Model uncertainties in light of MINERvA momentum and energy transfer data

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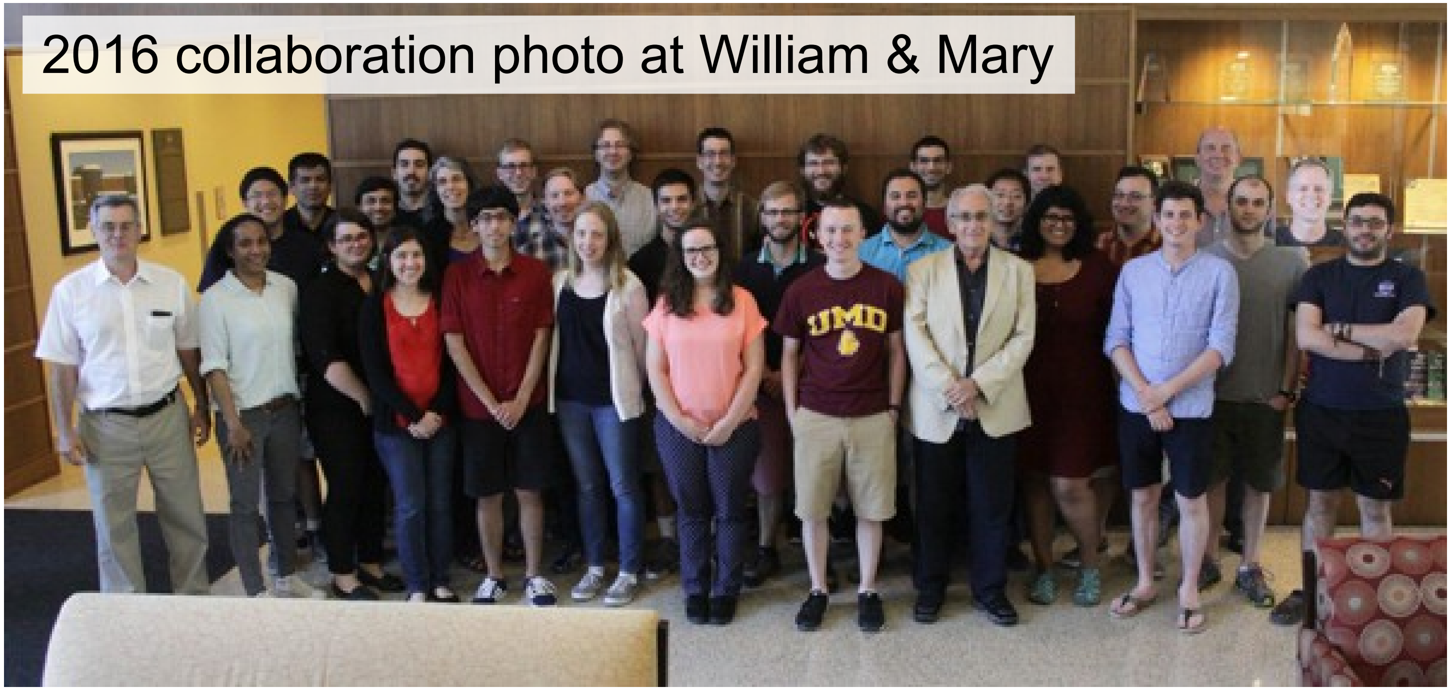
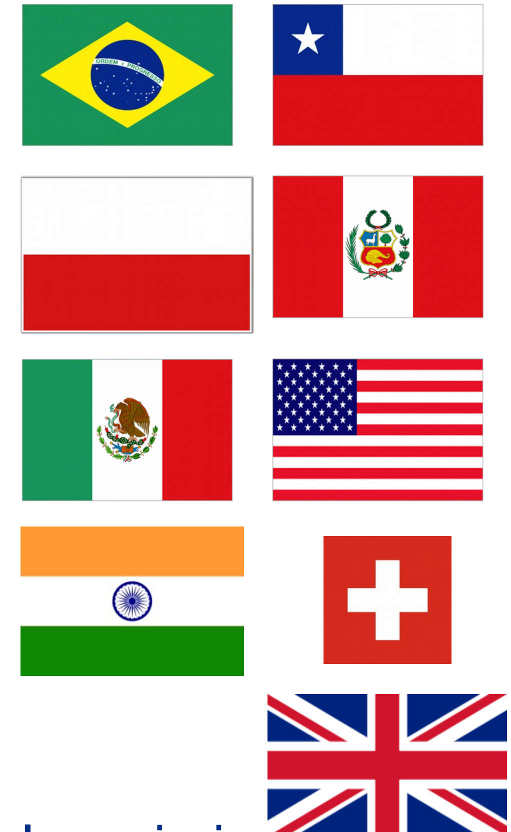
For the
MINERvA collaboration

Saint Surrounded by Three Pi Mesons
Salvador Dali
Figueres, Spain, 1957

Talk at NuInt17, Toronto, June

First of five key elements of MINERvA experiment



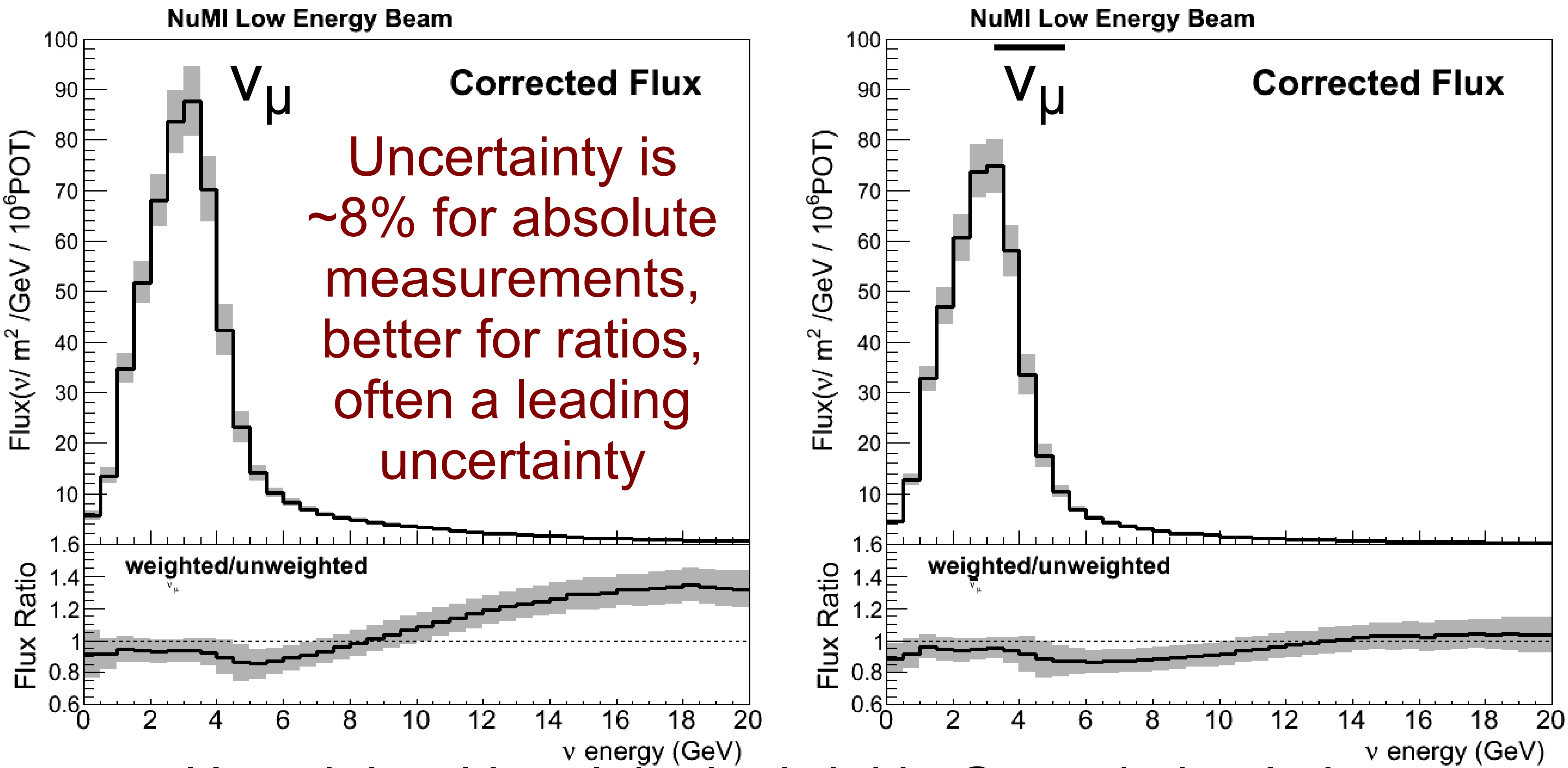


Aligarh Muslim University
Centro Brasileiro de Pesquisas Fisicas
Fermilab
University of Florida
Universite de Geneva
Universidad de Guanajuato
Hampton University
Massachusetts College of Liberal Arts
University of Minnesota at Duluth
University of Mississippi
Otterbein University
Universidad Nacional de Ingenieria
Potificia Universidad Catolica del Peru
University of Pennsylvania
University of Pittsburgh
University of Rochester
Rutgers, the State University of New Jersey
Universidad Tecnica Federico Santa Maria
Tufts University
College of William and Mary
University of Wroclaw

NuMI <3.5 GeV> beam has well characterized flux

L. Aliaga, M. Kordosky, T. Golan, [MINERvA], PRD 94 092005 (2016)

L. Aliaga ! Fermilab URA Outstanding Thesis Award 2016



Unweighted is original, ab-initio Geant4 simulation

Final flux based on hadron production and beam optics constraints

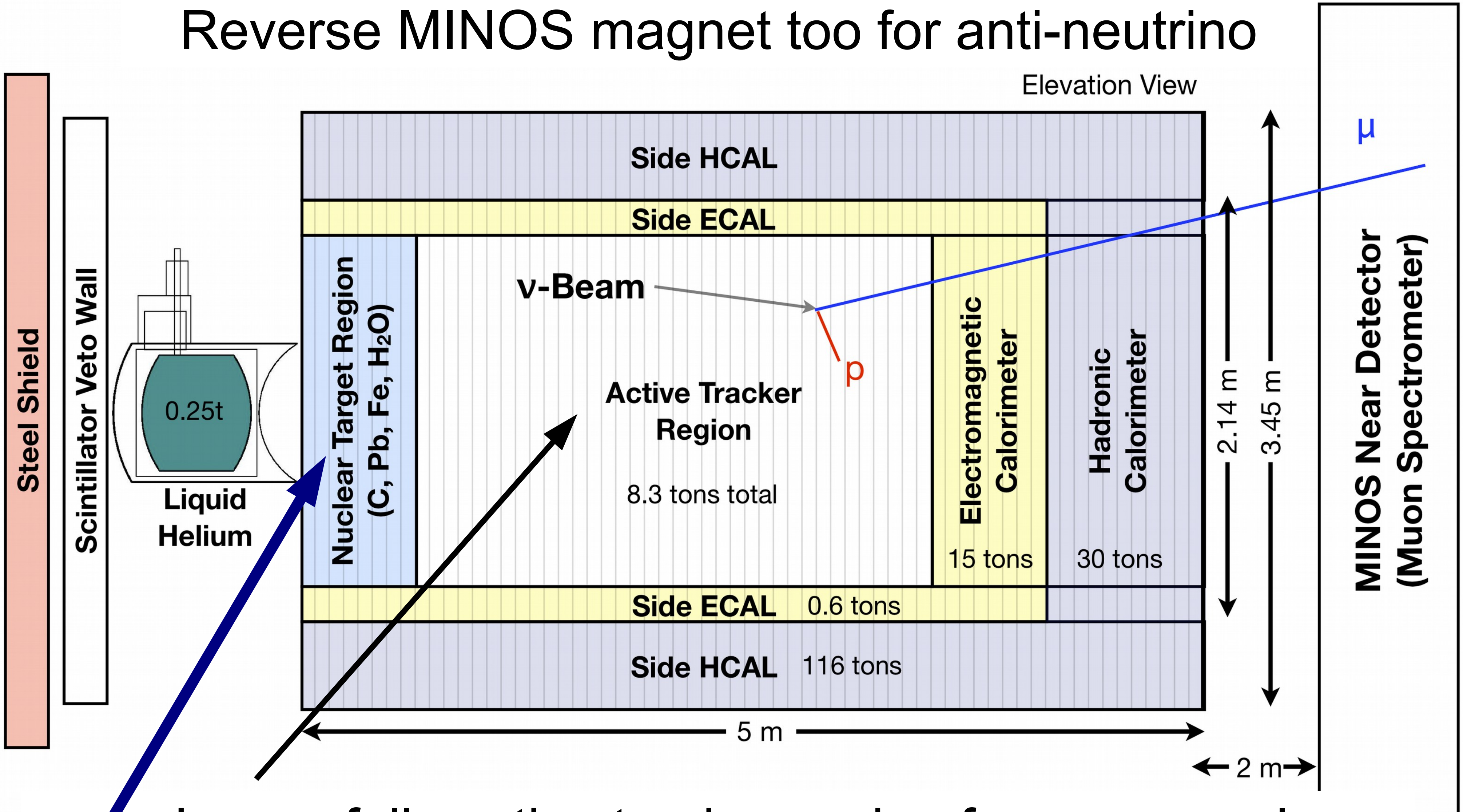
L. Aliaga talk on Monday

Denominator in our cross sections. (Uncertainties cancel for ratios)

MINERvA detector and nuclear target region

Detector is good at both tracking and calorimetry

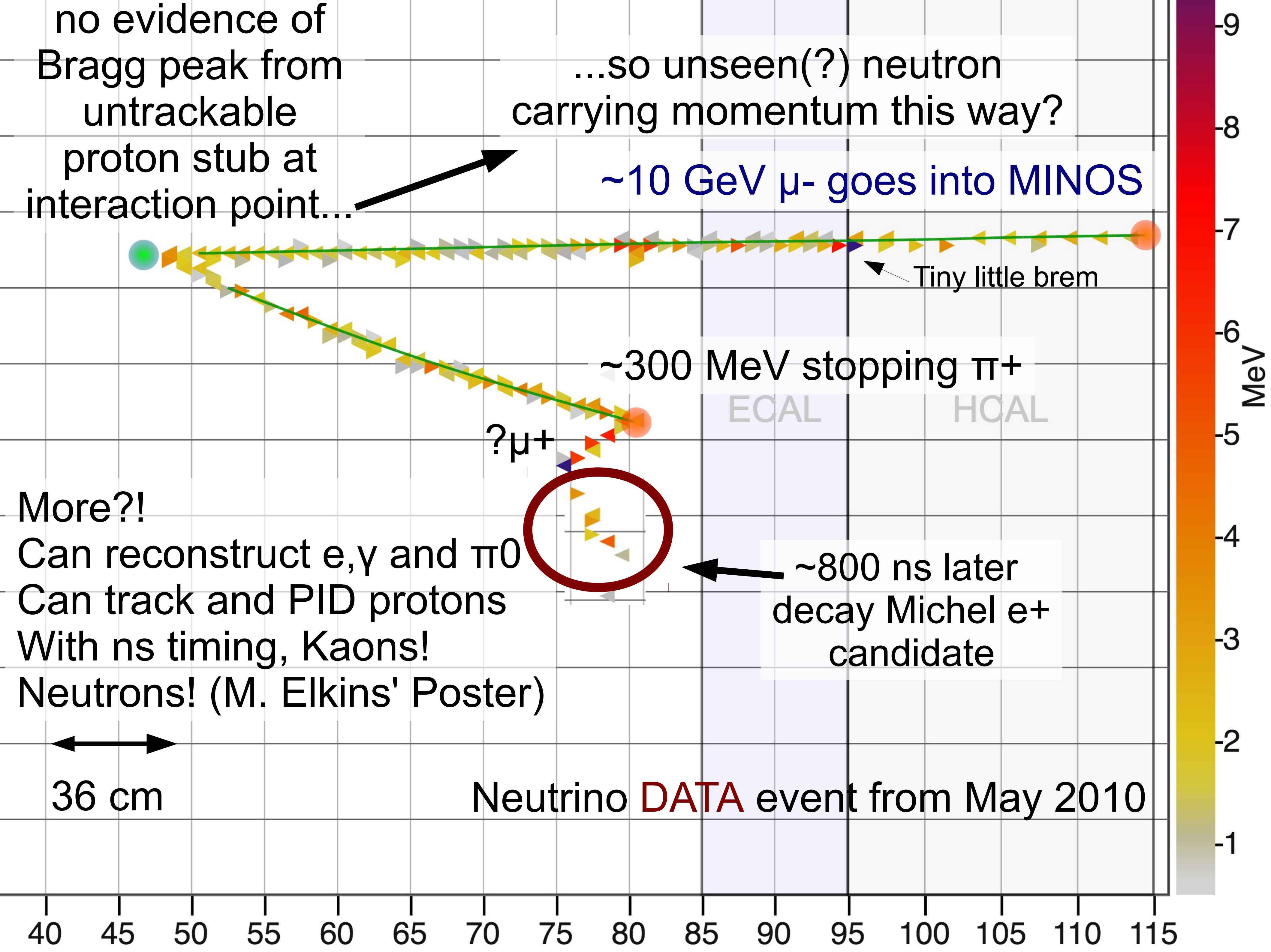
Reverse MINOS magnet too for anti-neutrino



Large, fully active tracker region for some analyses

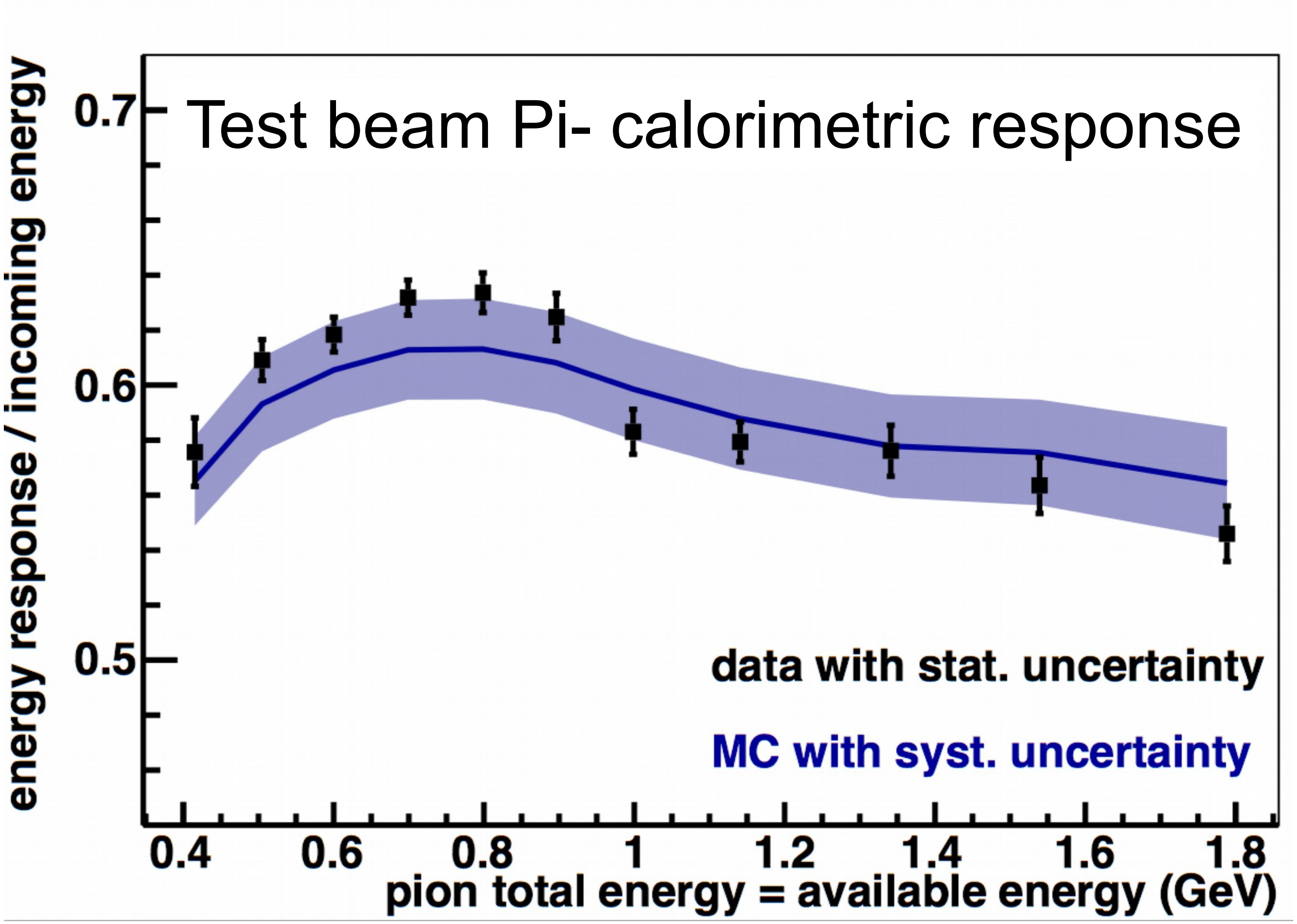
Ratios to passive target region for A-dependent analyses

Usually need μ in MINOS, < ~20 degrees, Enu > 2 GeV


no evidence of Bragg peak from untrackable proton stub at interaction point...
...so unseen(?) neutron carrying momentum this way?
~10 GeV μ- goes into MINOS
Tiny little brem
~300 MeV stopping π+
ECAL
HCAL
?μ+
More?!
Can reconstruct e,γ and π0
Can track and PID protons
With ns timing, Kaons!
Neutrons! (M. Elkins' Poster)
~800 ns later decay Michel e+ candidate
36 cm
Neutrino DATA event from May 2010
MeV
1
2
3
4
5
6
7
8
9
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115

Calorimetry constraints < 2 GeV from test beam data

Constrains Geant4 and Detector calorimetric response
4% for protons, pions < 2 GeV and 3% electrons ~ 0.5 GeV



Resolutions are also well described
(also in-situ constraint from π0 invariant mass peak)

Oscillation experiments and MINERvA q0,q3 data

Want to model the kinematics (QE, 2p2h, Delta)
and the hadron final state (proton, pion, neutron)
and have well justified and targeted model systematics

Goal of the whole MINERvA program (many talks and posters)
this talk, one measurement as an example

Rodrigues, Demgen, Miltenberger, [MINERvA]
PRL 116 071802 (2016)
exposes all these features at once

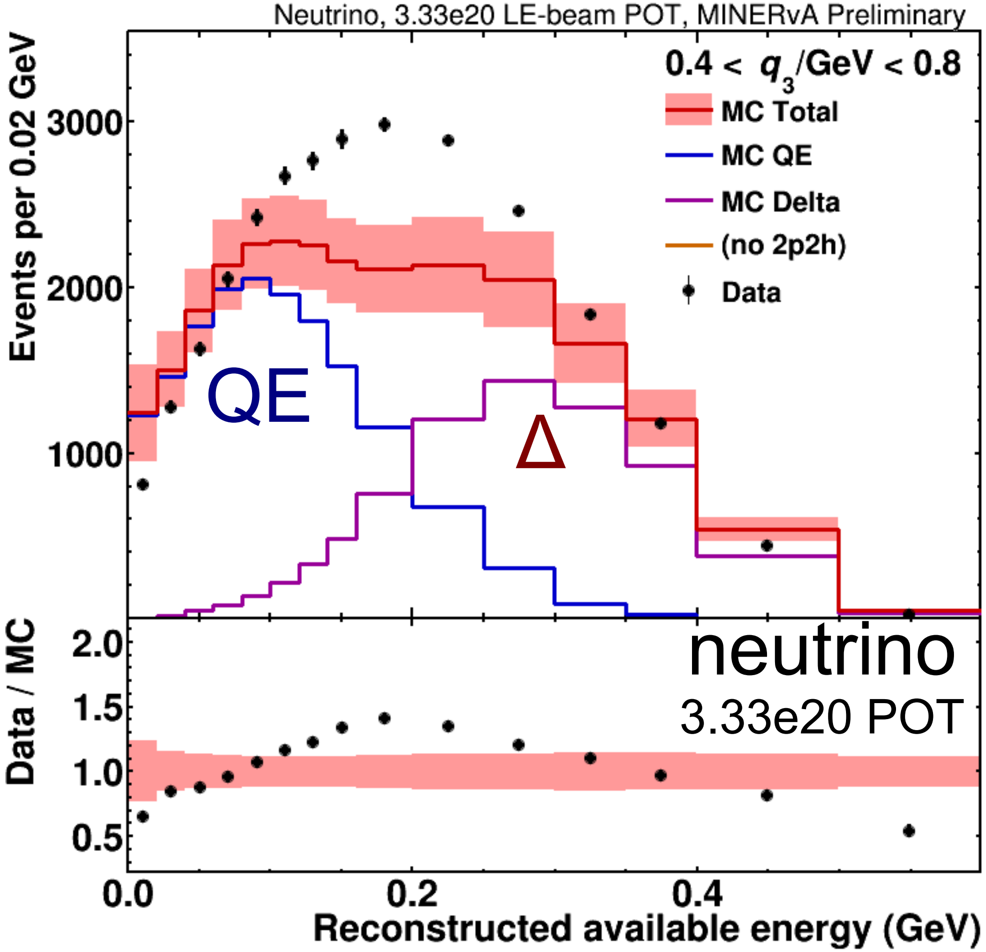
(c)

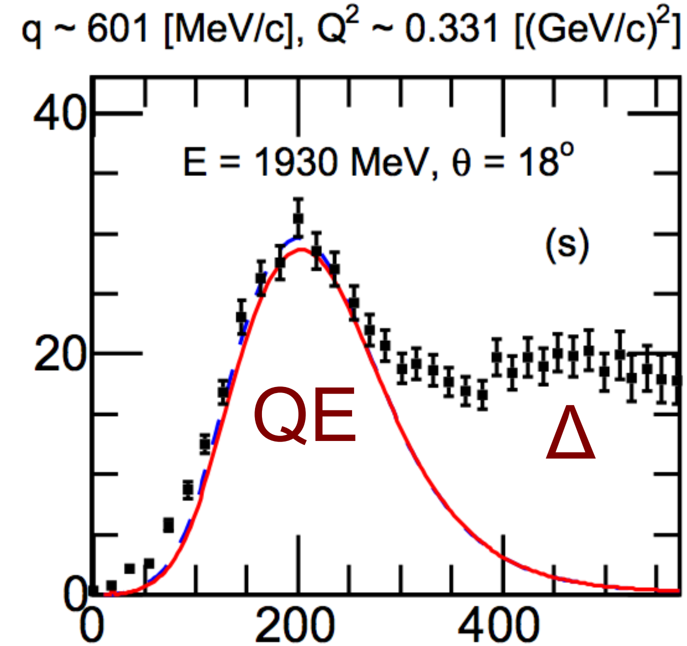
adorable unfolded kitten from Glen Cowan's Statistical Data Analysis book says...

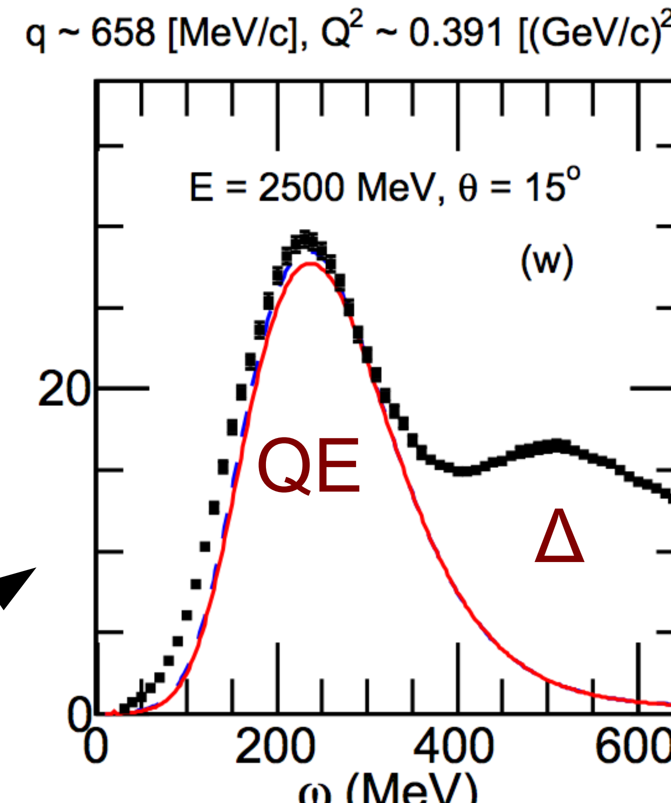
...to do CP violation probably need this for both neutrino and anti-neutrino

MINERvA Enu ~3.5 GeV

Inclusive, reco q ~ 600 MeV







Rodrigues, Demgen, Miltenberger et al. [MINERvA] PRL 116 071802

GENIE Fermi Gas, no RPA, no 2p2h

(e,e') study Pandey, Jachowicz, Van Cuyck, Ryckebusch, Martini, PRC 92 024606 (2015)

Technical slide: steps to calorimetric reconstruction

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 $E_{visible}$.

A. turn $E_{visible}$ into $E_{available}$ using detector MC, discounts neutrons
$E_{available}$ = Proton KE, $\pi^\pm$ KE, π^0, e, γ energy (plus heavier particles)
little neutrino model dependence (some anti-nu model dependence)

B. Use MC and correct to energy transfer q_0 (= E_{had} = ν = ω)
(unbiased, but correction has some dependence on neutrino model)

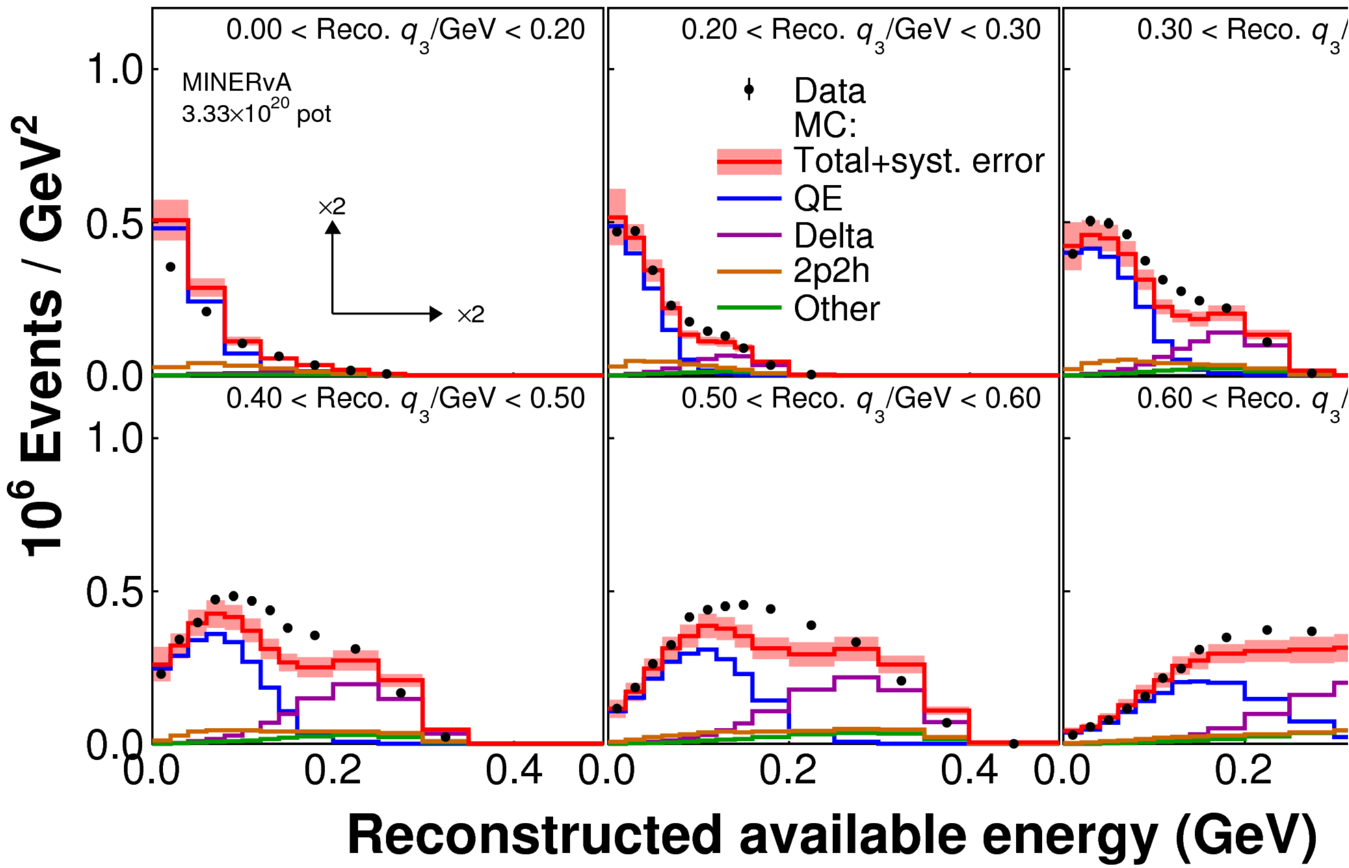
B. Estimated neutrino energy $E_\nu = E_\mu + q_0$

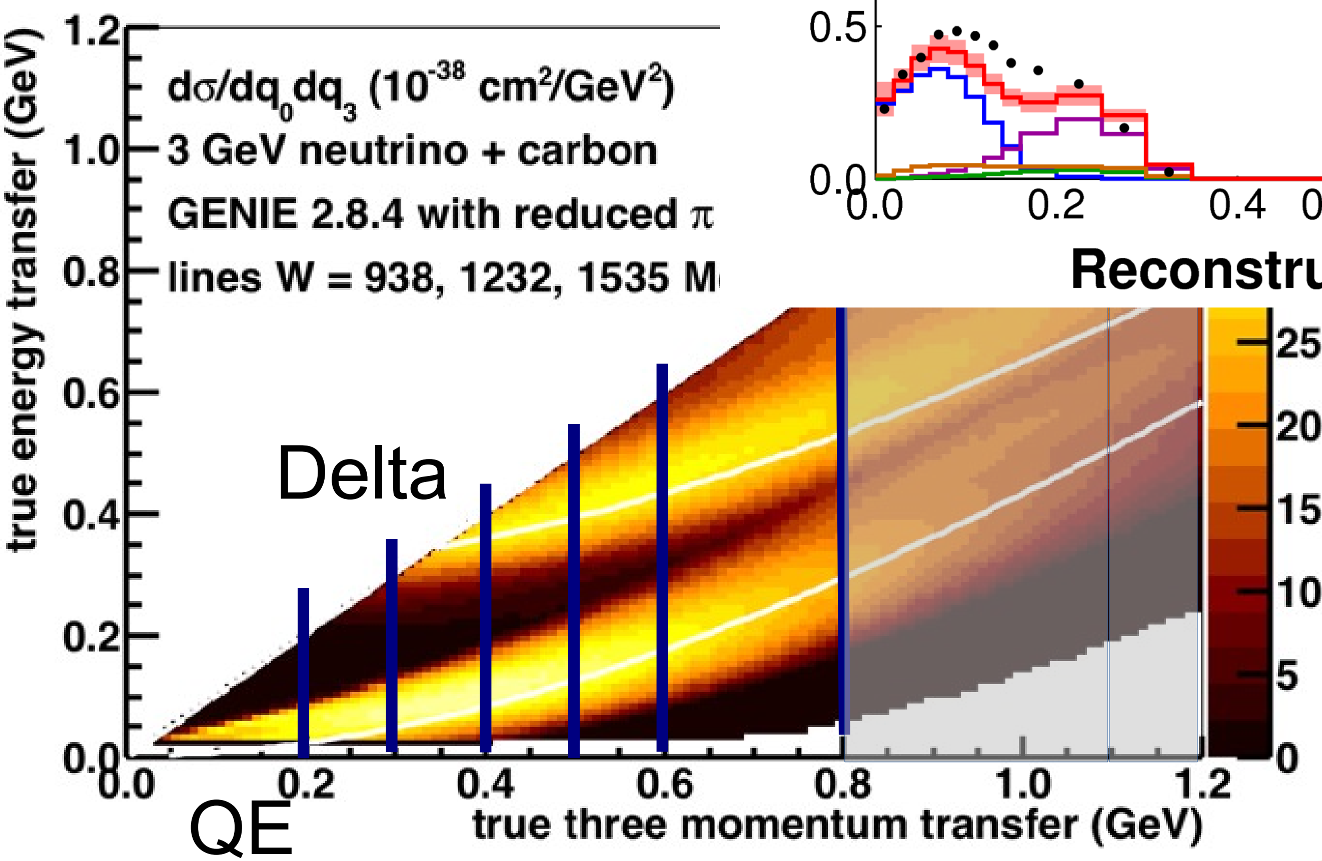
C. Estimated four-momentum $Q^2 = 2 E_\nu (E_\mu - p_\mu \cos\theta_\mu) - M_\mu^2$

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

Analysis goal: (e,e')-like detail in slices of q3

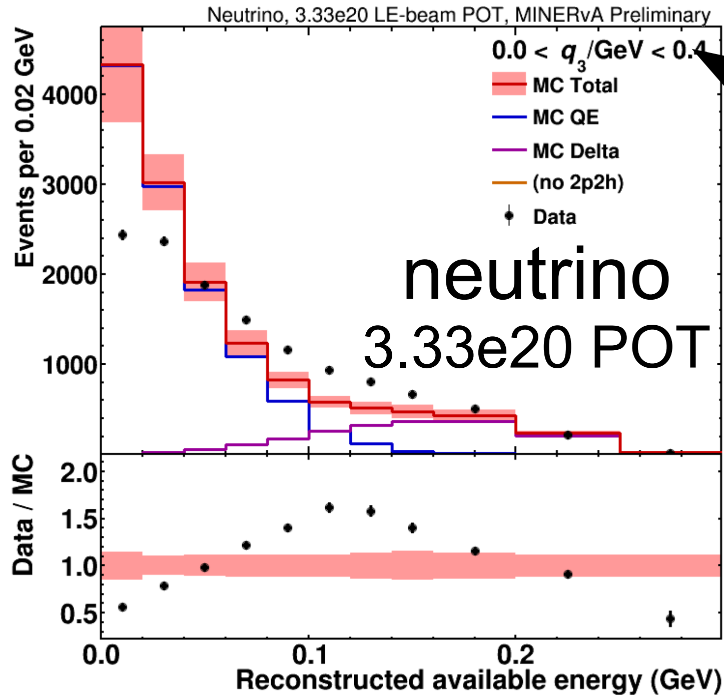
but use something more observable, detector-centric, less model dependent Eavail instead of true energy transfer

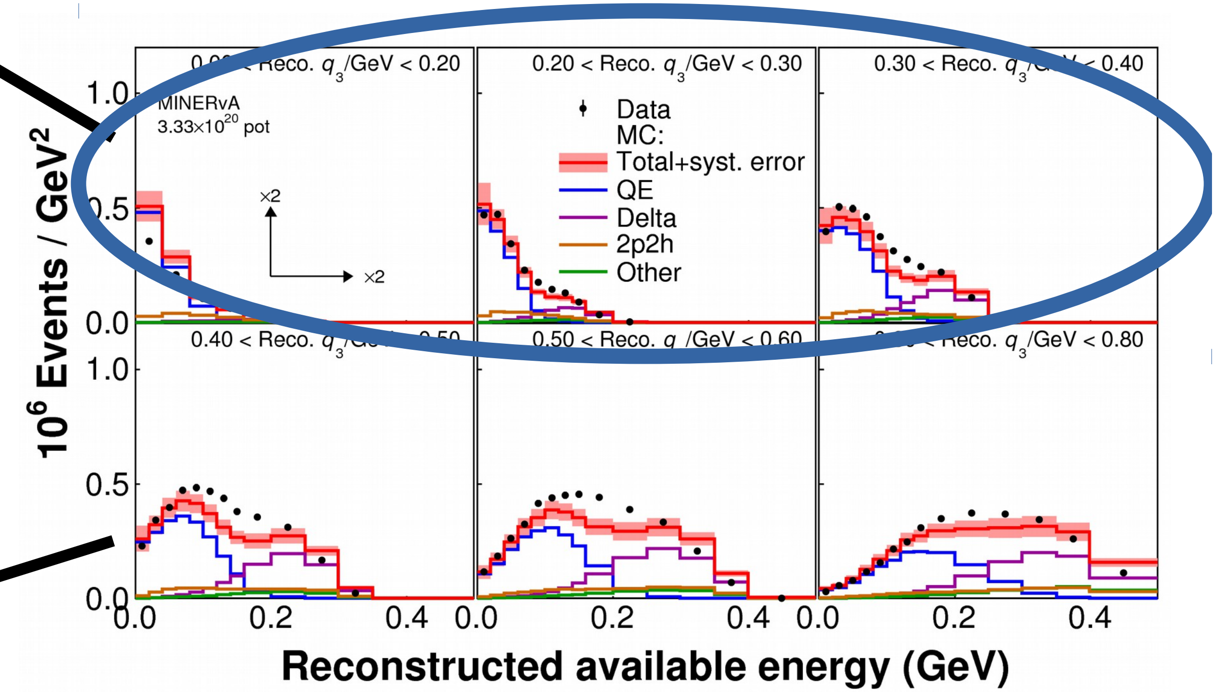


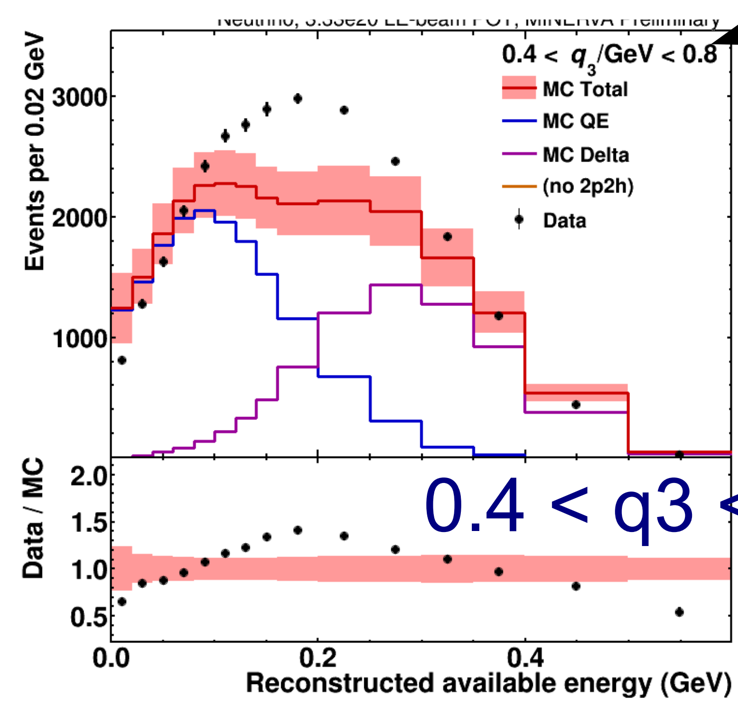


This cross section includes all GENIE nu+C processes, except 2p2h

0.0 < q3 < 0.4 GeV no RPA, no 2p2h







0.4 < q3 < 0.8 GeV

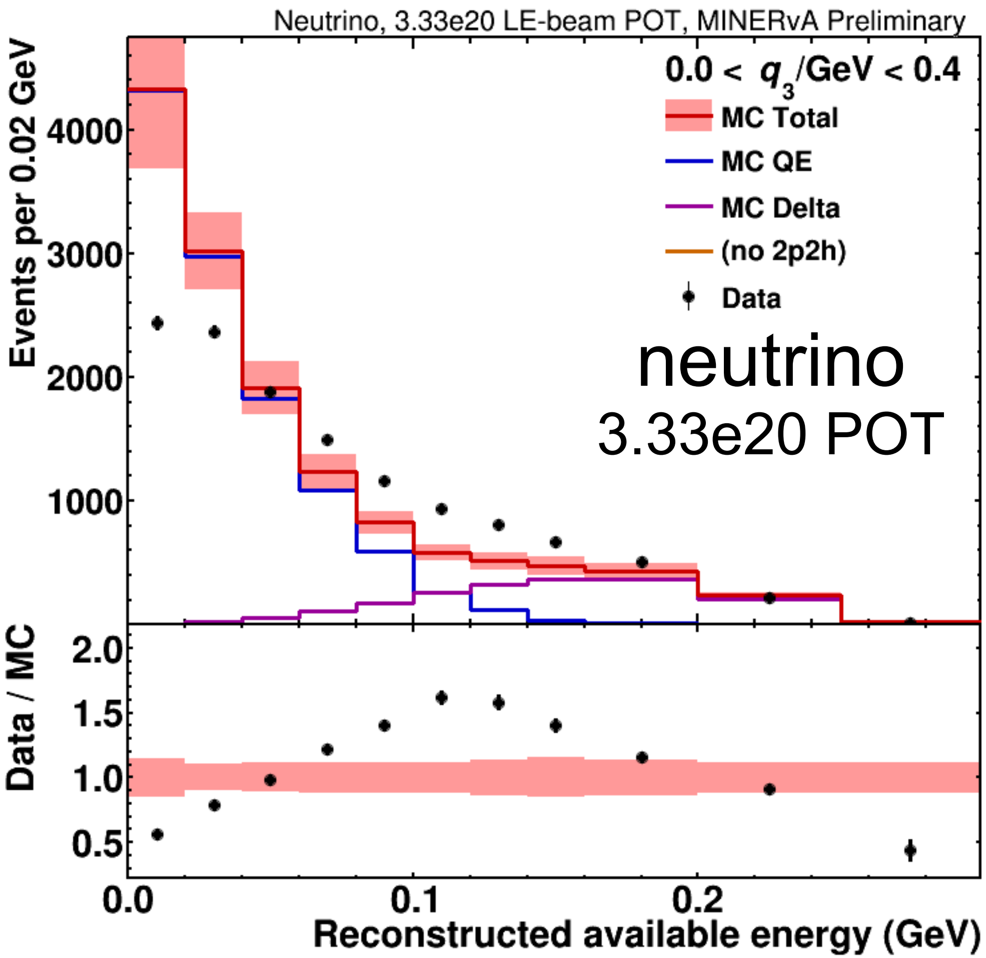
Reco data and chisquares (and unfolded cross sections) are from distributions made with resolution-driven six bins condensed into just two plots good for physics interpretation

Rodrigues, Demgen, Miltenberger et al. [MINERvA] PRL 116 071802

Can put one or two on a slide nice and big, flipbook models

q3 < 0.4 GeV, GENIE, pion base, no RPA, no 2p2h

X2 = 407 for 21 bins



Flipbook order
GENIE, no RPA, no 2p2h
yes RPA, no 2p2h
yes RPA, yes 2p2h
yes RPA, yes "tuned" 2p2h

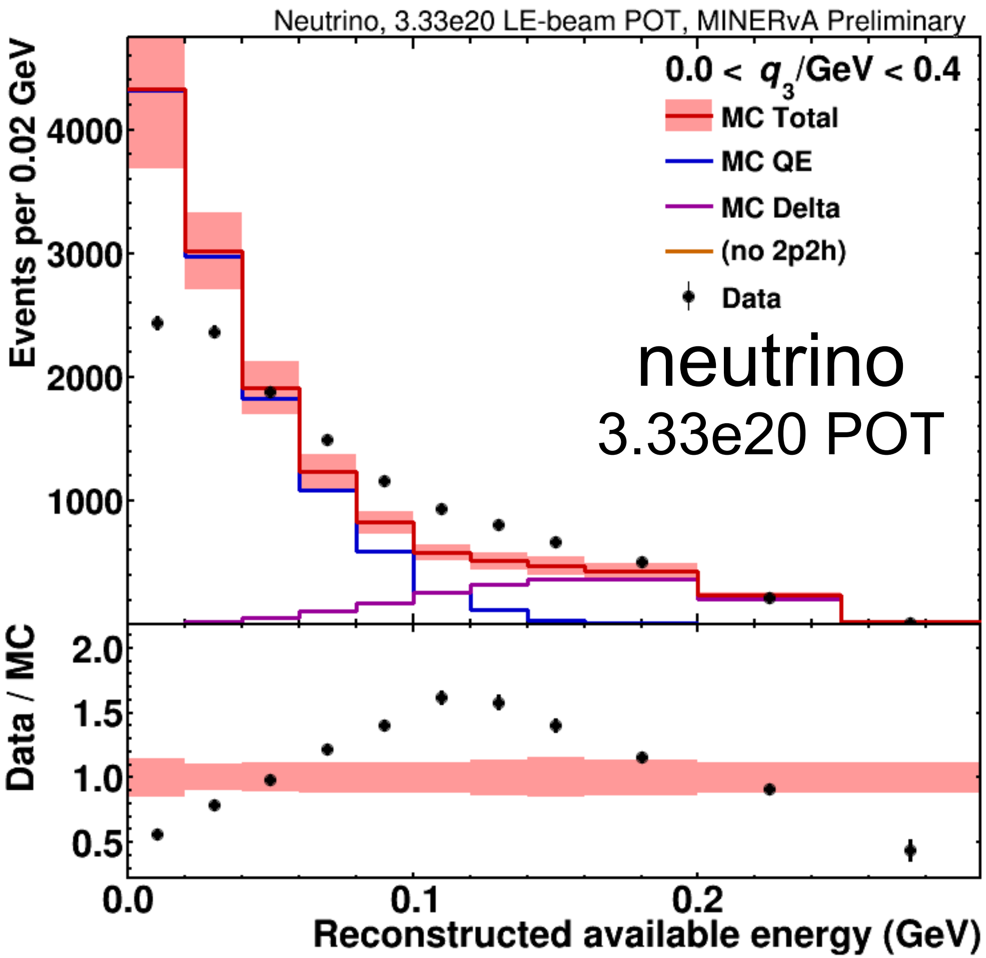
fun fact! stat errors will often be too small to see!

Chisquare with systematics is three q3 panels on prev. slide

What to look for:
Does the ratio look more flat ? Closer to 1.0 + error band?
Is the chisquare better? Can a different model do better?
Did the model change affect QE, Dip, or Delta region?

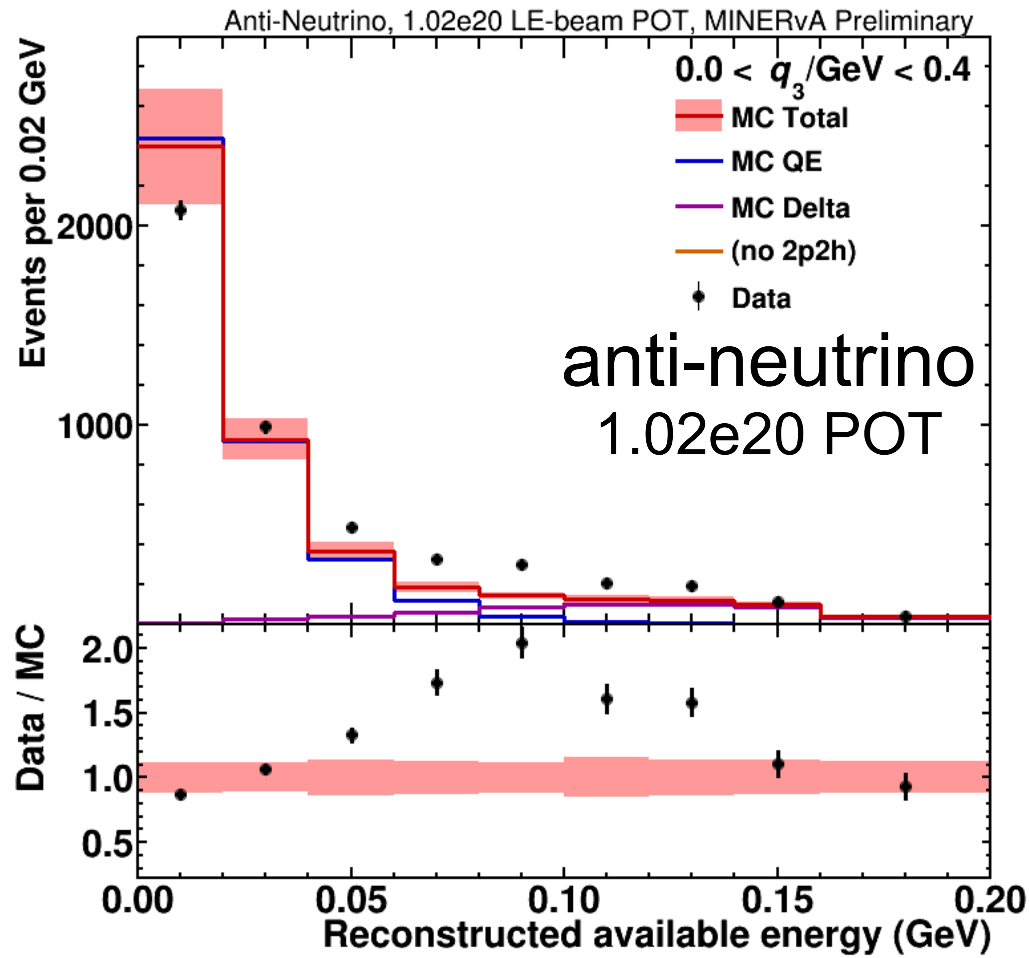
q3 < 0.4 GeV, GENIE, pion base, no RPA, no 2p2h

X2 = 407 for 21 bins



Rodrigues, Demgen, Miltenberger et al. [MINERvA] PRL 116 071802

X2 = 245 for 19 bins

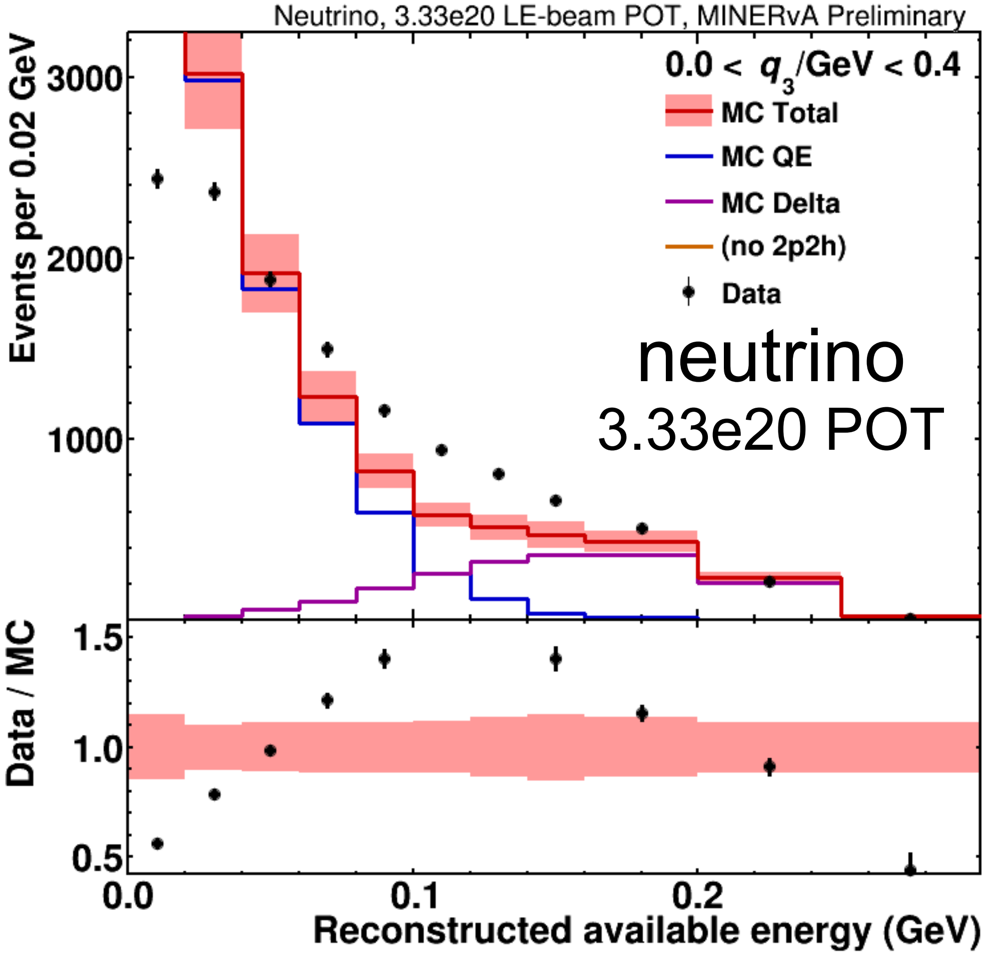


new for NuInt17
equivalent anti-neutrino distribution
neutrons dominate final state

Next slide is same data and model, just zoomed in to see detail

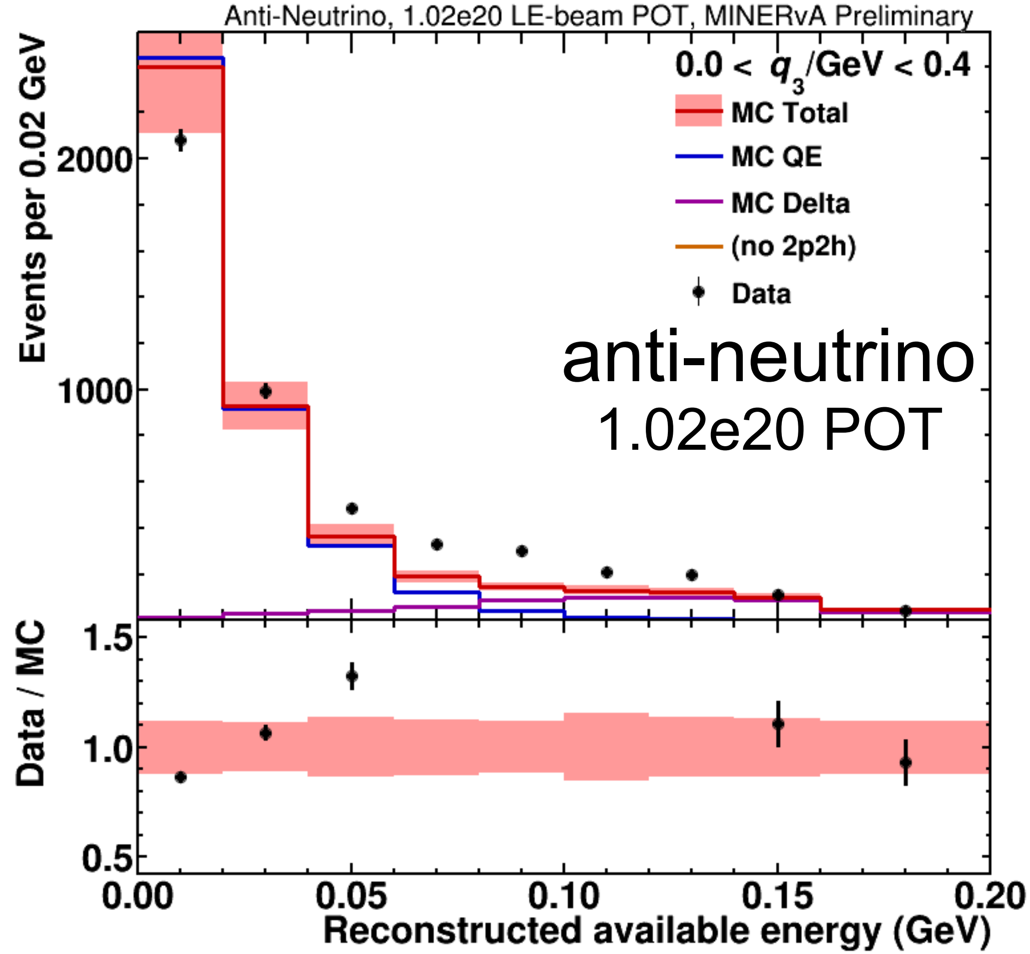
GENIE, pion base, no RPA, no 2p2h, zoom Y axis

X2 = 407 for 21 bins



Rodrigues, Demgen, Miltenberger et al. [MINERvA] PRL 116 071802

X2 = 245 for 19 bins

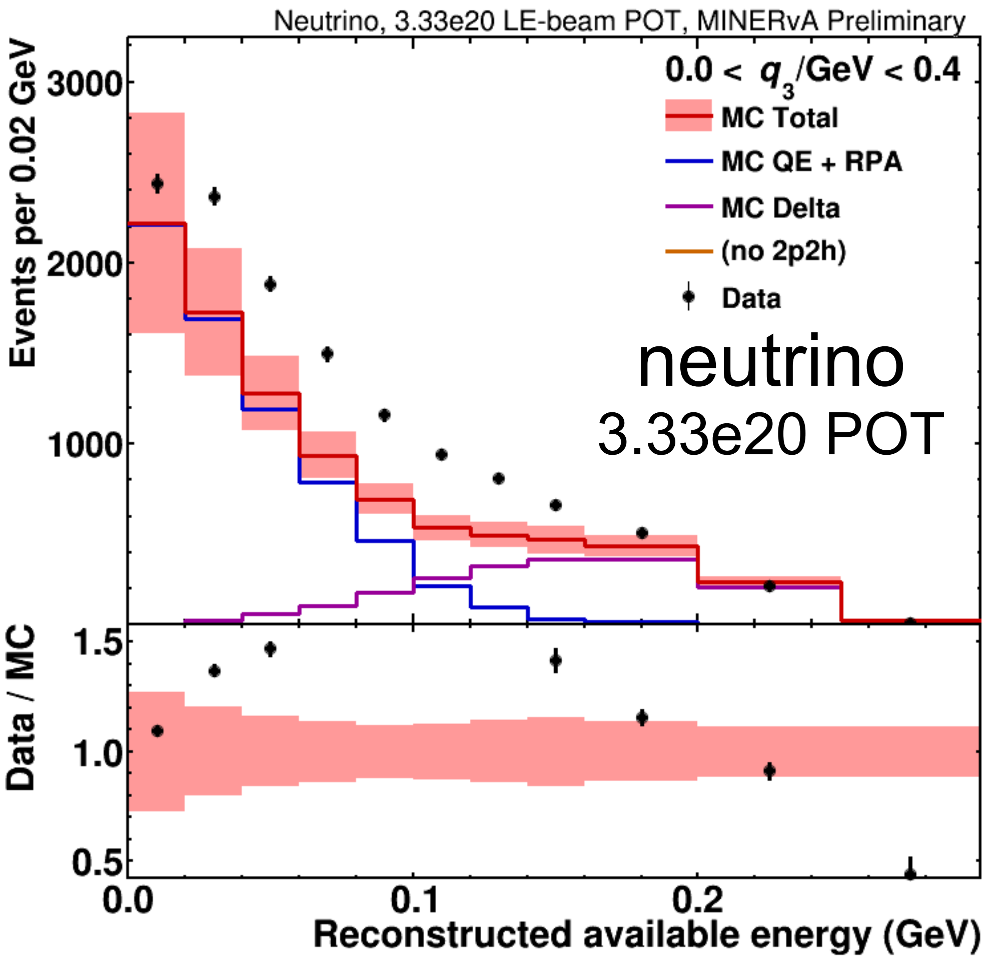


new for NuInt17 equivalent anti-neutrino distribution

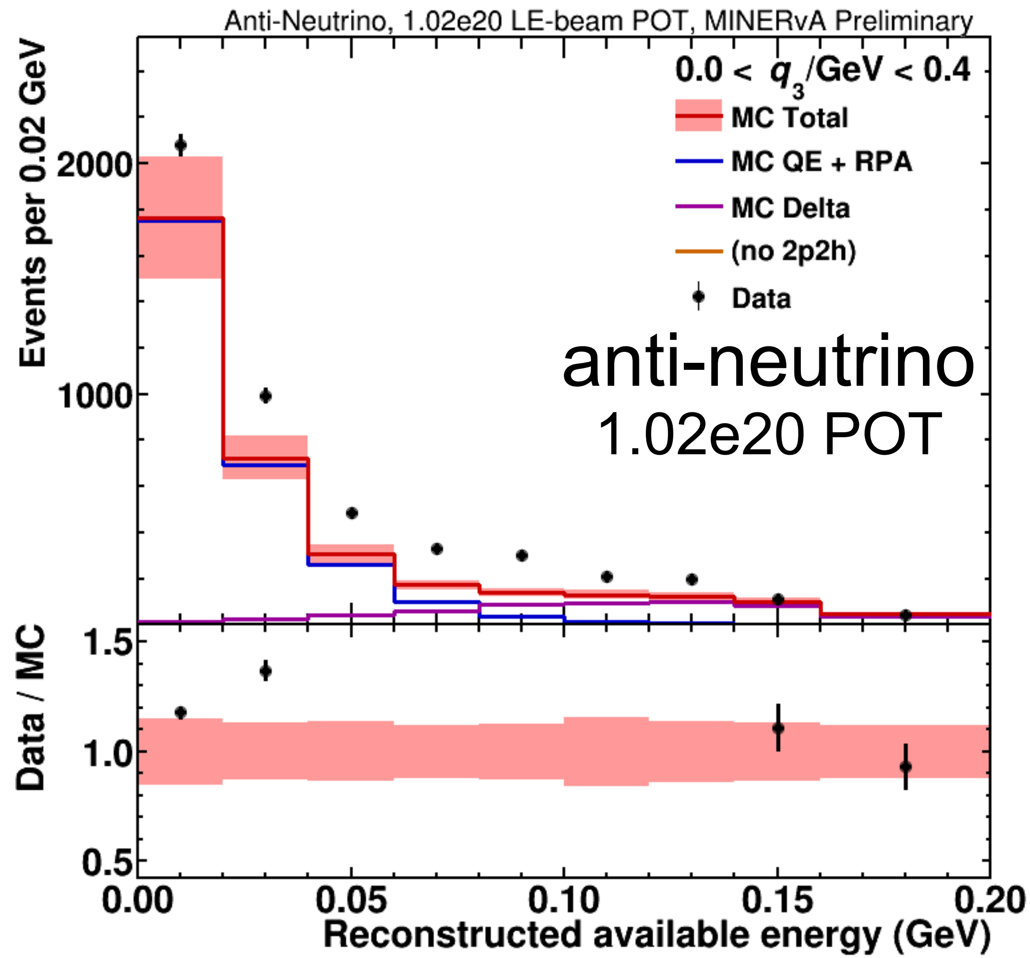
Same as the previous slide, but zoomed in.
Budget 20 seconds each, two comments per slide,
take questions at the end (in about four minutes).

GENIE, pion base, RPA, no 2p2h

X2 = 227 for 21 bins



X2 = 237 for 19 bins

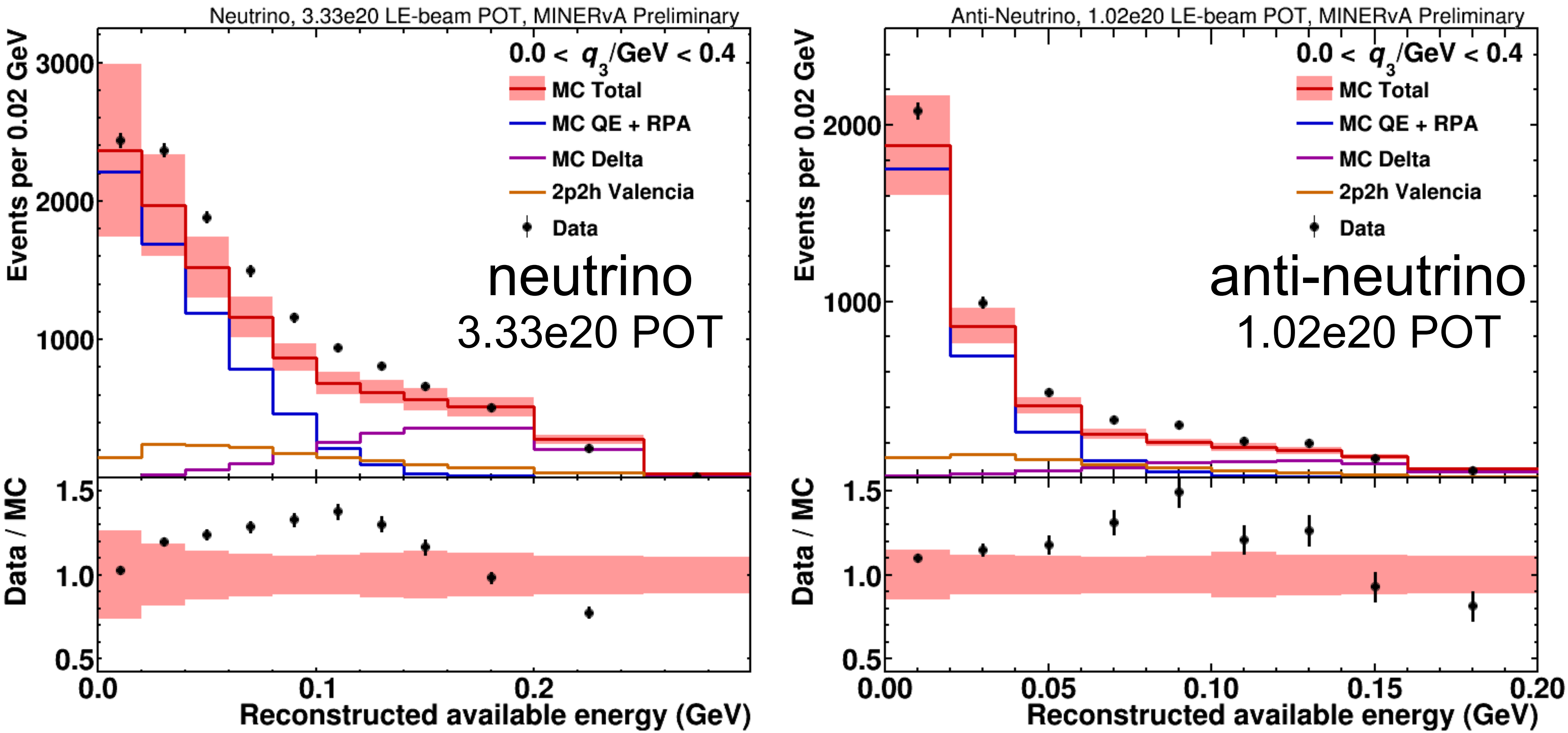


Add (updated) Valencia RPA weight and model error band

Valverde, Amaro, Nieves PLB 638 (2006) 325 with unpub. followup by F. Sanchez plus muon capture uncertainty and implementation R. Gran, arXiv:1705.02932

GENIE, Pion base, RPA, Valencia 2p2h

X2 = 138 for 21 bins | X2 = 84 for 19 bins



Add Valencia 2p2h, improves the dip region

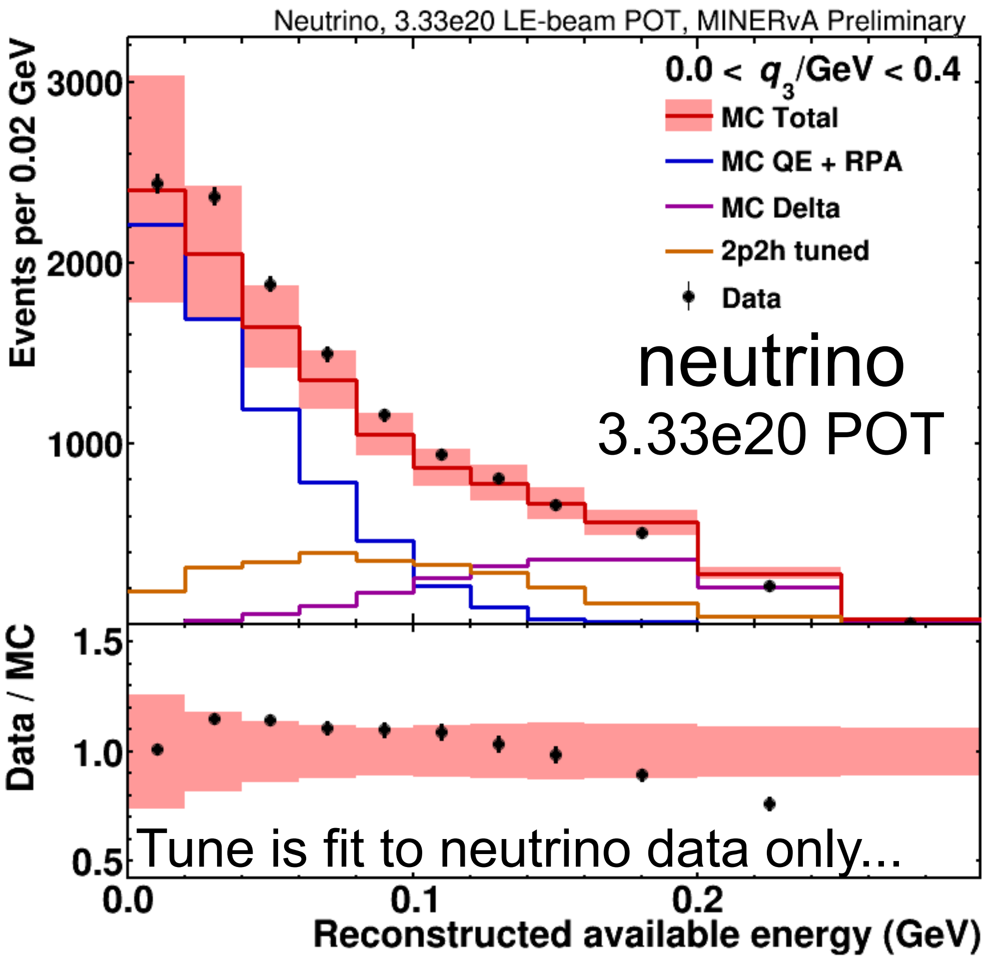
Nieves, Ruiz Simo, Vicente Vacas PRC83 (2011) 045501

and R.G., Nieves, Sanchez, Vicente Vacas PRD 88 (2013) 113007

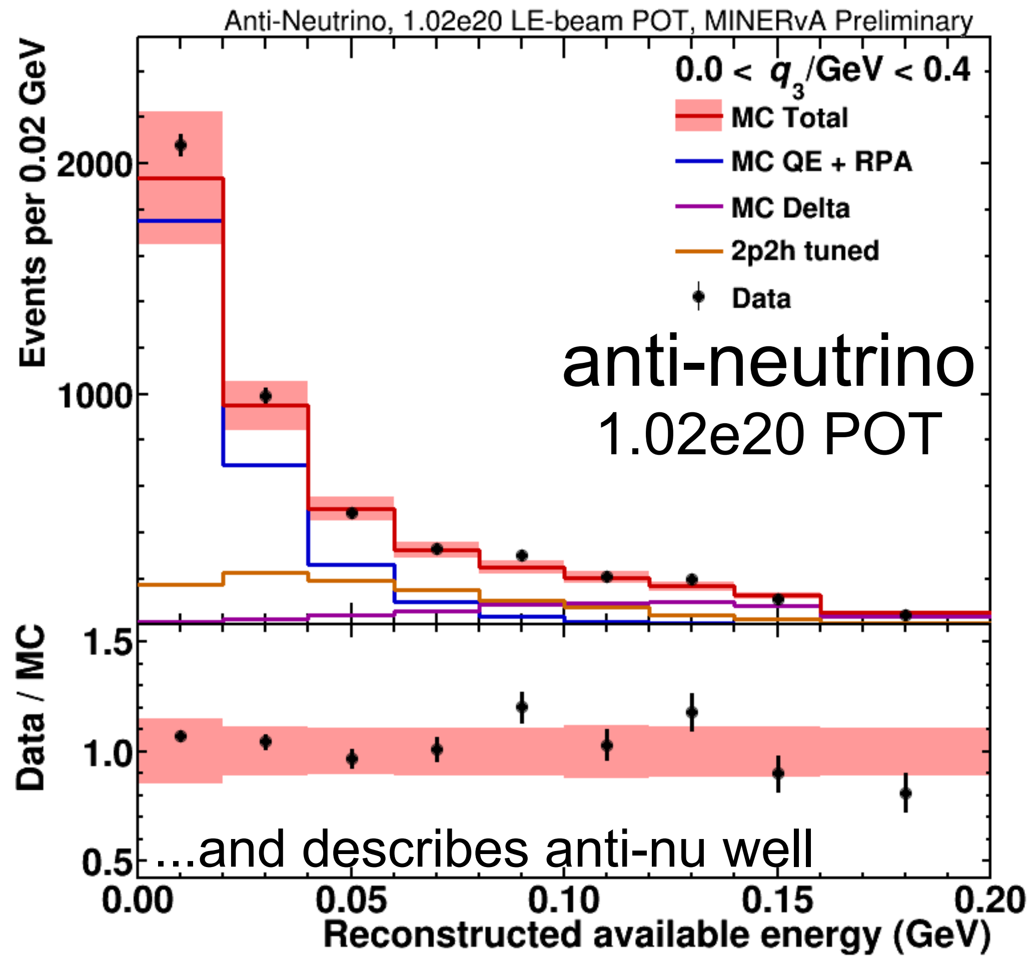
Same code as in Genie 2.12.6: J. Schwehr, R.G., D. Cherdack, arXiv:1705.02932

GENIE, Pion base, RPA, 2017 Tuned 2p2h

X2 = 76 for 21 bins



X2 = 50 for 19 bins



New: weighting up the 2p2h events with a 2D Gaussian weight

this base tune designed to empirically "Fill in" the dip region not whole kinematic range. Adds ~50% overall, but x2 in dip region

More on this in upcoming slides, and D. Ruterbories poster

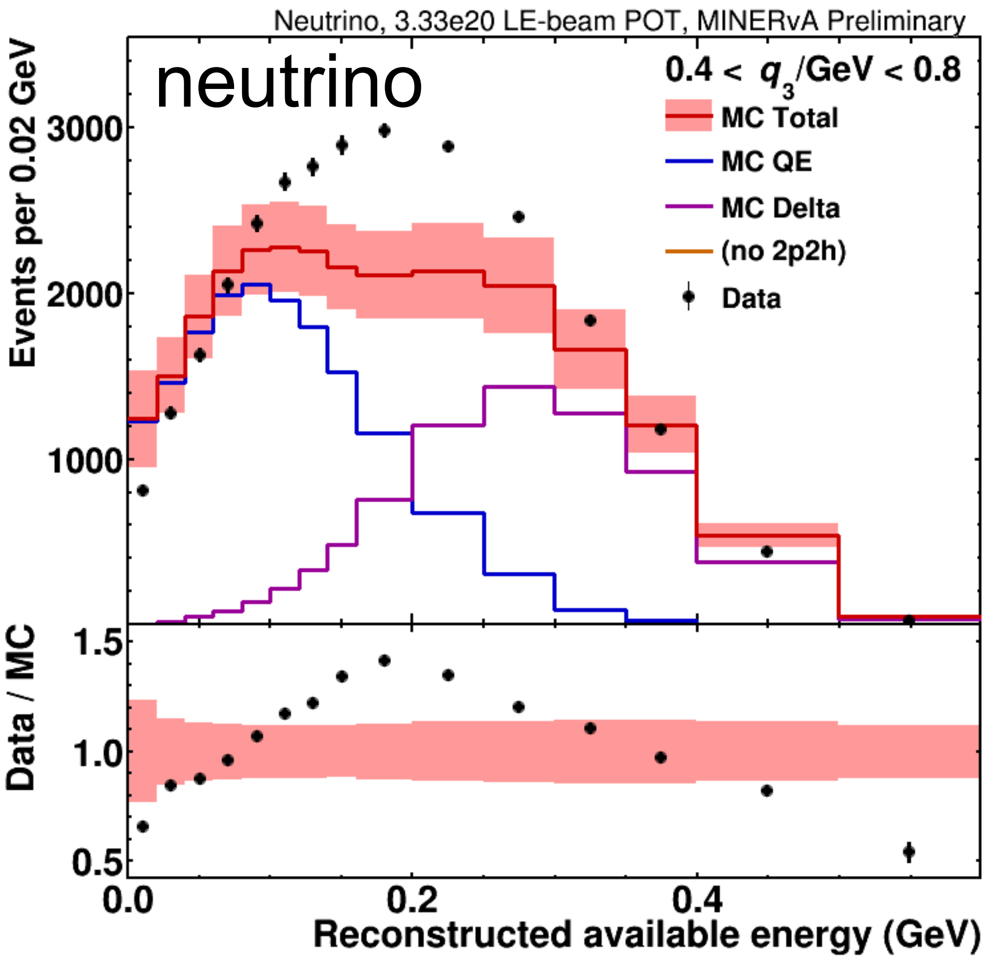
Those model elements
described the event rate
and the hadron spectrum
at the 10% level
up to the Delta peak!
(despite radically different neutron content)

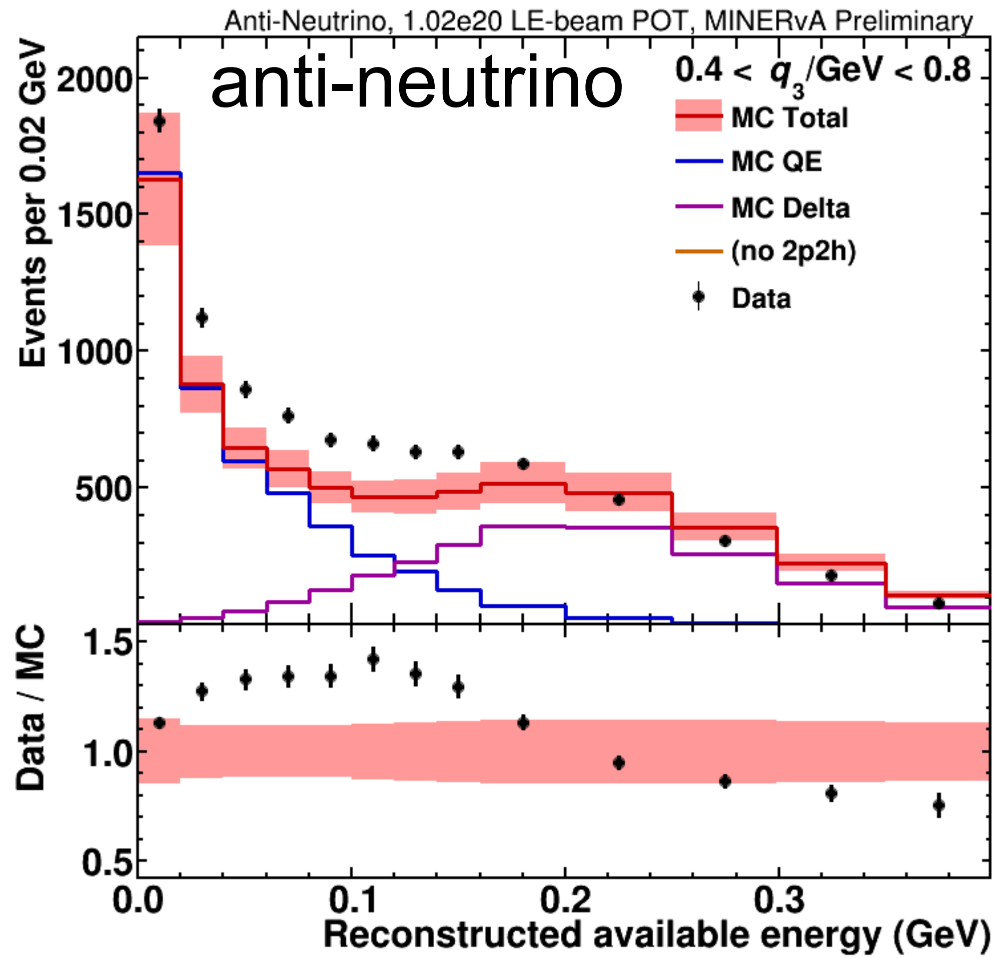
Lets do it again
$0.4 <$ reco q3 < 0.8 GeV

GENIE, pion base, no RPA, no 2p2h

X2 = 277 for 40 bins

X2 = 172 for 37 bins

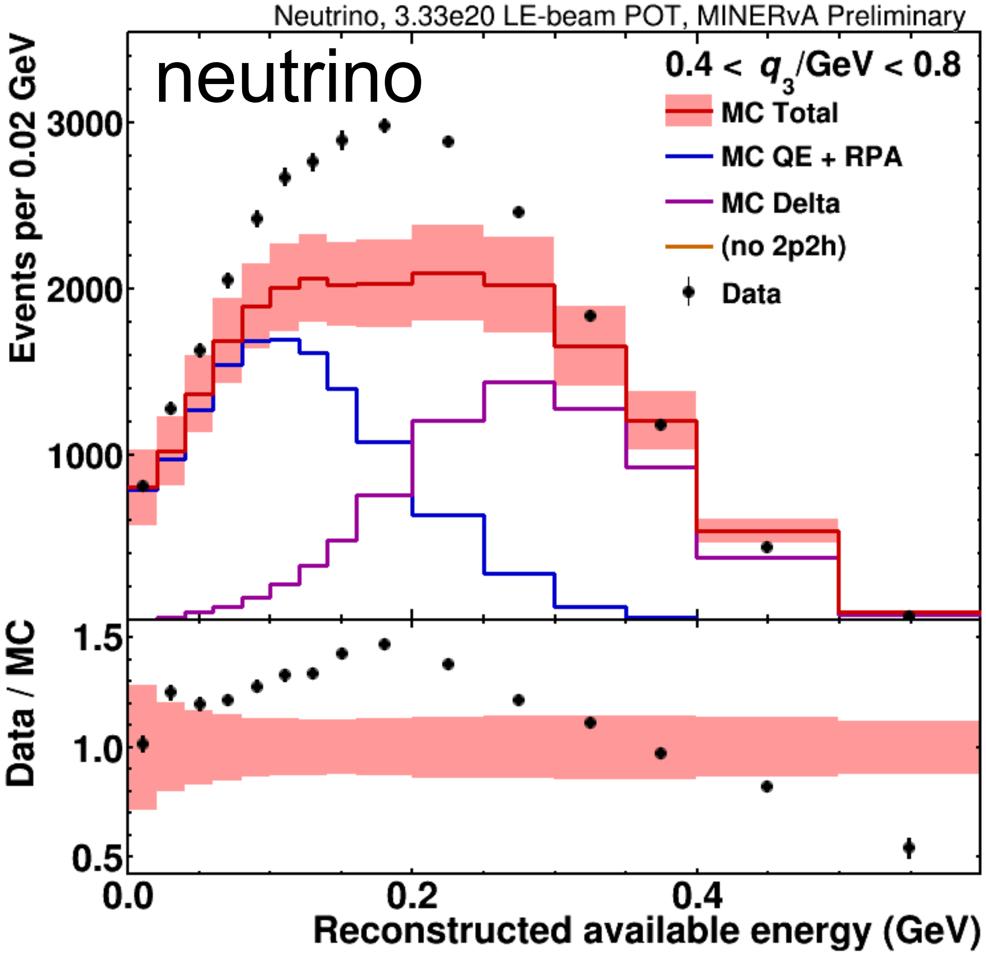


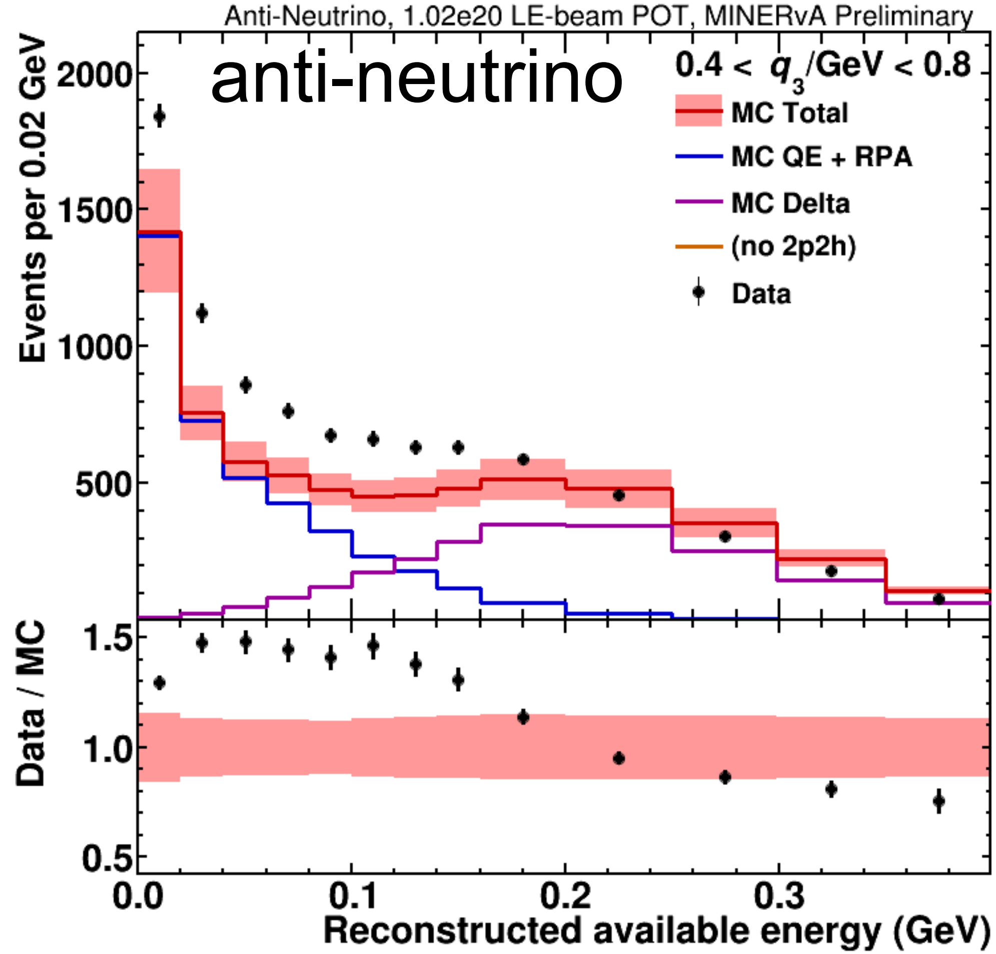


Don't need the wider y axis for this q3 range.
The neutron final states even more obviously cause high population in the first anti-neutrino bin.
discrepancies have same structure as at lower q3

GENIE, pion base, RPA, no 2p2h

X2 = 247 for 40 bins　　　X2 = 131 for 37 bins





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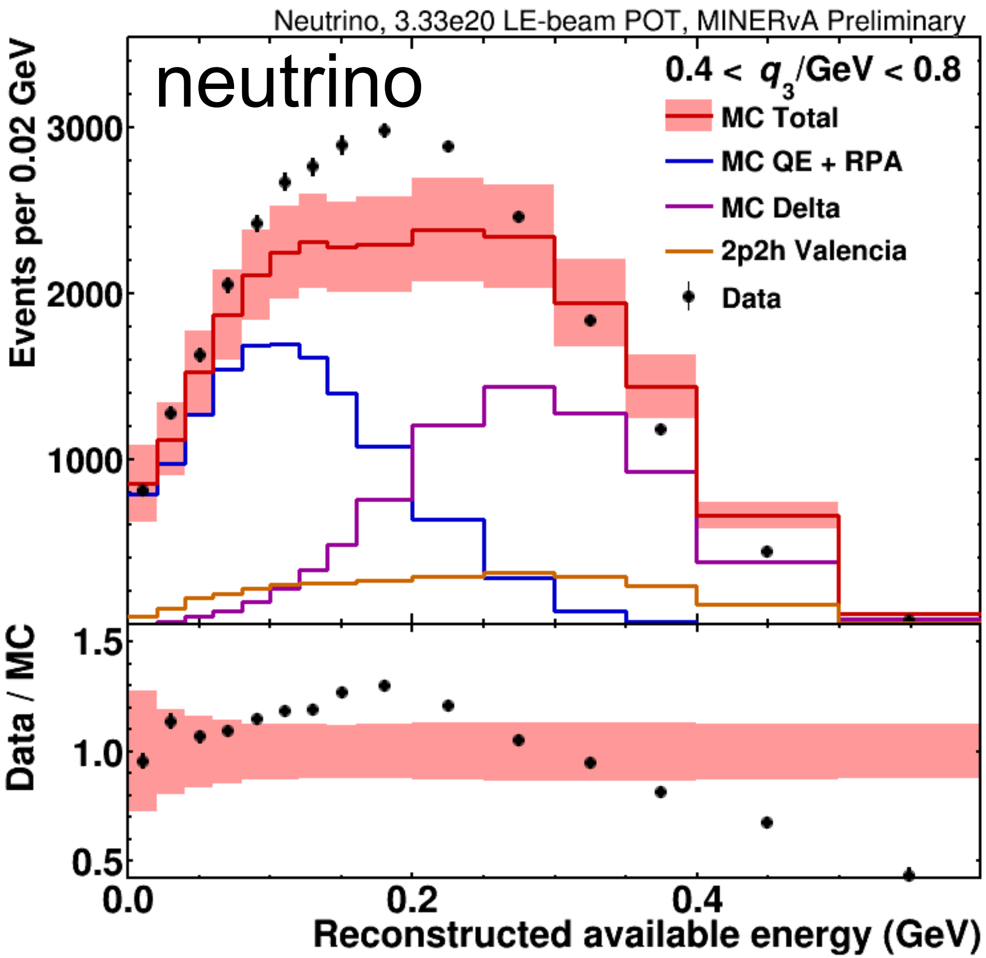
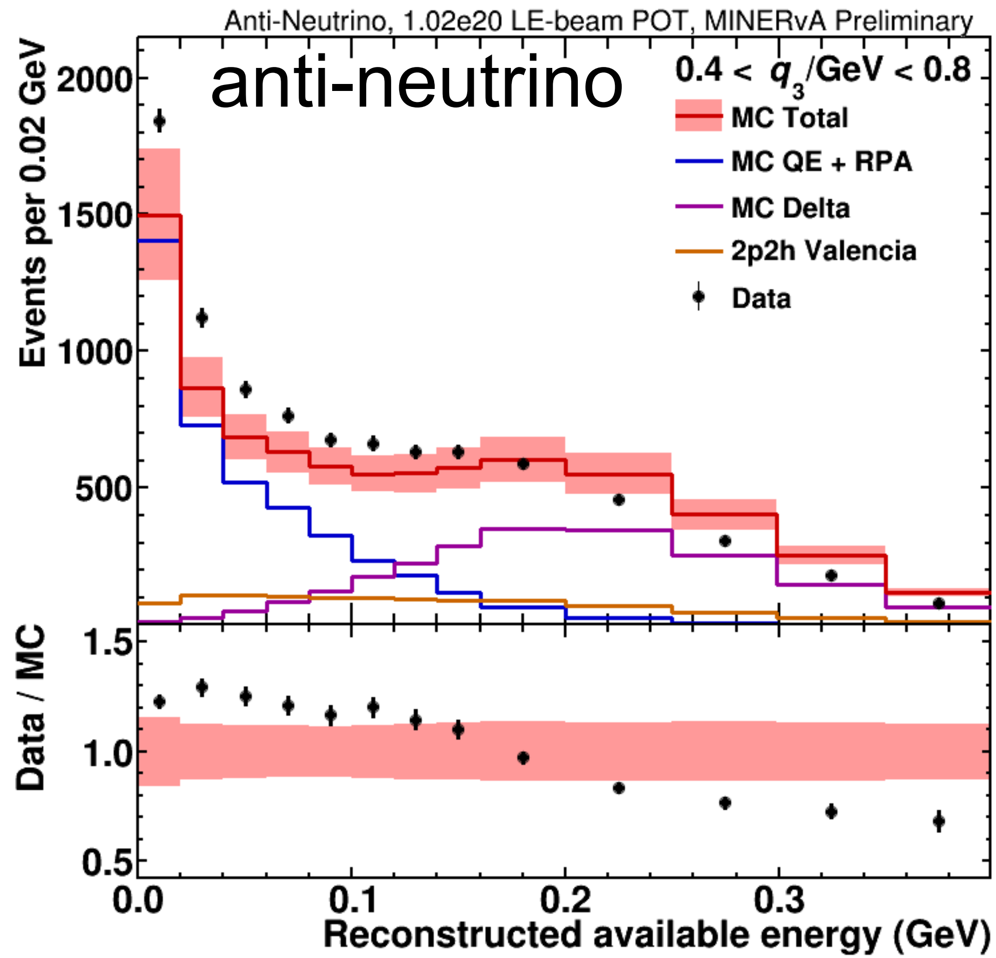
Valverde, Amaro, Nieves PLB 638 (2006) 325 with unp. followup by F. Sanchez plus muon capture uncertainty and implementation R. Gran, arXiv:1705.02932

GENIE, Pion base, RPA, Valencia 2p2h

X2 = 295 for 40 bins

X2 = 101 for 37 bins



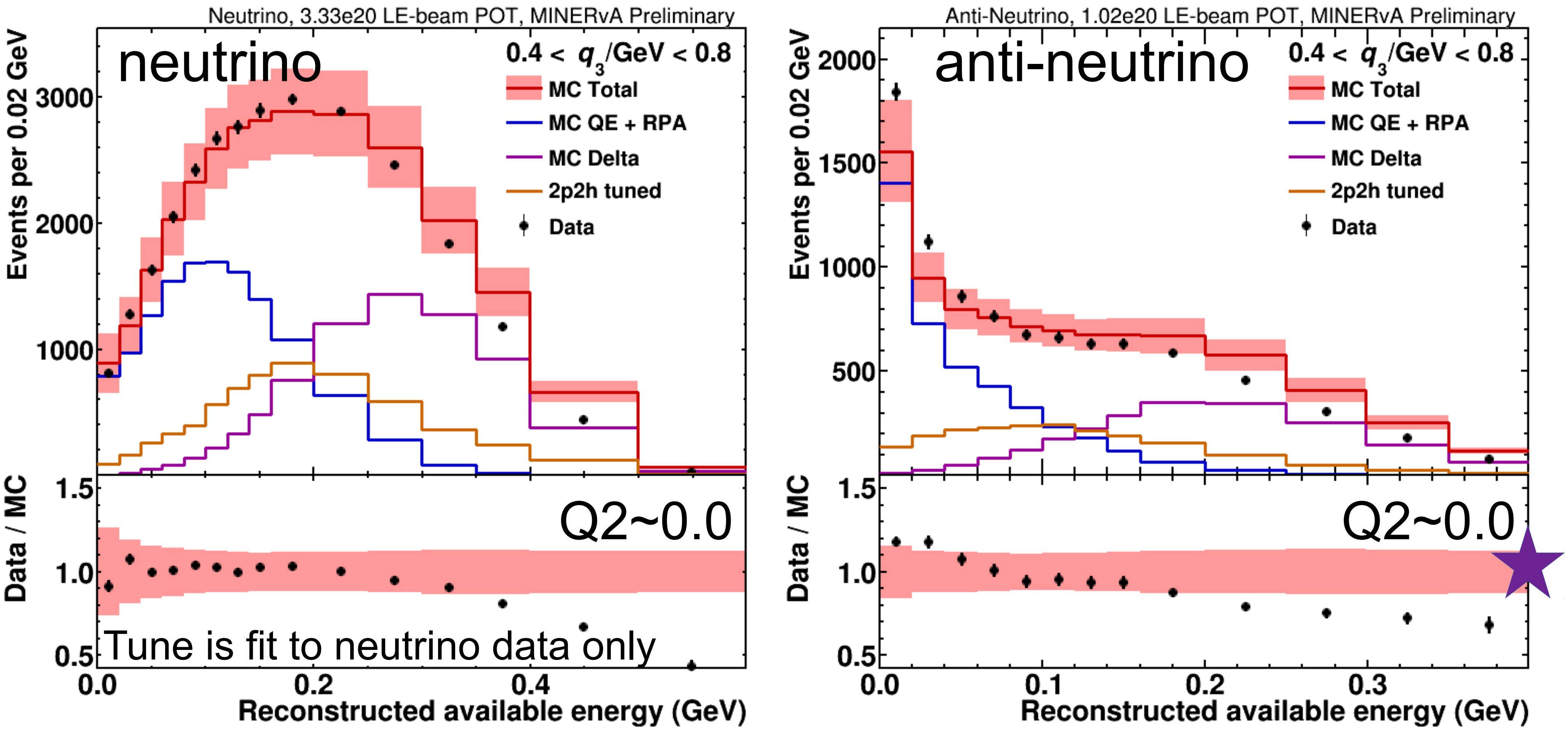


Add Valencia 2p2h, as previously published

Same code as in Genie 2.12.6 Schwehr, R.G., Cherdack, arXiv:1705.02932

GENIE, Pion base, RPA, 2017 Tuned 2p2h

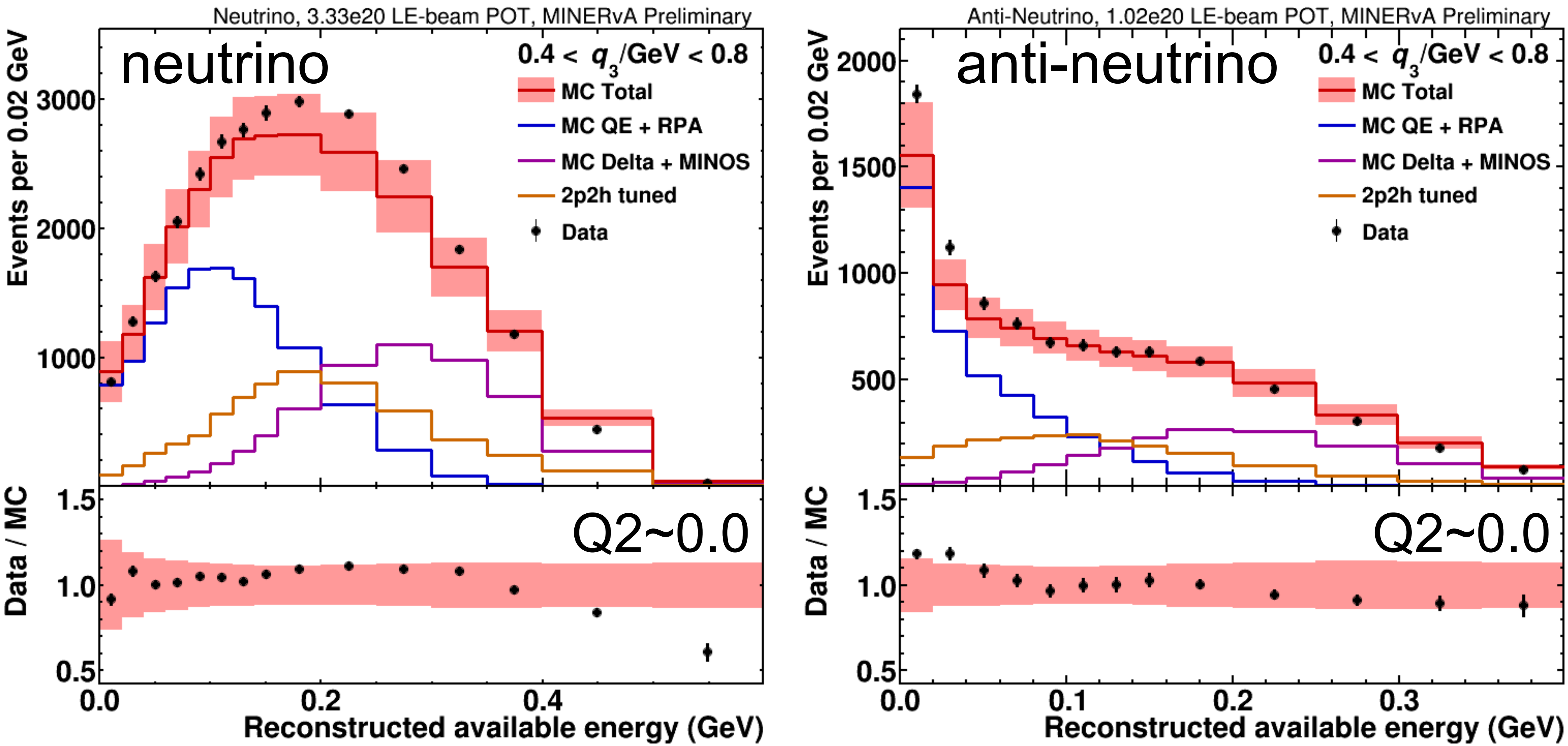
X2 = 158 for 40 bins   X2 = 86 for 37 bins



weighting up the 2p2h events with a 2D Gaussian weight
this base tune designed to empirically "Fill in" the dip region
not whole kinematic range. Adds ~50% overall, but x2 in dip region
Improves left plot by construction, those parameters are applied
to the anti-neutrino plot, which is also greatly improved!

GENIE, RPA, 2017 Tuned 2p2h, MINOS low-Q2 res

X2 = 144 for 40 bins X2 = 59 for 19 bins



New, add low Q2 suppression (RPA-like) to all GENIE resonances

prescription from Minos nu+Fe data PRD 91 (2015) 012005

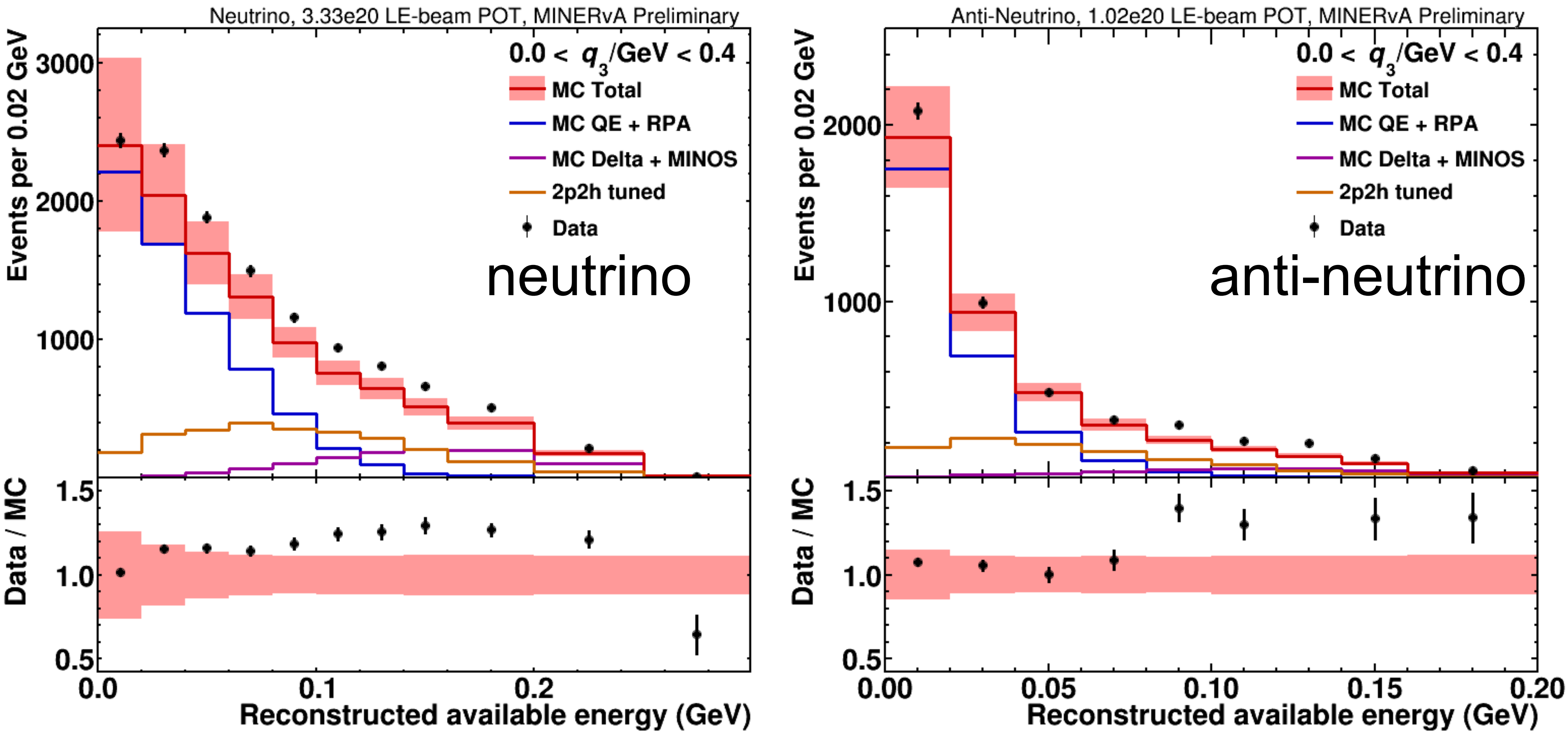
Seen also in MiniBooNE, K2K, others...

Thinking Pauli-blocking + RPA and/or SF-like effects

but for resonances. An improvement, but...

GENIE, RPA, 2017 Tuned 2p2h, MINOS low-Q2 res

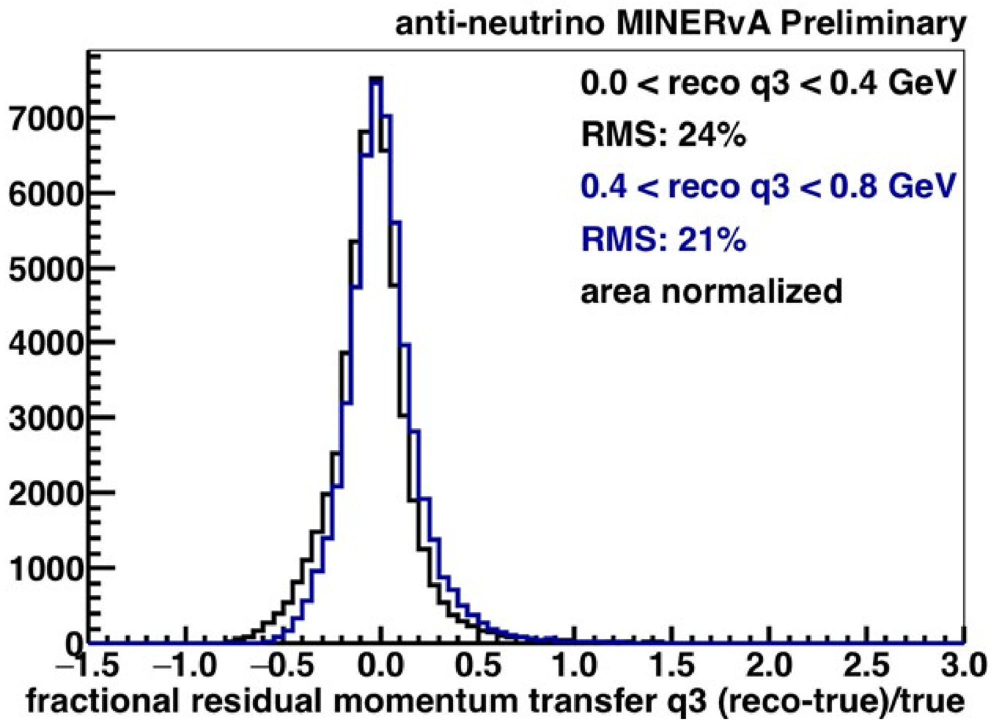
X2 = 106 for 21 bins | X2 = 132 for 19 bins

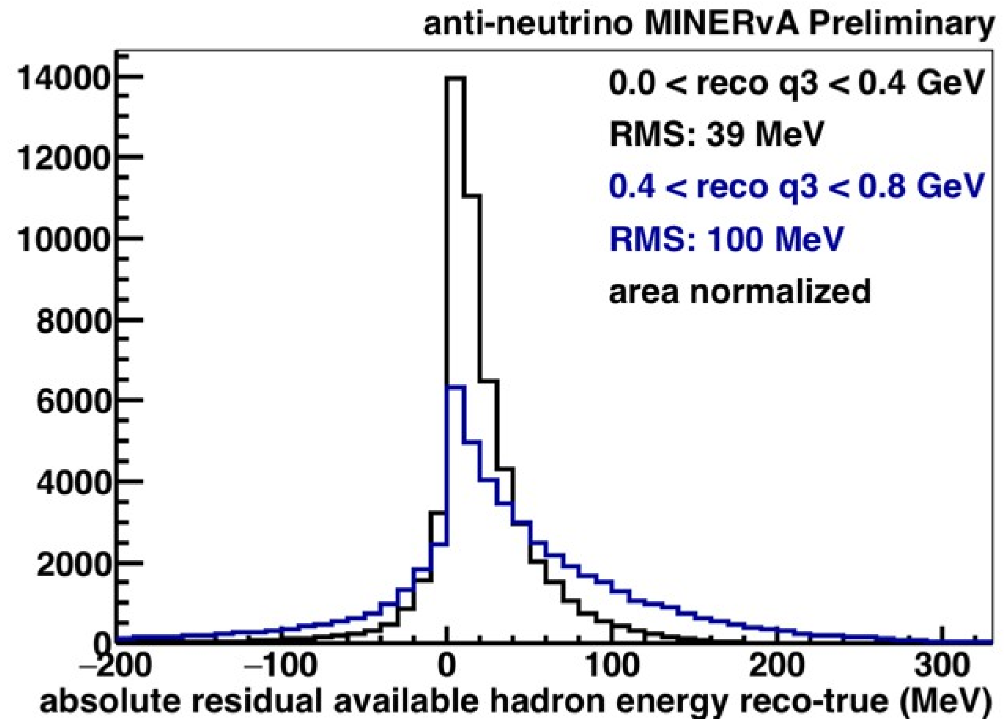


Add low Q2 suppression (RPA-like?) to all GENIE resonances
prescription from Minos nu+Fe sideband tune
Adamson, et al. PRD 91 (2015) 012005
This r(Q2) weight from Fe apparently is not quite right for CH
TOO MUCH, it goes to far.

Anti-neutrino kinematics resolutions

Same information as migration or unfolding matrix, but 1D projection



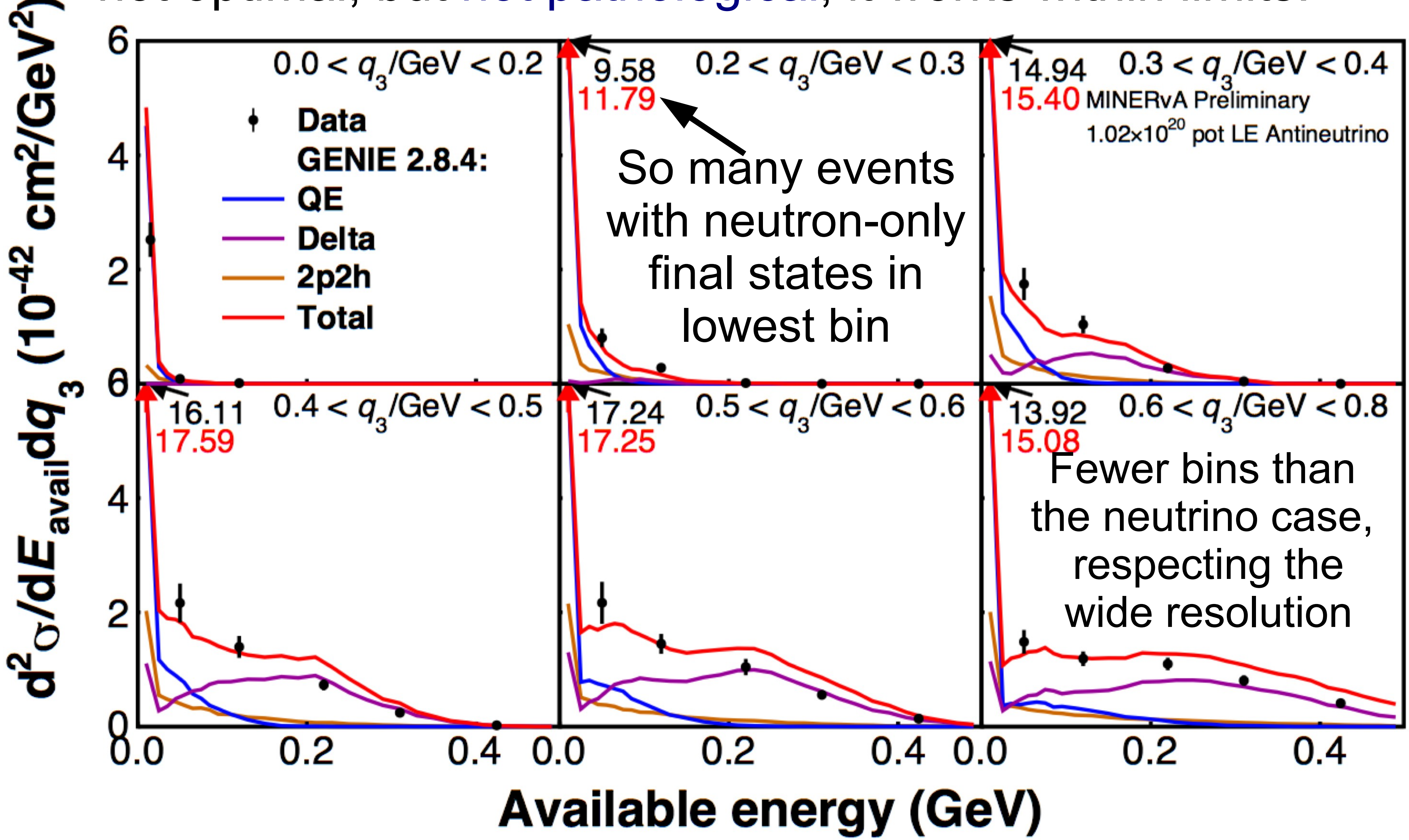


Our MC says the q3 estimator has good resolution and little bias.

$E_{available}$ = Proton KE, $\pi^{\pm}$ KE, π^0, e, γ energy (plus heavier particles) is wide because energy deposits from neutrons are not very correlated with neutron energy.
Its approximately a Gaussian peaked just above 0.0 with <half of the neutrons adding random 10s of MeV

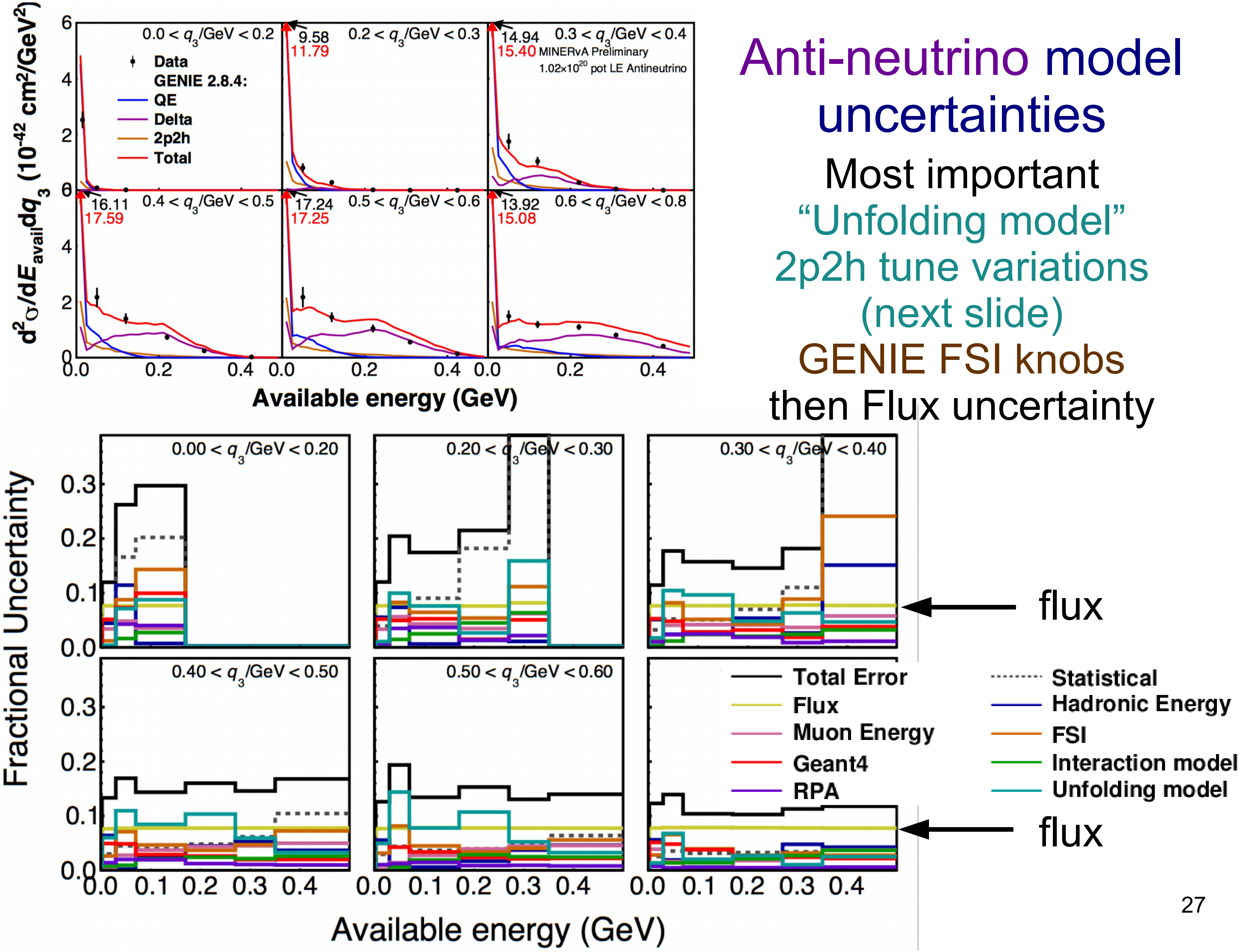
Unfolded anti-neutrino cross section

The resulting full unfolding matrix is not optimal for unfolding, not optimal, but not pathological, it works within limits.



breakdown of systematic uncertainties on next page

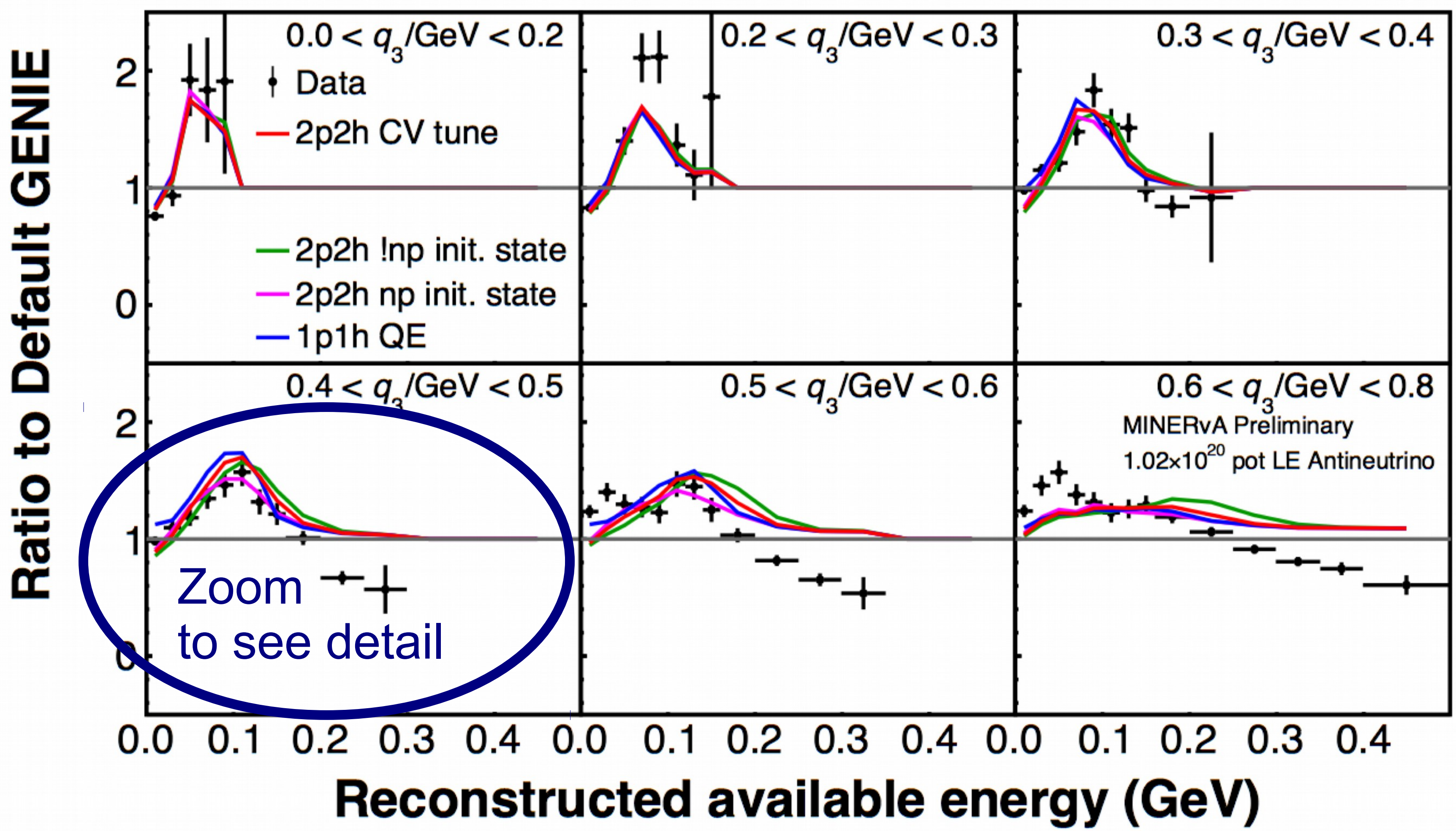
Anti-neutrino model uncertainties



Most important
"Unfolding model"
2p2h tune variations
(next slide)
GENIE FSI knobs
then Flux uncertainty

New uncertainty evaluations are needed to unfold

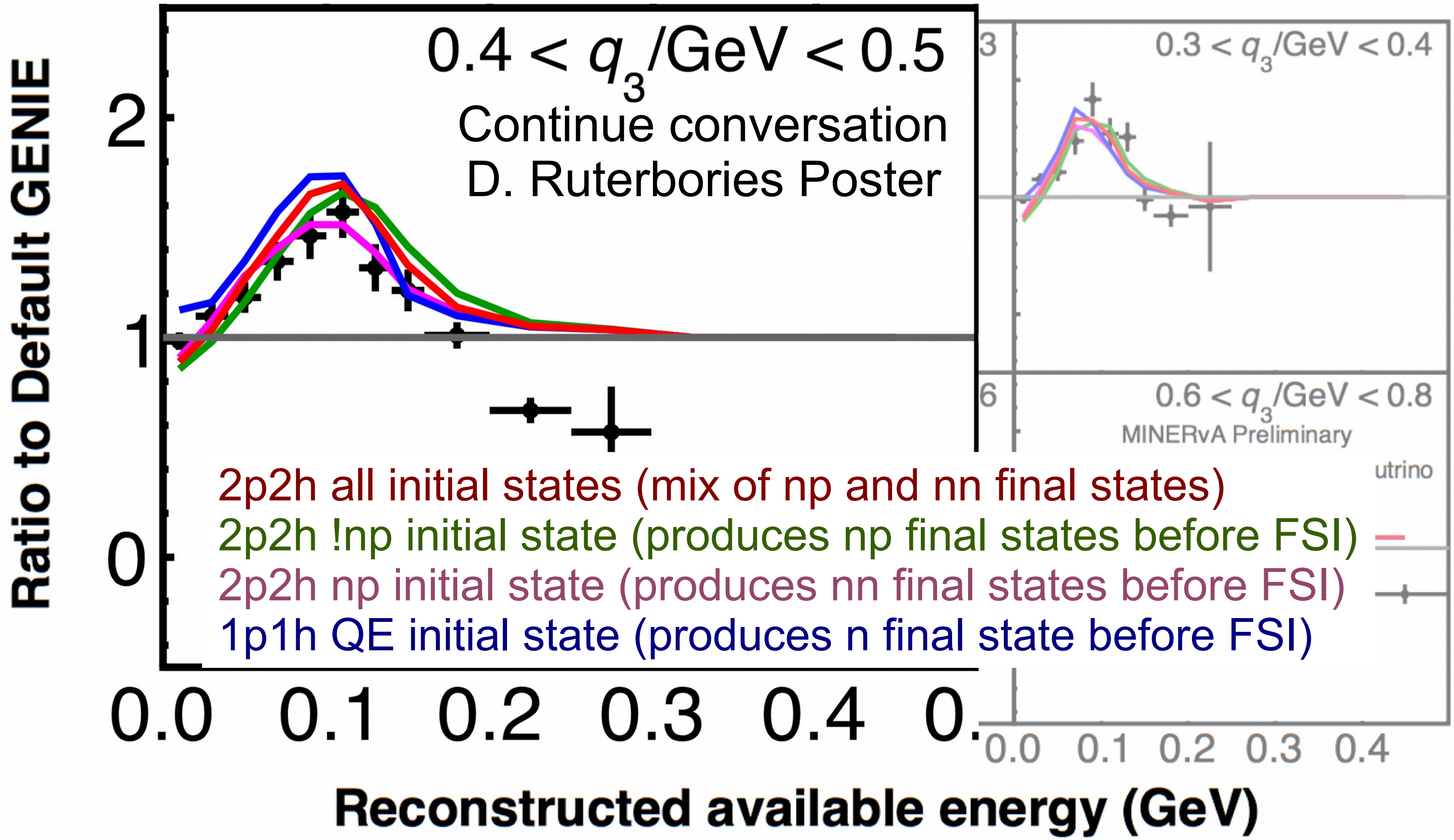
Three variations on the tuned 2p2h strength in the dip region
all fit to neutrino data, resulting parameters applied to anti-neutrino



Unfold again with each of these MC variations, result is different!
form that into the error band. Same with GENIE FSI knobs.
Model dependence in this analysis, technique ok for other analysis

New uncertainty evaluations are needed to unfold

Three variations on the tuned 2p2h strength in the dip region all fit to neutrino data, resulting parameters applied to anti-nu



Unfold again with each of these MC variations, result is different! form that into the error band. Same with GENIE FSI knobs. Model dependence in this analysis, technique ok for other analysis

Extremely important points on these uncertainties

The Fill-in extracted from the neutrino dip region
describes the anti-neutrino dip region. All variations work ok.
Suggest multiple physics (or combination) could be the cause.

Compared to $MA = 0.99^{+0.25}_{-0.15}$ …

1. The Fill-in the dip region tunes are designed to be
a better targeted expression of the model uncertainty
when used with a specific RPA model uncertainty
updated pion constraints from Deuterium and[1]
axial form factor uncertainty from Z expansion and Deuterium[2].

2. Like an oscillation experiment's results
our cross sections are better and uncertainty bands useful
if we start with better baseline models
and accurate and well-designed uncertainties
(and use side-band constraints and/or design in cancellations)

1. Rodrigues, Wilkinson, EPJC76, 8 (2016), PRD 90 112017 (2014) 2. Meyer, Betancourt, RG, Hill, PRD93 113015 (2016)

Conclusions: RPA+2p2h for neutrino works for anti-neutrino

This is despite radically different neutron content in the final states.

The experience leads to revised, targeted uncertainty expressions

Unfolding anti-neutrino works, despite neutron challenges

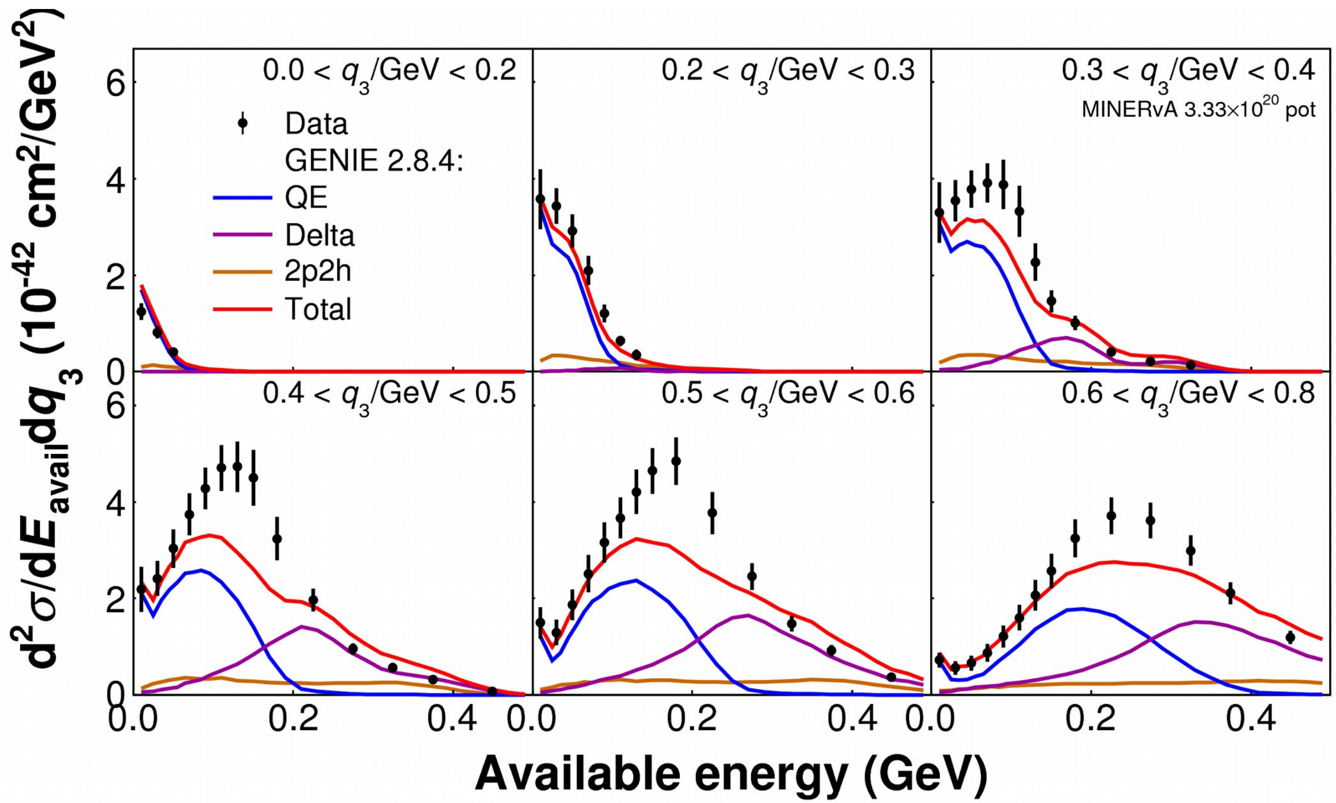
Can move from >50% effects to consider 10% effects

MINERvA at William & Mary ten years apart 2006 and 2016

Backup

Reco distribution with uncertainty breakdown

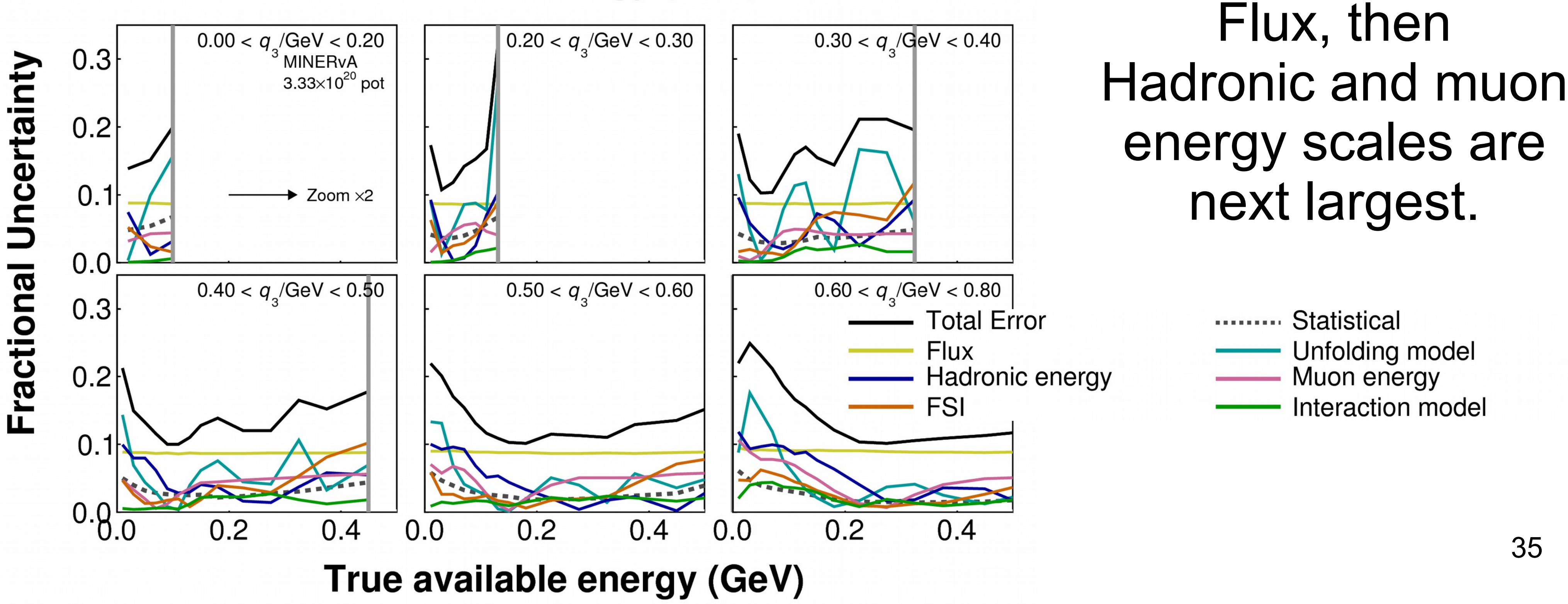
2016 neutrino result



RPA + Valencia 2p2h

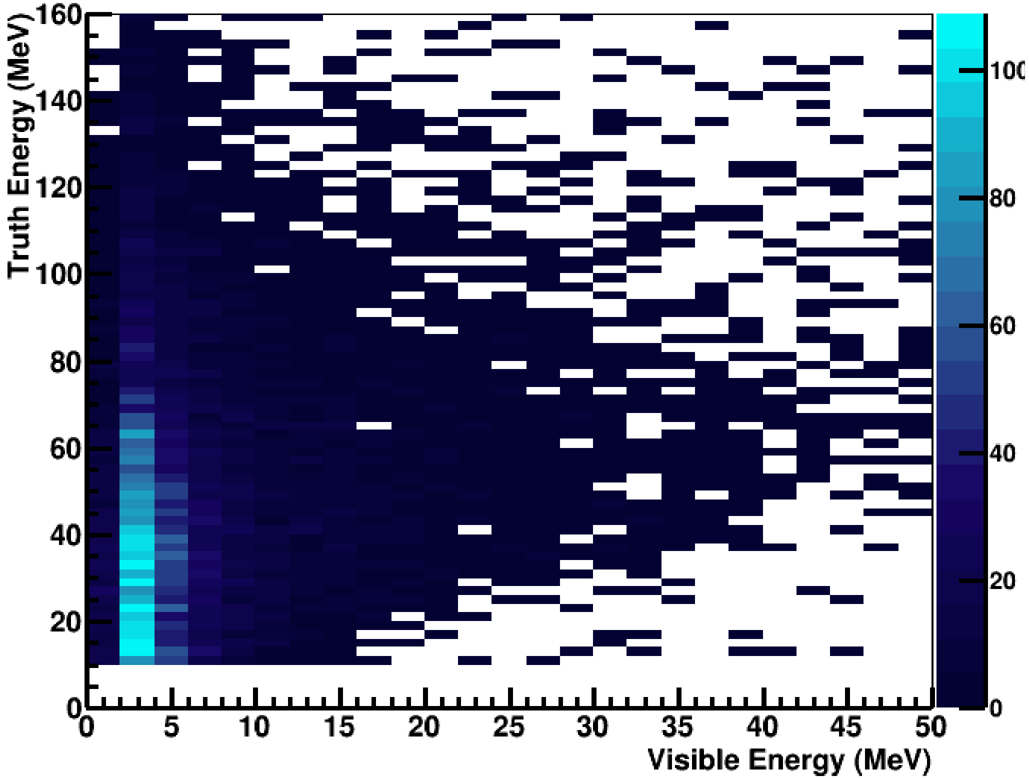
Unfolding model uncertainty means turn 2p2h off completely and reextract XSec.

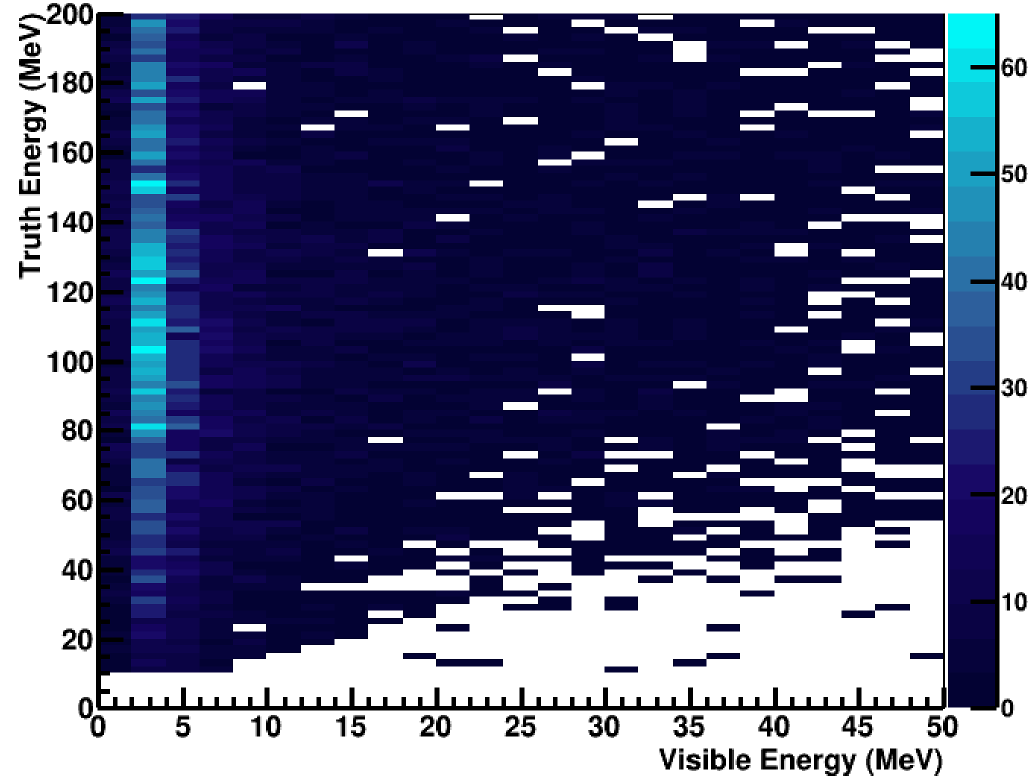
Flux, then Hadronic and muon energy scales are next largest.



Neutron response is uncorrelated with neutron energy

Second most likely outcome is 2 to 10 MeV of energy per neutron
Most likely, >55% of the time, nothing reconstructed at all.



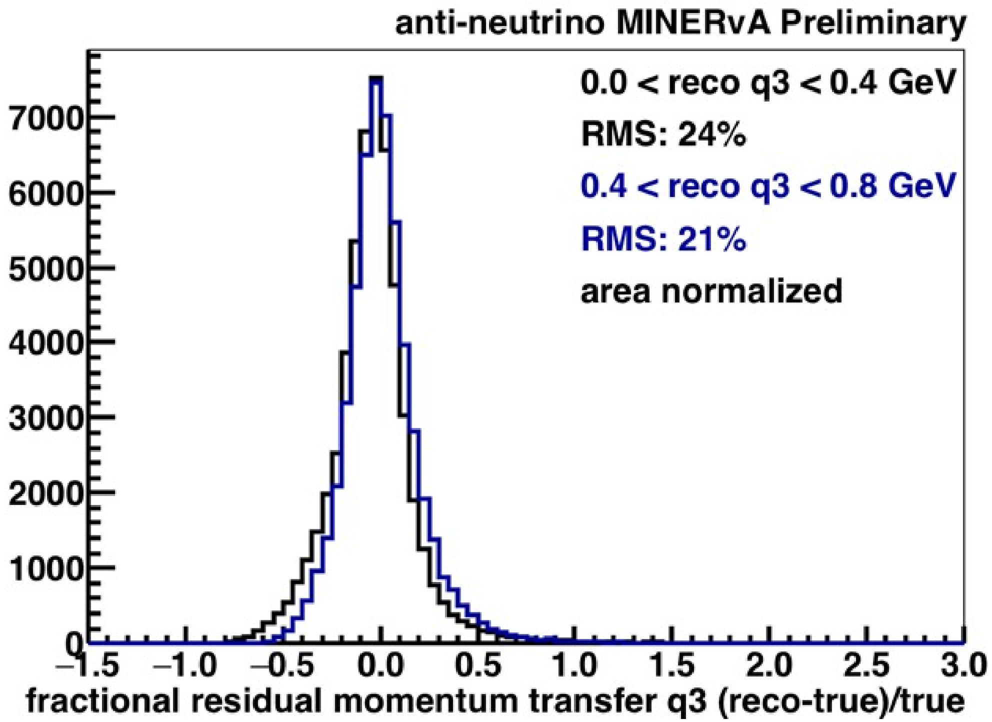


The extreme is below 10 MeV, where our MC thinks neutrons are essentially invisible.

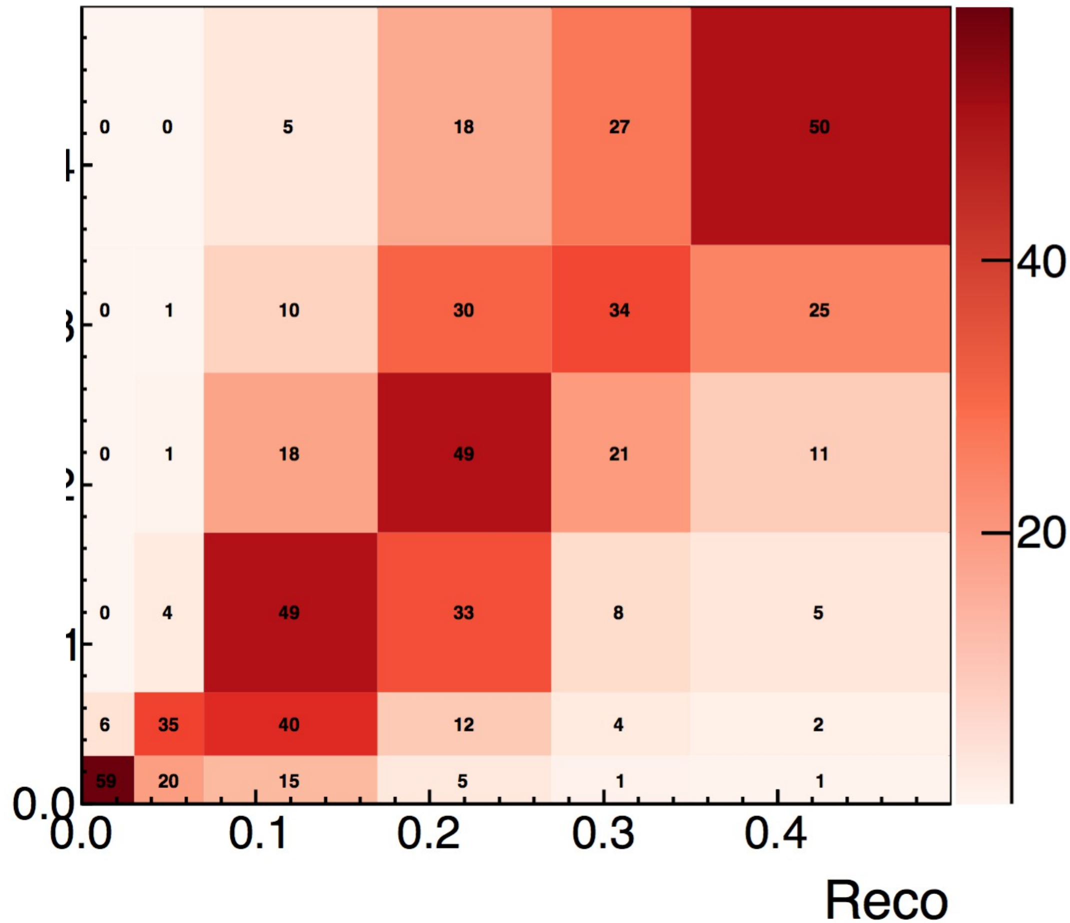
See also M. Elkins Poster

Resolutions and migration matrix for anti-neutrino

three momentum transfer resolution

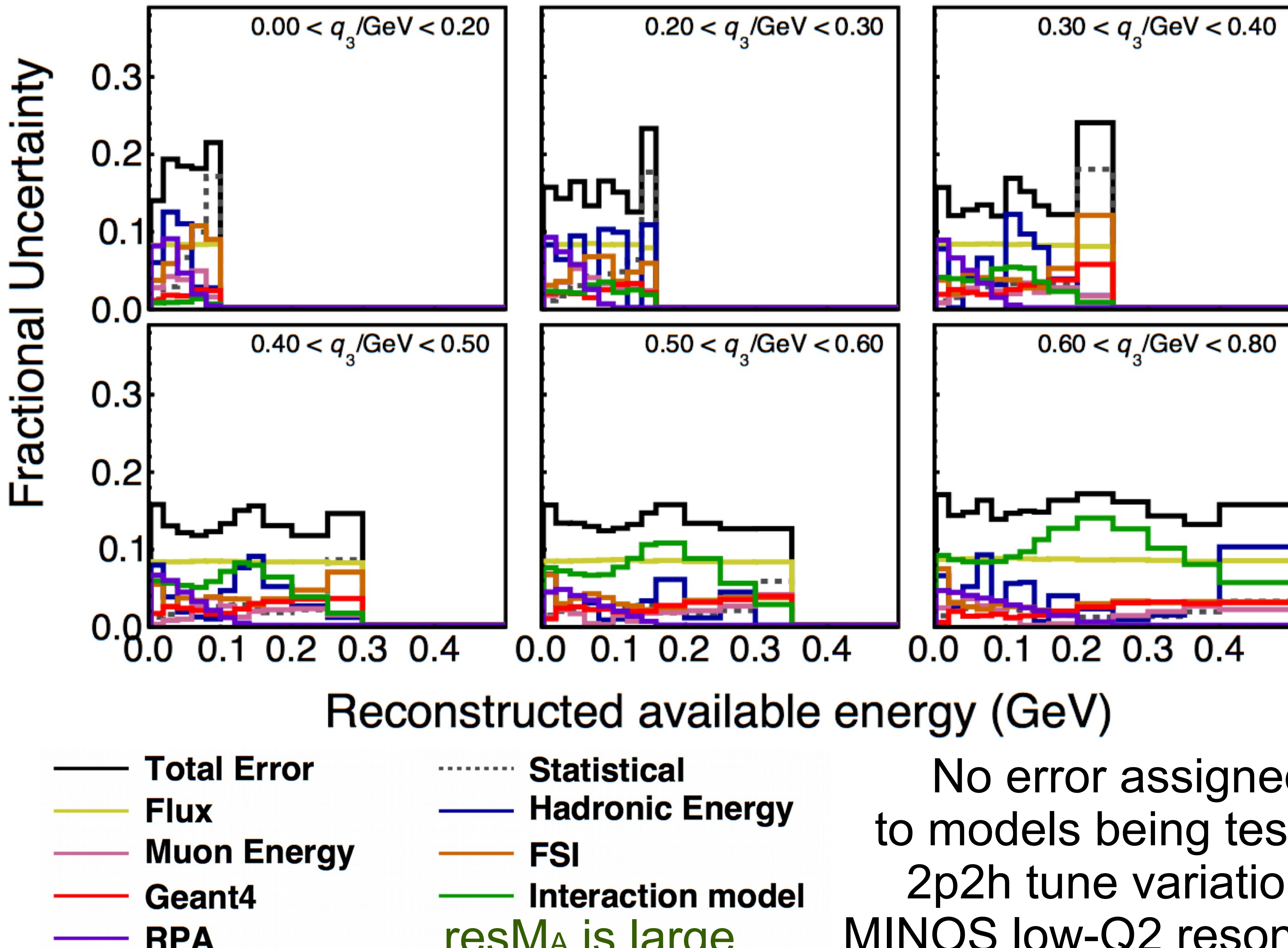


Available energy migration matrix



Evaluate model dependence by changing model seeing few percent shifts in the migration matrix propagating that to the resulting cross section

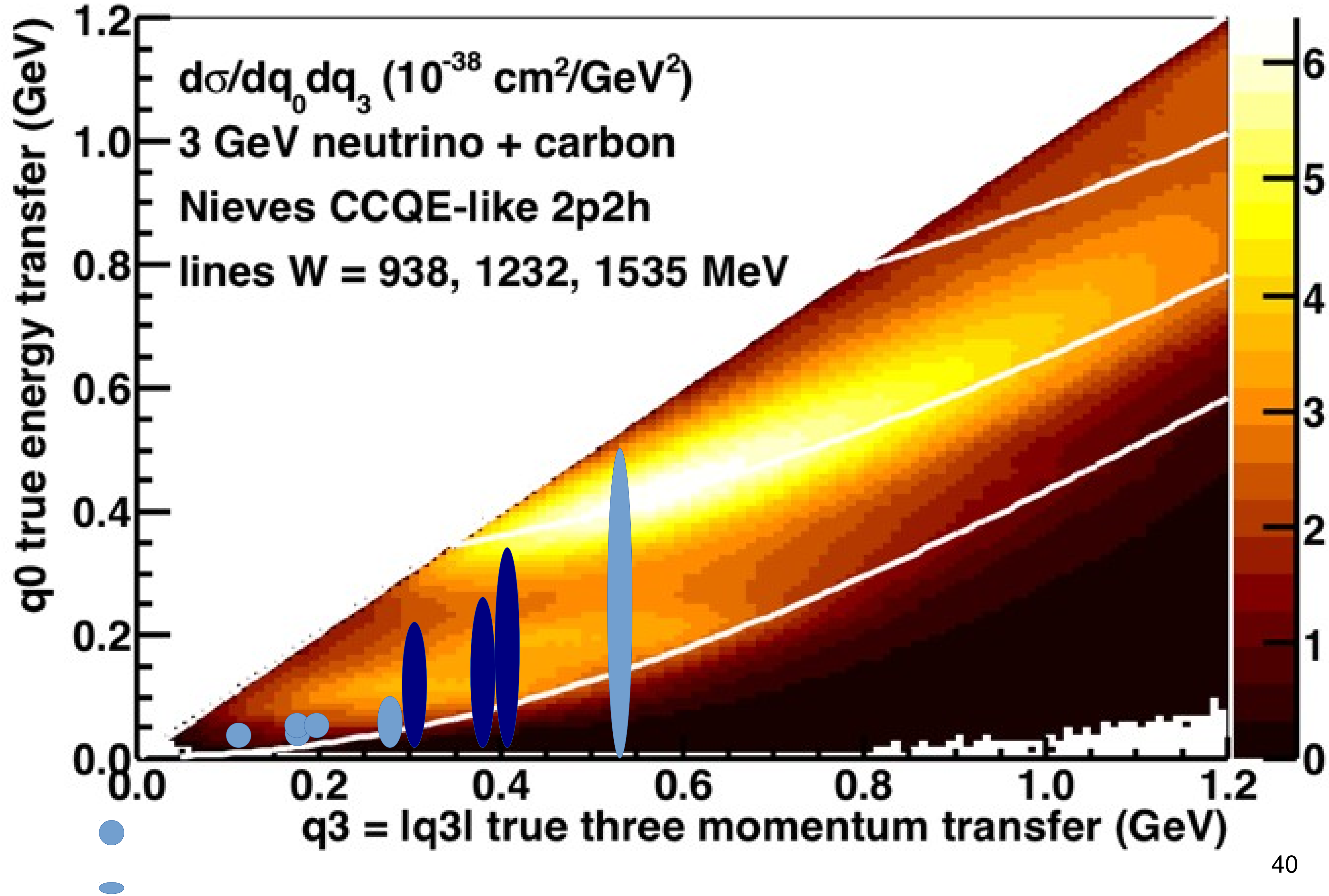
Systematic errors on the reconstructed distribution



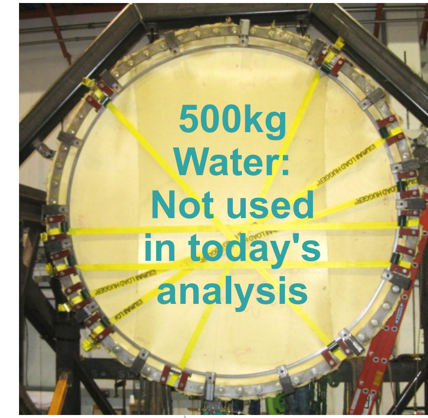
resMA is large

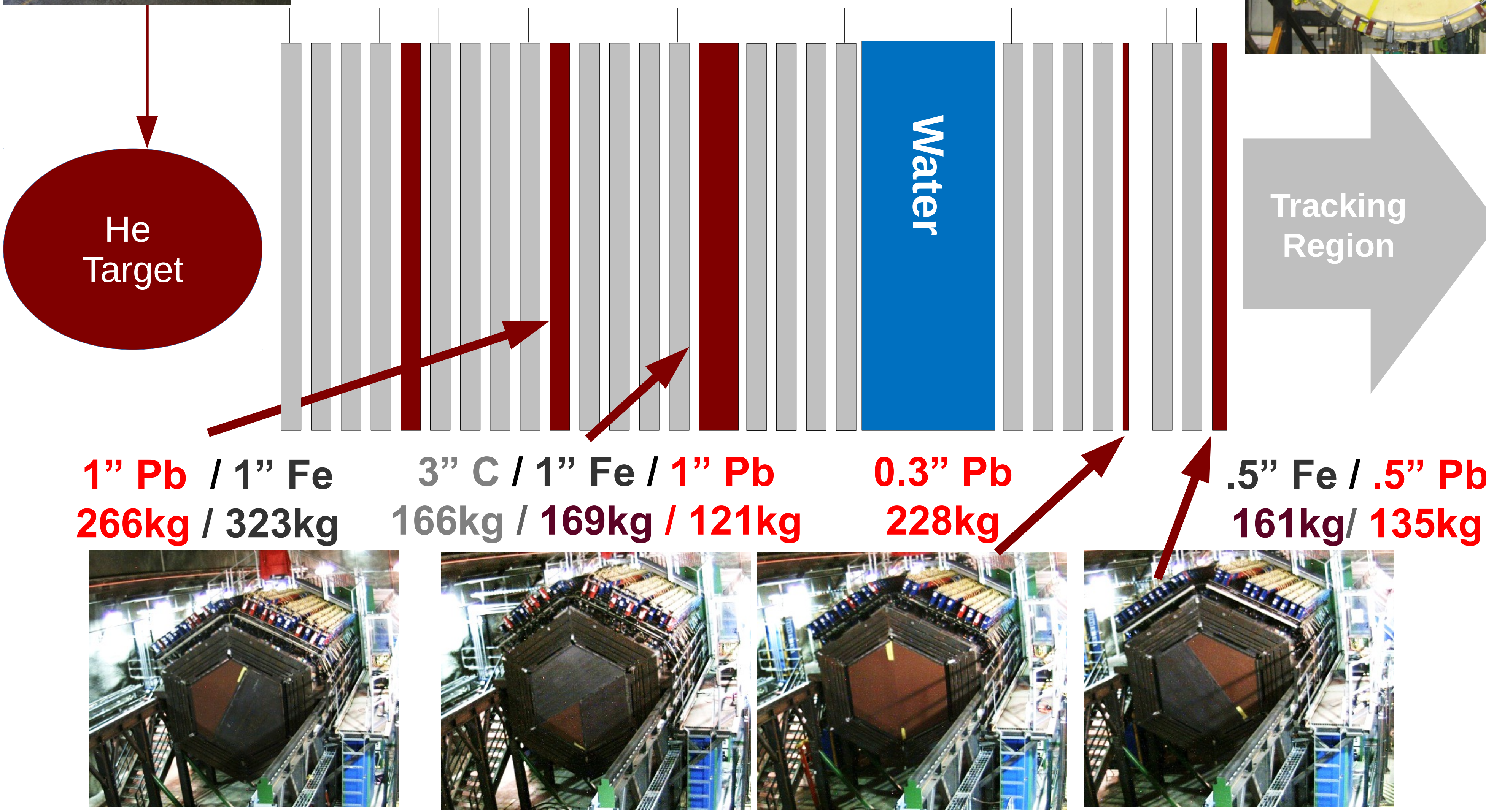
No error assigned
to models being tested:
2p2h tune variations
MINOS low-Q2 resonance

Trash slides


dσ/dq0dq3 (10-38 cm2/GeV2)
3 GeV neutrino + carbon
Nieves CCQE-like 2p2h
lines W = 938, 1232, 1535 MeV
q0 true energy transfer (GeV)
q3 = |q3| true three momentum transfer (GeV)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0
1
2
3
4
5
6

Passive targets region



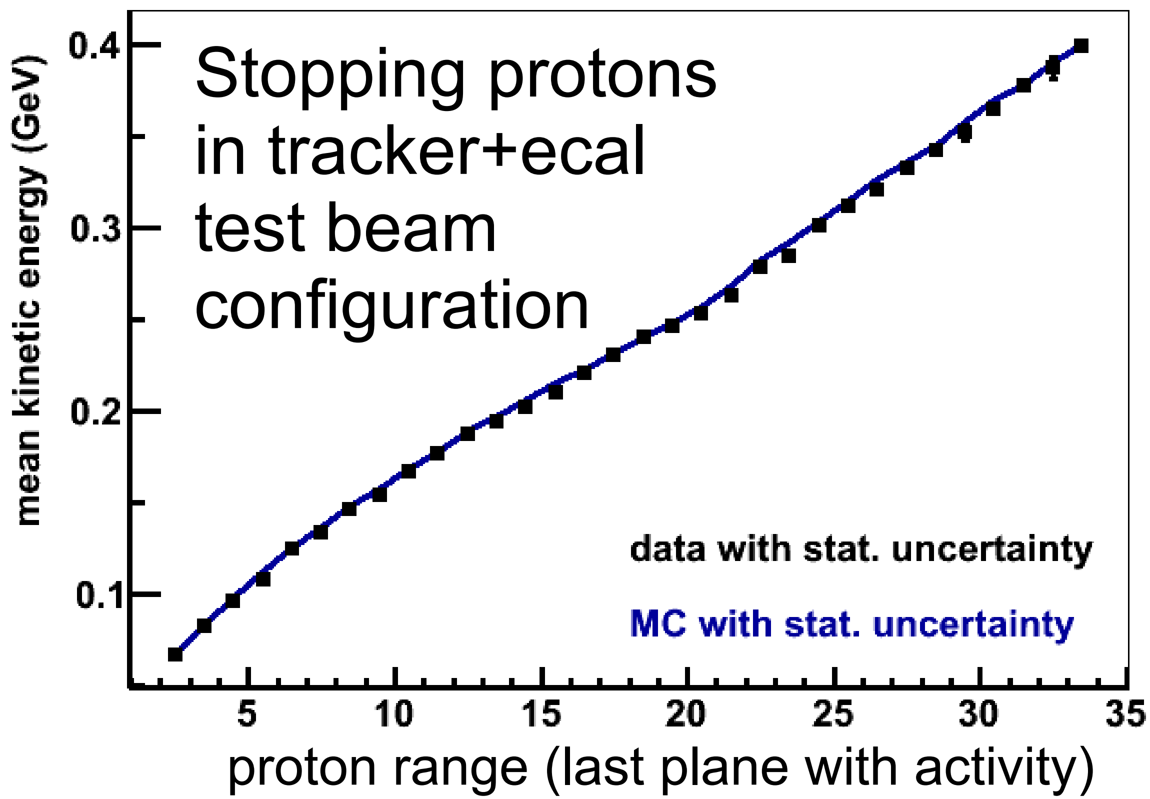


These lower four are included in the result presented today

Calorimetry constraints < 2 GeV from test beam data

Constrains Geant4 and Detector calorimetric response
4% for protons, pions < 2 GeV and 3% electrons ~ 0.5 GeV
Resolutions are well described
(also in-situ constraint from π0 invariant mass peak)

test beam proton energy vs. Range



Data (stat err too small to see)
MC prediction (not a fit)
Stopping proton range
reproduced by MC
off by only 1.3%

Also Birks' Law parameter
scintillator response
determined from the
Bragg peak at end of
these stopping protons

Mass model (g/cm2) corrected 2% after destructive test

take-home message for neutrino oscillation enthusiast

Starting with a global Fermi gas
adding the RPA effect
adding the Valencia 2p2h model
augmenting it with additional cross section strength
in the dip region...

describes the neutrino data at the 10% level (not perfect)
and simultaneously describes anti-neutrino data well
up to the Delta.

This is true despite going from neutron-poor to
neutron-rich final states affecting the
energy in the anti-nu final hadronic system.

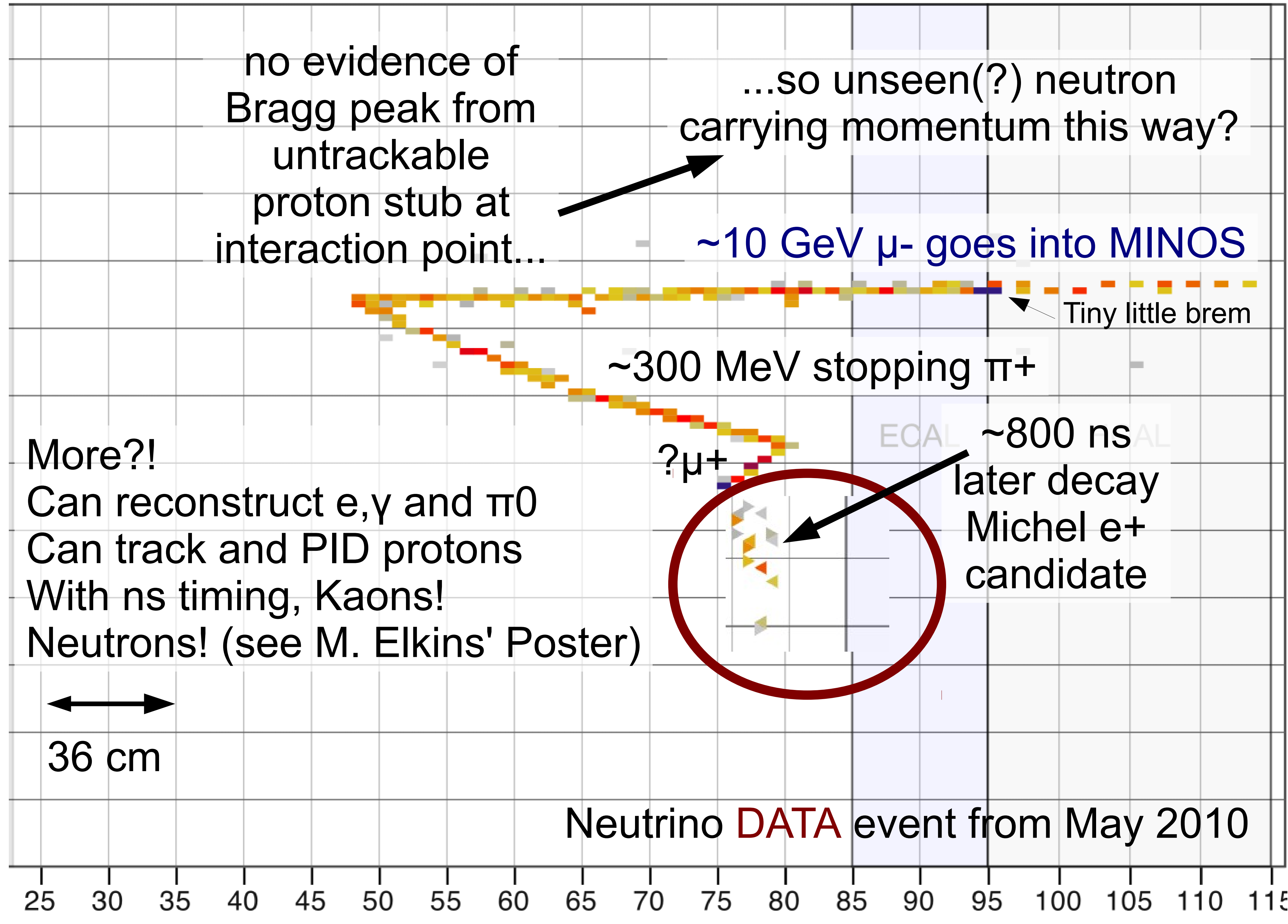
take-home message for neutrino interaction enthusiast

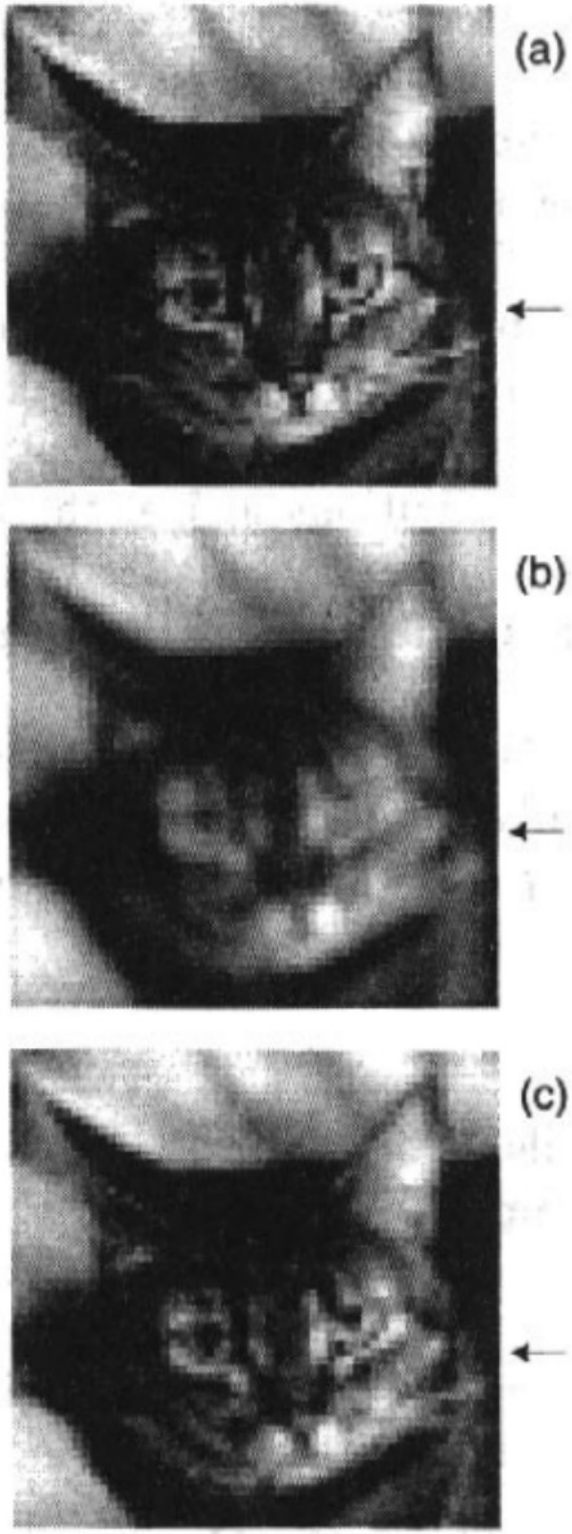
This way of describing the inclusive event rate
has the same kinematic expression as (e,e') data
and the same basic interpretation
despite the challenges with neutrino beams
and reconstructing a hadron system.

describes the neutrino data at the 10% level
and simultaneously describes anti-neutrino data well

But at the moment no immediate, unique solution
to improve this distribution still further.

Many models y'all will show this week
have 5 to 10% effects for these samples.
Will discuss a synthetic example, 2p2h tune, in a few slides.


no evidence of
Bragg peak from
untrackable
proton stub at
interaction point...
...so unseen(?) neutron
carrying momentum this way?
~10 GeV μ- goes into MINOS
Tiny little brem
~300 MeV stopping π+
ECAL
~800 ns
later decay
Michel e+
candidate
?μ+
More?!
Can reconstruct e,γ and π0
Can track and PID protons
With ns timing, Kaons!
Neutrons! (see M. Elkins' Poster)
36 cm
Neutrino DATA event from May 2010
25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115



An adorable kitten
was photographed
which was then smeared
and then unfolded
then printed in a book
then scanned to jpg
and displayed on a screen.

adorable
unfolded
kitten from
Glen Cowan's
Statistical Data
Analysis book
says...