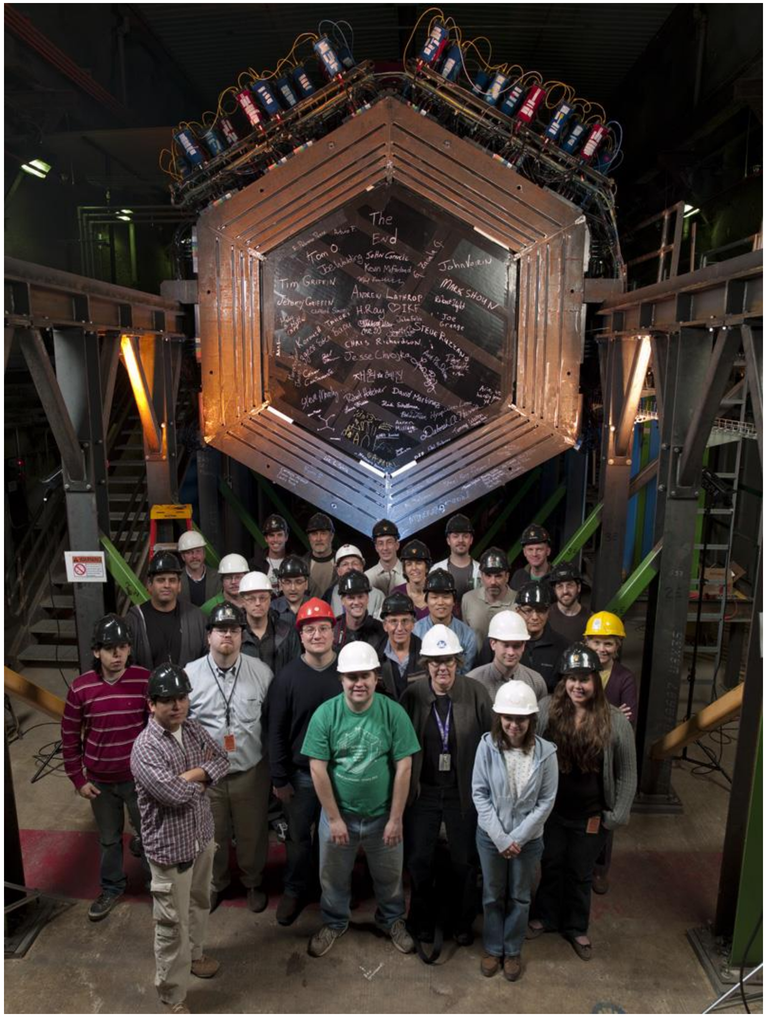
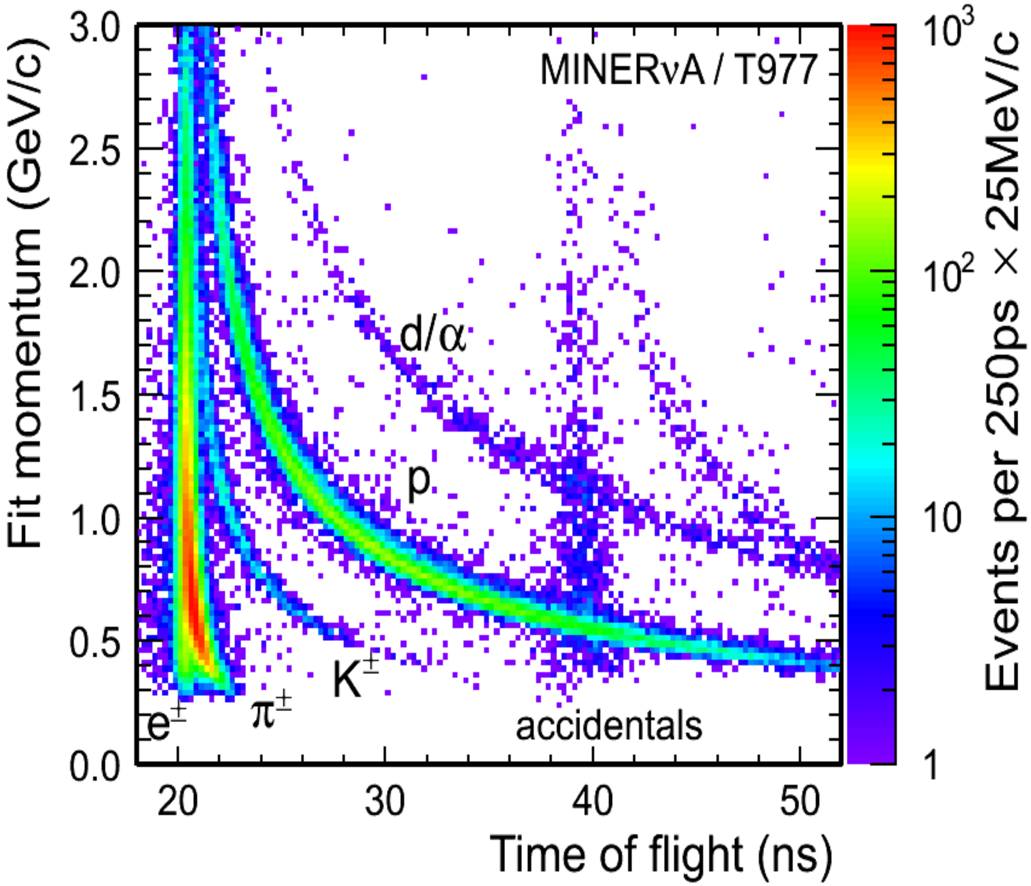
The (first) MINERνA Test Beam Experience

S. Manly (representing MINERvA)

CERN

ProtoDUNE Physics Workshop, June 2016

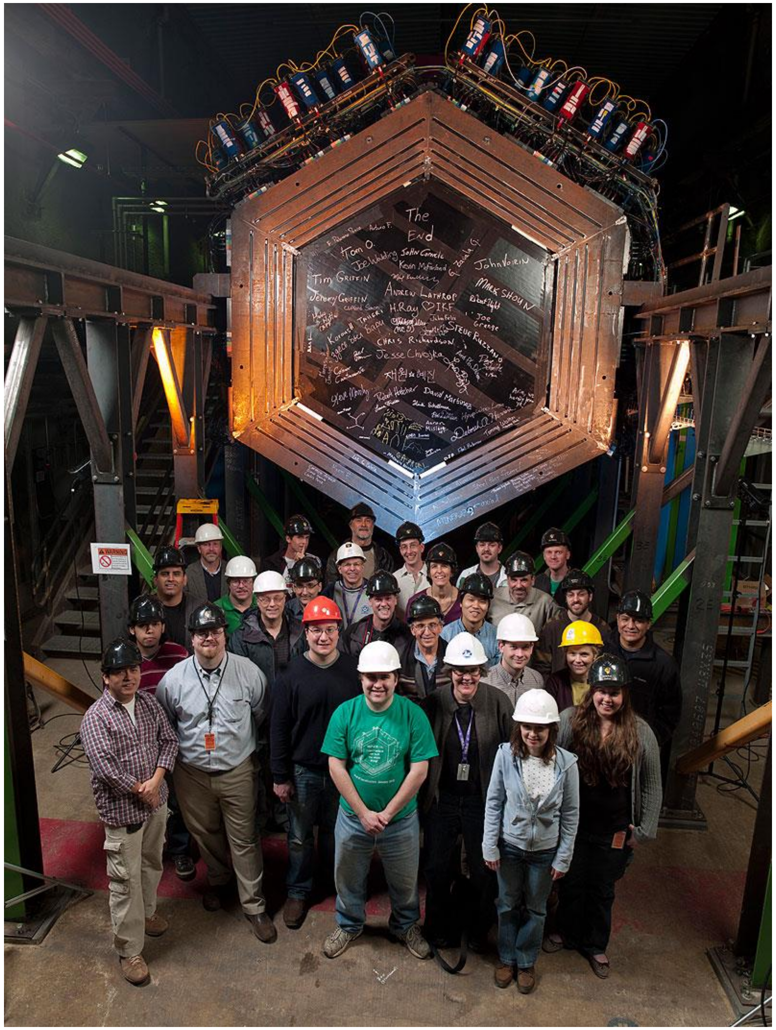


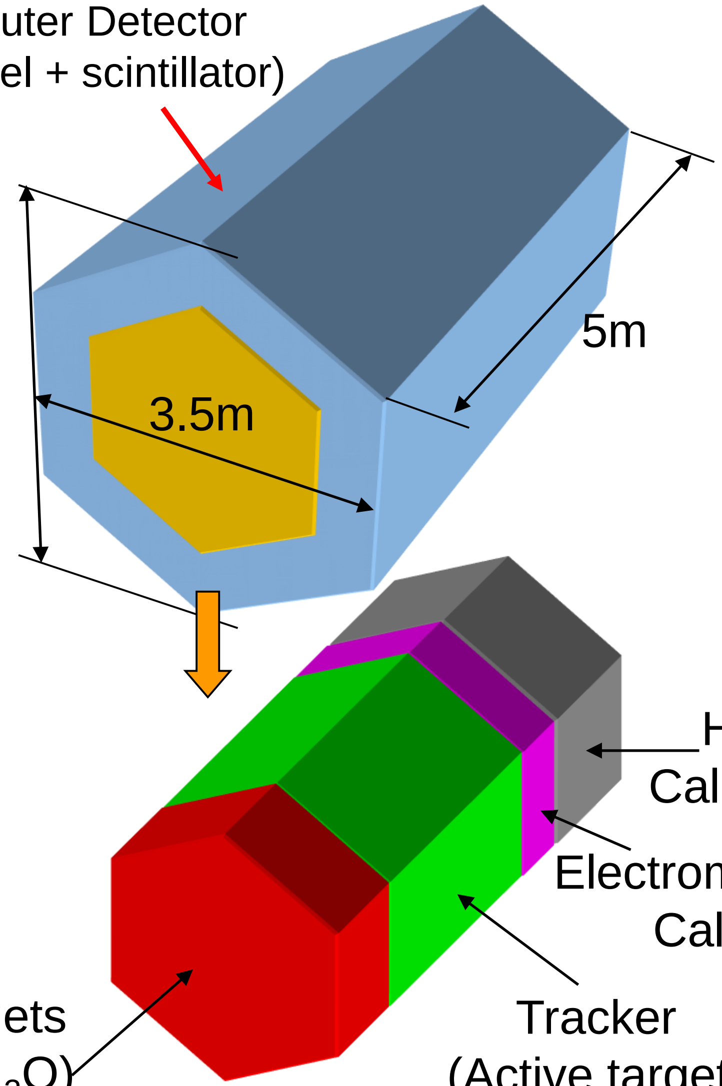


"MINERvA neutrino detector response measured with test beam data", Nucl. Inst. Meth. A789, (2015) pp 28-42.

"Design, Calibration and Performance of the MINERvA Detector", Nucl. Inst. and Meth. A743 (2014) p. 130.

MINERvA Detector





Outer Detector
(steel + scintillator)

Hadronic
Calorimetry

Electromagnetic
Calorimetry

Tracker
(Active target)

Nuclear Targets
(C, Pb, Fe, H_2O)

Primary aim: precision measurements of neutrino interaction cross sections on nuclear targets in the 1-10 GeV regime.

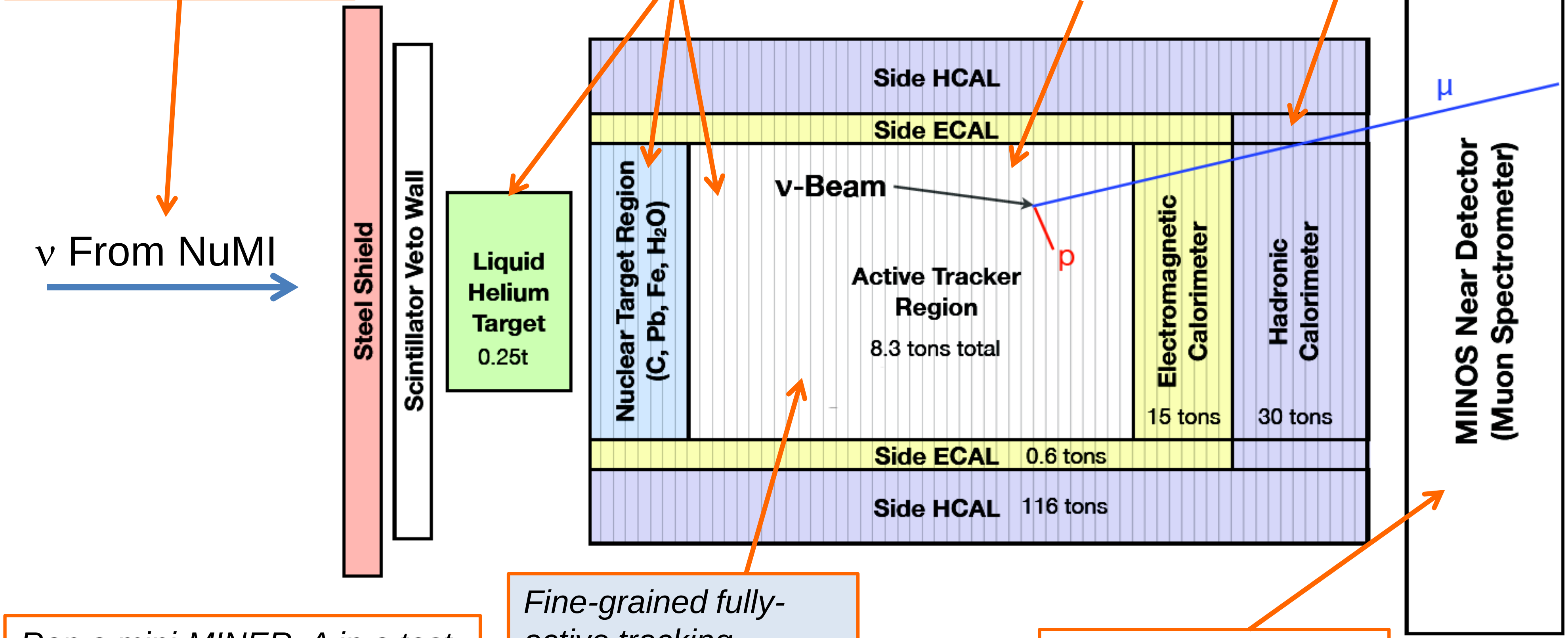
MINERνA

Intense beam, covers interesting energy range, configuration can be changed to help with flux tuning

Nuclear targets (can explore A-dependence of nuclear effects)

Containment (particle ID and topology ID)

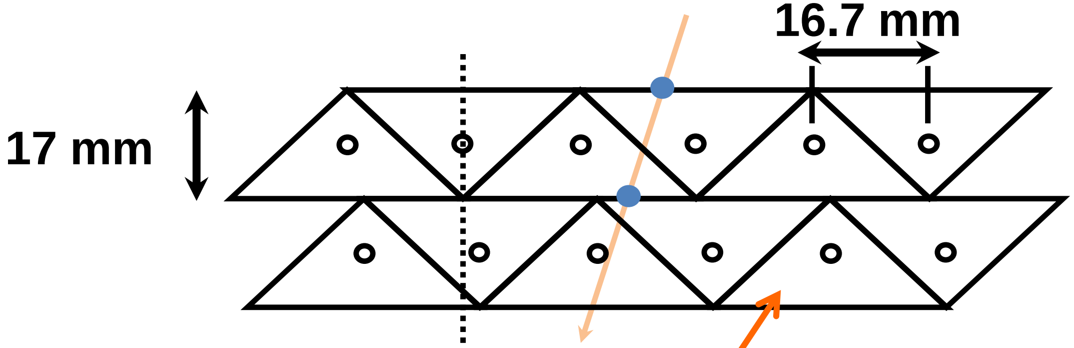
Large fiducial mass (large statistics)



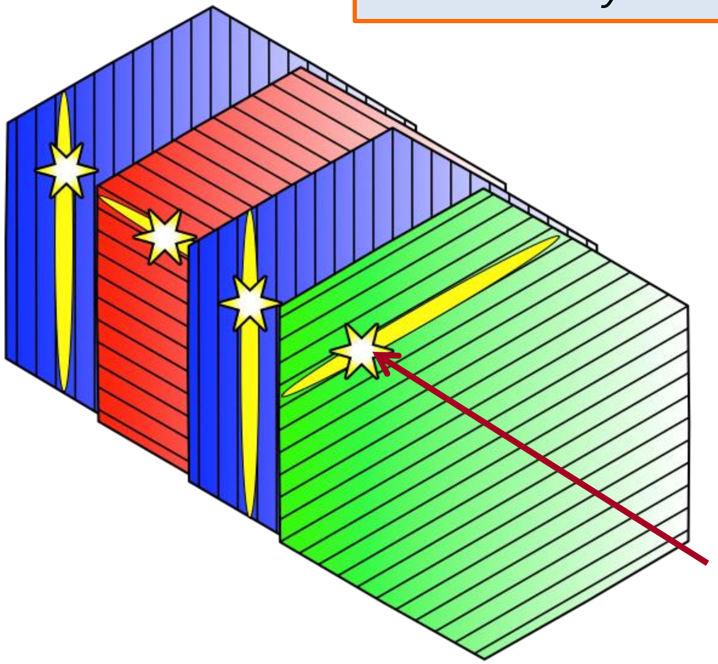
Ran a mini-MINERvA in a test beam in 2010, constrains our uncertainty in hadronic response

Fine-grained fully-active tracking (can select topologies and see vertex activity)

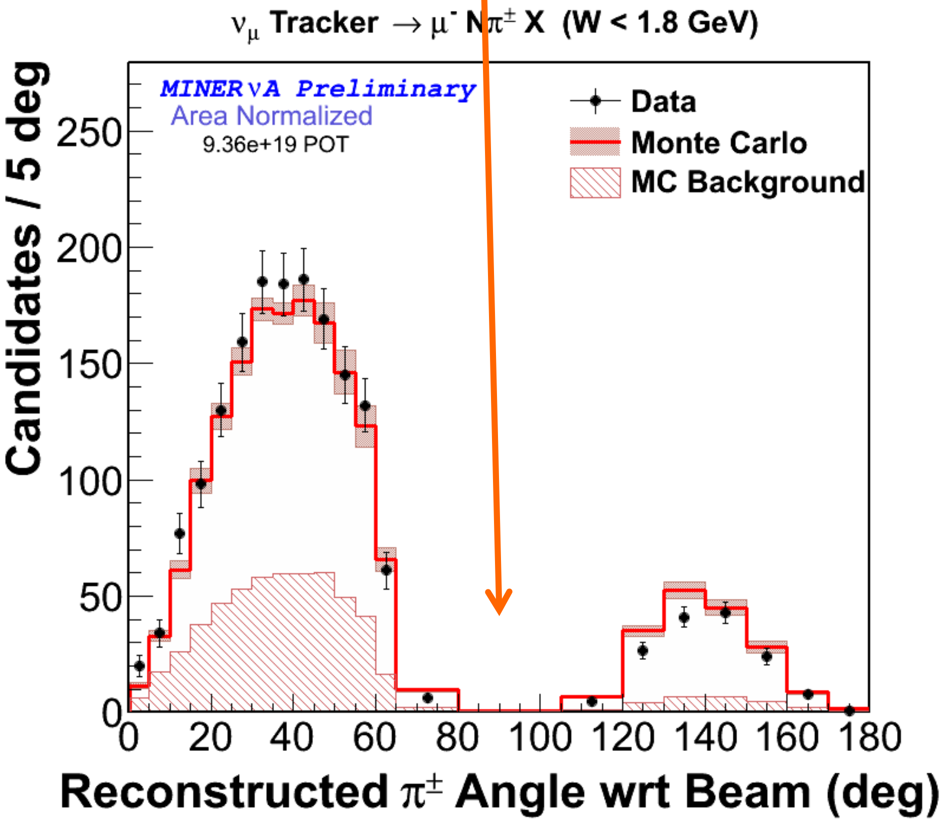
Magnetic spectrometer (momentum and sign analyze muons)



Fine-grained fully-active tracking
… but not quite a bubble chamber for looking at vertex activity



Construction of tracker gives a hole in reconstruction at 90º



Motivation and goals of MINERvA test beam

- TB1 (energies up to 2.0 GeV)
  - Birks law parameter for our polystyrene
  - Proton calorimetry
  - Pion calorimetry
  - Electron calorimetry (only up to 0.5 GeV)
  - Tracking test

- TB2 (2-8 GeV, little at 16 GeV)
  - energies above 2.0 GeV, hadron calorimetry
  - electrons energy above 500 MeV

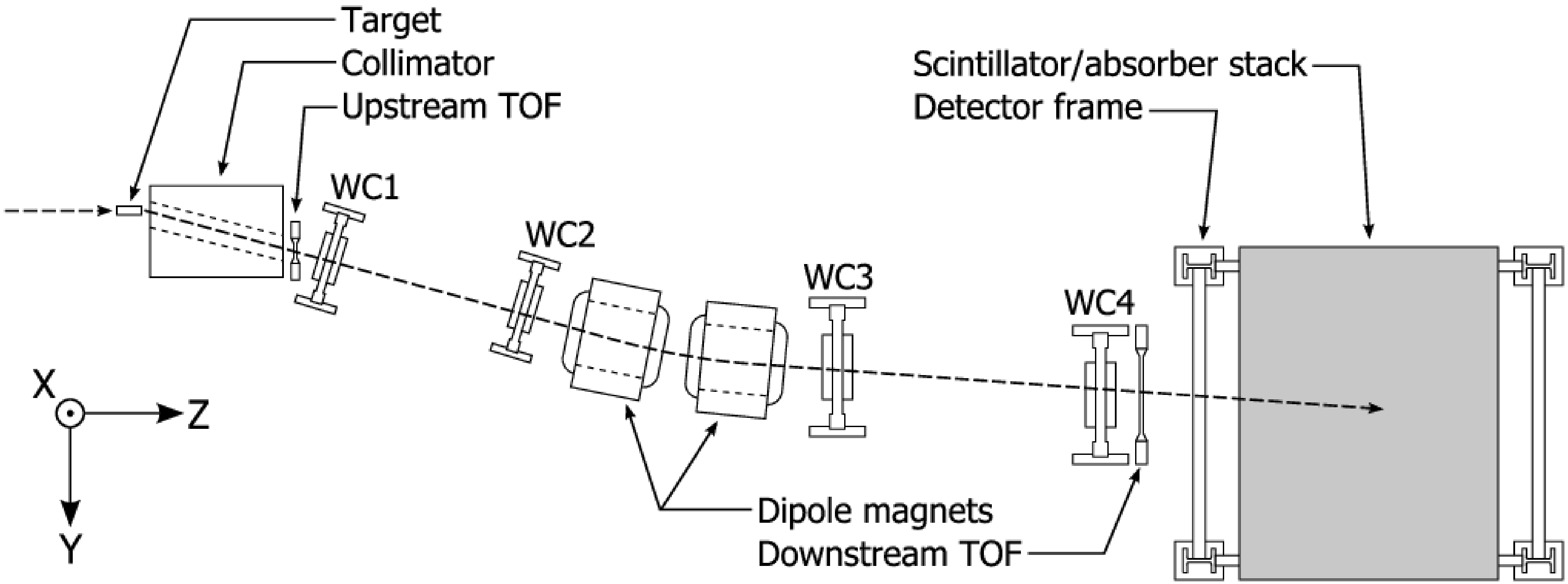
MINERvA: 2 separate test beam runs
FNAL test beam T977

- Low energy test beam (0.35-2.0 GeV)
- Data taken Mid-2010

- Medium energy test beam (2-8 GeV, special runs at 16 GeV)
- Data taken April-May 2015

MINERvA test
beam detector

Tertiary beam at Fermilab Test Beam Facility



The MINERvA test beam detector

Detector is structured to be as identical to MINERvA as reasonable except:

- smaller
  - 1m square planes, not 2m hexagons
  - only 40 planes deep, not 200+
- 50% more light per MeV = better resolution for some things
- removable, reconfigurable Pb and Fe absorber
- every-other-side readout:
  - mechanically smaller air gaps (closer to MINERvA)
  - mitigate spatial and angle dependence of incident beam

MINERvA test beam

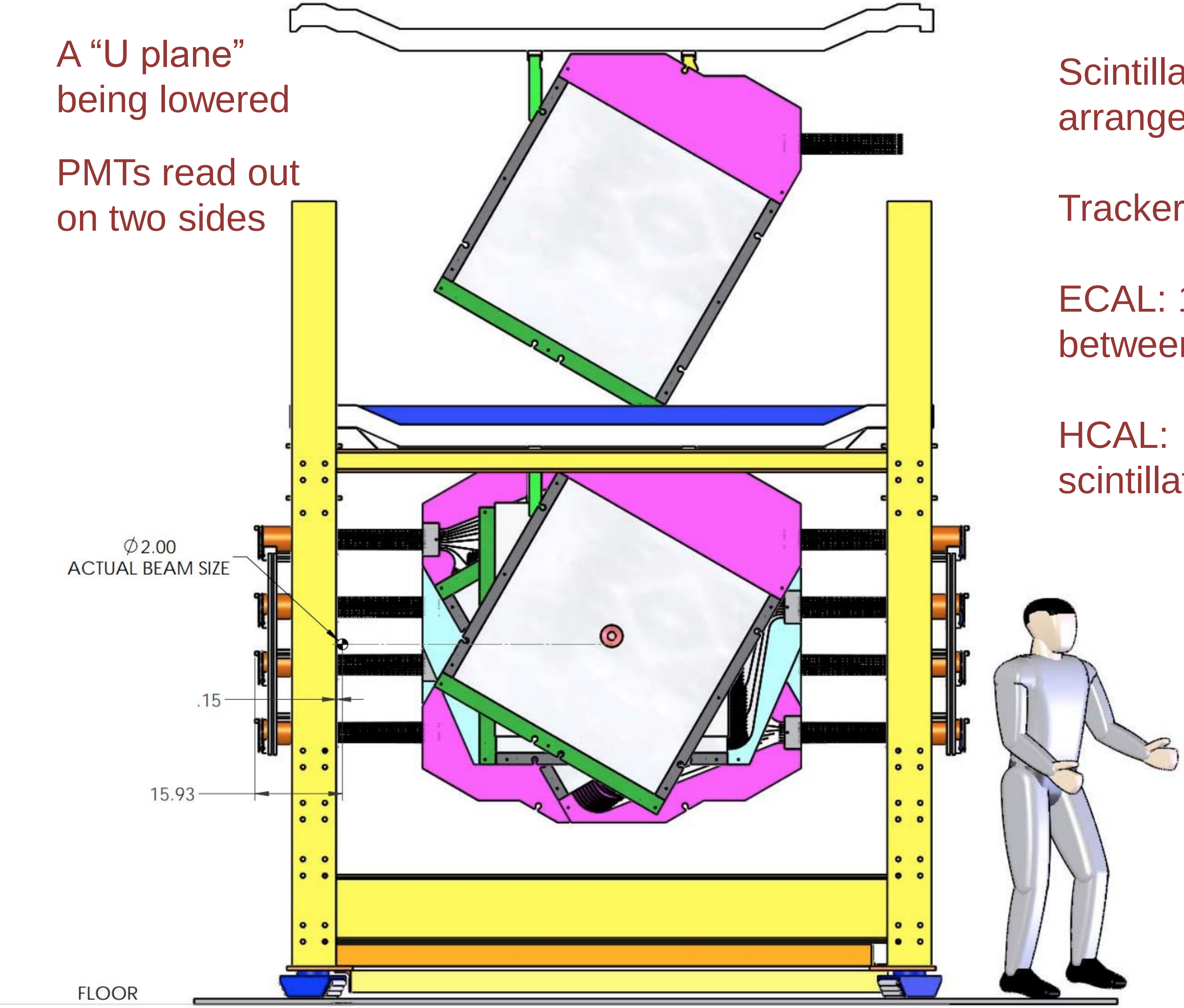
Tertiary beamline

MINERvA test beam detector

Reconfigureable

A “U plane” being lowered

PMTs read out on two sides



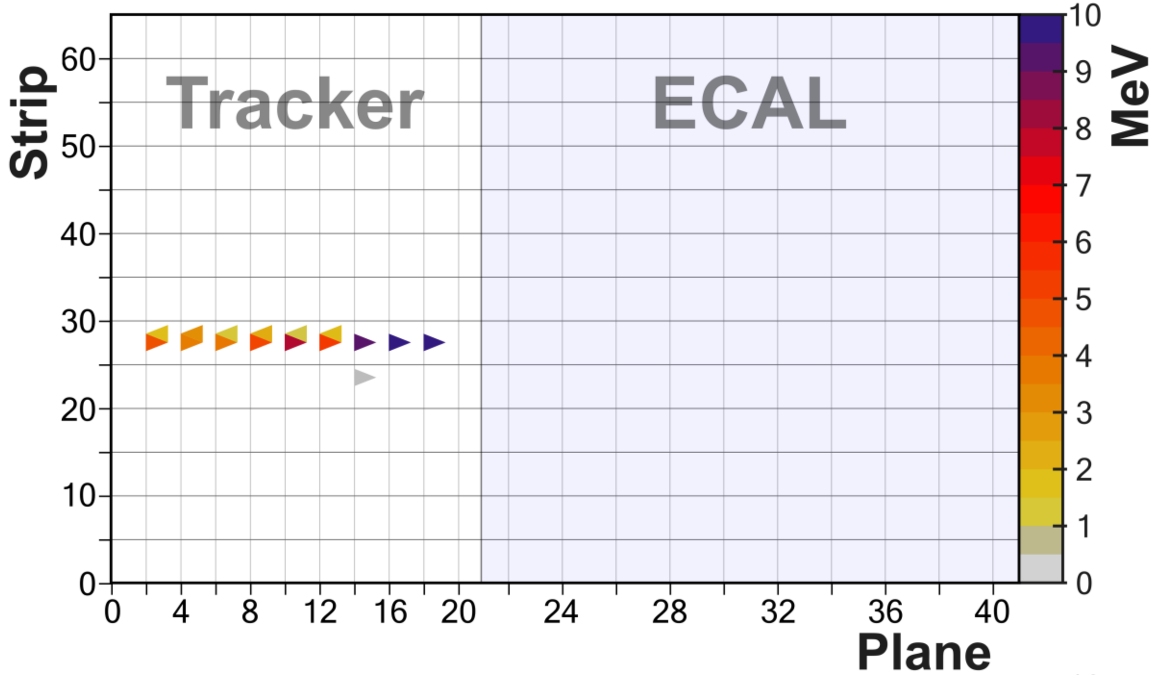
Scintillator: 1.7 cm thick, arranged in X,U,V

Tracker: no absorber

ECAL: 1.99 mm thick lead between scintillator planes

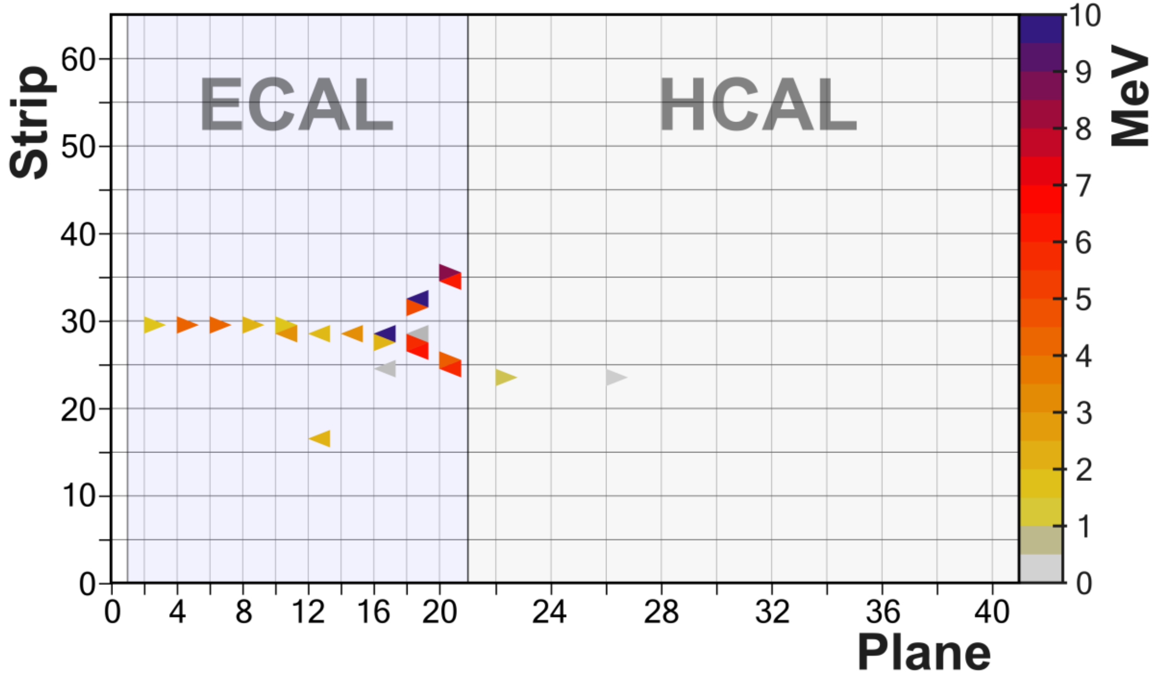
HCAL: 26 mm thick iron between scintillator planes

Took data in 2 different configurations



Pb and Fe absorber is reconfigured in two configurations
“TE” = tracker + ECAL
and
“EH” = ECAL + HCAL

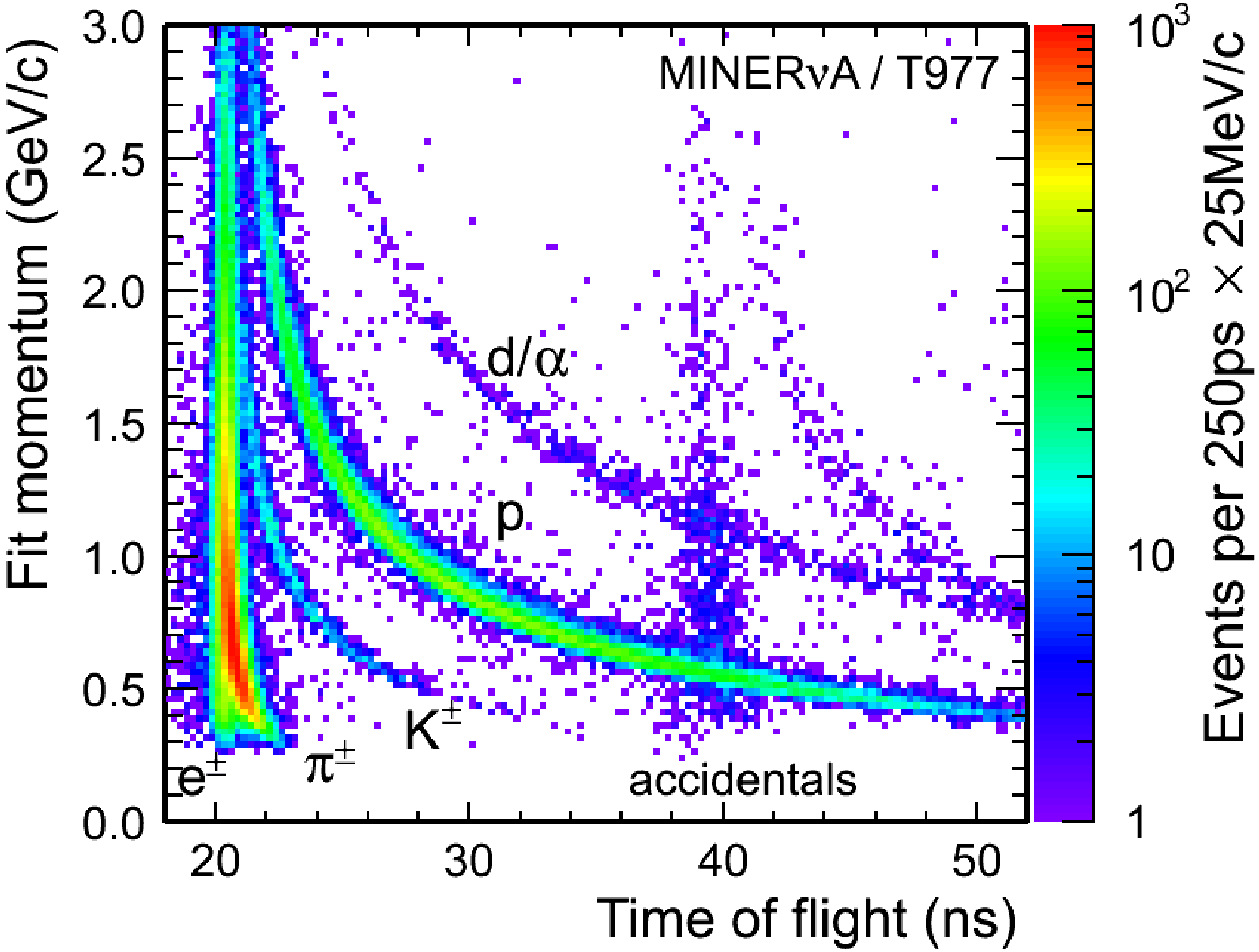
Proton stopping event
kinetic energy 220 MeV



Pi- interacting event
total energy 710 MeV

Both events from data
Energy from measured beamline momentum

Particle samples from this beam



- Species selection done using TOF and P measurements
- Very little wrong-species background except for e π separation
- Accidentals are a byproduct of accelerator 53MHz RF structure

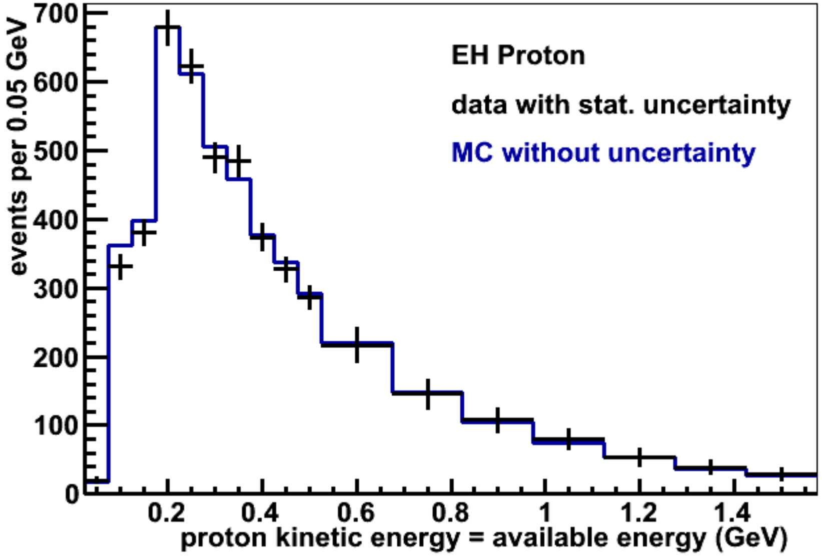
Data driven simulation

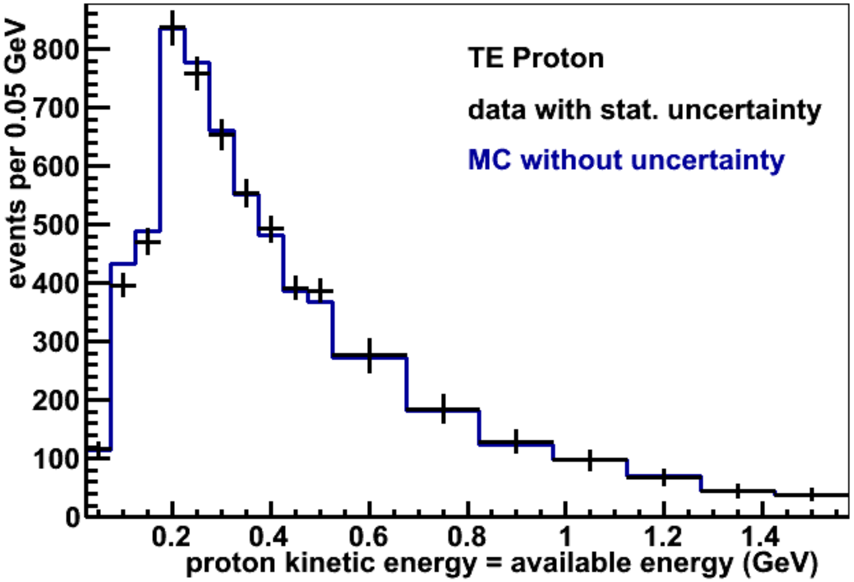
- Data events are used to seed the MC.
- They are started at WC3 and propagated to and into the detector by Geant4 9.4p2 with the QGSP_BERT hadronic physics list and required to pass all beam-detector cleaning/matching cuts
- They are smeared using particle-by-particle xy and p_z resolution and reused to give 20x to 40x MC samples.
- We do NOT use a simulation of the beamline (or its backgrounds)

Energy spectra

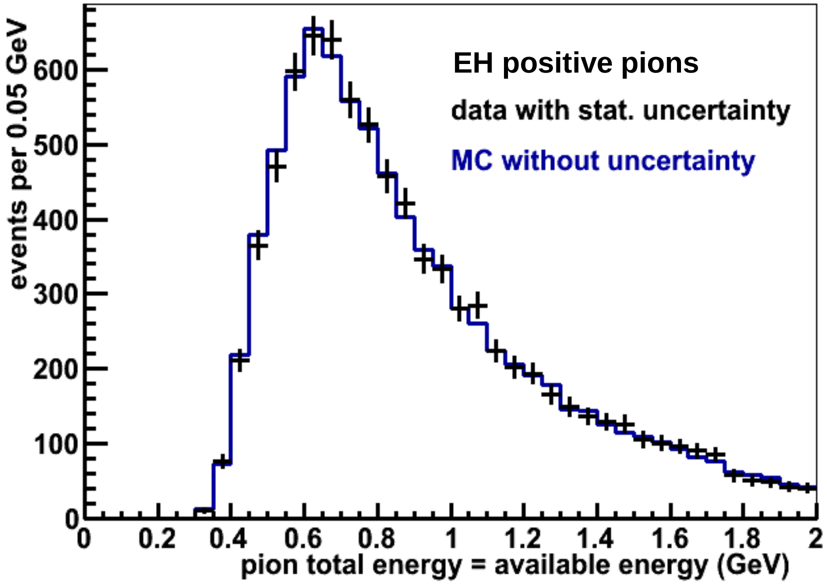
Spectra agree
by construction

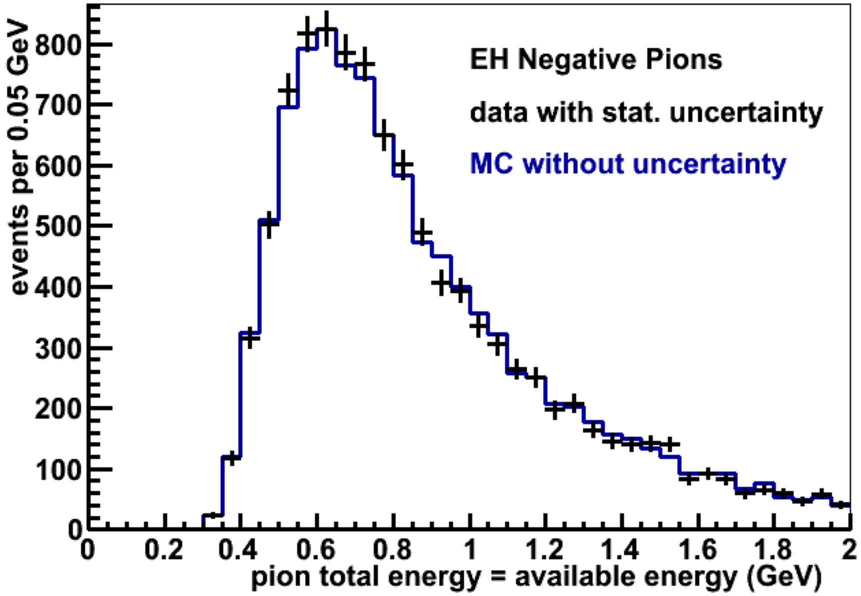
Protons

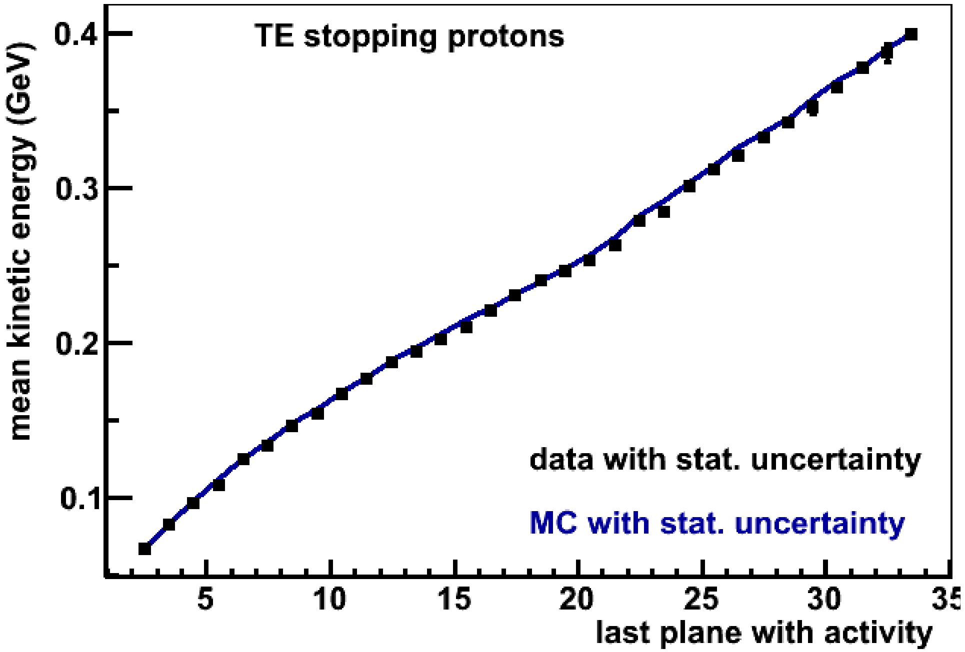


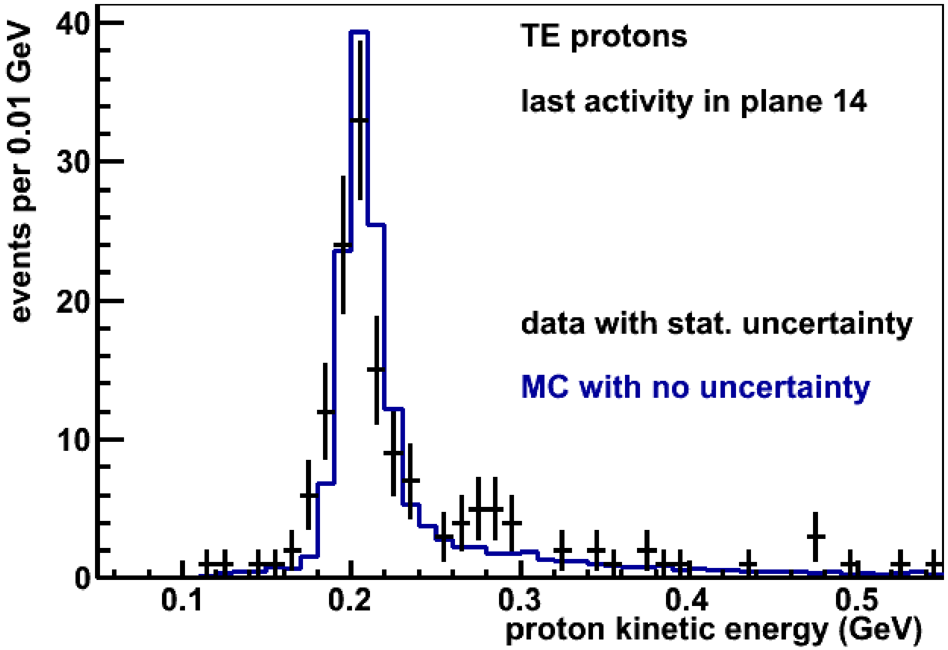


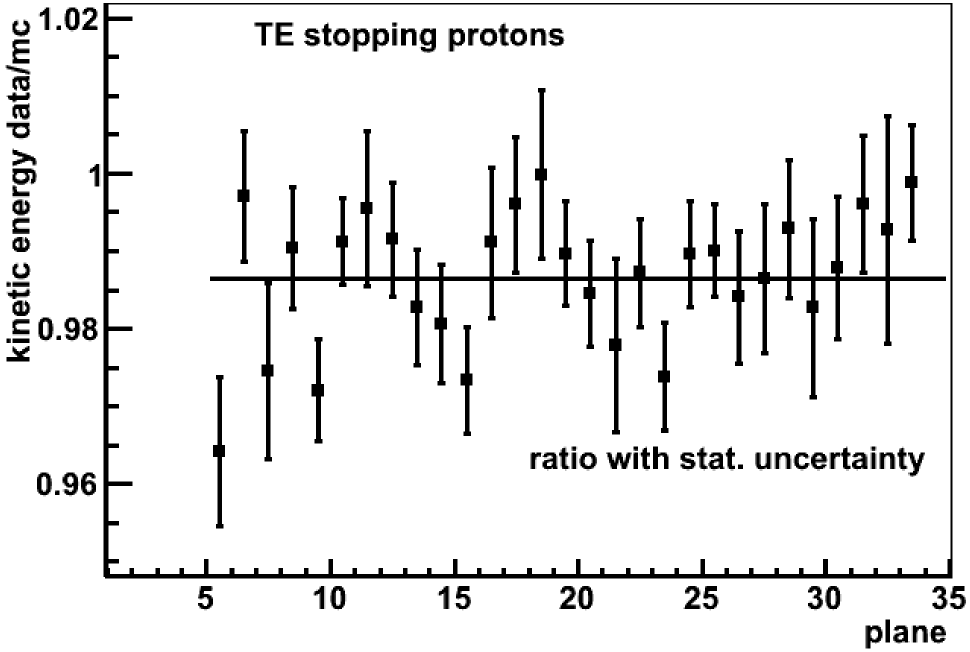
Pions (only EH config)











Proton range

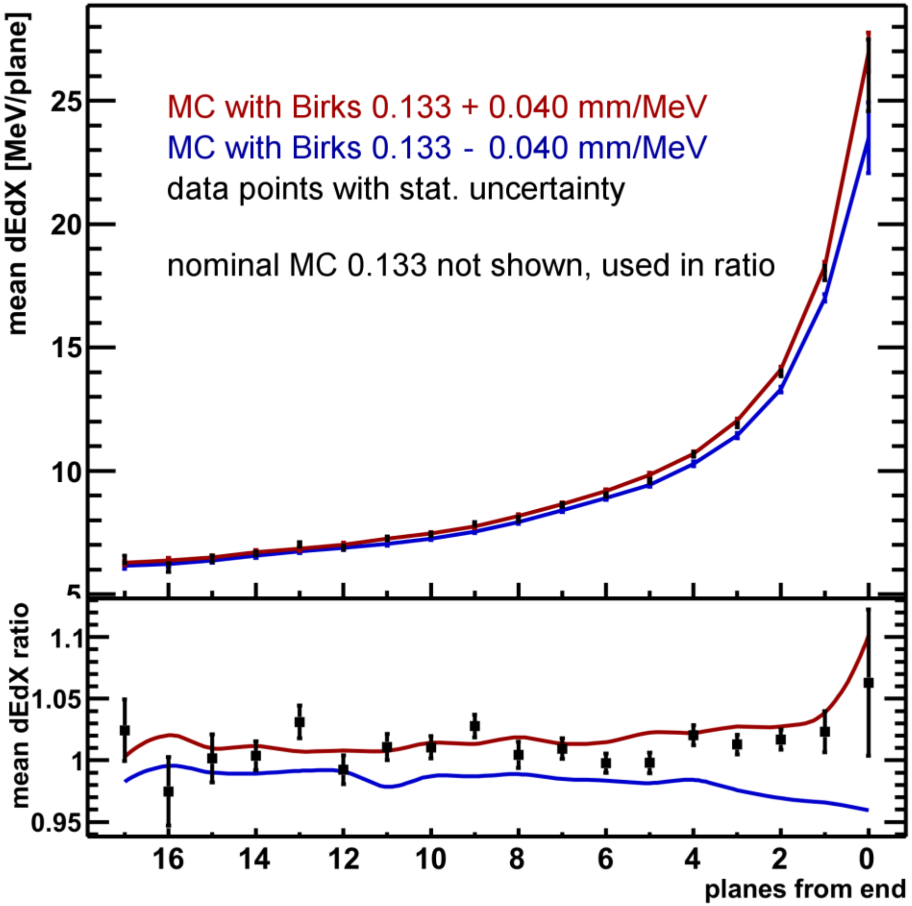
data points on the left
are mean of Gaussian fit to
peak like lower right
MC protons stop 1.3% short

Material Assay 1.5%
Beamline momentum 1.1%
Geant4 model uncertainty

Birks' law parameter calibration

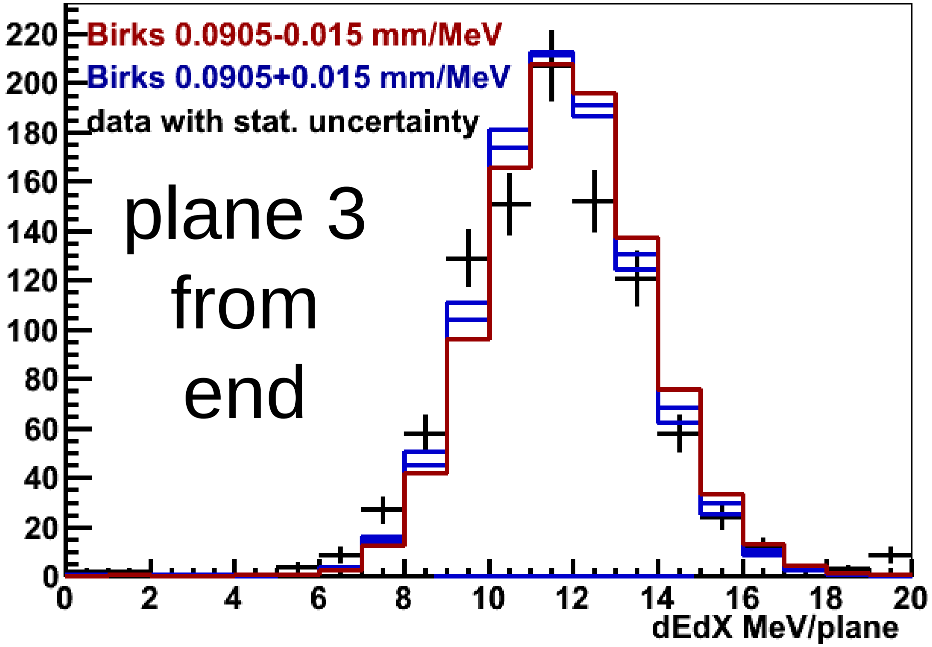
Birk’s law describes the quenching effect on scintillation photons produced by high, localized energy deposits. Will vary depending on specifics of detector.

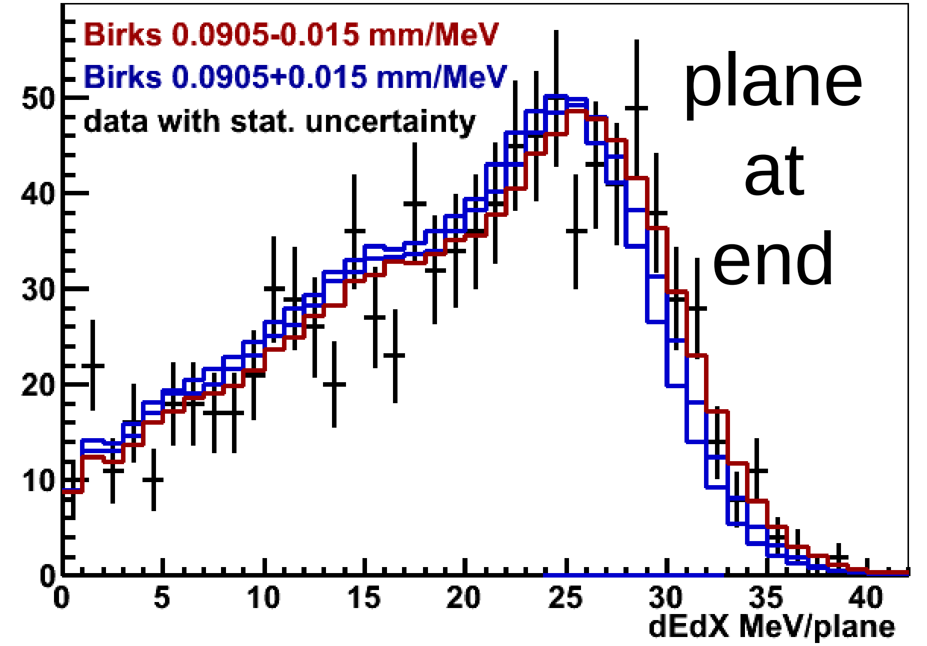
$$\text{Suppression factor} = \frac{1.0}{1.0 + \text{Birks Parameter} \times (dE/dx)}$$



For protons, dE/dx trend compared to nominal 0.133 ± 0.040 mm/MeV

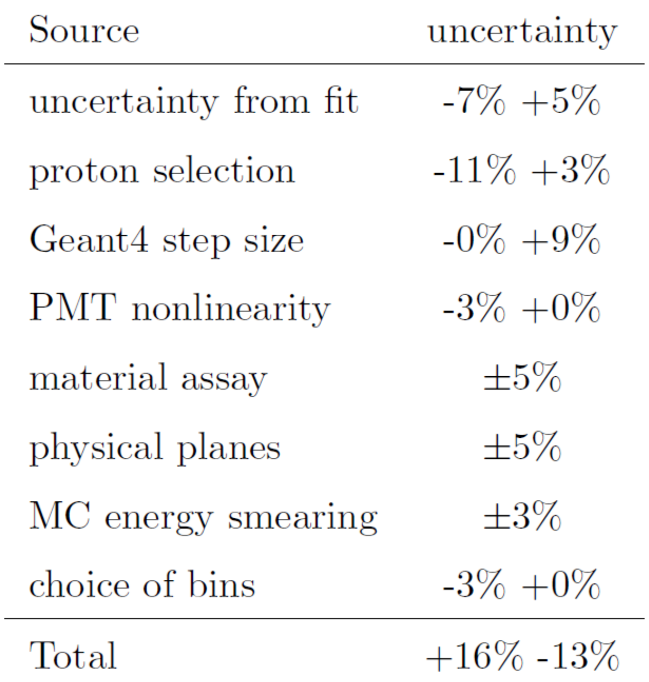
Birks' law parameter calibration





Best fit value found with iterative scan across three parameter space (in MC) of Birk’s parameter, energy scale, and smearing of reconstructed energy deposits

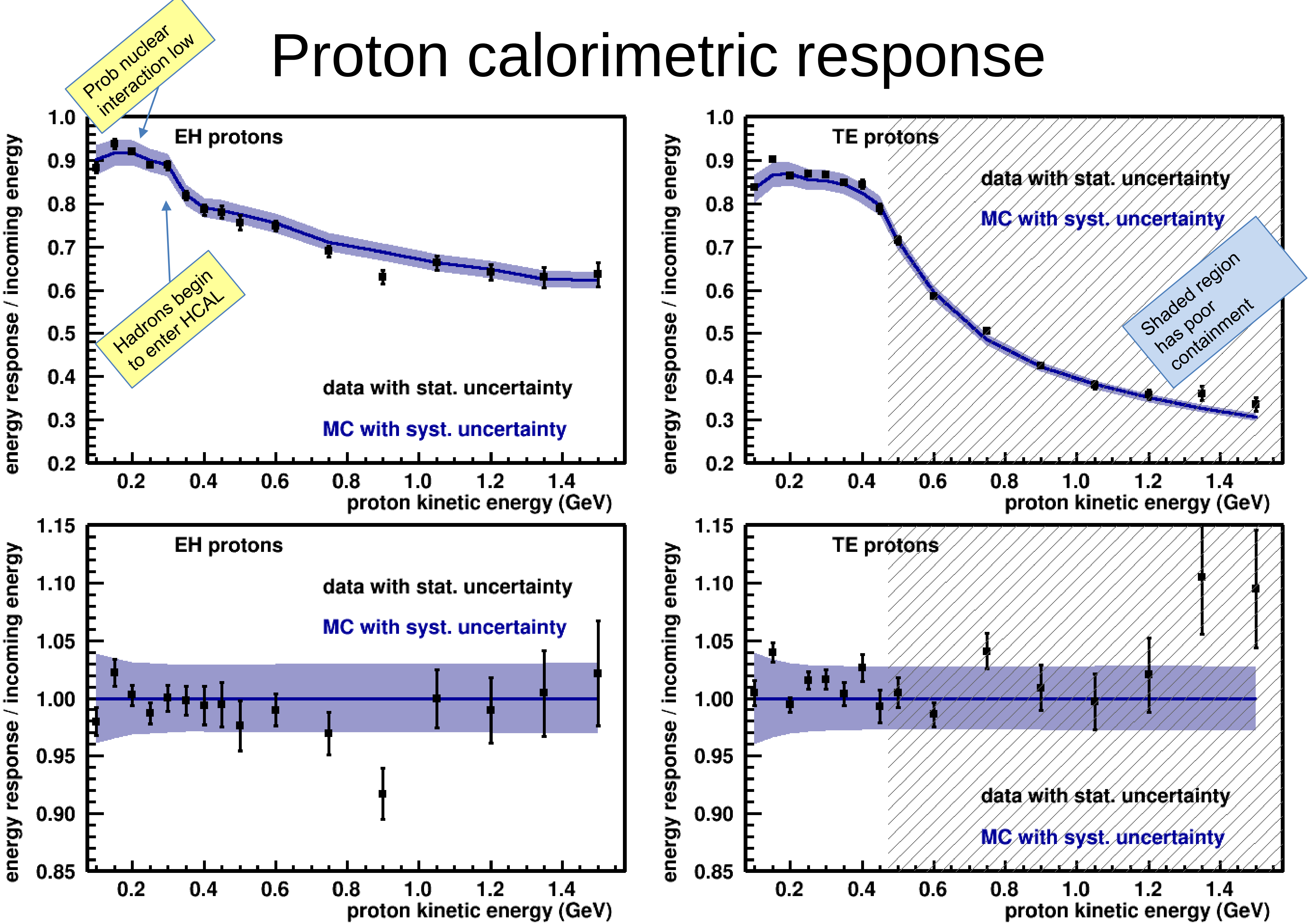
To left, profiles for individual points actually used to do the fit
shown at best fit 0.0905 ± 0.015



Source	uncertainty
uncertainty from fit	-7% +5%
proton selection	-11% +3%
Geant4 step size	-0% +9%
PMT nonlinearity	-3% +0%
material assay	±5%
physical planes	±5%
MC energy smearing	±3%
choice of bins	-3% +0%
Total	+16% -13%

Percent systematic uncertainties for Birk’s parameter evaluation.

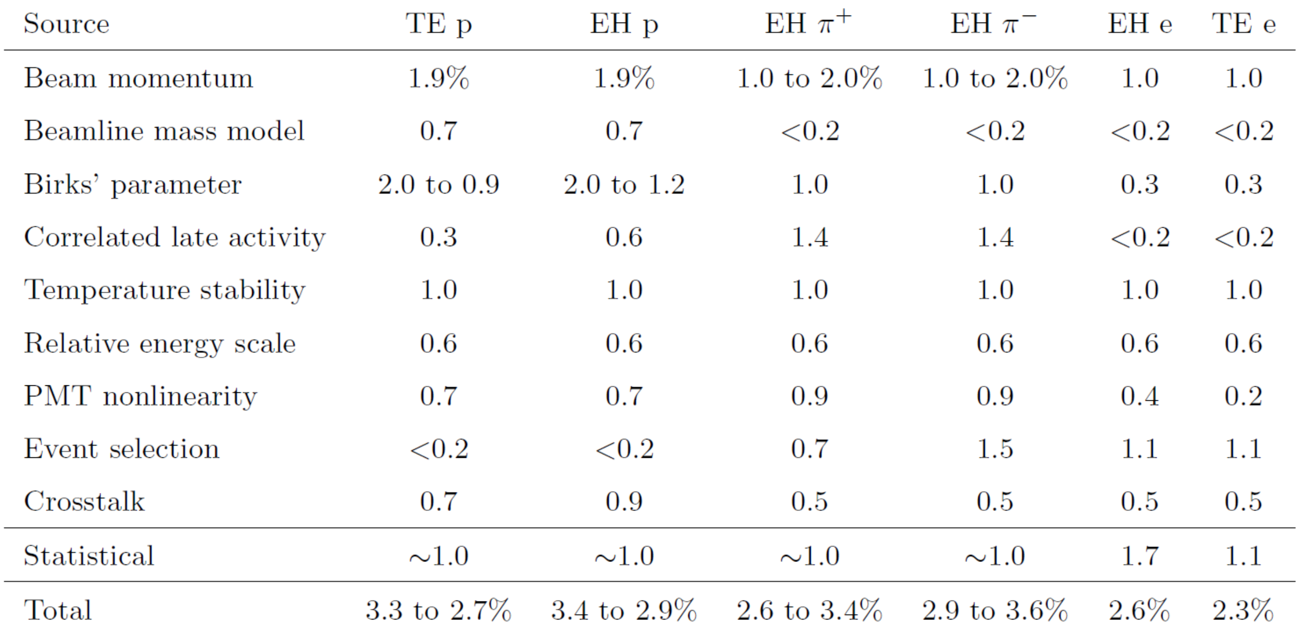
Proton calorimetric response



Prob nuclear interaction low

Hadrons begin to enter HCAL

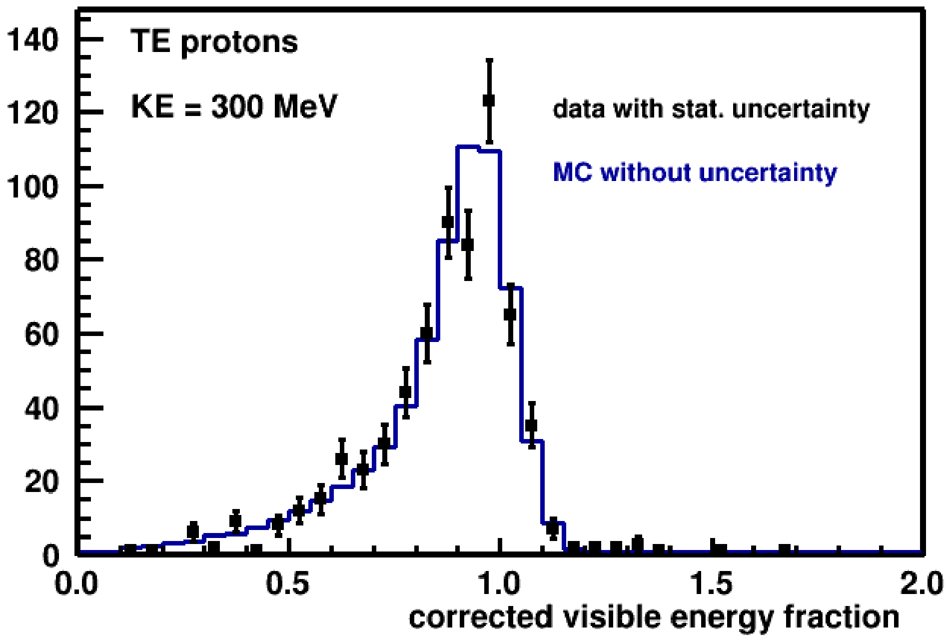
Shaded region has poor containment

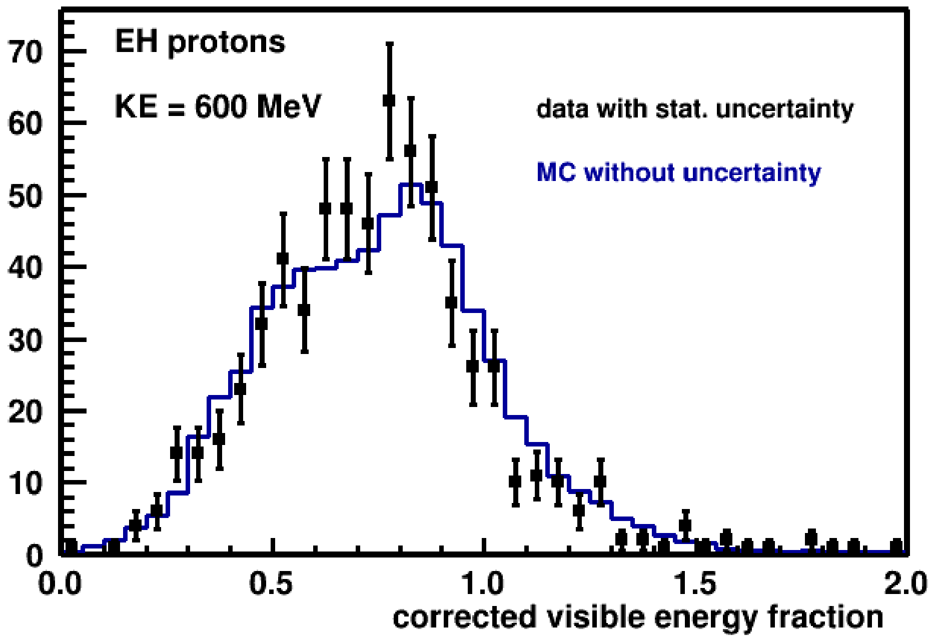


Source	TE p	EH p	EH π^+	EH π^-	EH e	TE e
Beam momentum	1.9%	1.9%	1.0 to 2.0%	1.0 to 2.0%	1.0	1.0
Beamline mass model	0.7	0.7	<0.2	<0.2	<0.2	<0.2
Birks' parameter	2.0 to 0.9	2.0 to 1.2	1.0	1.0	0.3	0.3
Correlated late activity	0.3	0.6	1.4	1.4	<0.2	<0.2
Temperature stability	1.0	1.0	1.0	1.0	1.0	1.0
Relative energy scale	0.6	0.6	0.6	0.6	0.6	0.6
PMT nonlinearity	0.7	0.7	0.9	0.9	0.4	0.2
Event selection	<0.2	<0.2	0.7	1.5	1.1	1.1
Crosstalk	0.7	0.9	0.5	0.5	0.5	0.5
Statistical	$\sim$1.0	$\sim$1.0	$\sim$1.0	$\sim$1.0	1.7	1.1
Total	3.3 to 2.7%	3.4 to 2.9%	2.6 to 3.4%	2.9 to 3.6%	2.6%	2.3%

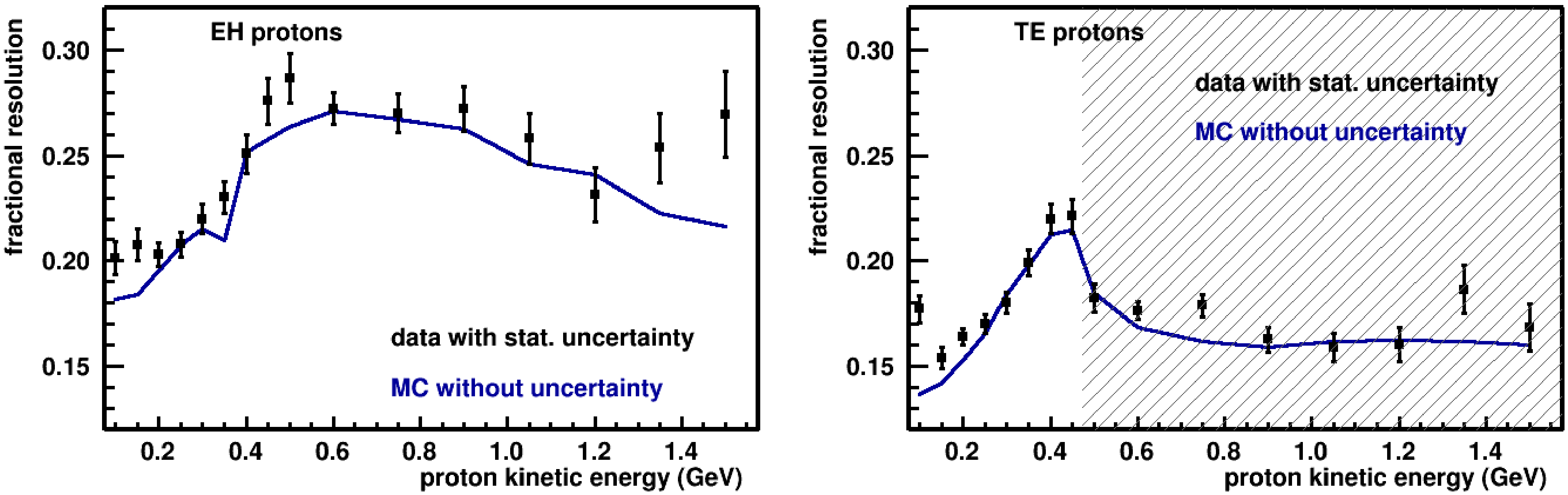
Errors for single particle fractional response.

Proton calorimetric response examples from two data points

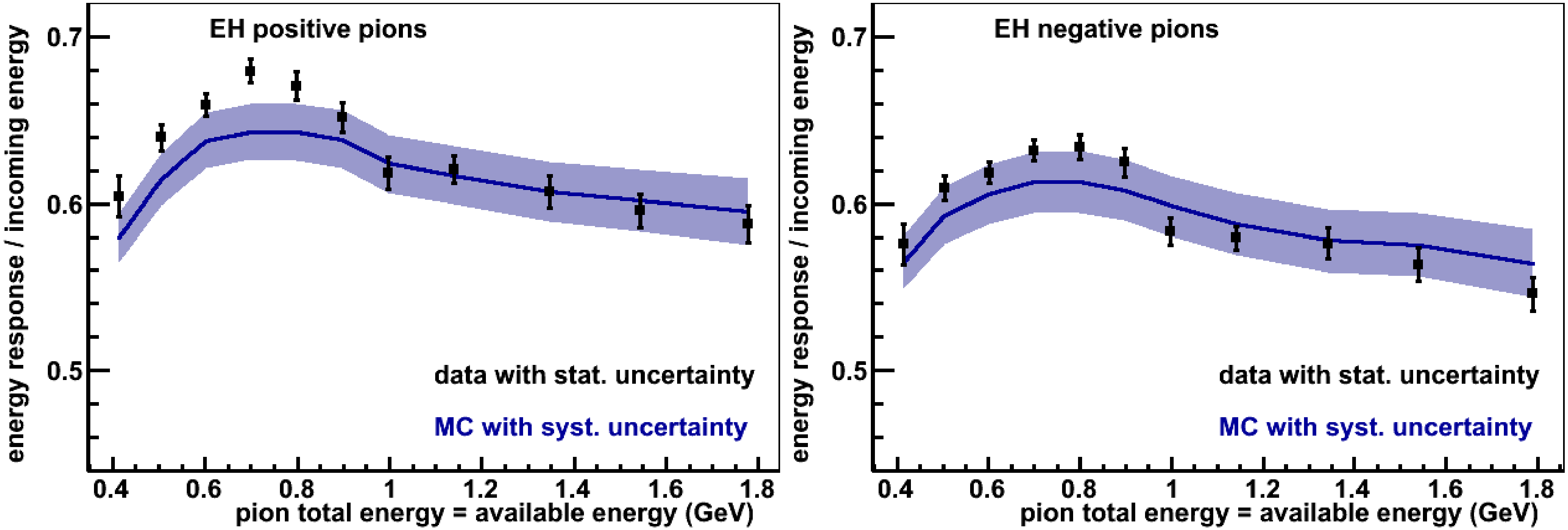




Proton calorimetric resolution



Pion calorimetric response

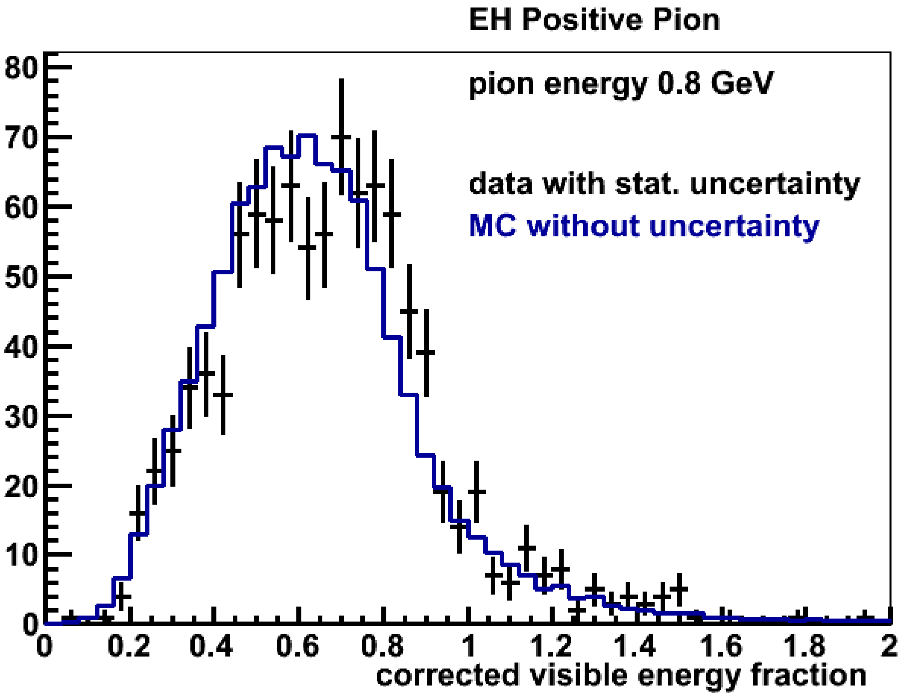


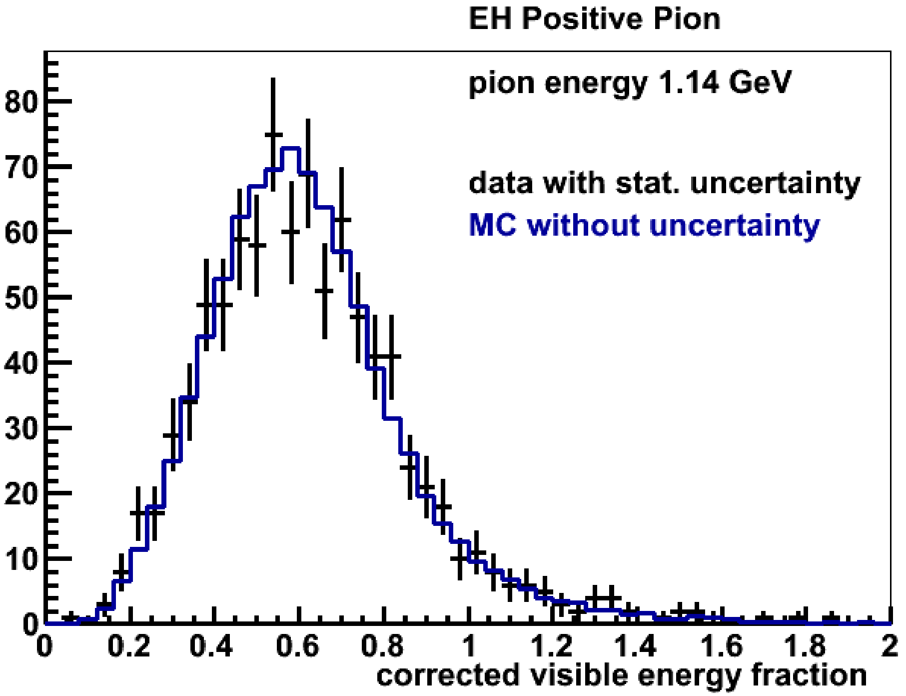
The ~0.03 error band is mostly correlated up and down.
Some uncertainties contribute to a
gentle ±0.02 relative (high/low) change

Two examples of the data that go into the pi+ calorimetry result

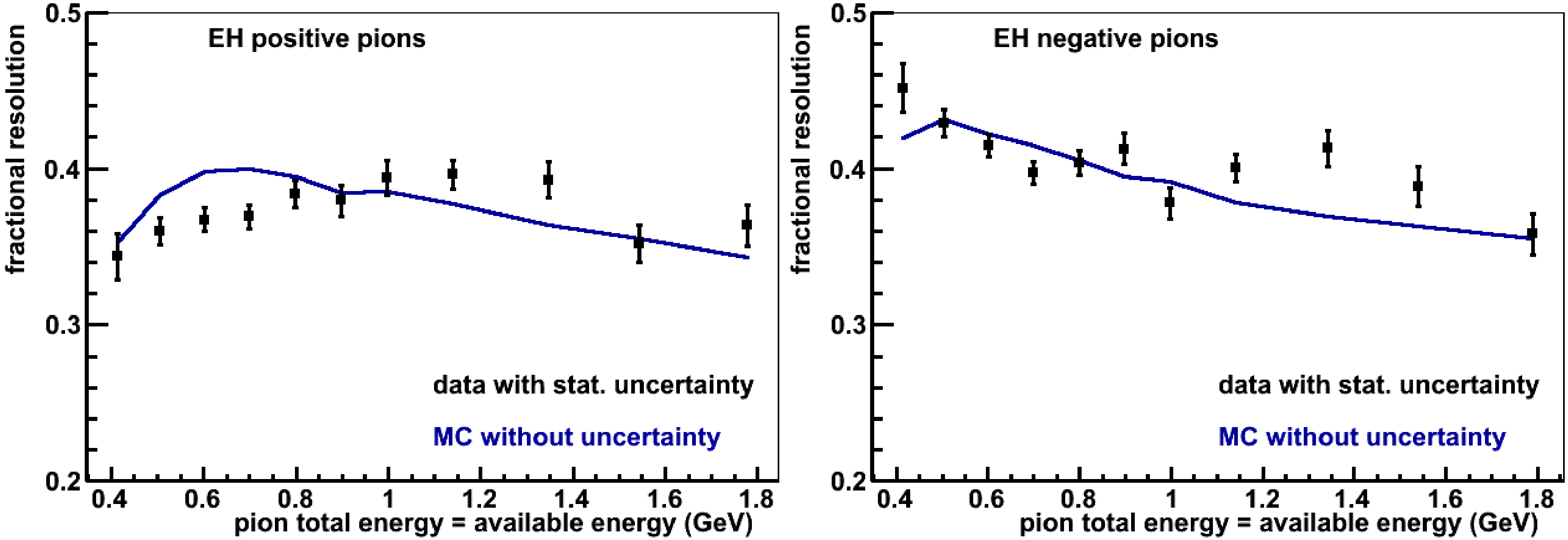
The corrected fraction is obtained event-by-event

The mean error on the mean RMS from each distribution are what are plotted for each bin in energy on next page

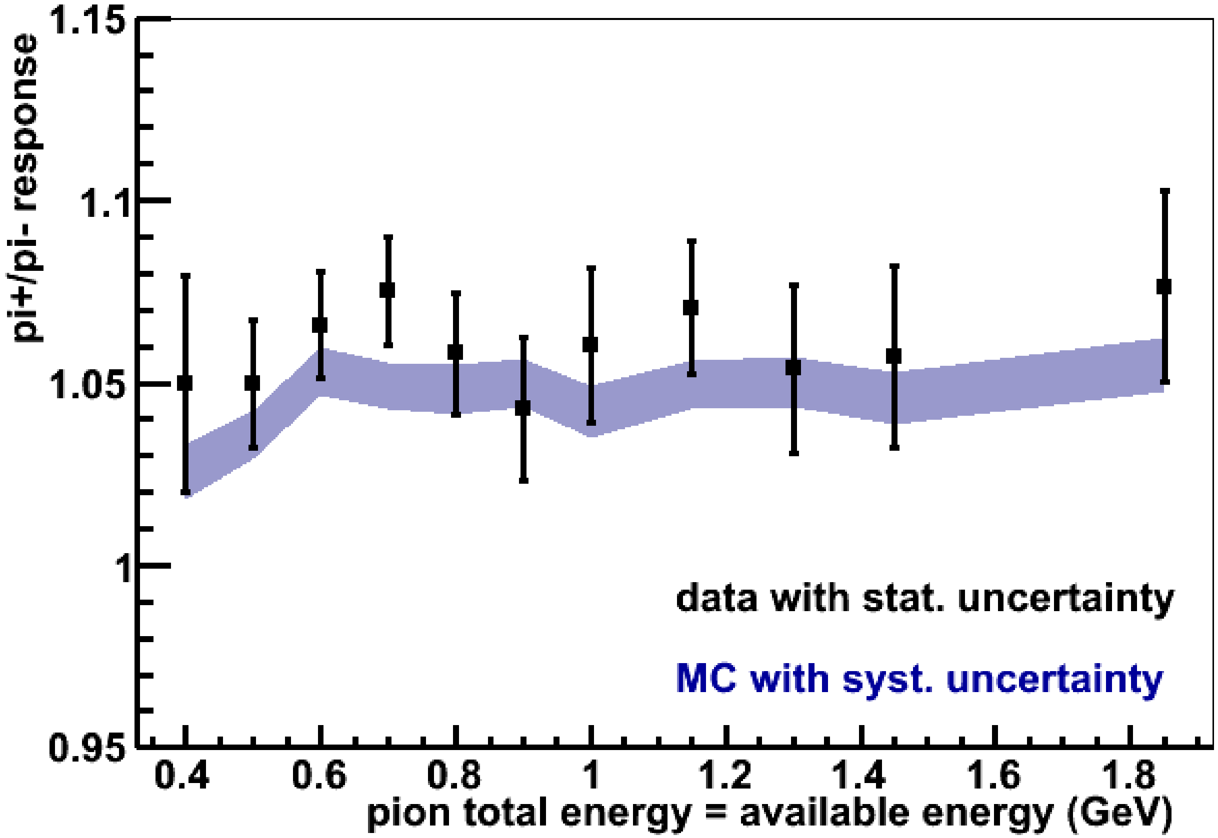




Pion fractional resolution (RMS)



ratio pi+ / pi- is flat, Geant4 is close to data



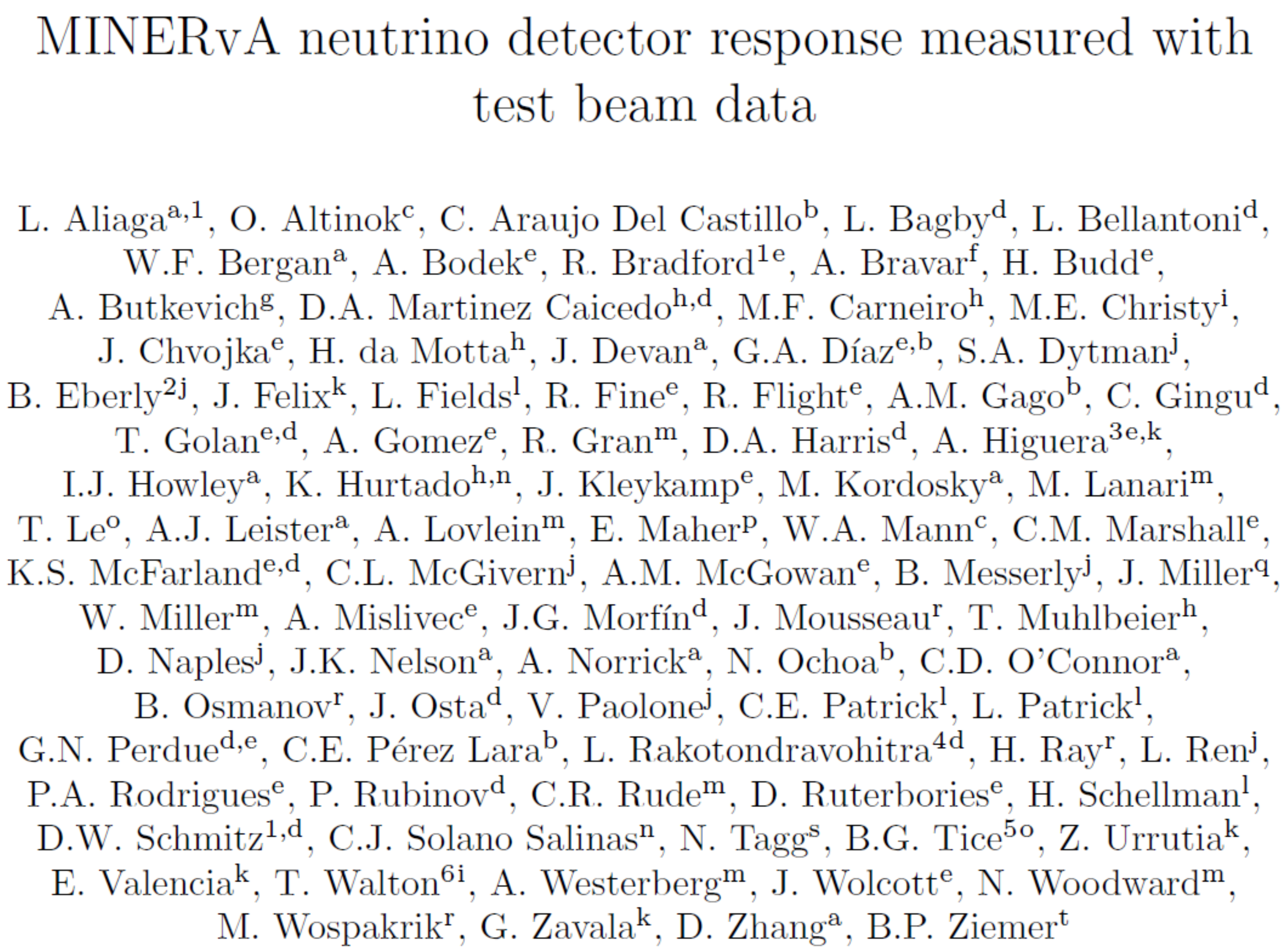
MC central value is with no systematic effects.
MC error band includes a 0.6% systematic
based on observed data running conditions between samples.
Data is everywhere high, just at or beyond one sigma.
5% pi+/pi- due to more neutron states after reaction for pi-

Some lessons for protoDUNE

No MINERvA approval for this list. My opinion and my selection of comments from people heavily involved in MINERvA's test beam experiments (Chris Marshall, Rik Gran, L. Bellantoni)

- Good idea to have functional software at start, including event display and ability to look for multiple tracks and activity not associated with triggered particle
- Calibration hard to do without data. But, good to start with something. MINERvA began with no timing calibration and no event display
- Helpful to have experienced DAQ/software people involved in effort. Pressure to use newbie students for experience while more experienced students working on thesis projects.
- Understand the specs of the beam to be delivered and set goals accordingly and/or discuss changes needed. (Momentum spread and intensity for different particle types and energies)
- Data taken mid-2010, NIM article published 2015, takes work/time to know what you are doing, more than 10 FTE years for calibration/analysis of TB data
- TB made a difference in our physics program. Birk analysis helped p vs. pi PID and enabled proton tagging part of 2p2h analysis.

Results shown in talk are from MINERvA’s first (low energy) test beam.



MINERvA neutrino detector response measured with test beam data

L. Aliaga[a,1], O. Altinok[c], C. Araujo Del Castillo[b], L. Bagby[d], L. Bellantoni[d],
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W. Miller[m], A. Mislivec[e], J.G. Morfín[d], J. Mousseau[r], T. Muhlbeier[h],
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B. Osmanov[r], J. Osta[d], V. Paolone[j], C.E. Patrick[l], L. Patrick[l],
G.N. Perdue[d,e], C.E. Pérez Lara[b], L. Rakotondravohitra[4d], H. Ray[r], L. Ren[j],
P.A. Rodrigues[e], P. Rubinov[d], C.R. Rude[m], D. Ruterbories[e], H. Schellman[l],
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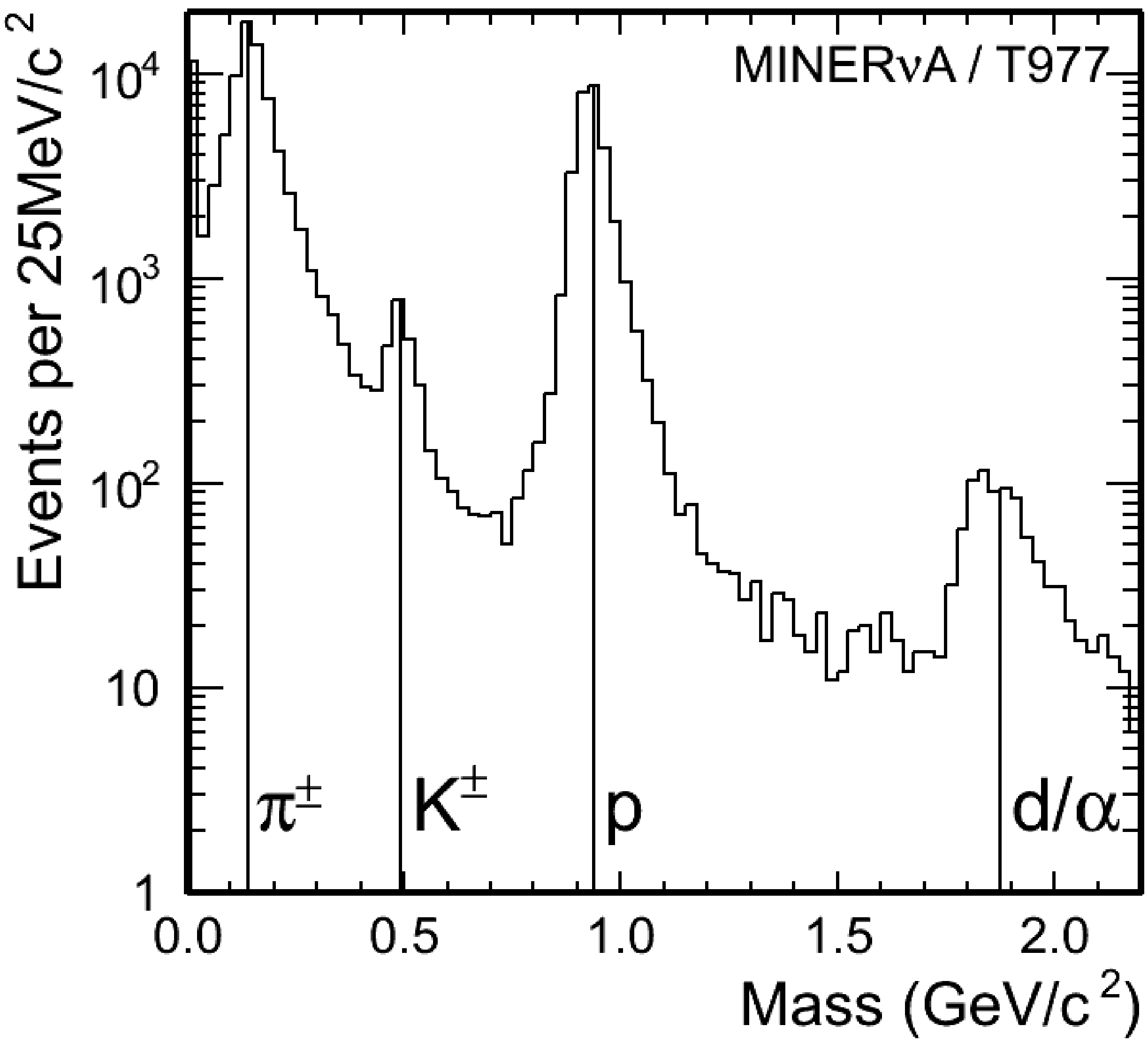
M. Wospakrik[r], G. Zavala[k], D. Zhang[a], B.P. Ziemer[t]

Thanks to Fermilab Test Beam Facility and Accelerator Division. The test beam detector design/construction was funded by an MRI from NSF.

Same data presented as reconstructed mass

log
scale!

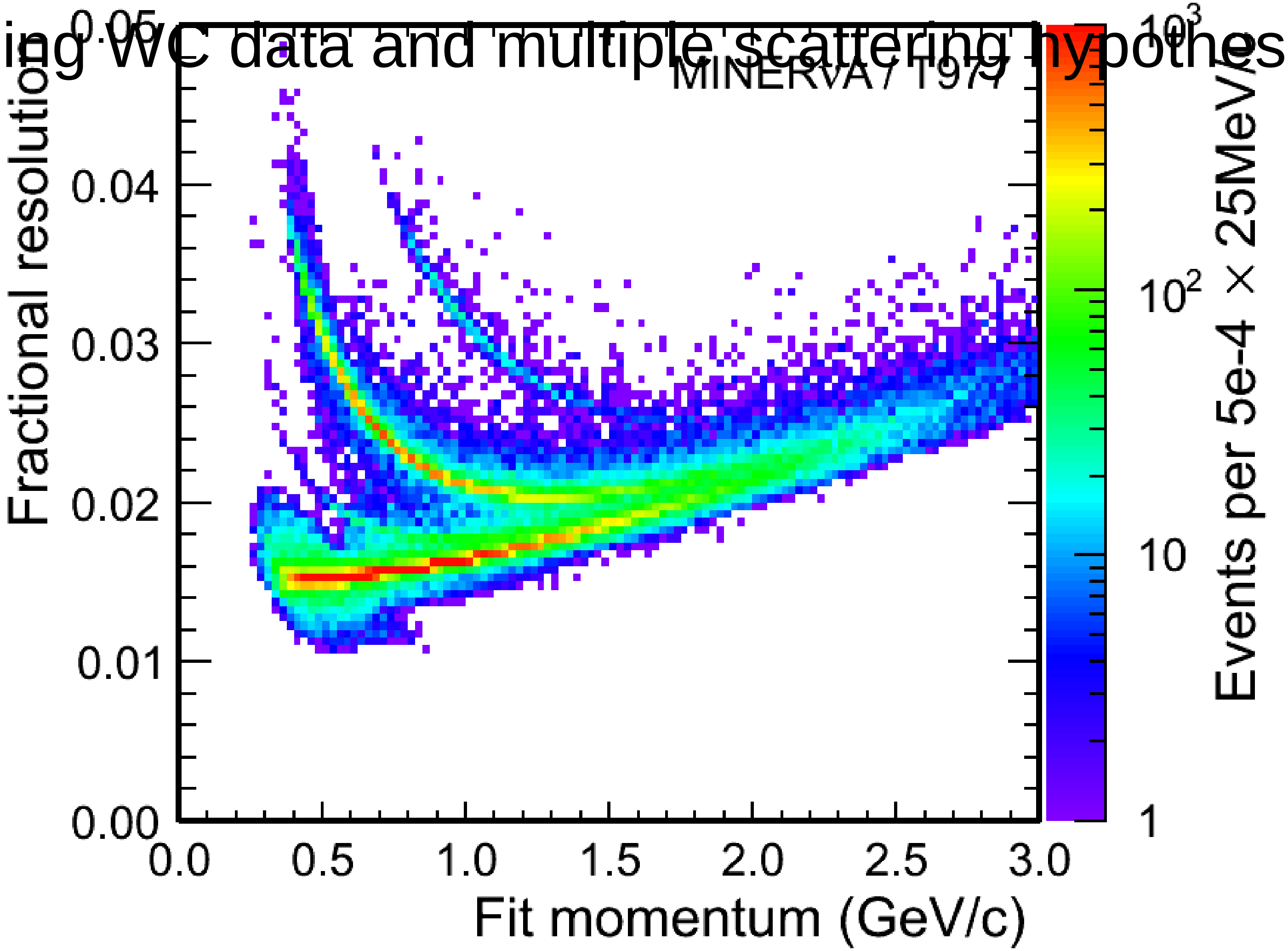


TOF resolution -> fluctuates to superluminal (mass undefined)

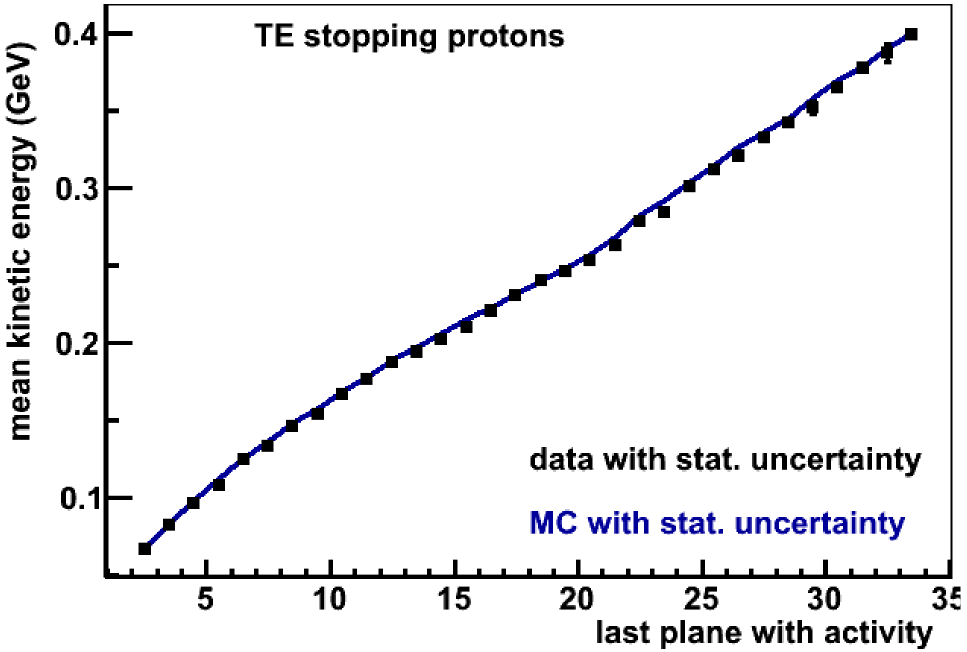
and are at 0.0 in this plot, but we keep those events anyway.

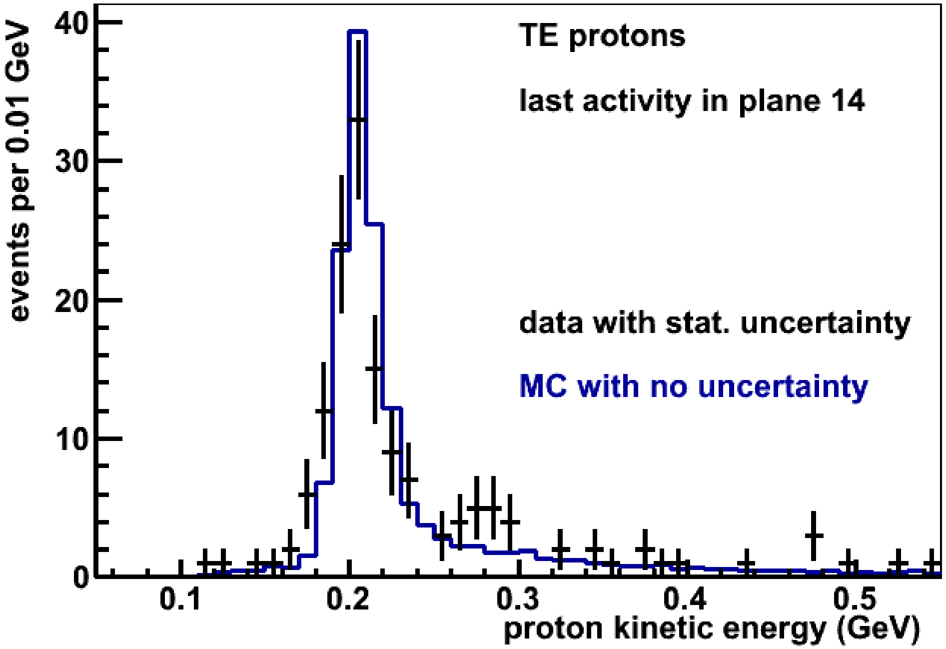
Resolution from Kalman fit, particle by particle

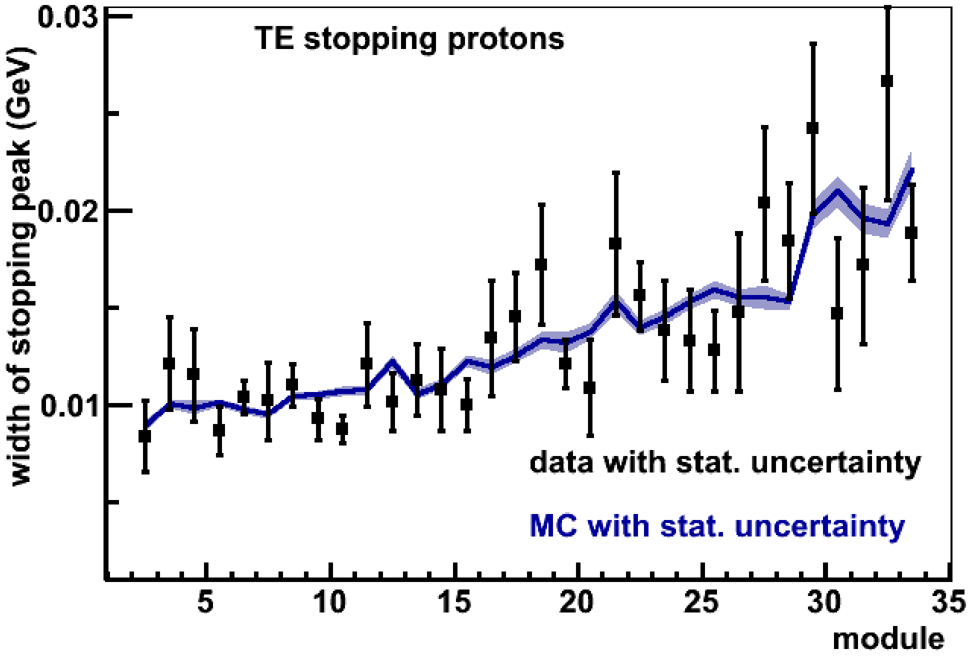
Resolution is figured on a particle by particle basis
using WC data and multiple scattering hypothesis



Experiment simulation is seeded from data
particles







Beamline resolution

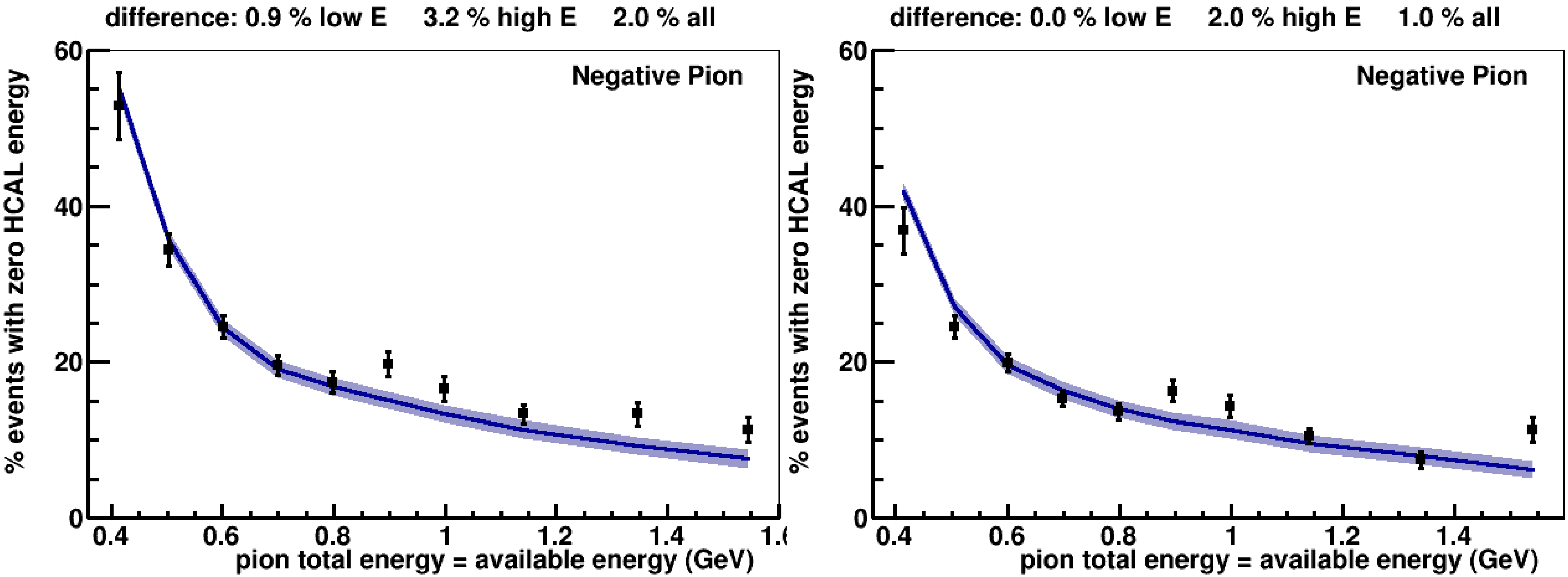
Top plots from previous slide.

Bottom plot shows the width of the stopping peak

This resolution is dominated by beamline characteristics and multiple scattering

our data-driven simulation gets it right

percent of events with negligible HCAL energy



These are events that were contained in the ECAL (low energy) and/or scattered hard out the side or backscattered out the front

The 0.9 GeV artifact shows up here too

Experiment systematic shift 1.2% (relative data to MC)

highly correlated up/down, has negligible energy dependence

sensitivity to Geant4 physics

The following figures show shifted MC vs nominal MC
The shifted MC is pretty extreme choice.

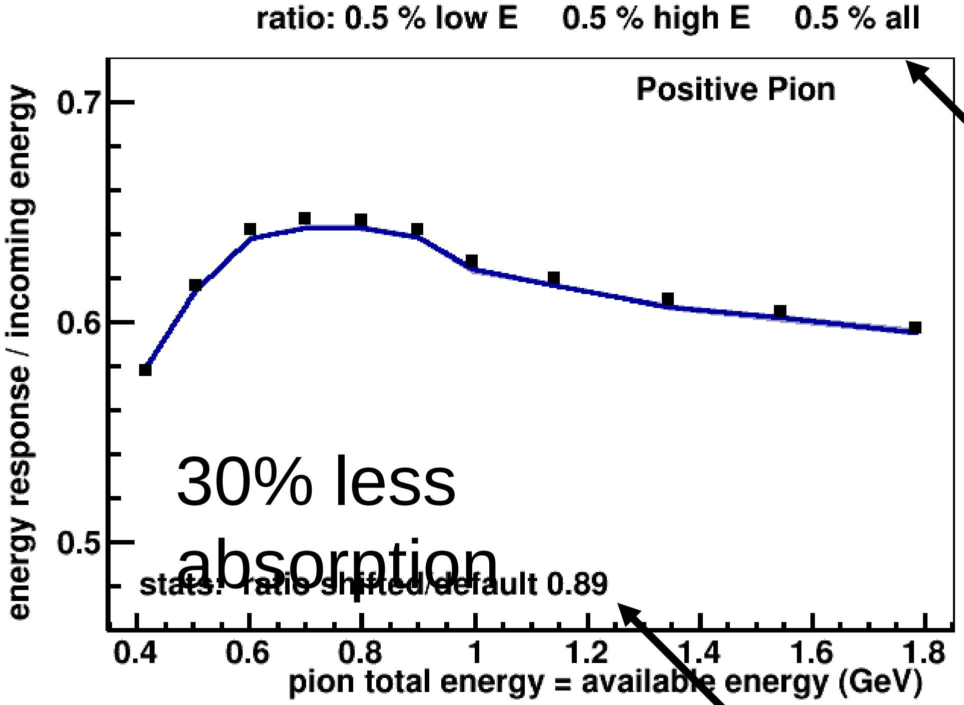
The shifted cross section is done in Geant4, increasing it 20%

The fate shifts are done using a random picker
to remove events before histogramming and averaging them
(like a downward-only reweight) based on
what happens at the truth first interaction point
or how far downstream that point was.

operational definition of first interaction point
first place where an inelastic scatter happens
or where an elastic scatter transfers at least 10 MeV

Large changes in the relative fraction of events
undergoing particular fates have a small effect on calorimetry.

detail on each of the next slides



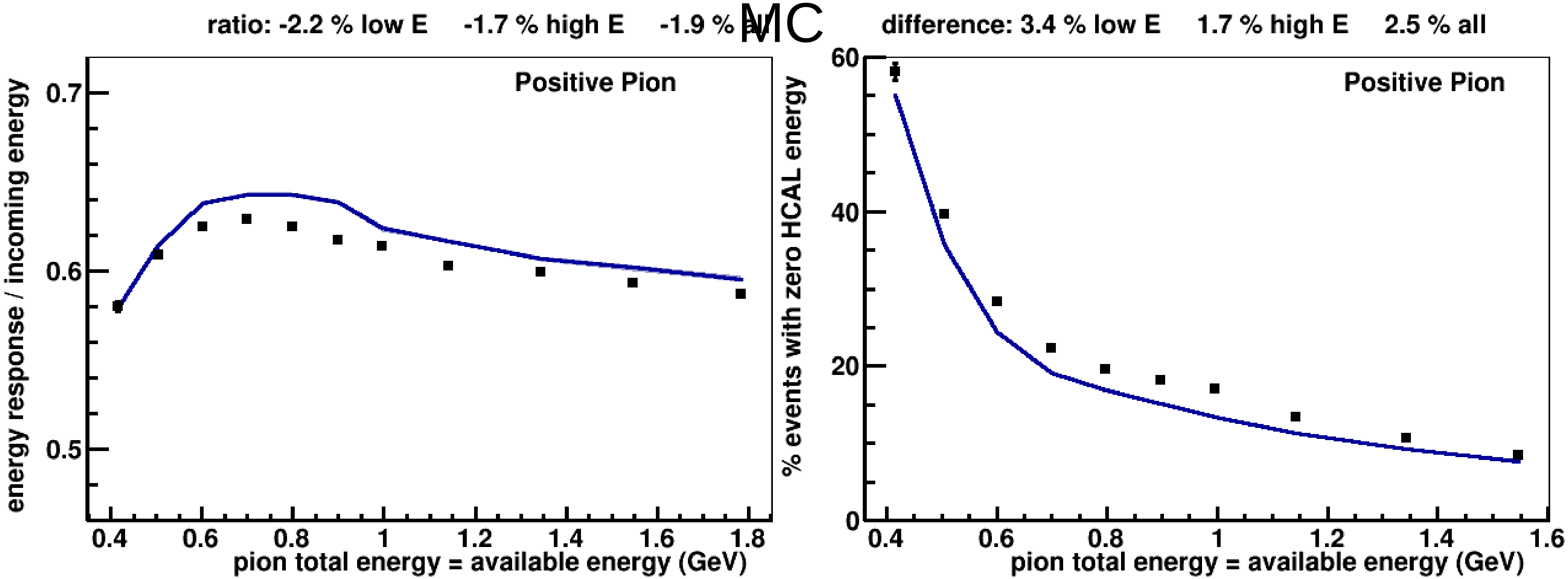
30% less absorption

If the change is very small then use the % change printed here, an average over five, ten data points

Fraction fewer events (removed by random picker) in the modified MC
If this is 30% less absorption you can how much total absorption there was

pi+ response with change in mean free path

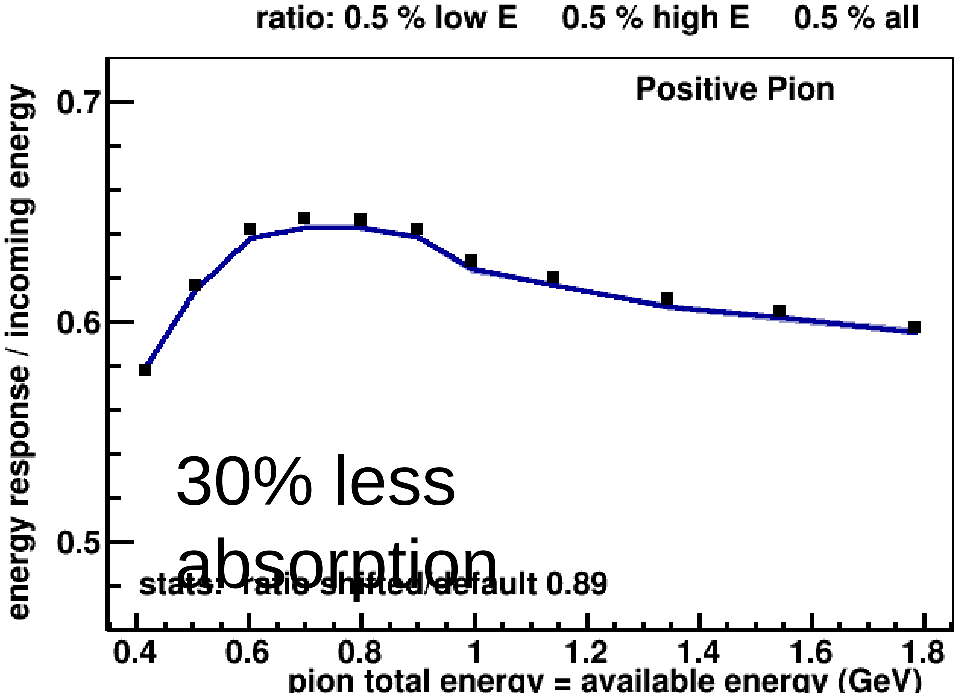
Points are new MC with 20% higher pi+N σ, line is nominal MC



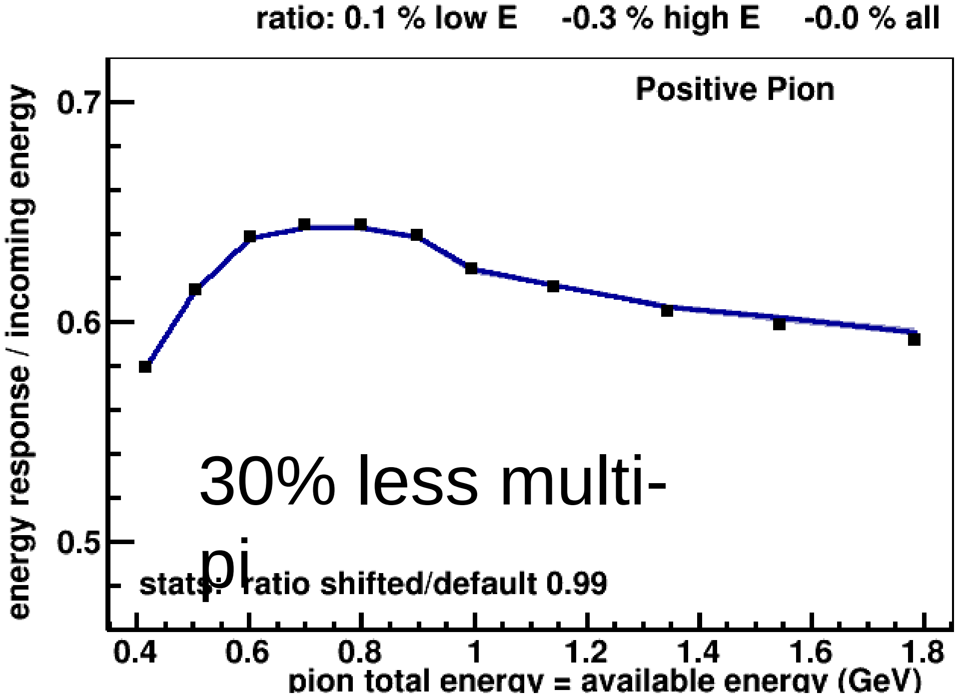
Change to response and zero HCAL
changing the cross section used by the Geant4
simulation
a 20% increase across all pion energies

pi+ response with change in interaction fates

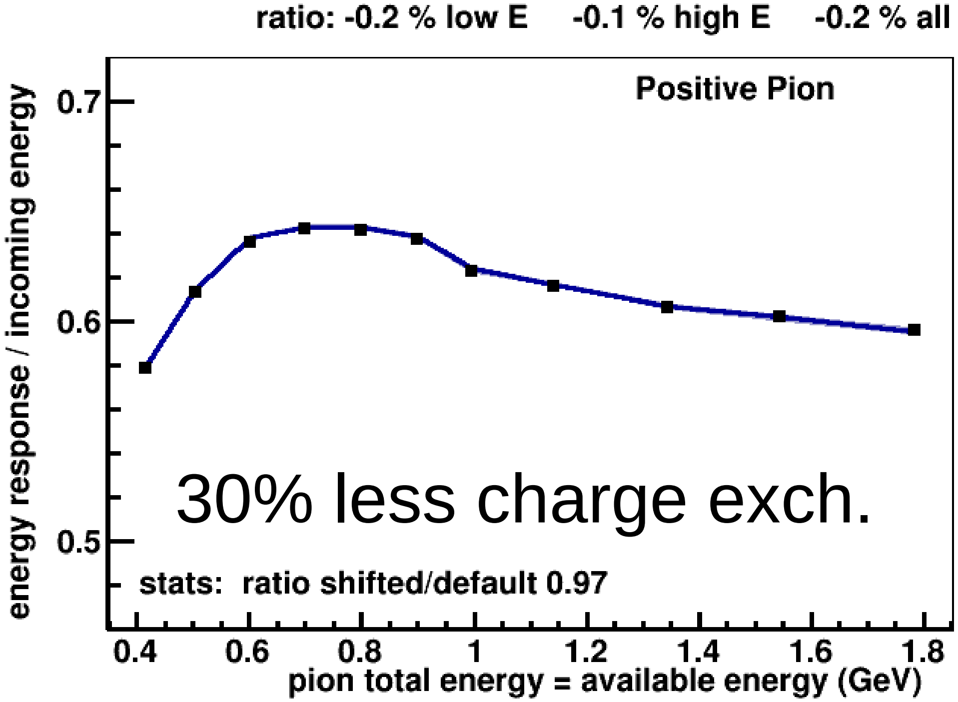
Fraction of percent difference in calorimetry, with these pretty healthy changes in fates


ratio: 0.5 % low E 0.5 % high E 0.5 % all

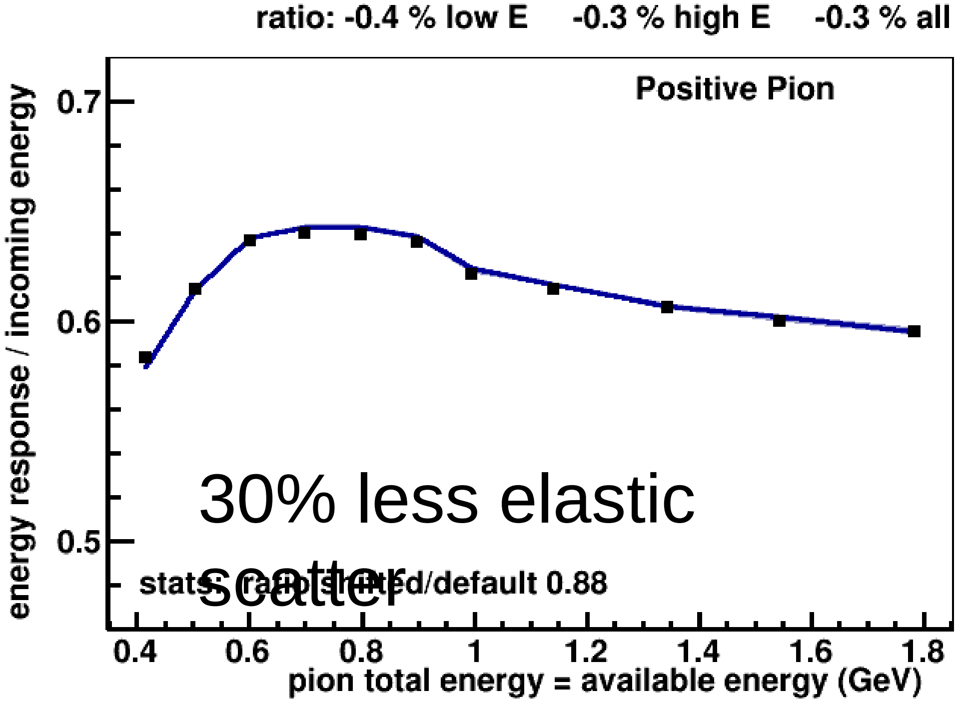
30% less absorption


ratio: 0.1 % low E -0.3 % high E -0.0 % all

30% less multi-pi


ratio: -0.2 % low E -0.1 % high E -0.2 % all

30% less charge exch.


ratio: -0.4 % low E -0.3 % high E -0.3 % all

30% less elastic scatter

The sensitivity plots stand on their own merit.
The data/MC comparisons also stand on their own merit.

It is reasonable to try to draw a conclusion
by putting these figures on slides one after another.
that conclusion would be hard to wrap a NIM around or event a long talk
but might naturally come up in discussion after a talk
so here are potential talking points, if the audience drives this interest

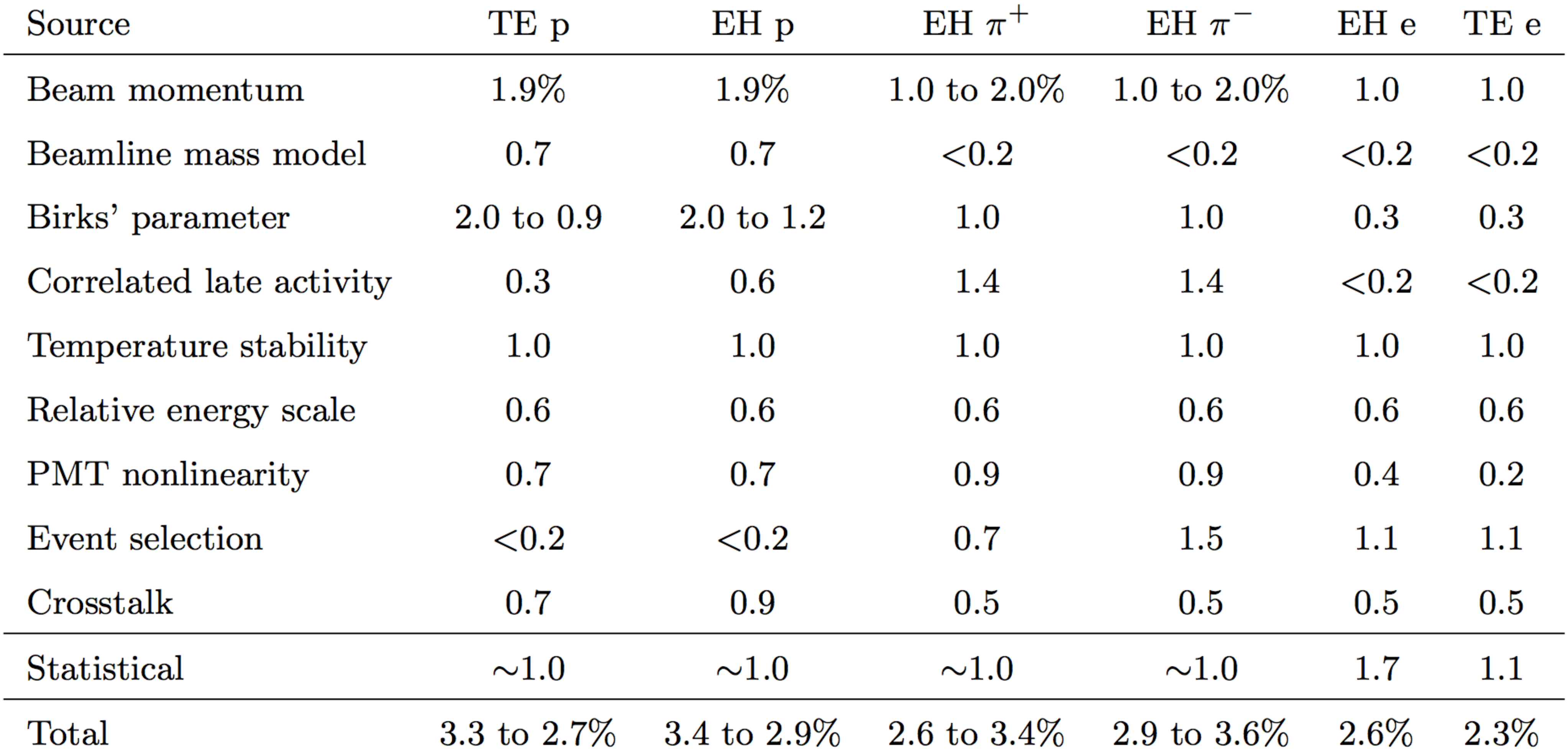
Beamline and detector systematic at two-sigma can produce discrepancies
with magnitudes approaching what is shown, maybe.

But no individual systematics we looked at can
produce the convolution of effects shown simultaneously:
A discrepancy that changes around 0.9 GeV pions, high vs. low energy
affects both response and zero HCAL at the same place
and affects both pi+ and pi- the same
goes wrong way compared to missing contamination
does not seem to affect protons at the same beam momenta

clear answer? hmm. Candidate: something funny about Geant4
does not change starting near 0.9 GeV but reality does ? Really?

In principle, we have additional topological information to analyze
if the interest, effort, and payoff all line up.

calorimetry systematics table from the paper



Source	TE p	EH p	EH π^+	EH π^-	EH e	TE e
Beam momentum	1.9%	1.9%	1.0 to 2.0%	1.0 to 2.0%	1.0	1.0
Beamline mass model	0.7	0.7	<0.2	<0.2	<0.2	<0.2
Birks' parameter	2.0 to 0.9	2.0 to 1.2	1.0	1.0	0.3	0.3
Correlated late activity	0.3	0.6	1.4	1.4	<0.2	<0.2
Temperature stability	1.0	1.0	1.0	1.0	1.0	1.0
Relative energy scale	0.6	0.6	0.6	0.6	0.6	0.6
PMT nonlinearity	0.7	0.7	0.9	0.9	0.4	0.2
Event selection	<0.2	<0.2	0.7	1.5	1.1	1.1
Crosstalk	0.7	0.9	0.5	0.5	0.5	0.5
Statistical	~1.0	~1.0	~1.0	~1.0	1.7	1.1
Total	3.3 to 2.7%	3.4 to 2.9%	2.6 to 3.4%	2.9 to 3.6%	2.6%	2.3%

electron support plots

There is only 400 to 500 MeV for the electron response
so there are no plots in the manuscript.

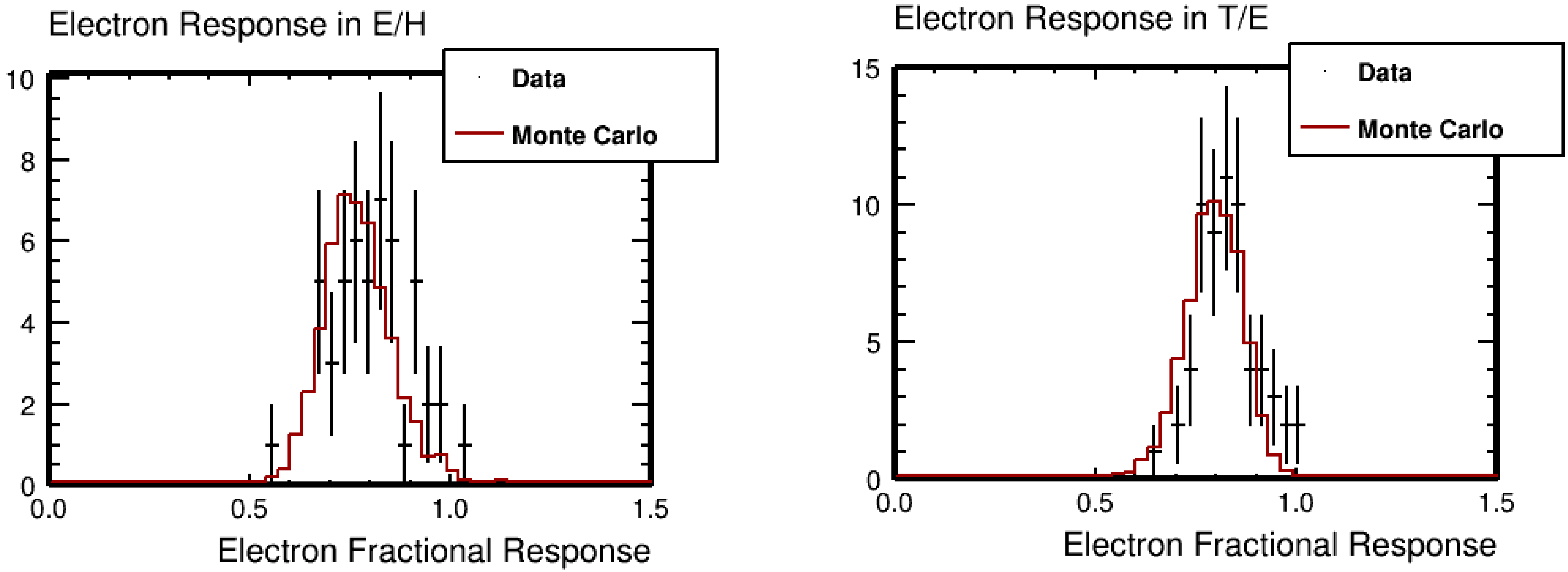
For expert giving technical talk
how the electrons were separated from pions
using topology information from testbeam MINERvA
detector

more complicated than separating pions and protons
which the beamline tags exceptionally well

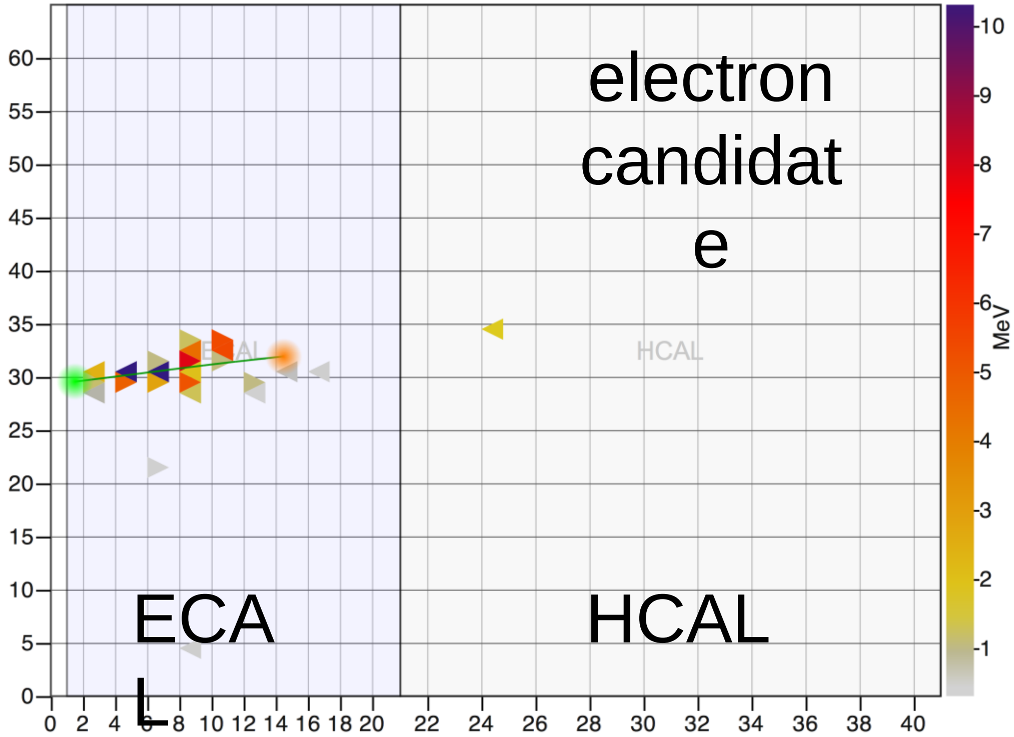
but topological electron tagging is a topic of interest in itself

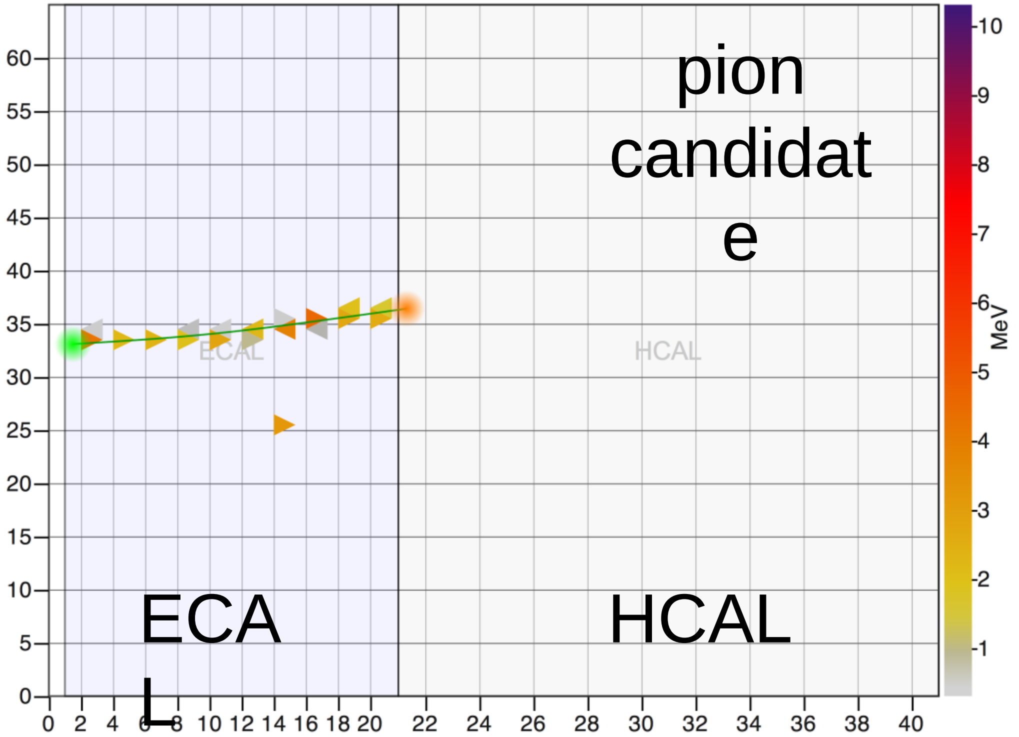
and its all kind of fun, of course.

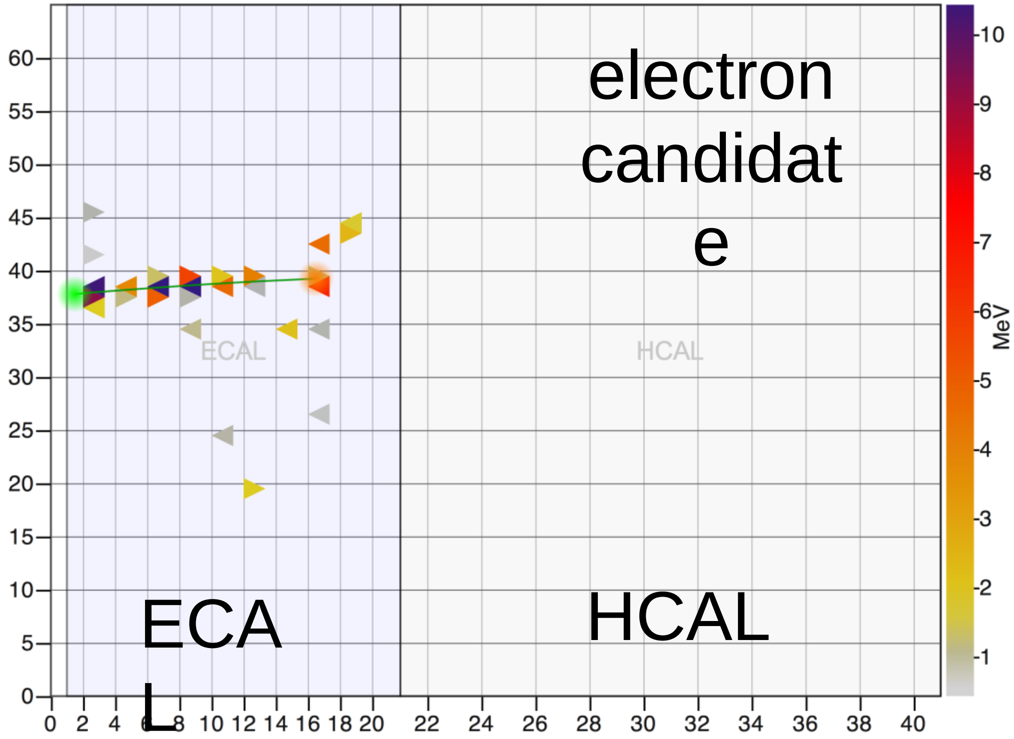
electron calorimetry

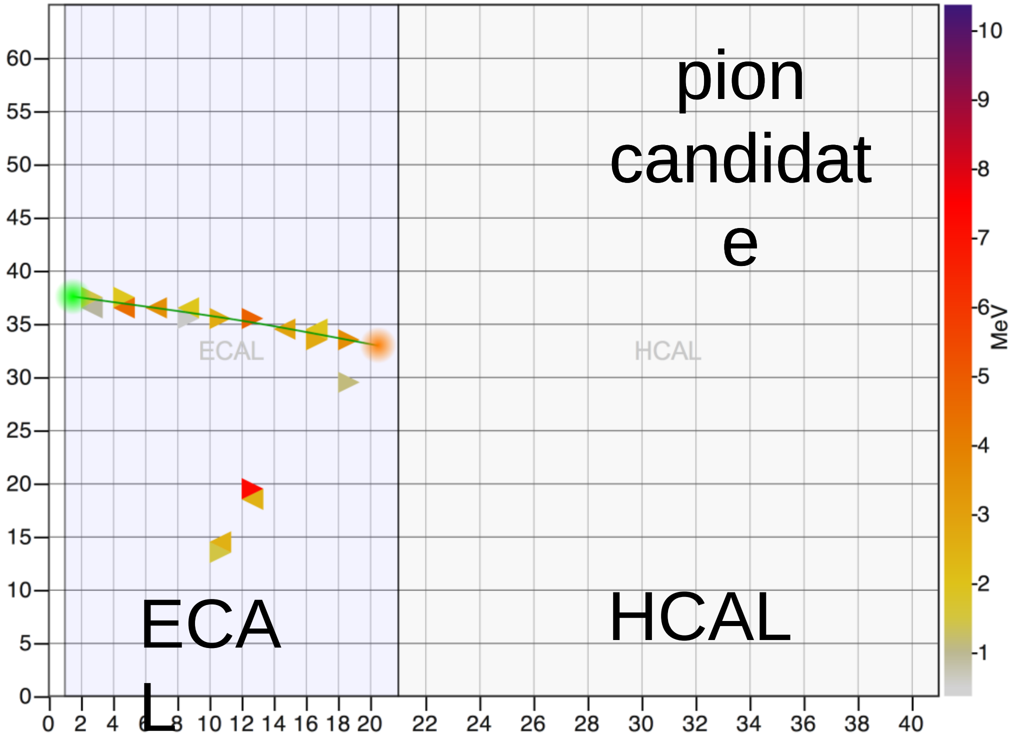


Electron response compared to MC
showing the MC underestimates the response by
3%


electron candidate
ECAL
HCAL
ECAL
HCAL
MeV
0 1 2 3 4 5 6 7 8 9 10
0 5 10 15 20 25 30 35 40 45 50 55 60
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40


pion candidate
ECAL
HCAL
ECAL
HCAL
MeV
0 1 2 3 4 5 6 7 8 9 10
0 5 10 15 20 25 30 35 40 45 50 55 60
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40


electron candidate
ECAL
HCAL
ECAL
HCAL
MeV
0 1 2 3 4 5 6 7 8 9 10
0 5 10 15 20 25 30 35 40 45 50 55 60
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40


pion candidate
ECAL
HCAL
ECAL
HCAL
MeV
0 1 2 3 4 5 6 7 8 9 10
0 5 10 15 20 25 30 35 40 45 50 55 60
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40

electron selection

For expert giving technical talk
how the electrons were separated from pions
using topology information from testbeam MINERvA detector

more complicated than separating pions and protons
which the beamline tags exceptionally well

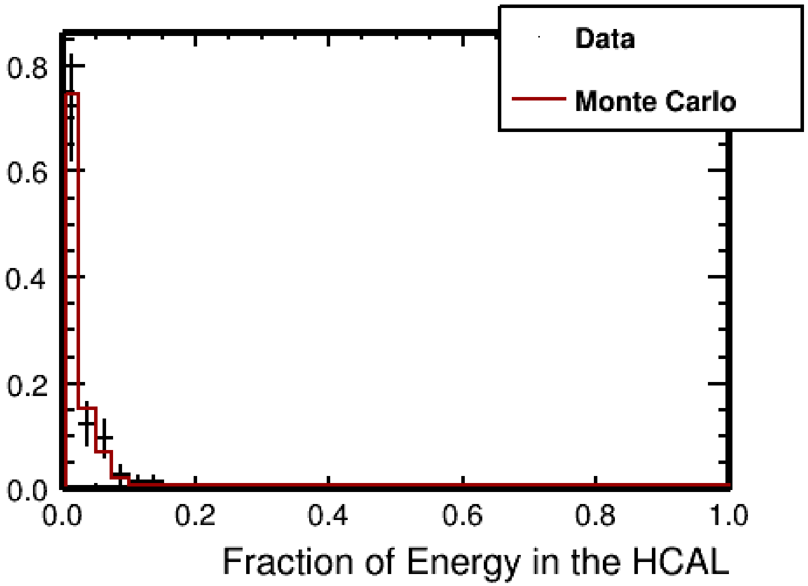
but topological electron tagging is a topic of interest in itself.

Compare top plot to bottom plot
to see the power of the topological selection.

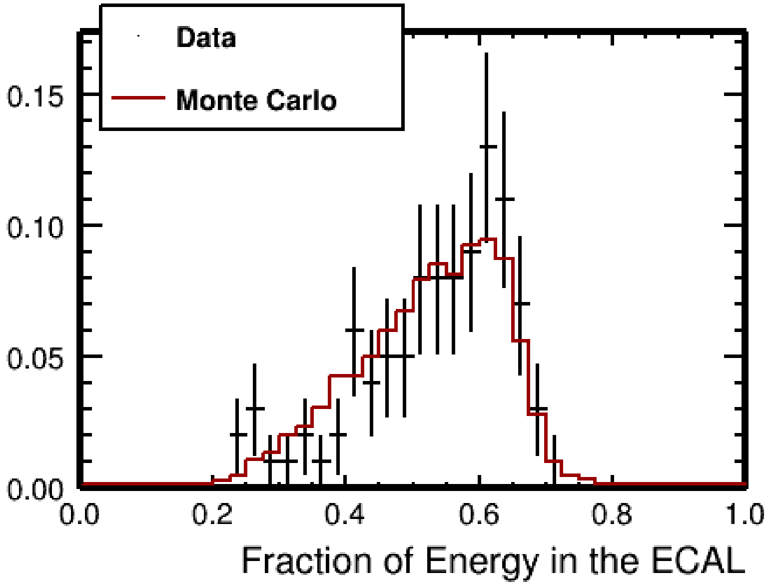
The anti-selected electrons' response is
negligibly different from the selected ones.
The topological selection does not bias calorimetry

Discriminant variables in the electron selection pion rejection fraction of energy in the back half of detector

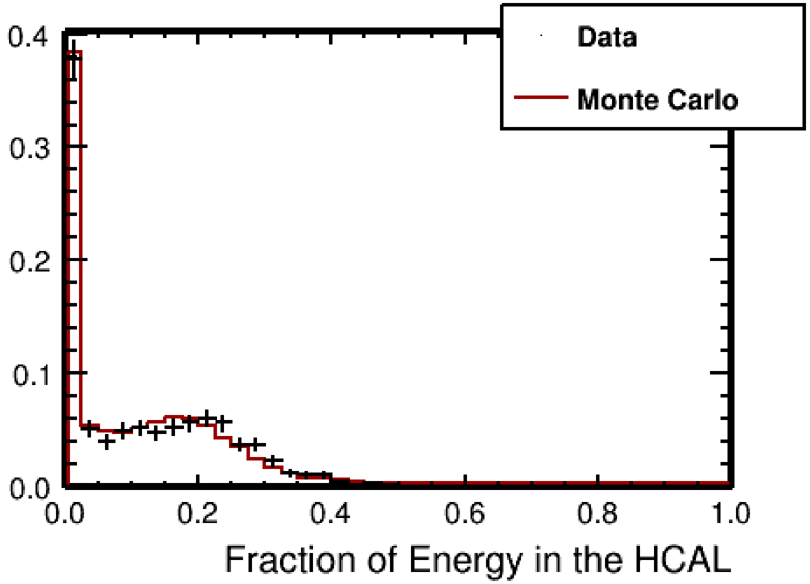
N-1 Plot Showing Fraction of Energy in the HCAL for E/H Electrons



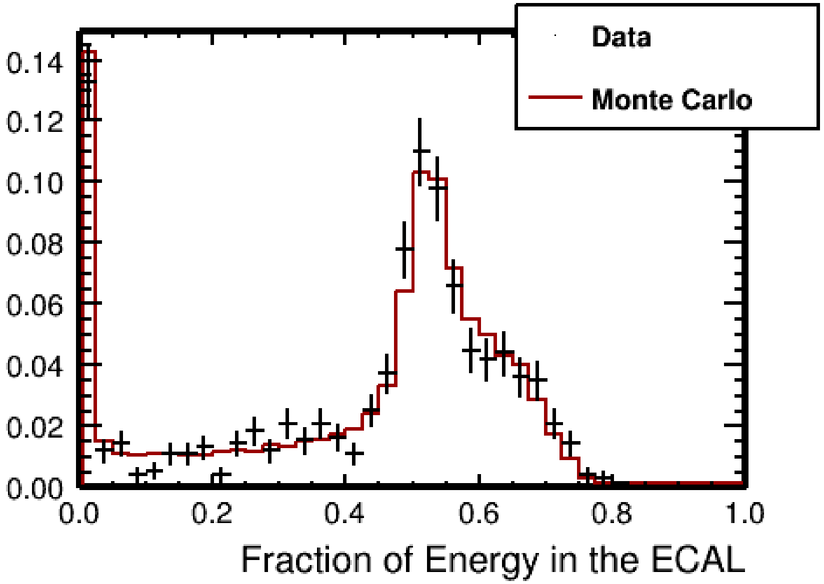
N-1 Plot Showing Fraction of Energy in the ECAL for T/E Electrons



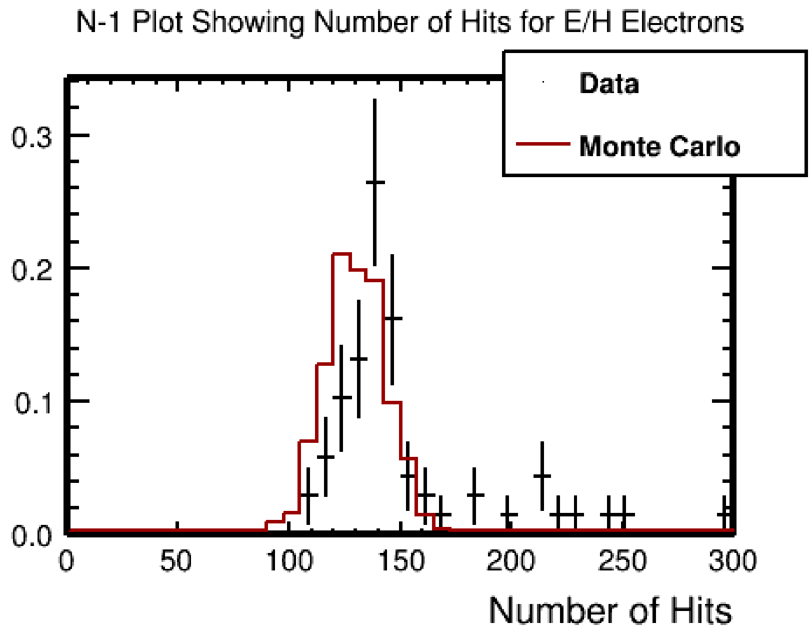
N-1 Plot Showing Fraction of Energy in the HCAL for E/H Pions

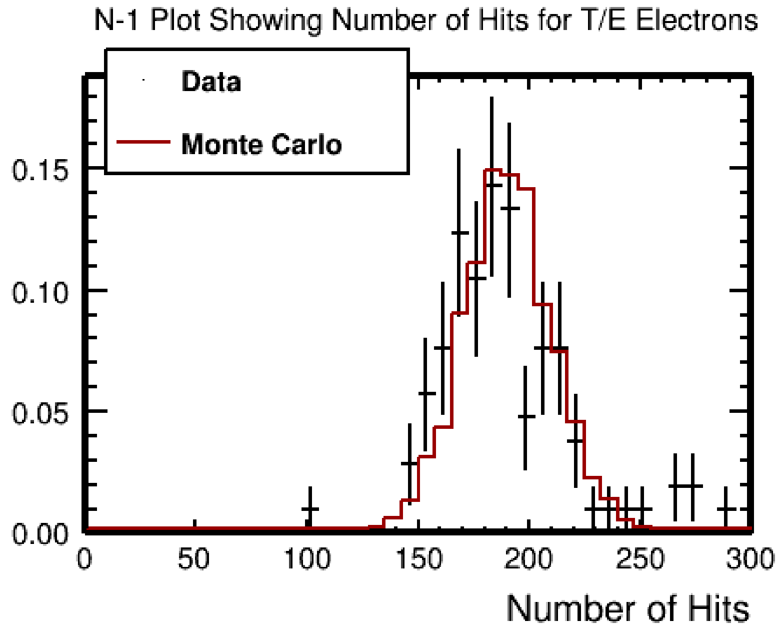


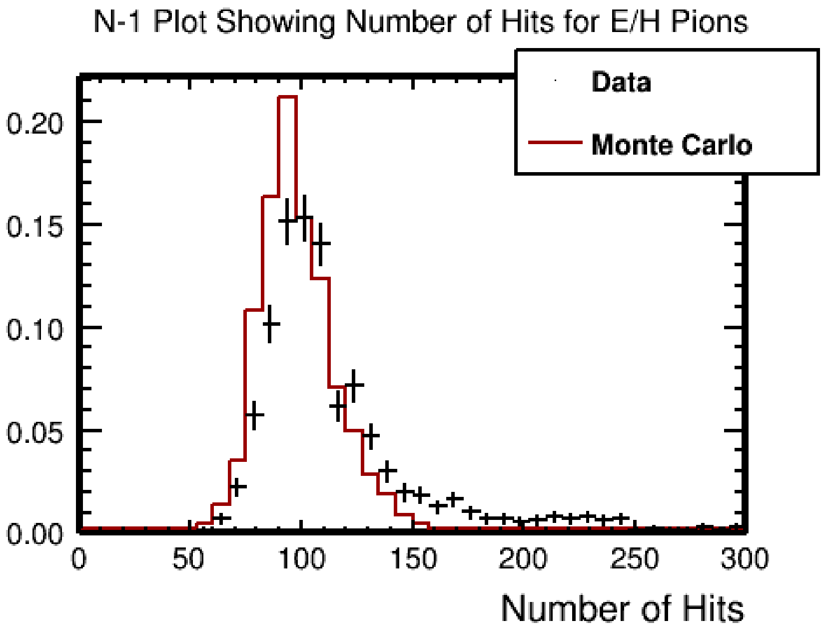
N-1 Plot Showing Fraction of Energy in the ECAL for T/E Pions

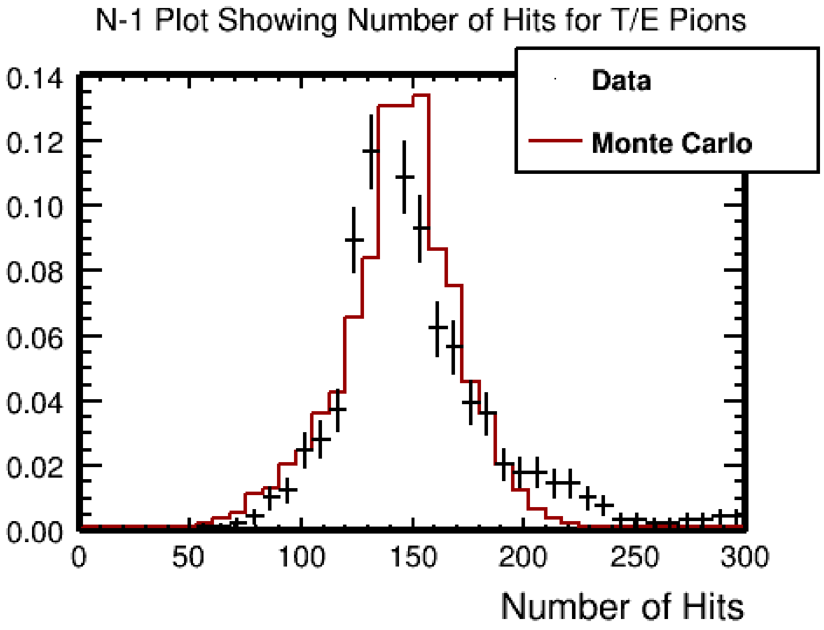


Discriminant variables in the electron selection pion rejection number of hits

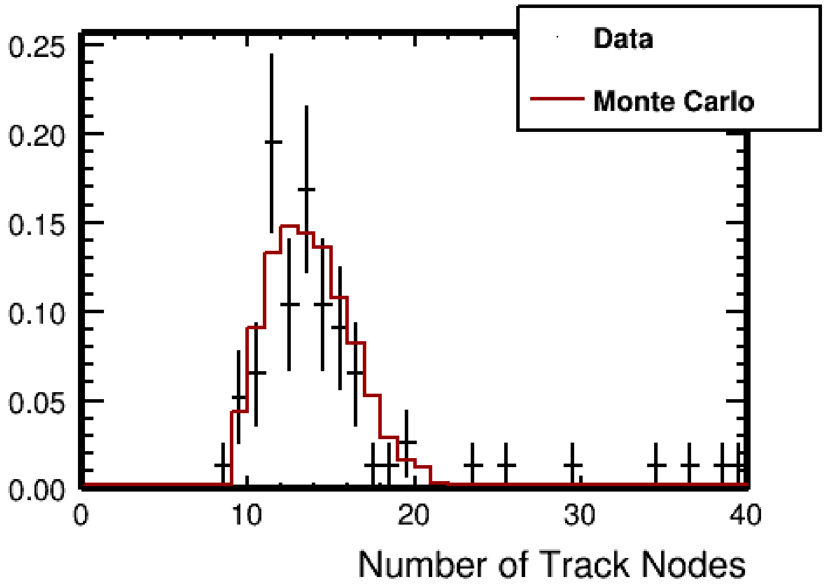

N-1 Plot Showing Number of Hits for E/H Electrons

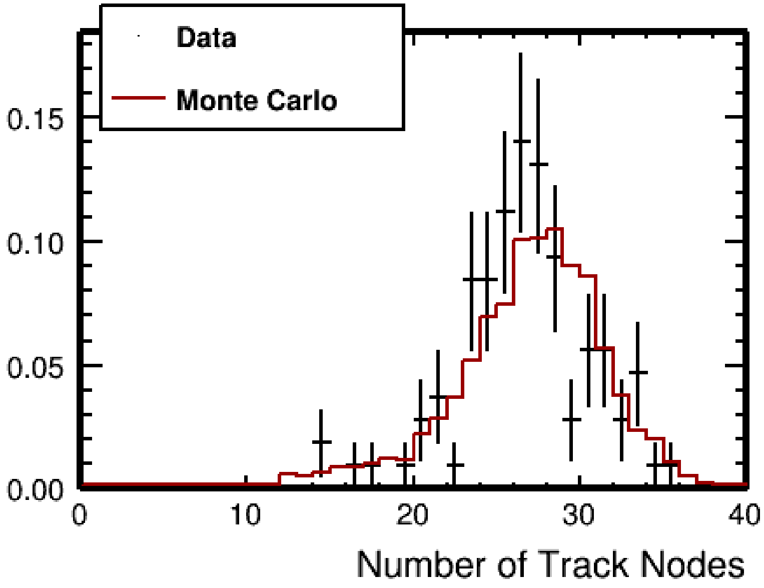

N-1 Plot Showing Number of Hits for T/E Electrons

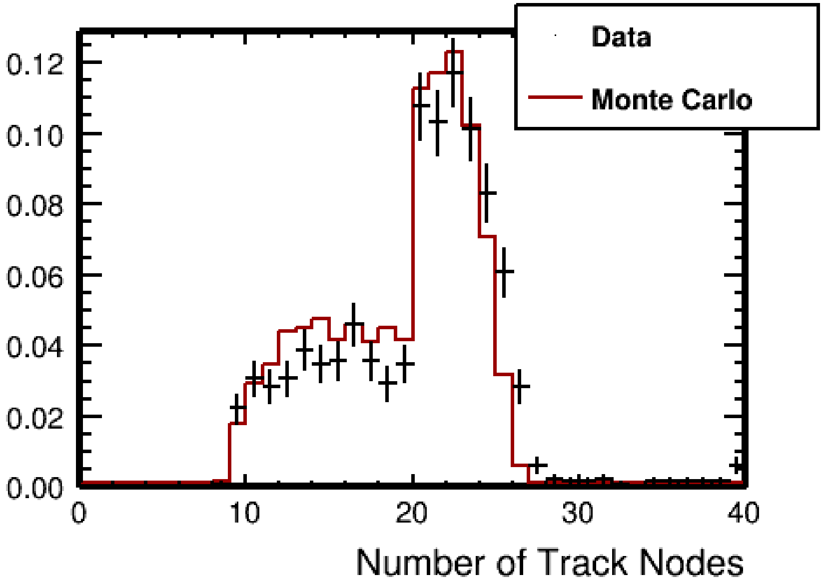

N-1 Plot Showing Number of Hits for E/H Pions

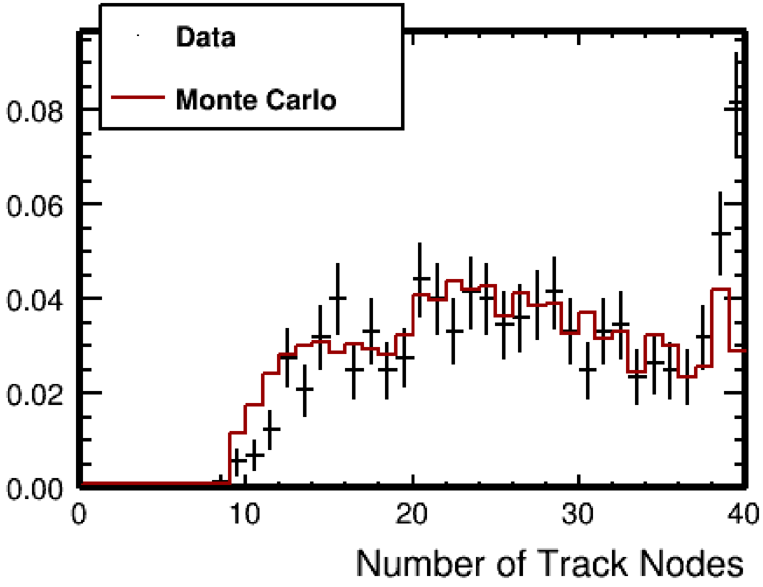

N-1 Plot Showing Number of Hits for T/E Pions

Discriminant variables in the electron selection pion rejection number of track nodes

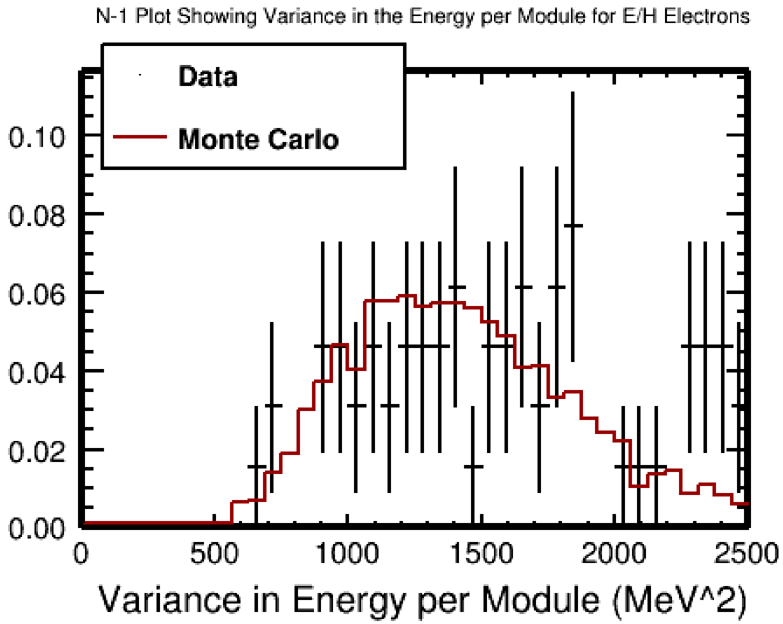

N-1 Plot Showing Number of Track Nodes for E/H Electrons

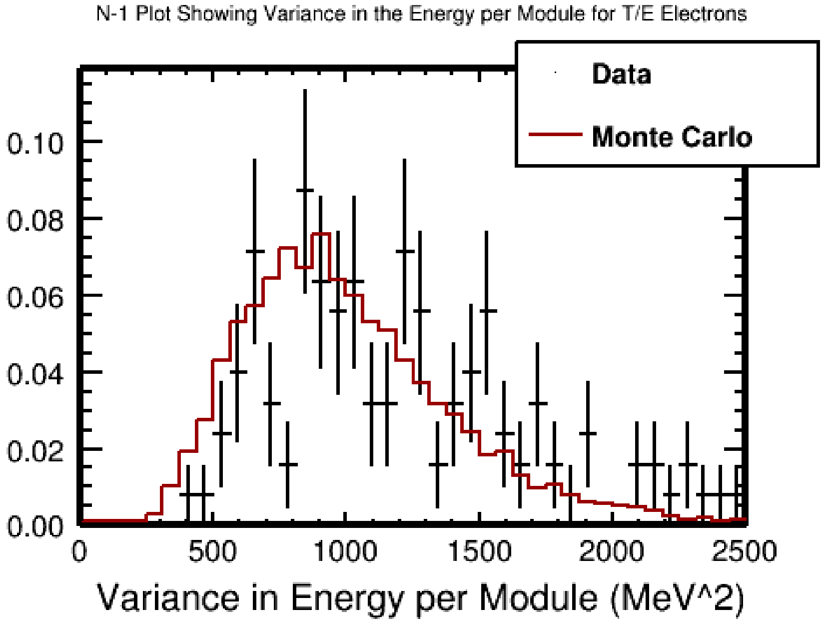

N-1 Plot Showing Number of Track Nodes for T/E Electrons

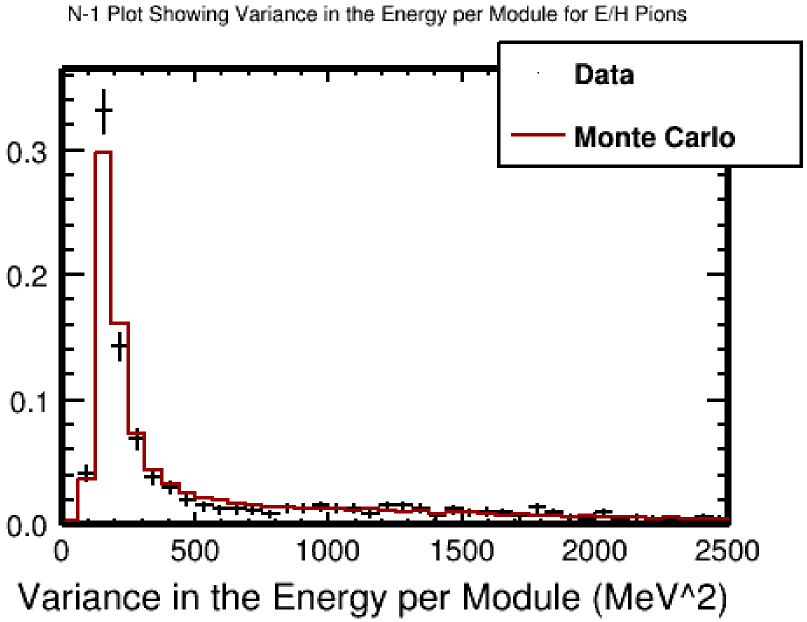

N-1 Plot Showing Number of Track Nodes for E/H Pions

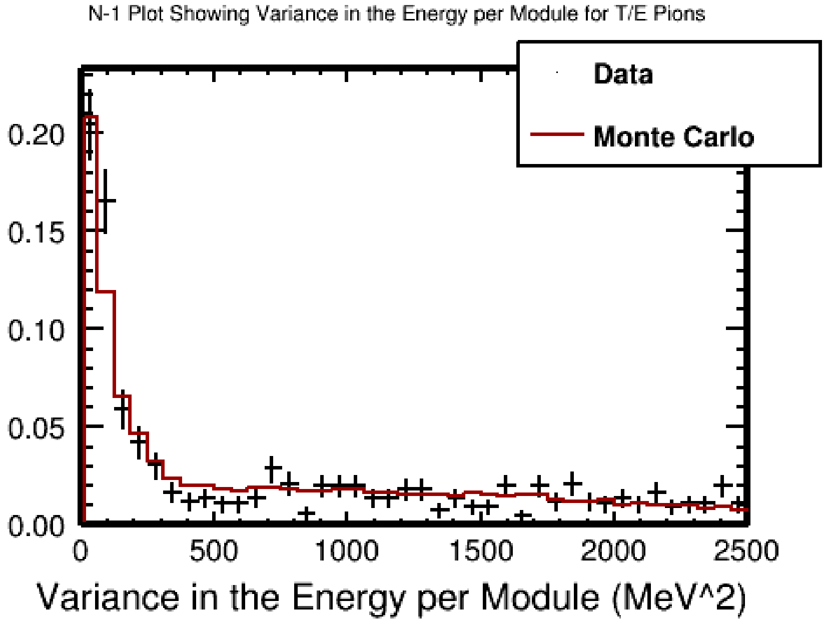

N-1 Plot Showing Number of Track Nodes for T/E Pions

Discriminant variables in the electron selection pion rejection variance in energy per module


N-1 Plot Showing Variance in the Energy per Module for E/H Electrons


N-1 Plot Showing Variance in the Energy per Module for T/E Electrons

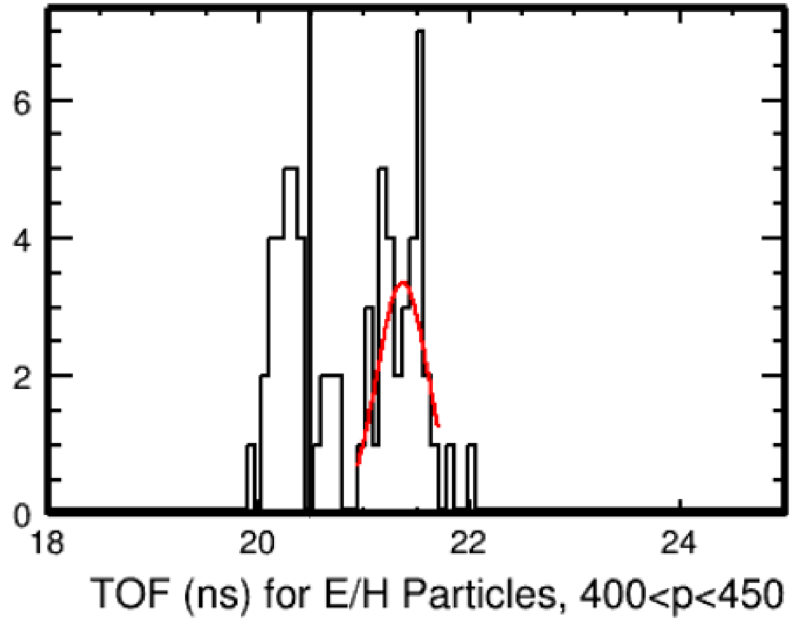

N-1 Plot Showing Variance in the Energy per Module for E/H Pions

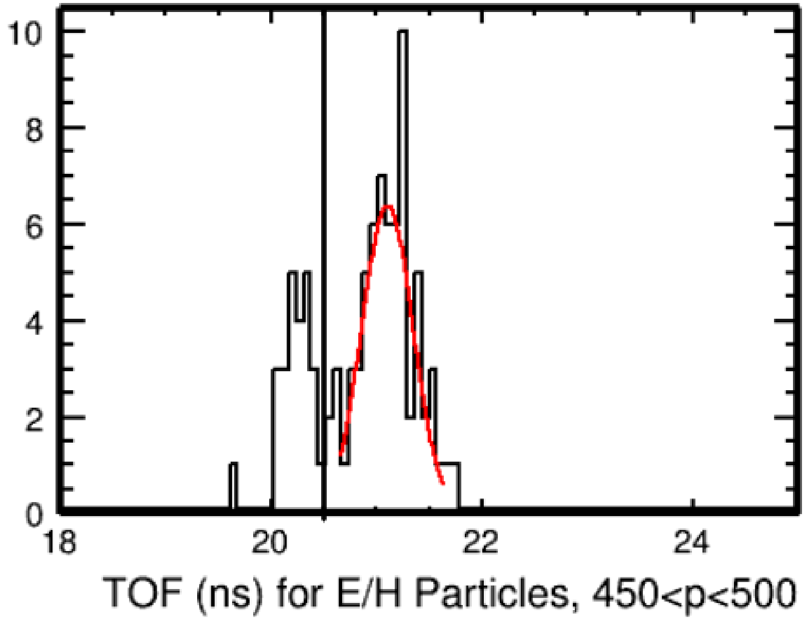

N-1 Plot Showing Variance in the Energy per Module for T/E Pions

Discriminant variables in the electron selection pion rejection

estimating remaining pion background in electron sample after all selections

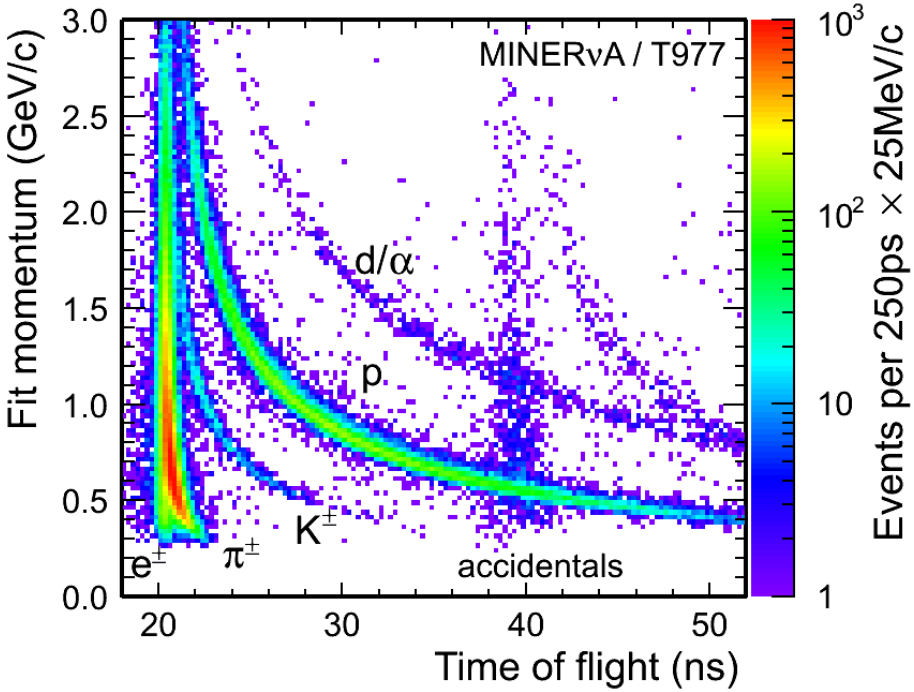
Horizontal axis is TOF.
Samples are 400 to 450 MeV/c and 450 to 500 MeV/c
higher E pion background (with Gaussian) moves faster.
Vertical line shows the 20.5 ns cut value.

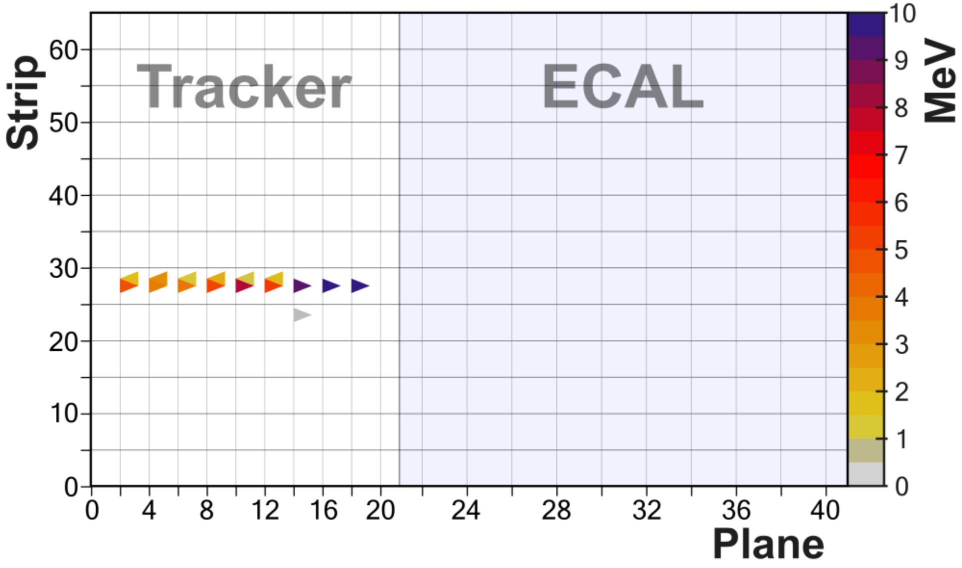




Testbeam2010 results: beam, detector, low level calibrations

Six weeks of data at Fermilab Test Beam Facility
In a 350 to 3000 MeV/c broadband tertiary beam





example proton event, used to measure Birks' parameter for scintillator response

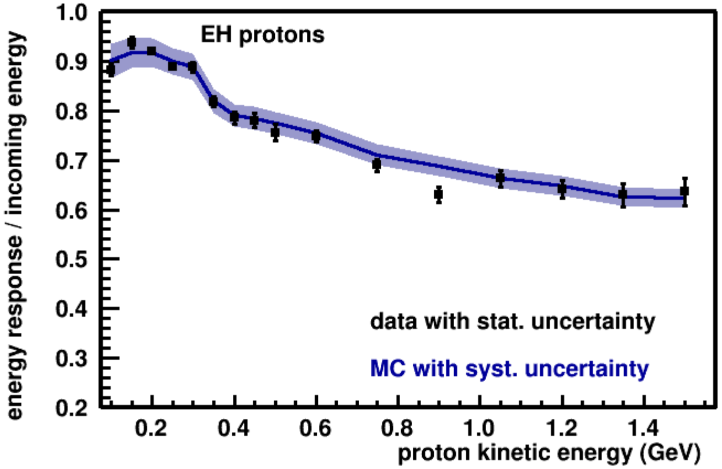
Testbeam2010 results: calorimetry

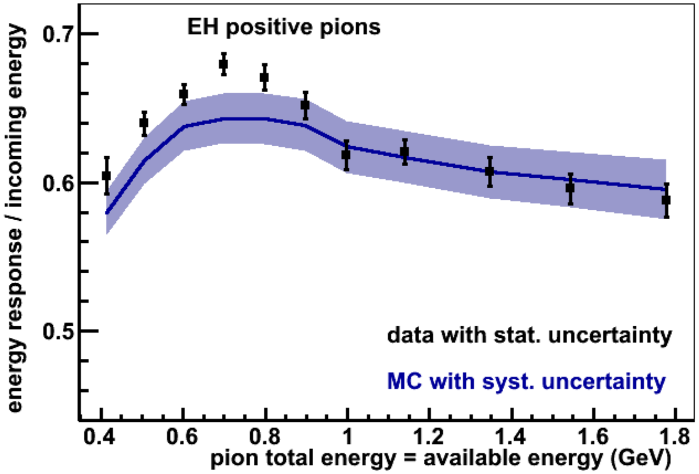
Measured calorimetric response of protons, pi+, pi- in ECAL+HCAL and e+ e- in ECAL with 3% accuracy from threshold to 2 GeV.

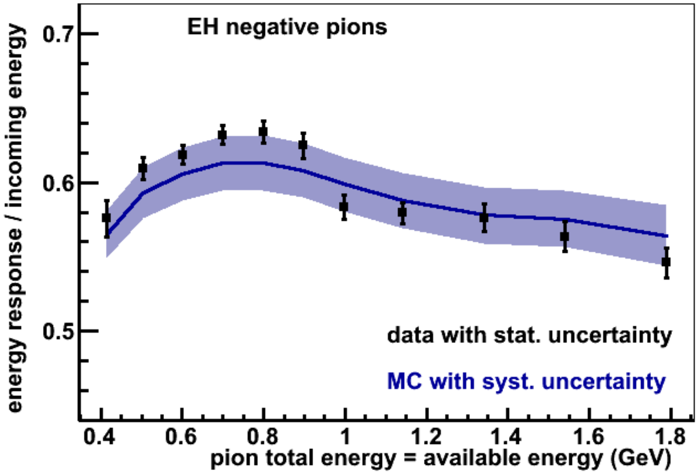
Geant4 9.6p2 with Bertini Cascade describes the data well.

Some disagreements at the 4% level are up to 2 standard deviations away.

Not shown in these figures,
MC electron response is 3% below data also just over one standard deviation away







Pi- data event interacting in ECAL with products going to HCAL