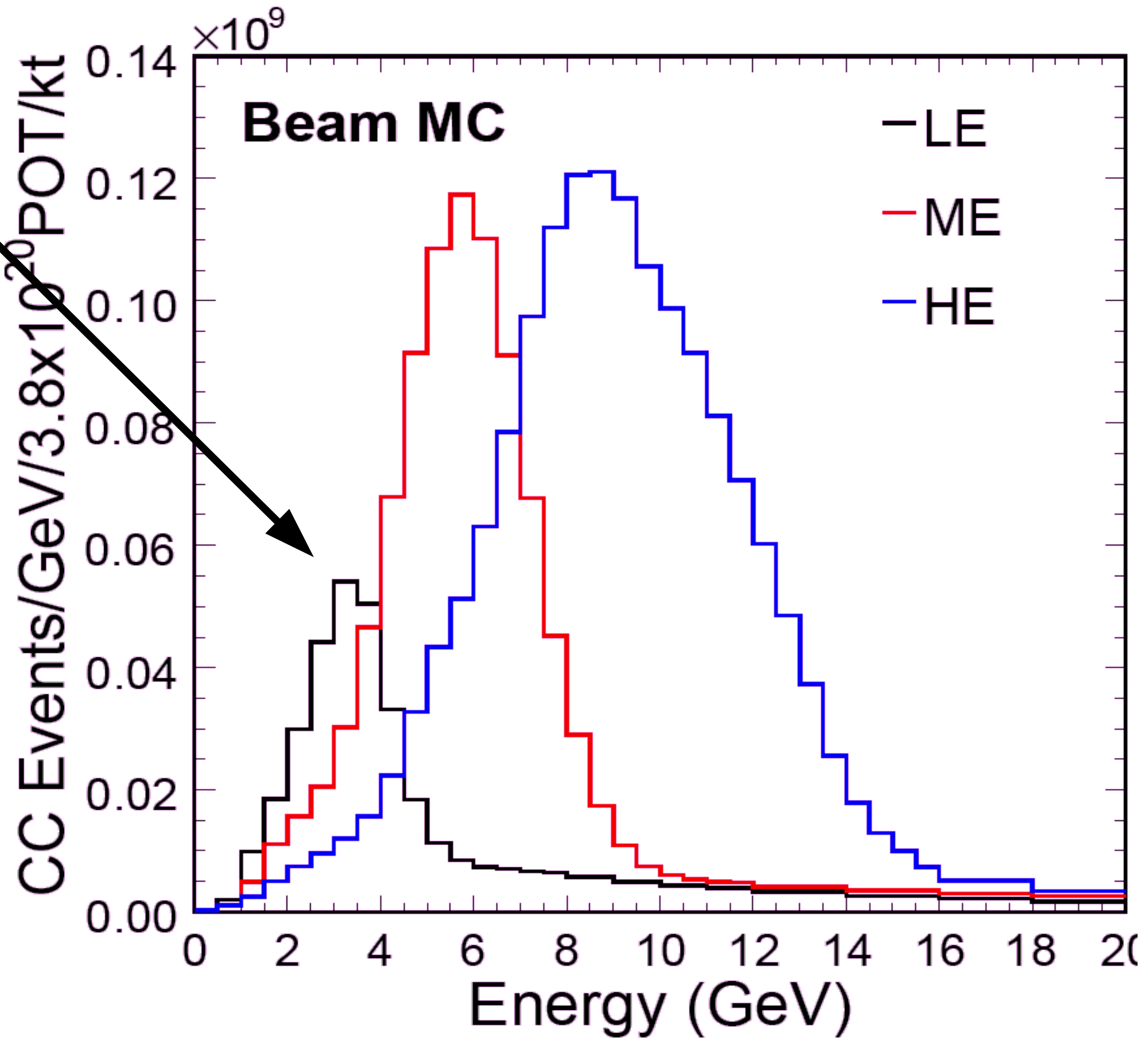
Continued progress toward final results.

MINOS

Most running in
LE Low Energy beam
Wide range of usable
energies: 1 to 20 GeV

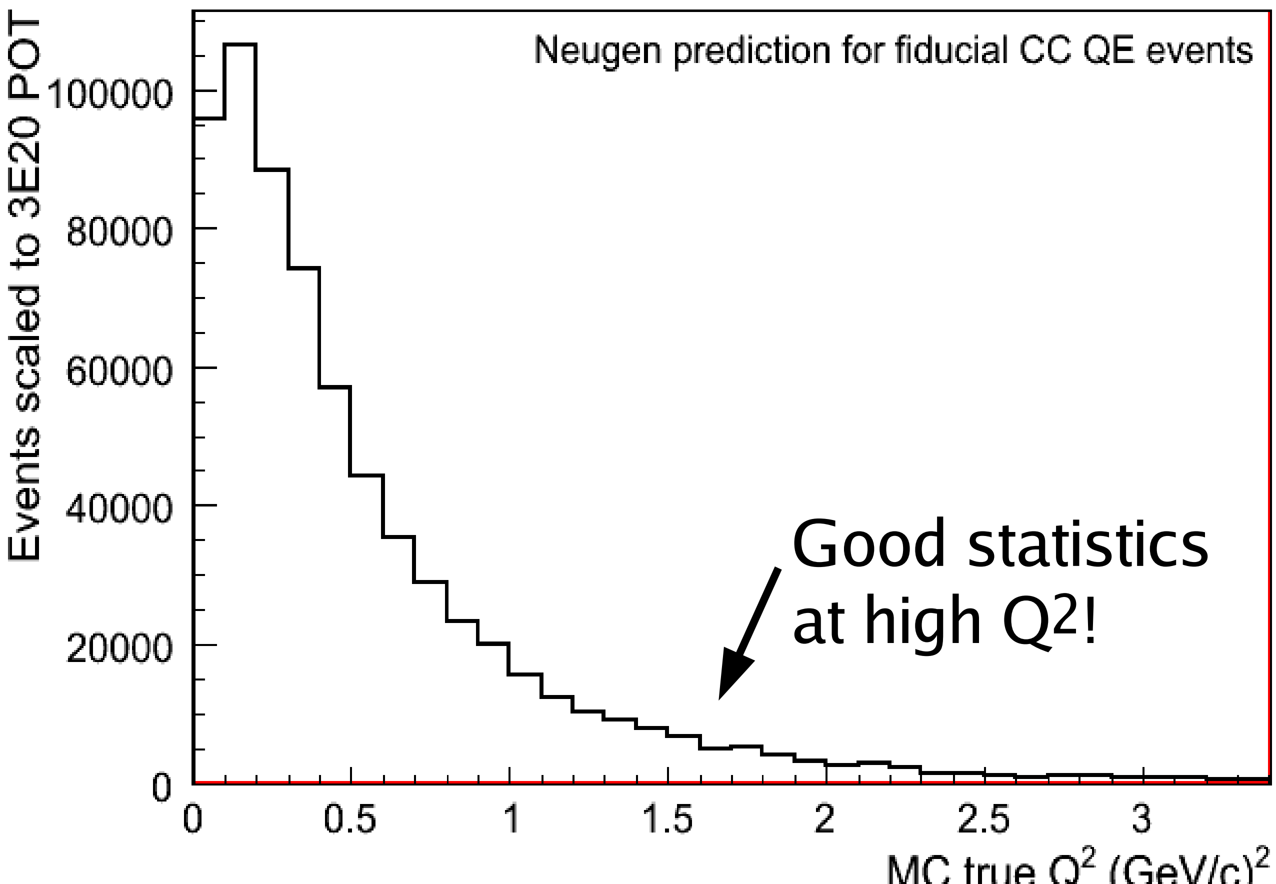
Other beams used to
study beam systematics!

MC predicts 800,000
QE interactions today
in 33 ton fiducial region
3e20 protons on target (POT)



MINOS QE analysis in progress

Muon momentum resolution
6% (range) and 13% (curvature)
Muon momentum bias +/- 2% measured from range
Muon angle resolution ~ 1 degree



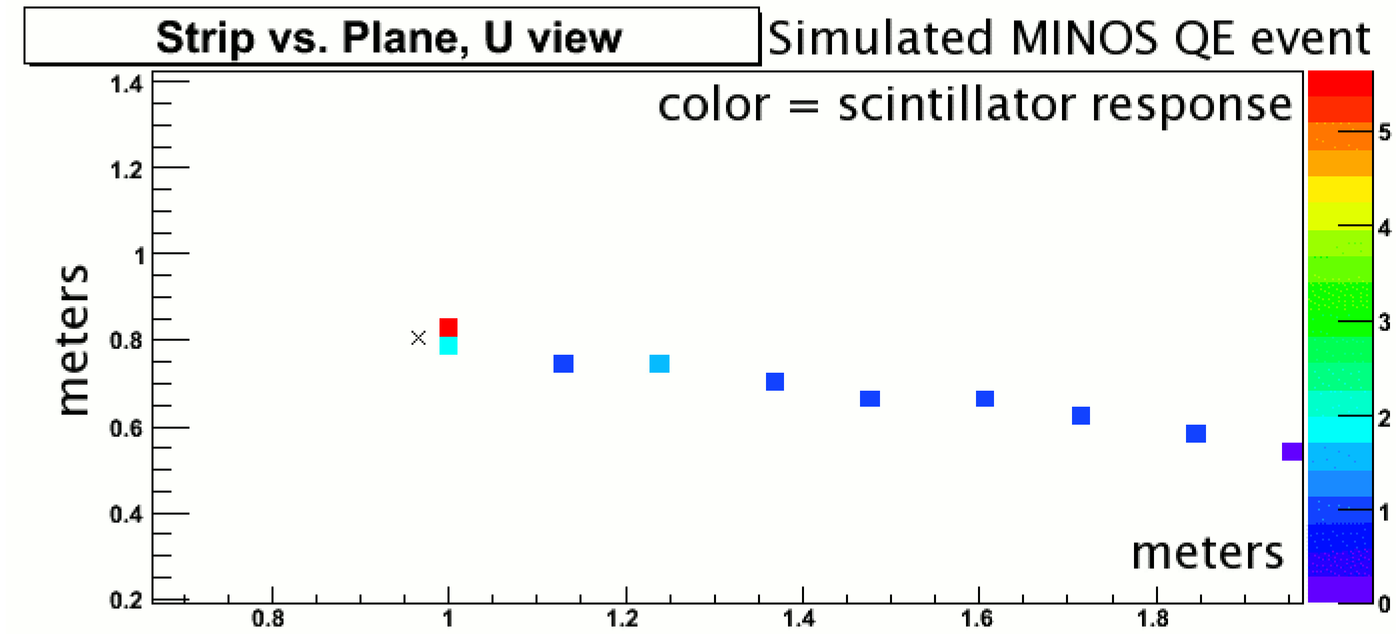
Q^2 resolution

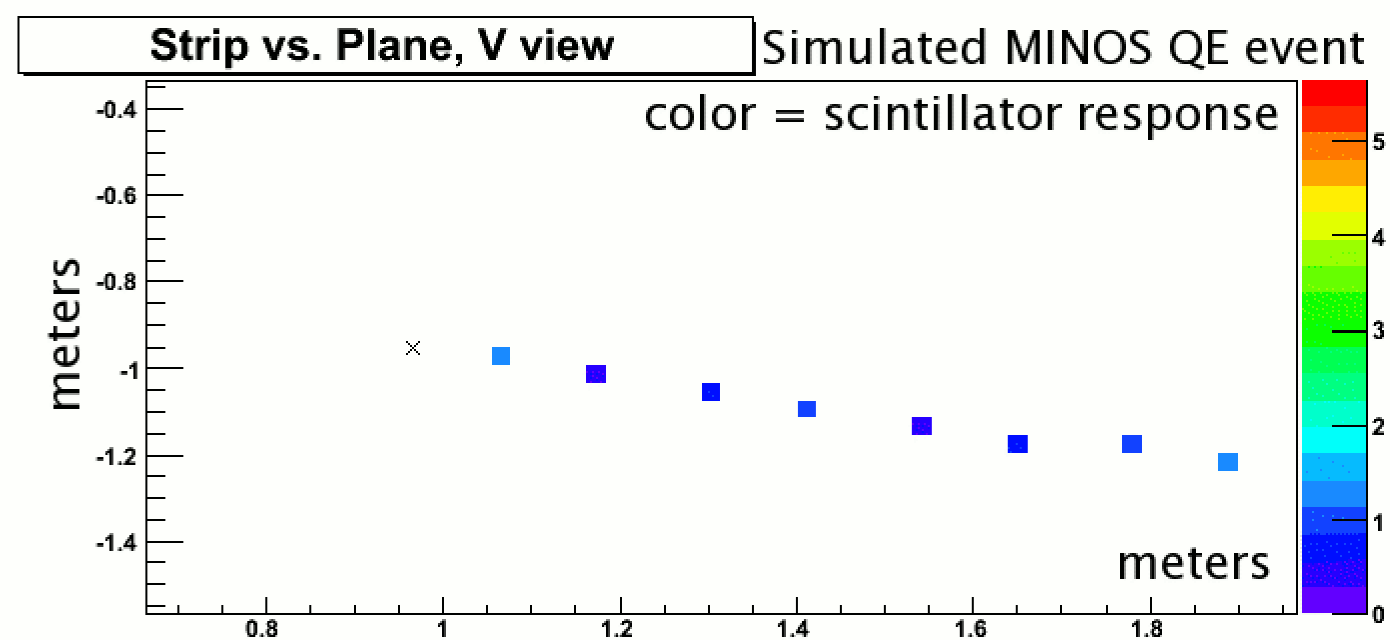
assuming QE kinematics

at $Q^2 = 0.3$
$\sim 0.1\ (GeV/c)^2$

at $Q^2 = 1.0$
$\sim 0.27\ (GeV/c)^2$

MINOS QE candidate event vertex view (MC)



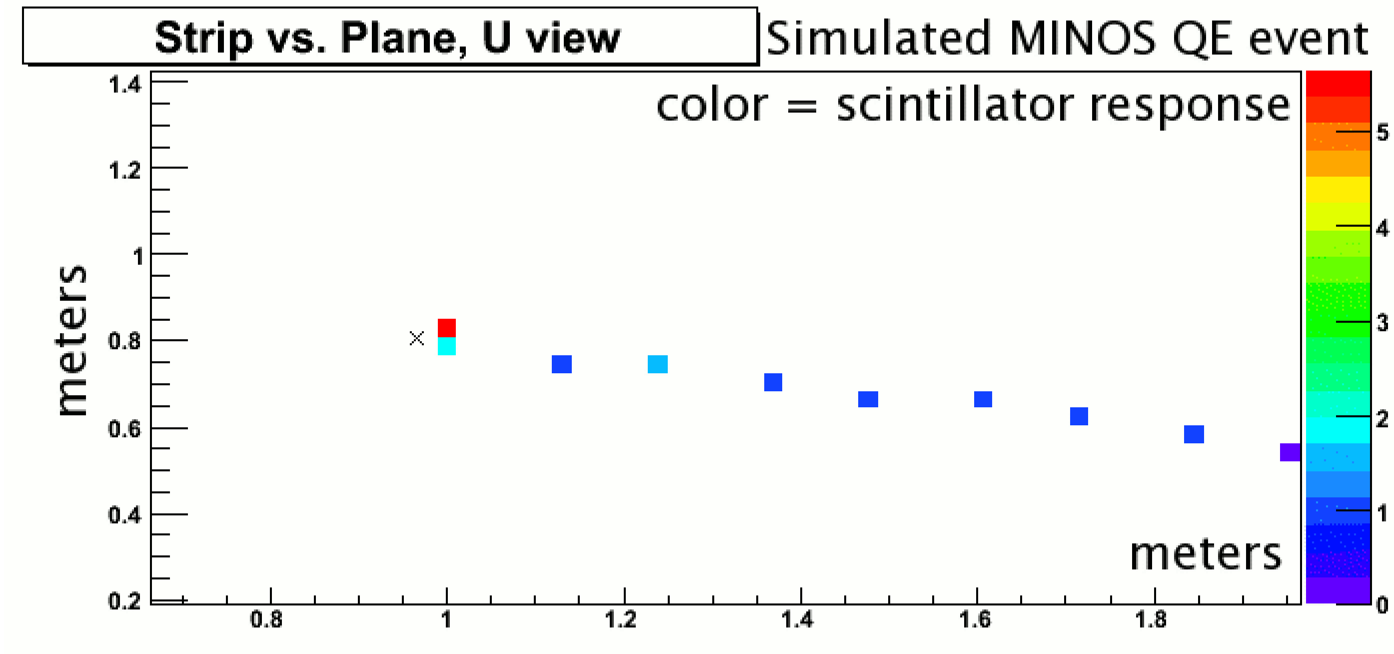


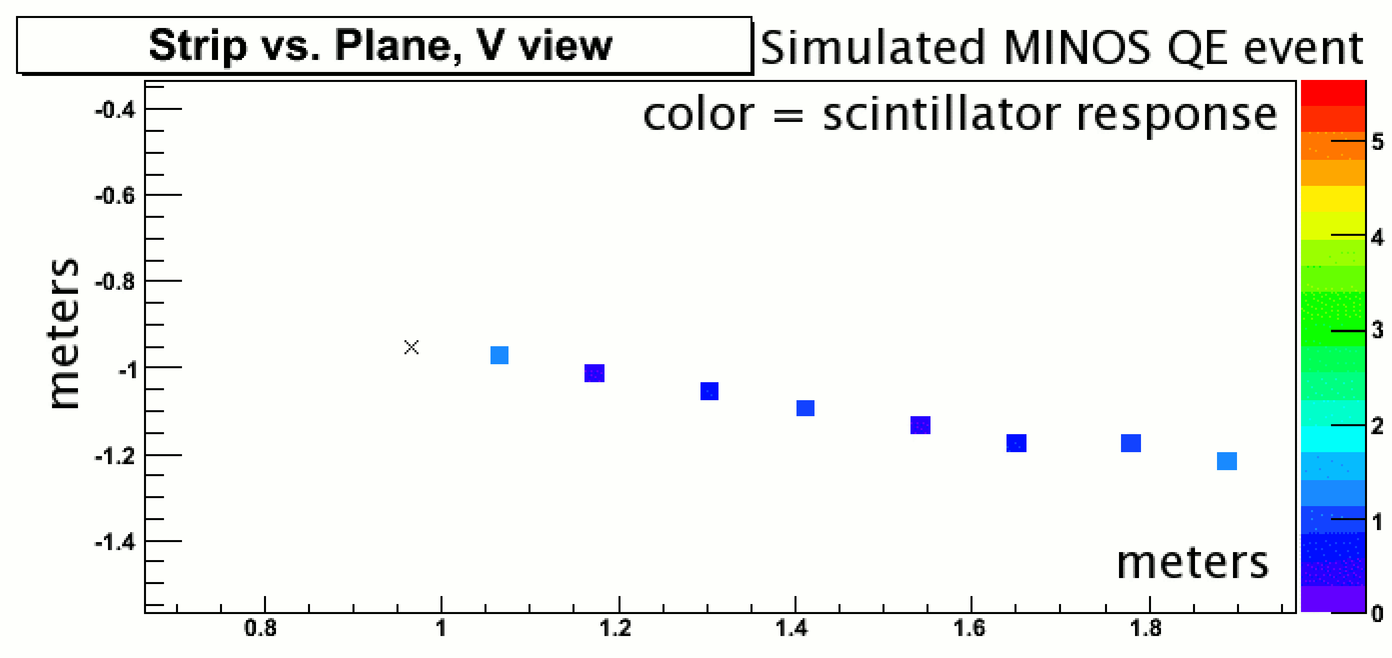
From a simulated 2.4 GeV muon neutrino QE interaction

~2.1 GeV/c muon
~0.7 GeV/c proton

muon travels another 3 meters off to the right, bends toward center of detector (negative charge)

MINOS QE candidate event vertex view (MC)





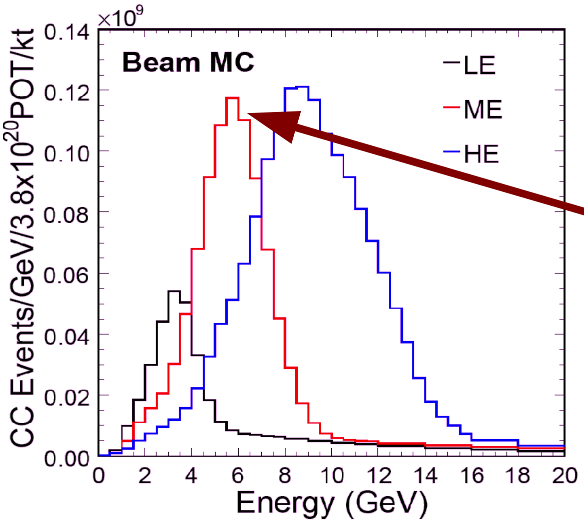
Three selections in progress now

Zero hadron activity ~70% pure QE

Low hadron activity ~60% pure QE

Visible 2nd track matches proton QE prediction ~45% QE, high Q2

1-pi backgrounds dominate



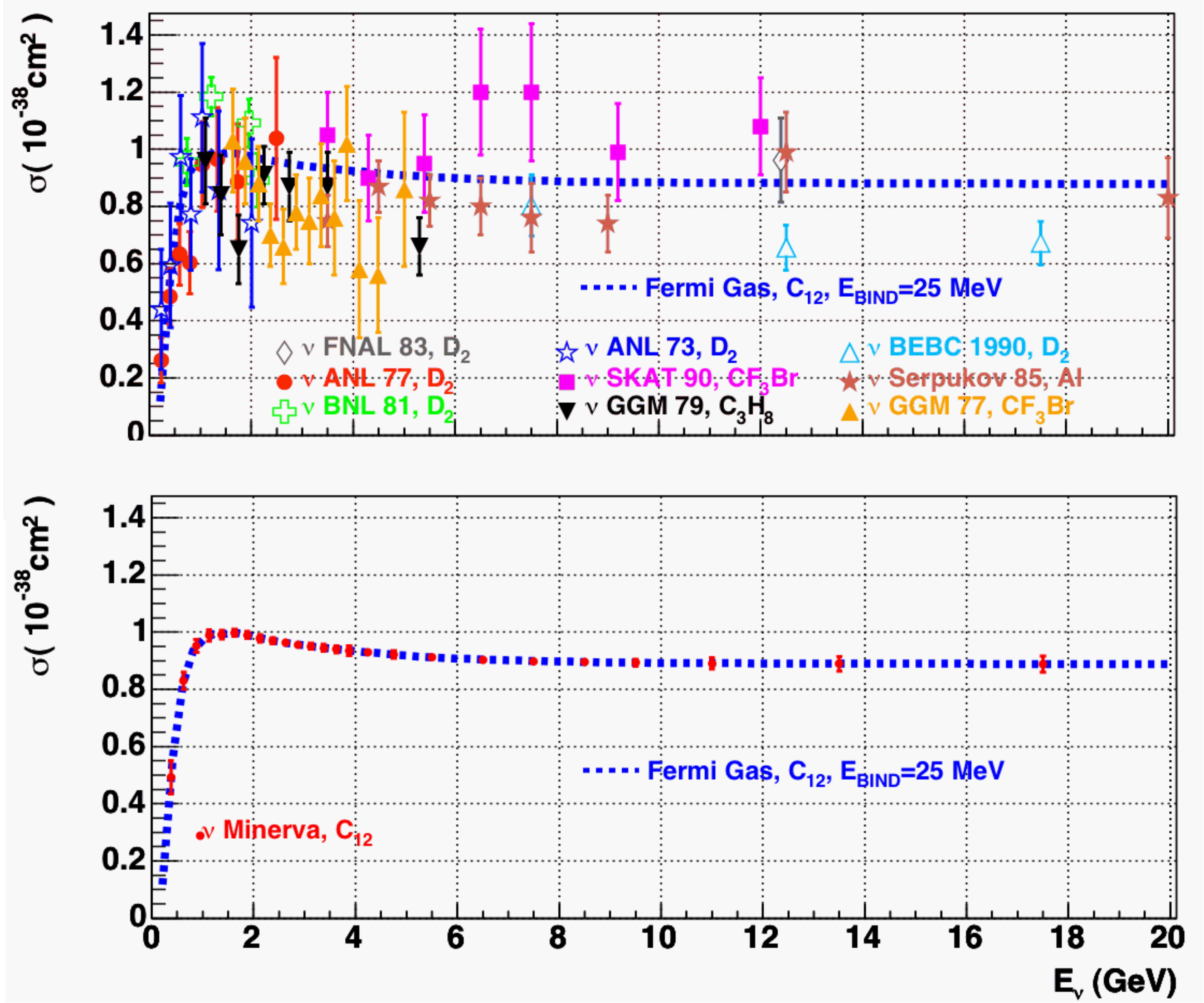
MINERvA

Will run mostly in ME-like beam + some LE
~800,000 QE events in fiducial CH target
plus smaller sub-samples on Pb, Fe, C, He

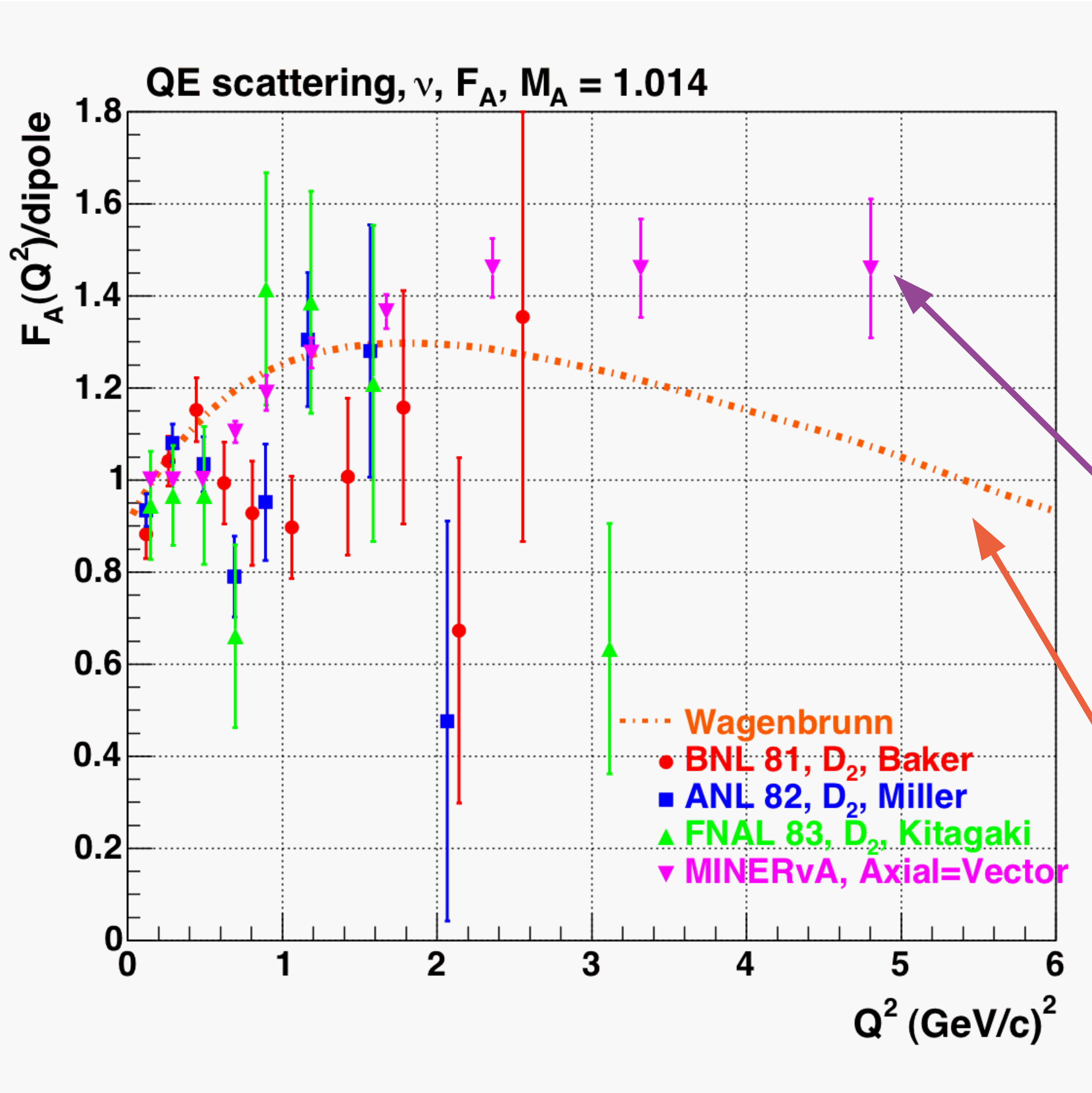
QE cross section vs. neutrino energy
Current measurements

Expected MINERvA result
statistical errors only
includes purity + efficiency

not included:
flux error ~5%
c.f. Sacha Kopp's Talk



MINERvA: Non-dipole Axial Form Factor?

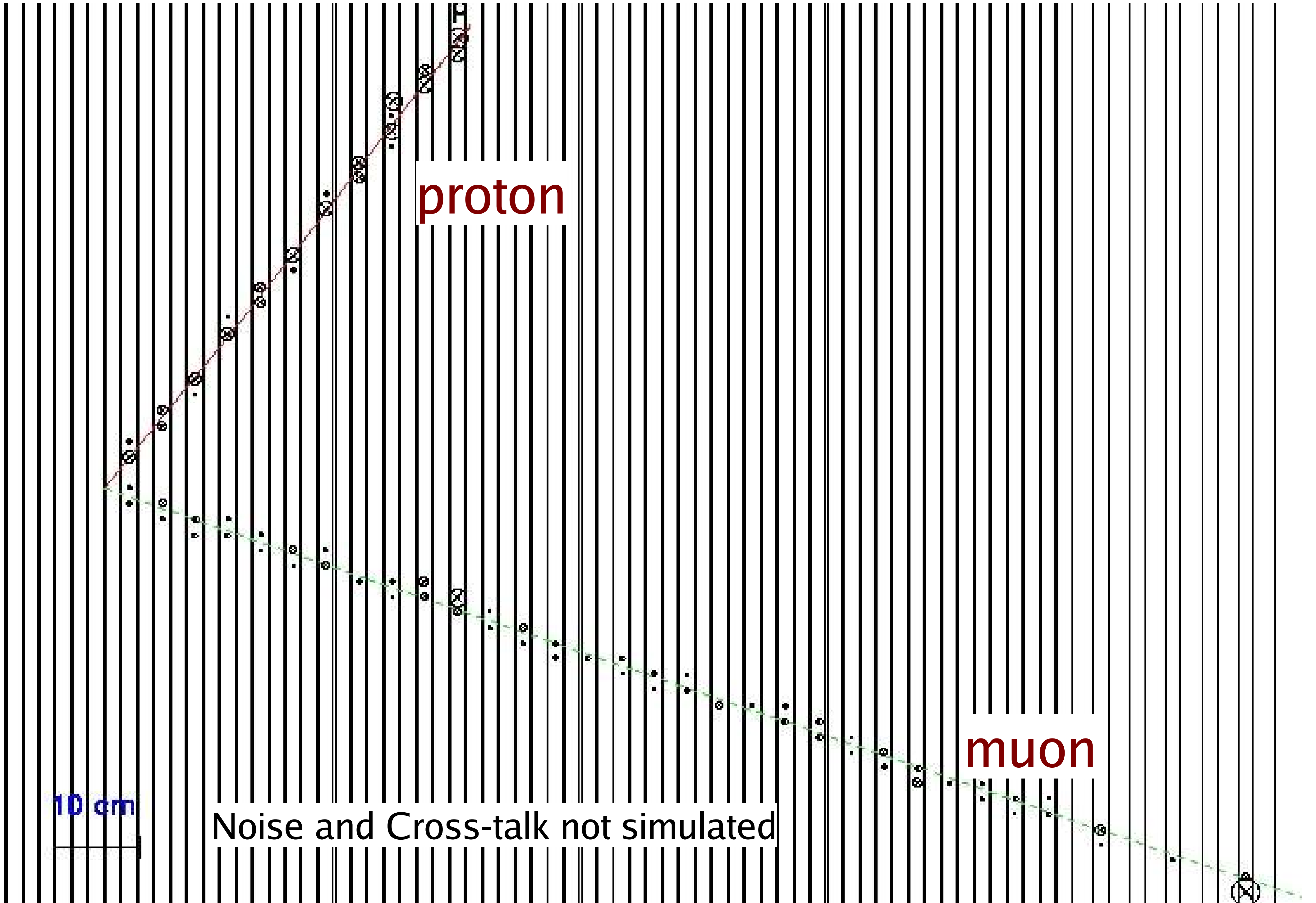


Expected ability to measure high Q^2 behavior and sensitivity to non-dipole F_A form factor

Simulated MINERvA "Axial=Vector" hypothesis (statistical errors only)

Wagenbrunn, et al. hep-ph/0212190

MINERvA Simulated 2.5 GeV Quasi-elastic Event

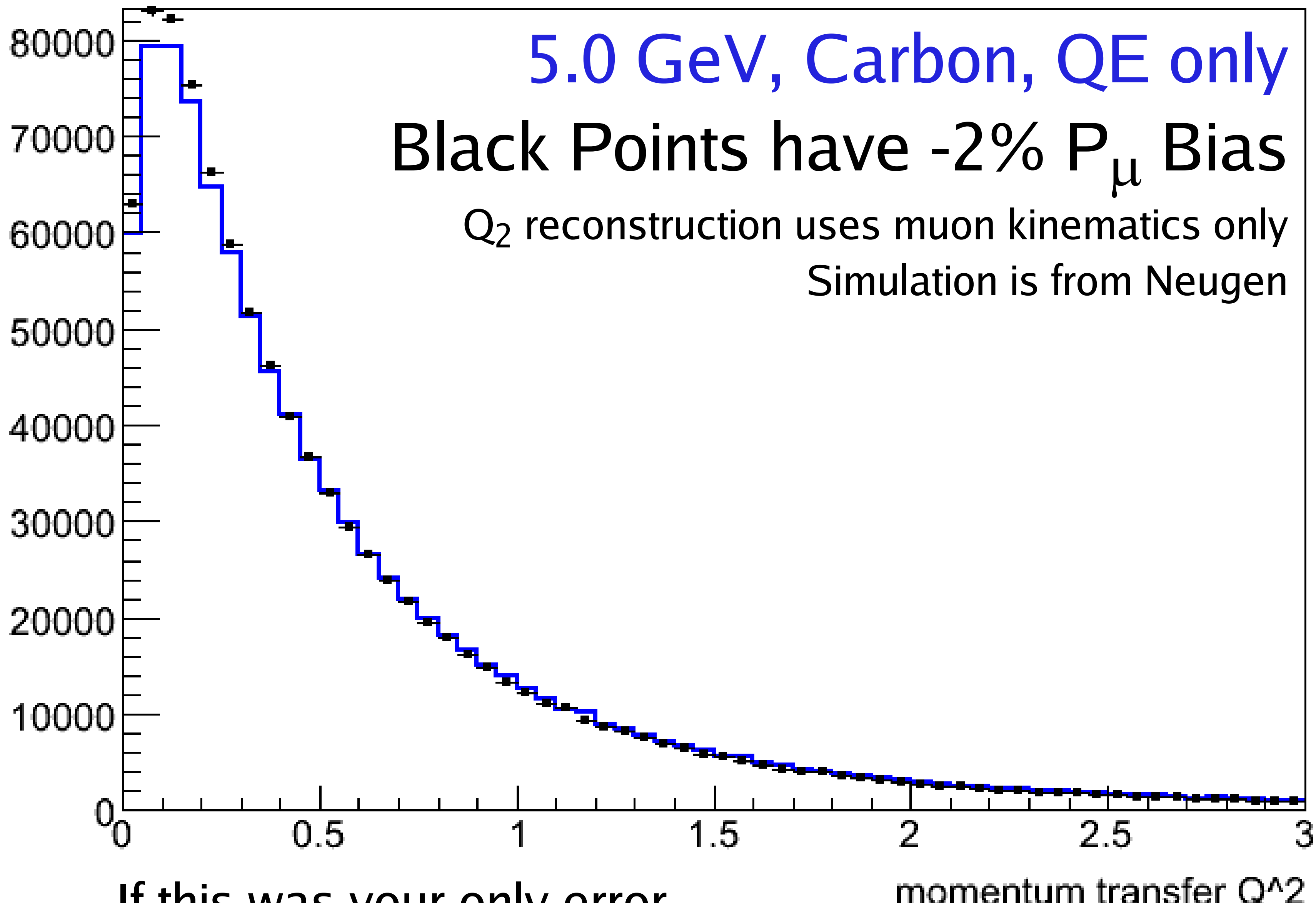


A look into the (near?) future

Ideas and points for discussion.

Some for experimenters
Some for theorists

Systematics Challenges: muon momentum bias



If this was your only error
Angle distribution is fine,
but p_μ and Q^2 data/MC disagree

Sources of effective muon momentum bias

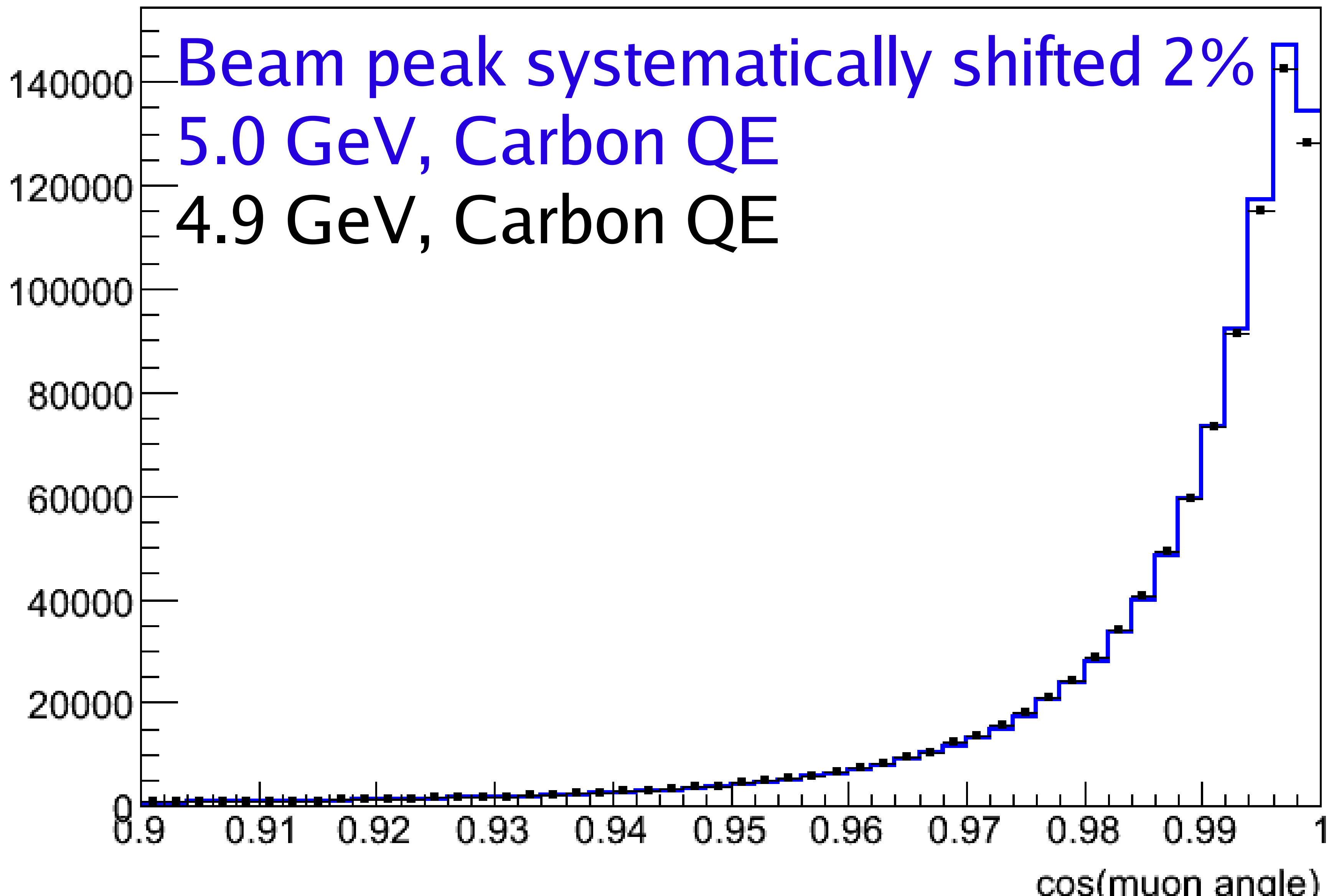
Detector Material Assay
Magnetic field errors

Track vertex and end bias

Geant3/Geant4 muon dE/dx simulation

Fermi Gas binding energy in reconstruction

Errors in the neutrino flux affect the angle



If this was your only error

Pmu and angle look odd, but Q2 comes out same

Summary of the kinds of errors

Flux peak shift affects p_{μ} and $\cos\theta$, not q^2

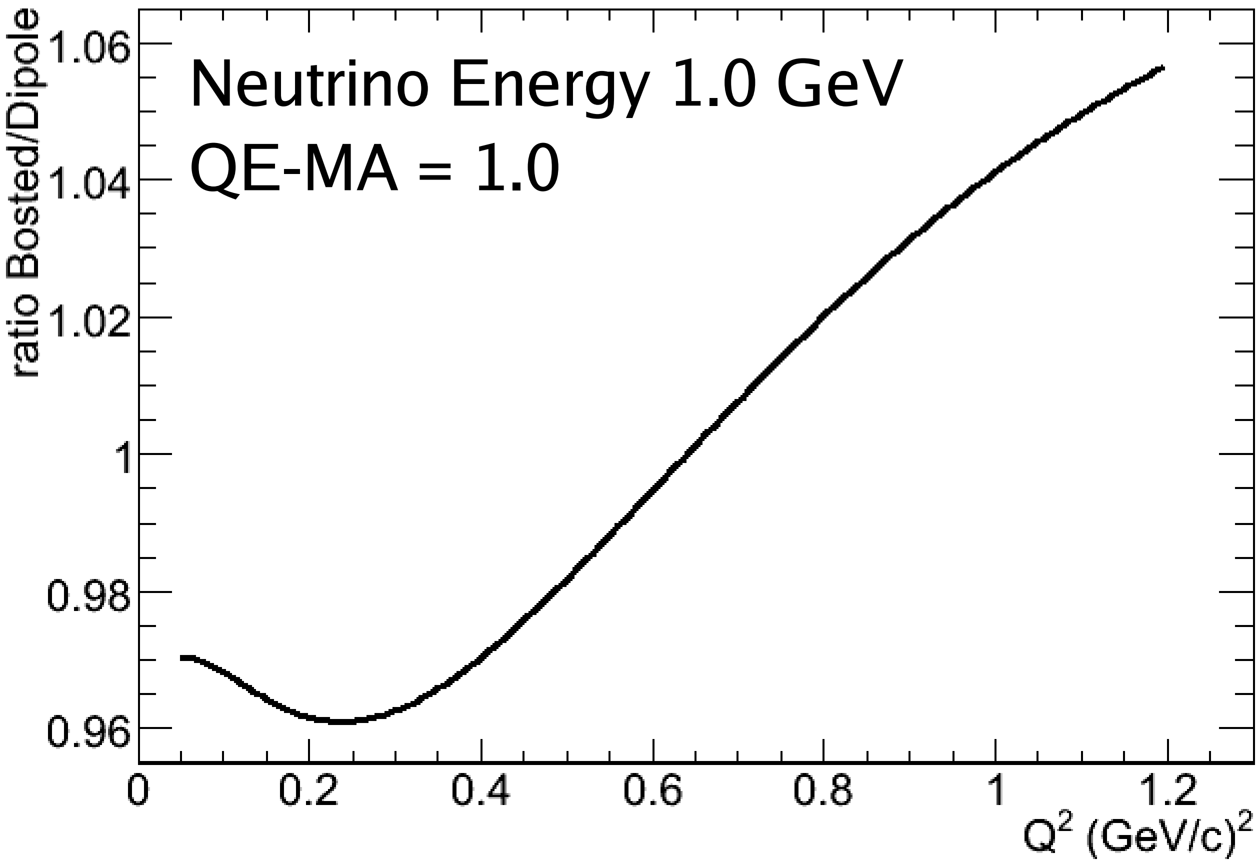
Muon momentum bias affects p_{μ} and q^2, not $\cos\theta$

MA affects all three at once

Q2 shape fits using muon kinematics
with the current and proposed detectors
will have to address these together

Changes to our model: new vector form factors

QE differential cross section



Effect of P. Bosted's parameterization

ratio $\frac{\text{Bosted}}{\text{Dipole}}$

~1.5% change in total cross section

Causes ~ 0.05 shifts in MA fits

How about in-medium form factor modifications?

Non-dipole axial form factors?

Changes to our model: beyond the Fermi Gas

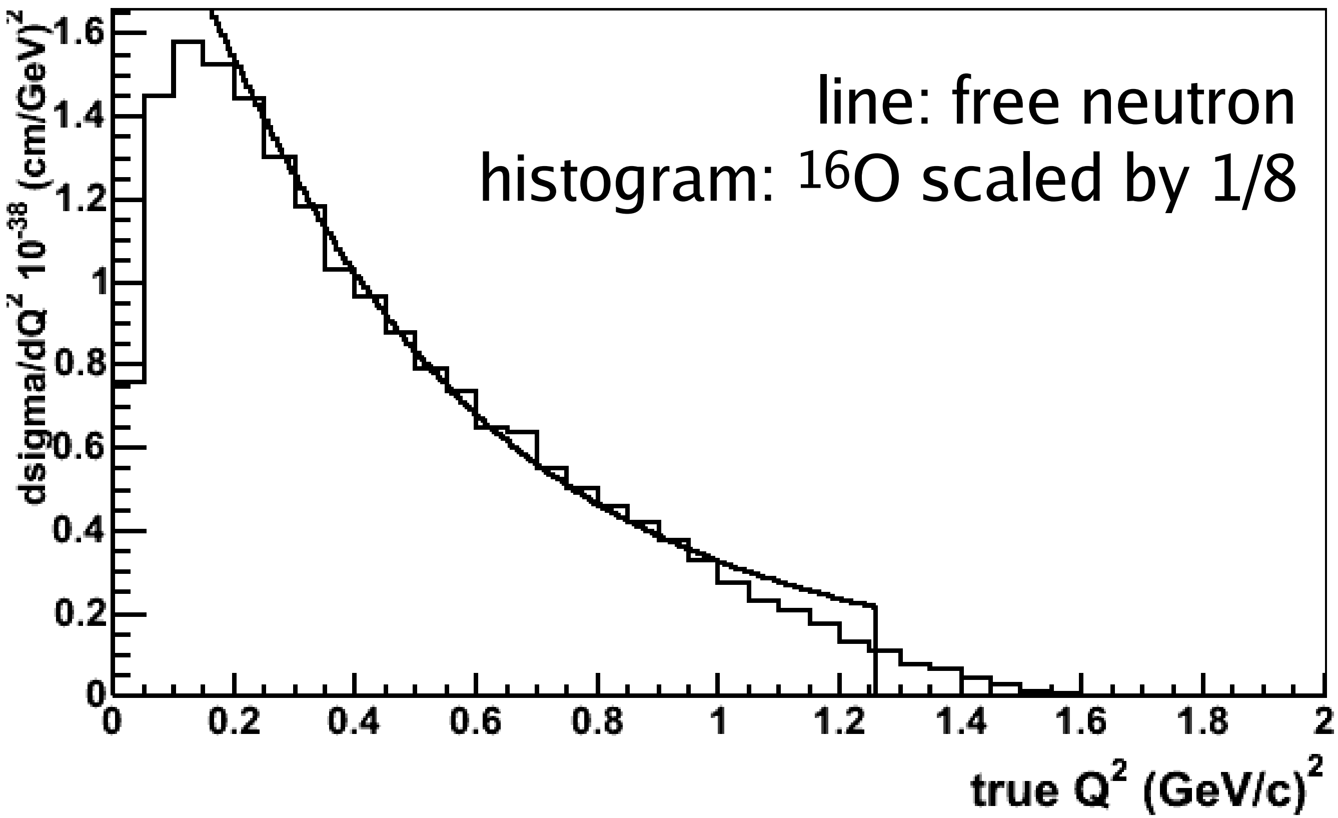
Spectral function
(Benhar today, work by several groups)

Scaling and Superscaling
(D. Day this morning, Barbaro at NuInt05)

There is work to put this into neutrino event generator
Need more code, or workable reweighting functions

Ways to express the effect of model uncertainties

At the moment, propagate errors onto our analysis
Soon, we provide unfolded differential cross sections



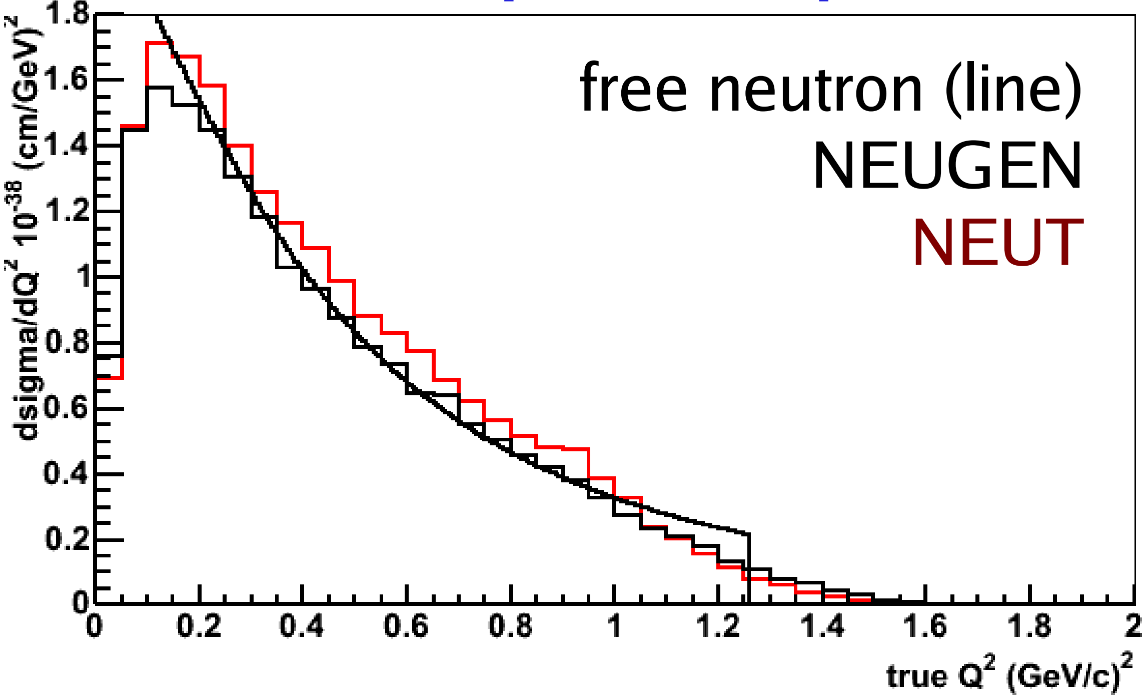
neutrino energy 1.0 GeV

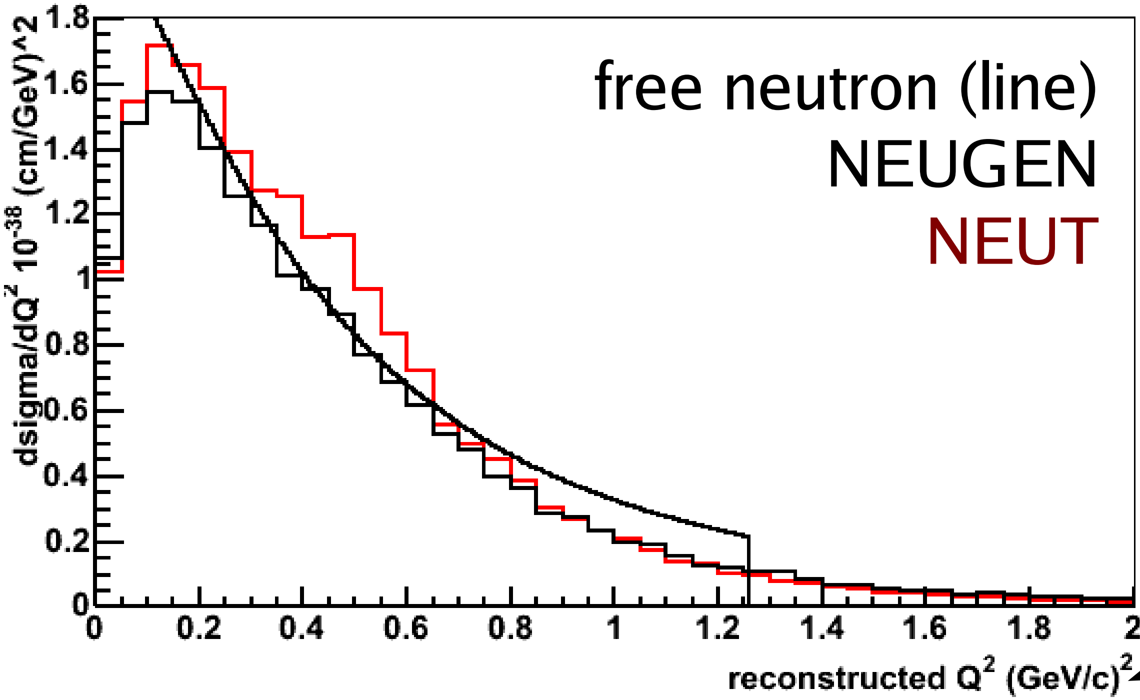
free neutron line:
dipole form factors
MA = 1.00

neugen histogram
BBBA form factors
MA = 0.99
Fermi Gas with
Bodek-Ritchie tail

If you need – make comparisons and take ratios
with the relevant free-nucleon $d\sigma/dQ^2$ calculation

Followup example: Neut and NEUGEN





True and Reco Q^2
For 1.0 GeV neutrino
on Oxygen or free neutron
with Oxygen scaled by 1/8

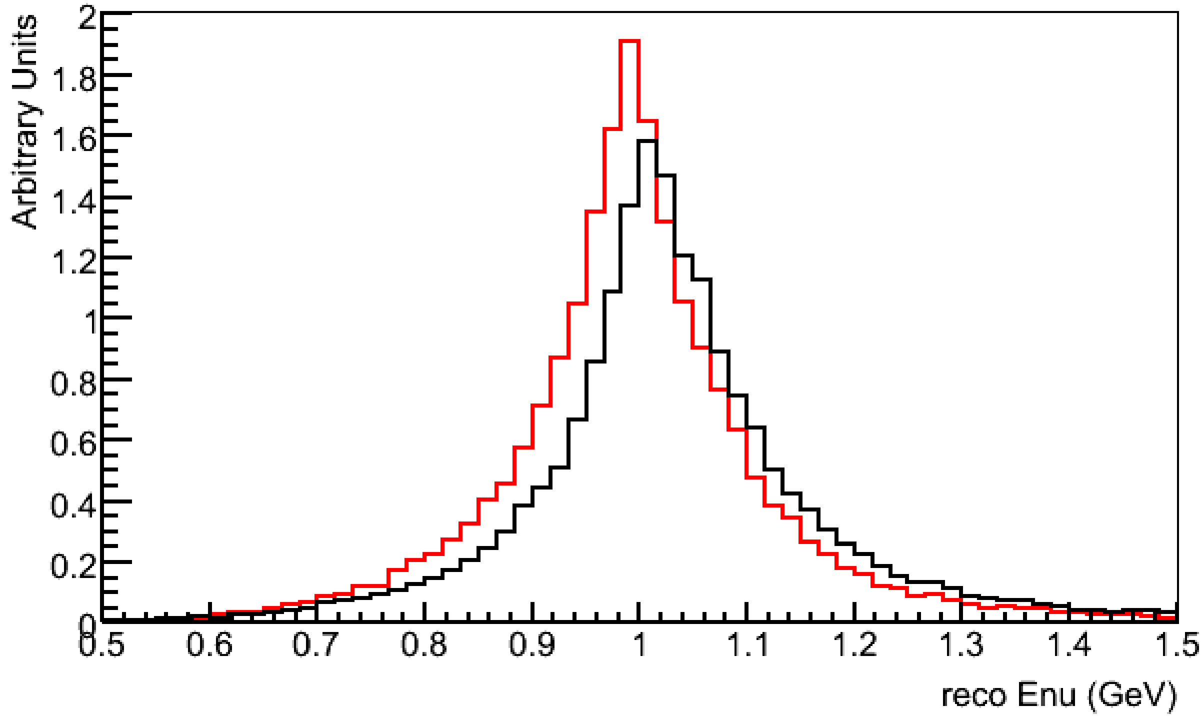
NEUT MA = 1.1
with dipole form factors
Straight Fermi Gas

NEUGEN MA = 0.99
with BBBA05 form factors
Fermi-Gas + Bodek-Ritchie

All three lines are scaled so that they integrate to the correct total cross section

From muon kinematics only

Followup example: Reco Enu from muon



Estimate has negligible bias if we use same "effective binding energy" of -27 MeV in the reconstruction as in the Fermi Gas model

Also effected by other nuclear effect models?

Basic QE interaction observables

Inclusive cross section $\sigma(E)$

reco Q2 distribution
reco neutrino energy distribution

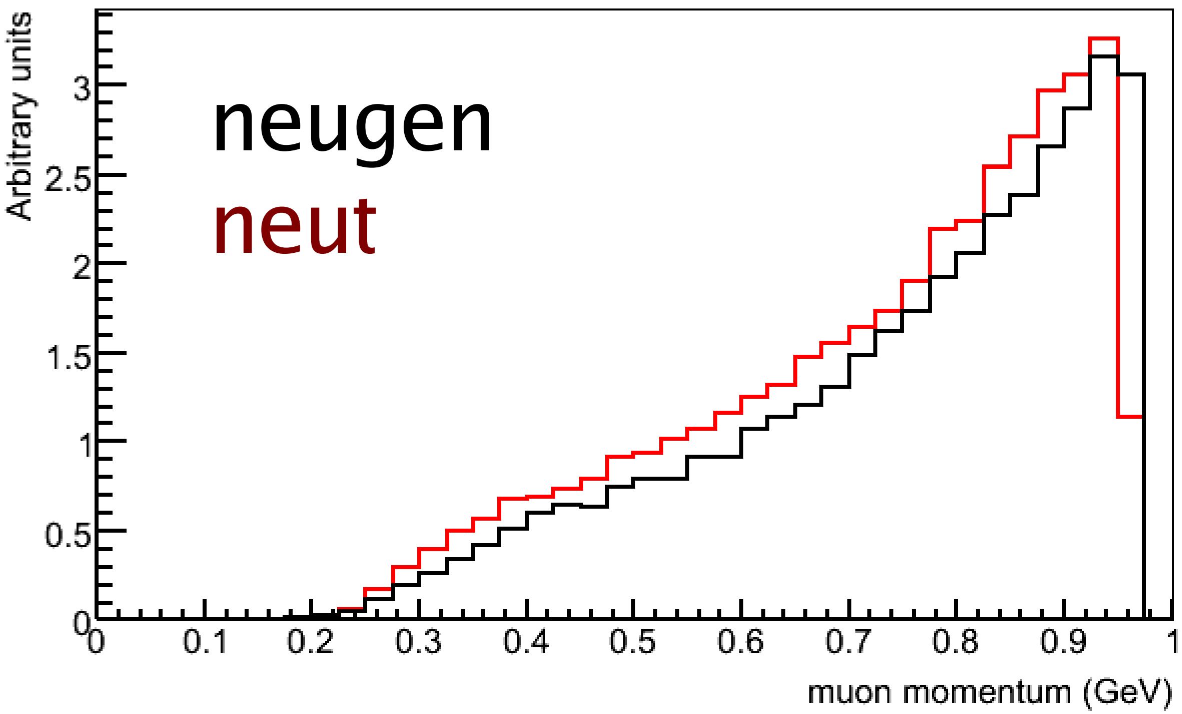
muon angle and muon momentum
also cos(muon angle)

proton angle and proton momentum
opening angle between muon and proton

Energies between 0.5 and 20 GeV
0.5, 0.7, 1.0, 2.0, 5.0, 10.0, 20.0 are good choices?
H/n, He, C, O, Ar, Fe, Pb are good choices?

Integrate over lepton angle

Because of the way many electron experiments are run (e,e'p) electron kinematics are plotted at a fixed angle.



Neutrino experiments have 4-pi coverage
With high statistics able to bin by angle in few degree bins
one degree resolution down to 0 degrees.

1 GeV incident neutrino correct relative rate is shown

Or ...
Integrate over all angles

Remember: not fixed energy nor fixed angle spectrometers

Conclusions / More discussion

Some very good neutrino data sets
available now and upcoming

Experiments must start to provide proper
cross sections
differential cross sections
take advantage of statistics to bin in angle, pmu

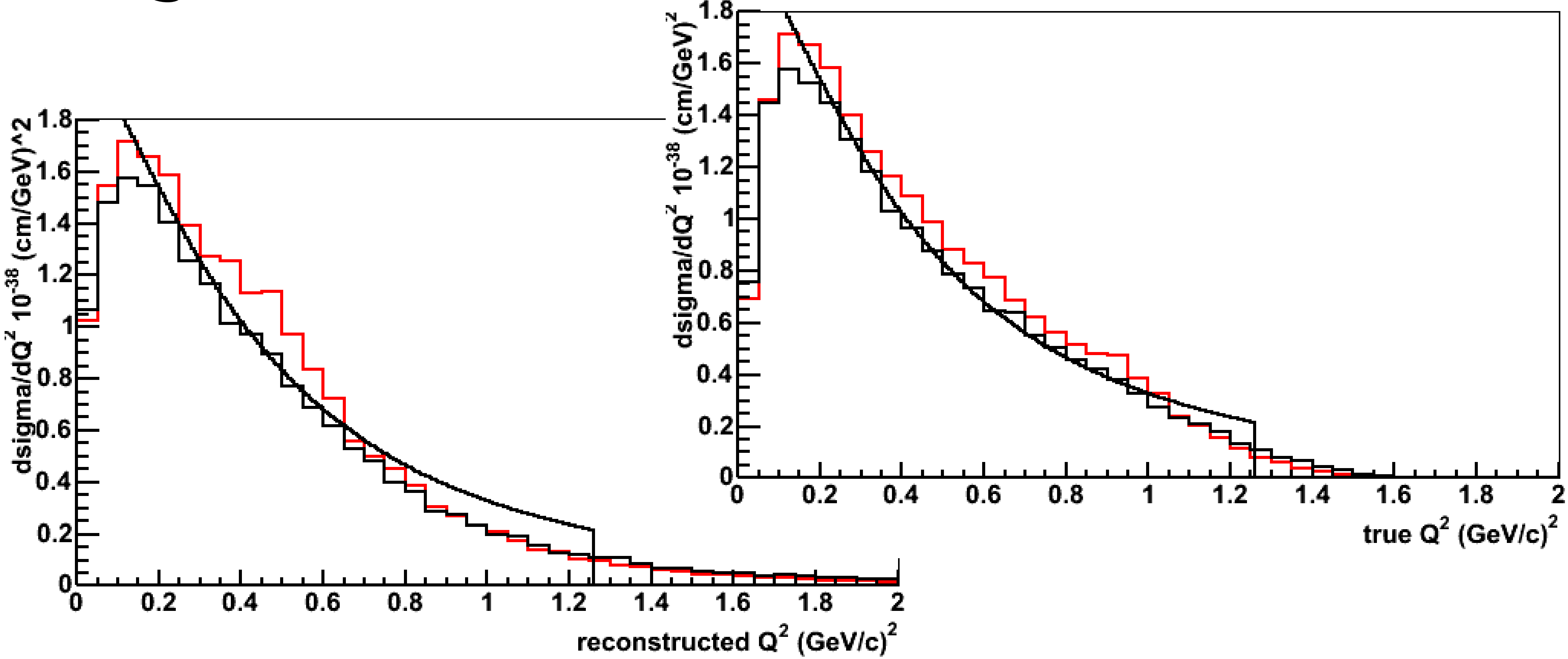
Continue (accelerate) incorporation of
known nuclear physics
as well as uncertain nuclear physics effects
into understanding neutrino data and systematics

Plots of neugen-neut comparison

There was some interest from several places for more comparisons of event generators. The generator authors supplied several 100,000 event samples in their default configuration, including the 1.0 GeV samples.

Here are basic QE comparisons for Neut (in black) and Neugen (in red)

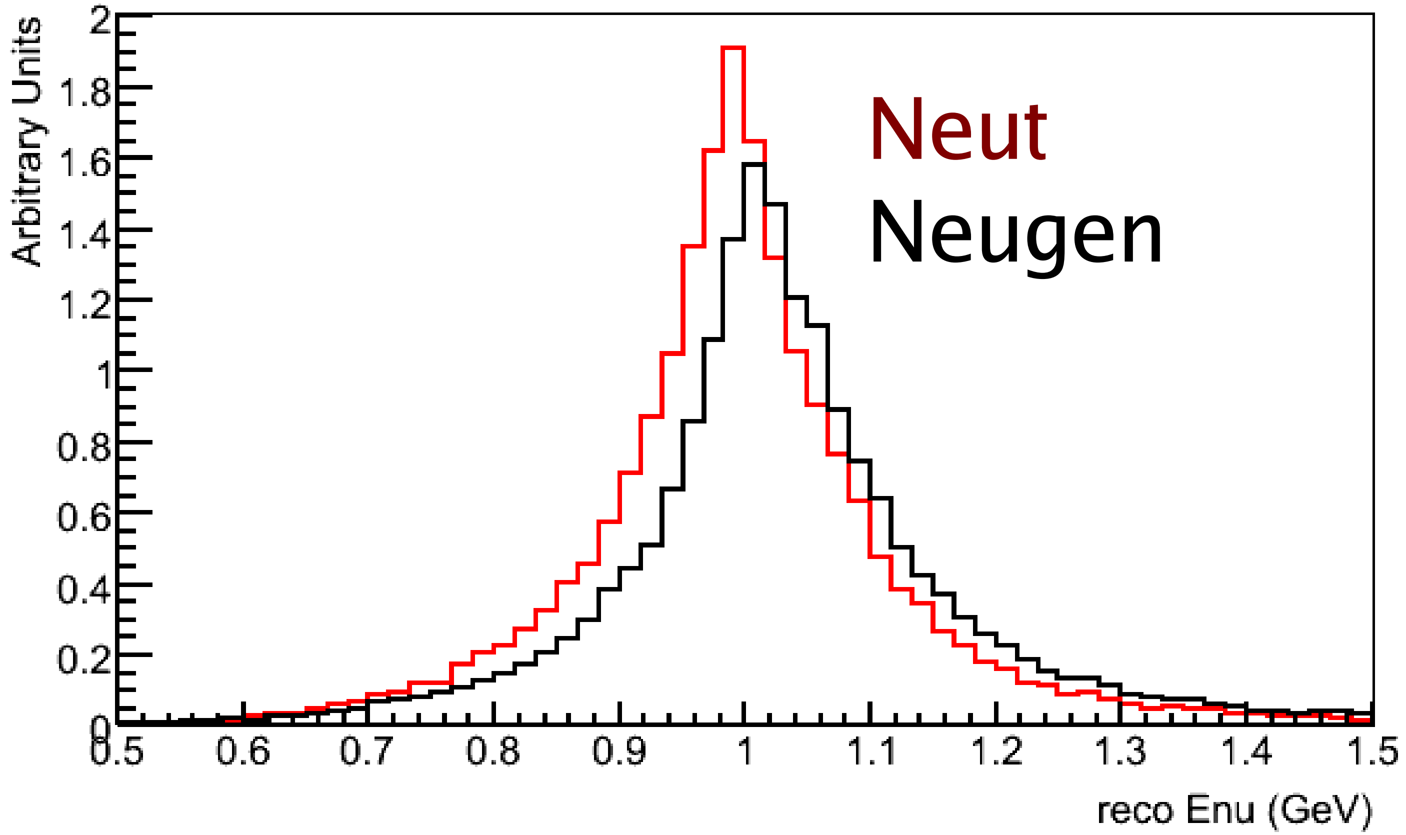
Neugen and Neut true and reco Q2 distribution



major shape and normalization differences from MA results represent the correct absolute cross section

More prominent bump in Neut is from differences in FG, Pauli Blocking, and the tail of the Fermi motion

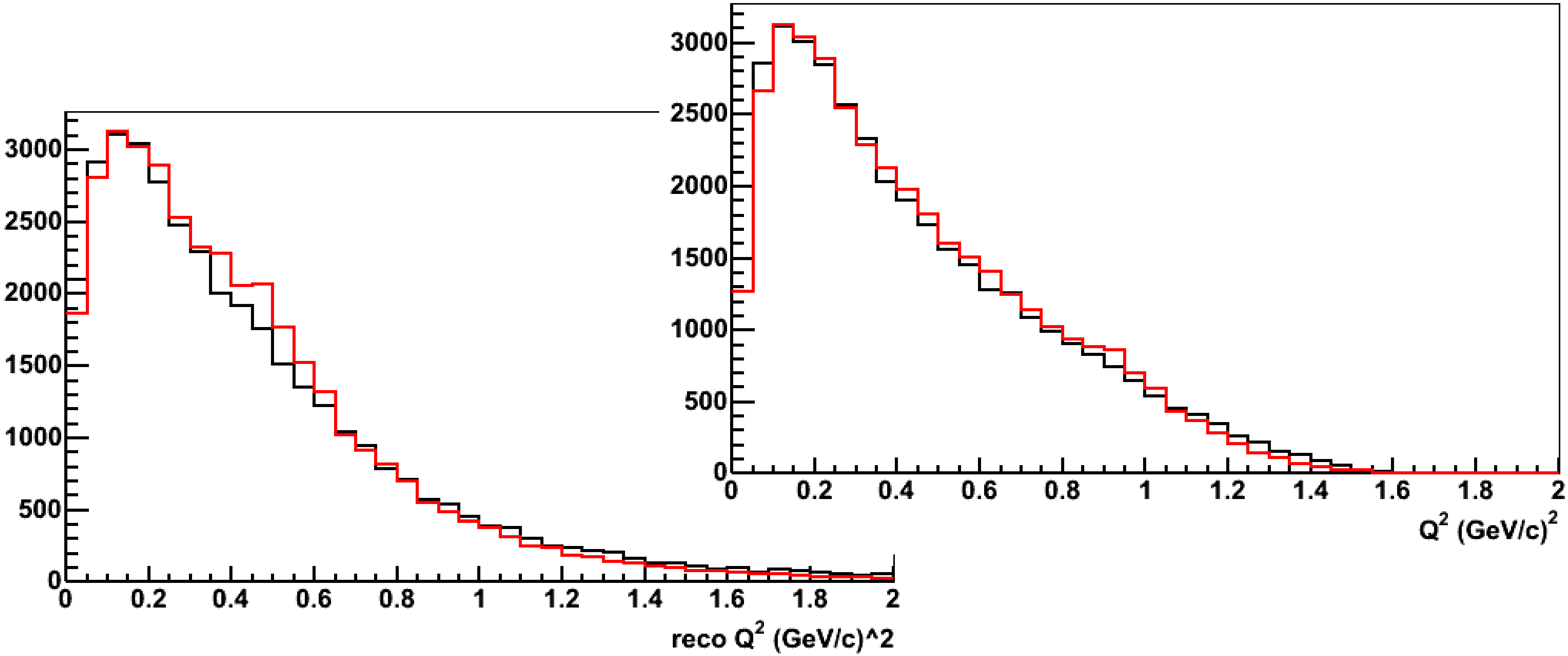
Neugen and Neut reco enu distribution



Results represent the correct absolute cross section (but unfortunately, the vertical scale is arbitray)

Binding energy -27 MeV is used for both.
Neut is unbiased, Neugen is shifted a little high.
Different Fermi Motion and binding energy parameters?

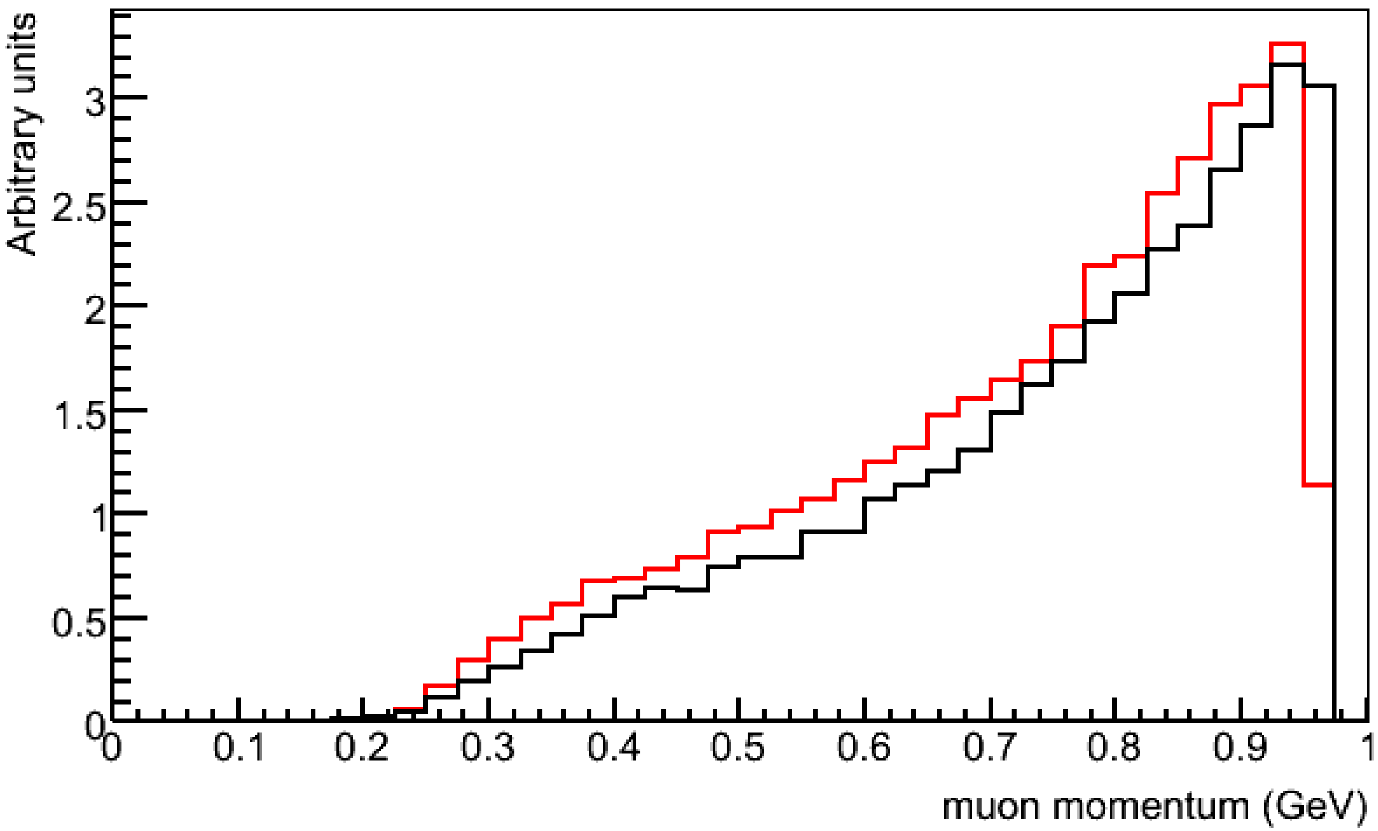
Neugen and Neut true and reco Q2 distribution



major shape and normalization differences from MA

In these plots:
Neut is normalized to the same number of events as neugen

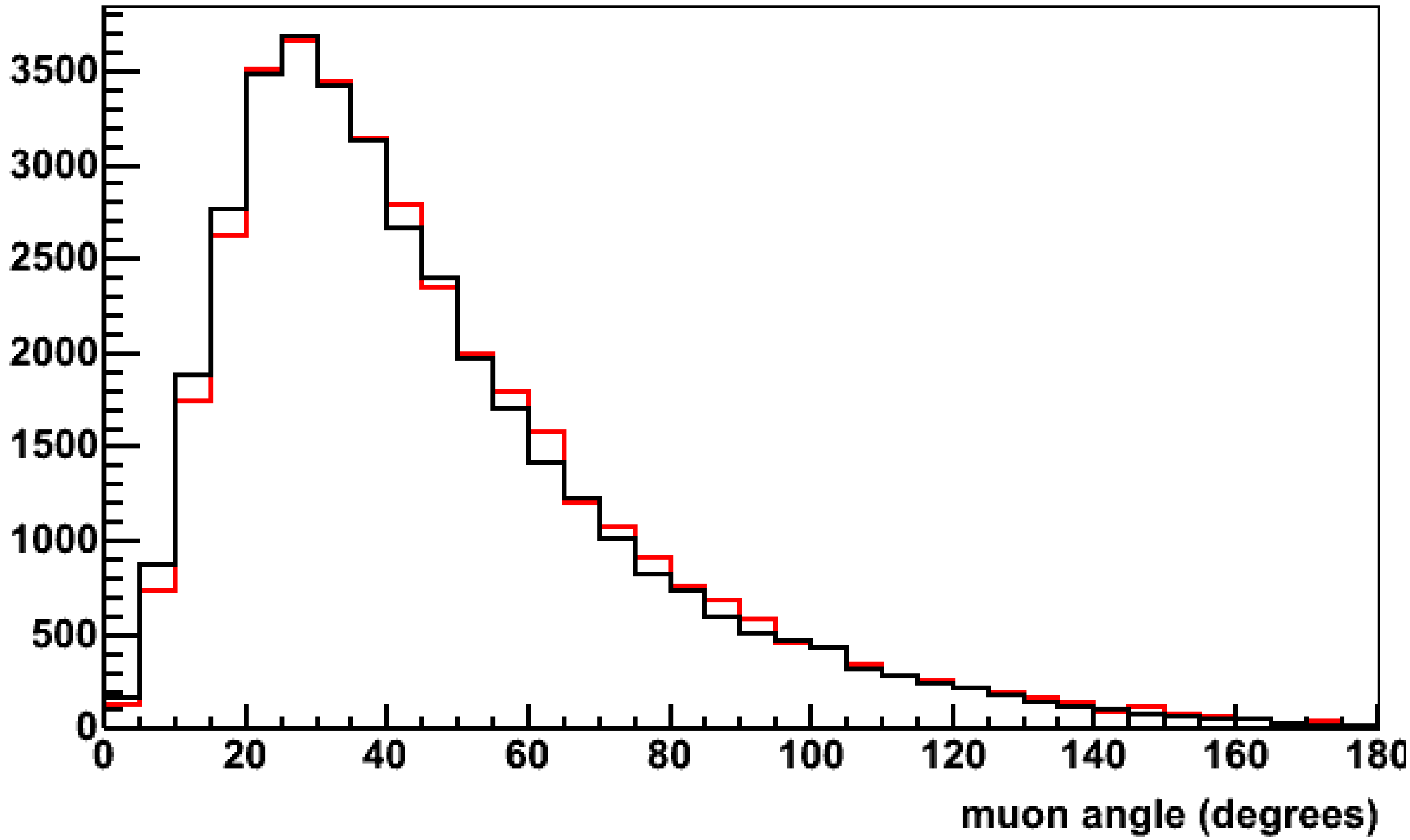
Neugen and Neut muon momentum distribution



Results represent the correct absolute cross section (but unfortunately, the vertical scale is arbitray)

Neugen is shifted high, I think because of the different Fermi Motion and binding energy parameter.

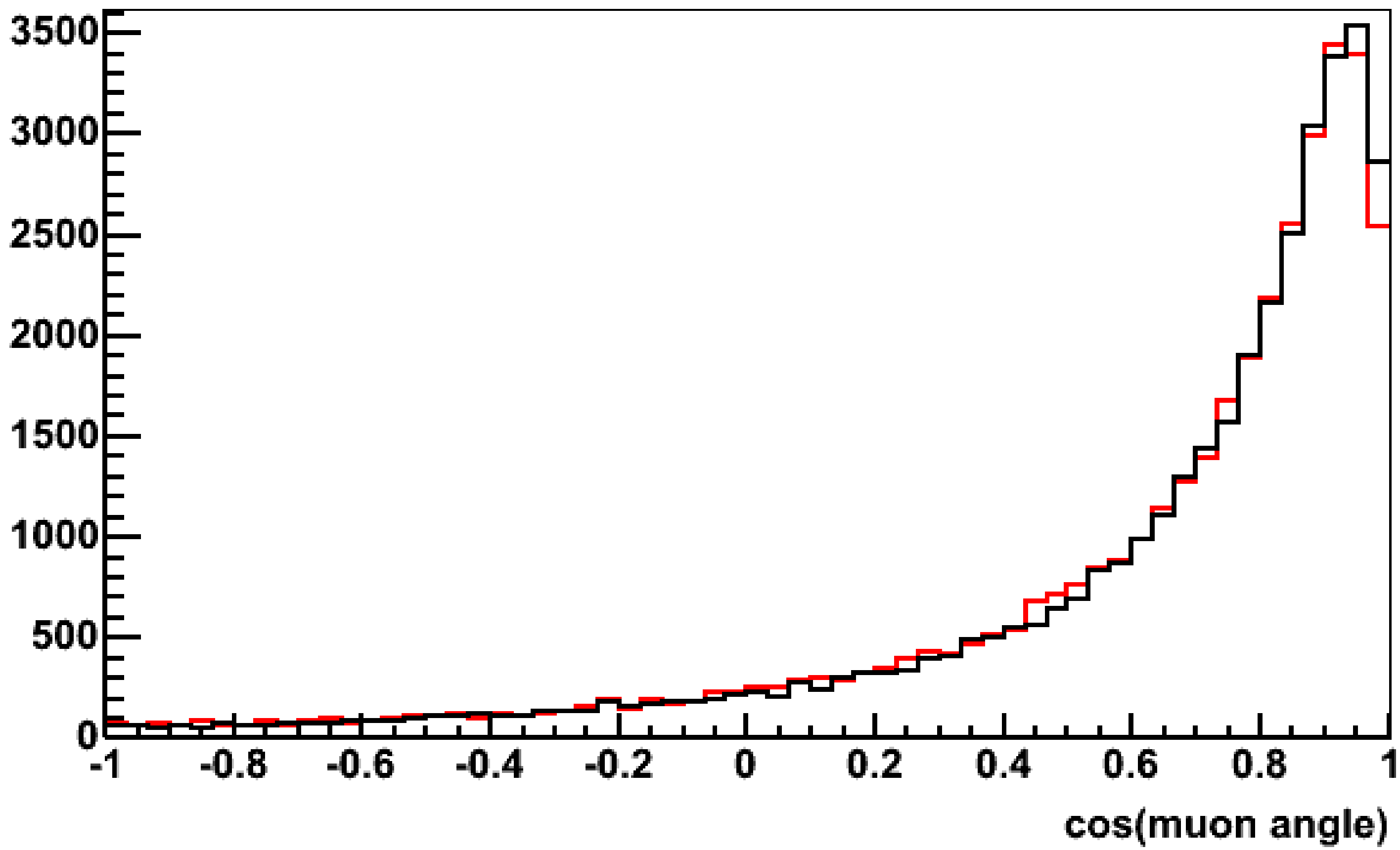
Neugen and Neut muon angle distribution



Not scaled: straight out of the ntuple

Affected mostly by MA
also nuclear model, rescattering

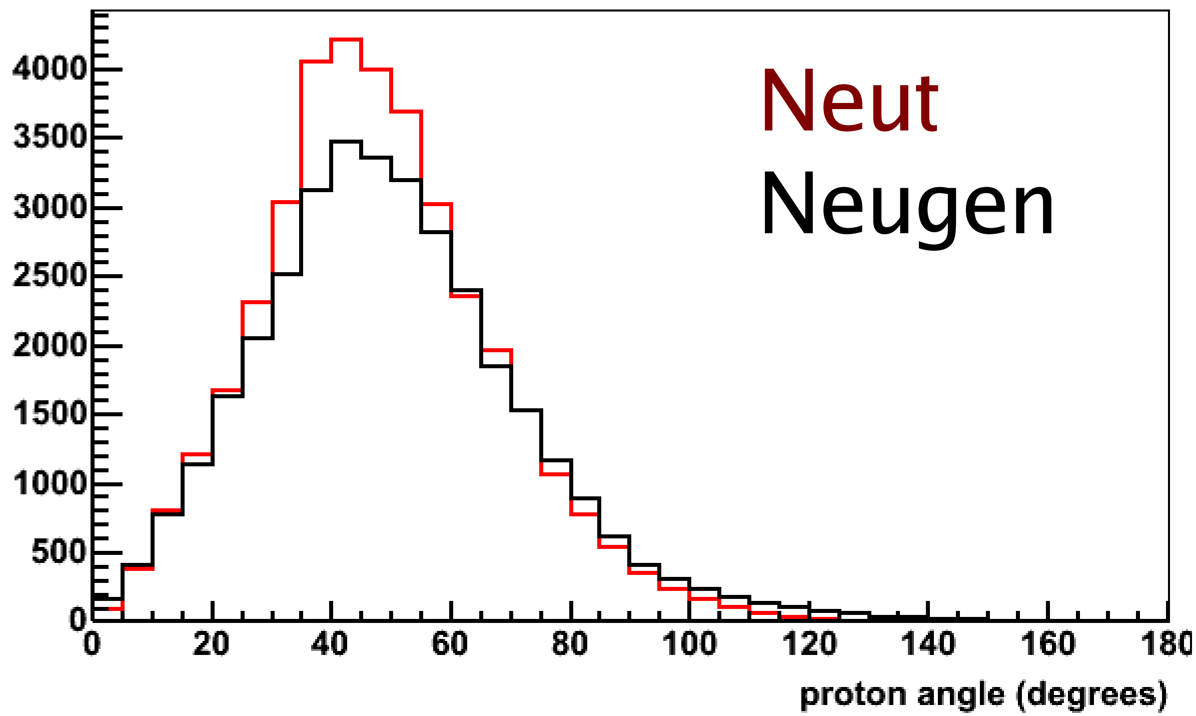
Neugen and Neut cos(muon angle) distribution



Not scaled: straight out of the ntuple

Affected mostly by MA
also nuclear model, rescattering

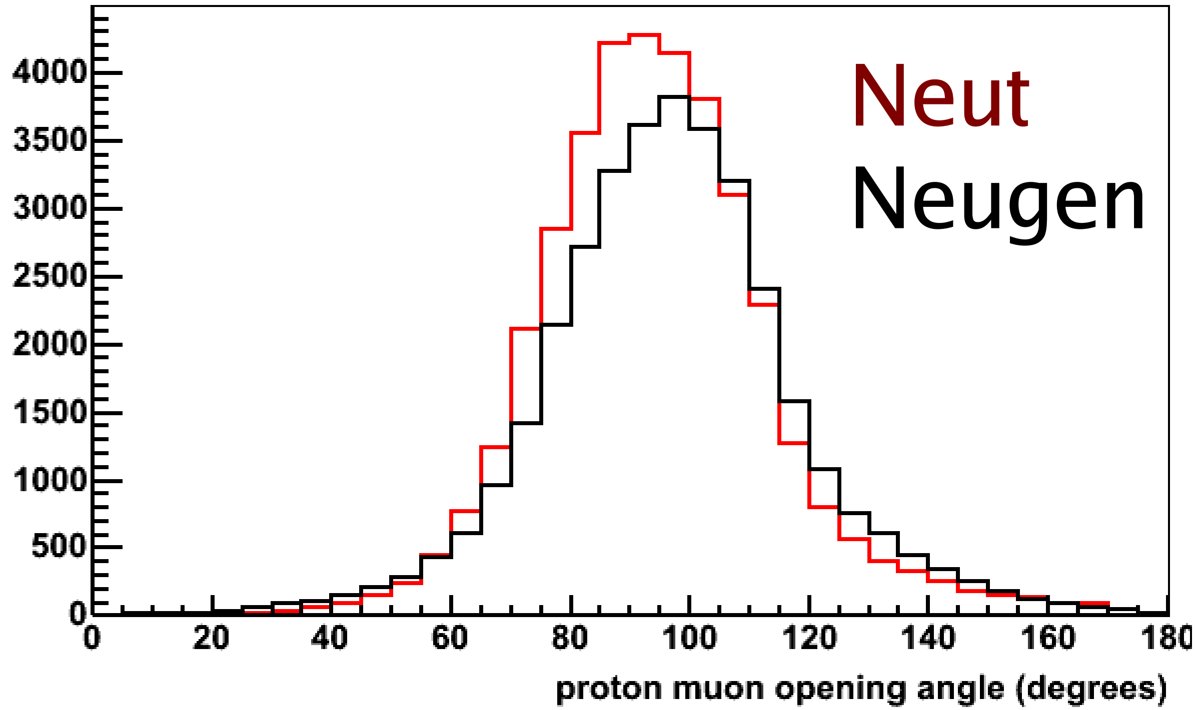
Neugen and Neut proton angle distribution



Not scaled: straight out of the ntuple
I specifically chose the most energetic proton

Affected mostly by MA?
also nuclear model, rescattering

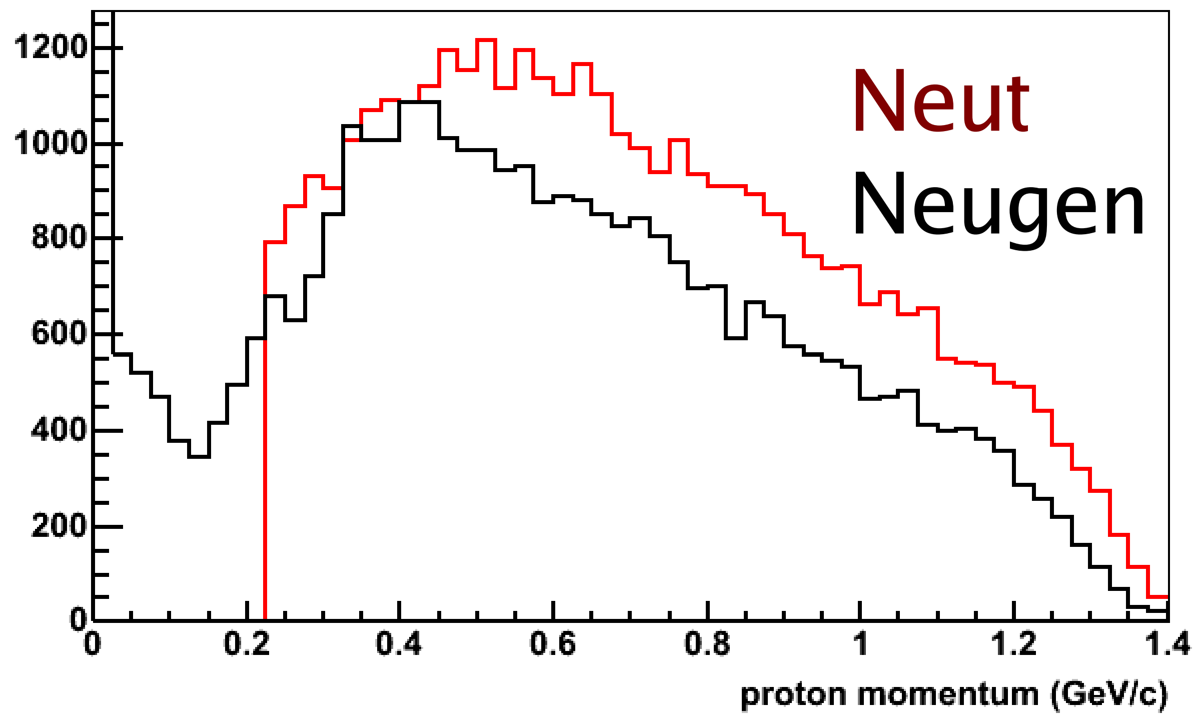
Neugen and Neut muon-proton opening angle



Not scaled: straight out of the ntuple
I specifically chose the most energetic proton

affected mostly by MA or rescattering?

Neugen and Neut proton momentum



Not scaled: straight out of the ntuple
most energetic proton in each event

Major differences from nuclear effects.
7% of Neugen protons do not exit nucleus cleanly
(2577 events with no proton at all)

QE generator comparisons: 1GeV Oxygen

Neugen "Daikon" Oxygen MA=0.99 BBBA

3. Total cross section is 20.293e-38 cm2
2. CCQE fraction .37754 -> CC-QE σ 7.5847e-38
1. per-neutron value is 1/8 of that = 0.9481e-38

Neut H2O MA=1.10 Dipole

1. Mitsuka gives per-neutron 1.02545e-38

Nuance Oxygen MA= Dipole

(Not enough information, so Nuance is not used.)

Free-nucleon MA=1.0+Bosted is 1.041e-38 cm2

Free-nucleon MA=1.1+Dipole is 1.157e-38 cm2

The values above are consistent with differences in MA and Pauli Blocking

Alternate Conclusion Slide

"Conflict, Romance Adventure"

-- Billboard Slogan for
Historic Fort William
Thunder Bay, Ontario