FERMILAB TEST BEAM UPDATE

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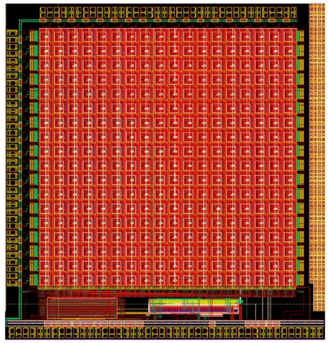
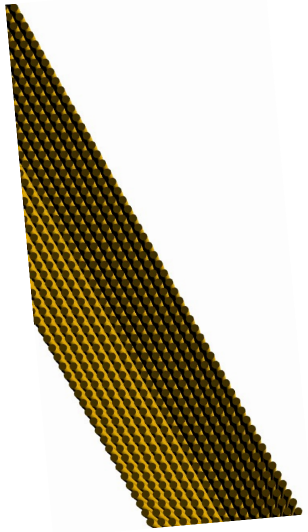
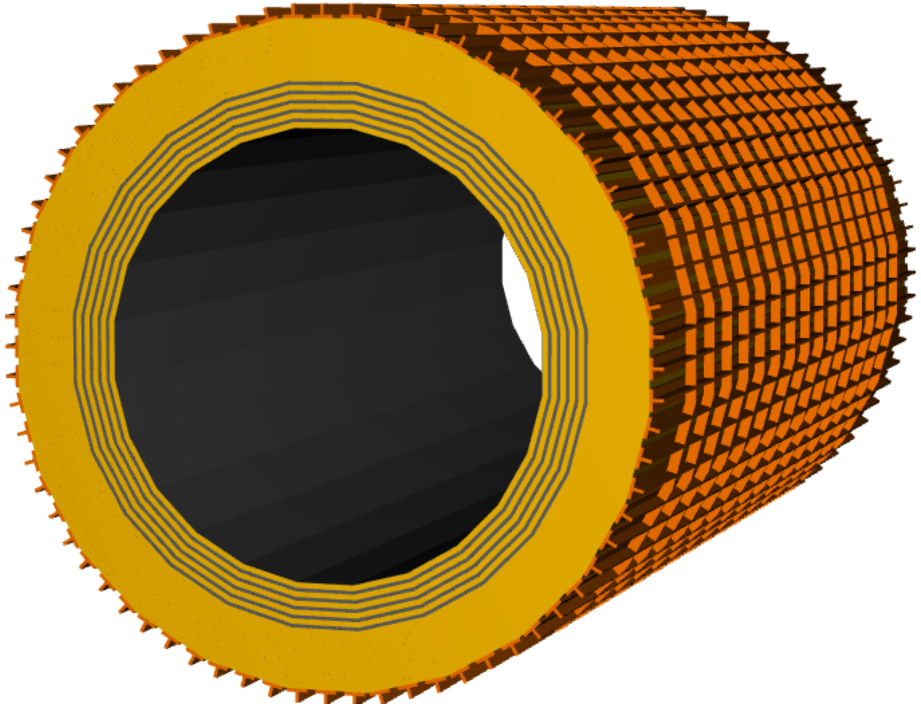
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

TEST BEAM R&D GOALS

- Benchmark detector performance in as realistic a configuration as possible with different beams at FNAL
  - Study e/π separation and overall π response
  - Characterize SciFi energy resolution & linearity at higher energy than GlueX
  - Demonstrate ability to operate AstroPix & SciFi in tandem

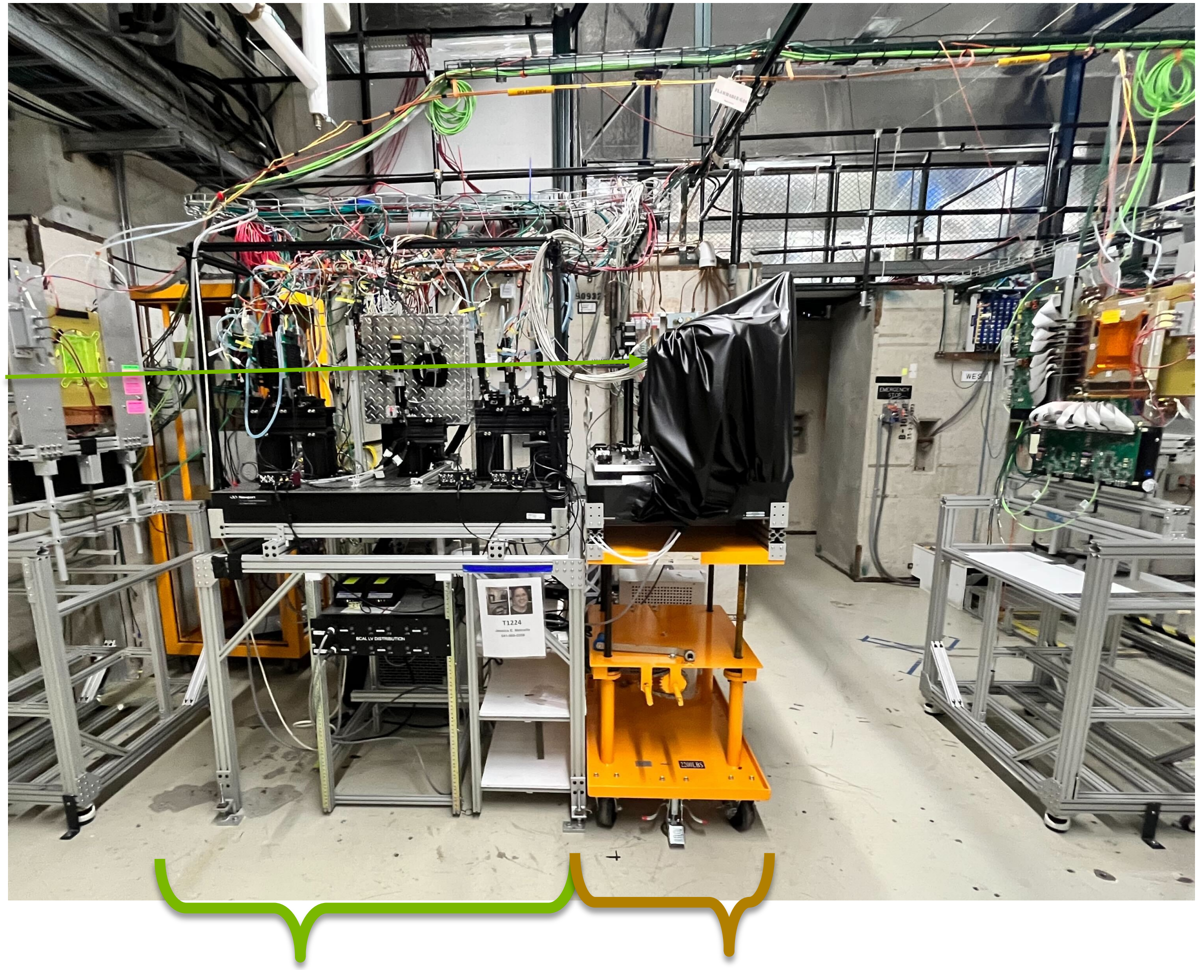






GENERAL SETUP

- Add BIC prototype calorimeter behind existing Argonne ATLAS Pixel telescope with AstroPix setup at MTest
- Rotating stage to simulate particles incident at angles up to 45° $(\eta \sim 1)$
- Ability to lower BIC setup out of the beam, no need to uninstall for other experiments to run

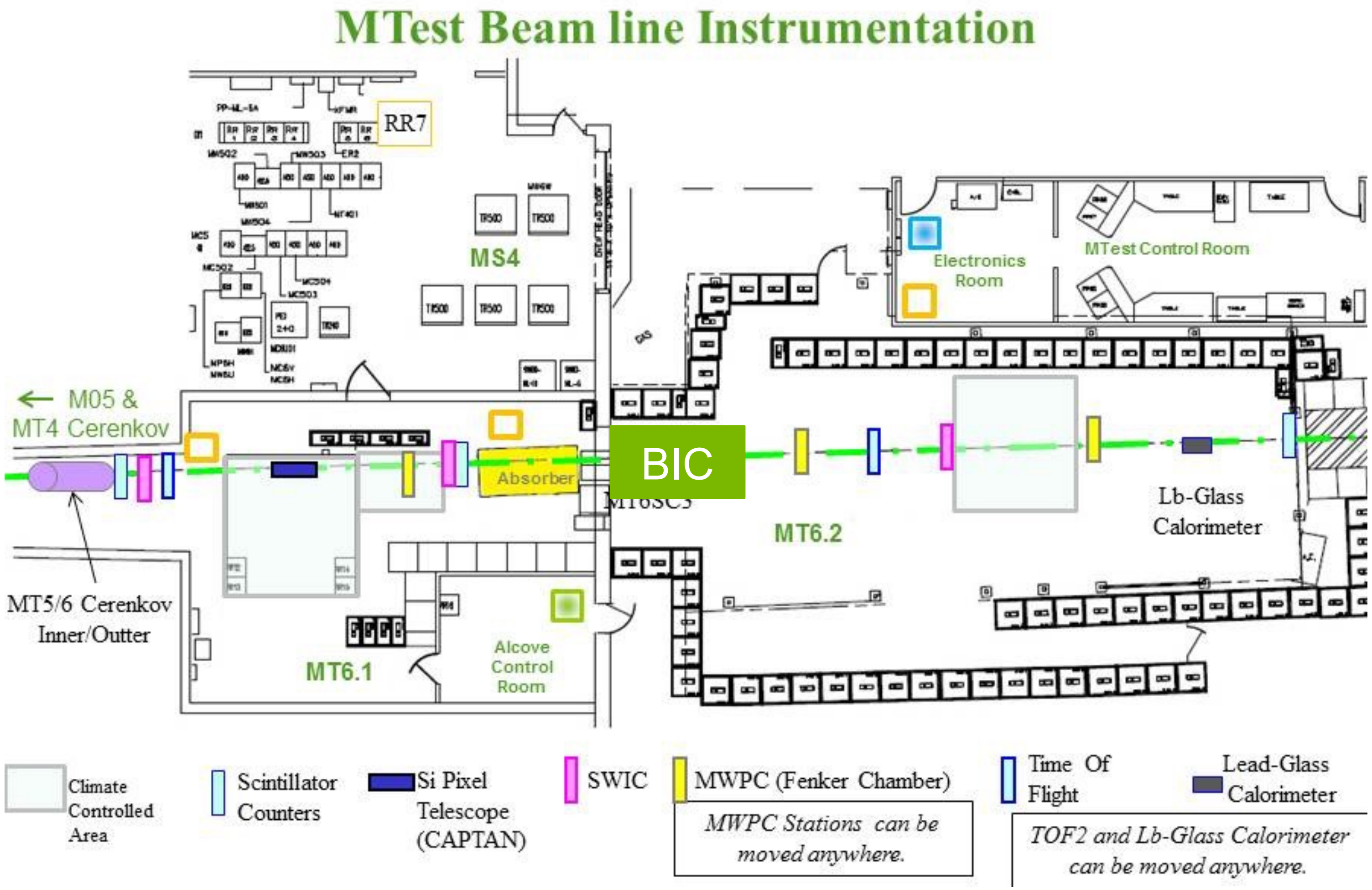


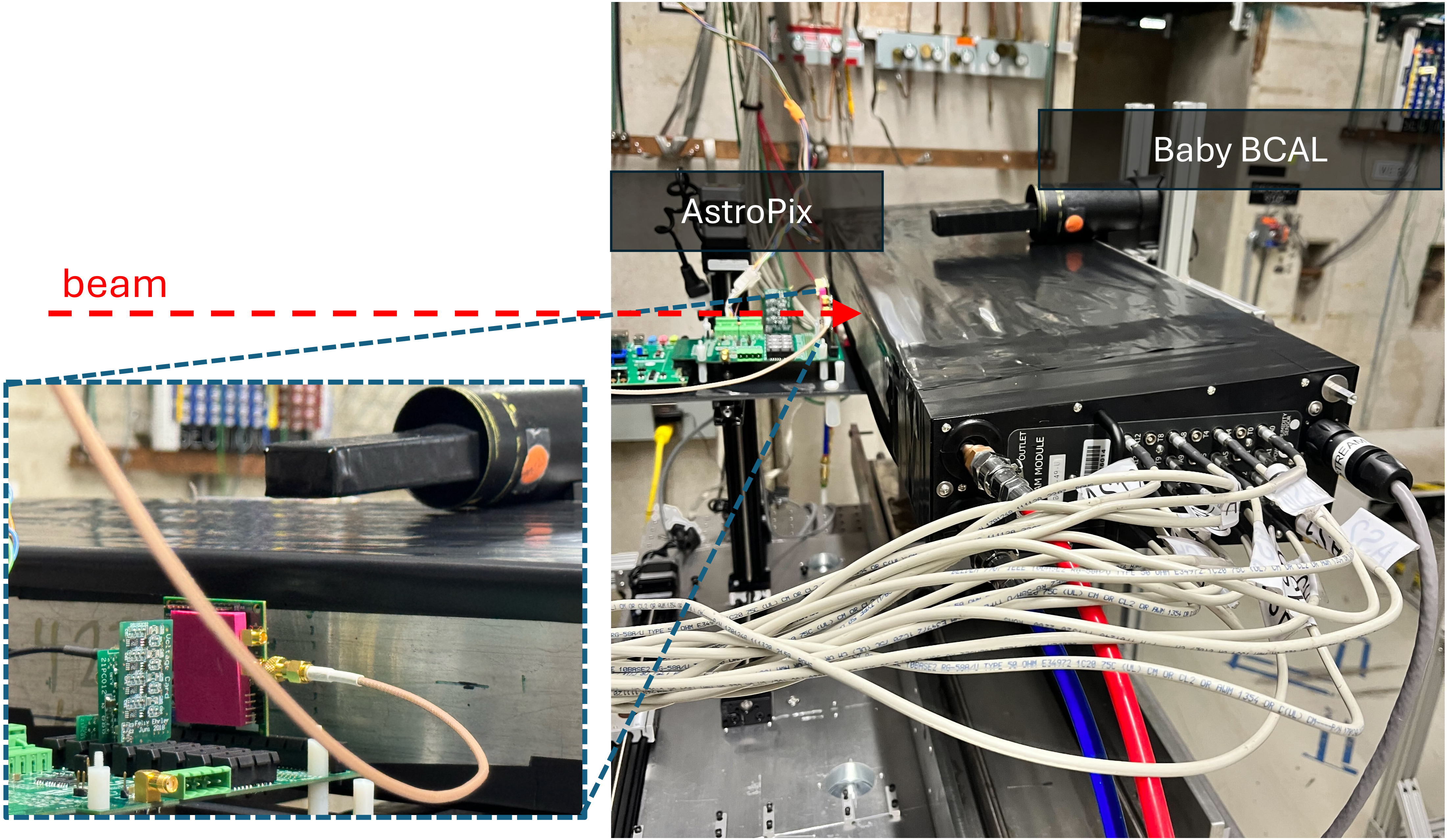
Current ANL AstroPix Telescope Setup

Baby BCal Setup

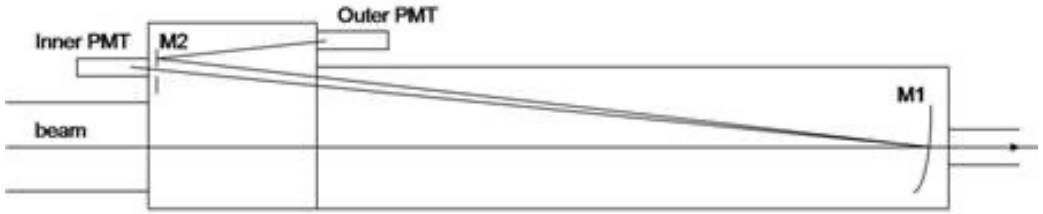
FERMILAB TEST BEAM FACILITY

- Nominal beam is 120 GeV protons from main injector
- Secondary hadron/electron beam from sending 120 GeV protons on a 30 cm thick aluminum target
- Scintillators provided by FTBF along beamline for trigger
- Two Cherenkovs for PID

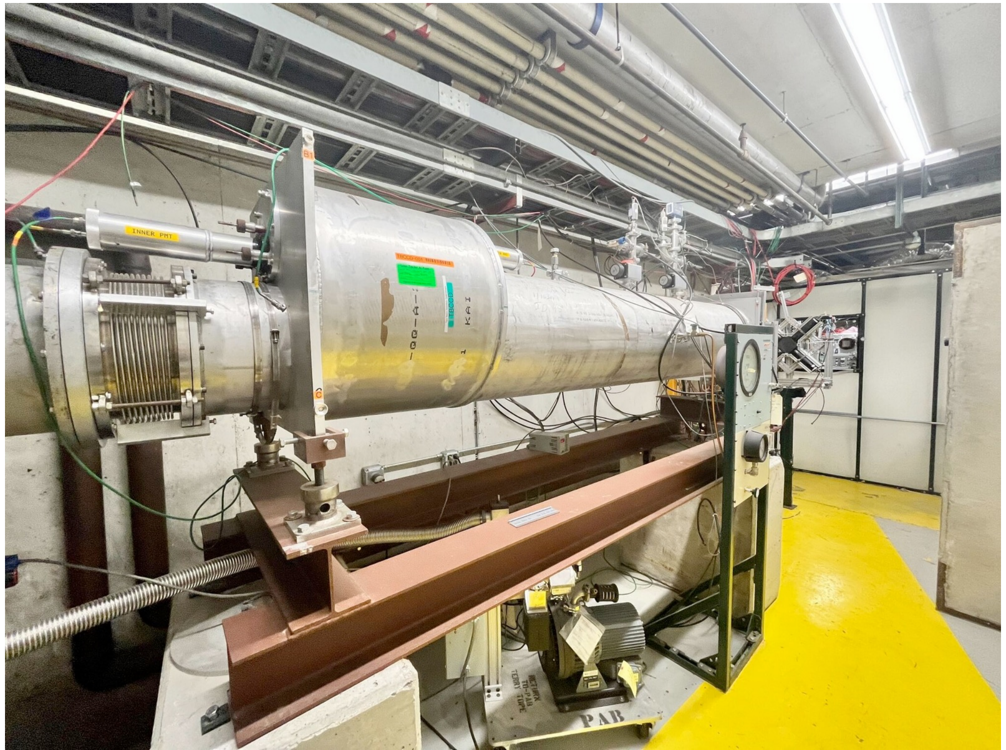


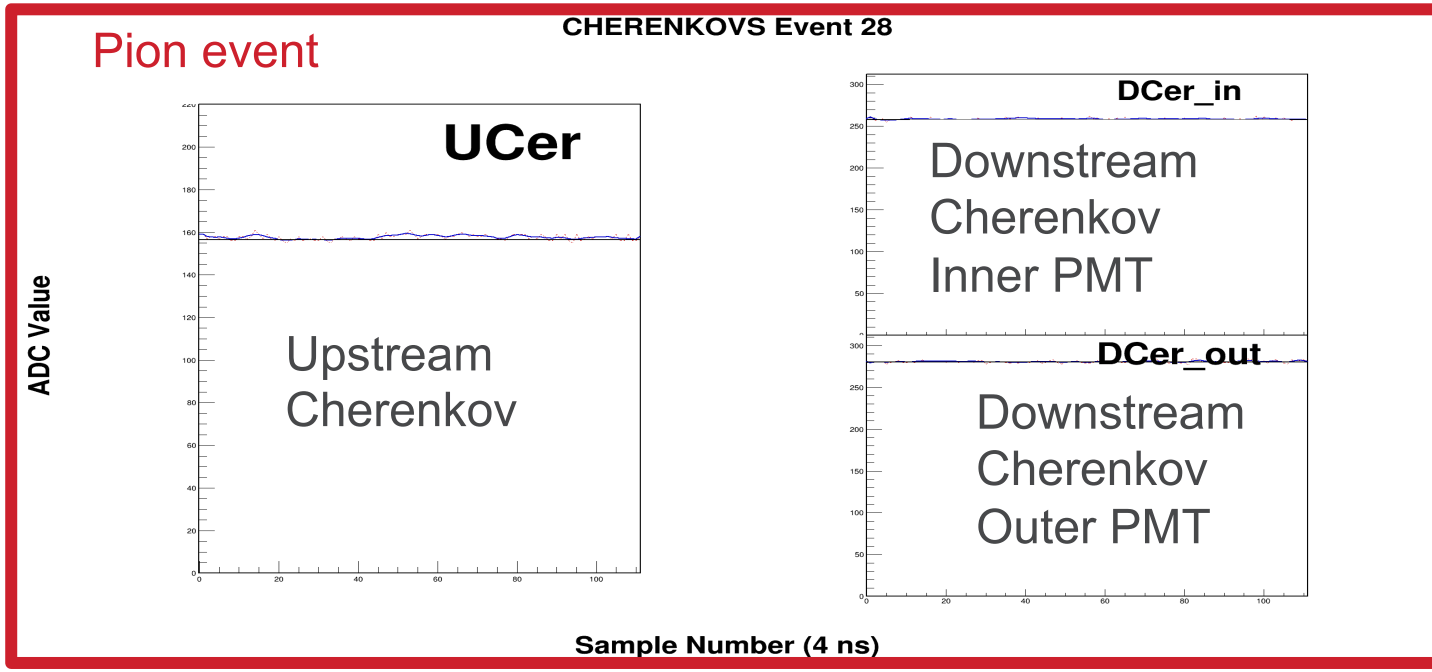

beam
AstroPix
Baby BCAL

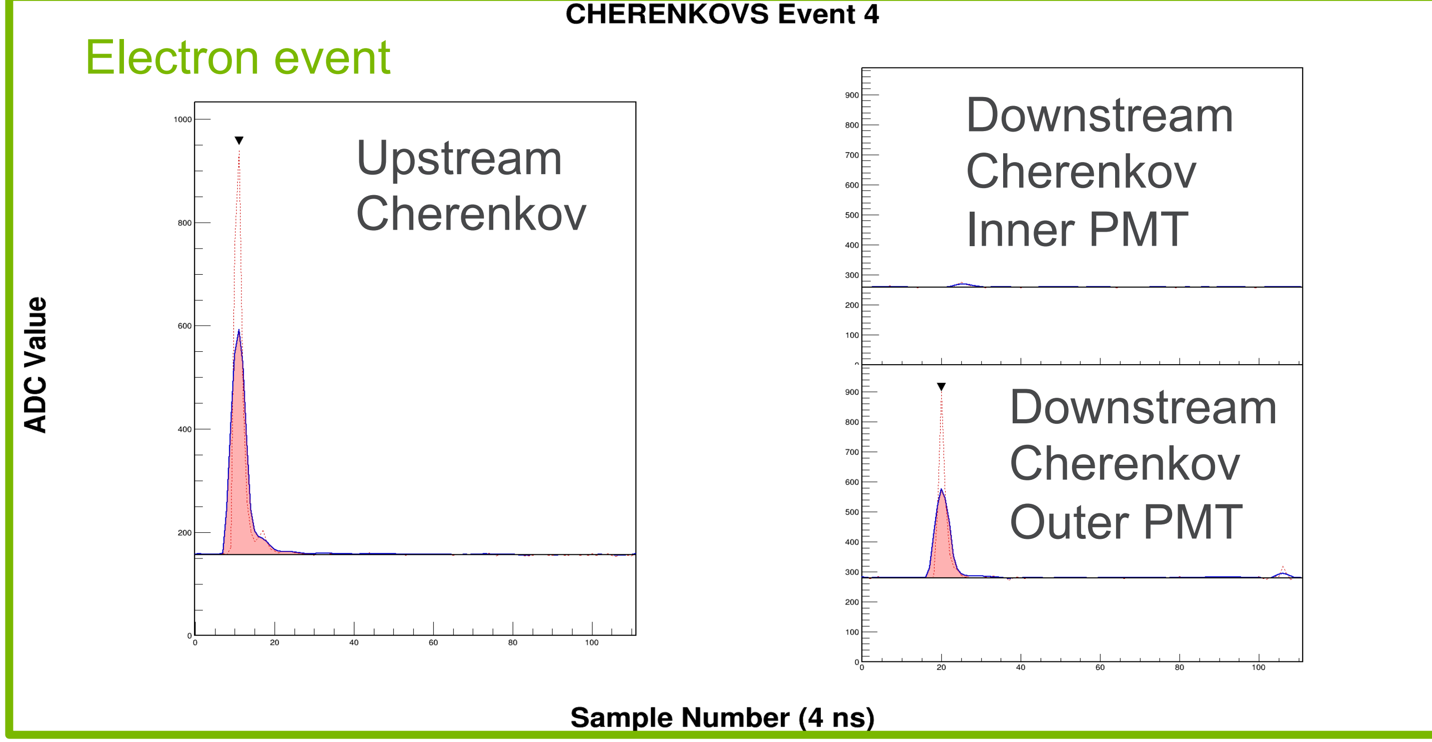
CHERENKOV DETECTORS



Downstream Cherenkov



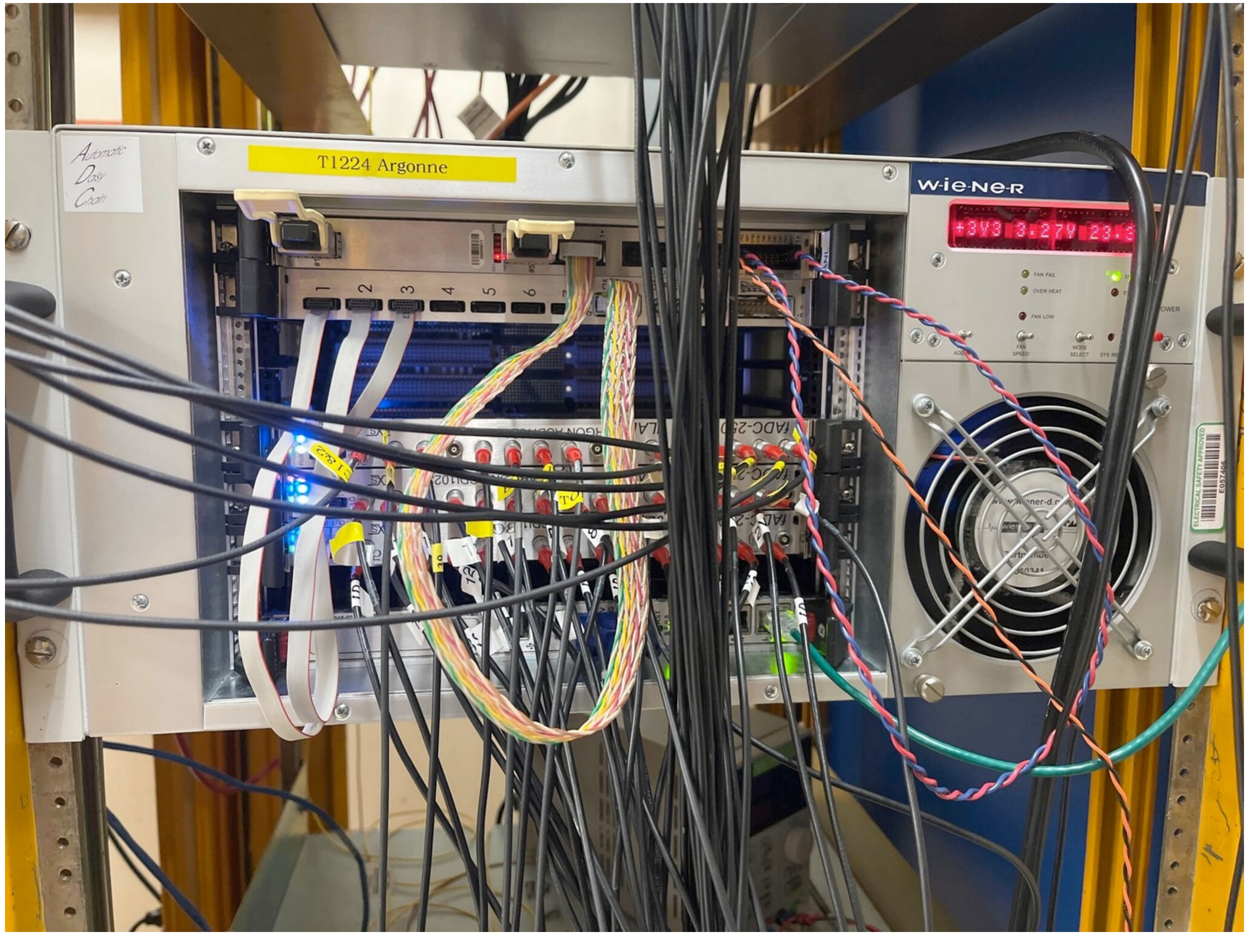




DAQ

- Used 3x 16 channel JLab 250 MHz fADCs in full waveform readout mode

- Sent analog signals from the N&S sets of 16 baby BCal channels into two blades of fADC, remaining blade used for FTBF detectors, cosmic ray paddles, AstroPix analog signal

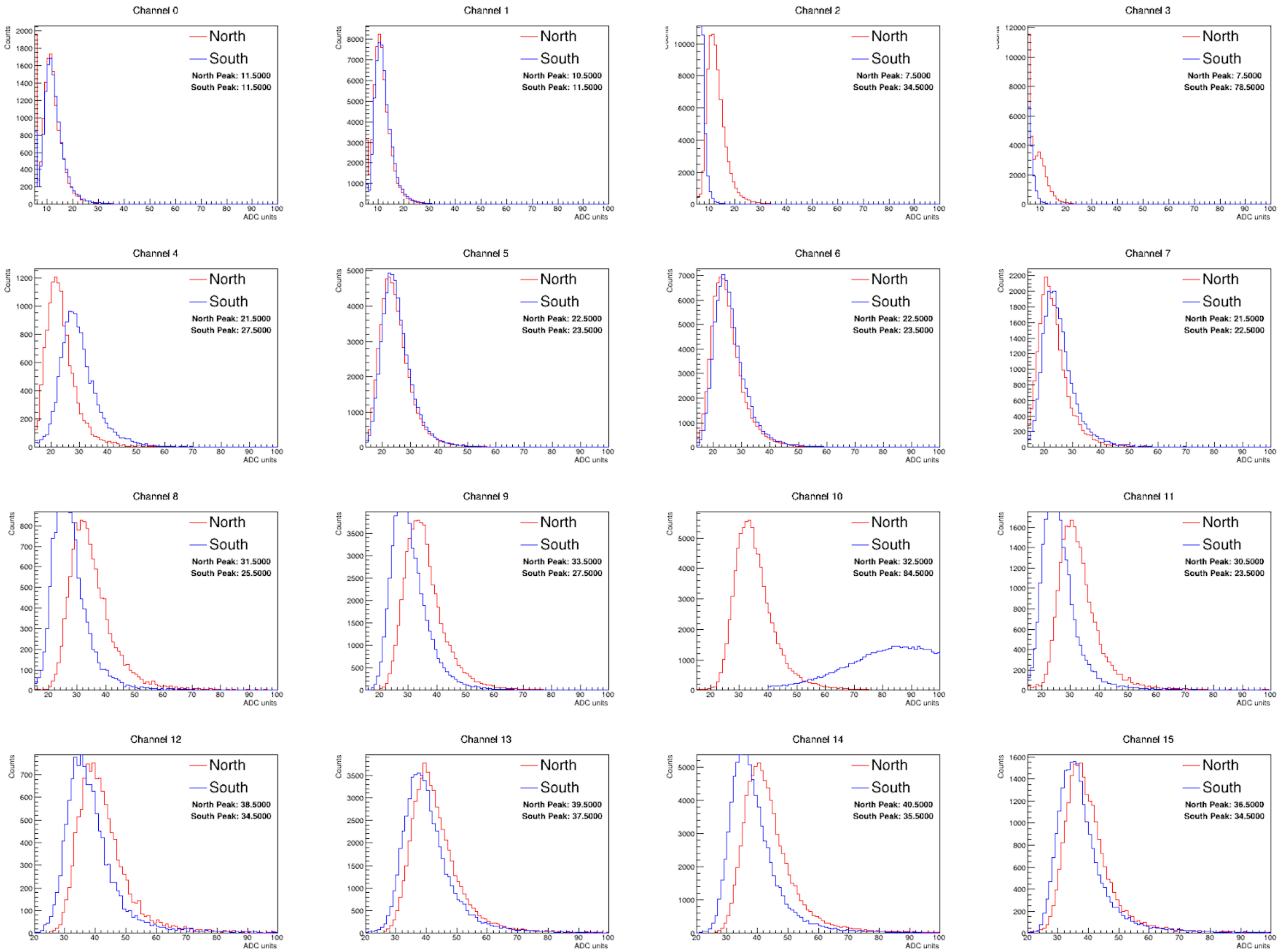


DATASETS

- Due to heat issues at FNAL, only ran for ~30% of our allotted week
- DAQ limited to ~7 kHz due to full waveform readout
- 120 GeV protons
  - Mostly parasitic overnight
  - Large dataset, few million events
- 10 GeV e/pi
  - Also large dataset, but mostly taken with FADC jumpers set in the wrong positions, so gain is 2x higher than it should be
  - After the jumper repositioning, took an hour and a half of e/pi at 10 GeV (540K)
- 10 GeV mu/pi
  - Taken with a lead sheet in the beam to absorb electrons
  - Provides a large MIP calibration dataset
- Energy scan e/pi
  - 4 GeV (1.4M), 6 GeV (440K), and 8 GeV (320K)
  - Took a larger 4 GeV because pions are rarer at low energies

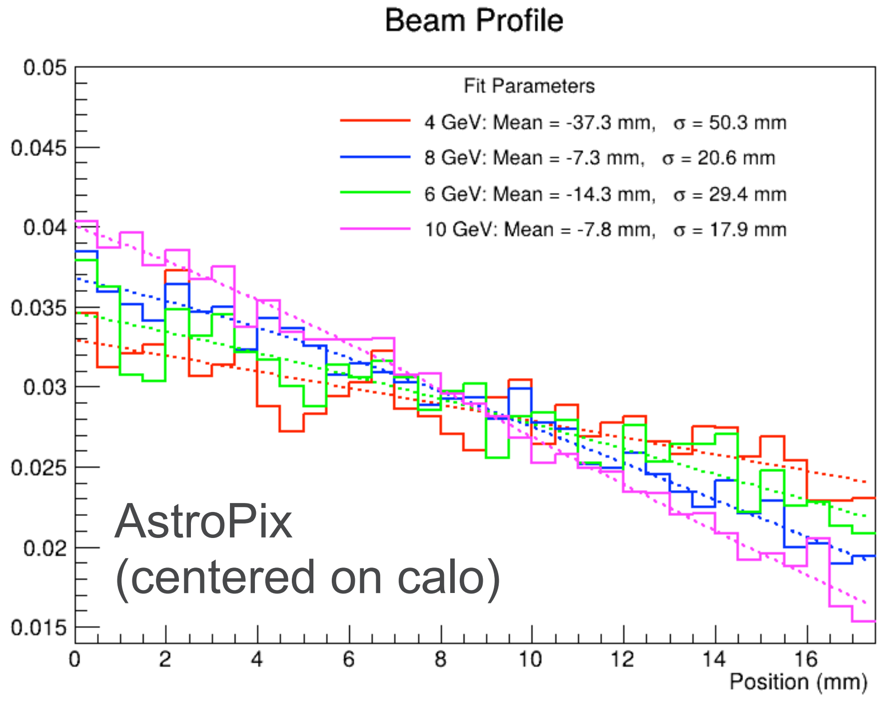
ENERGY CALIBRATION

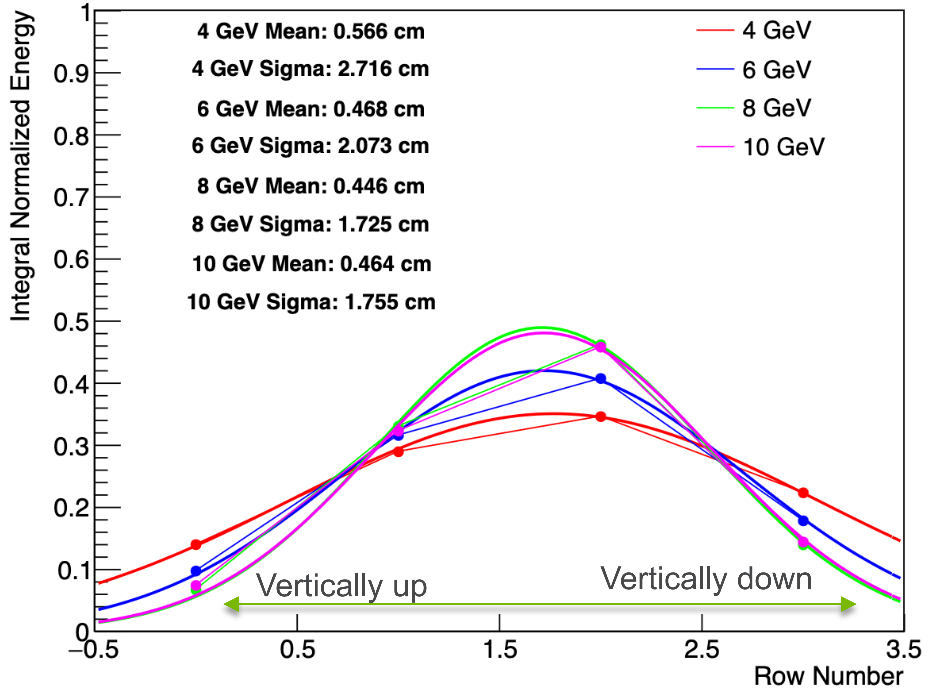
- Plot pulse heights in ADC units for events which left energy only in a line through the calorimeter
- Use muon/pion run to get clean MIP sample
- Nice MIP peak visible in all channels except for South 2&3



BEAM PROFILE

- For calo analysis, want to know the profile of the beam in the vertical direction
  - Determines amount of leakage
- Not much info from FTBF detectors
  - MWPCs were out of gas
  - SWICs showed poor performance for secondary beams
- Have AstroPix & Calo information
- Both agree beam widens at lower energy, both agree the beam center is vertically below the center of the calorimeter





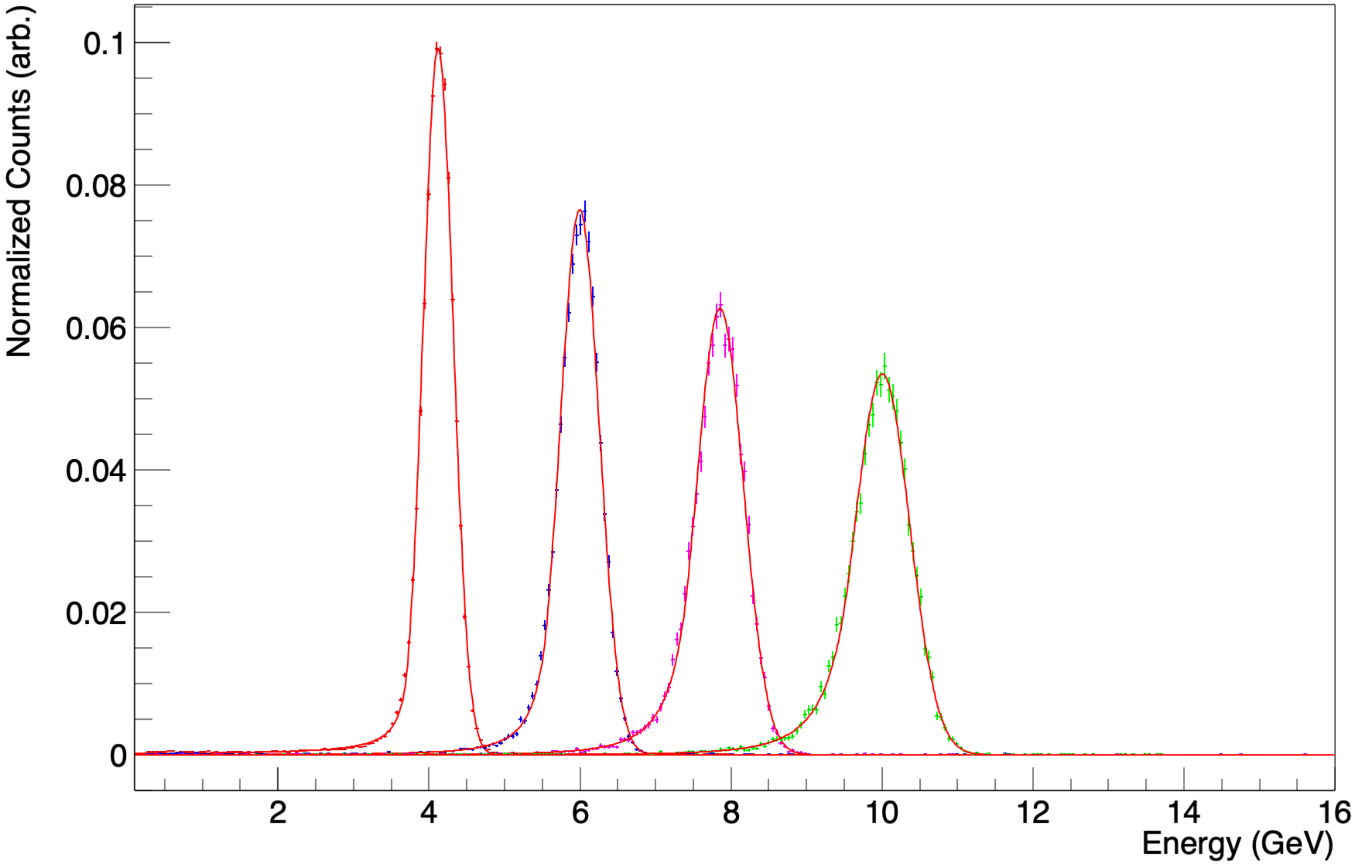
BEAM ΔP

- An important factor in understanding the energy response is the beam momentum spread
- This term enters as a constant term on the energy resolution
- Quoted beam spread is 2.7% at low energies, improving to 2% at 120 GeV
  - However, statement from Joe at FTBF is that: ”every calo group is telling me it looks like the momentum spread is higher than the website indicates it should be.”
- This number depends on beam tune, which can vary from run to run
- We see the 4 GeV beam is physically wider, which suggests it also has a larger momentum spread

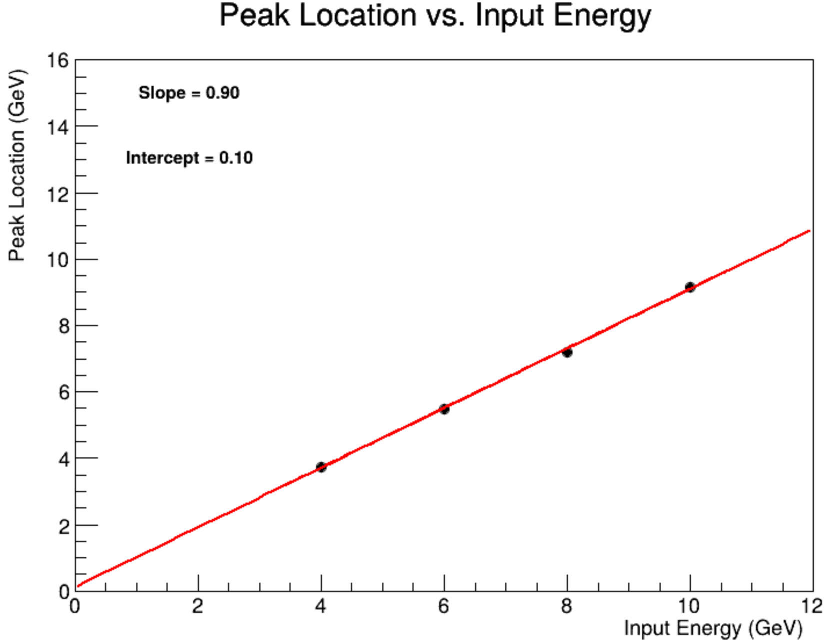
Energy	Mode[1]	Protons	Pions[2]	Highest Intensity[3]	Muons	Kaons	electrons	Spot Size[4]	Δp
10 GeV	LEπ +/-								
8 GeV	LEπ +/-		55%	750,000	98%			12mm	2.3%
6 GeV	LEπ +								
4 GeV	LEπ +/-		31%	400,000	74%			13mm	2.7%
3 GeV	LEπ +/-								2.7%
2 GeV	LEπ +/-		<30%	450,000				13mm	2.7%
1 GeV	LEπ +/-		<30%	69,000					2.7%

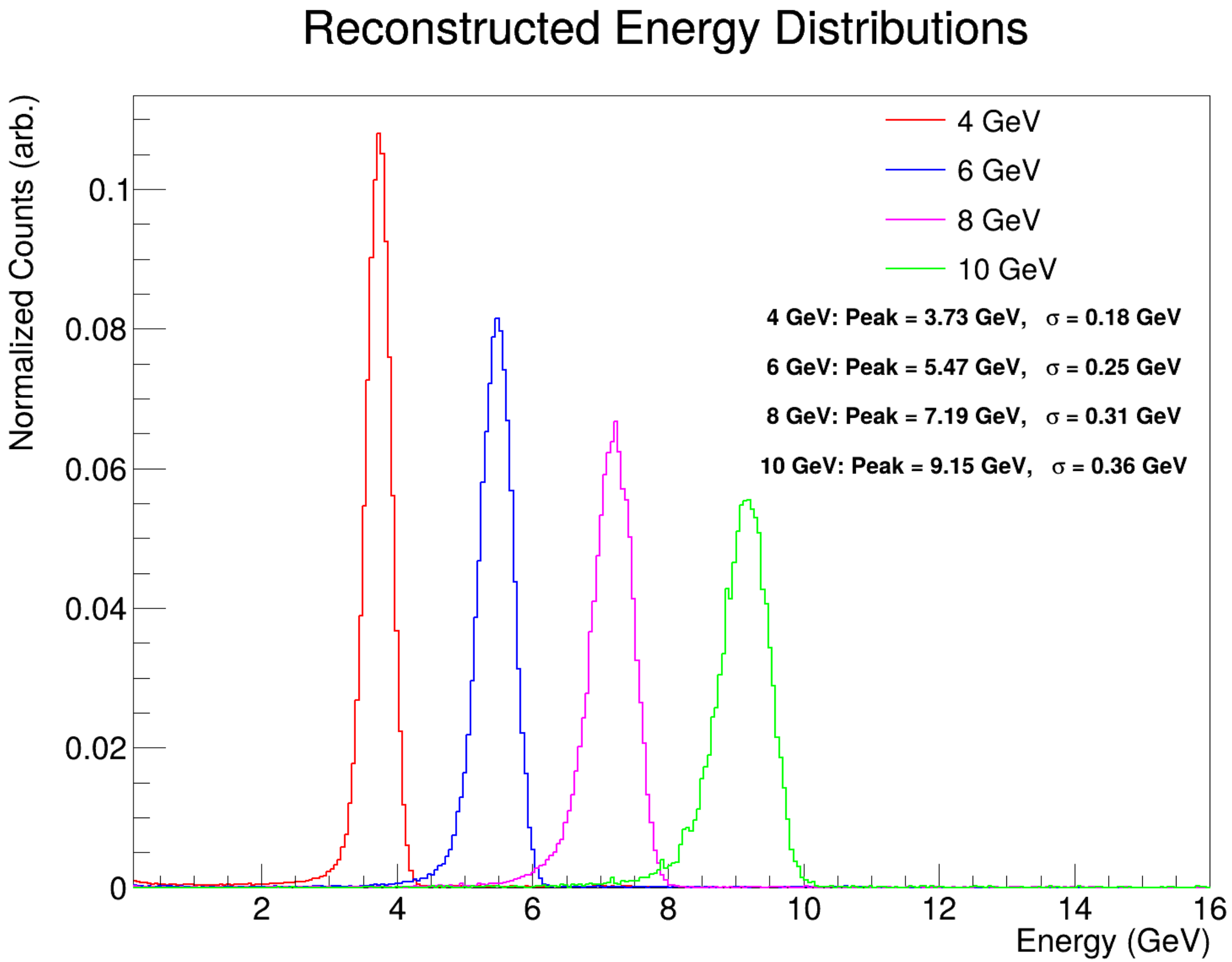
ENERGY RESOLUTION

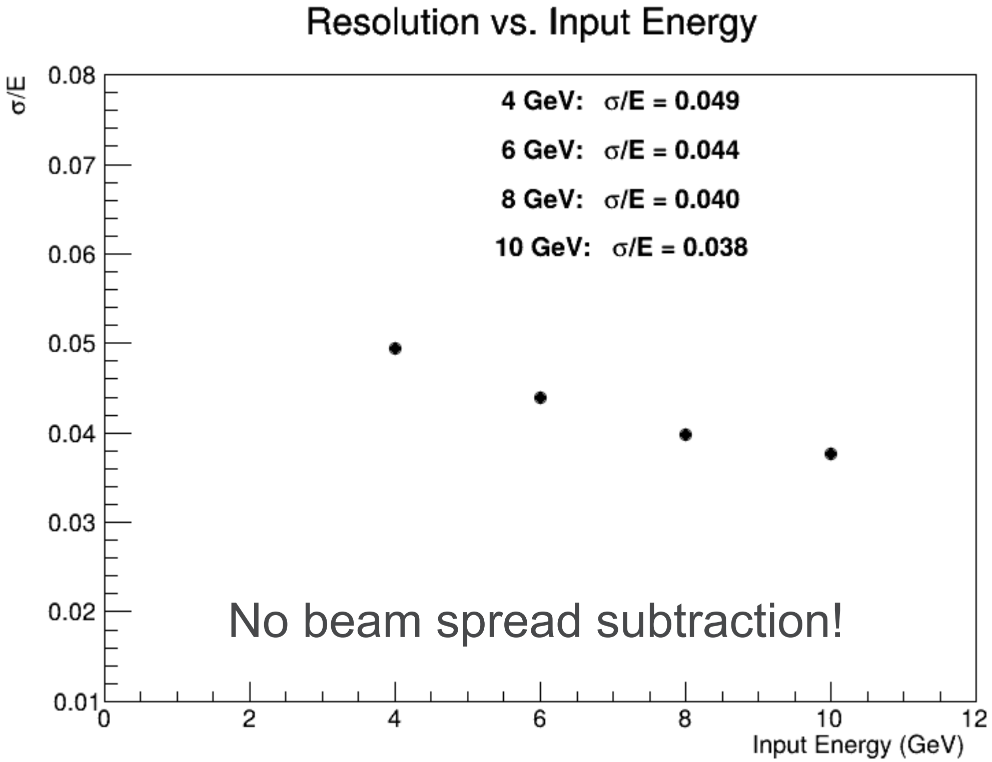
- Now that MIPs provided ADC units to energy conversion factors, can determine EM energy resolution
- Select electrons by selecting events where upstream Cherenkov & downstream Cherenkov outer PMT fired
- Some refinement cuts necessary
  - In particular, cuts to remove spurious signals and to improve containment of showers
- Total energy from geometric sum of N & S reconstructed energies



- Using only MIP calibration
- Containment & data quality cuts applied
- Achieves a reasonable resolution, but reconstructs the peaks about 10% lower than the beam energy we requested

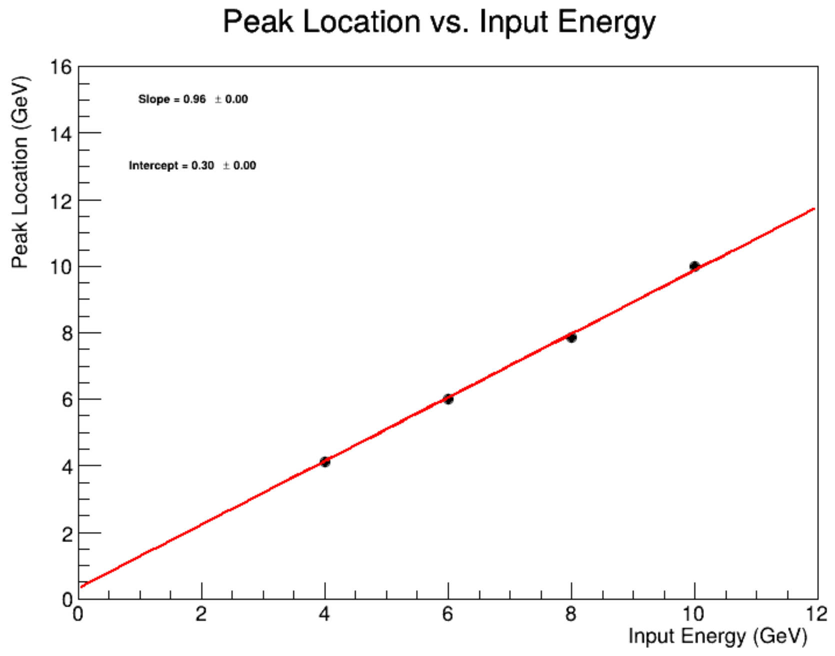


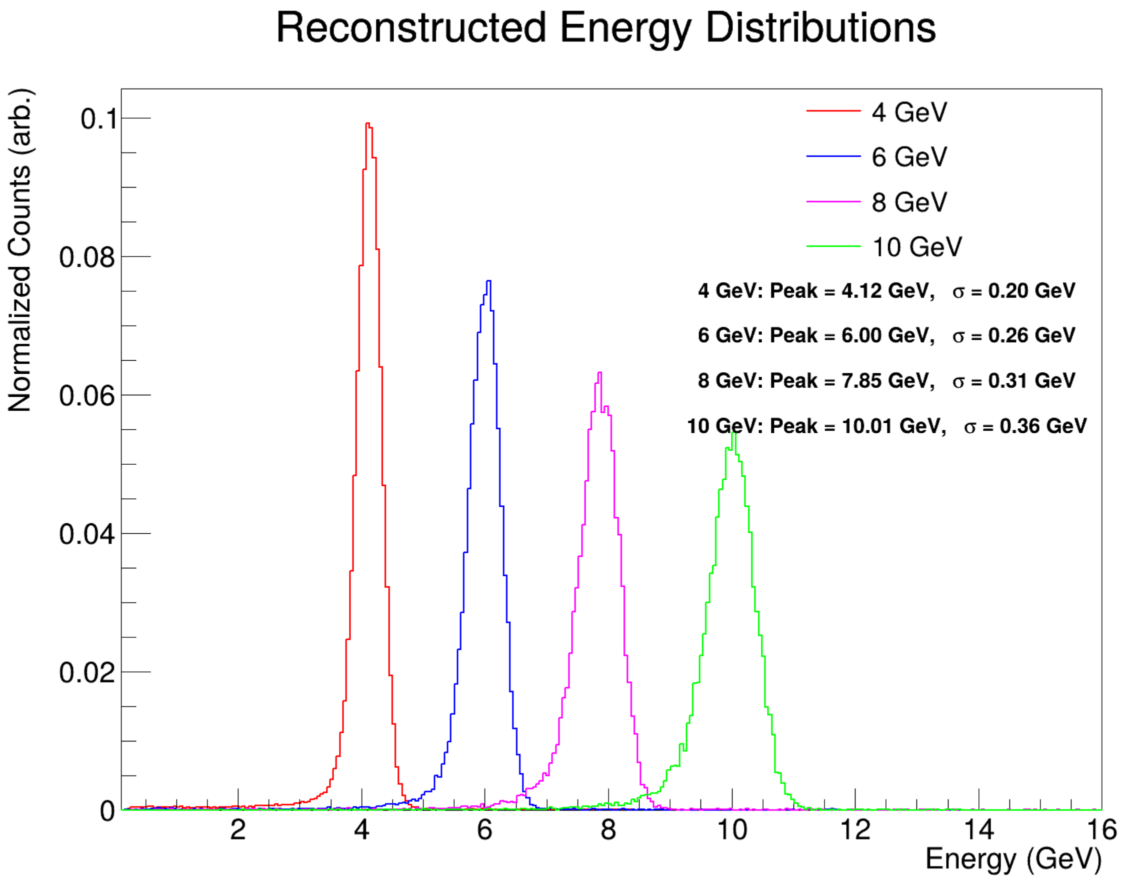


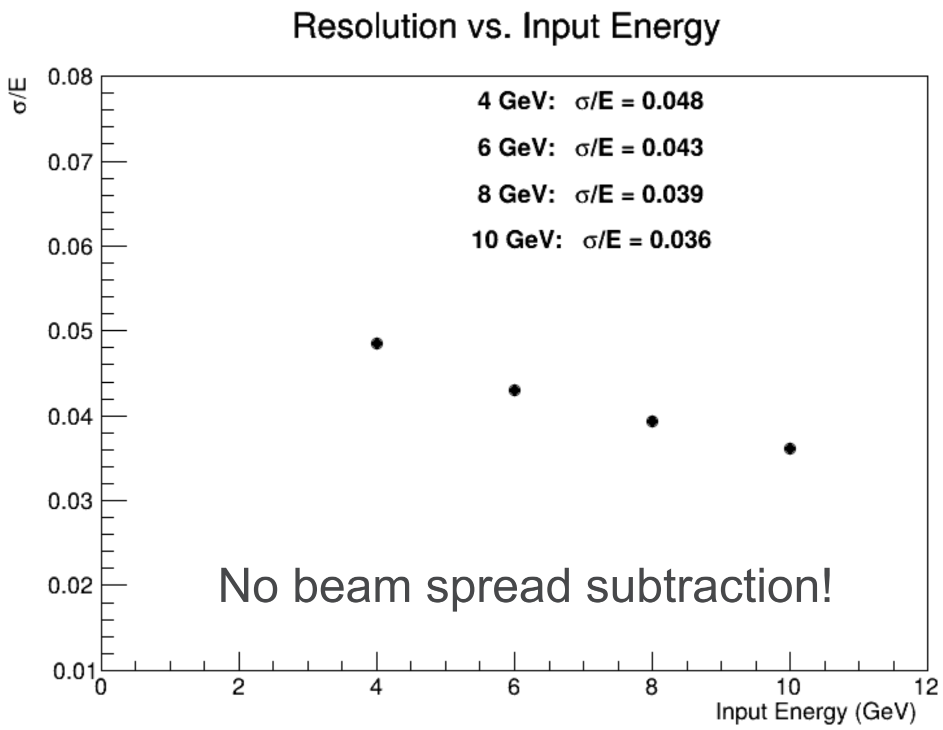


- Now using the MIP calibration as a starting point, use known electron beam energy to calibrate the sum of channels on each side to the “correct” energy
  - Similar to the GlueX technique

- This gets the peak locations ~correct (by construction)

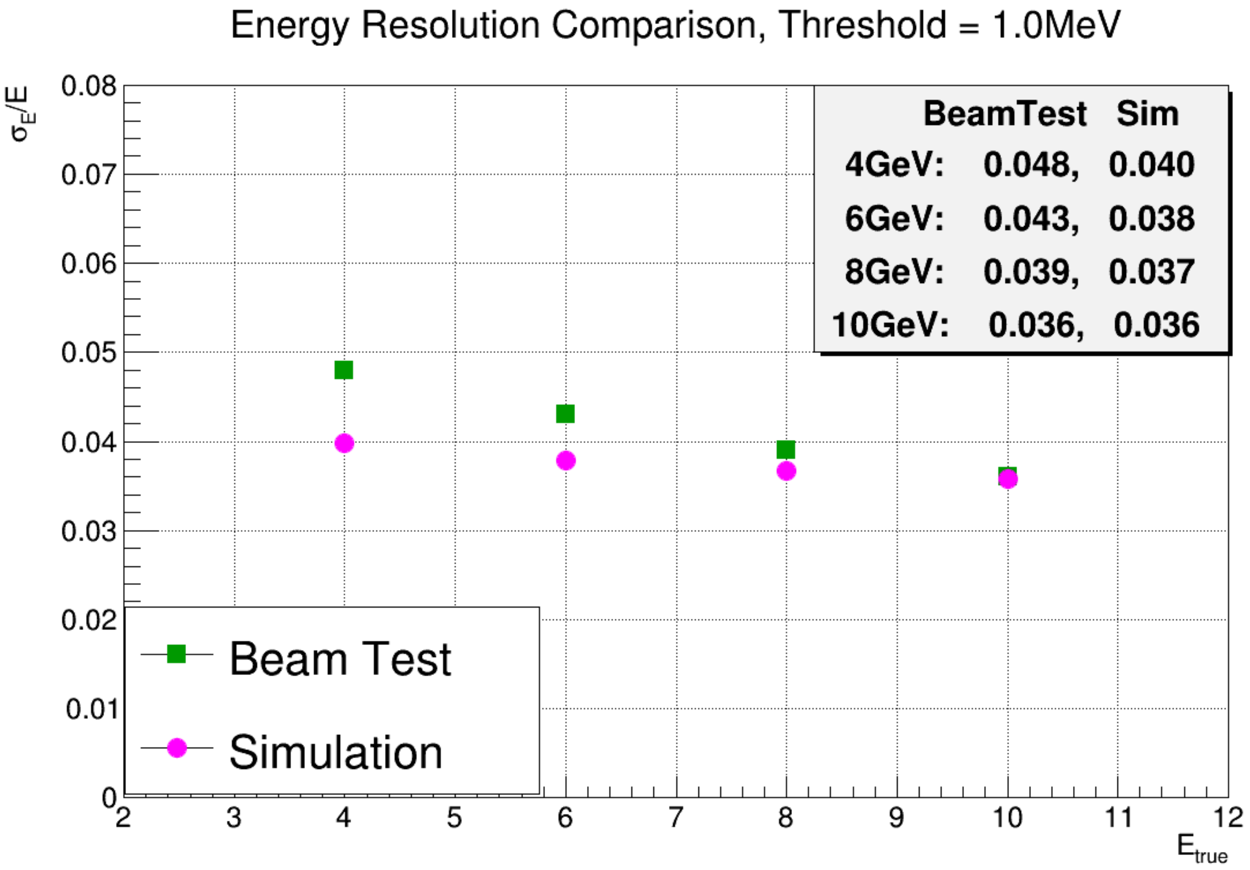






COMPARISON WITH SIMULATION

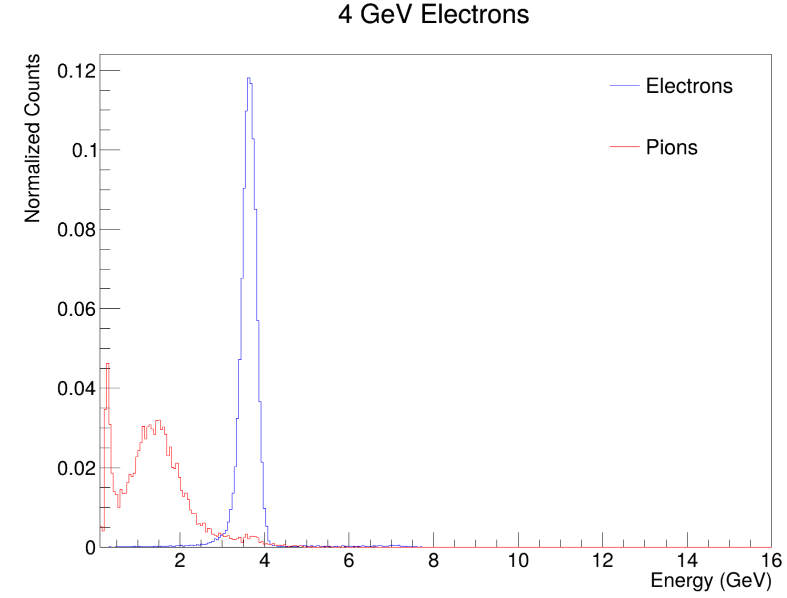
Baby BCal simulation by Jared Richards

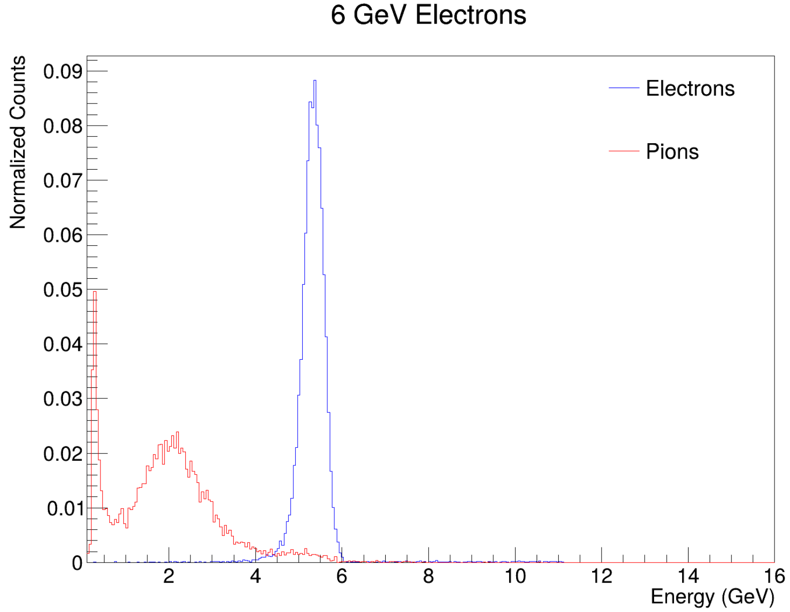


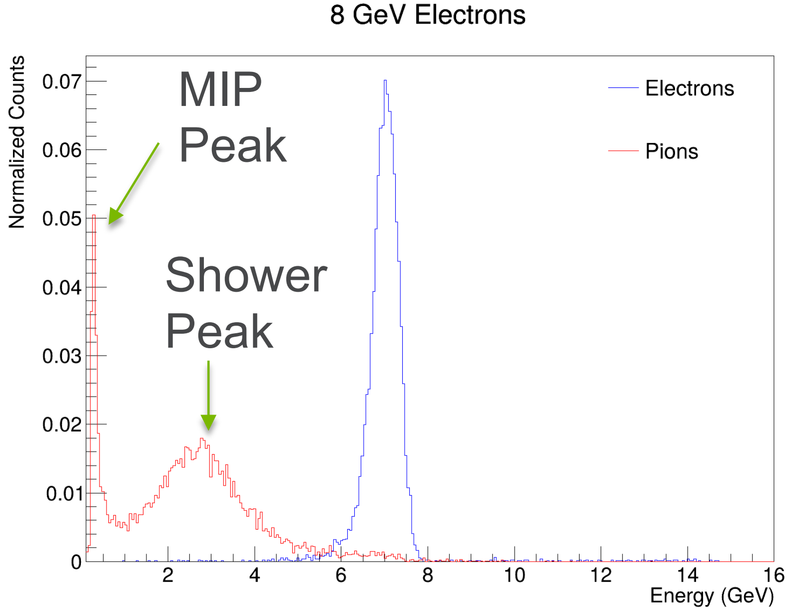
- Baby Bcal simulated including realistic beam δp & $\delta x, y$
- Fit a crystal ball to the simulated true energy deposit to determine best possible resolution
  - As expected, looks better than we observe
- Photostatistics not yet included in simulation
  - Will bring the simulation closer to the data, especially at lower energies
- Possible that beam spread changes as a function of energy

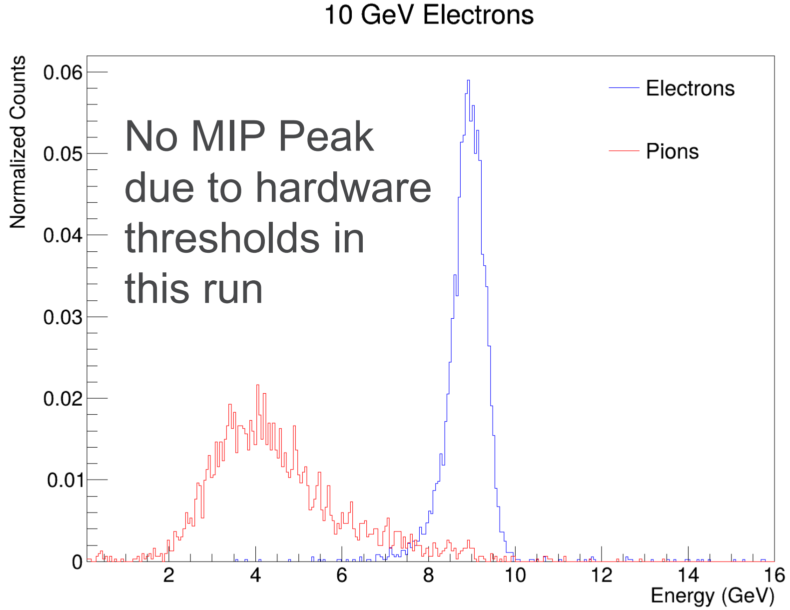
PION ENERGY RESPONSE

- Pions exhibit a MIP peak (left) and a shower peak (right)
- Select pions by requiring no hits in the Cherenkovs
  - **Apply same requirements on pions as applied in the previous slides (centered)**
- Want to study showering pions to determine electron/pion separation power
  - Due to longitudinal & transverse segmentation of calo, we can do better than a simple E/p method
- Note, pion sample contains energy-dependent admixture of muons!





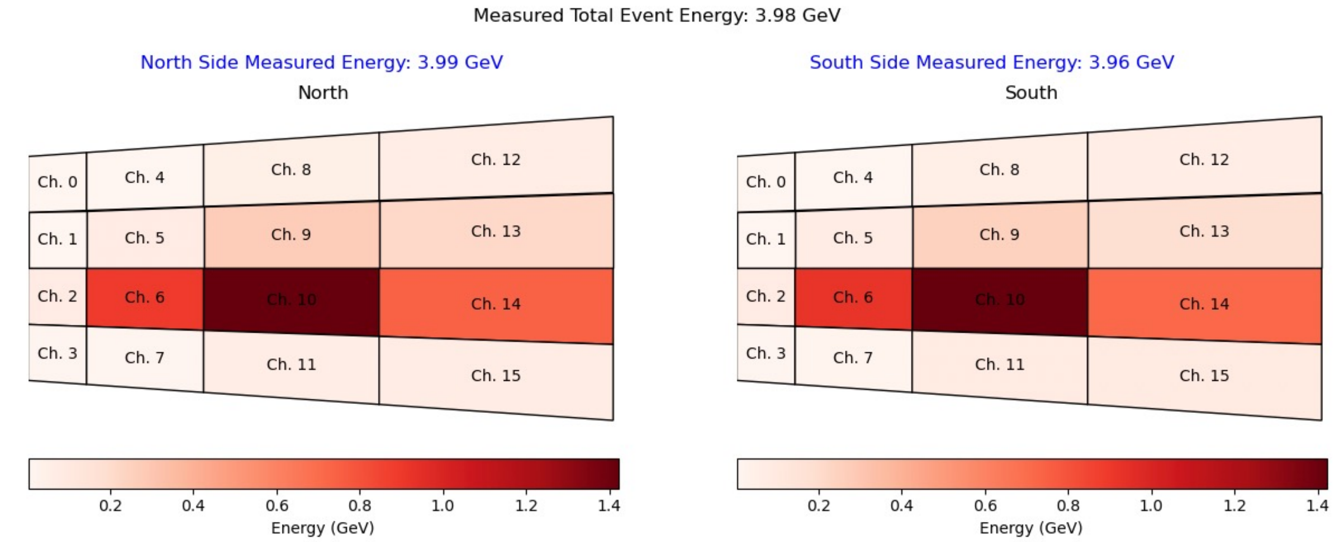


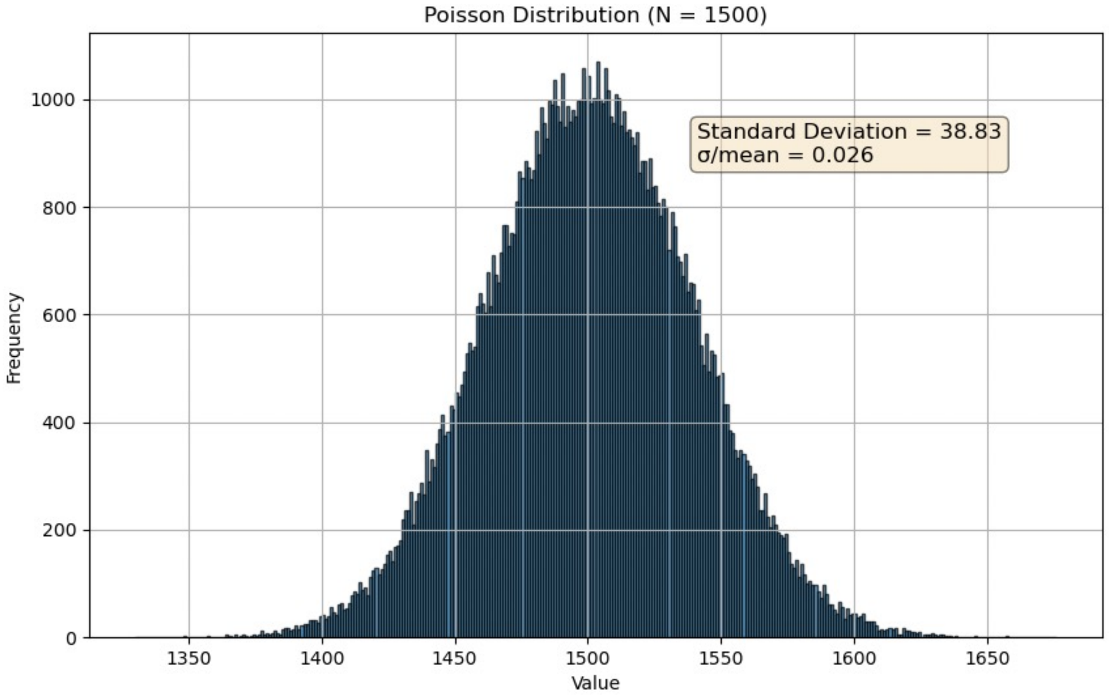


CONCLUSION

- Summer FNAL test beam campaign was very successful!
- Baby BCal responds essentially as expected
  - Energy resolution in the right ballpark
- Still improving the realism of the simulation
  - Once simulation is realistic, can obtain quantitative comparison of hadronic responses between simulation & reality

POISSON SMEARING

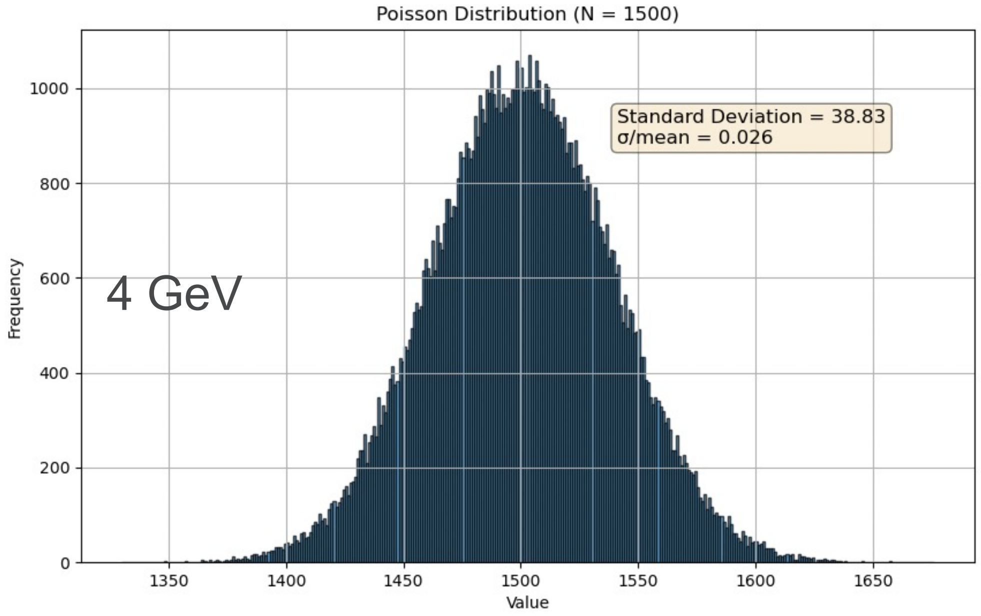


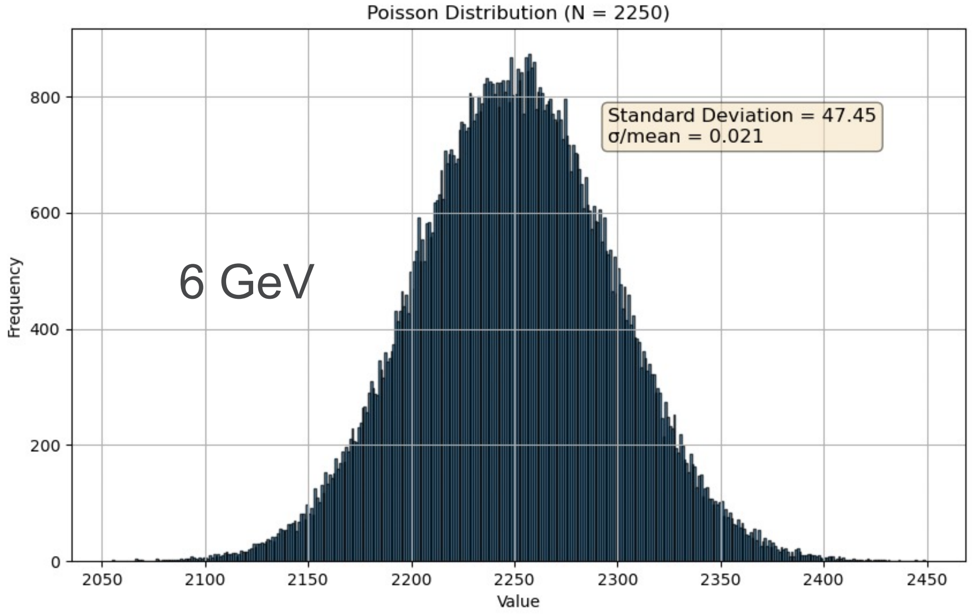


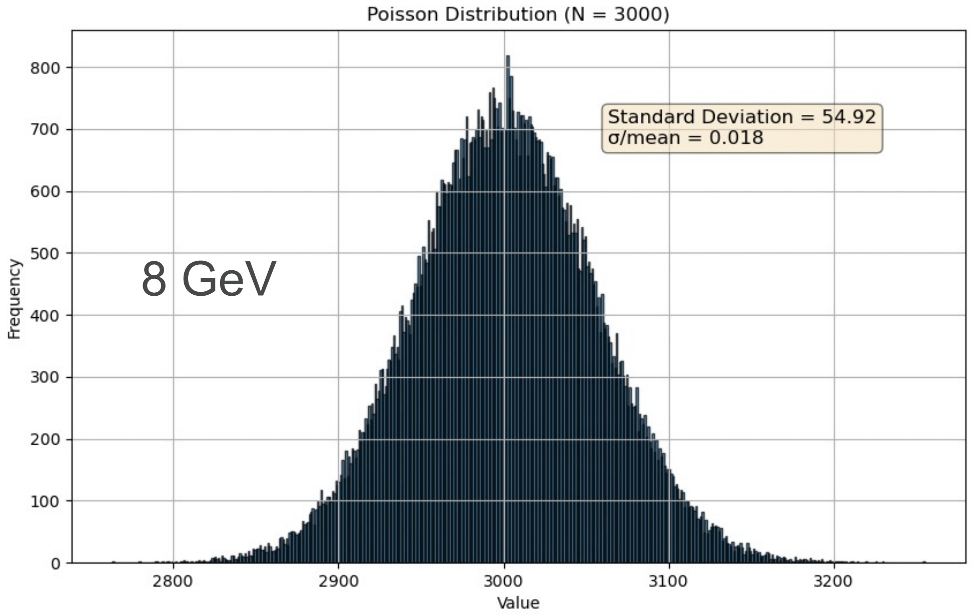
- Assume 1000 p.e. per GeV
  - Throw a poissonian with mean of 1500 to approximate the response of the hottest channel in a typical 4 GeV electron event

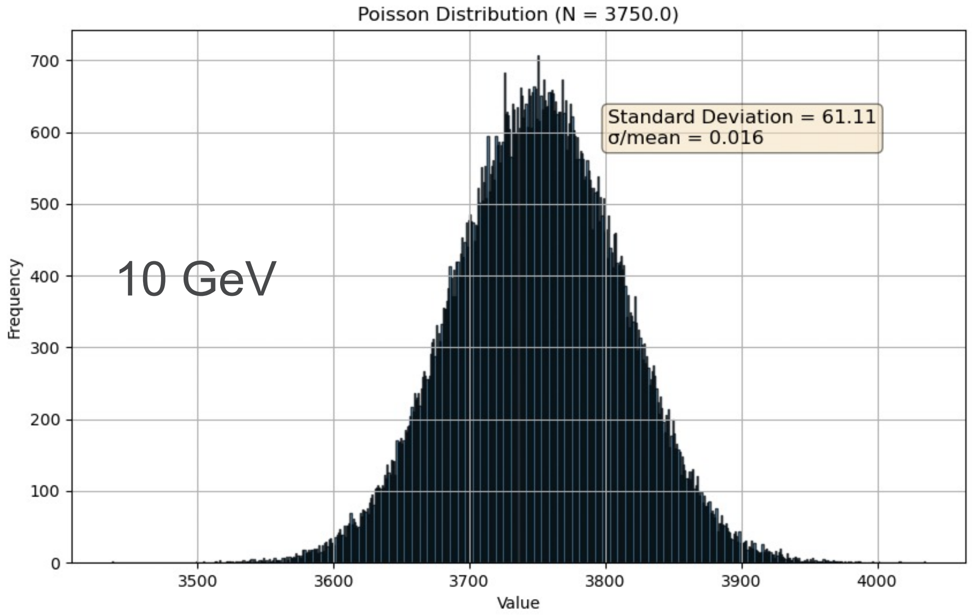
- Standard deviation divided by mean is non-negligible, and is thus far not included in the simulation
  - Could explain why the 4 GeV data is farther from the simulation than the higher energy data

POISSON SMEARING



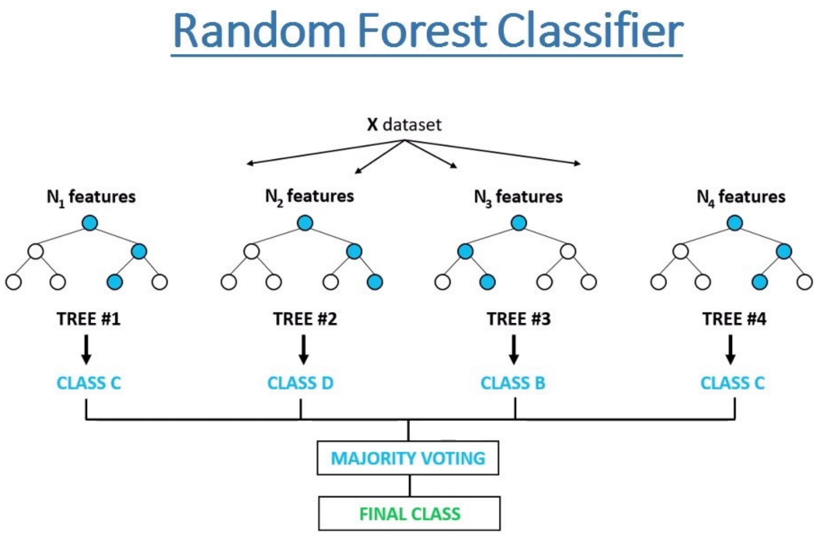






RANDOM FOREST CLASSIFICATION

- Tested a random forest ML classifier
  - Produces a “forest” of 100 decision trees and takes the majority decision
  - Well suited to binary classification tasks, less prone to overfitting



- Provided samples of electron data and pion data selected only with Cherenkov information
  - **Unfortunately, pion sample contains an unknown fraction of muons!**

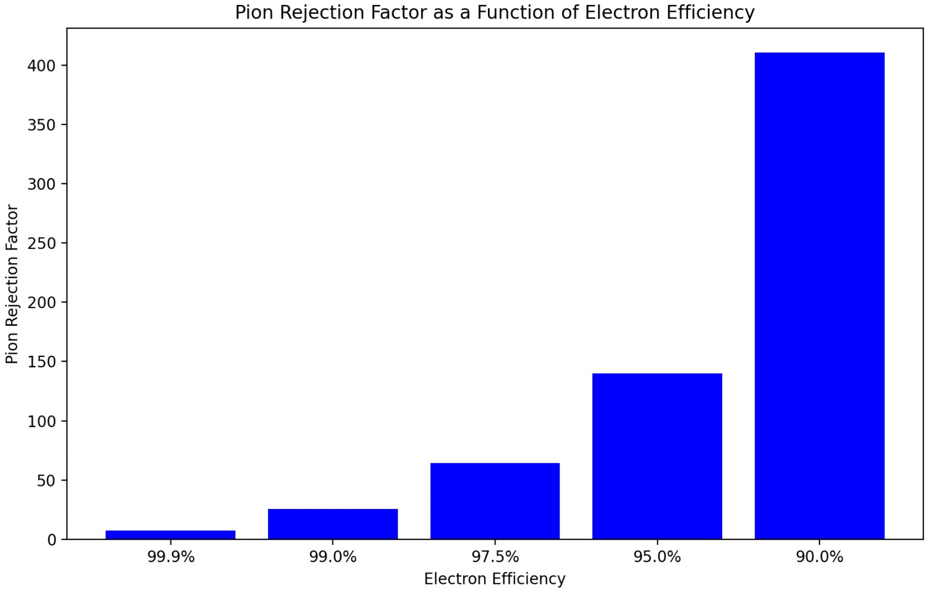
- No calibration applied, no channel masking, no cuts
  - Operates on raw ADC values

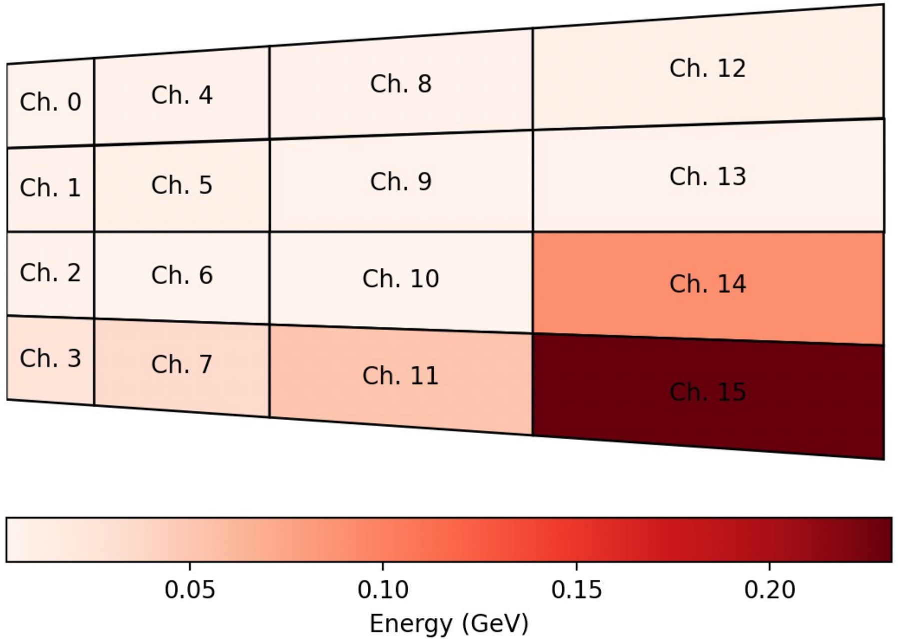
- Achieved a pi(/mu) rejection factor of ~150 for one run of the 4 GeV data

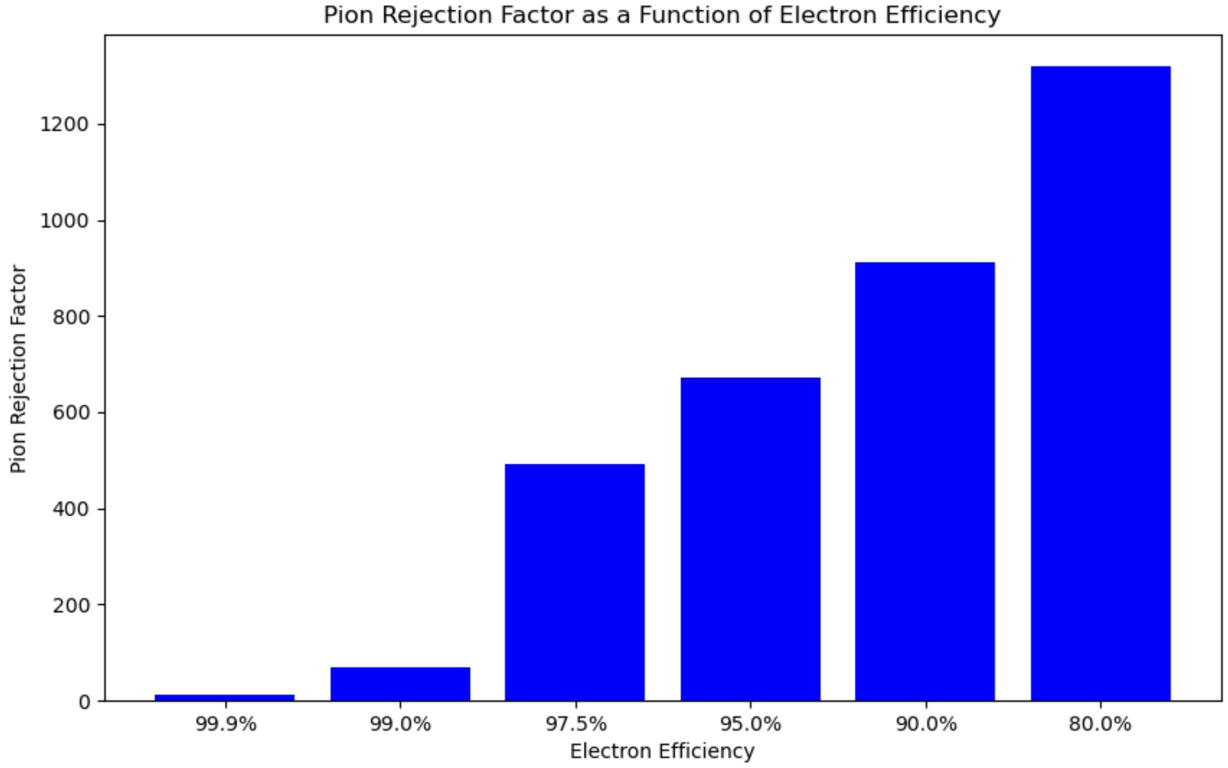
```
Pion Rejection Factor at 99.9% electron efficiency: 7.25063
Pion Rejection Factor at 99.0% electron efficiency: 29.55860
Pion Rejection Factor at 97.5% electron efficiency: 55.95882
Pion Rejection Factor at 95.0% electron efficiency: 154.09189
Pion Rejection Factor at 90.0% electron efficiency: 354.23820
Pion Rejection Factor at 80.0% electron efficiency: 938.30952
```

This is partially but not completely degenerate with E/p method

Feature	Importance
North 14 Amplitude	0.0595
South 15 Amplitude	0.0564
North 9 Amplitude	0.0540
North 11 Amplitude	0.0540
North 15 Amplitude	0.0530
North 10 Amplitude	0.0506
North 13 Amplitude	0.0488
South 14 Amplitude	0.0463
South 9 Amplitude	0.0455
North 8 Amplitude	0.0439
North 12 Amplitude	0.0406
South 13 Amplitude	0.0398
South 12 Amplitude	0.0362
South 11 Amplitude	0.0358
South 7 Amplitude	0.0298
South 8 Amplitude	0.0292
South 6 Amplitude	0.0249
South 4 Amplitude	0.0245
North 7 Amplitude	0.0227
South 10 Amplitude	0.0227
South 5 Amplitude	0.0213
North 6 Amplitude	0.0206
North 4 Amplitude	0.0195
North 5 Amplitude	0.0170
North 2 Amplitude	0.0153
South 0 Amplitude	0.0138
North 3 Amplitude	0.0137
South 1 Amplitude	0.0136
North 0 Amplitude	0.0133
South 3 Amplitude	0.0131
North 1 Amplitude	0.0130
South 2 Amplitude	0.0075

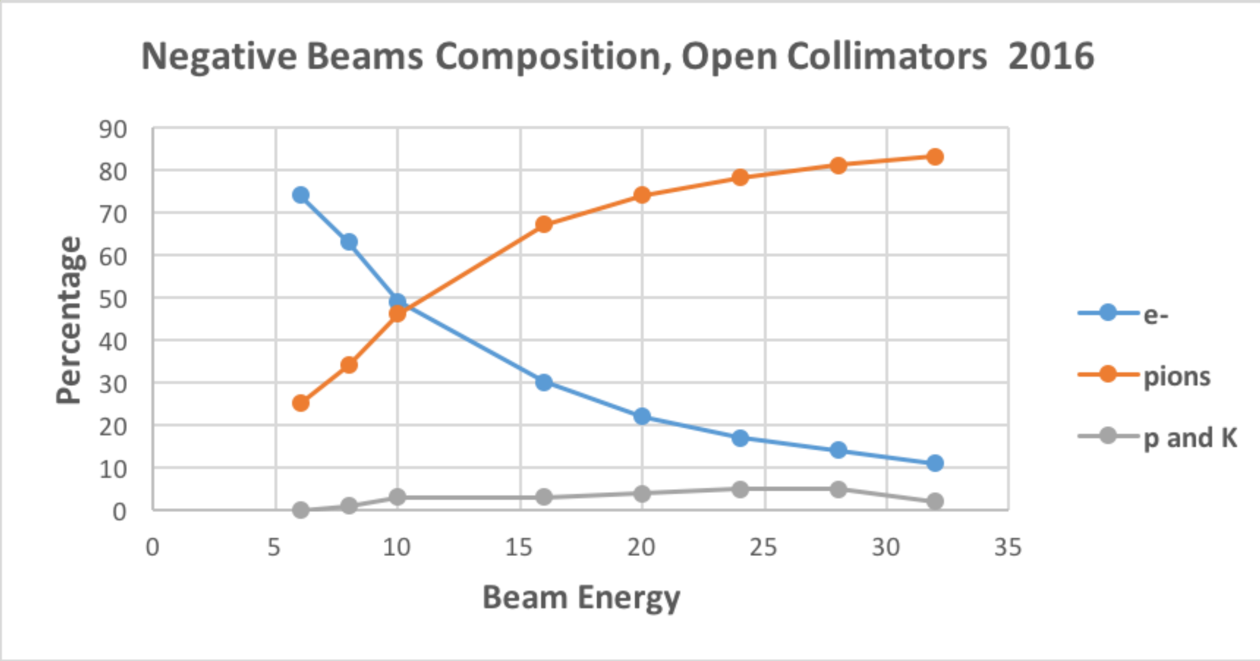







```
8 GeV:
Pion Rejection Factor at 99.9% electron efficiency: 10.72608
Pion Rejection Factor at 99.0% electron efficiency: 69.08765
Pion Rejection Factor at 97.5% electron efficiency: 491.44534
Pion Rejection Factor at 95.0% electron efficiency: 670.64641
Pion Rejection Factor at 90.0% electron efficiency: 912.68421
Pion Rejection Factor at 80.0% electron efficiency: 1319.42391
```

BEAM COMPOSITION

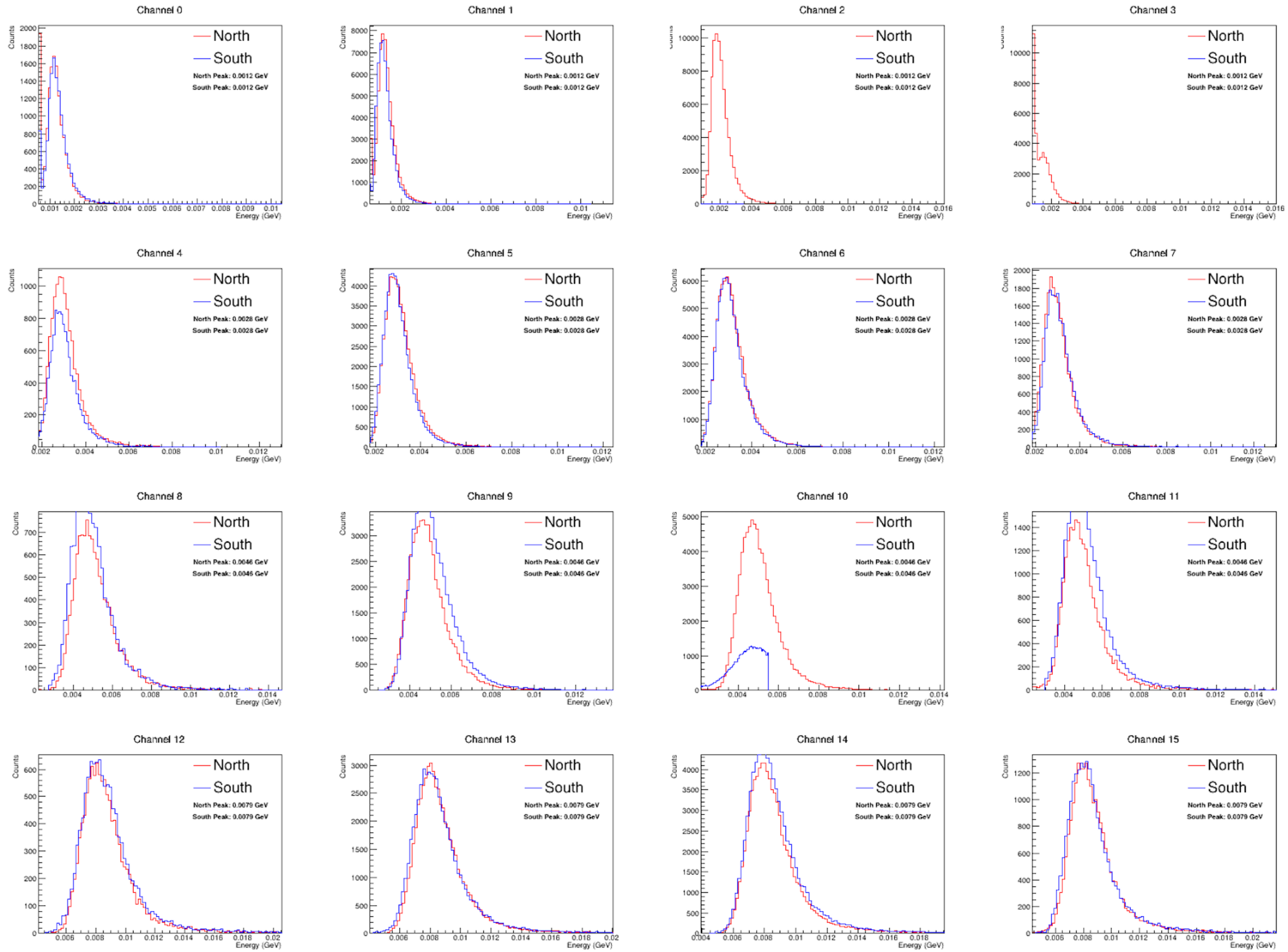


Energy	Mode[1]	Protons	Pions[2]	Highest Intensity[3]	Muons	Kaons	electrons	Spot Size[4]	Δp
120 GeV	Protons	100%	0	5E5	0	0	0	6mm	2%
60 GeV	pions +								
50 GeV	pions +								
40 GeV	pions +								
32 GeV	pions +/-			500,000					
30 GeV	pions +/-			500,000					
25 GeV	pions +/-			600,000					
20 GeV	pions +/-			500,000					
16 GeV	LEπ +/-		87%	1,000,000	100%			10mm	<4.5%
15 GeV	LEπ +/-								
12 GeV	LEπ –			500000					
10 GeV	LEπ +/-								
8 GeV	LEπ +/-		55%	750,000	98%			12mm	2.3%
6 GeV	LEπ +								
4 GeV	LEπ +/-		31%	400,000	74%			13mm	2.7%
3 GeV	LEπ +/-								2.7%
2 GeV	LEπ +/-		<30%	450,000				13mm	2.7%
1 GeV	LEπ +/-		<30%	69,000					2.7%

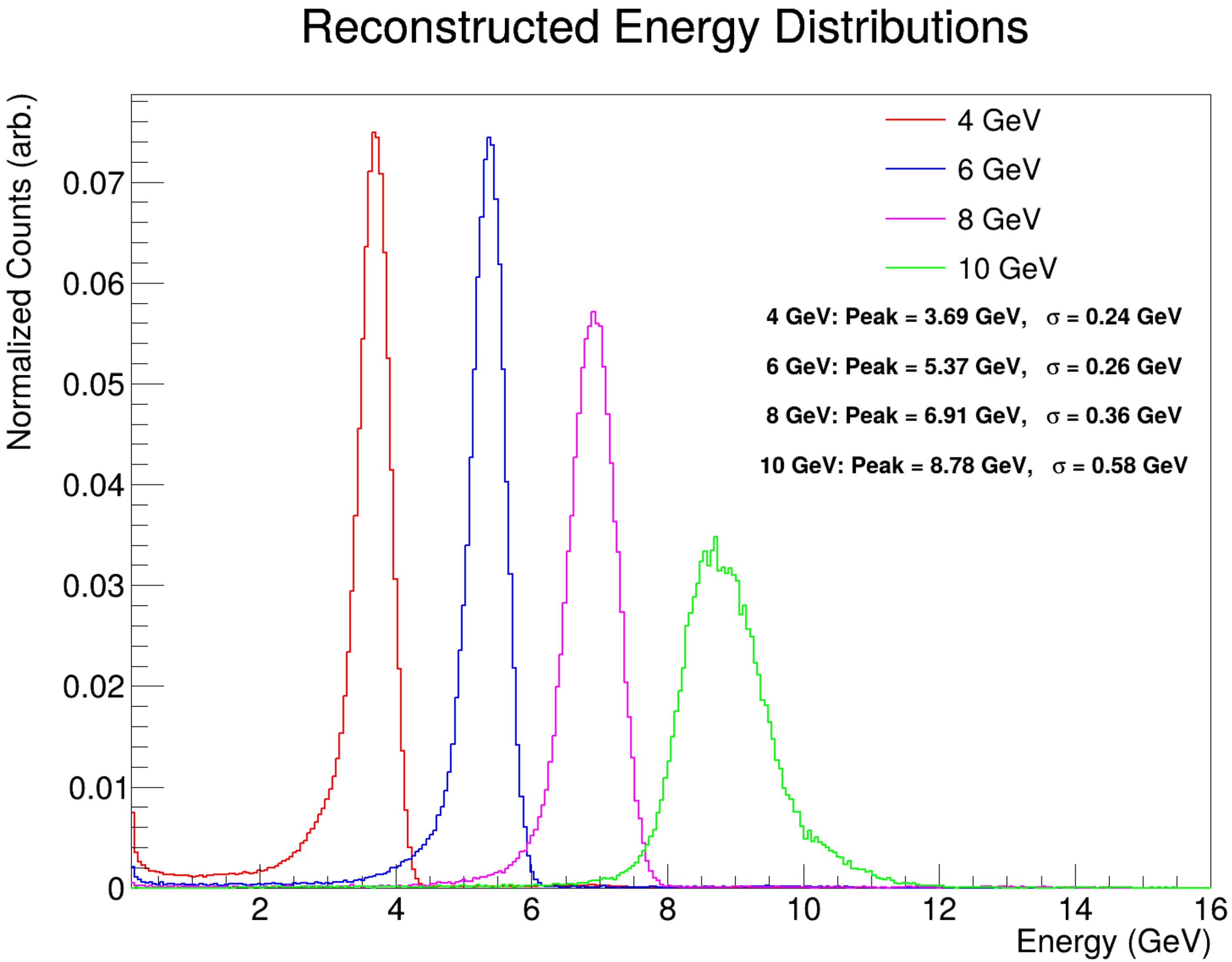
CALIBRATION

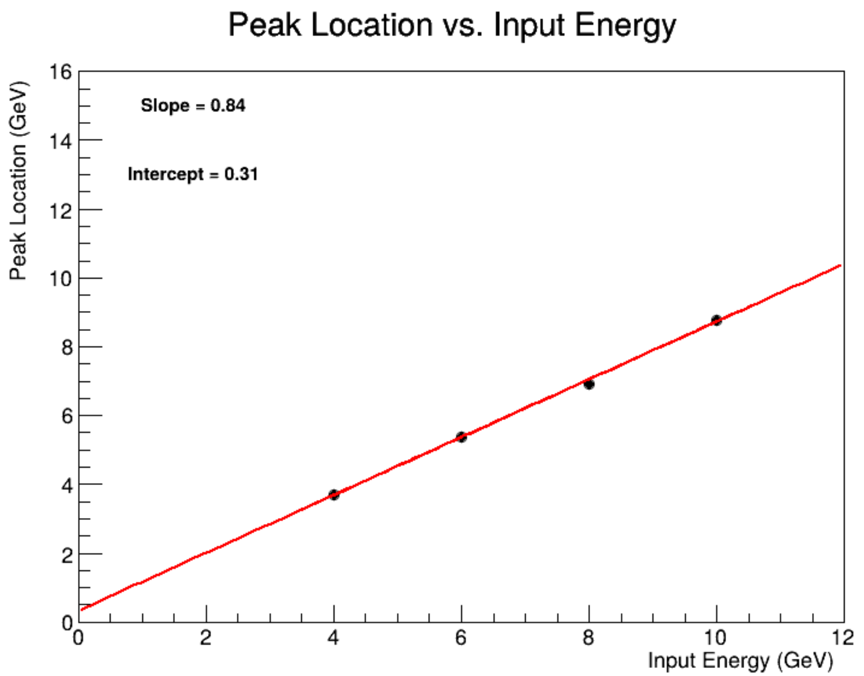
- Convert ADC to energy by adjusting the MIP peak location to the energy deposit determined from simulation

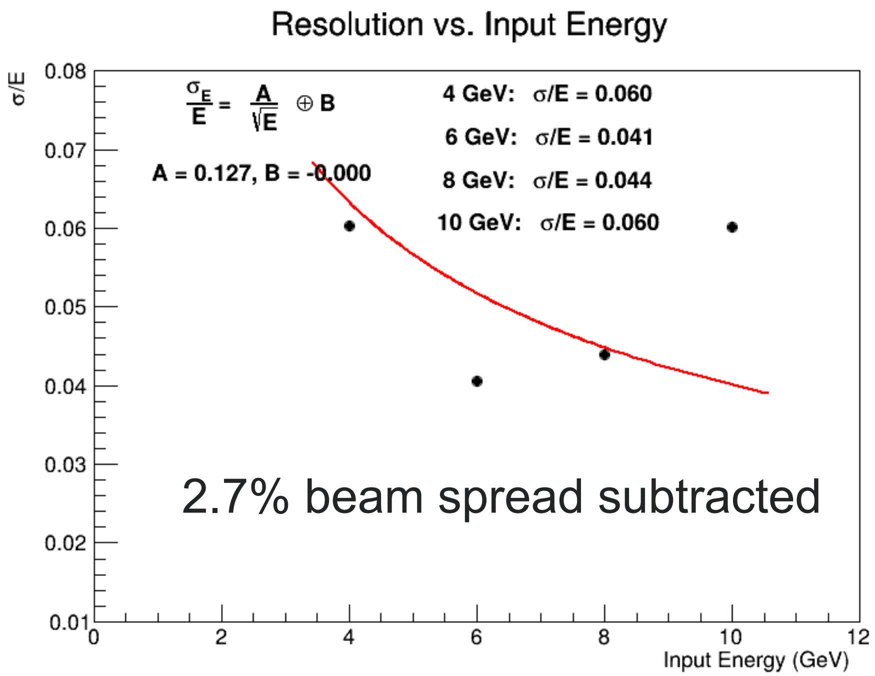
- “Manual” calibration used on South 2,3



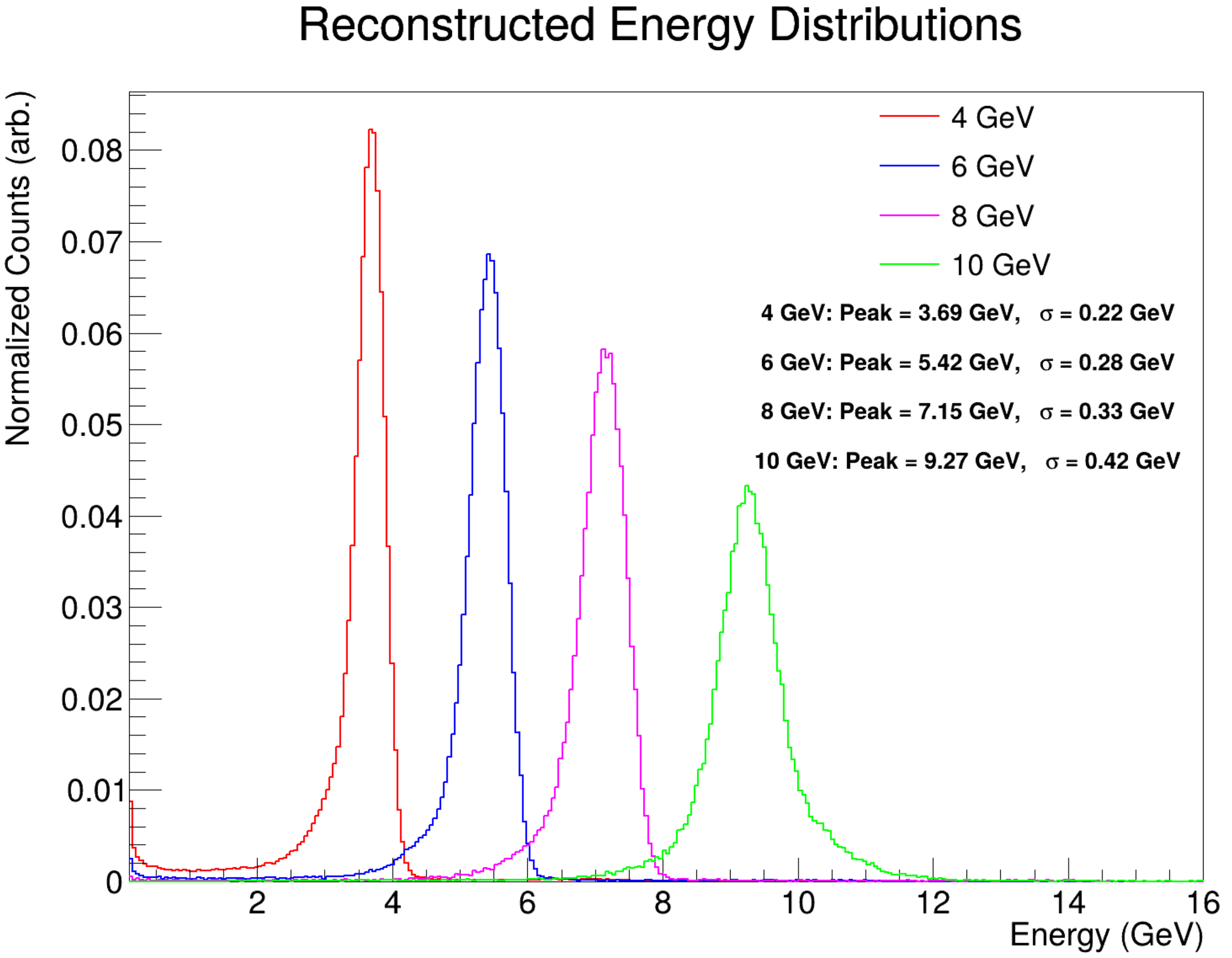
- Using only MIP calibration
- No containment cuts applied
- South 2, 3, 10 included

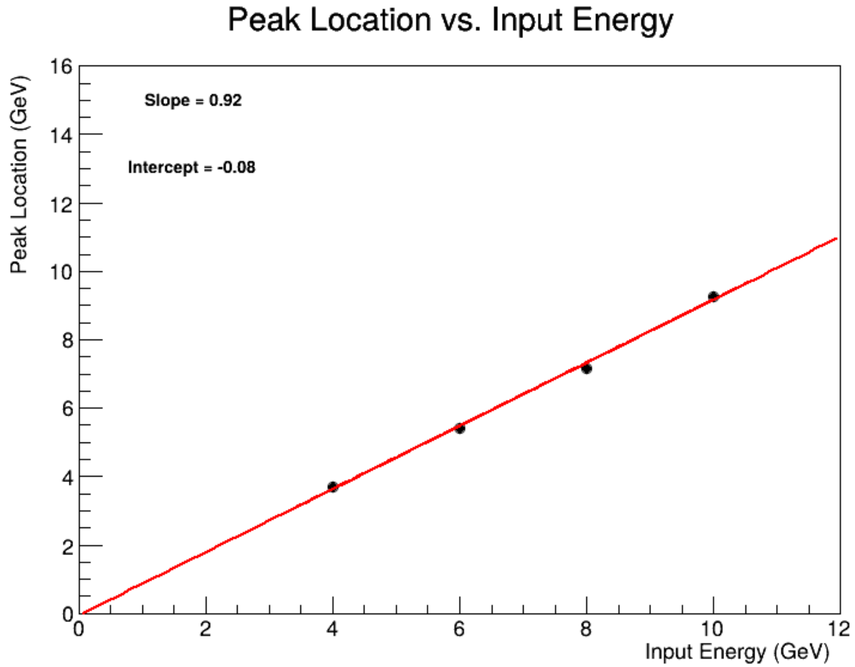


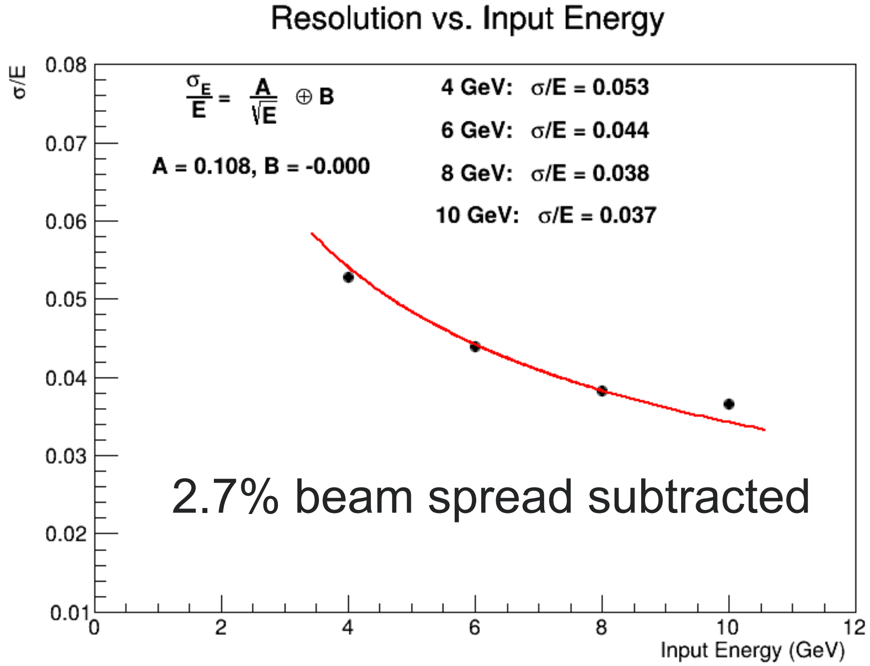




- Using only MIP calibration
- No containment cuts applied
- South 2, 3, 10 set equal to North 2, 3, 10

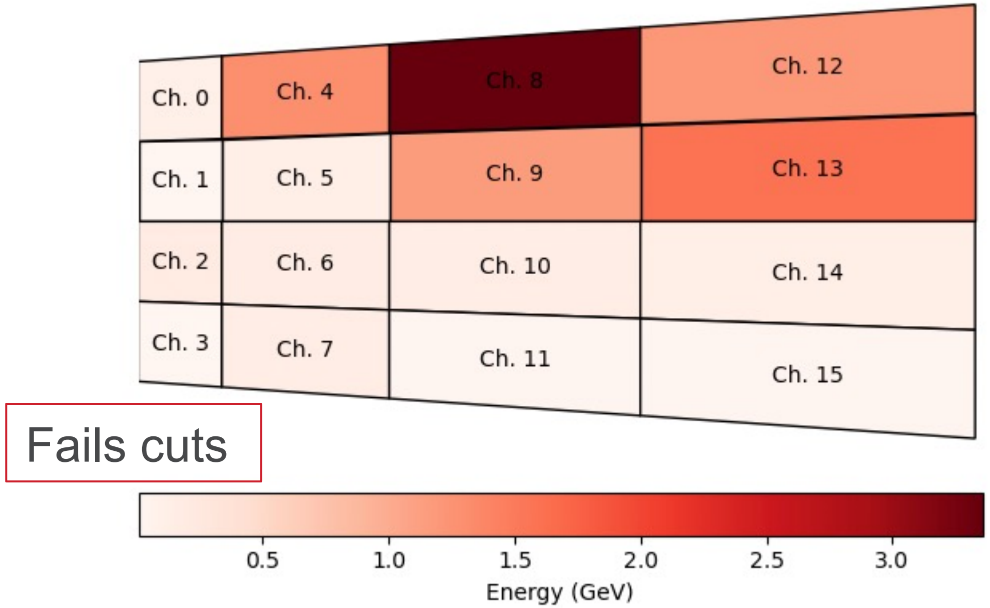


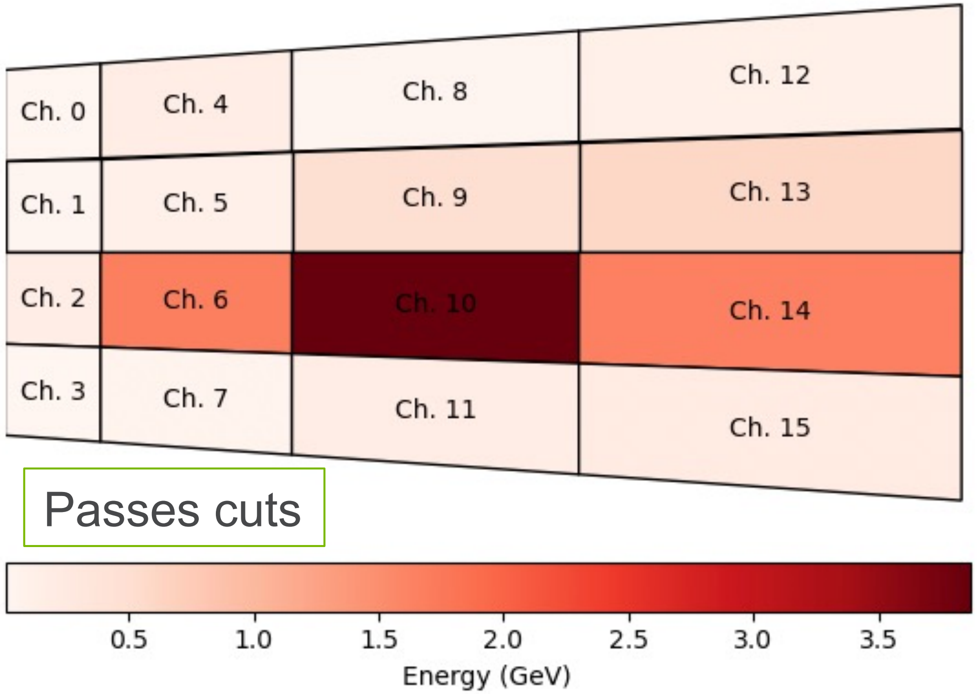


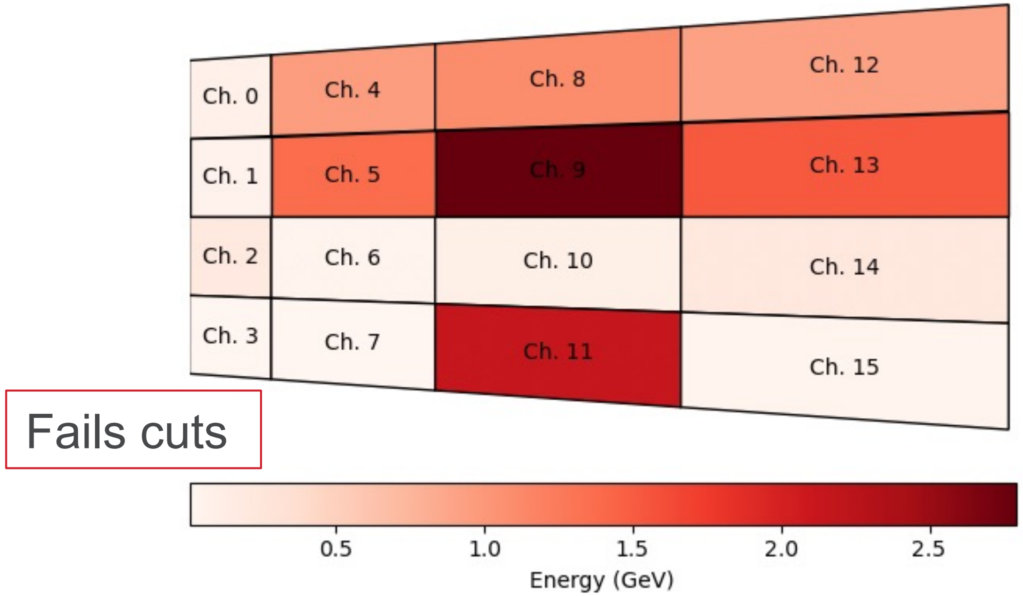


CONTAINMENT CUT

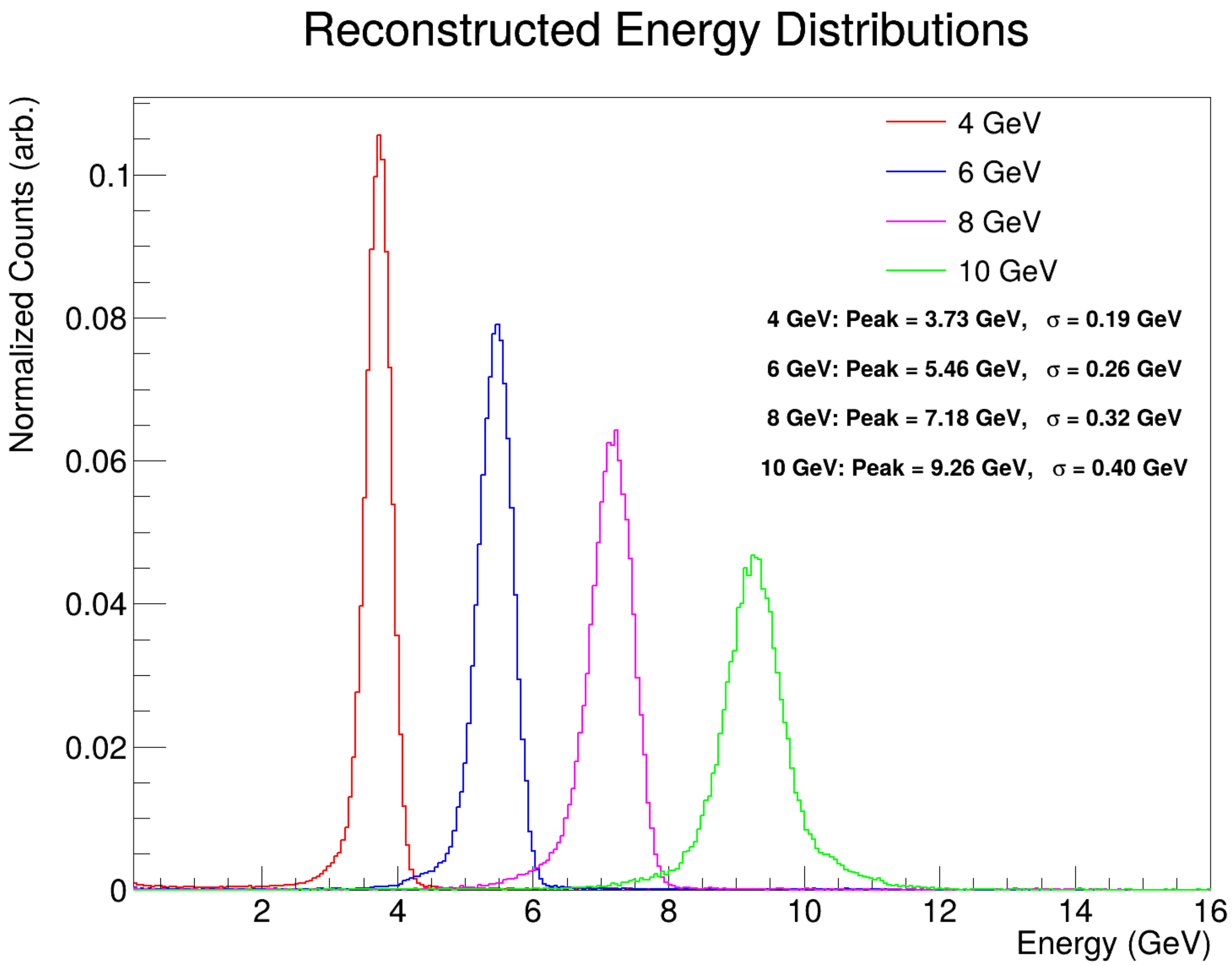
- Require that highest energy deposit is in channels 5, 6, 9, or 10
- Furthermore, require that second highest energy deposit is *neighboring* the highest energy deposit

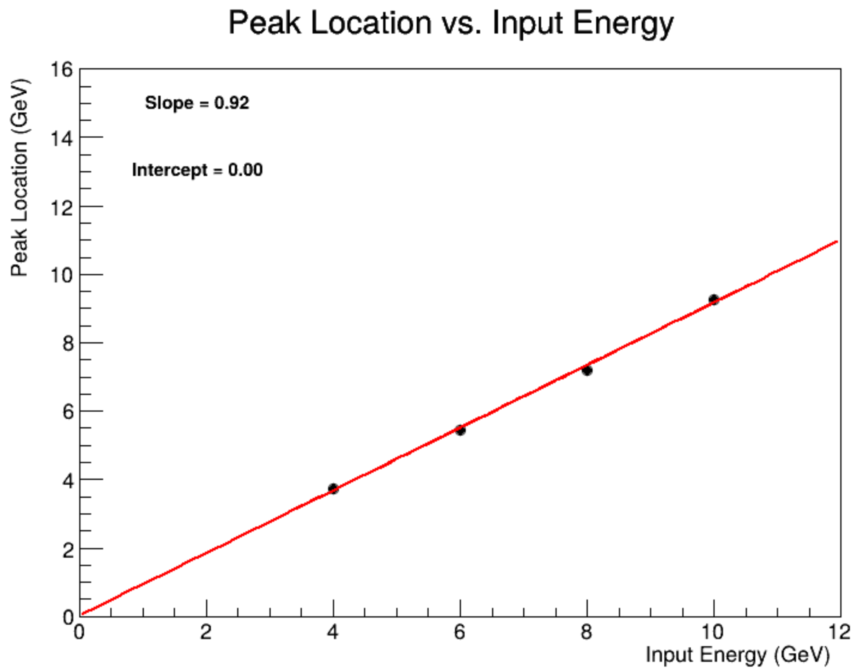


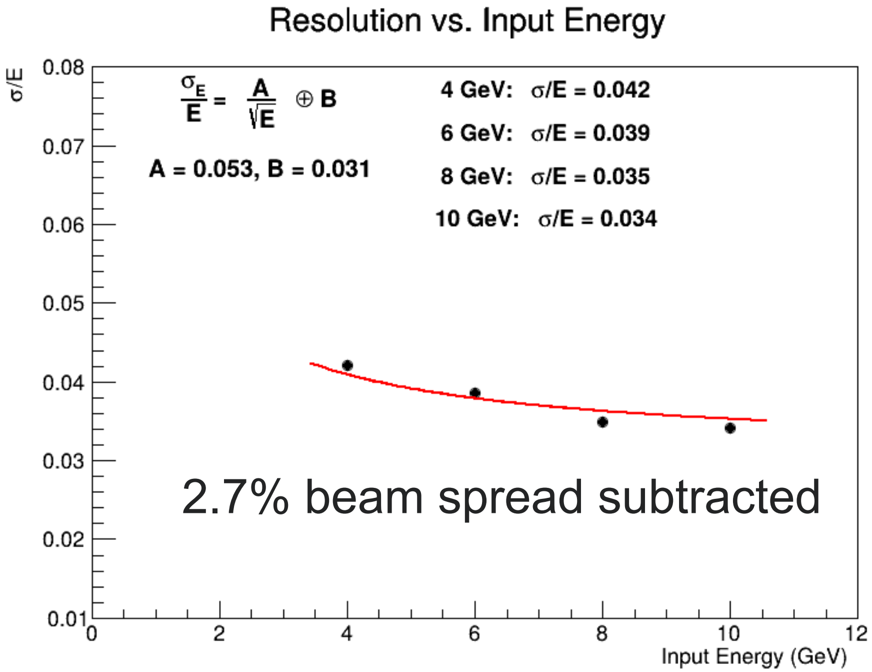




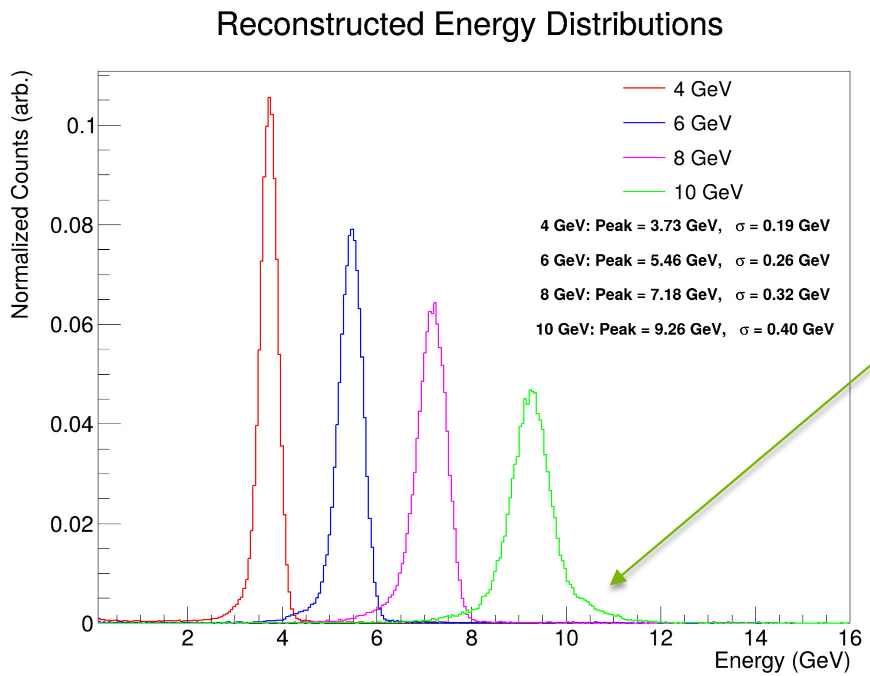
- Using only MIP calibration
- Containment cuts applied
- South 2, 3, 10 set equal to North 2, 3, 10





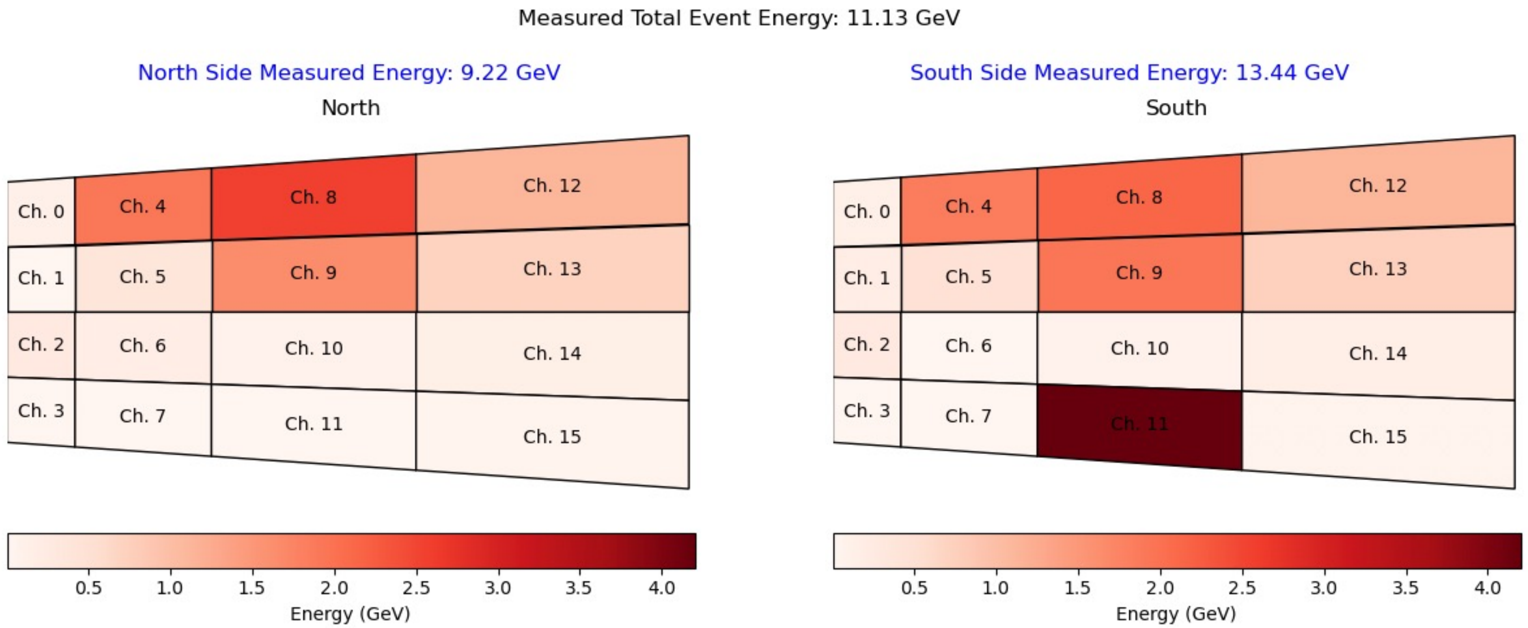


10 GEV TAIL

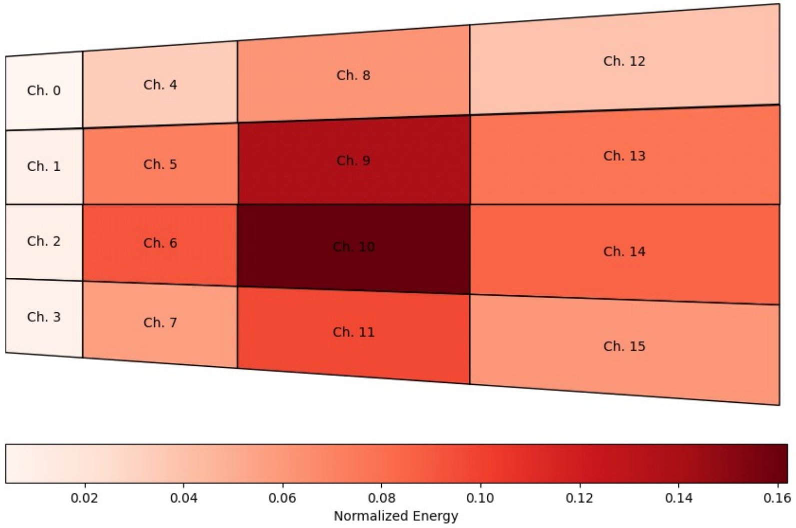


- Weird tail at high energies
  - Seen only in the 10 GeV data
  - Clearly non-crystal-ball-like

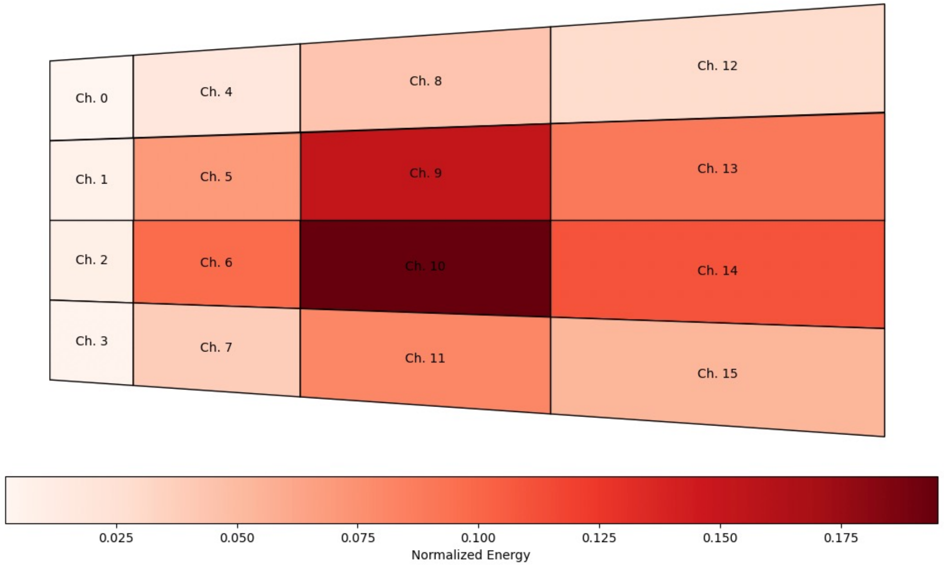
- Seemed like pileup at first, but upon further inspection seems to be localized to channels South 8 & 11, and only in 10 GeV data
  - Exclude events where N&S channels disagree by > 200 MeV



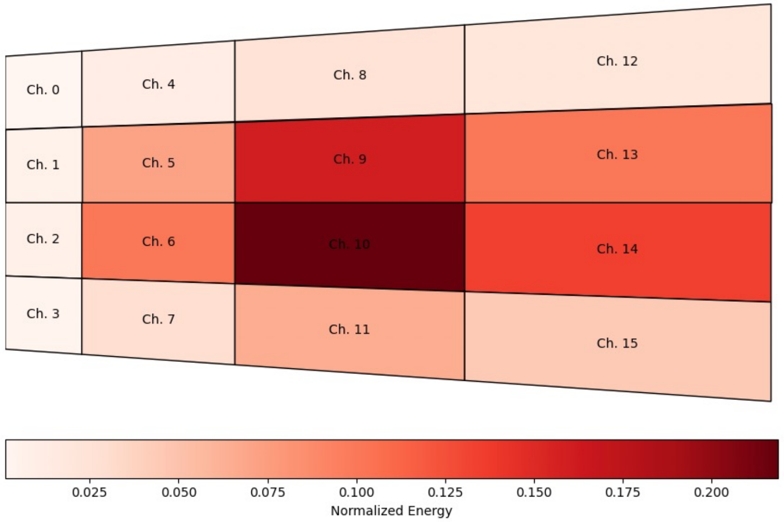
4 GeV



6 GeV



8 GeV



10 GeV