Proton Analyses with the LAT

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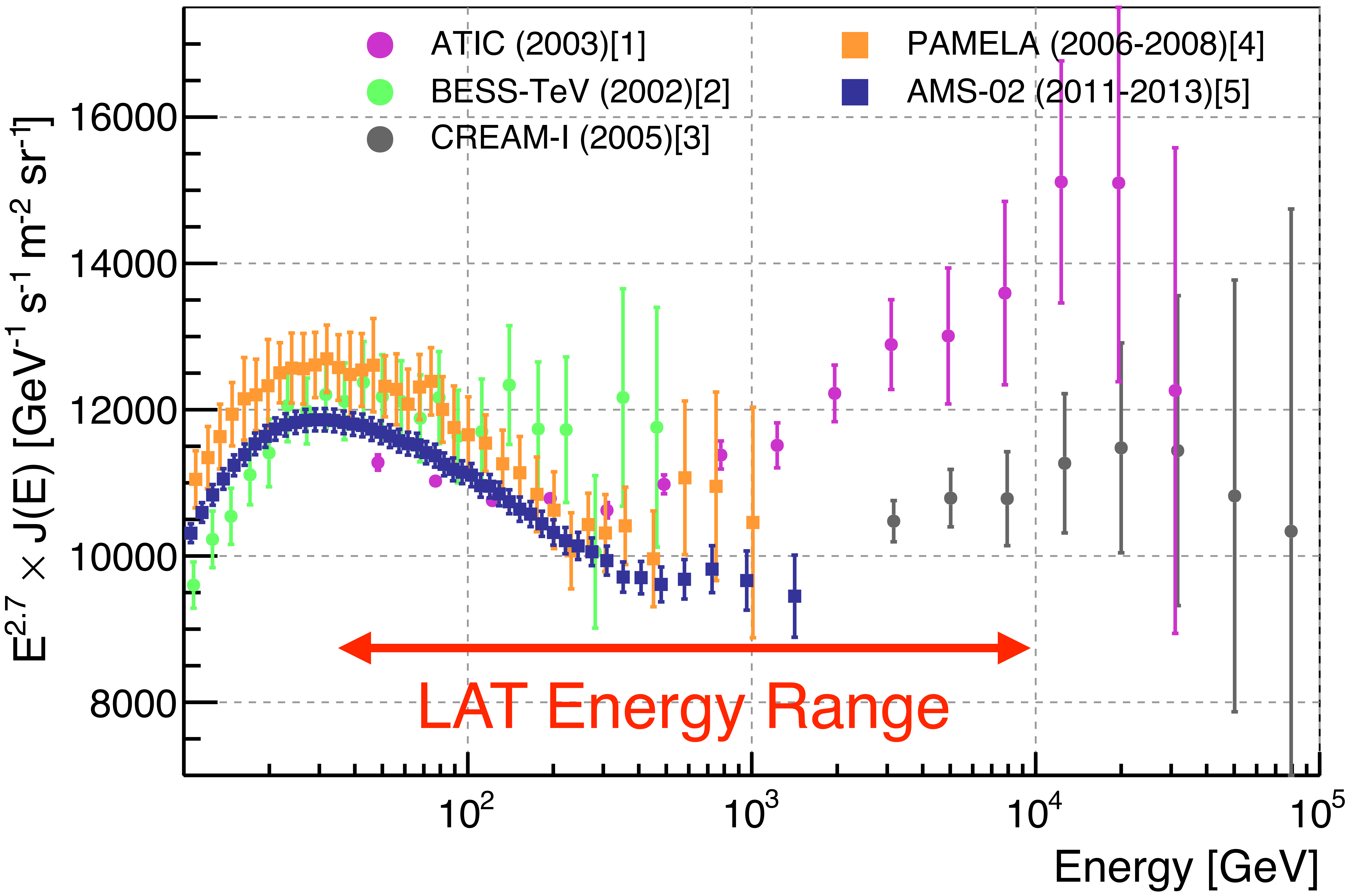
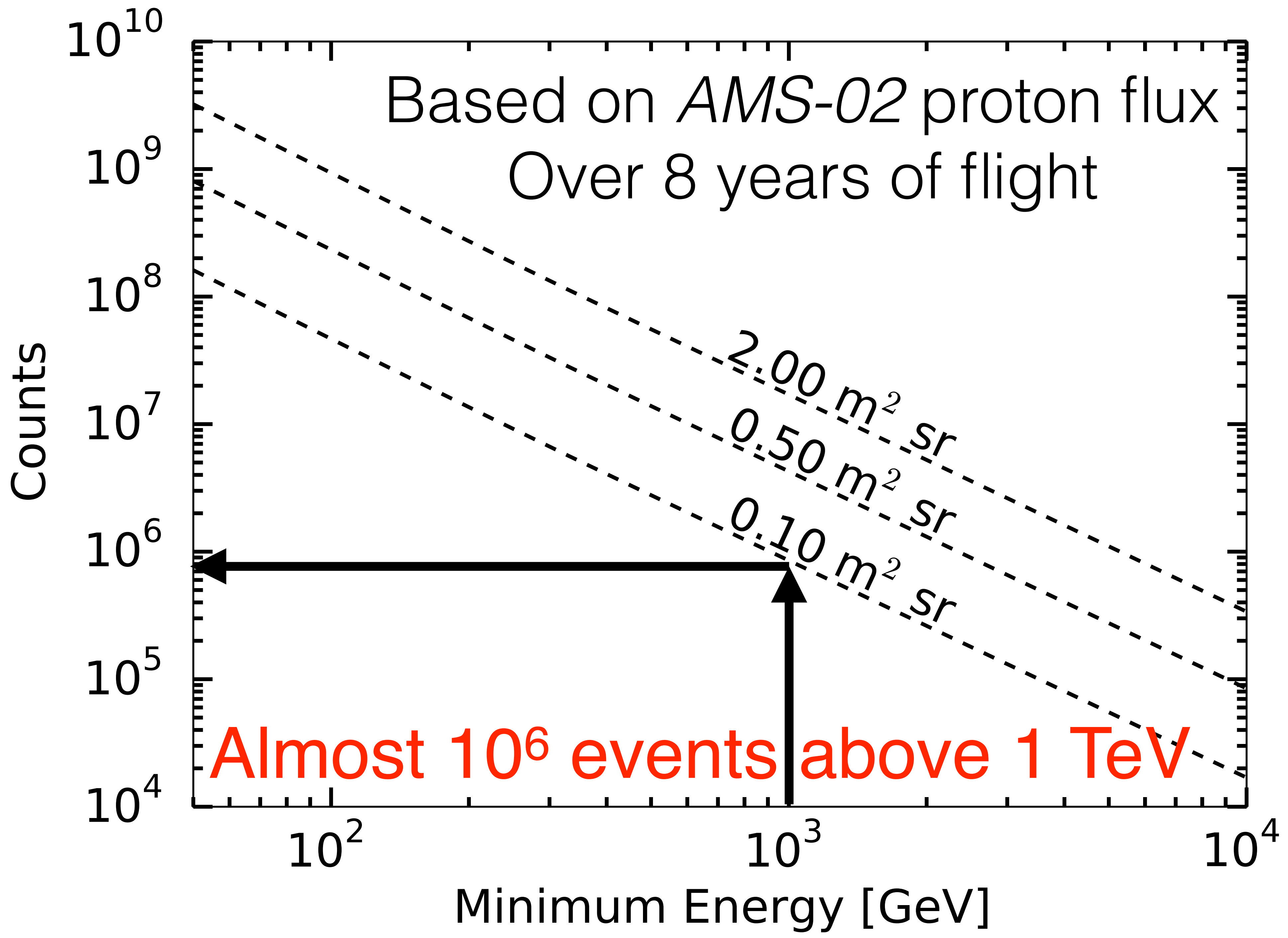
Current State of Cosmic-ray Protons

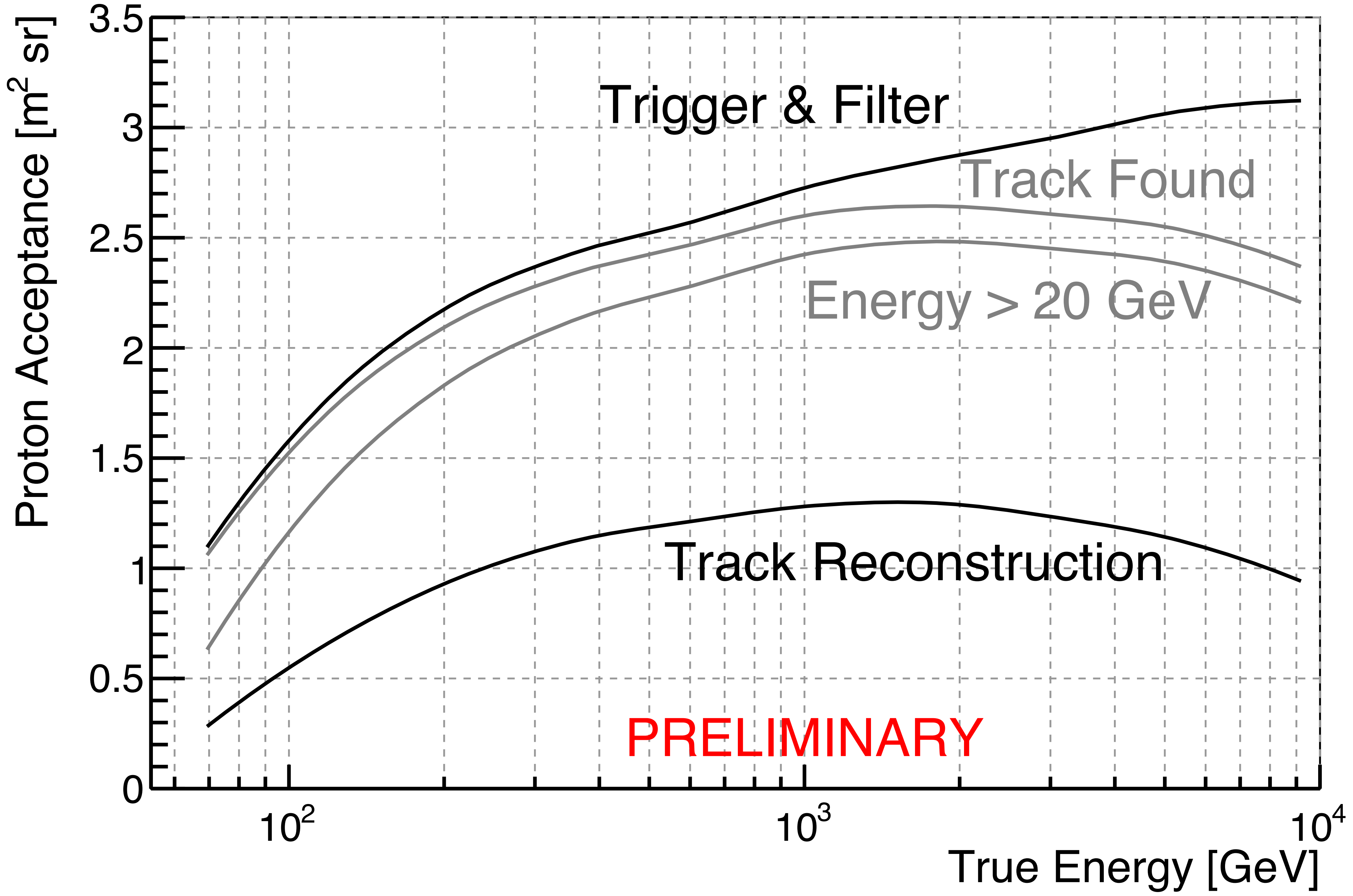
- Cosmic-ray protons pose an interesting problem
- *PAMELA* and *AMS-02* observe a spectral break at 350 - 400 GeV
- Spectral break needs reconciling with our understanding of CR propagation, acceleration, or sources
- Additional measurements can help constrain secondary index



Event Selection

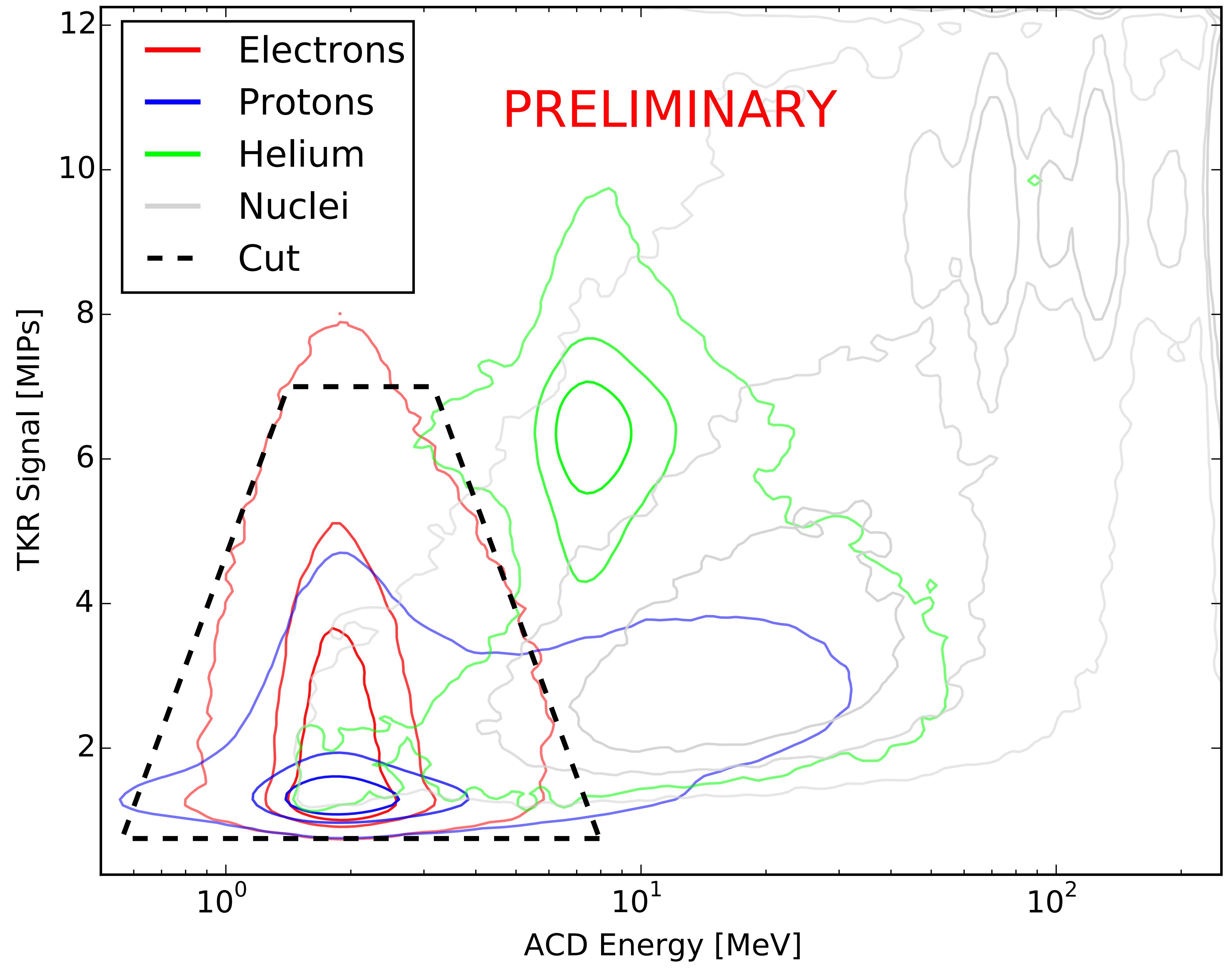
- The proton event selection is defined as:
  - Event has to trigger and pass onboard filters
  - Require event to have reconstructed track
  - Deposited energy > 20 GeV in CAL
  - Require a well reconstructed track using Pass 8 direction classifier
- Additional charge measurement using ACD and TKR
  - Efficiently removes Z > 1 cosmic rays

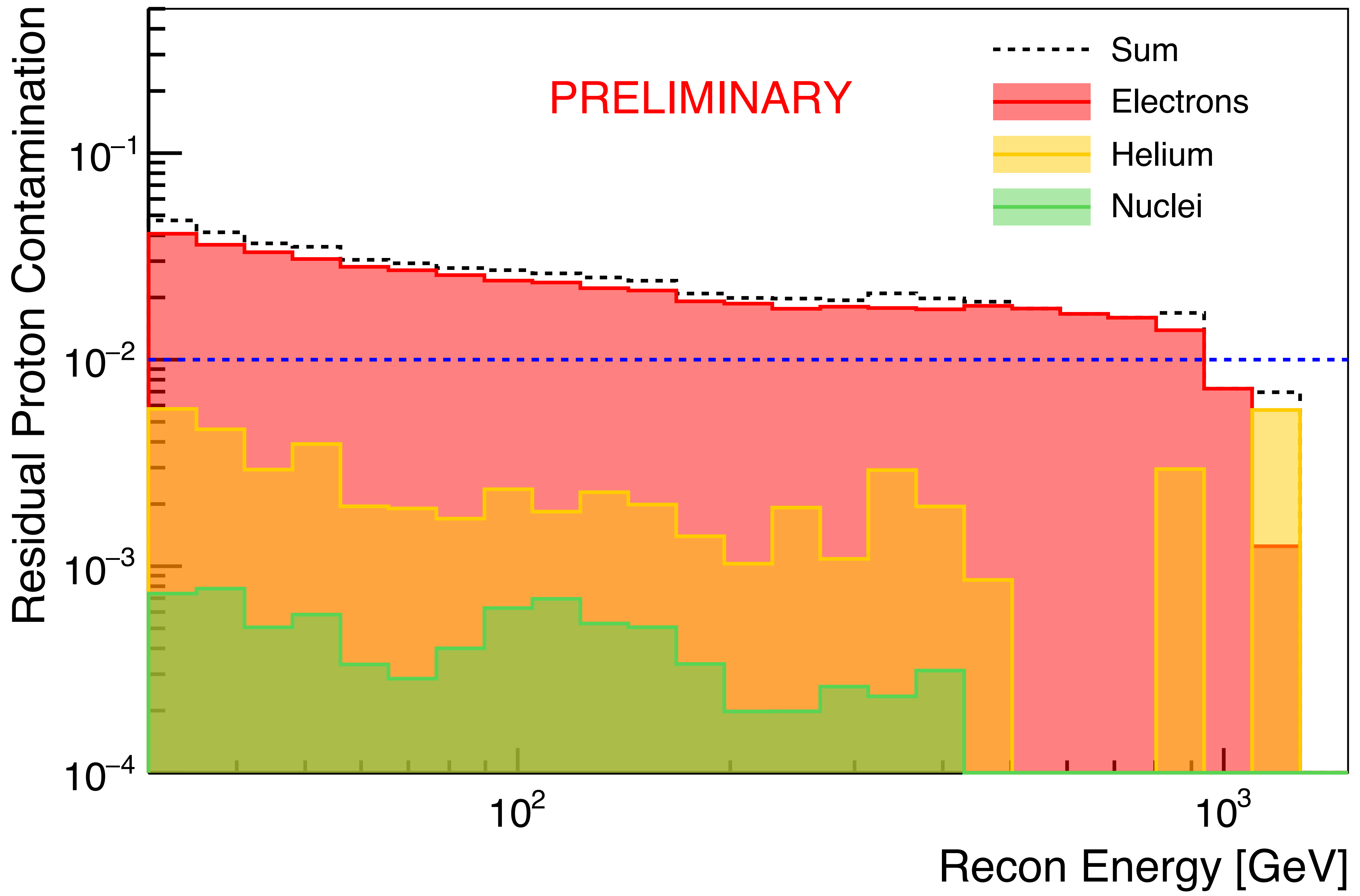




Charge Measurement

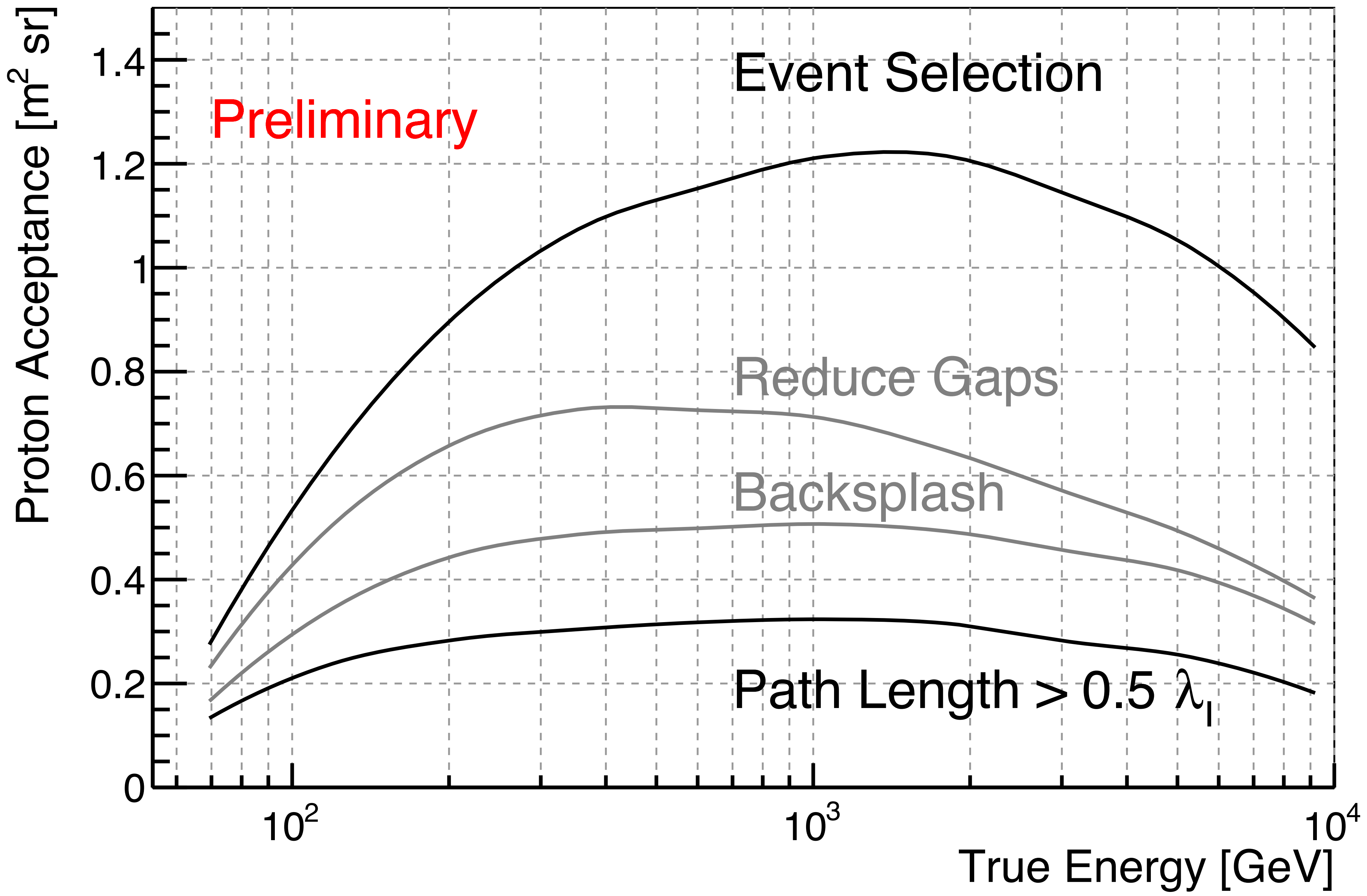
- Cosmic-ray helium and nuclei pose large contamination source for this study
- We use the TKR and the ACD to independently measure the charge of incoming cosmic ray in the LAT
  - Define a polygon in ACD-charge vs TKR-charge to select on protons
  - Developed using flight data and GEANT4 proton/electron/nuclei simulations
- Find a residual contamination from CR helium and nuclei less than 1%
- CR electrons are under 4%, decreasing with energy
  - We background subtract any residual electron contamination

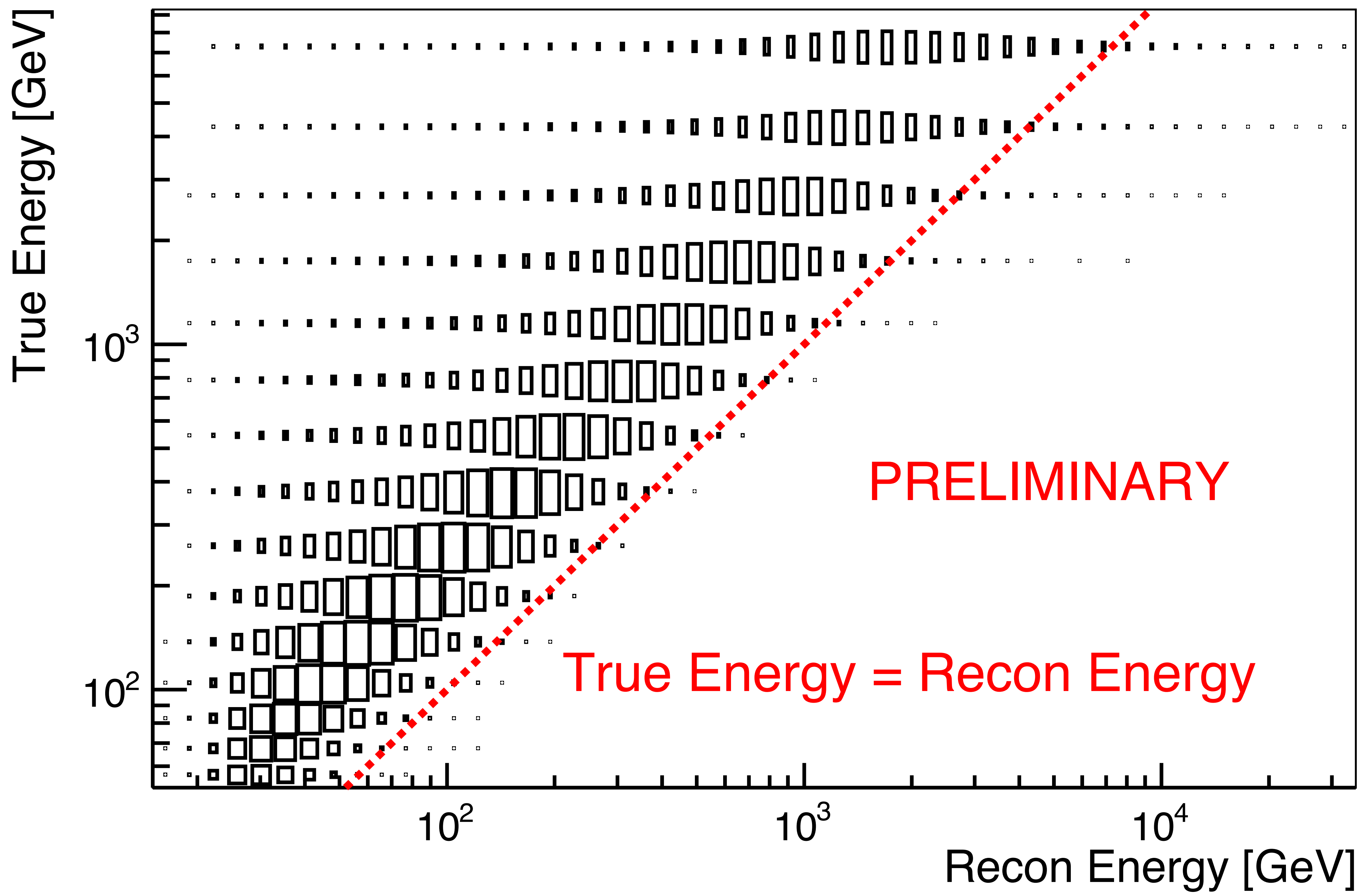




Energy Measurement

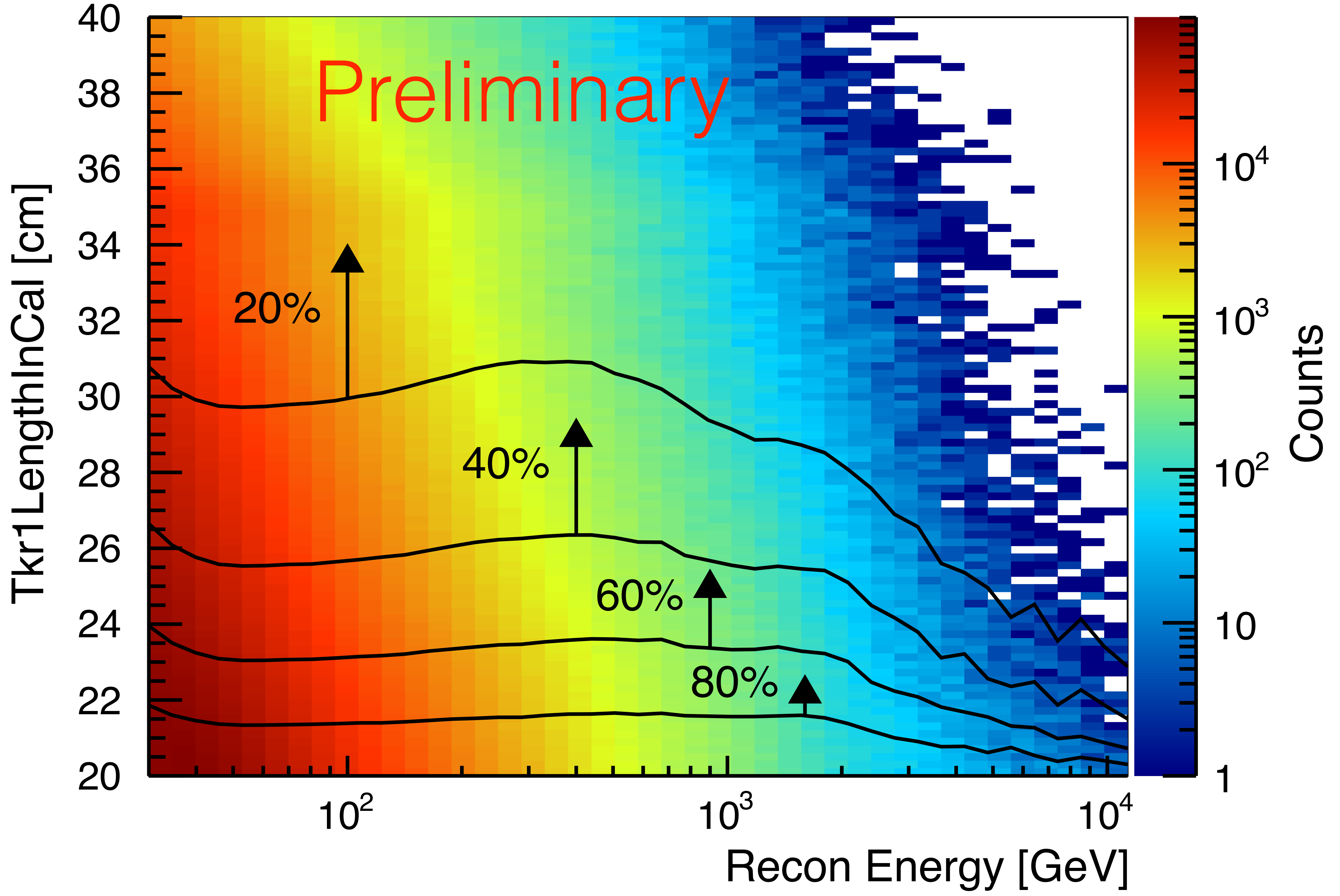
- We use the CAL to measure the energy of the proton induced shower
  - CAL is up to 2 λ_I at off axis angles
- Develop event selection to select ideal event topologies
  - Does not fall within gaps between CAL modules
  - Select events with low 'backsplash' into TKR
  - Require > 0.5 λ_I in the CAL
- We fit the profile of energy deposition to estimate the energy of the incident proton
  - Deposited energy primary from electromagnetic component of total shower

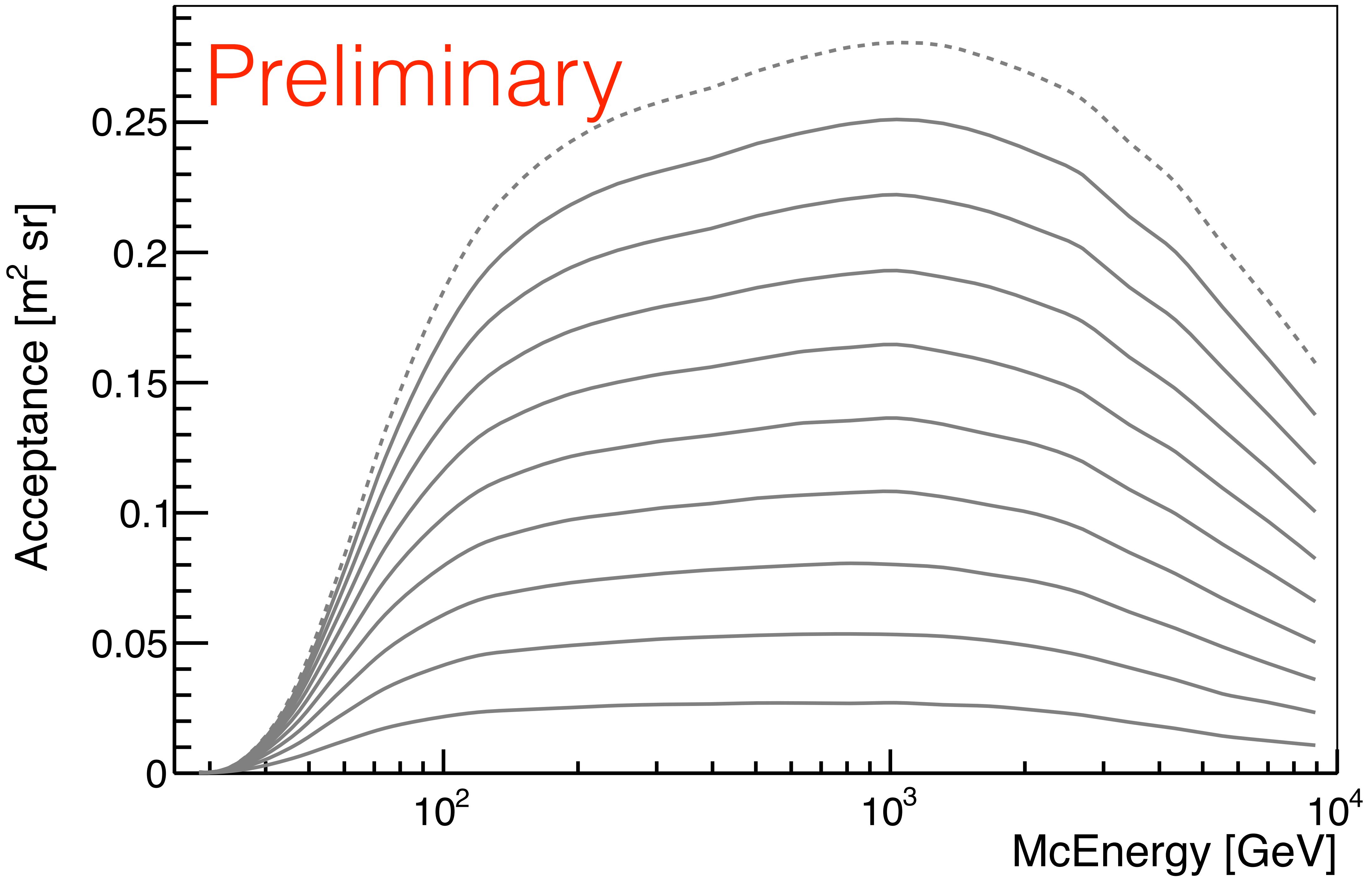




Signal Efficiency

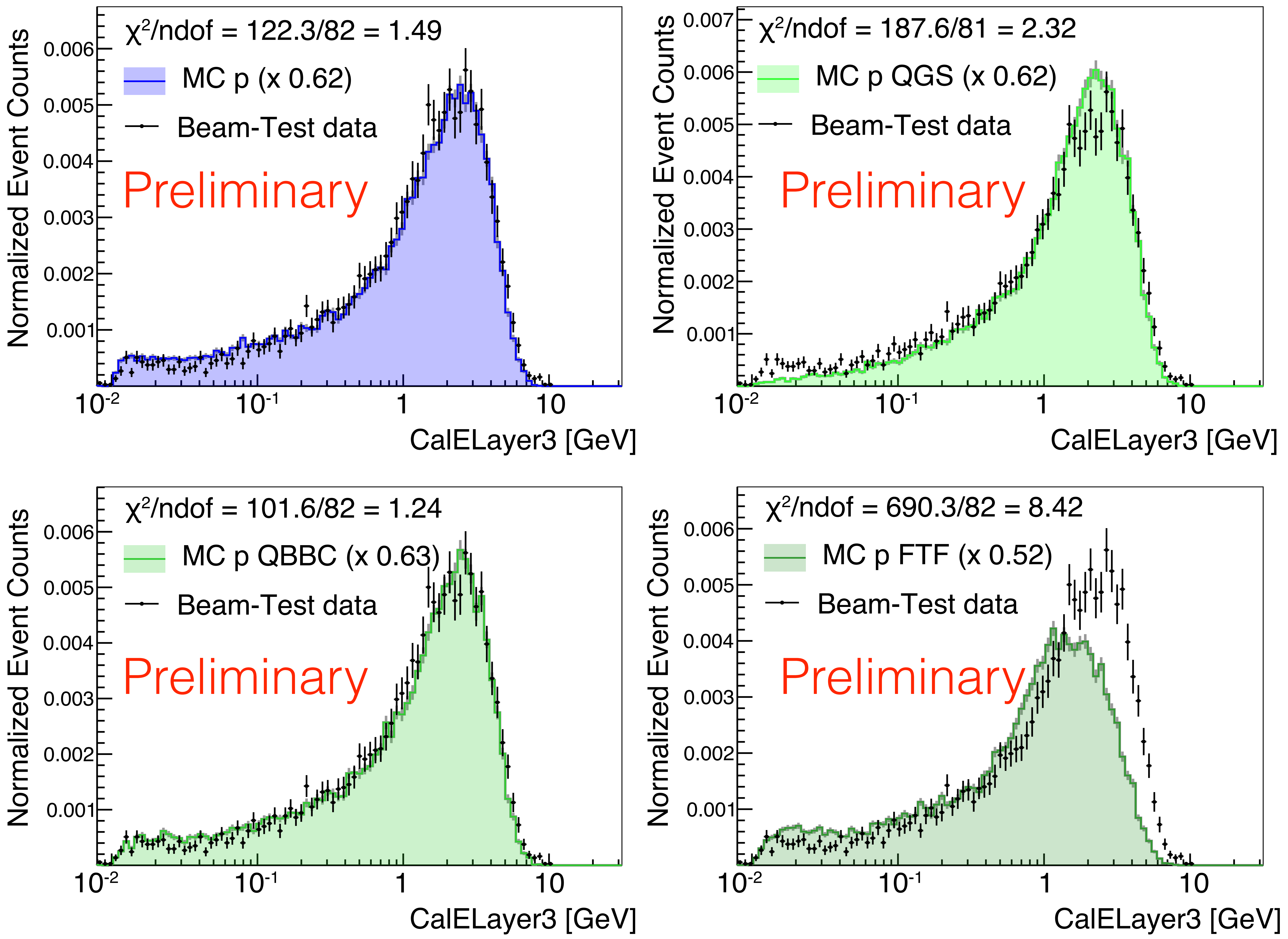
- Primary measure of systematic uncertainty in acceptance
- Test stability of spectral measurement over different path-lengths through LAT
  - Probes shower development through different geometric cross-sections of LAT
- Find energy dependent quantiles of path-length and produces cuts for 90% - 30% quantiles
- Produce different IRF for each quantile cut and reconstruct the spectrum
- The maximum variation of all spectra determines the uncertainty





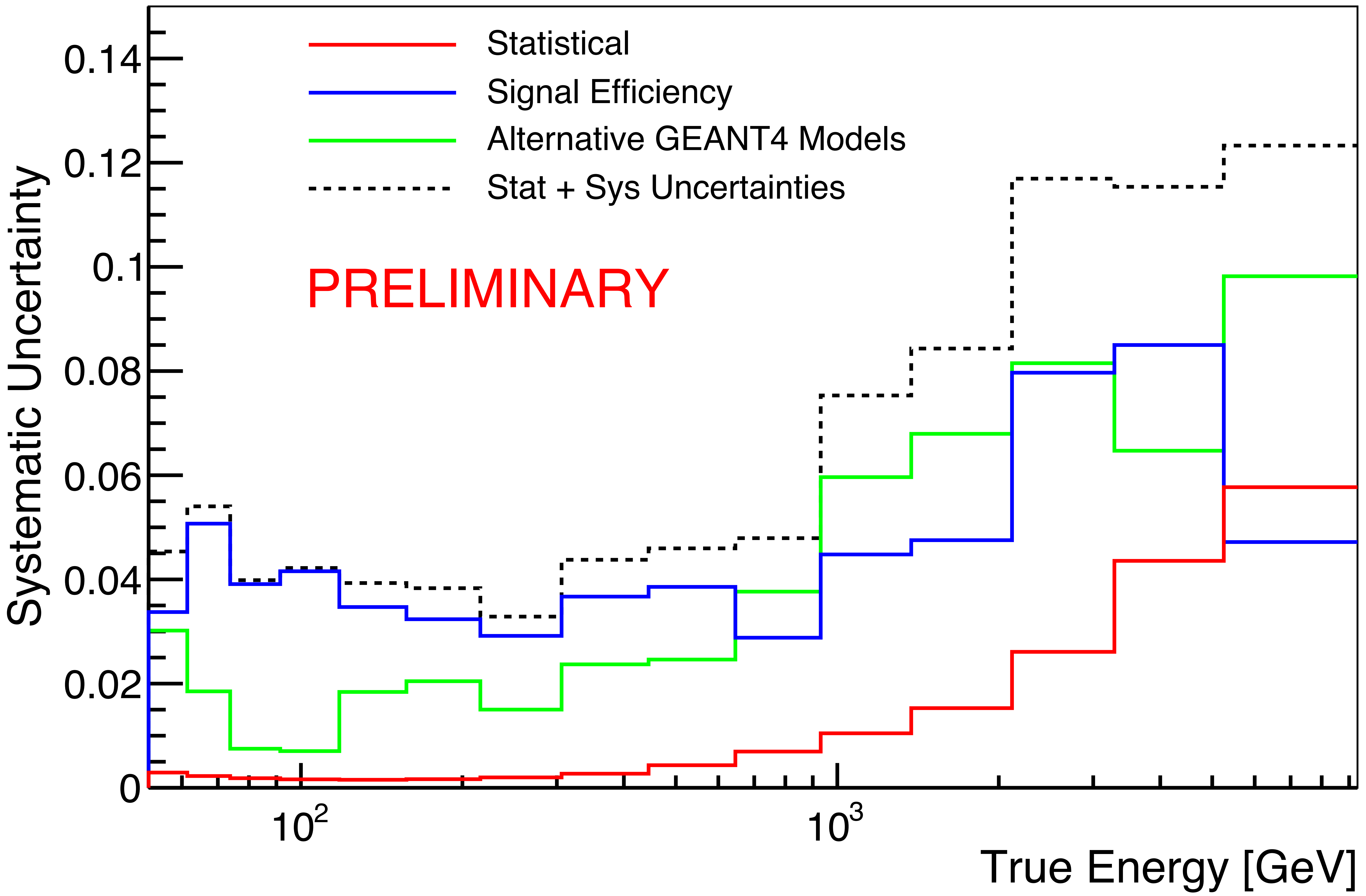
Alternative GEANT4 Hadronic Models

- Main measure of systematic uncertainties in energy deposition
- Produce dedicated proton simulations with alternative hadronic models in GEANT4 09-04-p1
  - Alternative models change shower development and deposited energy
- Tested 3 alternative models
  - Checked data/MC agreement from beam-test data
- Produce IRFs for each alternative models and unfold the spectrum
- Uncertainty is set from maximum variation of each alternative hadronic model



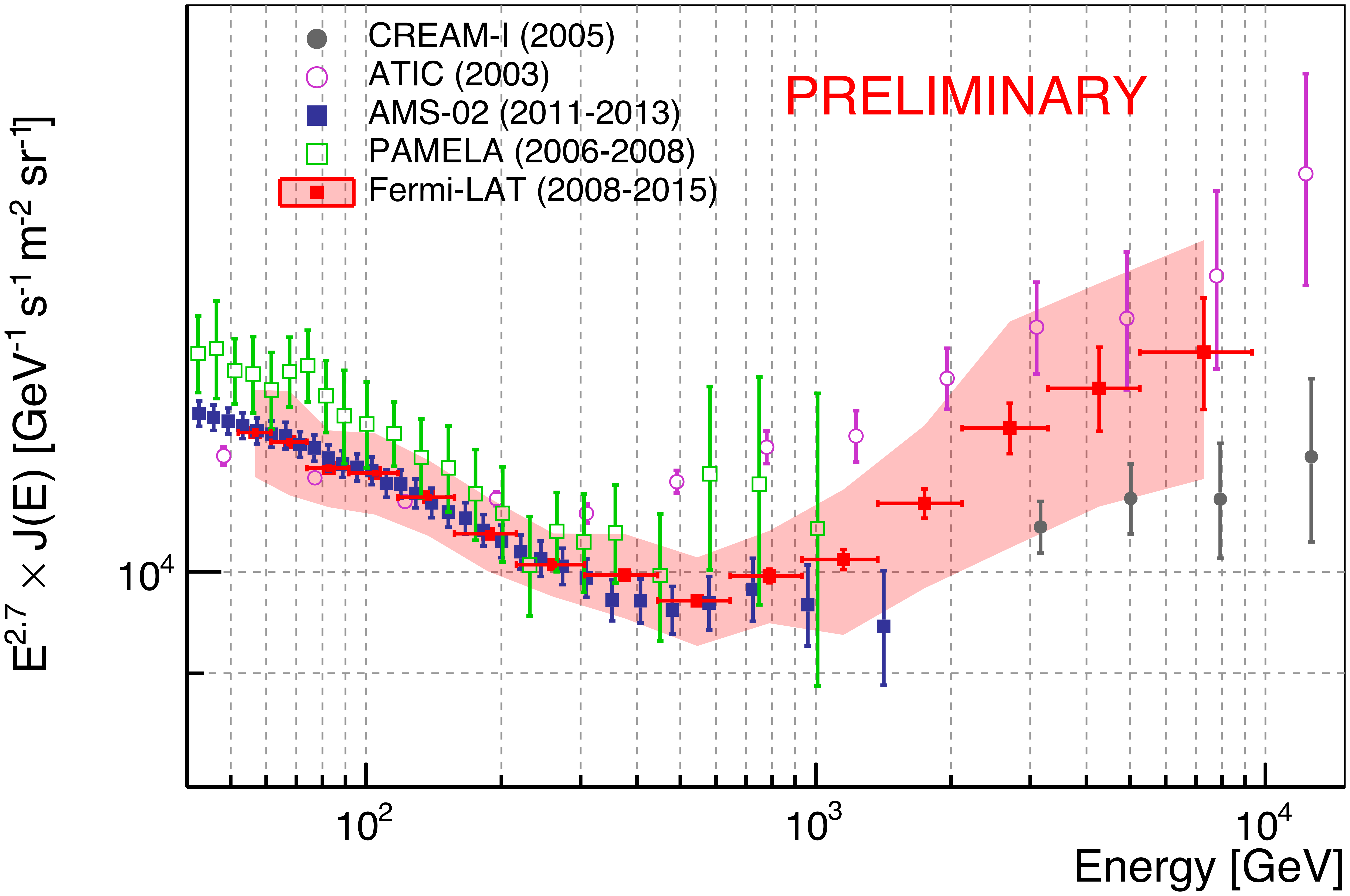
Systematic Uncertainties

- Acceptance uncertainties dominate at lower energies
- GEANT4 uncertainties dominate a higher energies
- This study is systematics dominated across entire energy range
- The uncertainty in the energy reconstruction is still being finalized
  - Therefore the our current estimated values are not shown



Cosmic-ray Proton Spectrum

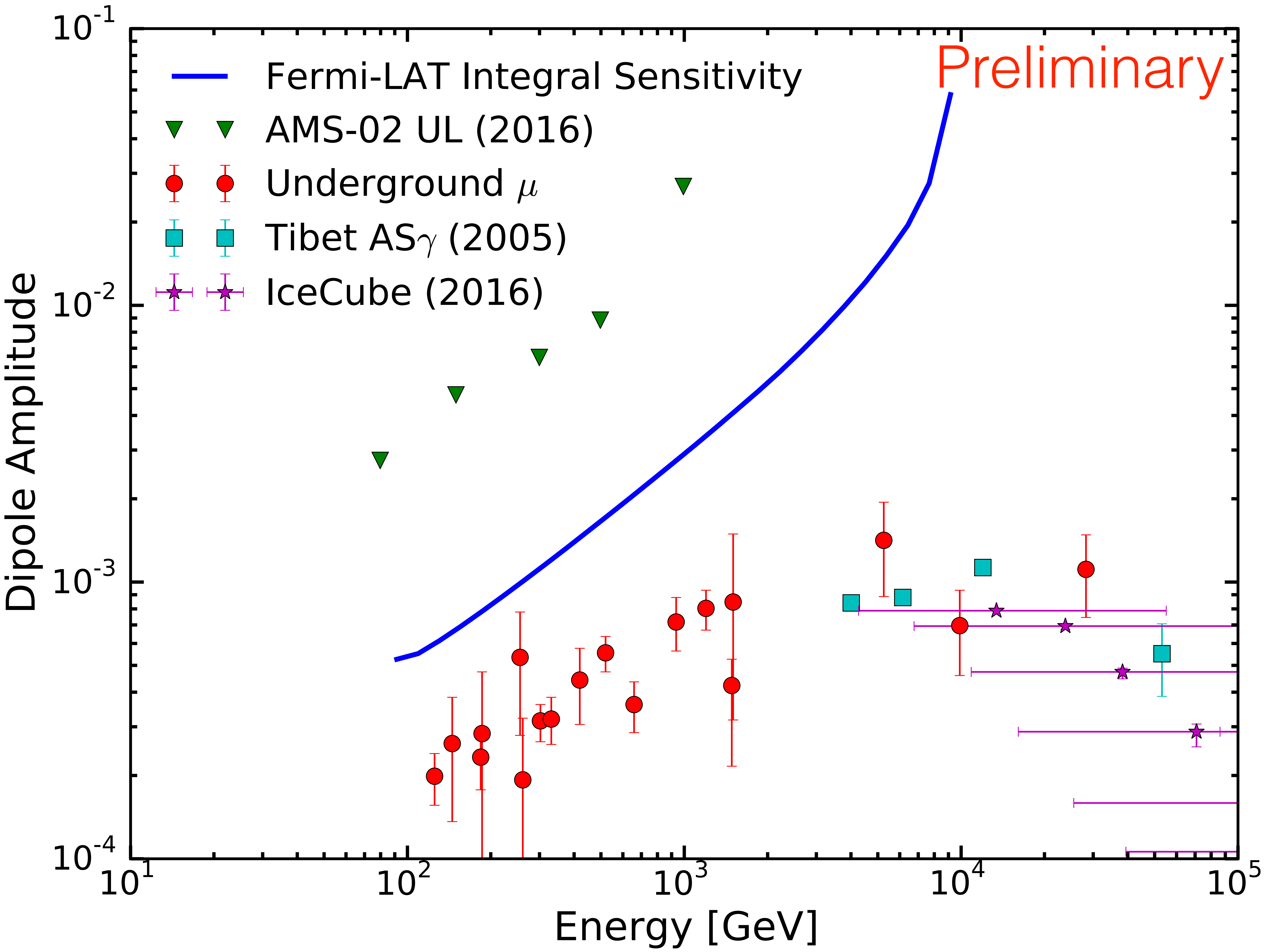
- Using 7 years of LAT flight data, August 4, 2008 to July 30, 2015
- Extends energy of space-based measurement to 9.5 TeV
- Red markers represent statistical uncertainty
- Red shaded region included systematic uncertainties
- Good agreement with other cosmic-ray measurements



Proton Anisotropy Study

- This effort is being lead by Matt Meehan of University of Wisconsin
- Additional event selection for anisotropy measurement
  - Remove back-entering events
  - Reduce CRE contamination
- Data-driven method to create reference map
  - Detector response to an isotropic sky
- No ground-based experiment can constrain declination-dependence of dipole
  - Best constraints on full-sky anisotropy
  - Best constraints on declination-dependence

Courtesy of Matt Meehan



Final Remarks

- The LAT proton spectrum has good agreement with other measurements such as AMS-02
  - Due to limited size of CAL, energy resolution is comparatively large but we can push to high energies due to large acceptance
- Analysis is systematics dominated across entire energy range
- We are finalizing the uncertainty in the reconstructed energy based off of work done by the CRE spectrum

Backup Slides

The Fermi LAT

- The Large Area Telescope (LAT) is one of two instruments on the *Fermi* Gamma-ray Space Telescope
- The LAT is a pair conversion telescope

Tracker (TKR)

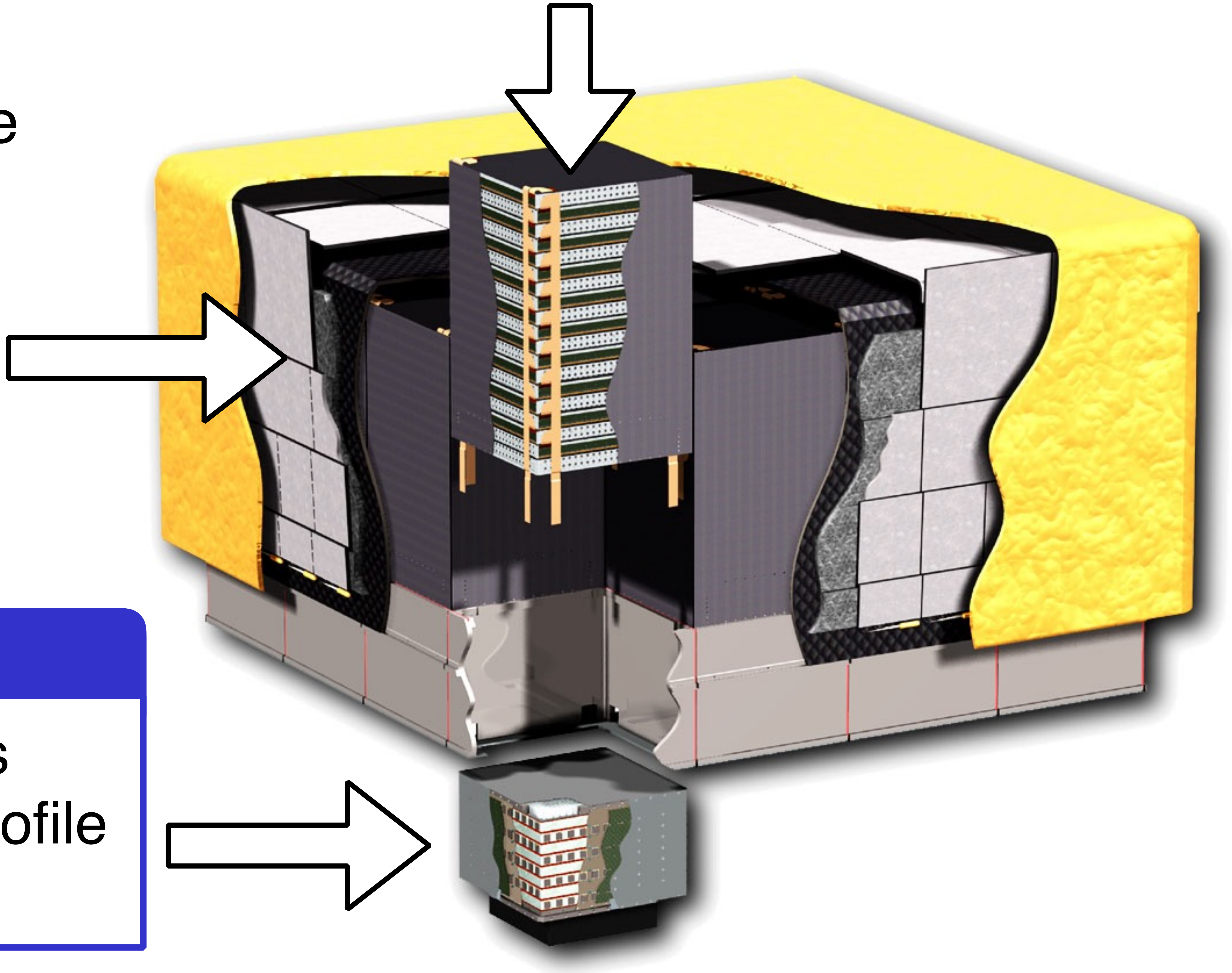
- 18 x-y layers of silicon strip detectors
- Used for direction reconstruction and particle identification

Anticoincidence Detector (ACD)

- 89 segmented plastic scintillating tiles
- Used for particle identification

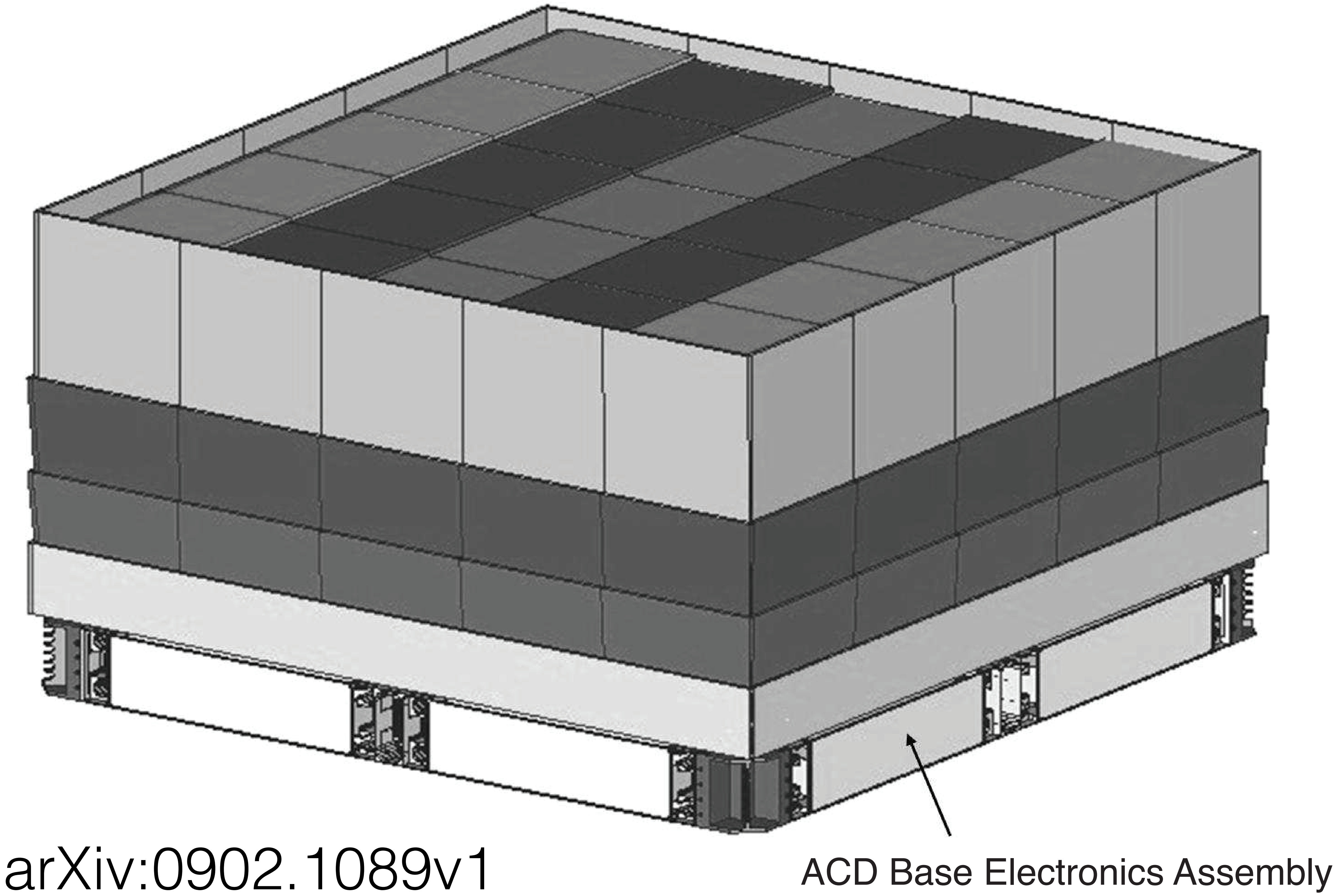
Calorimeter (CAL)

- 1536 CsI(Tl) crystals arranged in 8 layers
- Hodoscopic, image shower shape and profile
- Used for energy measurement



Anti-Coincidence Detector (ACD)

- ACD's main purpose is to detect CRs
- Consists of 89 plastic scintillating tiles and 8 plastic scintillating ribbons that cover the TKR
  - Top tiles arranged in a 5 x 5 grid
  - Side tiles arranged in 5 x 3 grid with single large tile on the bottom row
- Signal in each tile read by two PMTs
  - Each PMT has a dual range, linear low range and non-linear high range
- Energy deposition in ACD described by ionization
  - Can use this to identify charge of incident particle

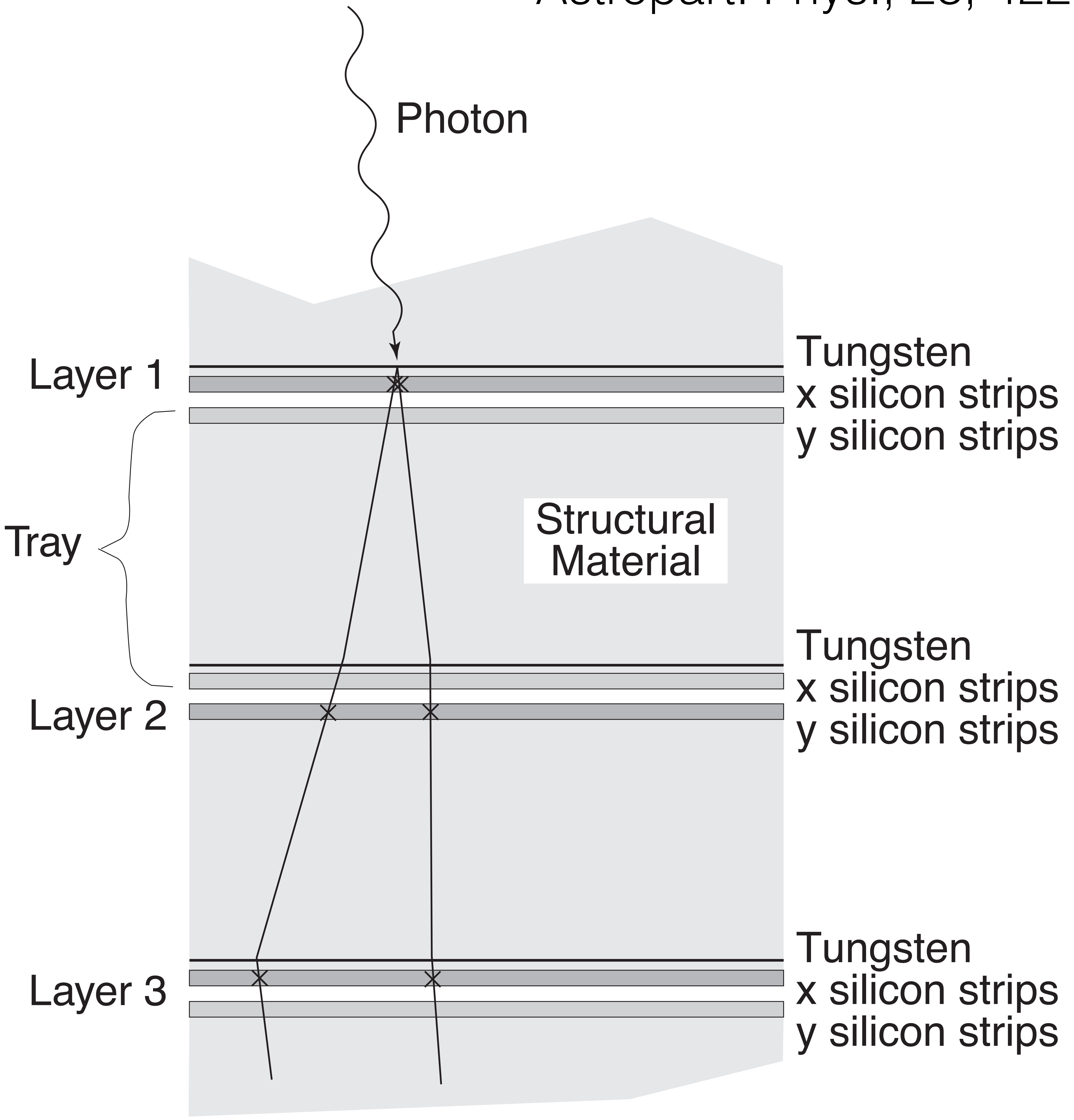


arXiv:0902.1089v1

The Tracker (TKR)

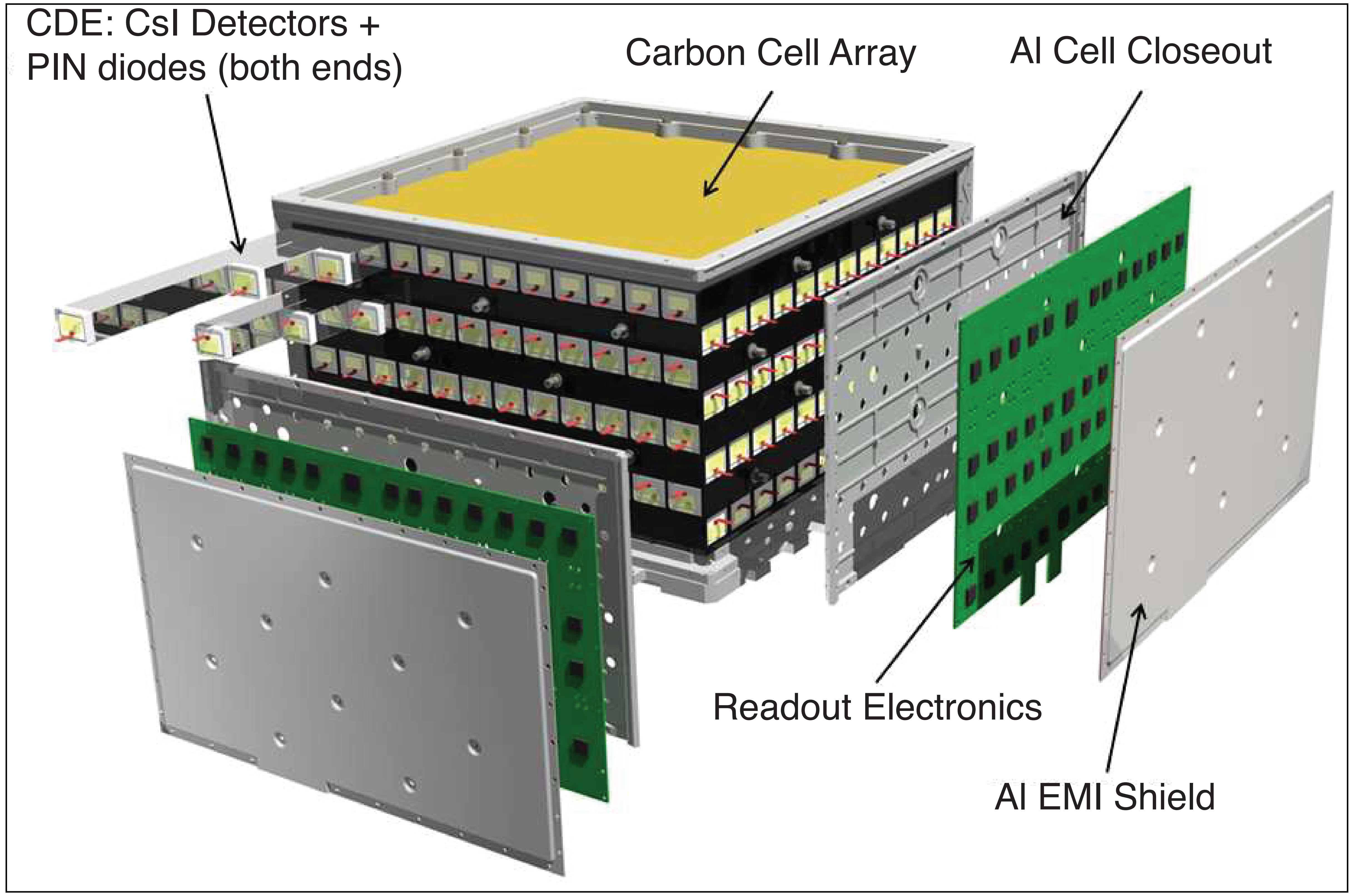
Astropart. Phys., 28, 422

- 16 layers of high Z tungsten foil
  - Convert photon to e^+ e^- pair
  - Last 4 conversion layers about 6 times thicker than previous 12
- 18 layers of silicon strip detectors
  - Measure position of charged particle
- TKR is 1.5 radiation lengths thick
- TKR is used to measure direction of incident cosmic-ray
  - Direction used to path-length correct signal and in reconstruction of several variables
- Additionally, energy deposited via ionization
  - Can use TKR as independent measure of CR charge



Calorimeter (CAL)

- Use CAL to measure CR energy and direction
- Composed of 16 modules; each module has 96 CsI(Tl) crystals
  - Arranged in 8 layers in alternating x-y directions
  - This allows for not only measuring energy deposition but also imaging of shower shape and direction
  - Shower shape can be used for particle identification
- 8.6 radiation lengths deep (0.5 nuclear interactions) at normal incidence
  - 2.5 nuclear interactions lengths for maximum off angle axis
- At higher energies shower leakage crystal saturation needs to be corrected and accounted

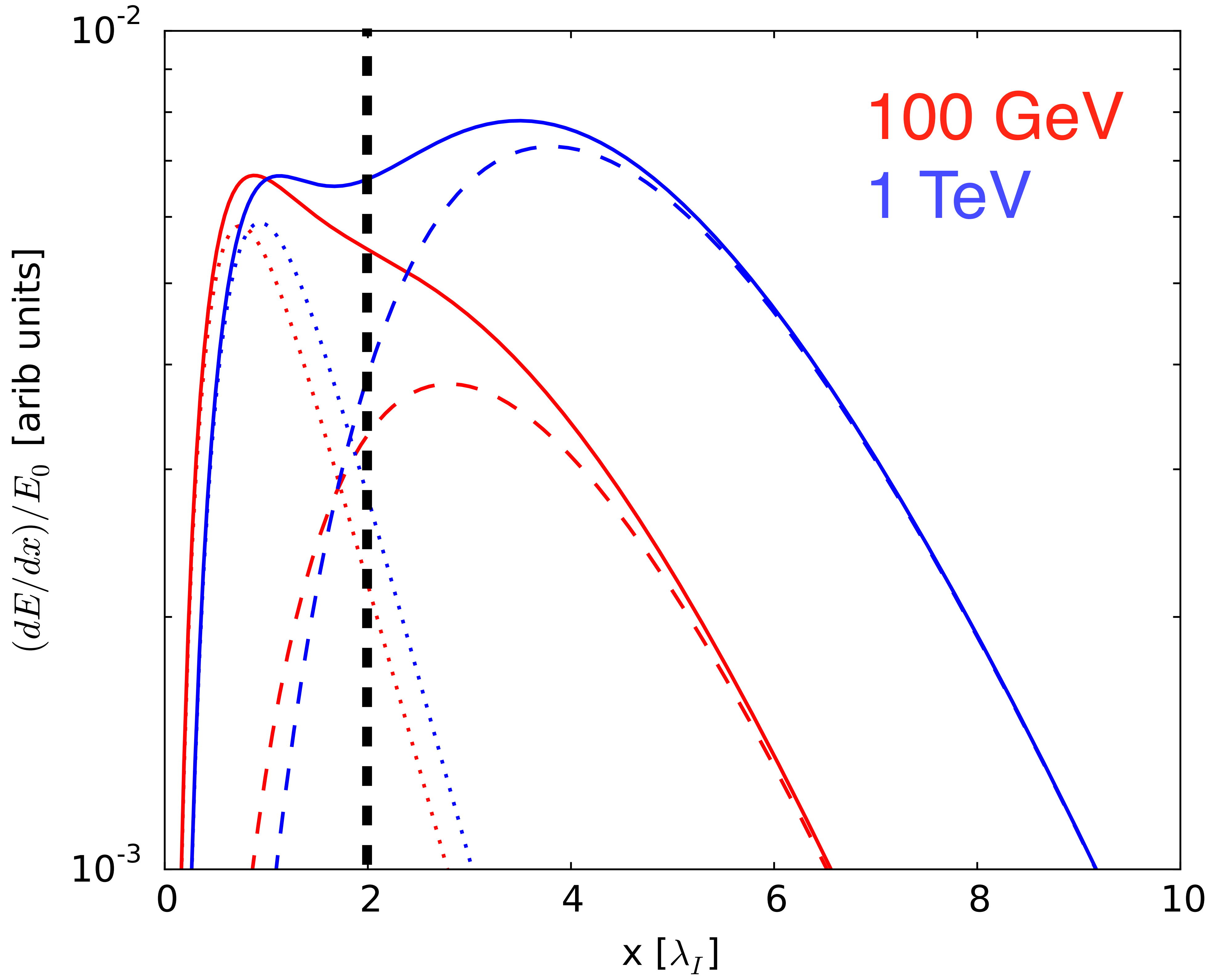


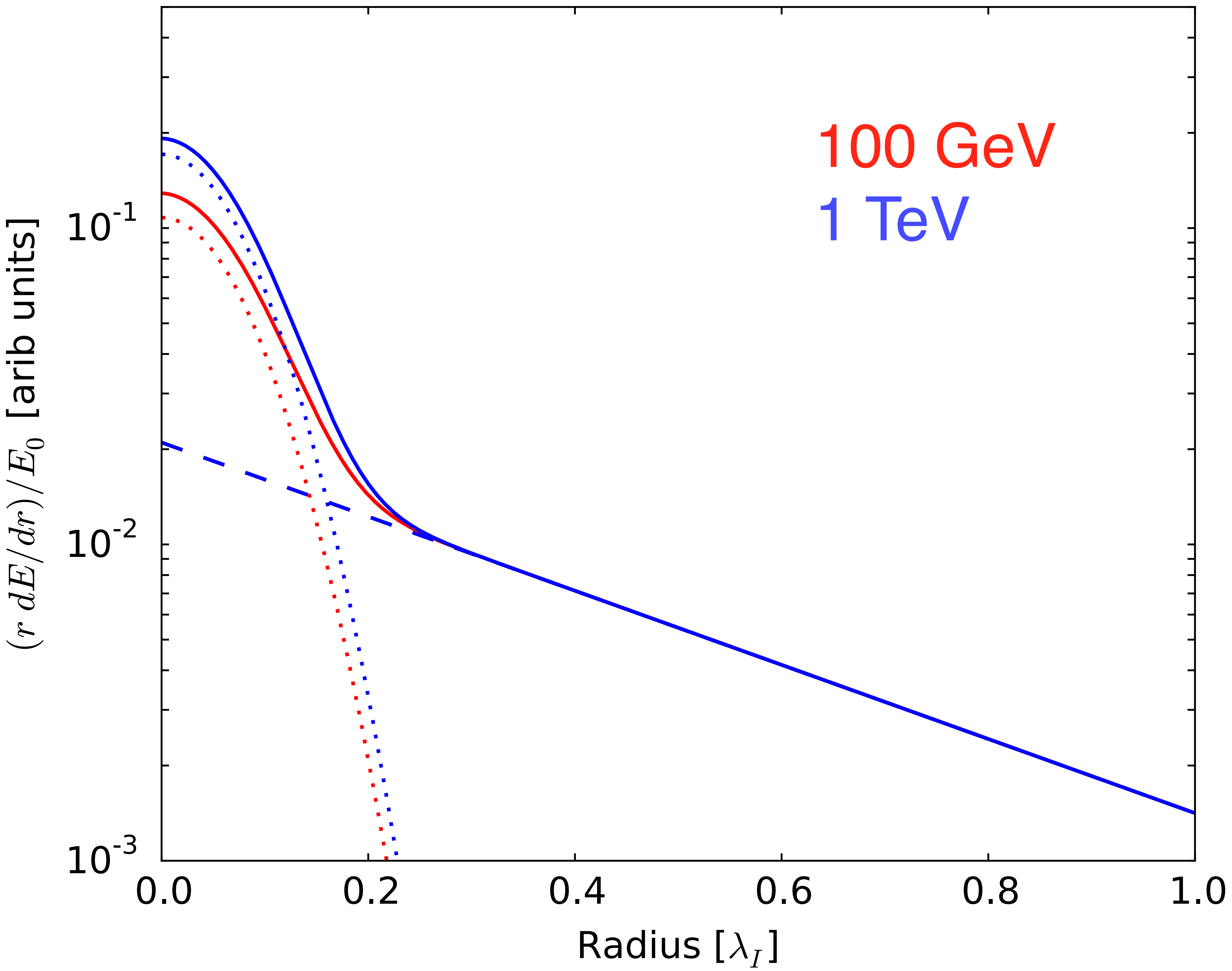
Atwood 2009 arXiv:0902.1089v1

Hadronic Showers in the LAT

- We can estimate how proton induced shower look like in the CAL

$$\left\langle \frac{dE(x)}{dx} \right\rangle = k\left(w\left[\frac{x}{X_0}\right]^{a-1} e^{-bx/X_0} + (1-w)\left[\frac{x}{\lambda_I}\right]^{a-1} e^{-dx/\lambda_I} \right)$$



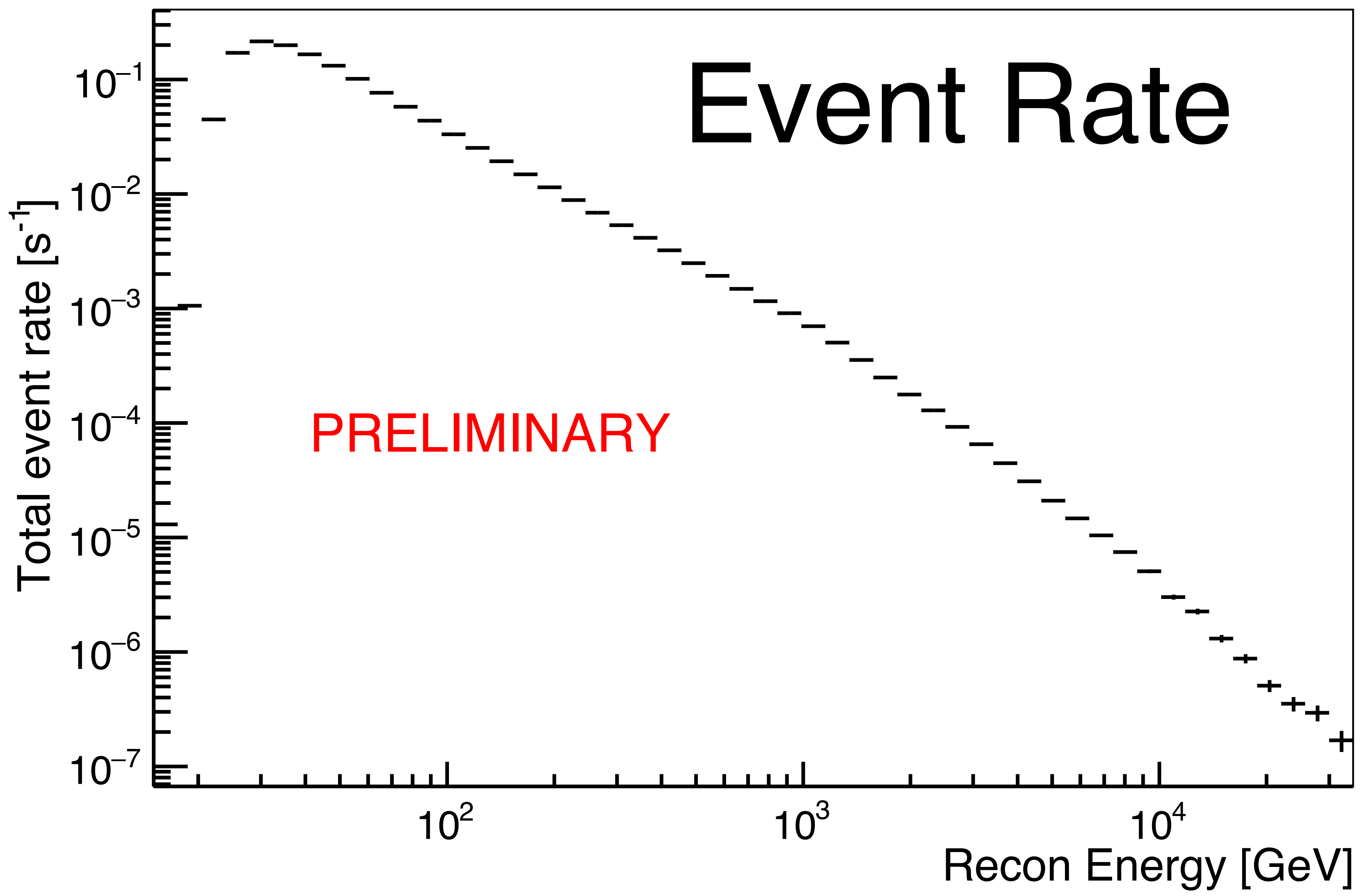


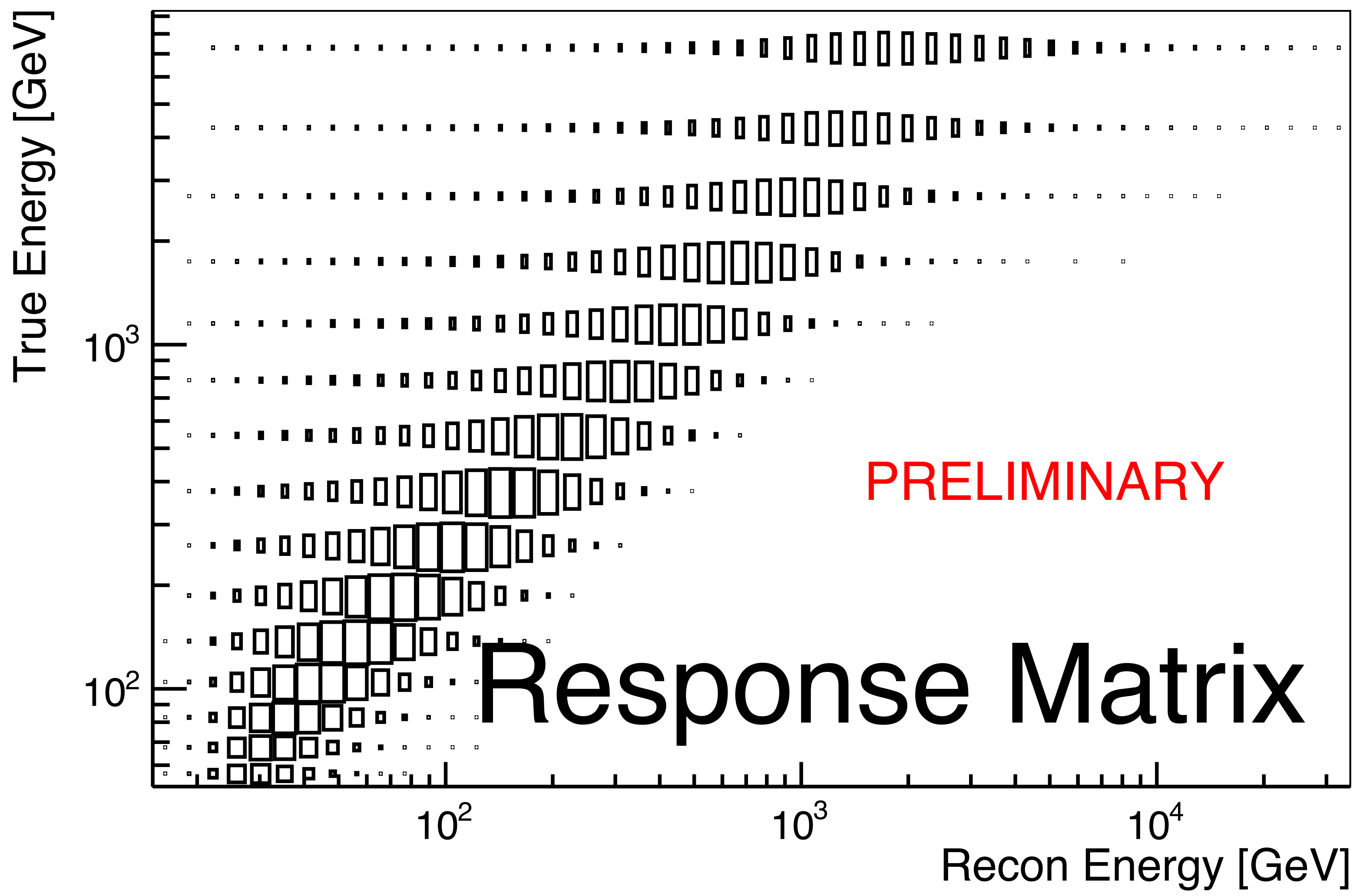
- Same can be seen for radial profile, EM core with hadronic extension

$$\left\langle \frac{dE}{dr} \right\rangle = \frac{B_1}{r} e^{-r/\lambda_1} + \frac{B_2}{r} e^{-r^2/\lambda_2^2}$$

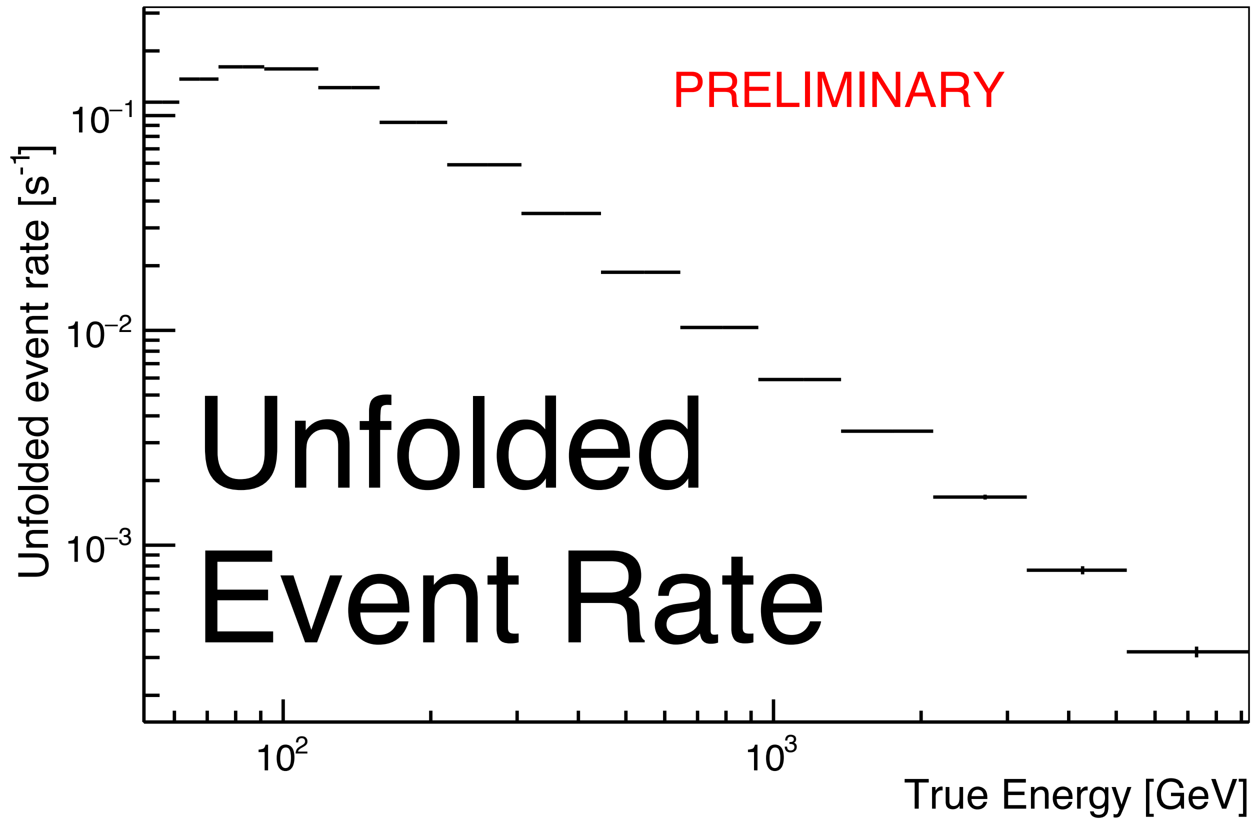
- EM component dominates early longitudinal profile and radial core

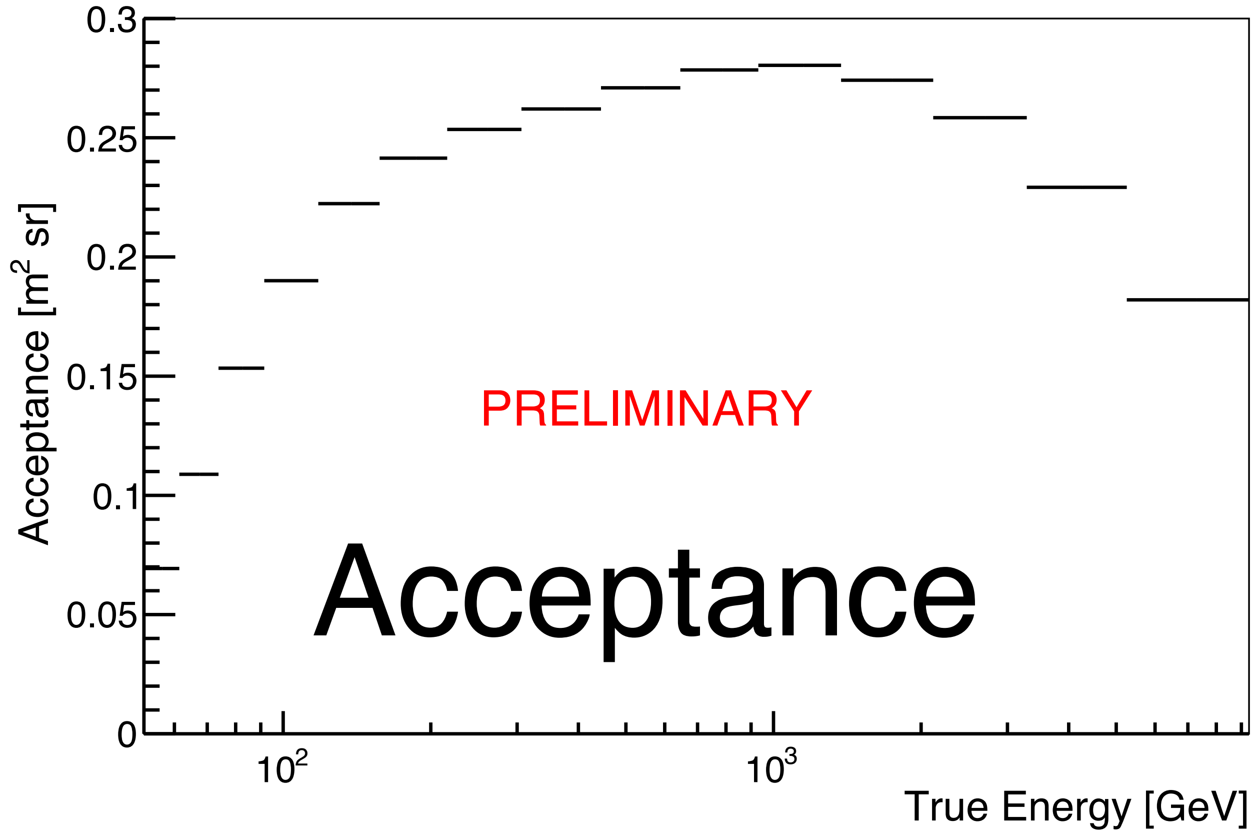
Unfolding The Spectrum





Unfold via
ROOT's TUnfold





Divide by
acceptance
and bin width