How I learned to stop worrying and love multi-nucleon effects (in neutrino-carbon interactions)

new MINERvA measurement
Phys. Rev. Lett. 116, 081802
arXiv.org:1511.05944

plus
interpretation for
oscillation experiments

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Saint Surrounded by Three Pi Mesons

Salvador Dali
Figueres, Spain, 1957

This work grew from collaborations with
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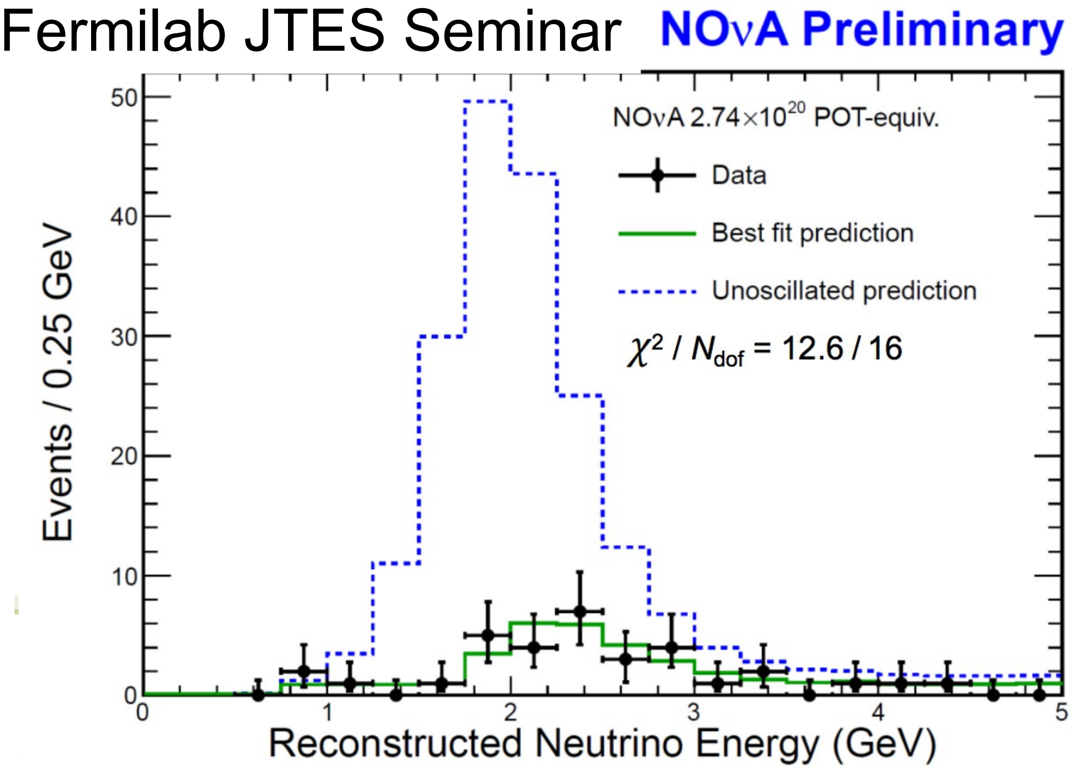
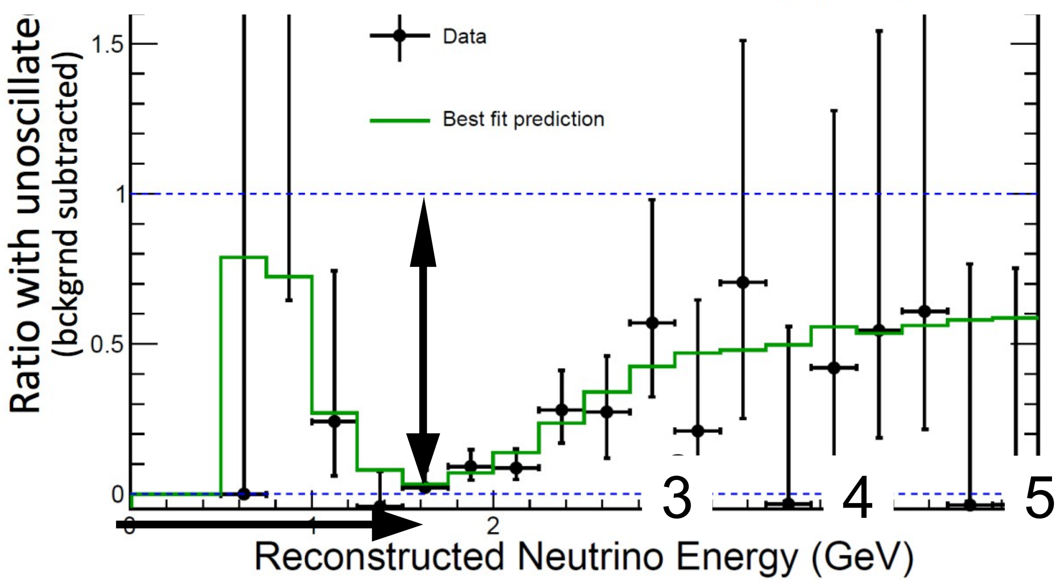
Juan Nieves,
Manolo Vicente Vacas (Valencia)

Phil Rodrigues (Rochester)
Ethan Miltenberger,
John Demgen, Miranda Elkins
Tom Schaffer (UMD M.S.)
Alec Lovlein, Jake Leistico
(UMD undergrads)

Oscillation experiments measure Ev spectra

R. Patterson/NOvA
Fermilab JTES Seminar





Extraction of
oscillation parameters
comes from comparing
predicted energy spectrum
with no oscillations
to the measured ones,
and fitting parameters.

This example from NOvA get:
$\sin^2 2\theta \sin^2(1.27\ \Delta(m^2)\ L/E)$
from depth and position
of oscillation maximum
at best fit.

Oscillation experiments measure Ev spectra

R. Patterson/NOvA
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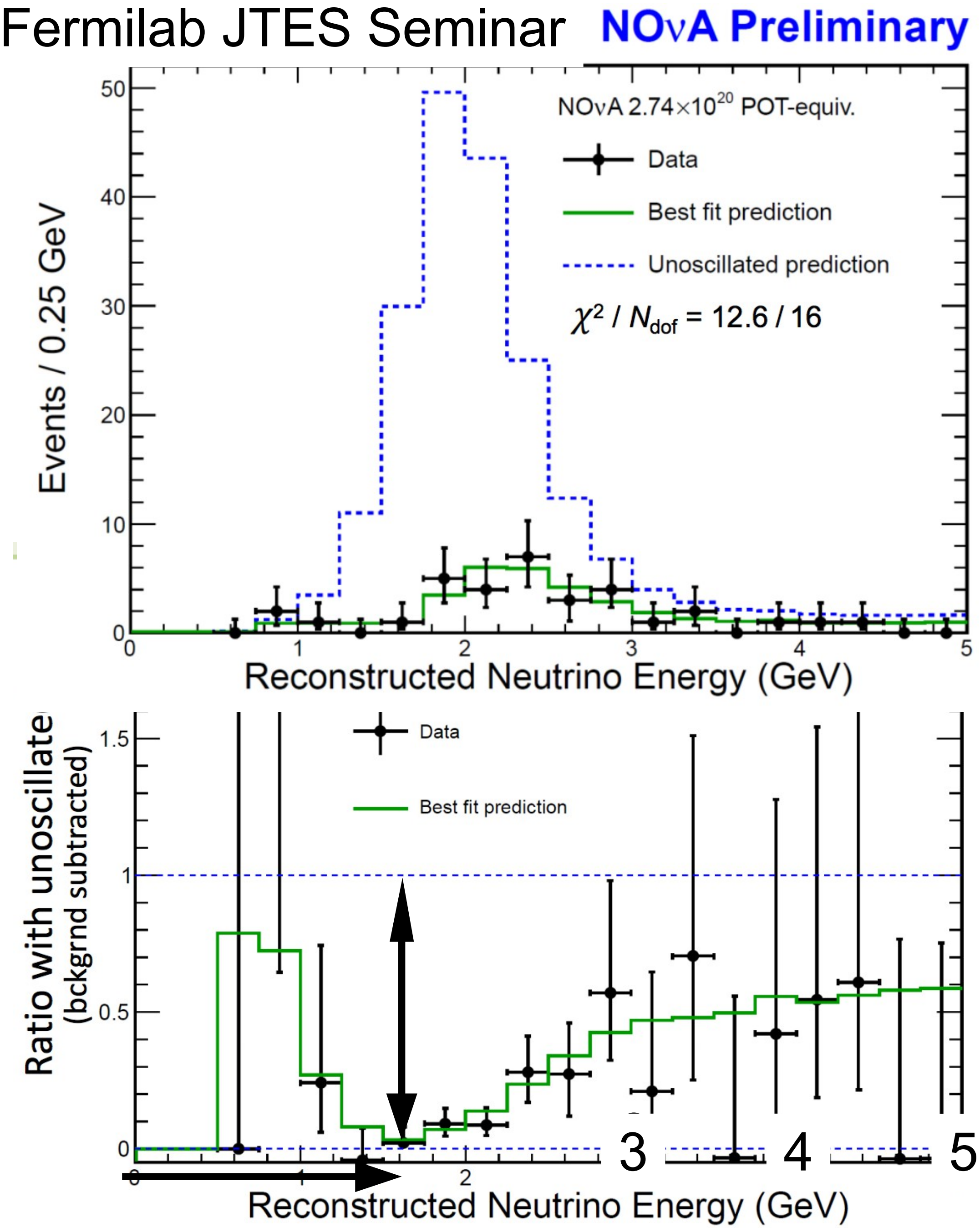

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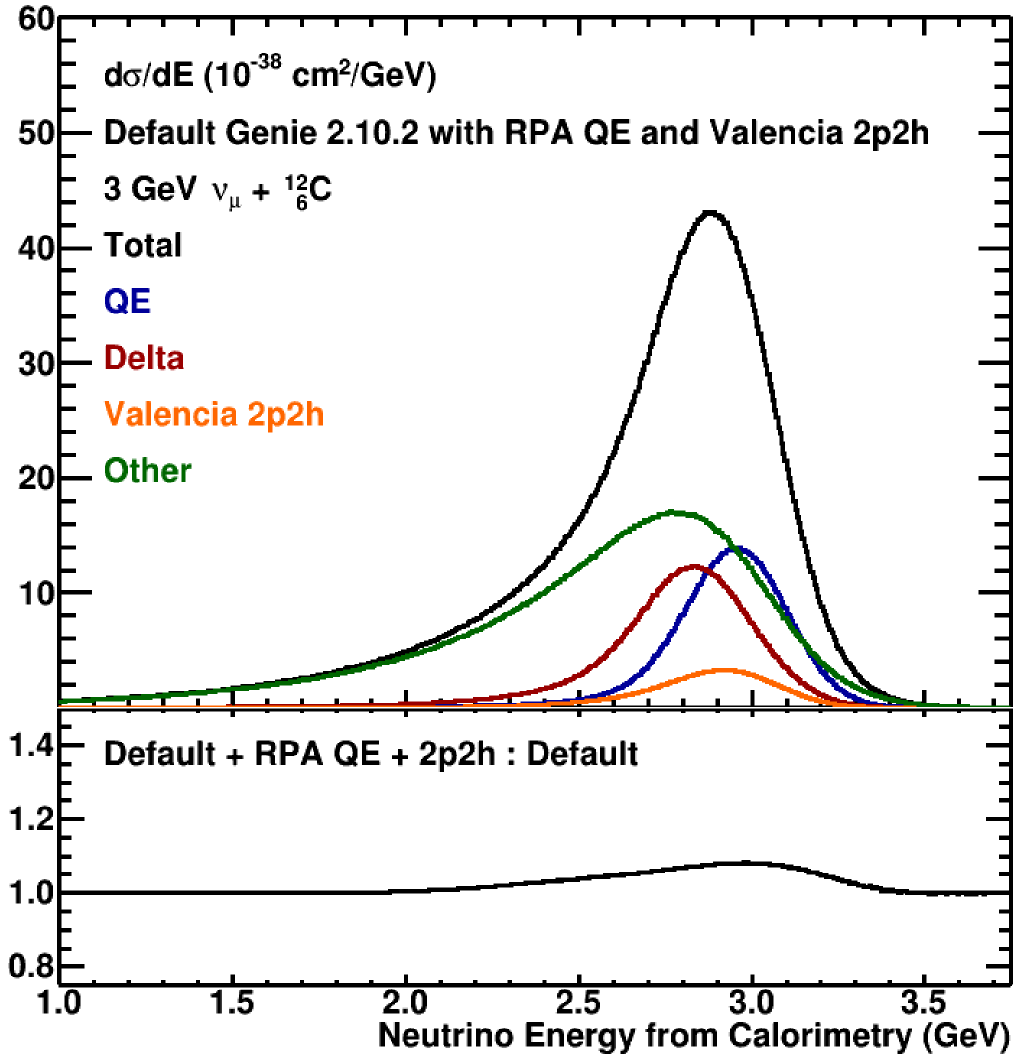
$\sin^2 2\theta \sin^2(1.27\ \Delta(m^2)\ L/E)$
from depth and position
of oscillation maximum

What if some poorly modeled
events are reconstructed
with too low energy?

This talk: events at 3 GeV
are reconstructed at 2 GeV?

Distortion of a mono-energetic 3 GeV neutrino sample

"Probability" that a 3 GeV neutrino is reconstructed at 2.5 or 2.0 GeV



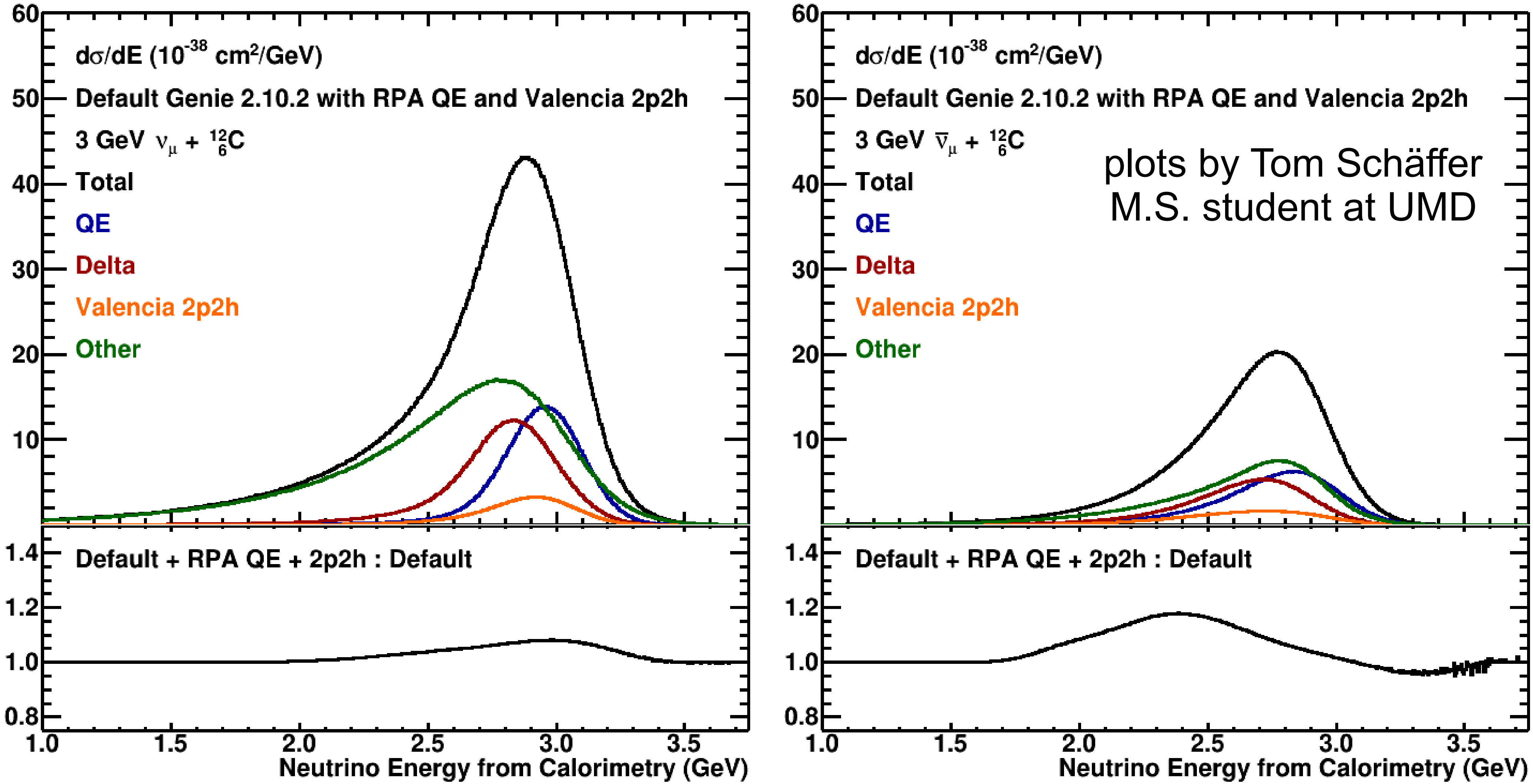
Simple resolution smearing
DUNE CDR-like
5% on Elepton
10% on (Ehad-Eneutron)
missing unbinding energy

If we dead-reckon XS
the tails to the left
are reconstructed
in osc max dip
for numu disappearance
OR shift the peak to lower E
for nue appearance

To the extent that cross section models are well constrained from external data or from the DUNE Near Detector, no problem.
Ratio shows distortion caused by ("worst case") not modeling 2p2h

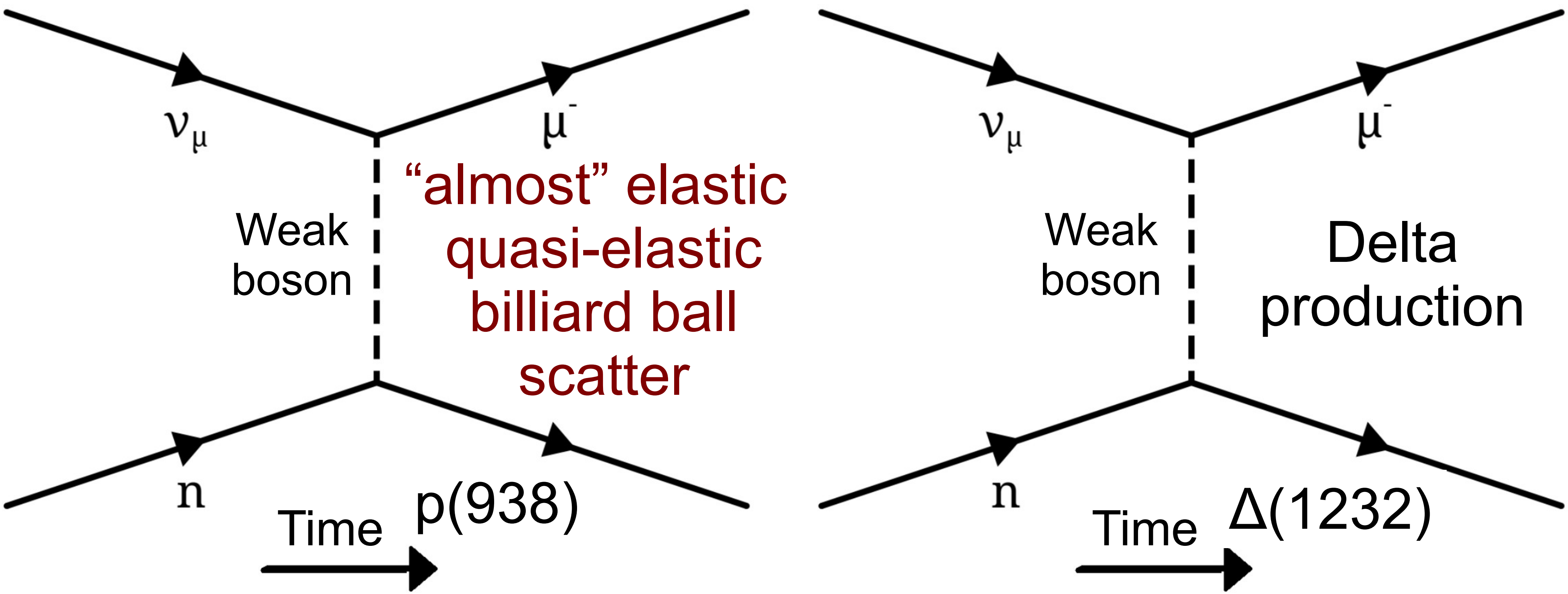
Distortion of mono-energetic 3 GeV anti-neutrinos

Probability that a 3 GeV neutrino is reconstructed at 2.5 or 2.0 GeV



A major error in extrapolating a component distorts the anti-neutrino differently than neutrino would fake CP violation signal, degrade sensitivity

Feynman diagrams for elastic and inelastic reactions



Today's results focus on the kinematics from the quasi-elastic to Delta resonance interactions.

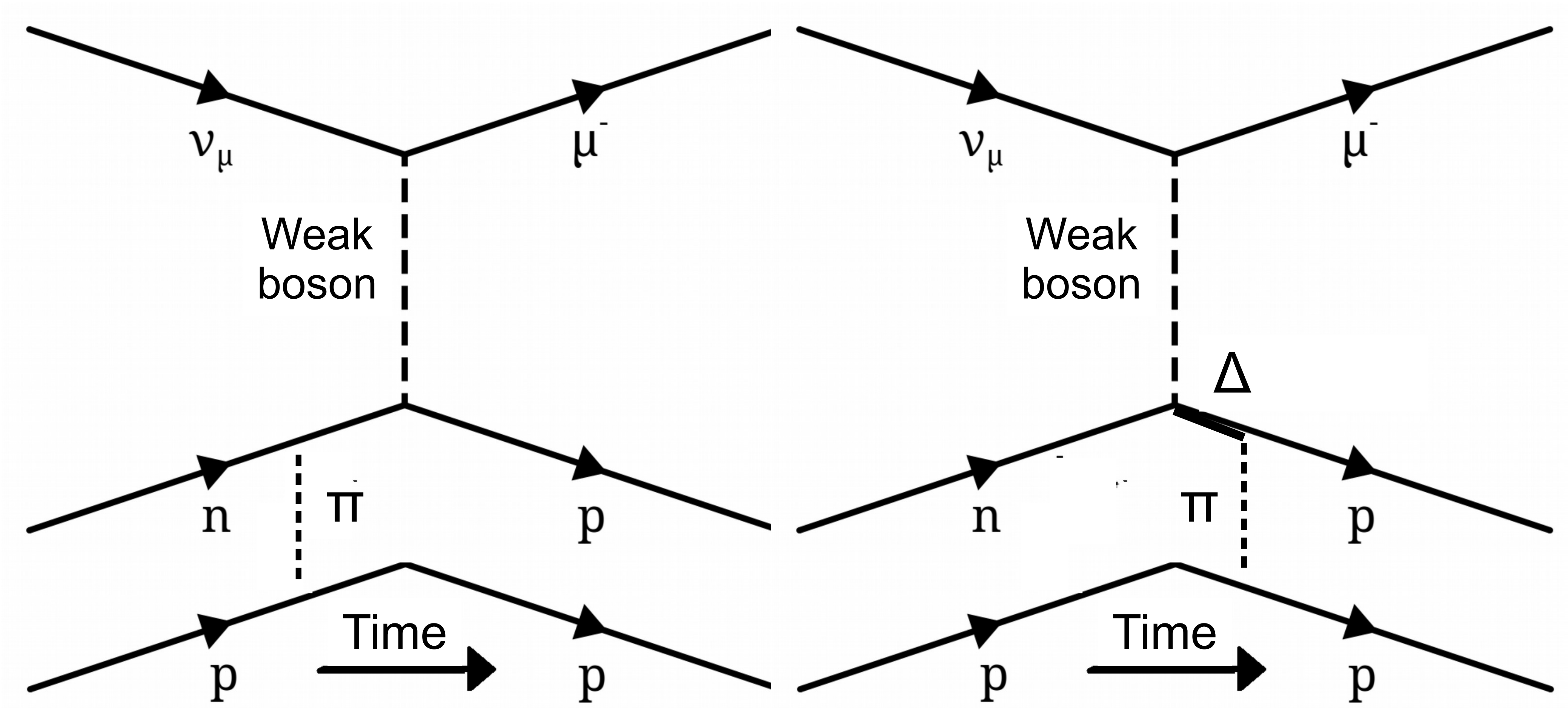
not the only topic, but very important for NOvA, T2K, DUNE.

Will refer to W as the (invariant) mass of the outgoing hadron.

QE has just a proton 0.938 GeV, Δ has 1.232 GeV

“2p2h” between the QE and the Δ(1232)?

Events where the reaction involved two nucleons



interaction with two particles in the process of pion exchange
both are knocked out, creating two holes in the nucleus (2p2h)
Not a single particle, more degrees of freedom,
can appear to have W between QE (0.938) and Δ (1.232)

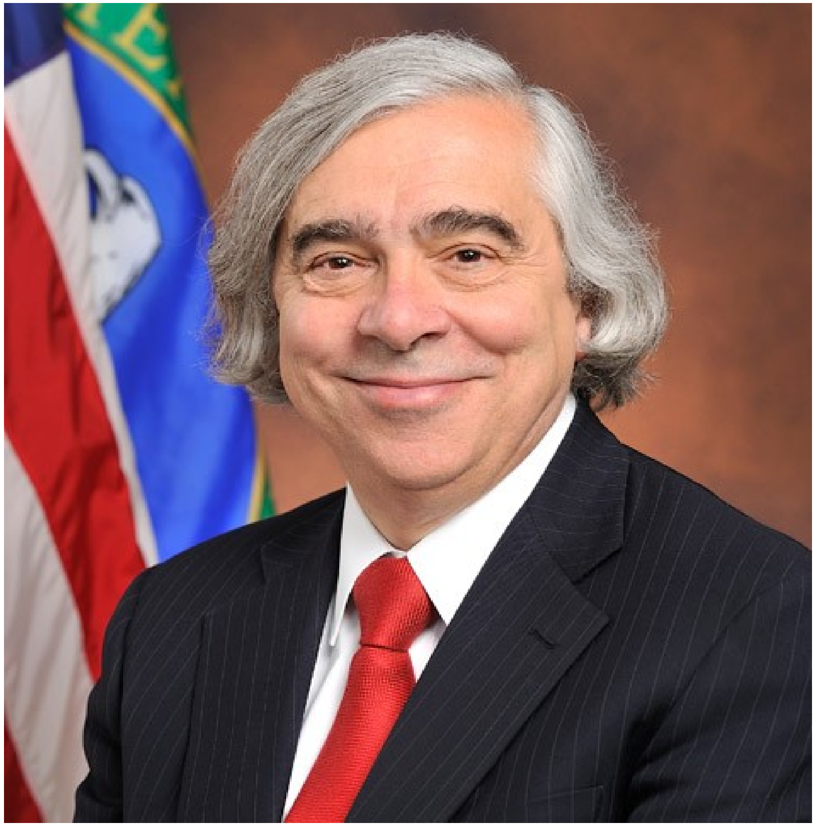
Just nucleons exchanging pi mesons

(sometimes called meson exchange currents)

If we can measure them and calculate diagrams we can model them. Then they don't harm oscillation measurements.

MINERvA has measured them and compared them to two models.

Energy Secretary says: the simplest model for carbon



R.A. Smith and E.J. Moniz
Nucl.Phys.B43 (1972)

The interaction is on one nucleon

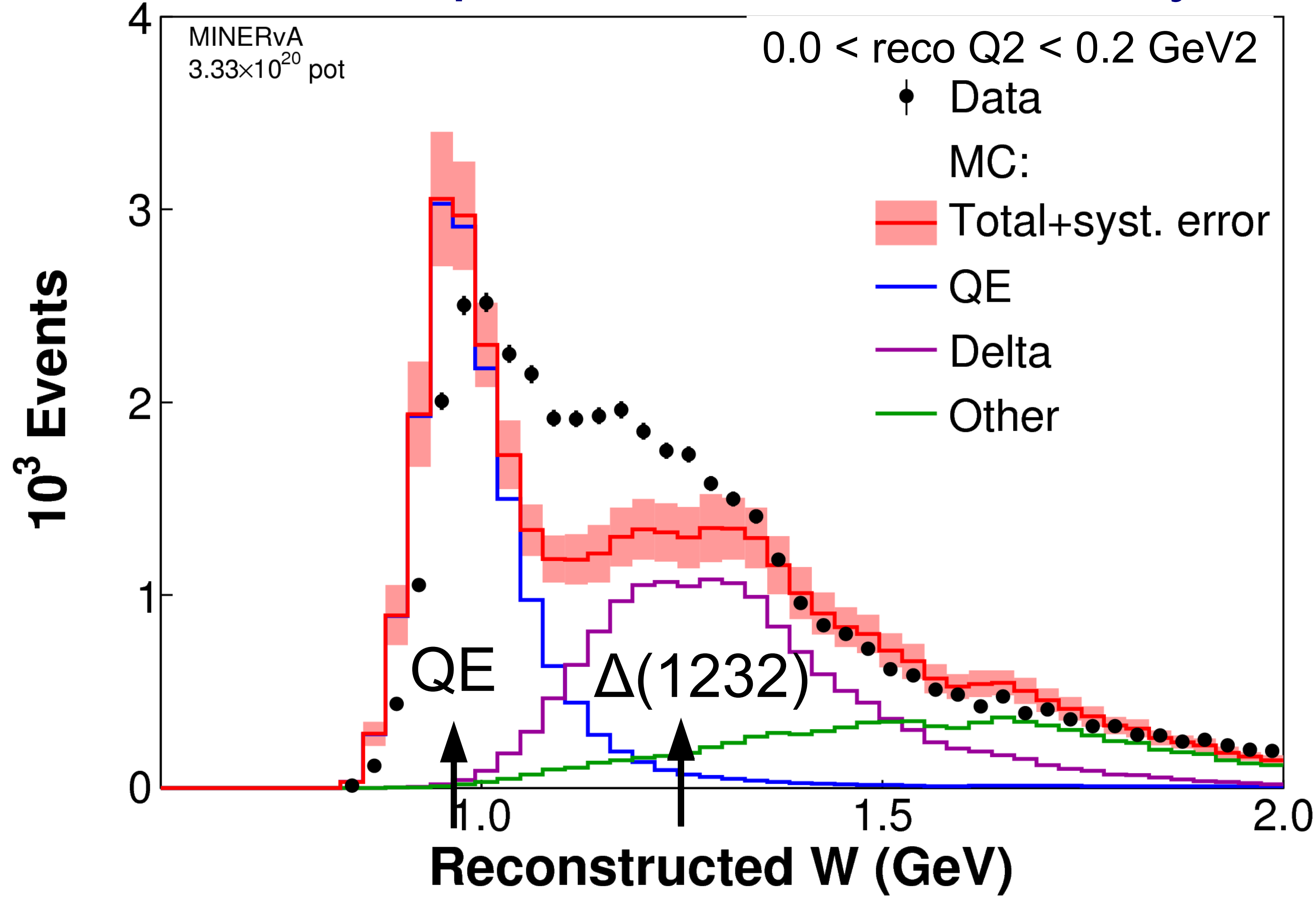
That nucleon is in motion (even relativistic) as required by the uncertainty principle for a bound/localized particle

The simplest form for giving nucleons some motion is a Fermi gas (see 4xxx stat physics)

has an energy cost of 25 MeV to unbind that nucleon

the reaction won't happen if the resulting nucleon has the same momentum as another nucleon (violates the Pauli exclusion principle for spin ½ fermions.)

MINERvA data compared to model with only QE and Δ



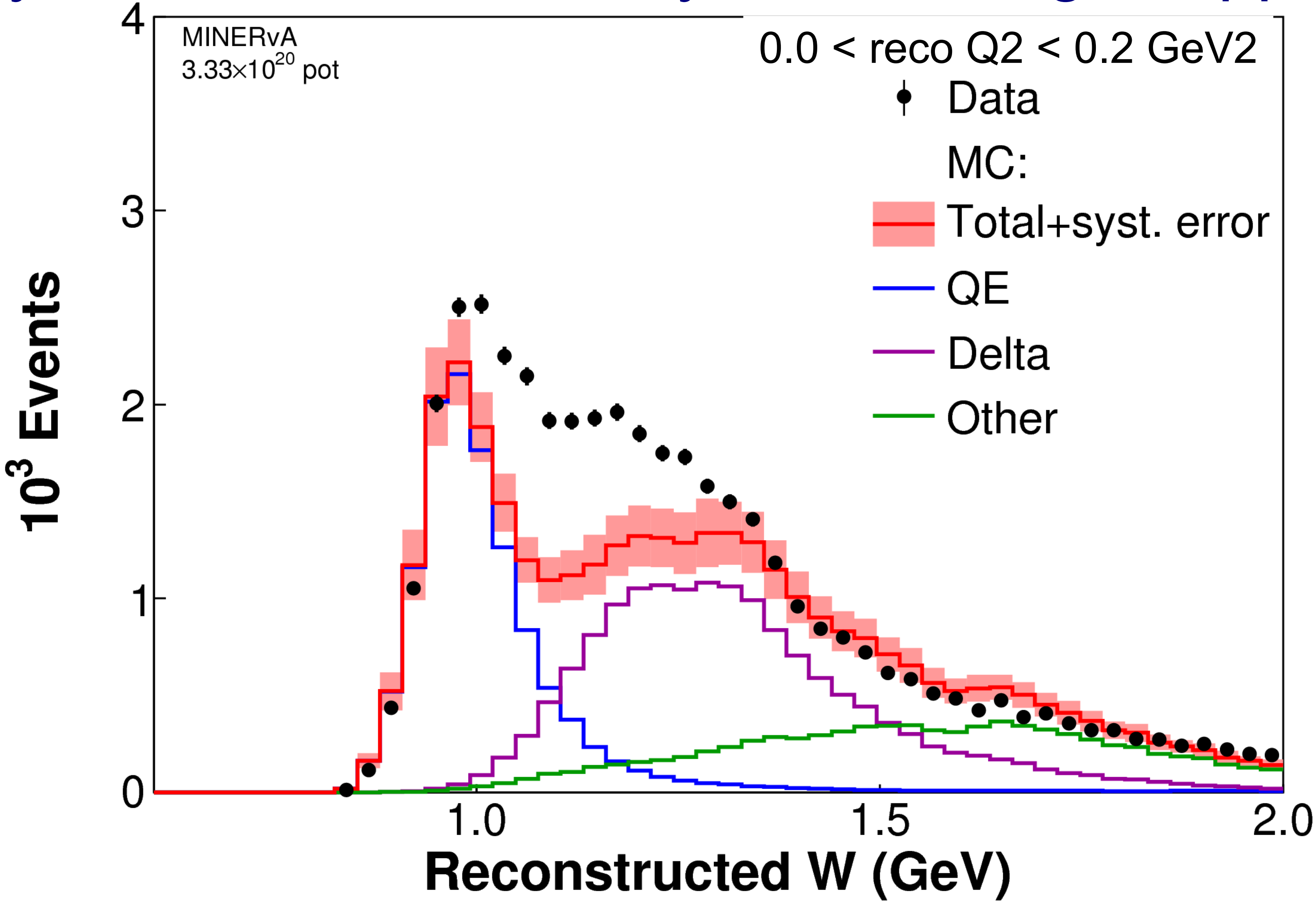
Fully simulated GENIE + MINERvA tuned pion

(GENIE is the name of a neutrino interaction computer code)

something is funny about the QE

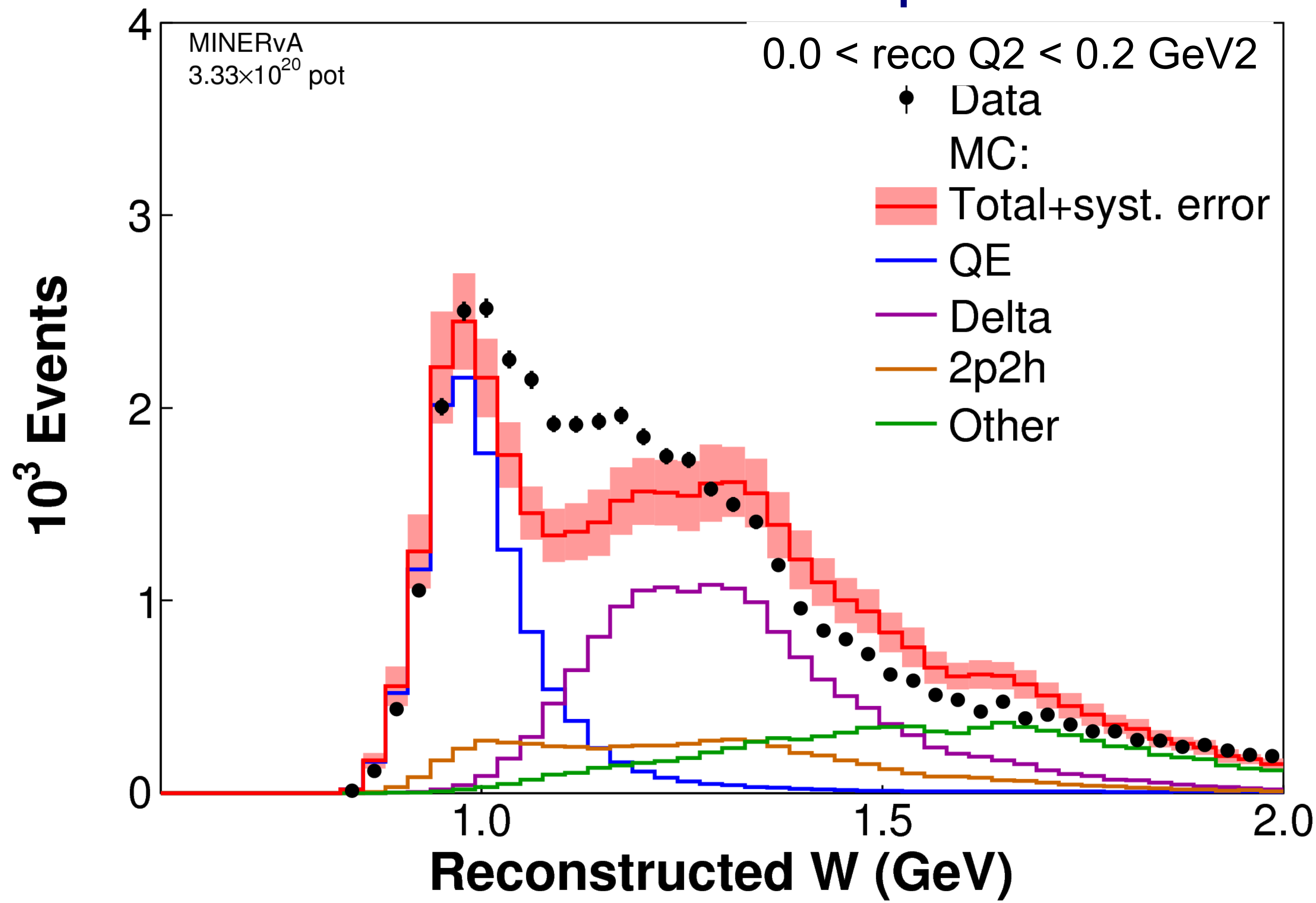
and the data might have a 2p2h process in the dip

Modify model with “RPA”-style screening / suppression



RPA is a technique to model a screening of the nucleon significant as momentum-transfers approach zero.
Nucleon equivalent to the polarization screening effect.
Valencia RPA model for QE is tuned to muon capture data

QE with RPA and Valencia 2p2h interactions



The 2p2h process contributes broadly
fills in the region between QE and Δ
does not produce perfect agreement – need more?

Wanted: a cross section, not event rate comparisons

Why? so model builders can compare to our data directly, without having to use the full MINERvA detector simulation. Allows faster progress toward better models !

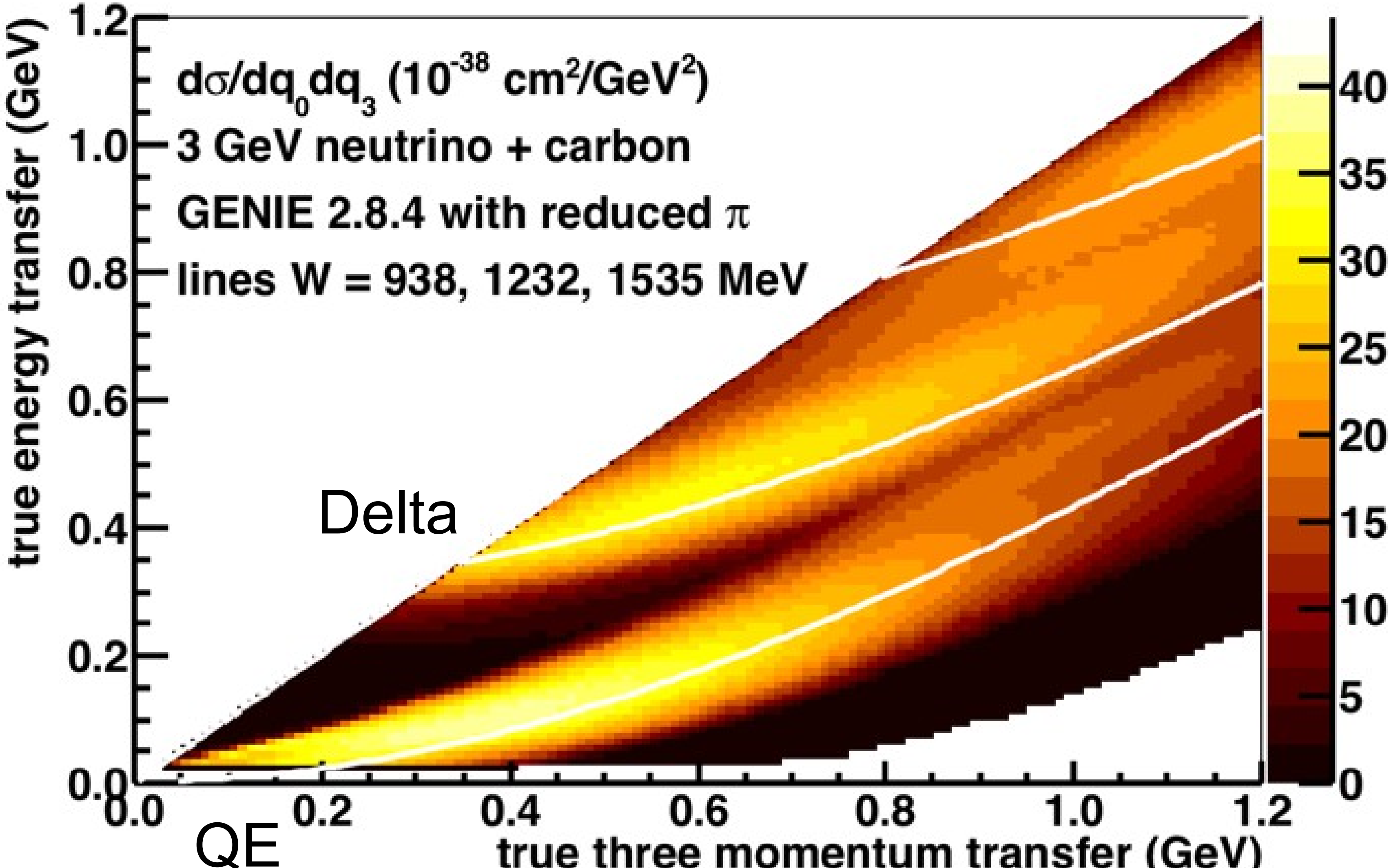
Problem: can't unfold detector smearing to W at all places in the spectrum with zero predicted cross section

Problem: want to carefully avoid model dependence makes the resulting cross section long-lived, maximally useful

Do this with $d\sigma/dp_\mu \, d\theta_\mu$ (or $d\sigma/dQ^2$ from muon kinematics) could be okay in a “narrow band” limited Ev beam

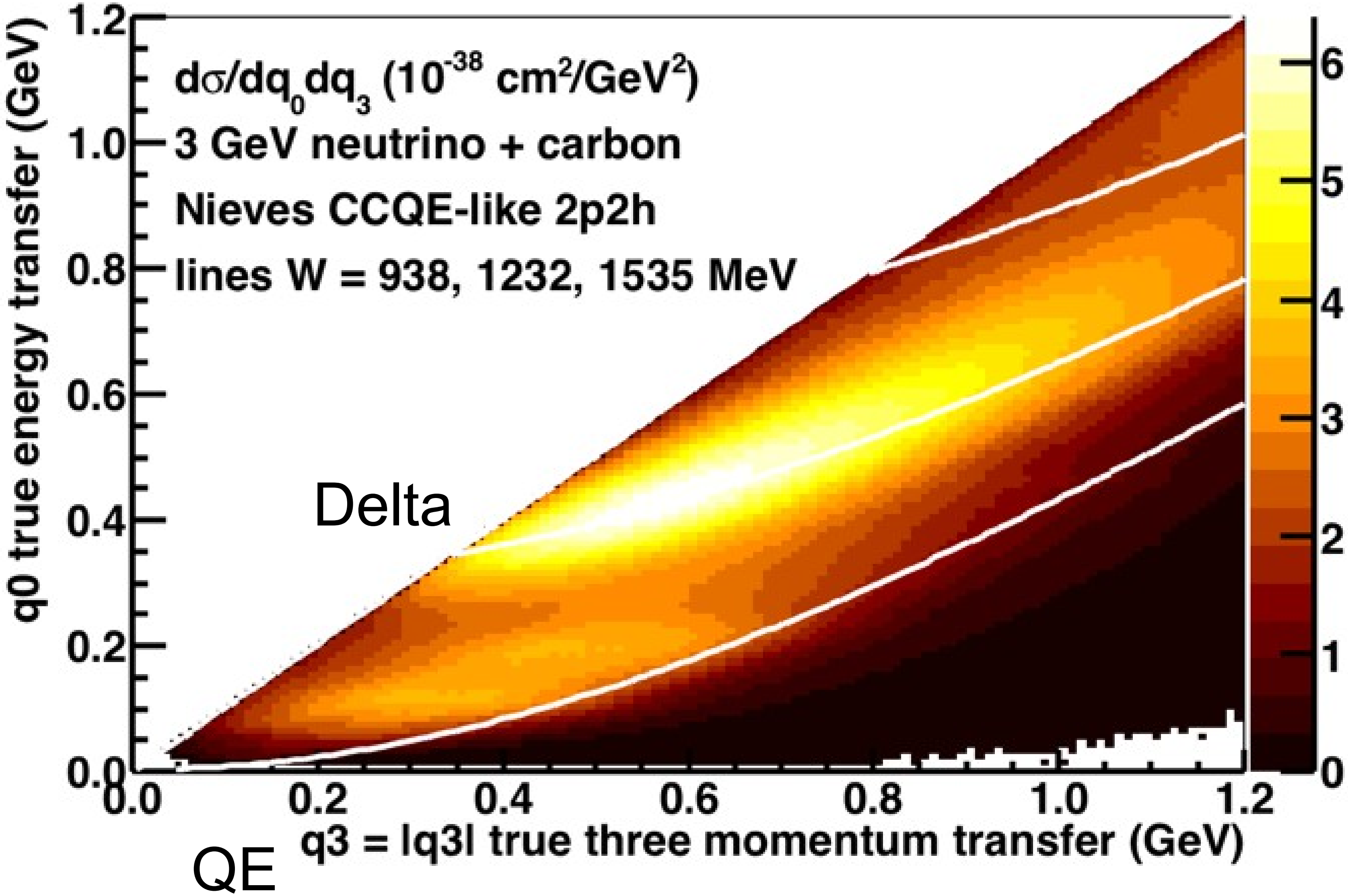
Former doesn't give the full picture I showed latter isn't the beam MINERvA is using

three-momentum and energy transfer vs. W



Can't get this with muon kinematics alone in broad band beam
use MINERvA's abilities as hadron calorimeter

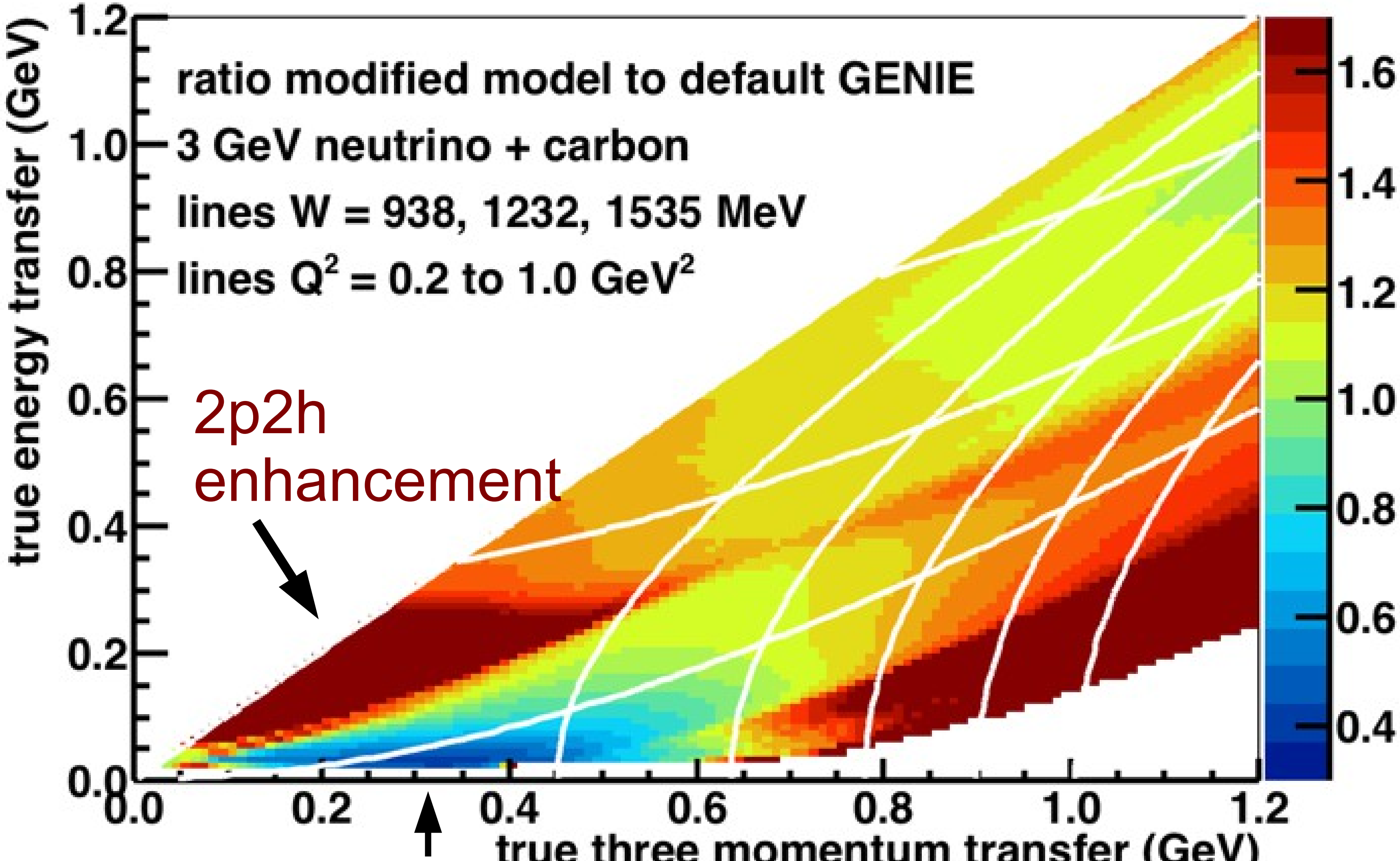
Valencia QE-like (no pion) 2p2h prediction



significant sorta-QE component but at W ~ 1.0

Large W = 1.232 GeV Δ component

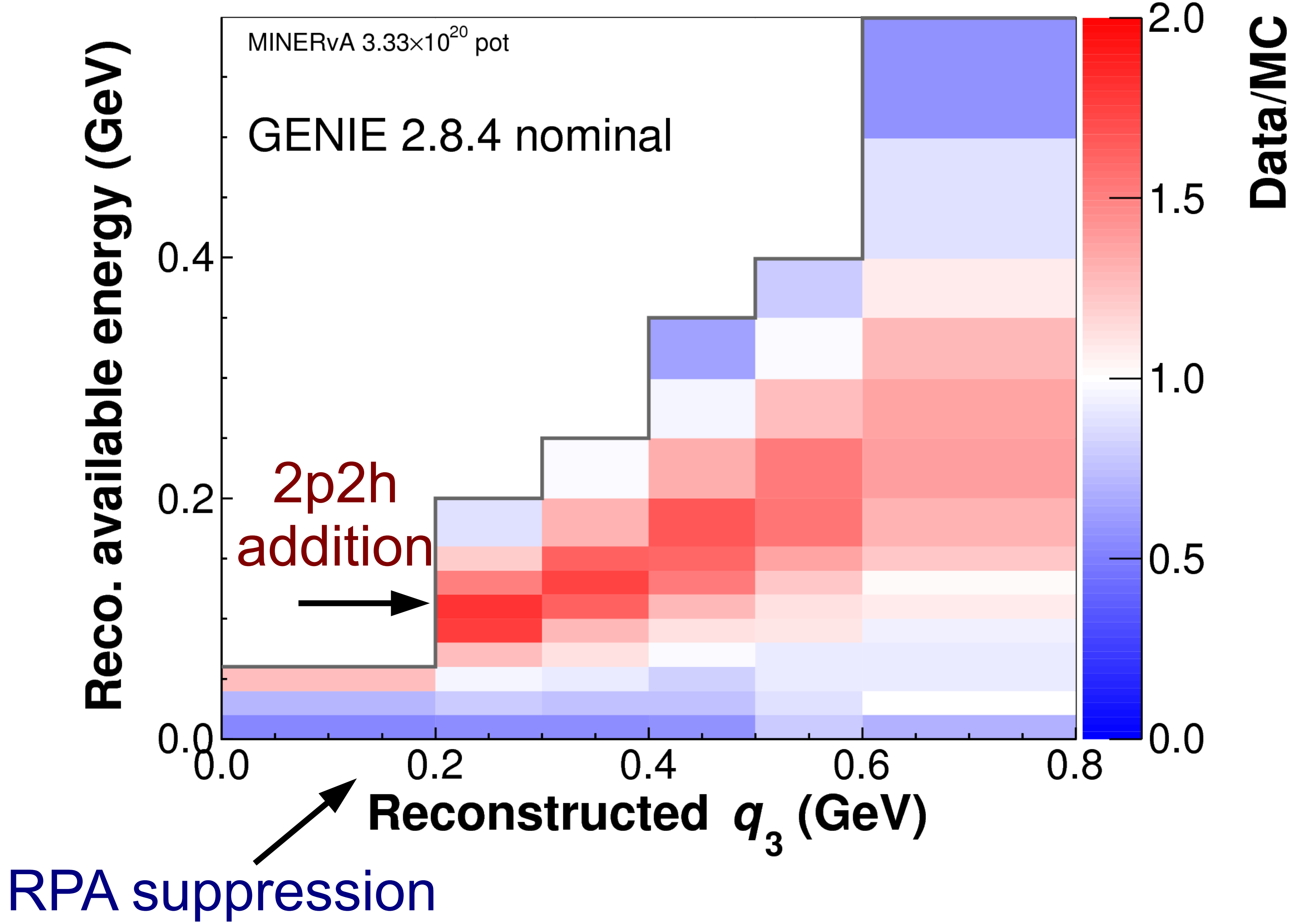
ratio (RPA+2p2h+GENIE) / GENIE



RPA suppression

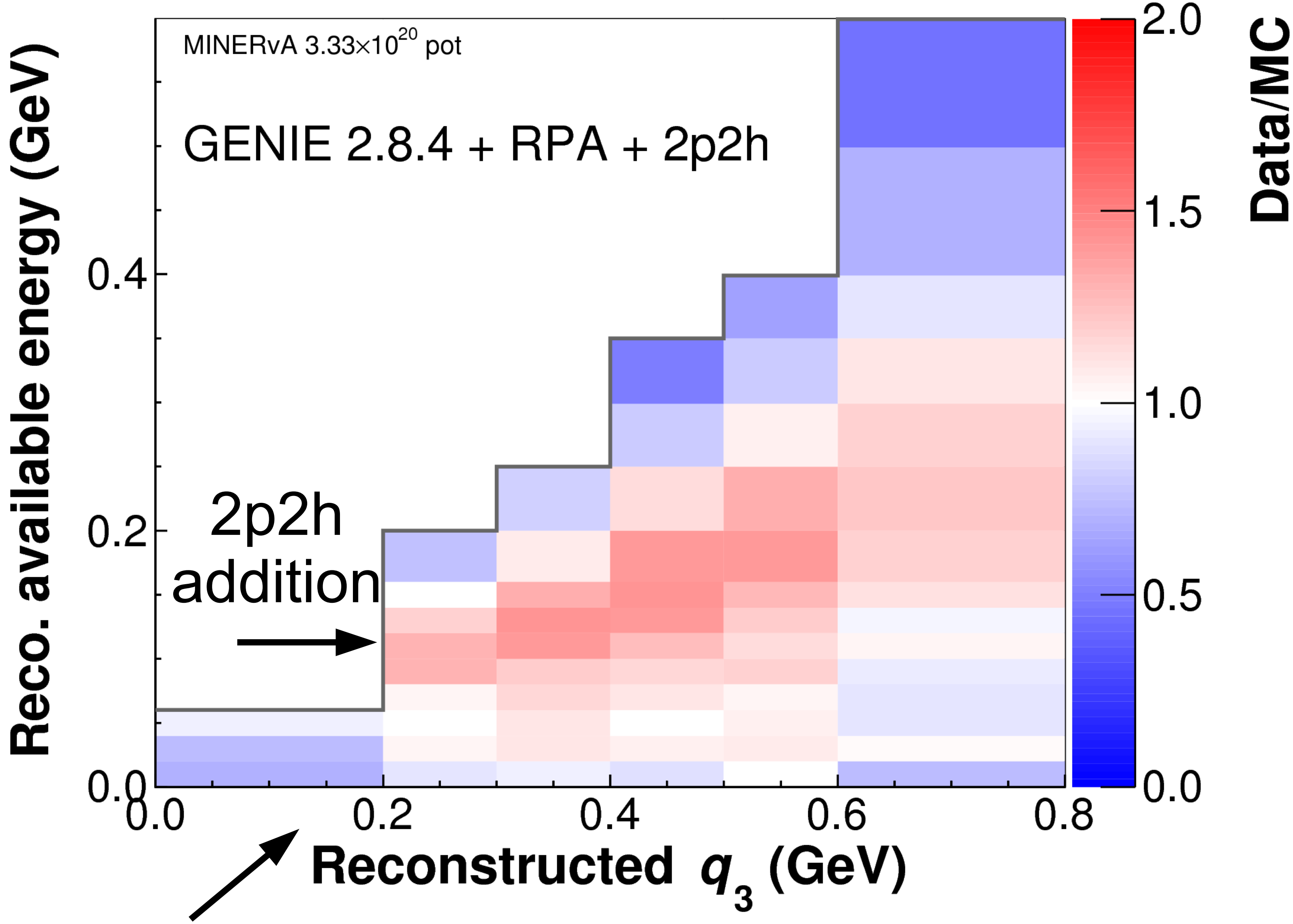
This prediction matches the story I told with the W plots
contains the same information, but leads to a cross section

Ratio Data / (GENIE without RPA and 2p2h)



Like the model ratio, but with binned, reconstructed quantities

Ratio Data / (GENIE with RPA and 2p2h)



RPA suppression

Notice the 2D bins
six bins in q3, up to 15 on vertical axis

Technical slide

We do not start knowing the energy of the neutrino, only the direction.

Measure the energy E_μ and angle θ_μ of the outgoing muon.

Measure the detected energy attributed to hadrons $E_{visible}$.
Make a correction from that to energy transfer q_0 (or E_{had} or ν or ω)
(correction has some dependence on neutrino model)

Estimated muon energy = $E_\mu + q_0$

Estimated four-momentum $Q^2 = 2\, E_\nu\, (E_\mu - p_\mu \cos\theta_\mu) - M_\mu^2$

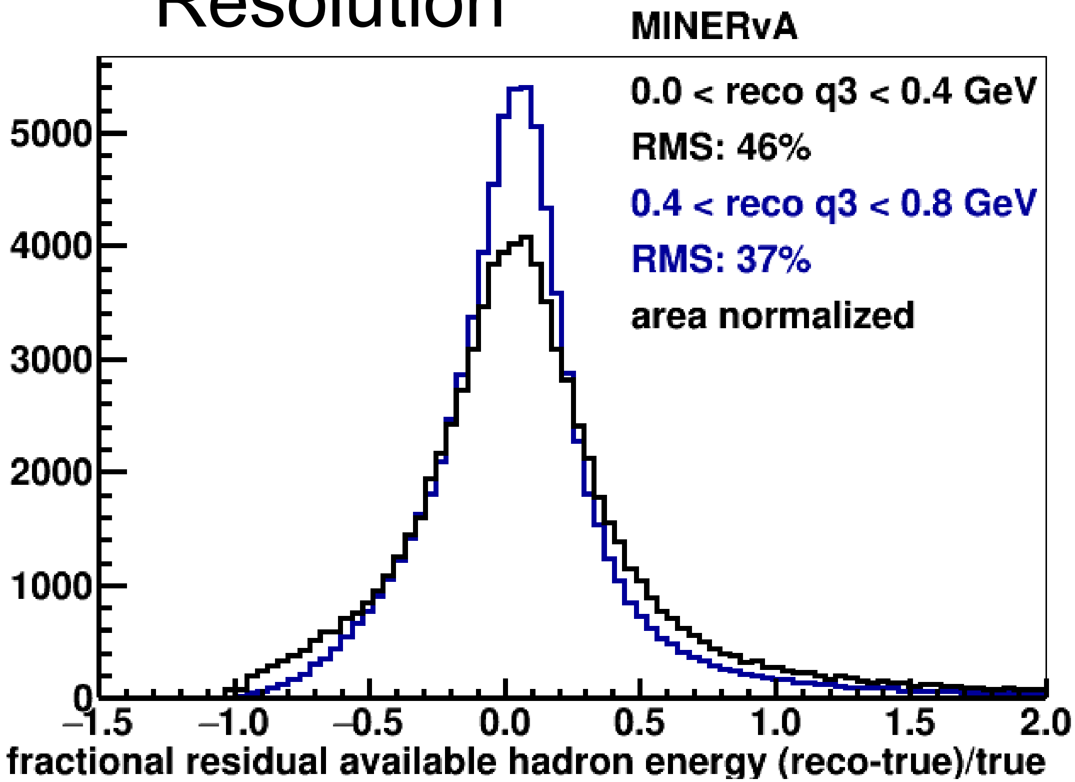
Estimated momentum transfer $q_3 = \mathrm{Sqrt}(Q^2 + q_0^2)$

If desired, estimate $W = M_n^2 + 2\, M_n\, q_0 - Q^2$

Turn $E_{visible}$ into (next slide) $E_{available}$ = using detector MC
(discounts neutrons, has little neutrino model dependence)

Vertical axis is a special energy estimator

Resolution



Use known resolution
to "unfold" reconstructed data
(similar image processing
to unblur a photograph)

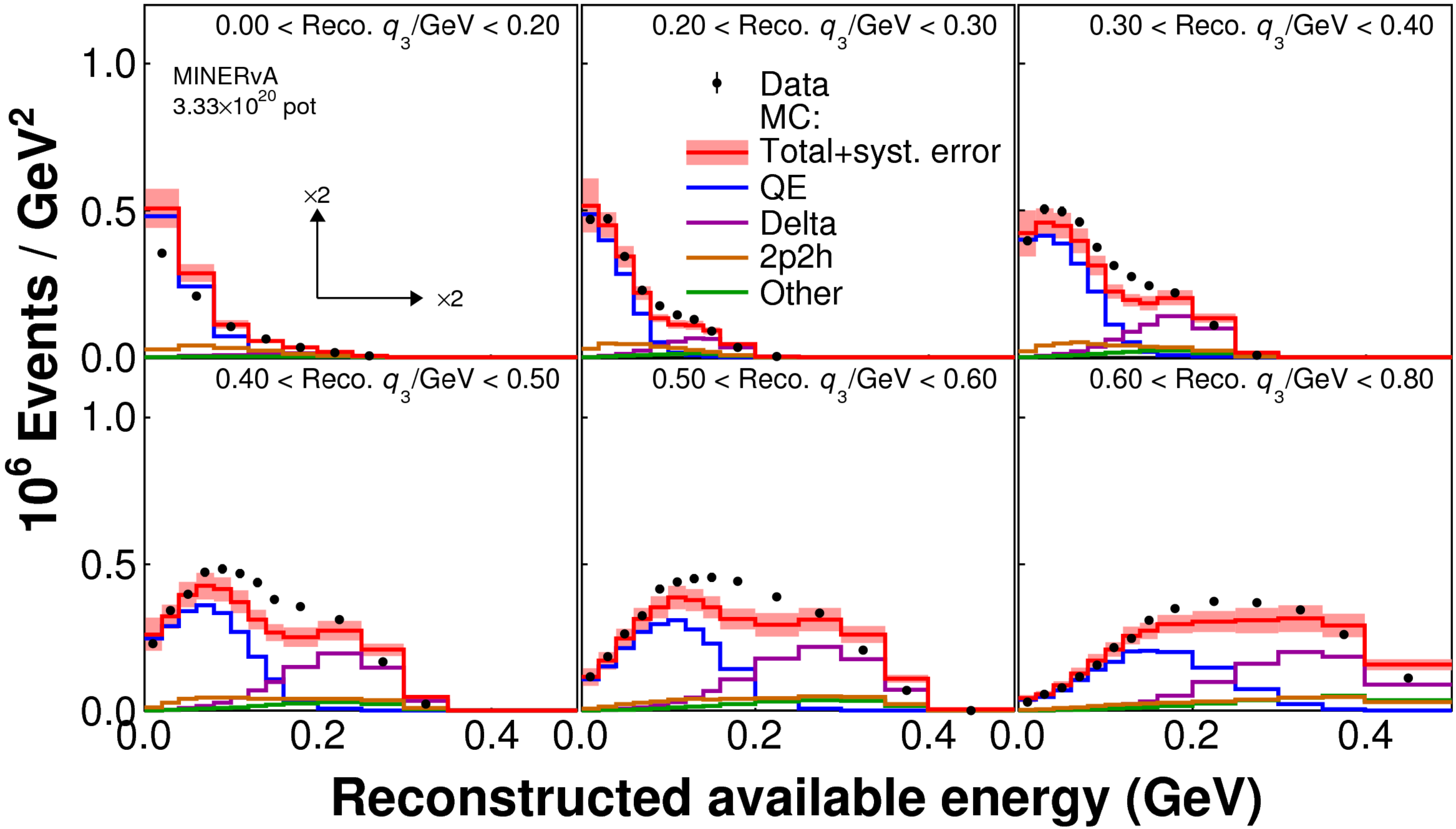
is NOT energy transfer
unfolding has the same
pathology as W
and model dependence from
unknown neutron content
(MINERvA doesn't measure
neutron energy very well)

Available energy Eavail is
KE(p,$\pi^{\pm}$) + E(π^0,e,γ,K)
not neutrons
not nucleon removal energy

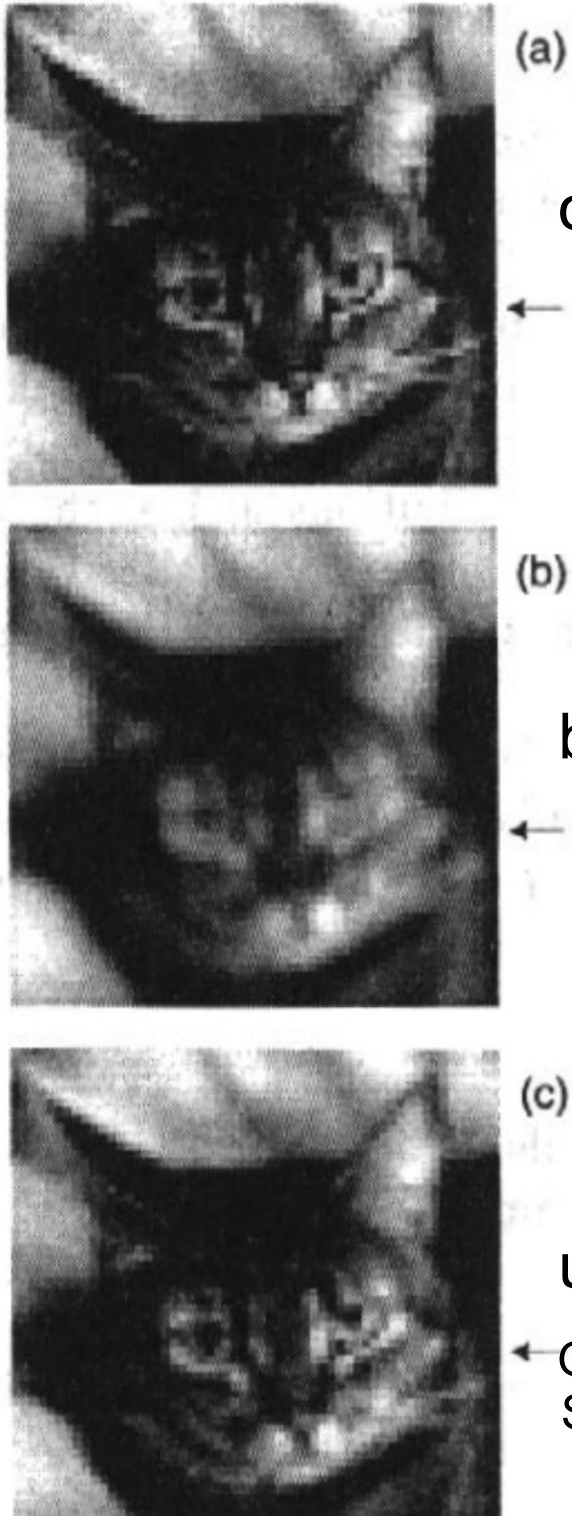
depends on detector model
test beam calibrations

The inputs to the earlier 2D plot, before unfolding

Model is GENIE with RPA suppression and 2p2h events



Examples of 2D unfolding



original

blurred

unfolded

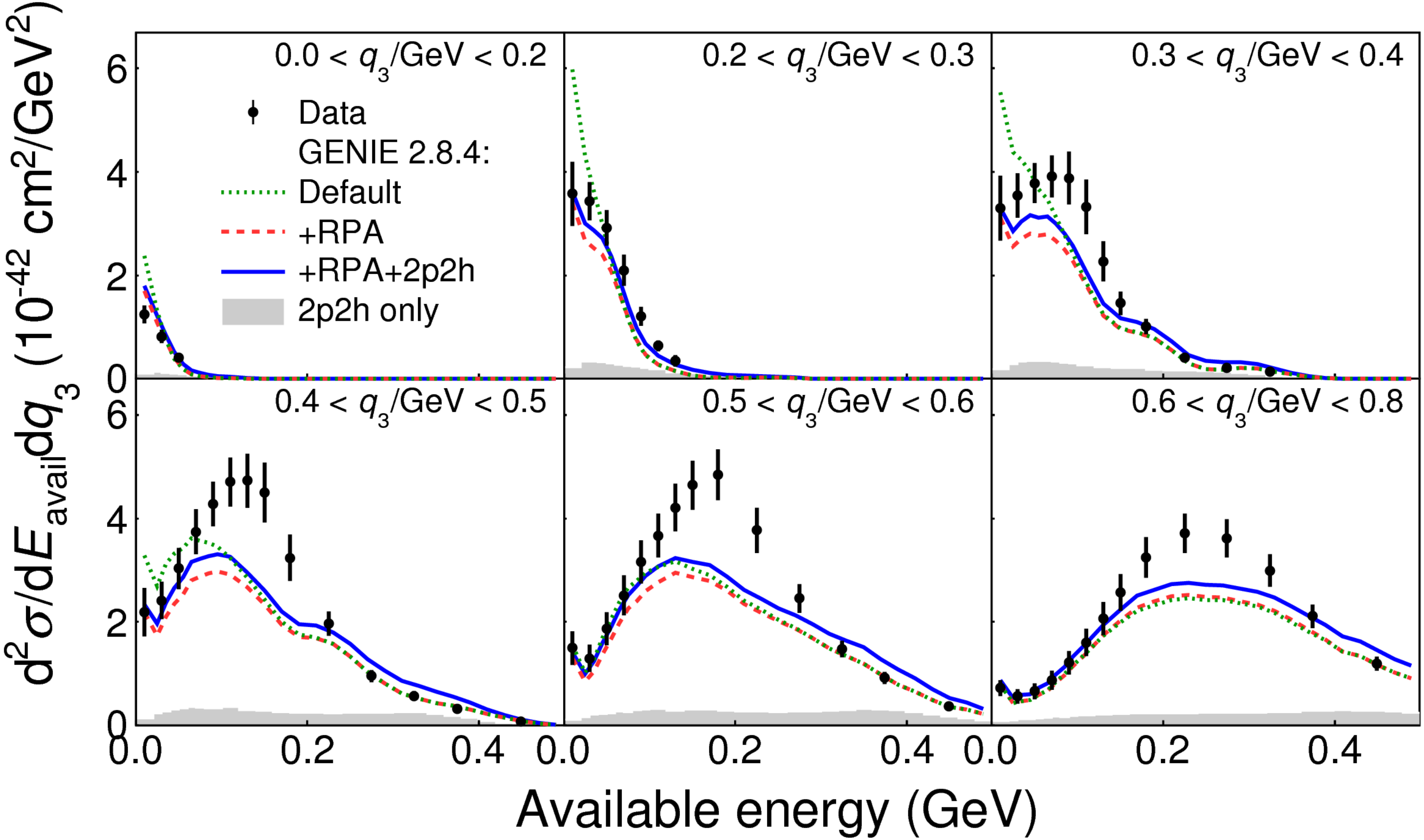
G. Cowan Statistical Data Analysis

requires you know smearing function

blurred unfolded

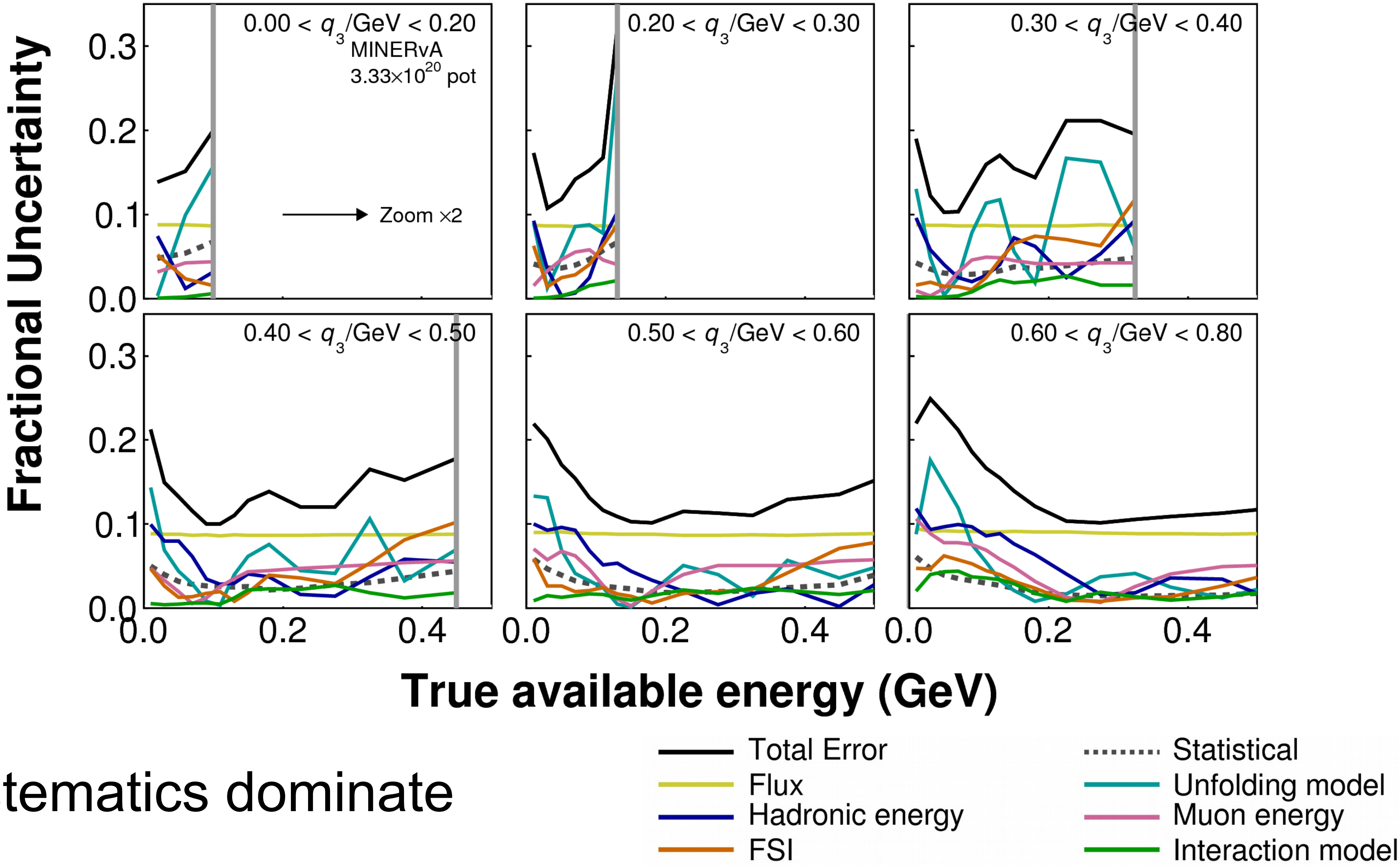
image S. Oser found on the web

Unfolded, double differential cross section



You can make the dashed curves from the GENIE code.
GENIE code to go from red to blue curve, in progress.

Sources of uncertainty on the cross section

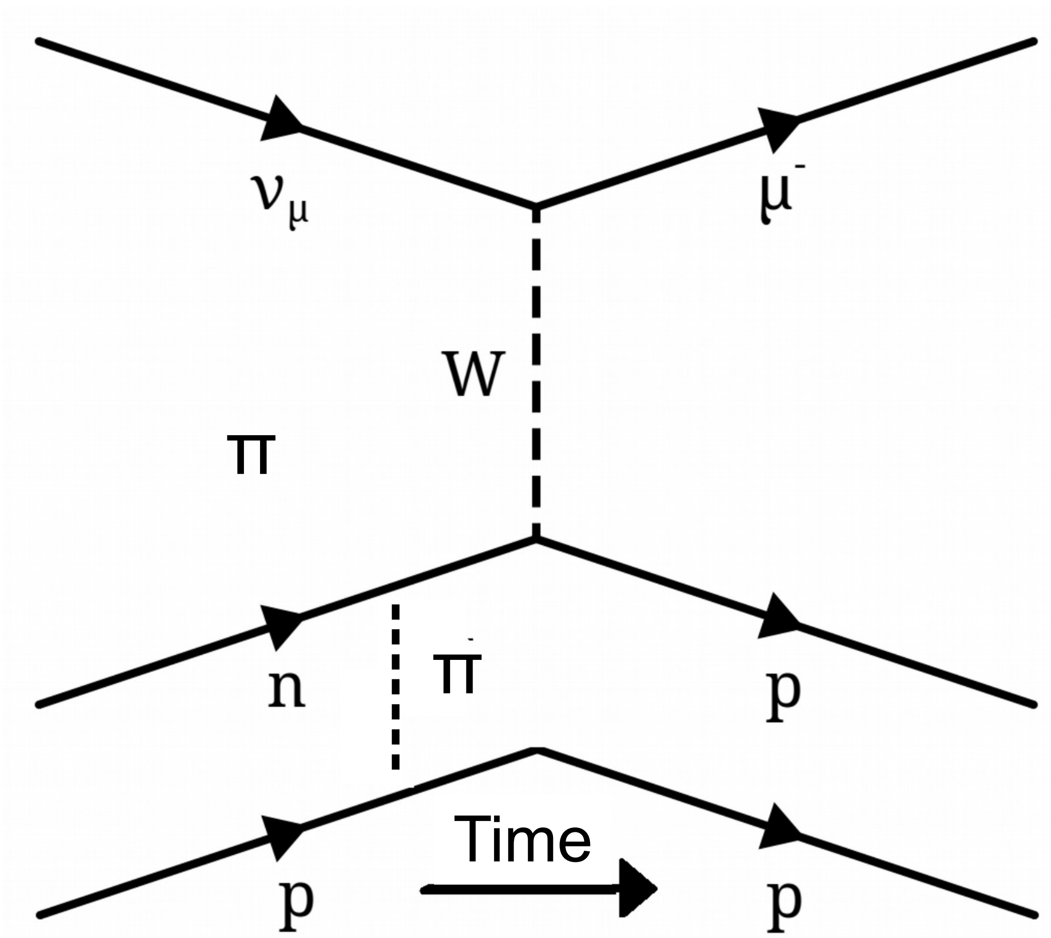


Systematics dominate

Several systematics have same size effects

Model dependence in "Unfolding", "FSI", "Interaction"

Proton counting as signature



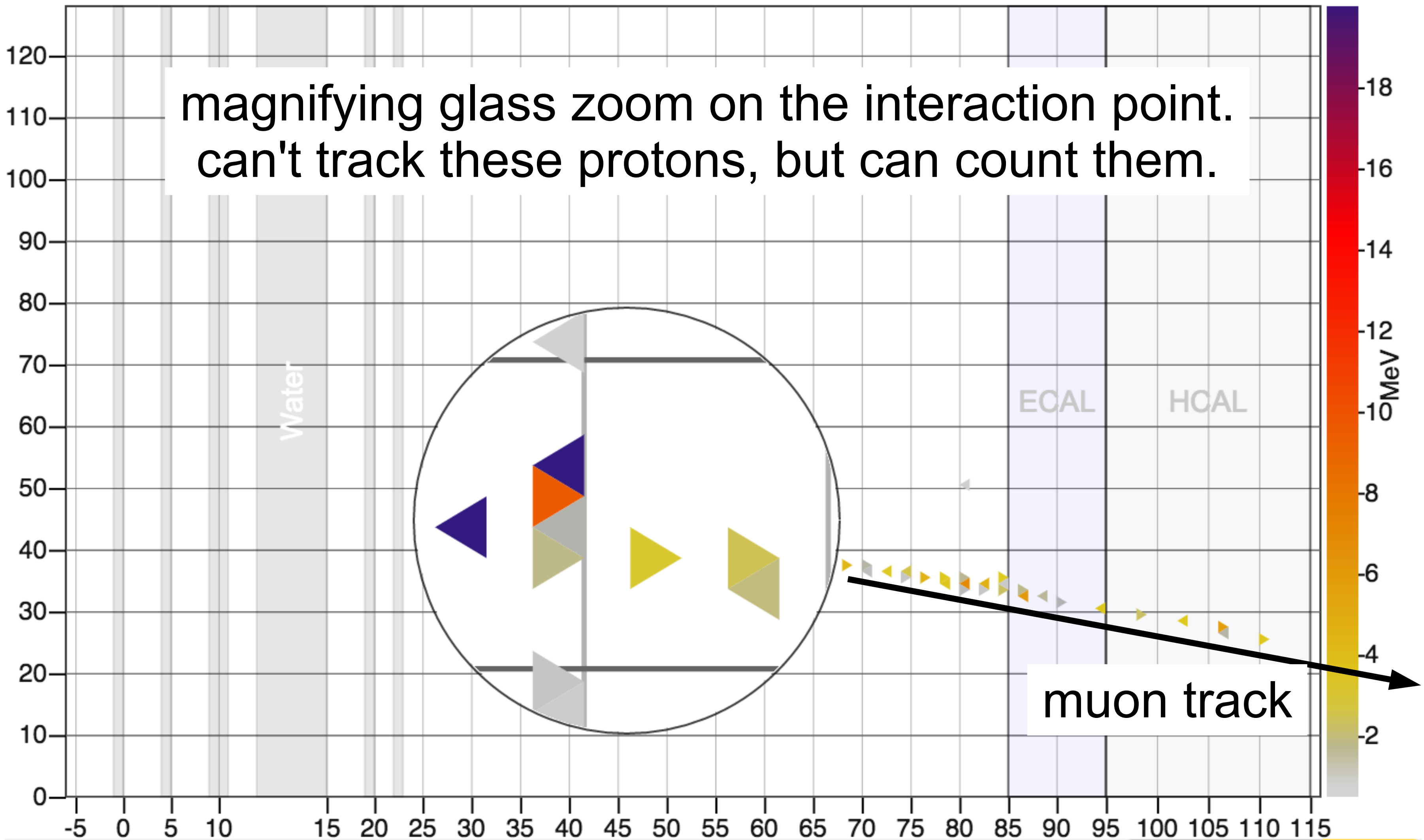
Processes like these should have two protons come out.

We use a characteristic signature for a proton the "Bragg Peak" a large energy deposit at end of the protons range

(same feature of protons is used to kill cancer cells in proton-accelerator based cancer therapy)

These events are more likely to produce two or three strips with more than 20 MeV near the vertex

Two protons leaving two 20-MeV hits



Simulated event with two protons, some neutrons, no pions
One proton had 32 MeV, stopped right away.
Other proton had 109 MeV, traveled five planes.
We look for protons only near the vertex

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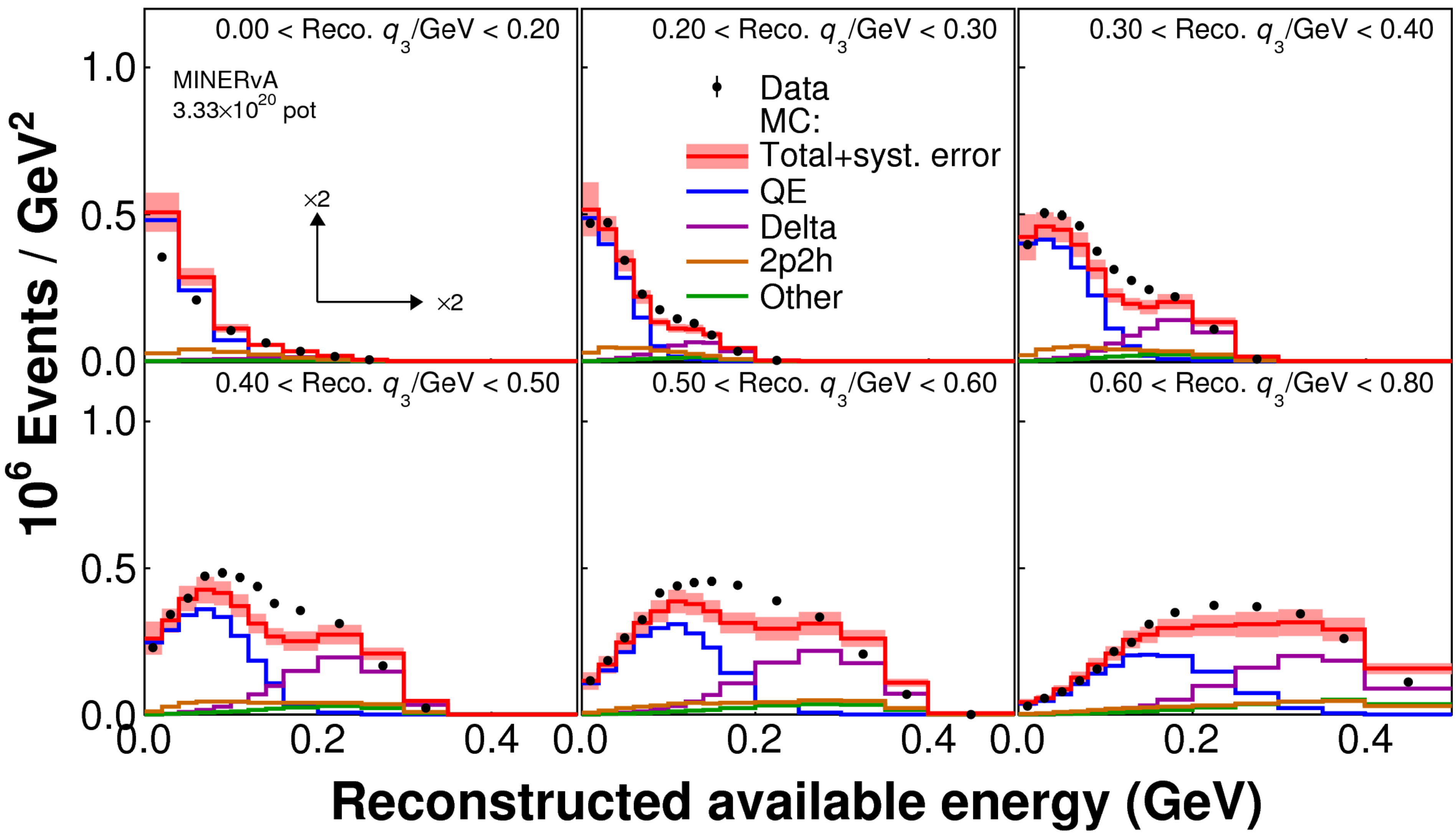
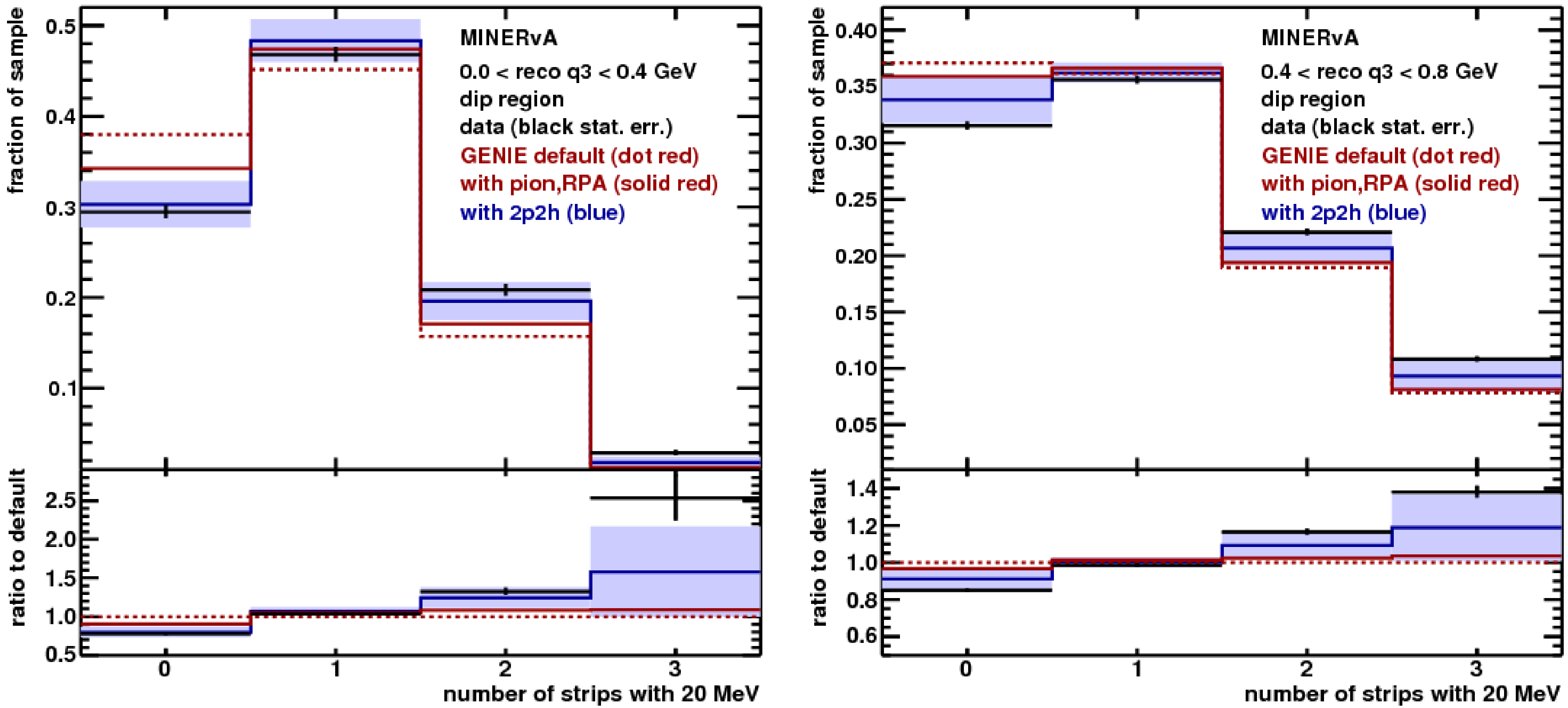


For proton counting, two regions of q3 and look only in the dip-region

Proton counting for two regions of q3



Easiest to focus on the ratio plot at the bottom, 2 and 3 protons

The 2p2h model is shifted much closer to the data

Without 2p2h, poor description of the data, $\chi 2 = 15.1$ for 6 dof

Data want more 2p2h, or use all the error band, $\chi 2 = 7.5$

Conclusions

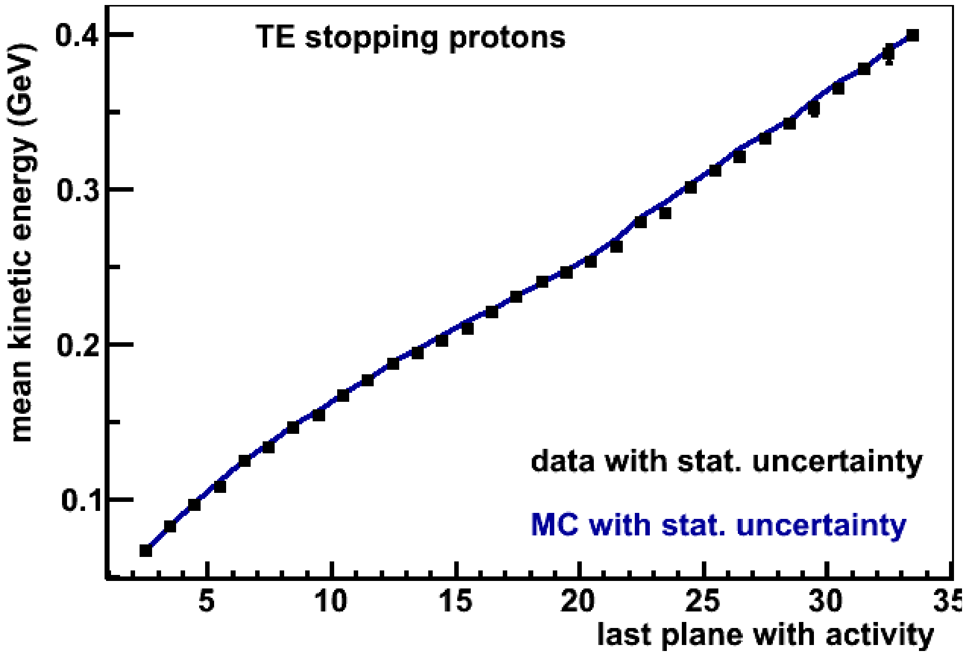
These data are best described with
Valencia RPA screening applied to QE
2p2h component similar to Valencia 2p2h model
but the data want more of it

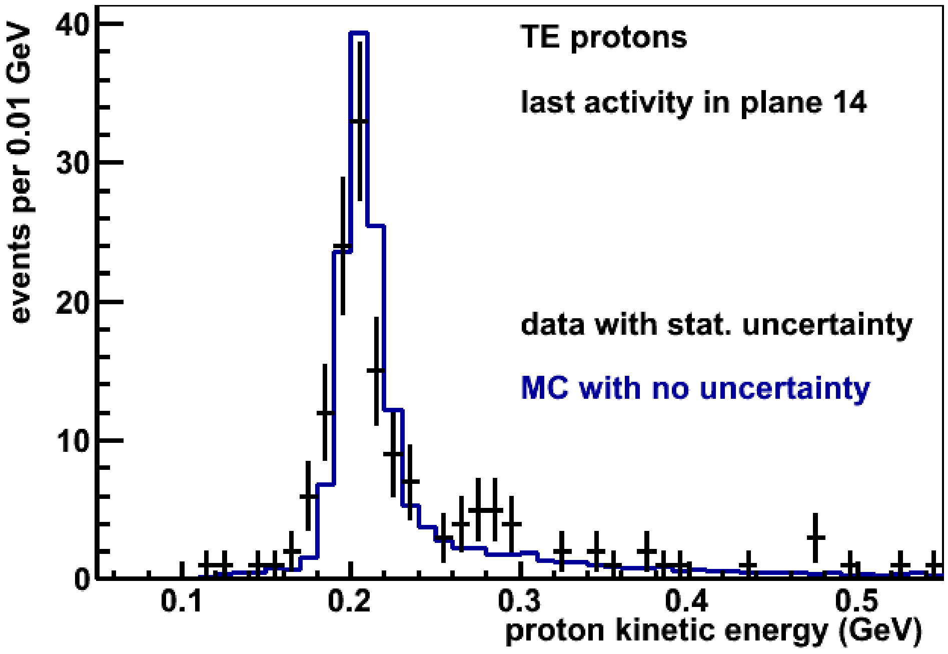
We have produced a differential cross section
which will enable the interaction community
to continue to produce improved models

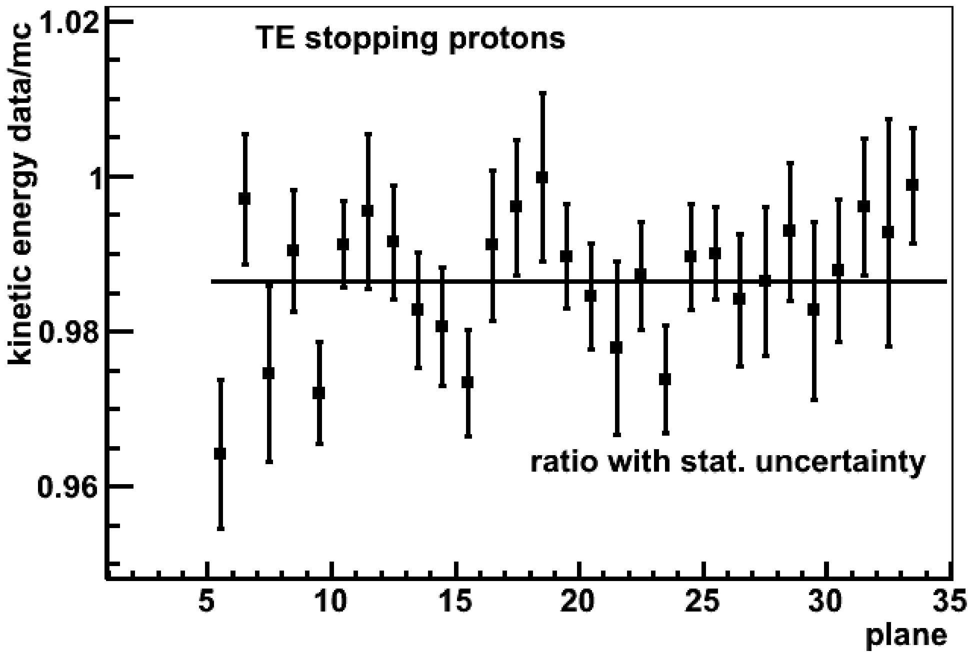
Some early models are available to experimenters
through event generators.

These are already being incorporated into
oscillation analysis by T2K, NOvA, DUNE

How events affect oscillation analysis





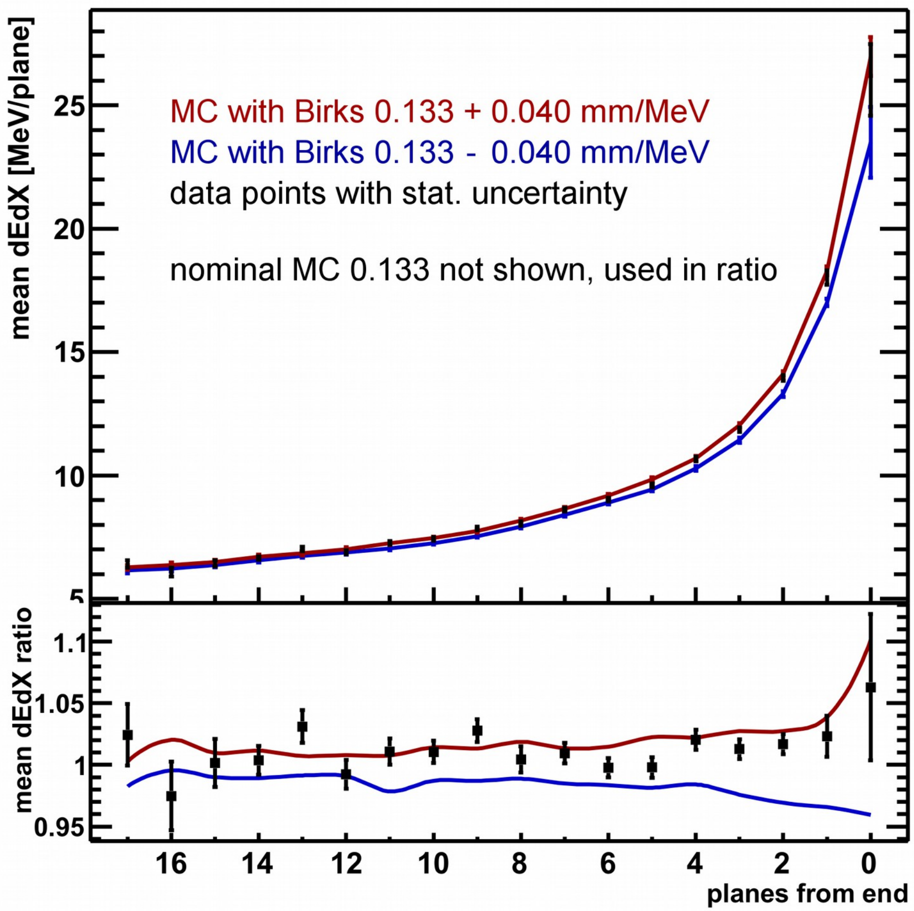


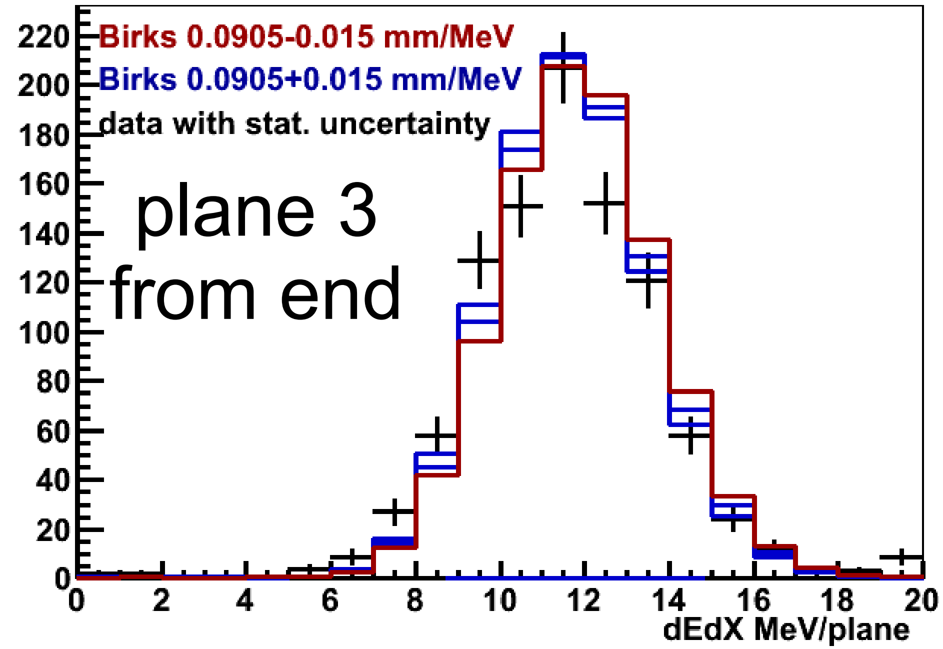
Proton range

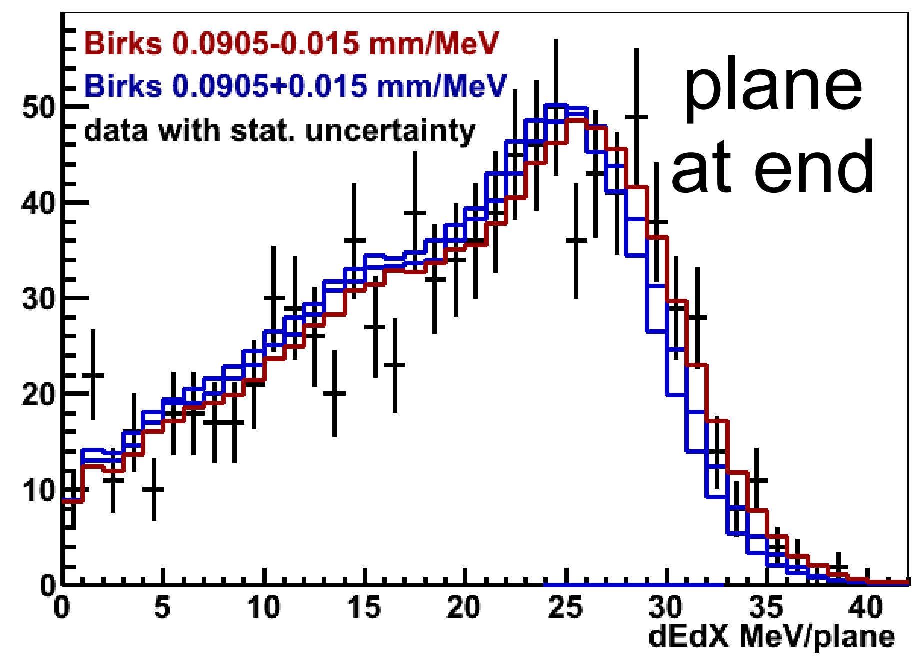
data points on the left
are mean of Gaussian fit to
peak like lower right
MC protons stop 1.3% short

Material Assay 1.5%
Beamline momentum 1.1%
Geant4 model uncertainty

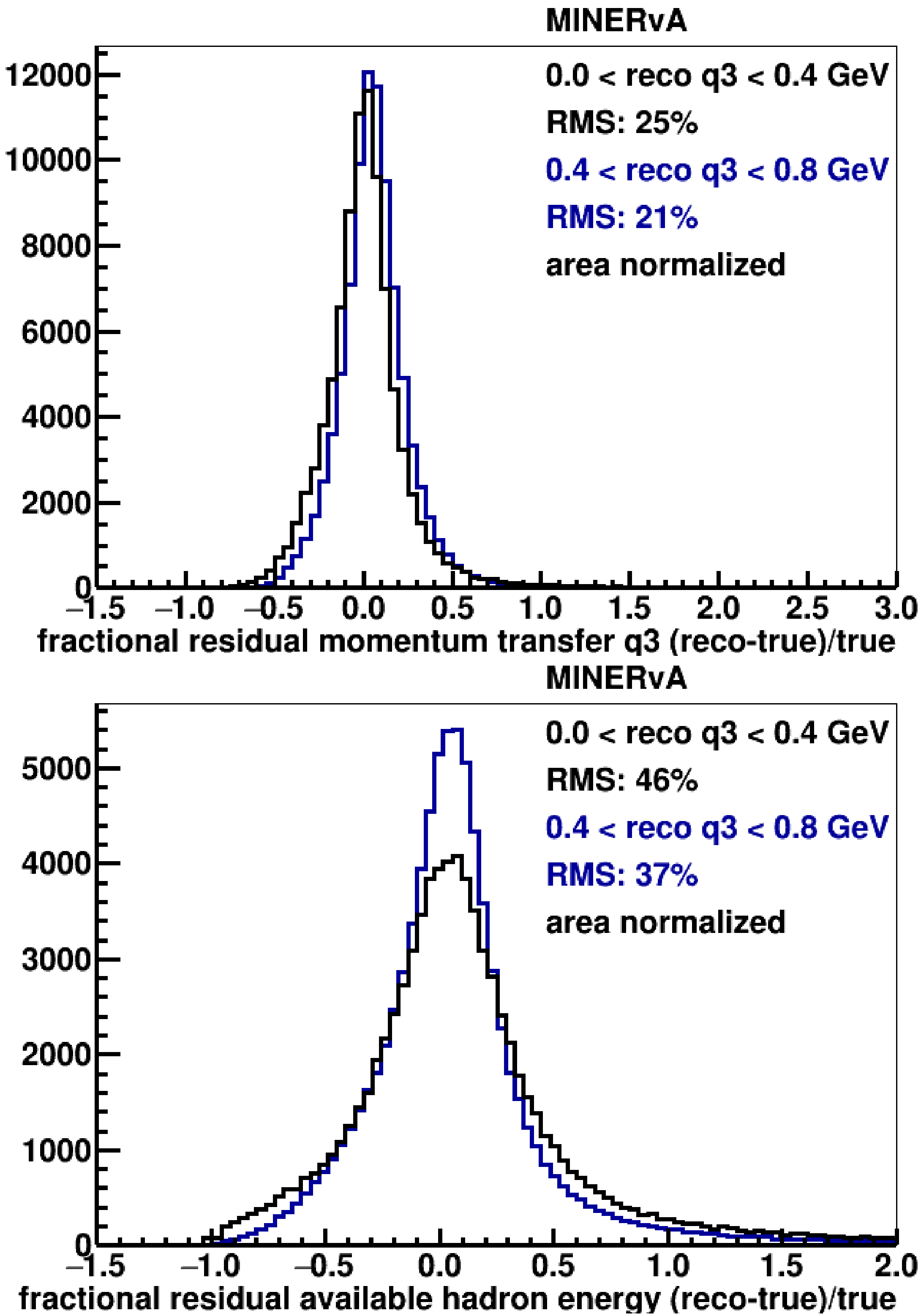
Birks' law parameter calibration







(above) dEdX trend compared to nominal 0.133 ± 0.040 mm/MeV
(right) profiles for individual points actually used to do the fit shown at best fit 0.0905 ± 0.015



Six bins of
momentum-transfer
is a good match
for the resolution.
Some model dependence

Lower figure
is NOT energy transfer
unfolding has the same
pathology as W
and model dependence from
unknown neutron content

Eavail is
KE(p,pi±) + E(π0,e,γ,K)
not neutrons
not nucleon removal energy
depends on detector model
test beam calibrations

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