Fermi-LAT Measurement of Cosmic-ray Proton Spectrum Paper Outline - Version 0

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Abstract

The Pass 8 gamma-ray simulation and reconstruction package for the Large Area Telescope (LAT) on the Fermi Gamma-ray Space Telescope has allowed for the development of a new cosmic-ray proton analysis. Using the Pass 8 direction and energy reconstruction, we create a new proton event selection. This event selection has an acceptance of 1 m^2 sr over the incident proton energy range from 50 GeV to over 8 TeV and when applied to over 7 years of LAT observations provides over 700 million events for a spectral measurement. The systematic errors in the acceptance and energy reconstruction require careful study and will contribute significantly to the spectral measurement. The event selection and spectral measurement of the Pass 8 proton analysis opens the door to additional proton analyses with the LAT, such as the evaluation of proton anisotropy. We present a detailed study on the measurement of the cosmic-ray proton spectrum with Pass 8 data for the Fermi LAT.

1 Introduction

(I) Describe overview of LAT

- (A) Launch date to give early context of how much data there is available
- (B) Orbital parameters to show what kind of space environment we have to deal with
- (C) Development of Pass 8, short list of improvements and how this enables use to make a new proton analysis with the LAT

(II) Discuss recent developments of the CR proton spectrum from instruments

- (A) AMS-02 observes break in spectrum at 300 GeV
- (B) Potentially resolves discrepancy between satellite measurements in 100s GeV energy and balloon-borne measurements
- (C) But.... AMS-02 only goes to 1.8 TeV, statistics limited due to small acceptance and X years of flight
- (D) Gap left between 1.8 TeV of AMS-02 and 3 TeV of CREAM

(III) Goals of this analysis

- (A) Measure the cosmic-ray proton spectrum from 50ish GeV to several TeV
- (B) Fermi LAT in unique position to measure spectrum spanning between satellite measurements and balloon borne measurements
- (C) Also able to confirm spectral break as currently only seen by AMS-02 and possibly by Pamela
- (D) Create a new data set of cosmic-ray protons for future analysis (I'm not sure we really need this in the paper but might be nice to mention)

(IV) Event selection for high quality proton sample

(V) Energy reconstruction, biases, energy resolution, and limitations

(VI) Describe out instrument response: acceptance and contamination

(VII) Describe the methods used for spectral reconstruction: unfolding and forward folding using response matrix derived from MCs

(VIII) Describe evaluation of systematic uncertainties

- (A) Due to event selection: acceptance and contamination
- (B) Energy measurement: absolute energy scale and energy resolution
- (C) From hadronic model of Geant4 simulations
- (D) Spectral reconstruction: comparing unfolding and forward folding methods

(IX) Finally discuss observations and features of measured spectral, including possible spectral break and agreement with recent results (definitely need to but this in context with other measurements since while energy resolution is poor and systematics less precises than AMS-02 we can extend the energy further into the region of balloon-borne detectors which have never been done before and makes a quantitative connection between two different observation environments)

2 Event Analysis

(I) Overview

- (A) Description of the LAT
- (B) 4×4 array of towers which measure direction and energy of incoming cosmic-ray
- (C) Each tower is composed of TKR and CAL
- (D) TKR information
  - (i) Each TKR module is 18 x-y planes of silicon-strip detectors with tungsten converter foil
  - (ii) Total of 1.5 X_0 at normal incidence (should convert this to nuclear interaction length)
  - (iii) X-Y nature and depth of TKR allows for determination of initial direction of cosmic-ray
  - (iv) Additionally able to measure the time over threshold of CR
  - (v) ToT allows for measurement of signal $\propto \mathrm{Z}^2$
  - (vi) The last 4(?) Tungsten converter foils are thicker than the previous layers to ensure gamma-rays convert within TKR
- (E) CAL information
  - (i) CAL is homogeneous electromagnetic calorimeter
  - (ii) Each CAL module is 96 CsI(Tl) crystals in an hodoscopic array in 8 layers.
  - (iii) The hodoscopic nature of the CAL allows for measuring the shape and evolution of each particle shower which can be used with a profile fitter to determine the incident energy of the cosmic-ray
  - (iv) additional the imagine capability of the CAL allows for the measurement of the direction of the incident CR
  - (v) At normal incidence the CAL is 0.5 λ_i lengths deep but at horizontal incidence is it 1.5 λ_i deep
- (F) Anti-coincidence detector (ACD) surrounds the 4×4 tower array
- (G) ACD information
  - (i) 89 segmented covering 5 sides of the tower array
  - (ii) Each tile independently measures deposited energy from CR
  - (iii) Deposited energy $\propto \mathrm{Z}^2$

(H) Description of the LAT triggers and filters and point towards the paper with more information

(I) LAT was not designed for accurate measurement of hadronic showers

   (i) Very shallow homogeneous calorimeter not idea for fully capturing energy hadronic shower profile

   (ii) Compare to CREAM and/or AMS-02

   (iii) Unable to measure energy on an event by event basis, need to focus on a statistical ensemble approach with high event rate

   (iv) Therefore need to be aware of limitation of energy measurement and associated systematic uncertainties

(II) Pass 8 Event Reconstruction

(A) I'm not 100% sure of the depth of this section but seeing as though we are using Pass 8 and that was a somewhat critical step into enabling this analysis's possibility I think having a dedicated section in the Event analysis chapter might make sense. If we put it anywhere it should be rather early before the simulations and after the describing the instrument

(B) Pass 8 is the new event reconstruction and simulation software developed by the Fermi LAT collaboration that drastically improves LAT's performance

(C) New event classification using boosted decision trees in TMVA

   (i) Several new Pass 8 variables have been created to determine the quality of the direction, energy, and gamma-ray quality

(D) More variables gives better separation between hadronic and leptonic showers in TMVA

(E) Improved profile to fitting to particle showers improves energy measurement

   (i) The New Full Profile fitter is able to extend the longitudinal profile of the shower outside the CAL therefore estimating the amount of energy leakage for high energy events, > 100 GeV

   (ii) Two energies derived from new full profile fitter, one for TKR directions and one for CAL directions

(F) New tree based TKR reconstruction allows for direction reconstruction at higher angles and larger energies

(G) New ACD reconstruction provides better particle identification, lowering the contamination of proton sample

(H) Is there something else I am missing from Pass 8? There is no Pass 8 paper to reference this so I am not sure how in depth I should go into this discussion.

(III) Monte Carlo simulations

(A) Need to stress the importance of the simulations since this is how we derive all of our instrument response functions

(B) Also use simulations for the development of TMVA selection to remove contamination for other CRs

(C) Simulations based on Geant4

(D) LAT instrument and spacecraft are fully simulated within Geant4

(E) Particles with distributions of energies, directions, and charges are generated and propagated with realistic physics models for interactions with the simulated LAT which create raw data

(F) Raw simulated data is processed through the same Pass 8 reconstruction software as flight data

(G) We preform extensive comparison between simulated data and flight data to ensure results from MC analyses can be reliably applied flight data

(H) Three types of simulations are used this analysis:

(I) Proton simulation

    (i) Simulation run from 4 GeV to 20 TeV
    (ii) Cover 4π sr
    (iii) Created with an $dN/dE \propto E^{-1.5}$ spectral index
    (iv) Original purpose to study Pass 8 CR rejection for studying extragalactic background light
    (v) This produces a simulation event sample of over X million events

  (J) Electron simulation
    (i) 10 GeV to 10 TeV
    (ii) Cover 2π sr (the top half of the instrument)
    (iii) Created with a $dN/dE \propto E^{-1.0}$ spectral index
    (iv) Original purpose of studying instrument response for cosmic-ray electron analysis
    (v) This produces a simulation event sample of over X million events

  (K) Background simulation
    (i) The background simulation was created to accurately simulate the cosmic-ray environment of the LAT during space flight
    (ii) It contains CR particle from Z = 1 to Z = 26, electrons, positrons, neutrons, and Earth albedo gamma-rays
    (iii) All particles are simulated with realistic fluxes using results from recent CR experiments
    (iv) The background simulation used in this analysis simulates about 8 days worth of livetime
    (v) Protons range: 4 GeV - 10 TeV and 4π sr
    (vi) Electrons/Positrons range: 4 GeV - 10 TeV and 4π sr
    (vii) Helium range: 4 GeV - 20 TeV and 4π sr
    (viii) Heavier CR range: 2 GeV/amu - 50 GeV/amu and 4π sr
    (ix) Fluxes are taken to be near solar minimum

  (L) All simulations are produces with an additional setting called overlay events
    (i) Overlay events are created from diagnostic events from flight data and signal is added on top of the simulated data
    (ii) This is mimic the effect of having two events simultaneous enter the LAT (for such high events rates at lower energies is a reasonable assumption)
    (iii) Pass 8 has many new algorithms to handle and reduce the effect of two simultaneous events interacting with the LAT

(IV) Event Selection

  (A) Minimum Quality Cuts
    (i) We want a selection of hight quality protons for the spectral analysis
    (ii) TkrNumTracks > 0: Require an event to have at least one track
    (iii) WP8CTPSFTail > 0.5: WP8CTPSFTail is a new Pass 8 TMVA variable which determines the quality of direction reconstruction, this ensures the track is well reconstructed
    (iv) CalEnergyRaw > 20 GeV: This utilizes the high pass filter on the LAT. Any event with a deposited energy greater than 20 GeV is downloaded from the LAT. This means for events with CalEnergyRaw > 20 GeV is not effected by and lower energy filters which are difficult to understand for protons
    (v) CalTrackAngle < 0.3: Ensure the difference between the CAL and TKR directions is small.
    (vi) CalNewCfpSat: Ensure that the variables resulting new full profile fitter are not saturated
    (vii) Tkr1LengthInCal > 200.0: Want a long path length through the calorimeter and does not fall within gaps of CAL. More active material will help ensure more deposited energy and a better reconstructed energy

    - (viii) CalLeakCorr > 0.25: CalLeakCorr is a correction for the amount of shower leakage out of the CAL. This is defined for electromagnetic showers and therefore poorly represents the intrinsically wider and more stochastic nature of hadronic showers. We want to minimize the effect of this variable on the analysis.
    - (ix) log10(TkrTree1ThickRLnNodes) < 1.0: To make sure events convert within the beginning of CAL and not last few layers of TKR (don't want to lose energy to TKR) we ensure the last few layers of the TKR do not have too many events This also helps with backslash and again losing energy back into the TKR
    - (x) These cuts ensure the direction and energy are well reconstructed, still need remove contamination source from helium + heavier CRs and electrons
- (B) Helium and Heavier Ion Cut
    - (i) To remove $|Z| > 1$ CRs we use two independent measures of charge in the LAT
    - (ii) Tkr1TotTrAve
        - (a) The average time over threshold of signal in TKR
        - (b) Signal is ionization of CR interacting with silicon trips, therefore Signal $\propto Z^2$ in units of MIPs
    - (iii) Acd2PLCTkr1TileActDistEnergy
        - (a) The path length corrected energy deposited in the ACD in units of MeV
        - (b) Signal once again due to ionization of CR interacting with plastic scintillator, therefore AcdPlcEnergy $\propto Z^2$
    - (iv) Using these two measures of charge we create of phase-space of Tkr1TotTrAve vs Acd2PLCTkr1TileActDistEnergy
    - (v) Designate a polygon in that phase-space around $\mathrm{Z}^2 = 1$ using BKG simulation
        - (a) It should be noted that Geant4 does not accurately recreate the rate of heavy ions interacting with the LAT, it greatly under estimates the event rate
        - (b) But since ionization is relatively simple and these heavy CRs aren't showering in the ACD or TKR, the amount of ionization energy is fairly accurate
        - (c) What this means is we can define the polygon and trust the position of the polygon in flight data
    - (vi) We also include an additional cut on Acd2Cal1TriggerEnergy15
        - (a) Acd2Cal1TriggerEnergy15 is the energy deposited around a 15° cone from the CAL direction
        - (b) The reason for this is a population of large angle heavy CRs priests after the cut, they tend to have a poor TKR direction reconstruction but good CAL direction reconstruction. We demand the Acd2Cal1TriggerEnergy15 ¡ 30 MeV
    - (vii) This greatly reduces the contamination of heavier ions and alphas to under 1% and decreasing at higher energies
    - (viii) Also since ionization is $\propto Z^2$ we cannot differentiate protons from electrons using this cut
- (C) Proton Classifier
    - (i) To remove electrons from the proton sample we develop an event classifier with TMVA using protons as signal and electrons and background
    - (ii) Since leptonic and hadronic showers are fundamentally different we can use several variables of merit from Pass 8 reconstruction to build a multi-variate analysis and differential protons from electrons
        - (a) The CALs ability to image showers means we have several variables with trace shower size and evolution (hadronic showers are much wider and longer than leptonic showers)
        - (b) Additional variables like centroid position of the shower, and size of the track left in the TKR also are able to distinguish between leptonic and hadronic showers
    - (iii) Using simulations previously described with a boosted decision tree with TMVA to train classifier

- (iv) Using classifier output we can select on an optimal value for each energy bin and create an energy dependent event selection
  - (a) This is critical because the proton classifier's ability to distinguish protons from electrons is energy dependent
  - (b) Classifier has trouble separating events at high energies (all events look very similar at highest energies since instrument is small compared to size of TeV showers)
- (v) The optimal value for each energy bin is selected by using the ROC curve (signal efficiency to background rejection) ensuring the derivative of the ROC curve is below a defined tolerance
- (vi) We also use several different proton scanning efficiencies
  - (a) Find energy dependent cut on proton classifier output which ensures a predefined (90%,80%, 70%, etc...) is achieved
  - (b) This allows us to probe systematic errors associated with the proton classifier, acceptance, and contamination
  - (c) We produce a spectrum for each different scanning efficiency and compare it to the optimized selection
- (vii) We use a template fitter developed by the Fermi-LAT electron analysis to evaluate the data/MC agreement for the variables used in the training the classifier and the output of the classifier
  - (a) Data/MC agreement is very important
  - (b) MC needs to properly recreate data variables in order trust classifier is giving the desired results
  - (c) Discrepancies between Data/MC in training variables will translate to systematic errors associated with classifier
  - (d) Also dependent on how important the variable is for training the classifier
  - (e) Data/MC agreement for classifier output is very good
  - (f) Hopefully systematic uncertainties are low

(V) Energy Measurement

- (A) Using the profile fitter developed for Pass 8 gamma-ray reconstruction we can estimate the energy of the incident proton
  - (i) The shallow geometry of the CAL mean the shower is not completely contained within CAL and there is significant leakage outside the CAL
  - (ii) The profile fitter can help mitigate this effect
  - (iii) The profile fitter has some large limitations, it was designed for electromagnetic showers
  - (iv) Therefore it only has one length component instead of the two component profile usually used for hadronic showers
  - (v) This translates to the reconstructed energy typically has large energy dependent bias and rather poor energy resolution
  - (vi) We specifically use CalNewCfpCalEnergy for our reconstructed energy variable.
  - (vii) This variable uses the CAL direction instead of the TKR direction and does not assume the proton begins showering with in TKR, therefore better accounting for the start of the shower and reconstructing the energy a bit better at energies above 100 GeV
  - (viii) Still better than using CalEnergyRaw
- (B) Energy resolution and bias
  - (i) Because of the limitations of the profile fitter it can be difficult to measure the energy resolution
  - (ii) To do so we use Proton simulations and find E_{rec}/E_{true}
  - (iii) We fit this distribution with function DEFINE FUCNTION LATER and find the with and bias of the distribution

        - (iv) Because of the side distribution we cannot simply add missing energy, therefore we need to scale with distribution in order unbias the distribution
        - (v) From this unbiased distribution we can find the energy resolution
        - (vi) Energy resolution tends to increase at as energy increases (not unexpected since at higher energies the shower will leak more and more out of the CAL)
        - (vii) 68% energy resolution is stable between 100 GeV and 3 TeV at about $\sim 30\%$
        - (viii) Definitely not the best but purpose of study is extend energy measurement no to have the best energy resolution
        - (ix) This translates to about 12 energy bins in the final spectrum
    - (C) Minimum Energy
        - (i) The minimum energy is determined from the HiPass filter
        - (ii) The HiPass filter begins at CalEnergyRaw > 20 GeV
        - (iii) Since CalEnergyRaw has such a poor energy resolution (compared to CalNewCfpCalEnergy) this sets up a minimum energy that can be used for the spectral analysis
        - (iv) The mean of this distribution is 54 GeV. This means the minimum energy we can reliably expect is 54 GeV

3 Spectral Analysis

- (I) Instrument Acceptance
    - (A) Acceptance is defined as the produce to the instrument field of view and the effective area
    - (B) It is calculated using the proton MC across the entire desired energy range and angular range in true energy instead of reconstructed energy

$$\mathscr{A}(E) = 4\pi sr \times A_{gen} \times \frac{N_{\mathrm{pass}}(E)}{N_{\mathrm{gen}}(E)} \tag{1}$$

        - (i) Effective area is simply calculated by dividing the number of events passing the event selection in each energy bin and the total number of events generated in that energy bin and then multiply by the generation area (typically $6m^2$)
        - (ii) The energy variable is done in true energy
    - (C) We find acceptance for the optimal event selection and each constant signal scanning efficiency
        - (i) The optimal event selection has a maximum acceptance of about 0.2 m^2 sr
        - (ii) We ideally want flat acceptance across as most of the energy range as possible
        - (iii) This is to ensure potential spectral features are not from changes in the acceptance
        - (iv) Fall of off acceptance above a few TeV is due events not passing selection cut and large saturating effects and small instrument not being able to contain entire shower
    - (D) We use a large enough simulation such that statistical error associated with acceptance is $< 1\%$
- (II) Residual Contamination
    - (A) Two sources of contamination: Z > 1 CRs and Electrons
    - (B) Heavier CR Contamination
        - (i) Helium is the primary sources in the contamination source
        - (ii) The rest of the heavier CRs typically have a harder spectrum and are easier to remove than Helium (the Z^2 dependence more easily separates higher Z elements)
        - (iii) To estimate the residual contamination we use BKG simulation and scale the event rates for helium and heavy CRs to flight rates using the template fitter and find an overall correction factors

(iv) We then use those correction factors for helium and heavier CR for event rates after applying the cut (we have to do this because after applying the cut there are not enough event rates to determine the correction factors)

(v) This results in the helium cut effective reducing the contamination to less than 1% (predominately at $\sim$50 of GeV)

(vi) We know this is not an effect of no events at higher energies from generation because the maximum generation energy for helium is 20 TeV and 50 GeV/amu for other elements (which often is about to 1TeV in total kinetic energy)

(C) Electron Contamination

(i) The proton classifier is the main method of reducing electron contamination

(ii) Electron contamination before the applying energy dependent classifier output cuts the electron contamination is estimated at about 5%

(iii) This is calculated by reweighing the spectrum of dedicated proton and electron simulations to realistic spectra for previous experiments

(iv) We also estimate the live time for the reweighed simulations to create an event rate for each CR species and then find the residual contamination in the proton signal

(v) The estimated electron contamination after applying the energy dependent proton classifier ranges from less than 1% to down to 1×10^{-2}% of residual contamination

(vi) We also find the contamination for the different scanning efficiencies

(vii) The highest contamination is at the highest energies where the distinguishing power of the LAT between hadronic and leptonic showers is greatly reduces due the LAT's small size and large size of said particle showers

(viii) This is not really a problem because even with out the proton classifier the electron contamination is still very small

(III) Spectral Reconstruction

(A) There are two methods we use to reconstruct the incident proton cosmic-ray spectrum: Unfolding and Forward Folding

(i) The reason for a folding method is because the reconstructed energy does not completely recreate the true energy as is done with the electron and gamma-ray events

(ii) We must use a response matrix to determine the event rates in true energy from reconstructed energy

(iii) The inversion problem means we have to use one of these methods in order to find the true spectrum

(iv) The two methods are analogous and provide a good check to make sure the folding process is working and everything is understood

(B) Unfolding

(i) Using TUnfold an unfolding package based in ROOT

(ii) We use a Thikonov regularization (based on curvature) and minimize the regularization term based on a tau scan (Thikonov is a standard unfolding regularization method)

(iii) Unfolding is nice because it does not require a model for the incident particle spectrum and therefore makes no assumption of the about the incident proton spectrum

(iv) Using a response matrix determine from proton simulations with each of the event selection cuts (a response matrix for each proton classifier cut as well)

(v) The true energy binning is determined from the energy resolution from the proton simulation with all cuts (except for the proton classier cuts) applied

(vi) The reconstructed energy binning is just set to be larger than the binning of the true energy binning (under sampled case)

(vii) The minimum true energy bin is determine above

        (viii) The maximum true energy bin is determine the number of events to ensure low statistical uncertainties
        (ix) Data file taken from flight data with each event selection
        (x) The output of the unfolding is the event rate in true energy which is used to compute the differential flux spectrum

    (C) Forward Folding
        (i) Forward folding assumes an input spectral model, takes the acceptances, response matrix, and contamination and creates an event rate in true energy by minimizing differences between reconstructed flight event rates and data flight rate
        (ii) Can try different spectral models including power-law and broken power-law
        (iii) Determine which model has the lowest χ^2_{red} and best spectral model
        (iv) Unfortunately, have to assume a spectral model
        (v) The true energy binning is determined from the energy resolution from the proton simulation with all cuts (except for the proton classier cuts) applied
        (vi) The reconstructed energy binning is just set to be larger than the binning of the true energy binning (under sampled case)
        (vii) The minimum true energy bin is determine above
        (viii) The maximum true energy bin is determine the number of events to ensure low statistical uncertainties
        (ix) Data file taken from flight data with each event selection
        (x) The output of the unfolding is the event rate in true energy which is used to compute the differential flux spectrum

    (D) Once the event rate is determined from either unfolding and forward folding, we subtract the estimated contamination from the event rate in true energy, divide the by the acceptances, and divide each bin by the bin-width in true energy to get the differential energy dependent flux spectrum

    (E) This is done for the optimized event selection and each scanning efficiency

    (F) The scanning efficiencies are used to probe systematic errors, which is discussed next

(IV) Systematic Uncertainties

    (A) Acceptance Uncertainties
        (i) Systematic Uncertainties in the acceptance are determined from the scanning efficiencies of the proton classifier
        (ii) Each proton scanning efficiency will create a different acceptance, different event rate, and different contamination
        (iii) If proton classifier and simulations well represent the data then each spectrum will give similar results
        (iv) This is very similar to the bootstrapping method in determining the systematic Uncertainties for gamma-ray data for the LAT
        (v) These Uncertainties are energy dependent and increase as incident energy increases
        (vi) They are estimated to be $X\%$ at $\sim$100 GeV and $X\%$ at $\sim$1 TeV I need to figure out how large these actually are compared to the optimized selection

    (B) Contamination Uncertainties
        (i) Systematic uncertainties associated with the contaminations are expected to be low
        (ii) Since the estimated contaminations are low for both the electron and heavy ion contamination we do not expect any systematic Uncertainties to significantly effect the resultant spectrum
        (iii) Heavy Ion Uncertainties would have the largest effect since the heavy ion Geant4 simulations are pretty poor but the estimated contamination is still below 1% at the lowest energy

(iv) It would be reasonable to assume the heavy ion contamination at lowest energy is $\sim 1\%$ and there fore negligible compared to other systematic Uncertainties

(v) Electron contaminations are handled in a similar way to acceptance Uncertainties with the different constant scanning efficiencies from the proton classifier

(C) Geant4 Simulation Uncertainties

- (i) Geant4 has potential uncertainties in the simulation of protons
- (ii) We can determine the quality of simulations by examining accelerator experiments with much more control over their particle sources like CALICE and LHC
  - (a) Geant4 tends to underestimate both transverse and longitudinal shower development by up to to $\sim 15\%$
  - (b) Geant4 uncertainties on relative energy resolutions for protons are considered small
  - (c) Absolute energy deposition is under 10%
- (iii) Here is are the physics lists that GR's version of Geant4 use specifically for proton simulations This is something I need to look up really soon such that we can have a better understanding what what we are dealing with. I am sure it is just sitting somewhere in GR but I still have to look for it... sigh...
  - (a) Physics List stuff
- (iv) We can also examine Pass 8 reconstructed beamtest data from 2006.
  - (a) Original beamtest data was taken in 2006 with a spare flight towers called the "Calibration Unit"
  - (b) We can compare this beamtest data to simulations and get an idea quality of simulations when looking at energy deposition, shower size, and shower width
  - (c) We can also use the BT data to confirm what other accelerator experiments have observed with Geant4 uncertainties

(D) Energy Measurement Uncertainties

- (i) To estimate systematic Uncertainties associated with the energy measurement, specifically with energy resolution and abolsute energy scale, there are two ways of doing so
- (ii) Geomagnetic Ridigity cutoff
  - (a) This would entail looking at the geomagnetic rigidity cut off and observing proton event rates as function of McIllwain L parameter
  - (b) It would involve using diagnostic data and ray tracing code in order to distinguish trapped protons from cosmic-ray protons
  - (c) GRC provides a feature at specific energies that can be used to estimate the absolute energy scale
  - (d) UNFORTUNETLY the tracer code is highly dependent on energy resolution as we have seen the energy resolution is pretty poor for protons
  - (e) This method seems very involved and has limited probing capability and predominantly works at lower energies
- (iii) Beamtest Data and Simulation
  - (a) Original beamtest data was taken in 2006 with a spare flight towers called the "Calibration Unit"
  - (b) Several configurations were taken of proton data:

Particle	Energy (GeV)	Incident Angle (degrees)	Number of Events
Proton	20	0	100211
Proton	100	0	37183
Proton	100	45	28128
Proton	100	90	24784
Proton	150	0	8958

  - (c) While not ideal, we can use the data/mc agreement to estimate systematic errors associated with absolute energy scale and energy resolution

(d) Preliminary study suggests that there is generally good agreement between Pass 8 Beamtest data and simulations

(e) Absolute energy scale for protons agrees within $\pm 5\%$ and relative energy resolution is under $\pm 10\%$

(f) Absolute energy scale is more important that relative energy resolution, since the absolute energy scale is a parameter that determines the absolute flux

(E) Spectral Reconstruction Uncertainties

(i) We can explore potential systematic errors in the energy redistribution of event by trying two different methods

(ii) Unfolding and forward folding are two methods to solve the inverse problem

(iii) They should produce the same results and give a nice probe into potential systematics

(iv) I would not expect this to be a large effect, smaller than acceptance or energy measurement but it is something else to check. I am thinking of a possible way of estimating the effect but it might also be easier to run unfolding and forward folding together and combine the results since we already have code for forward folding established. If it turns out to be small it is still a nice check to make sure the unfolding processes is working correctly, which it totally should be.

4 Results and Discussion

(I)