Search for new Phenomena in Cosmic Rays with new Balloon-borne and Space-borne Experiments

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Aachen


town hall (1330)


Imperial Cathedral (800)

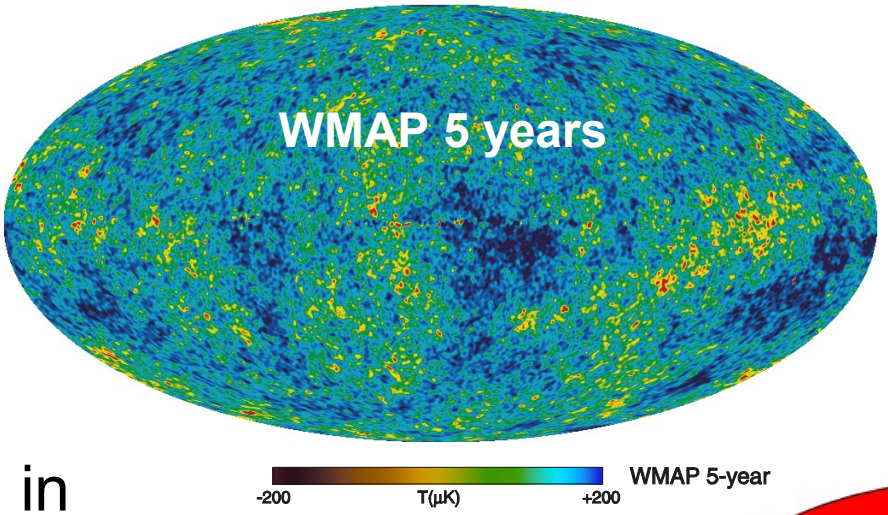

RWTH Aachen
Physics Department

Outline

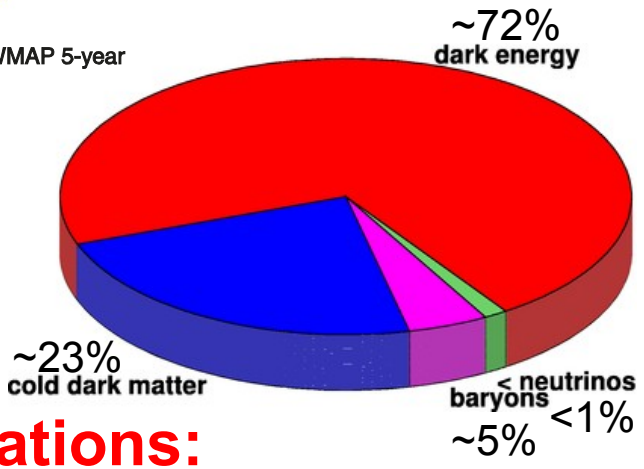
- cosmic-ray measurements: motivation and status of in the GeV to TeV range
- the **PEBS detector** in **Earth's atmosphere**:
  - experimental challenges: long duration balloon flights, residual atmosphere
  - simulation of cosmic ray measurements at the South Pole in Earth's atmosphere and prospects for PEBS $e^{+/-}$ measurements
- the **AMS-02 detector** for the ISS in **Space**:
  - experimental challenges: Space qualification, no gravity
  - performance of the anticoincidence counter for antimatter search

Exciting times to search for new phenomena!

Particle & Astrophysics



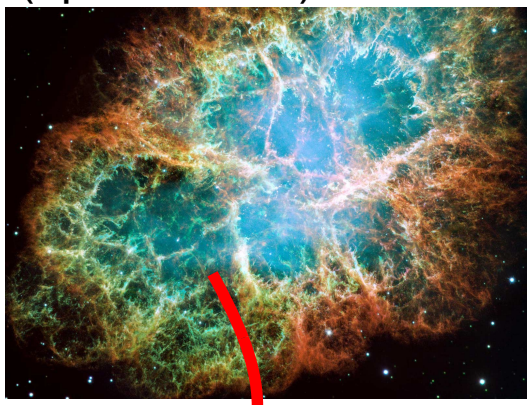
- particle physics & astrophysics are merging
- particle physics methods are used in astrophysics, particle physics input from astrophysics

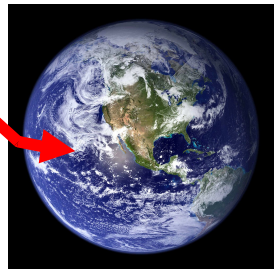


- **important observations cry for explanations:**
  - Dark matter exists! What is its nature?
  - Where does the asymmetry between matter and antimatter in the universe come from (baryogenesis)?

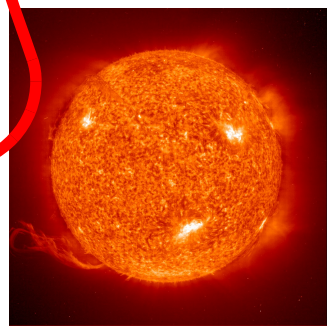
Cosmic Rays as Messengers

sources and acceleration:
supernovae shocks
(up to 10^{15}eV)



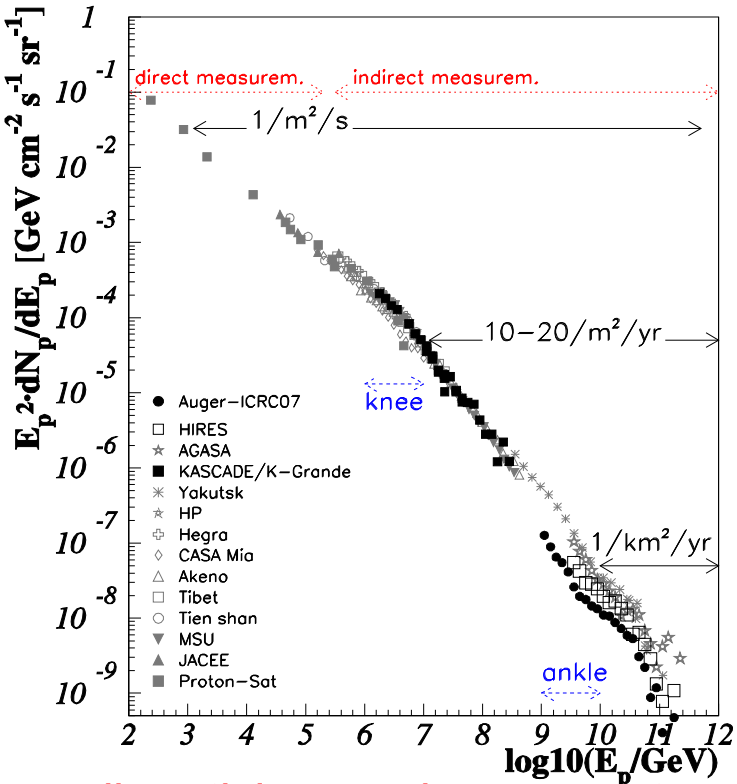


deflection in Earth's magnetic field interactions with the atmosphere



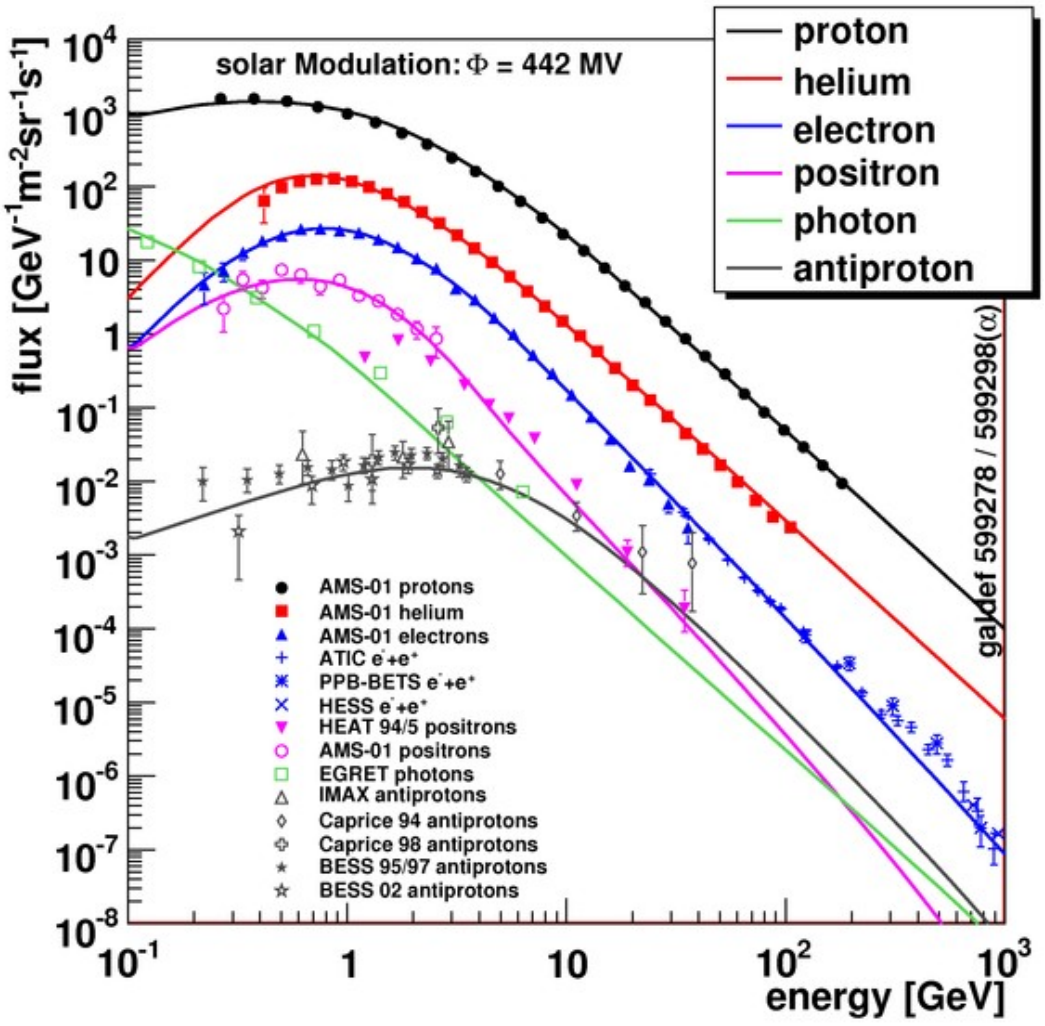
modulation by solar wind

scattering in magnetic fields, interaction with interstellar medium (γ, $e^{-/+}$, $\bar{p}$, ν, $\bar{D}$ production), decay, diffusion, reacceleration



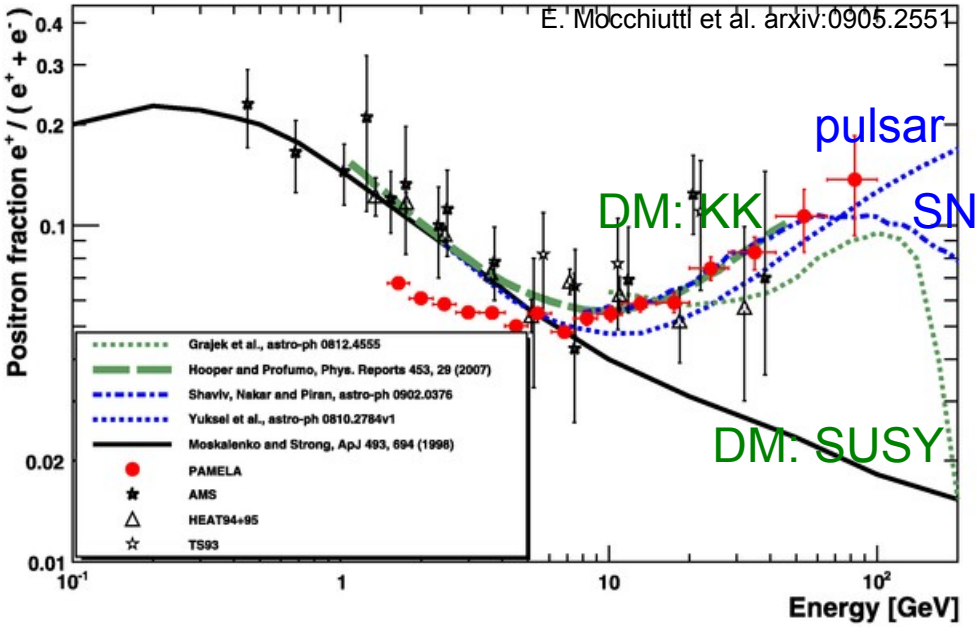
all particle cosmic-ray spectrum

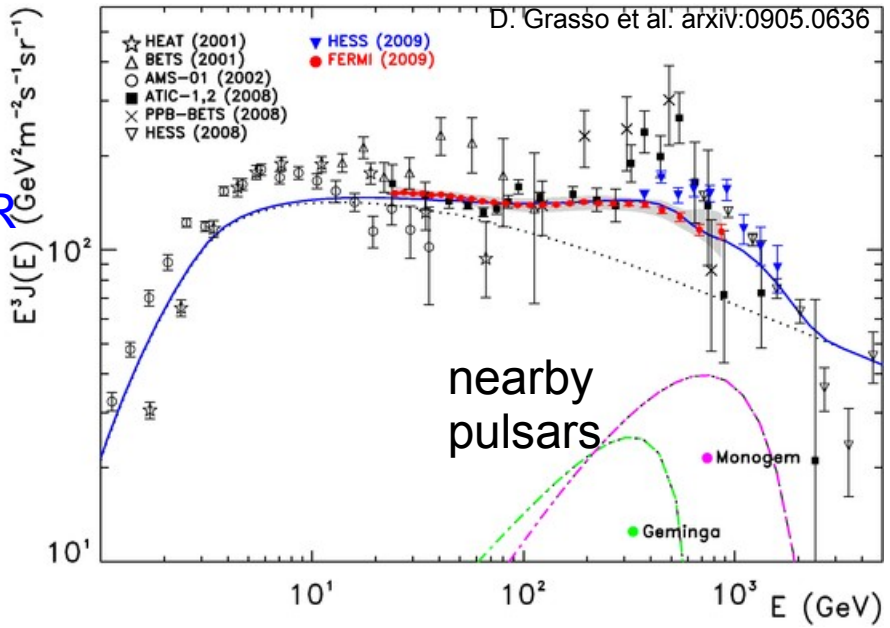
Cosmic Rays in the GeV – TeV Range



- in general good agreement of models
- what we already learned:
  - Particle physics
  - Interstellar medium
  - γ-astronomy
  - …
- **search for new phenomena**:
  - dark matter
  - astrophysical objects
  - baryogenesis
  - unexpected things?

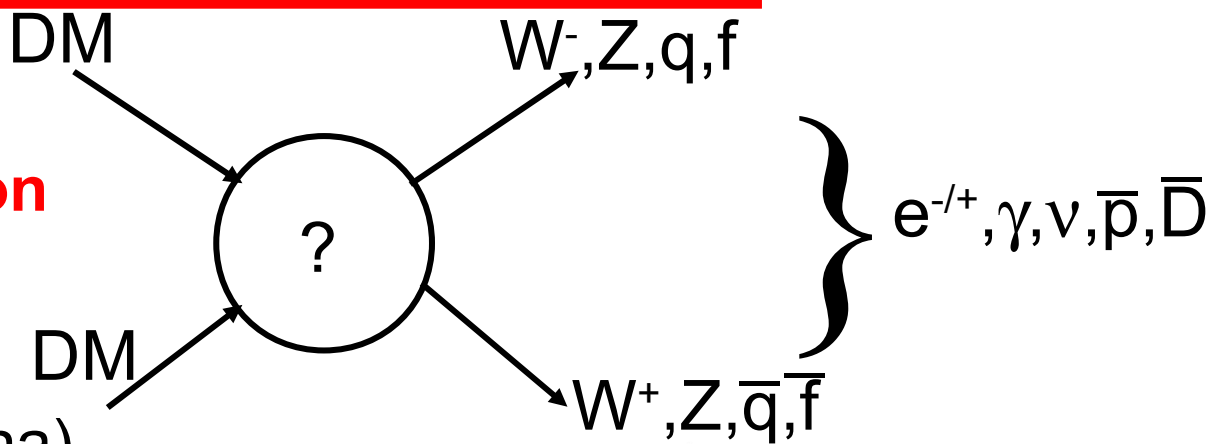
Positron Fraction & Electron Flux





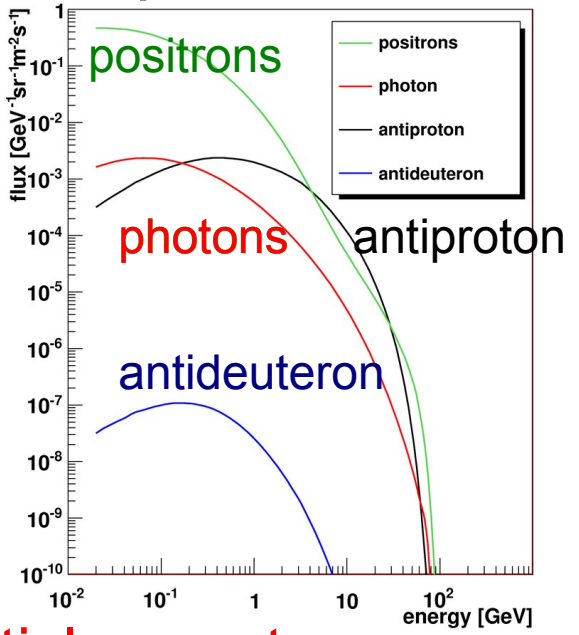
- **unexplained features** in positron and electron spectra
- **proposed theories**: dark matter, pulsars, supernova remnant acceleration

Dark Matter

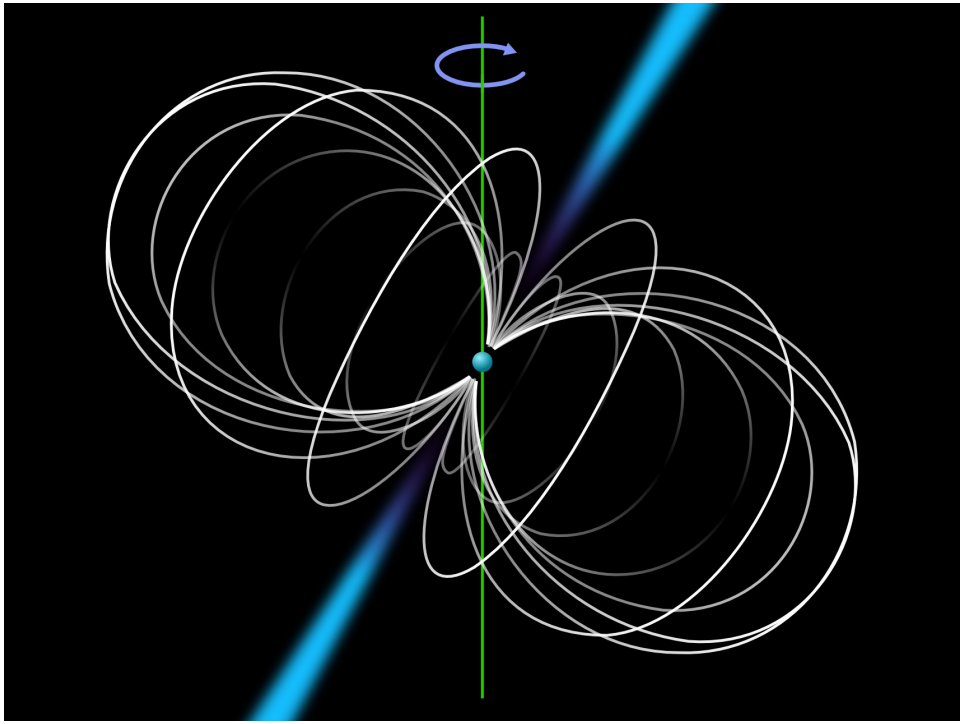


dark matter annihilation

- different scenarios:
  - Supersymmetry: neutralino (majorana)
  - Kaluza-Klein universal extra dimensions: 1st excitation of photon (boson)
- requires boost factors:
  - subhalos of dark matter
  - recent theoretical developments: Sommerfeld enhancement, internal bremsstrahlung
- indirect dark matter searches are especially sensitive to extra contributions in the antiparticle spectra



Pulsars



- spinning and magnetized neutron stars
- pulsars emit synchrotron radiation (lighthouse effect)
- γ-ray pulsars can produce electron and positrons via pair production in the magnetosphere
- positrons and electrons can be accelerated in PWN or SNR shocks
- assumed injection spectrum: $f_p(E) = E^{-\Gamma} \exp\left(-\frac{E}{E_c}\right)$
- preferred candidates: distance < 1 kpc, age T > $5 \cdot 10^4$yr, E_c=~1000GeV

Baryogenesis

standard models of particle physics and cosmology:
equal amounts of matter and antimatter in Big Bang, but:

$$\frac{n_B}{n_\gamma} < 6.5 \cdot 10^{-10}$$

any explanation needs (Sakharov):

- Baryon number is not conserved.
- Interaction rates for baryons and antibaryons are different. CP must be violated!
- The Universe cannot be in thermal equilibrium.

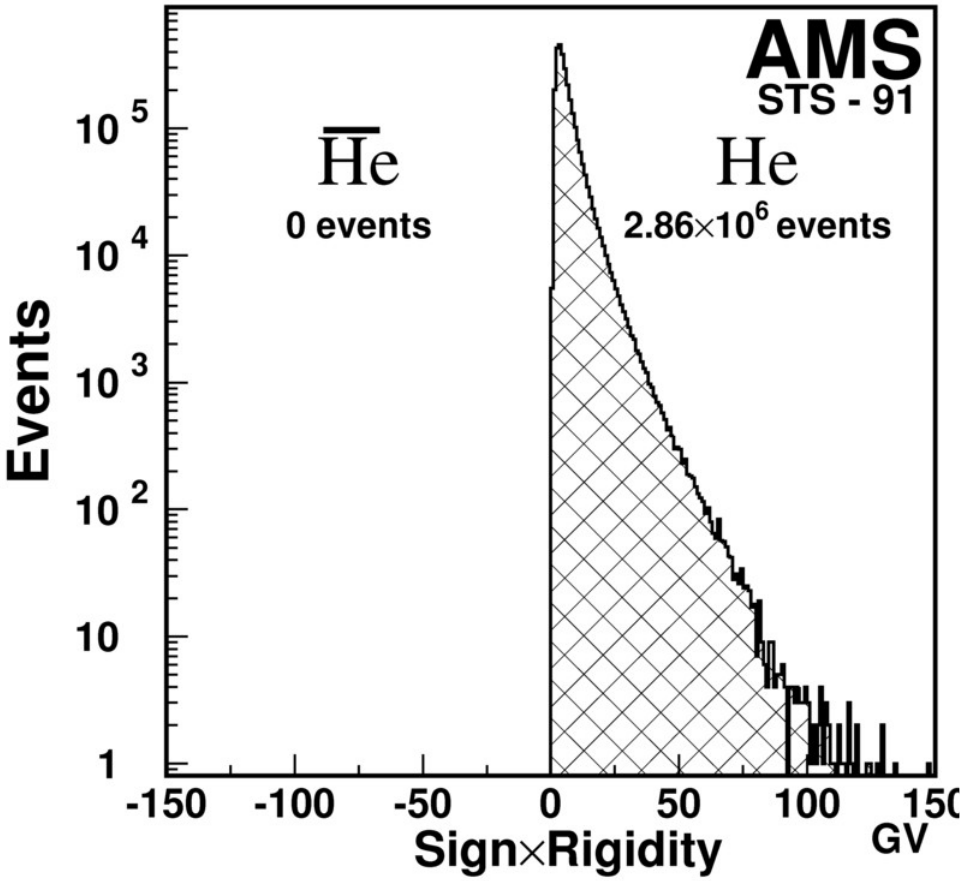
different approaches:

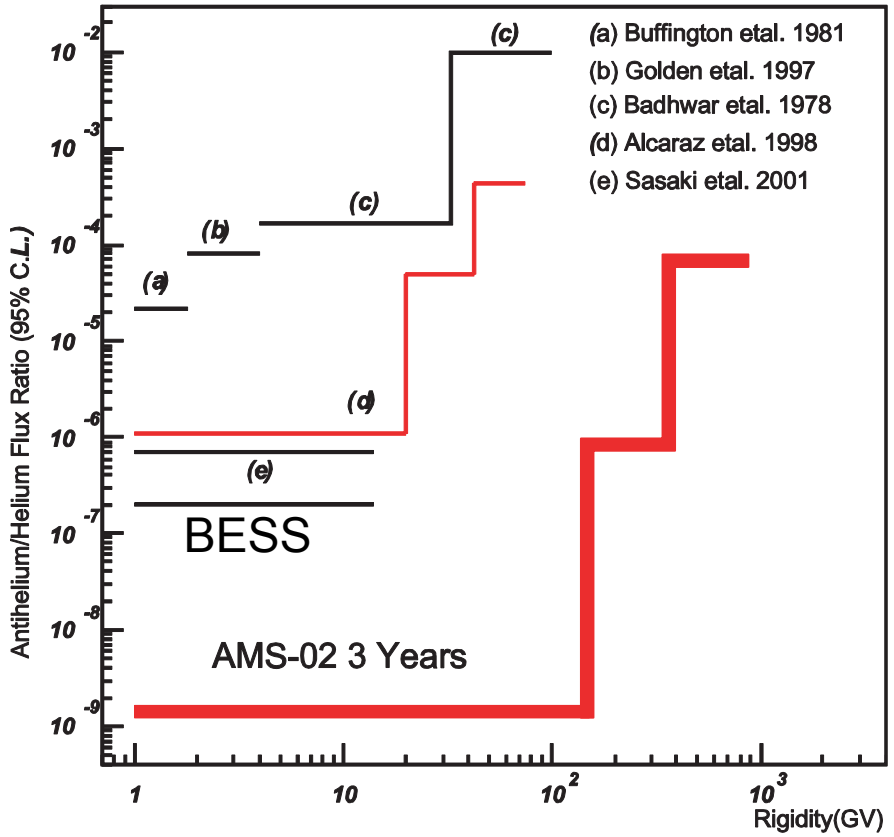
- dynamical CP violation
- separation of matter and antimatter in the early universe

implications of antimatter measurements:

- NO(!) production of antihelium in our matter dominated universe possible!
- bound on antihelium/anticarbon contrains distance between galaxies and antigalaxies and baryogenesis theories

Search for Antihelium





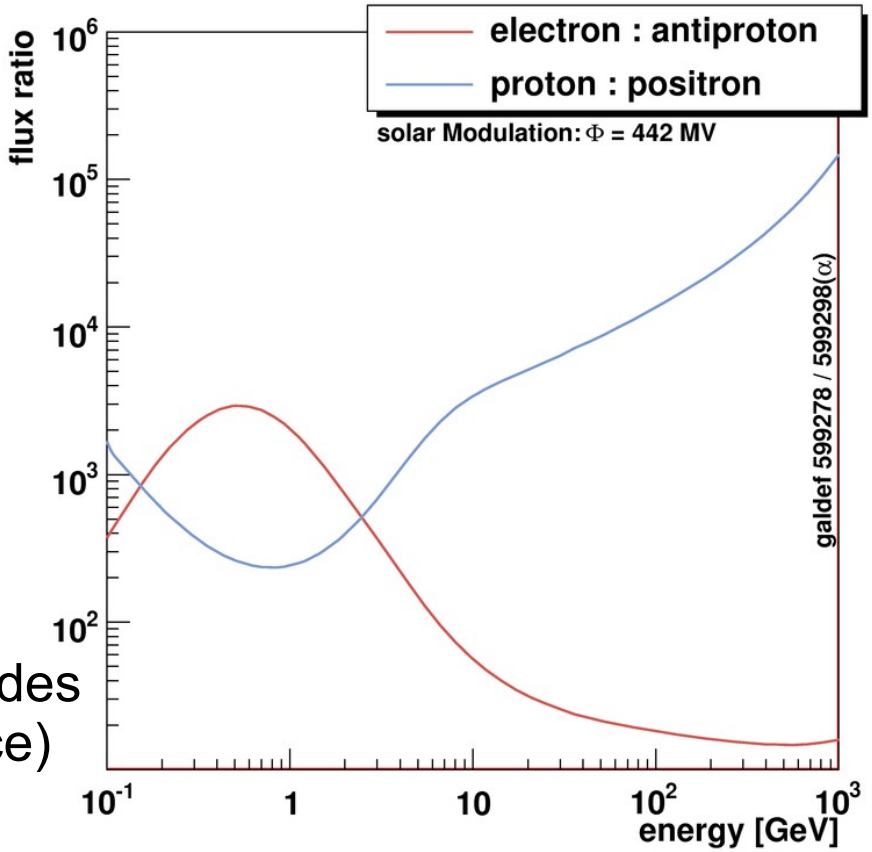
- so far no antimatter found in cosmic rays. Needs a very good discrimination between Helium and Antihelium

→ Veto by **Anticoincidence Counter**

New Cosmic-Ray Detectors

general requirements for direct measurements of cosmic rays up to TeV energies with balloons and in Space:

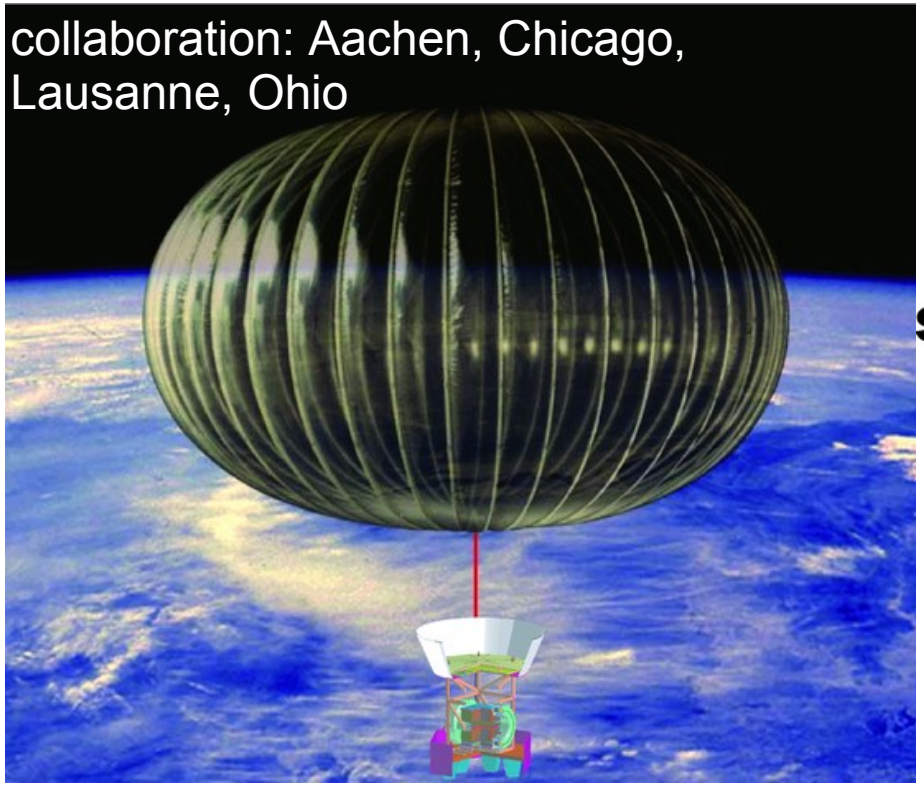
- good proton suppression to measure electrons, positrons, photons, antiprotons, antimatter
- good momentum resolution
- long flight time and large acceptance
- small sources of background (high altitudes with balloons in the atmosphere or Space)
- very robust behavior (shocks up to 10g possible), harsh environment

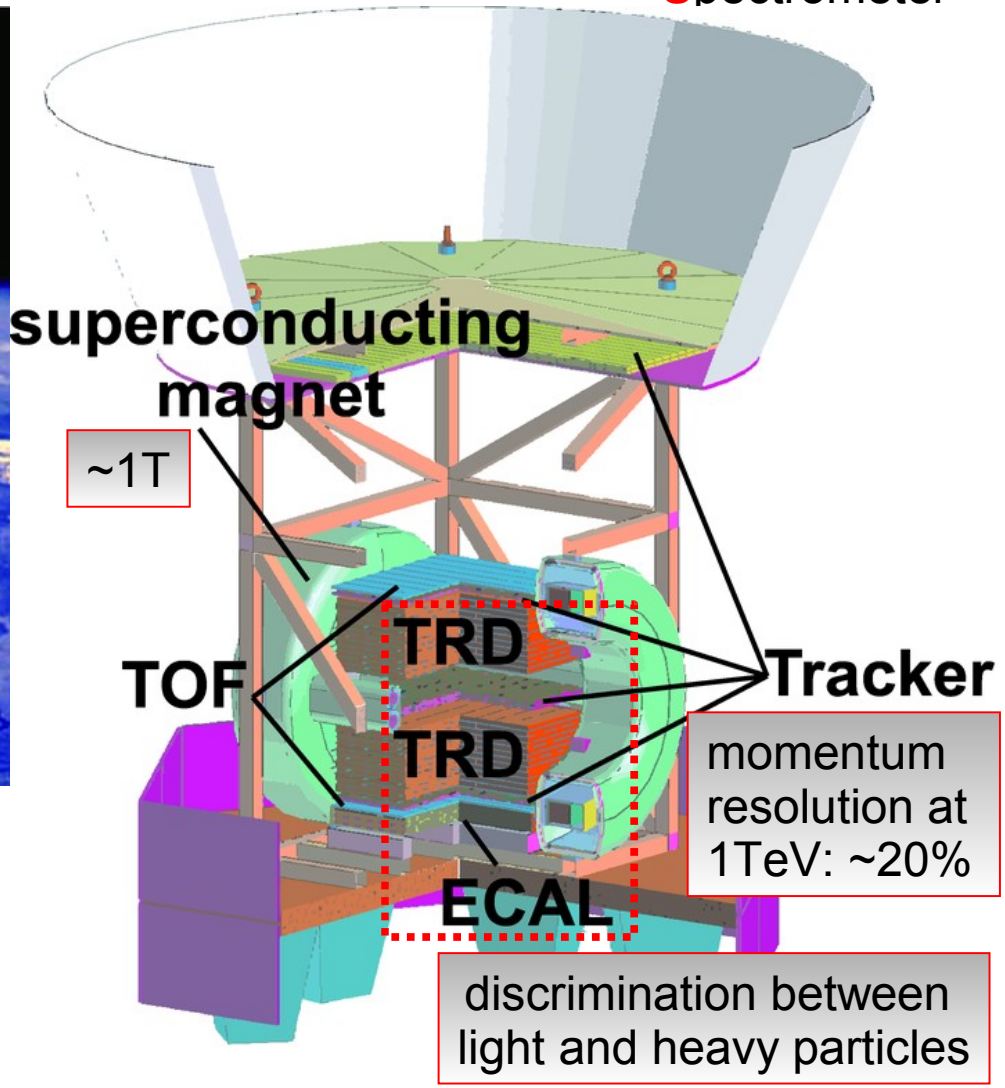


The PEBS Detector

Positron
Electron
Balloon
Spectrometer

collaboration: Aachen, Chicago, Lausanne, Ohio



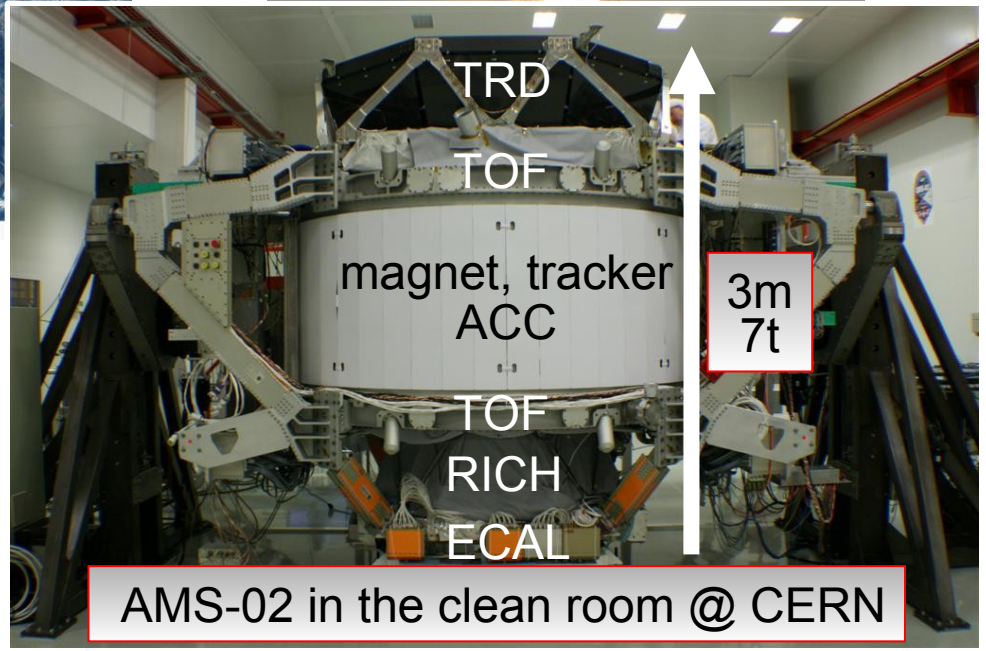


- planned balloon flights at the North and South Pole in Earth's atmosphere at ~40km (starting from 2014)
- in total ~100 days, acceptance: 0.3m^{2}sr
- proposal decision by NASA next month
- goal: **$e^{-/+}$ data up to 2TeV**

The AMS-02 Detector

Alpha
Magnetic
Spectrometer

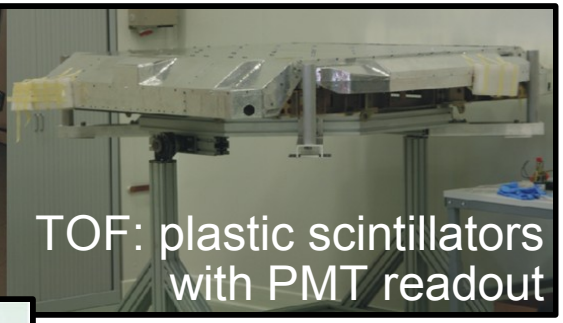
- very successful precursor AMS-01 was flown on a Space Shuttle in 1998
- flight with Space Shuttle to ISS STS-134, Discovery, Sep. 2010
- operation in space for 3 years
- spectroscopy of cosmic rays
- measurement/bounds on antimatter

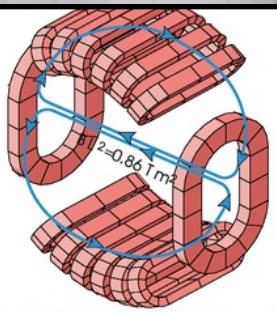


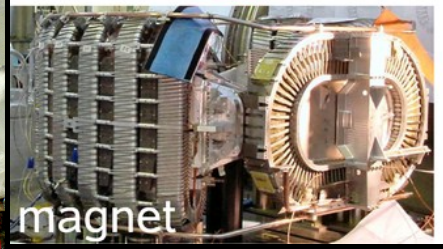
AMS-02 in the clean room @ CERN

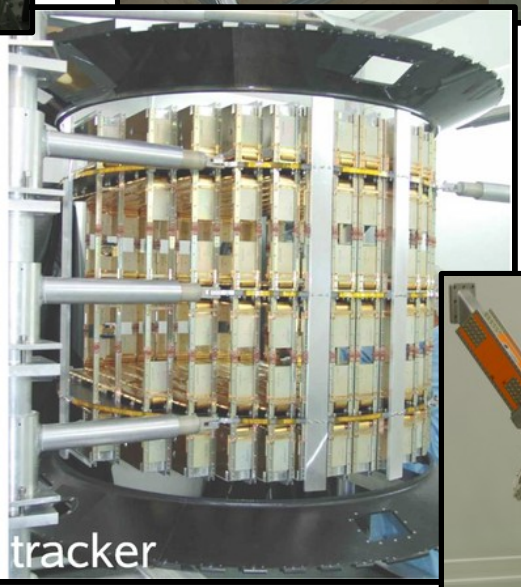
AMS-02 Components


TRD: 20 layers radiator and proportional tubes

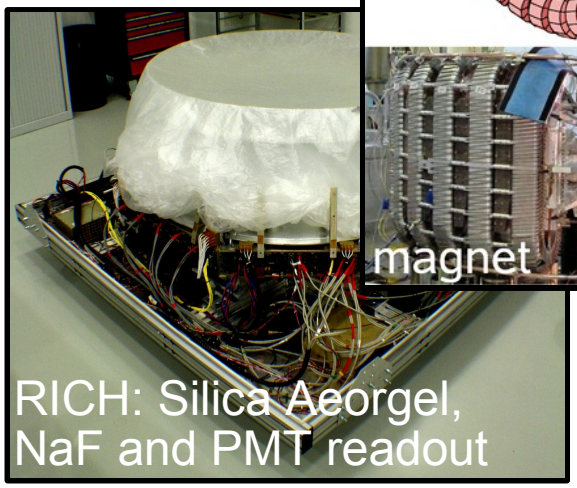


TOF: plastic scintillators with PMT readout




magnet


tracker

superconducting magnet
B~0.8T, silicon tracker:
9μm resolution
mom. res. @ **1TeV: ~40%**


RICH: Silica Aeorgel, NaF and PMT readout

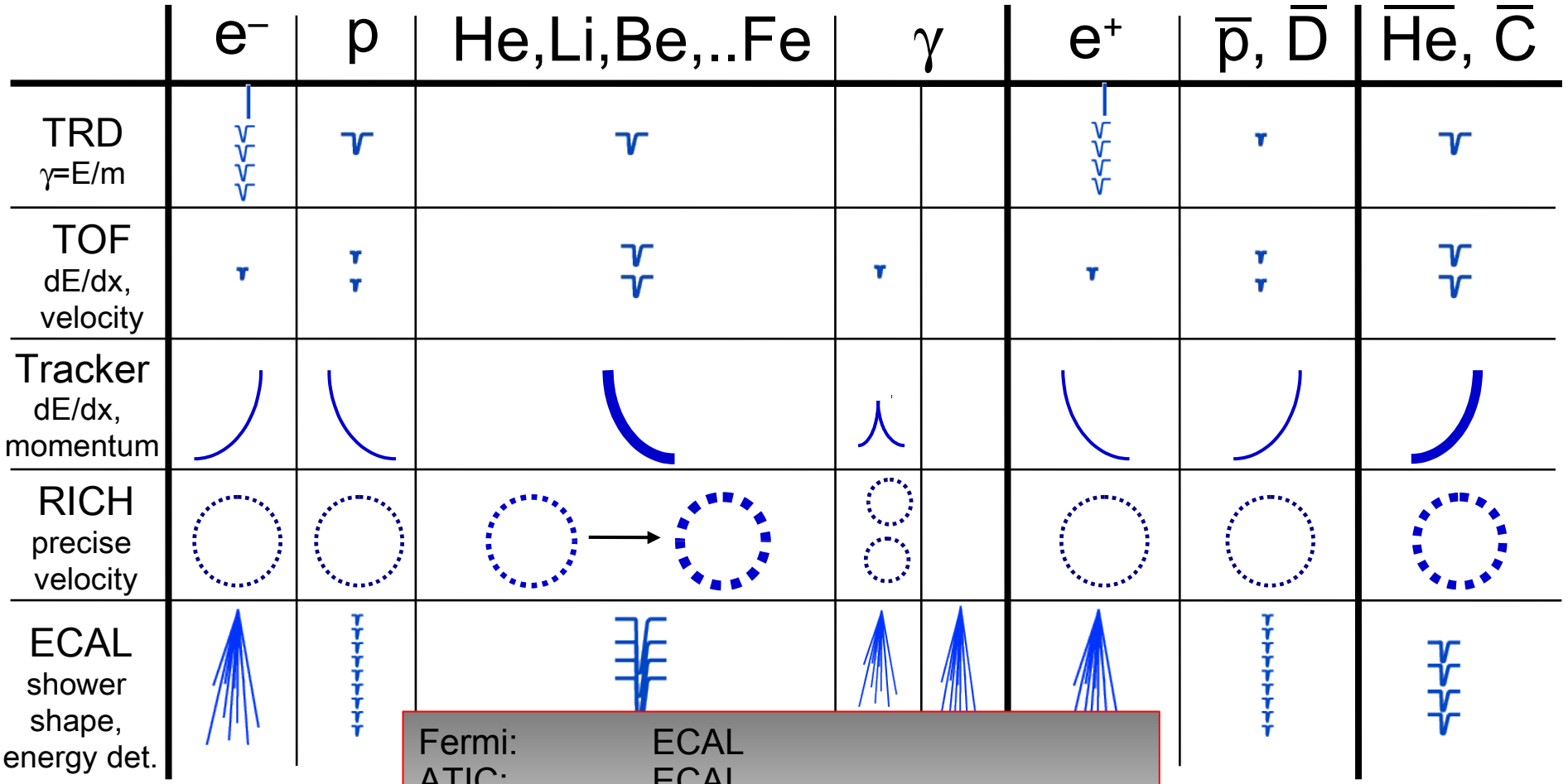
All components have to withstand Space conditions!


ECAL: lead with scintillating fibers and PMT readout

+ Anticoincidence Counter (ACC)

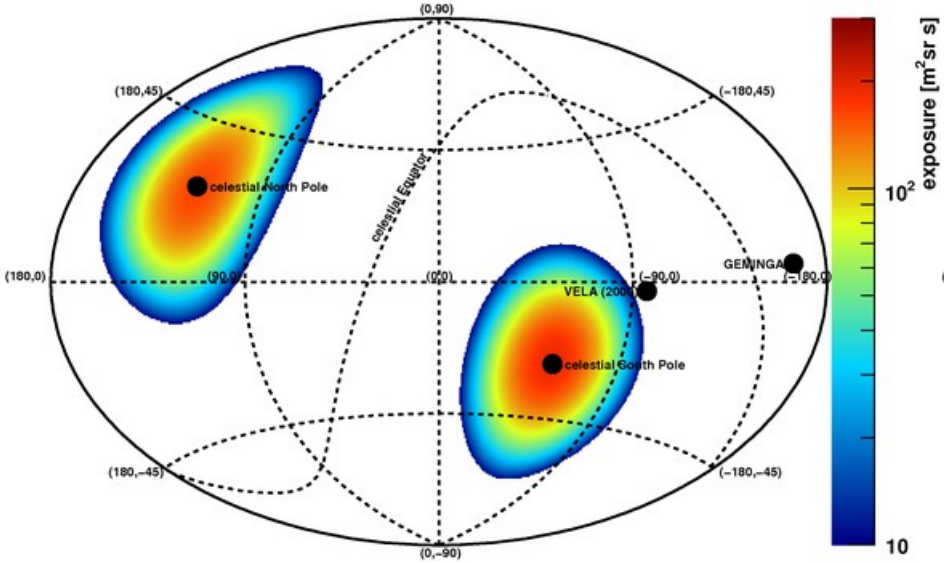
Detector Characteristics

Event-by-event reconstruction!

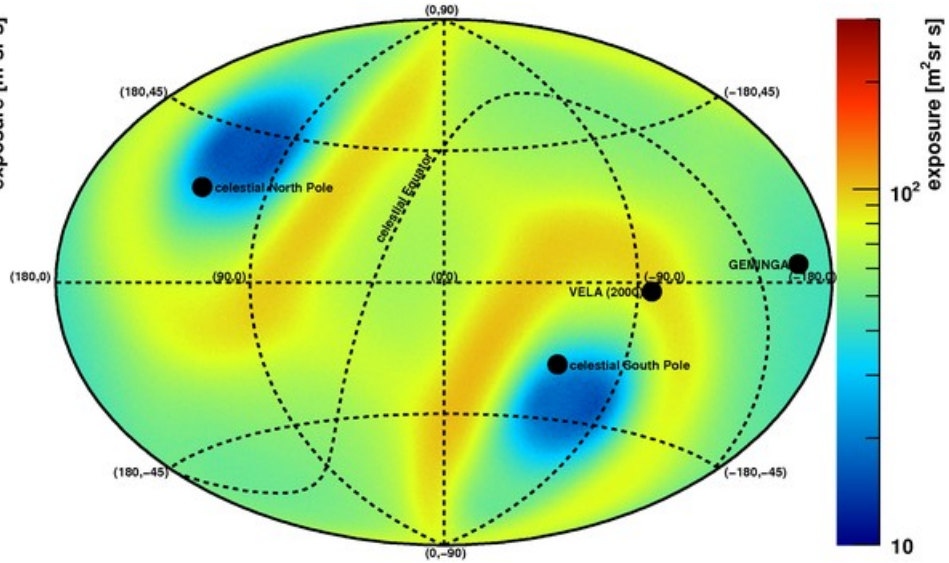


Fermi:	ECAL
ATIC:	ECAL
PAMELA:	magnet + ECAL
PEBS:	**magnet + ECAL + TRD**
AMS-02:	**magnet + ECAL + TRD +RICH**

Sky Coverage



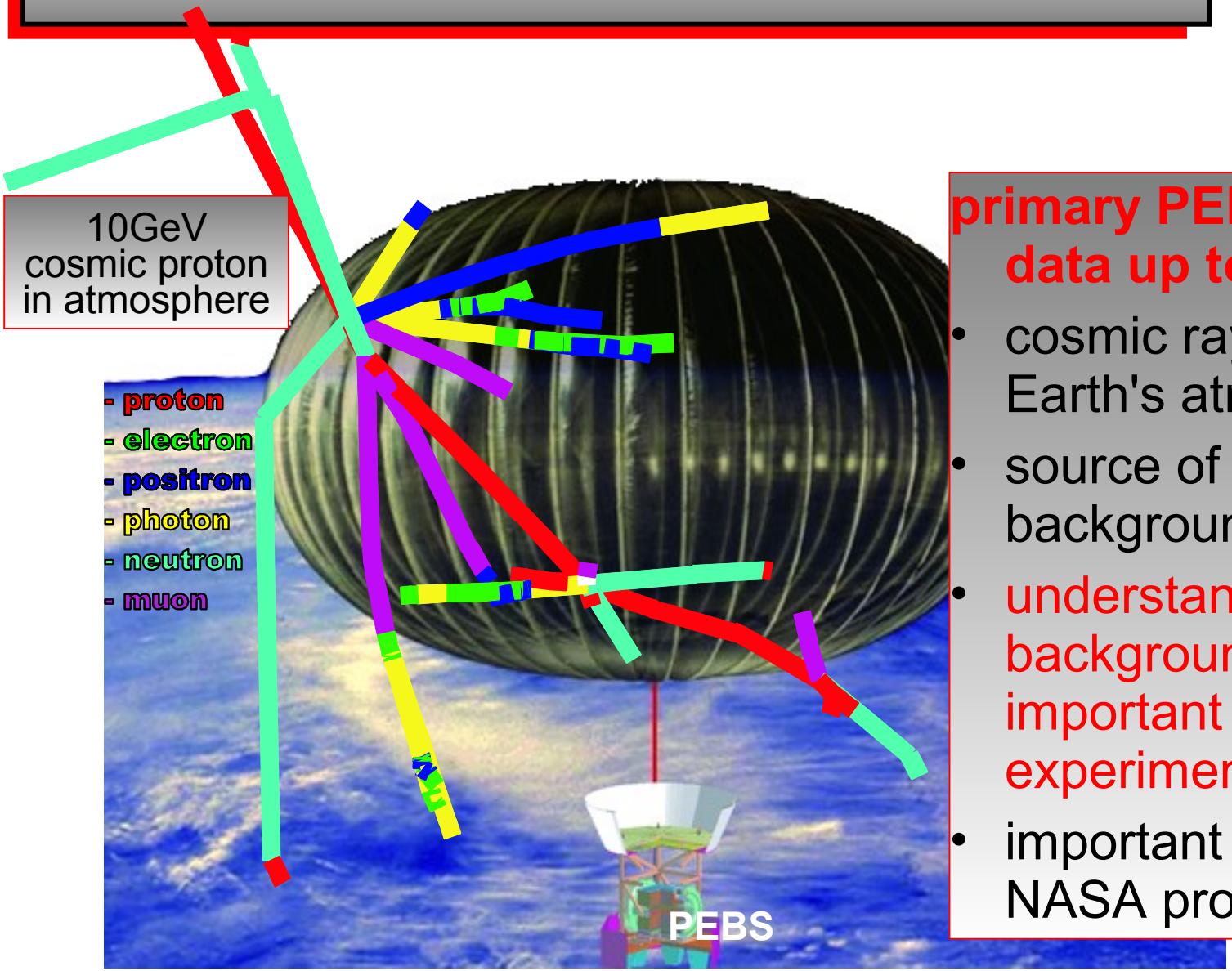
PEBS coverage with balloon flights at the North and South Pole



AMS-02 coverage for the International Space Station orbit

- **only both types** of experiments are able to deliver a homogeneously illuminated picture of the sky
- **important to look for sources of TeV $e^{-/+}$** and to distinguish between dark matter and pulsar models: large statistics are needed, anisotropies of 1% expected!

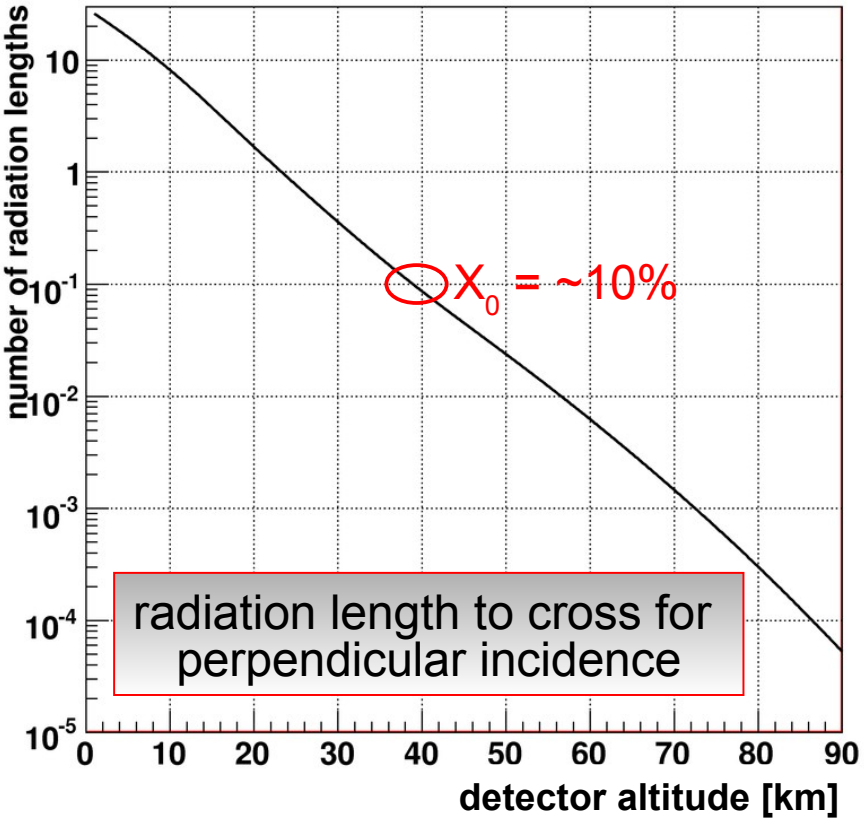
Balloon Experiments and Atmosphere

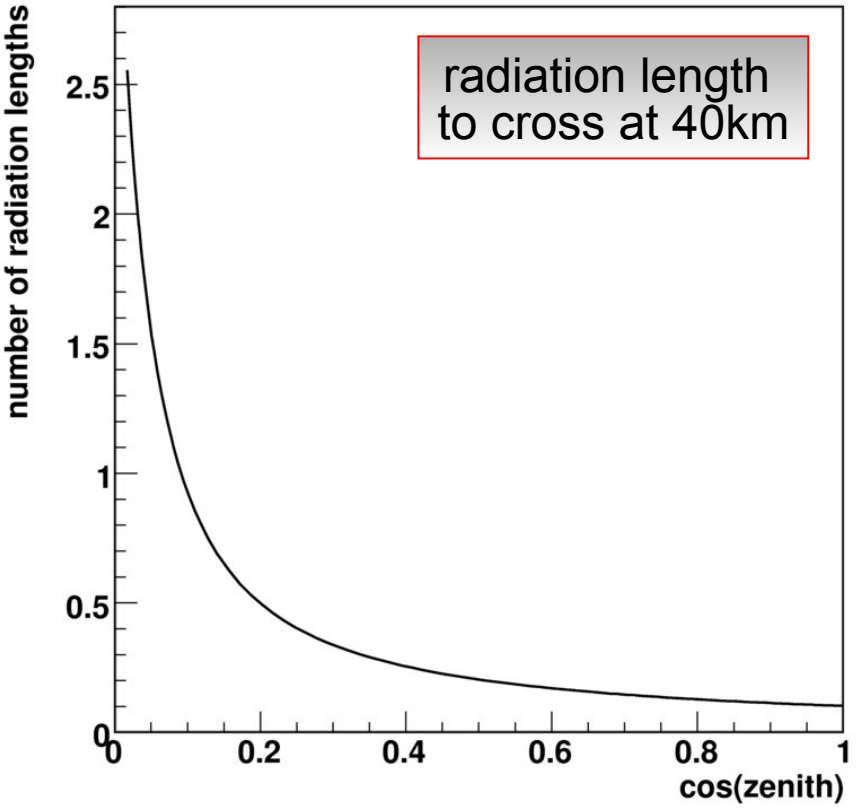


primary PEBS goal: $e^{-/+}$ data up to 2TeV

- cosmic rays interact in Earth's atmosphere
- source of particle background
- understanding of background is very important for balloon experiments!
- important input to NASA proposal

Residual Atmosphere

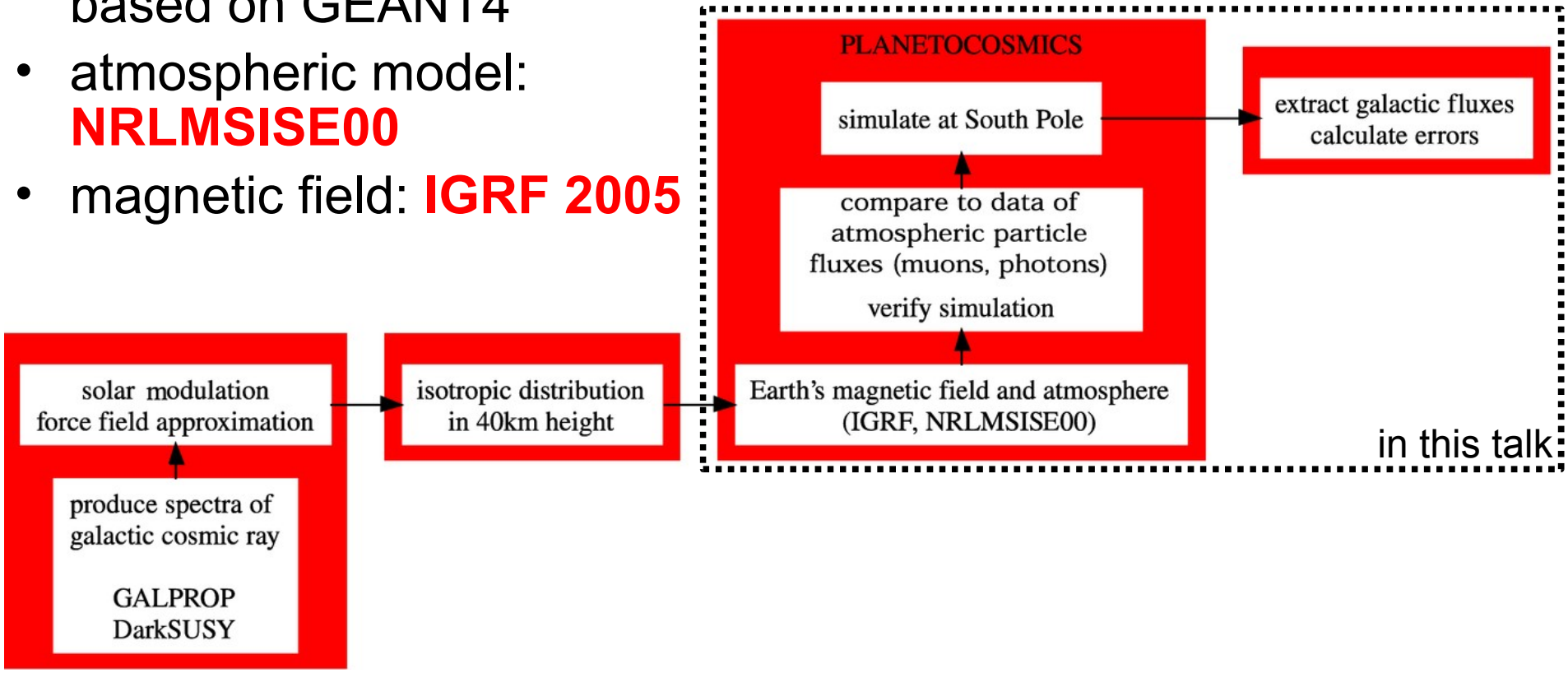




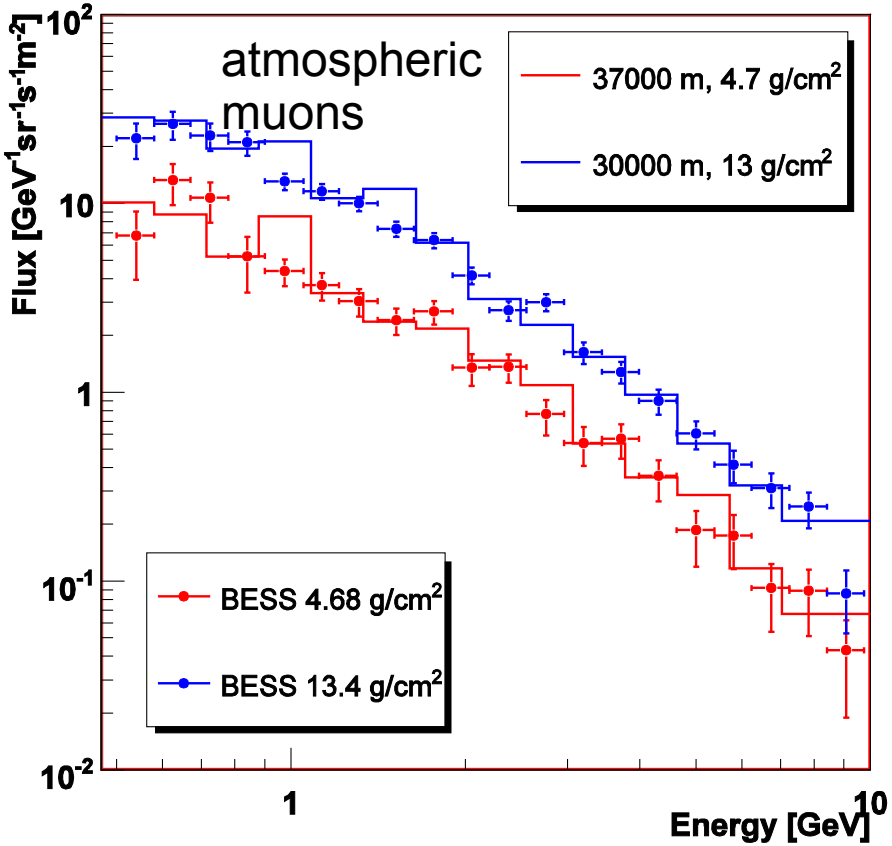
- grammage of matter in front of 40km: ~3.8g/cm^2
  cosmic rays traversed in Space: 6 – 10g/cm^2
- on average ~10% of a radiation length (nuclear mean free pathlength ~5%) before 40km: **Atmospheric background has to be calculated!**

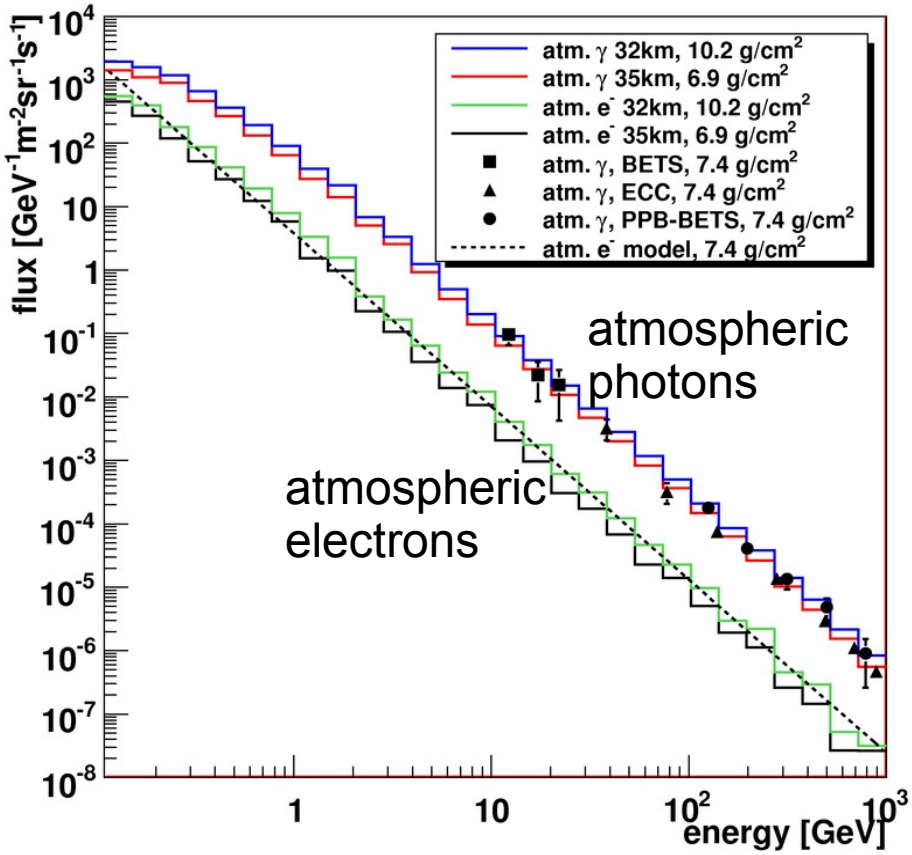
Analysis of atmospheric Background

- use of program package: **PLANETOCOSMICS** based on GEANT4
- atmospheric model: **NRLMSISE00**
- magnetic field: **IGRF 2005**



Comparison of Backgrounds

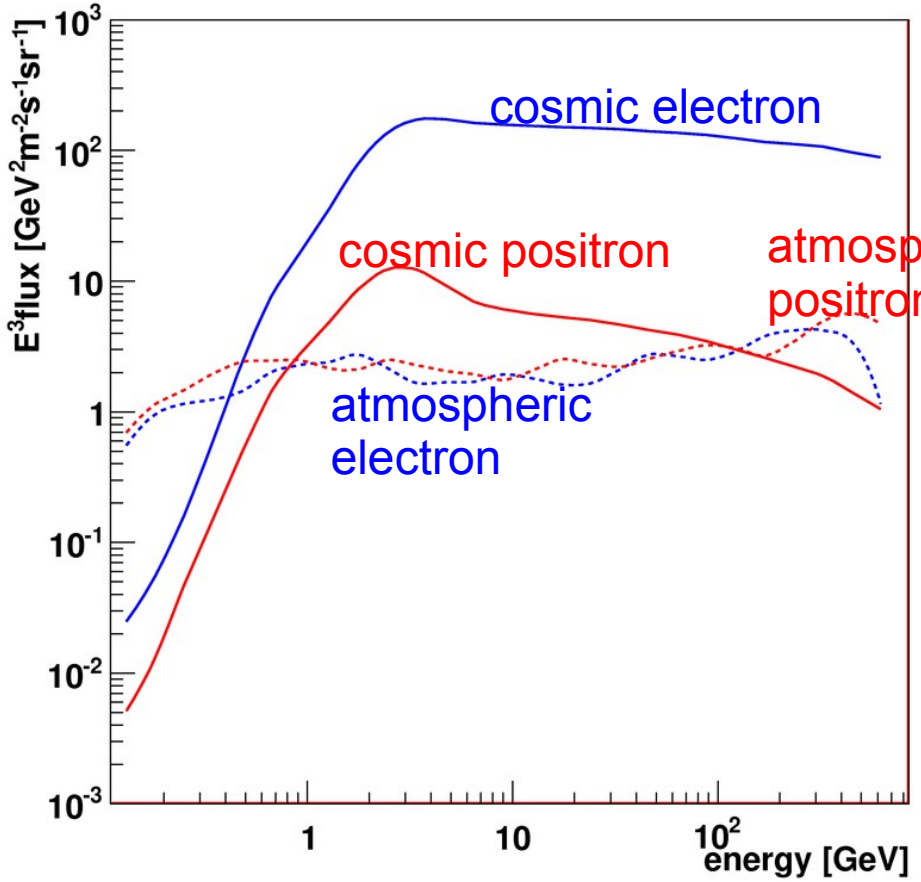




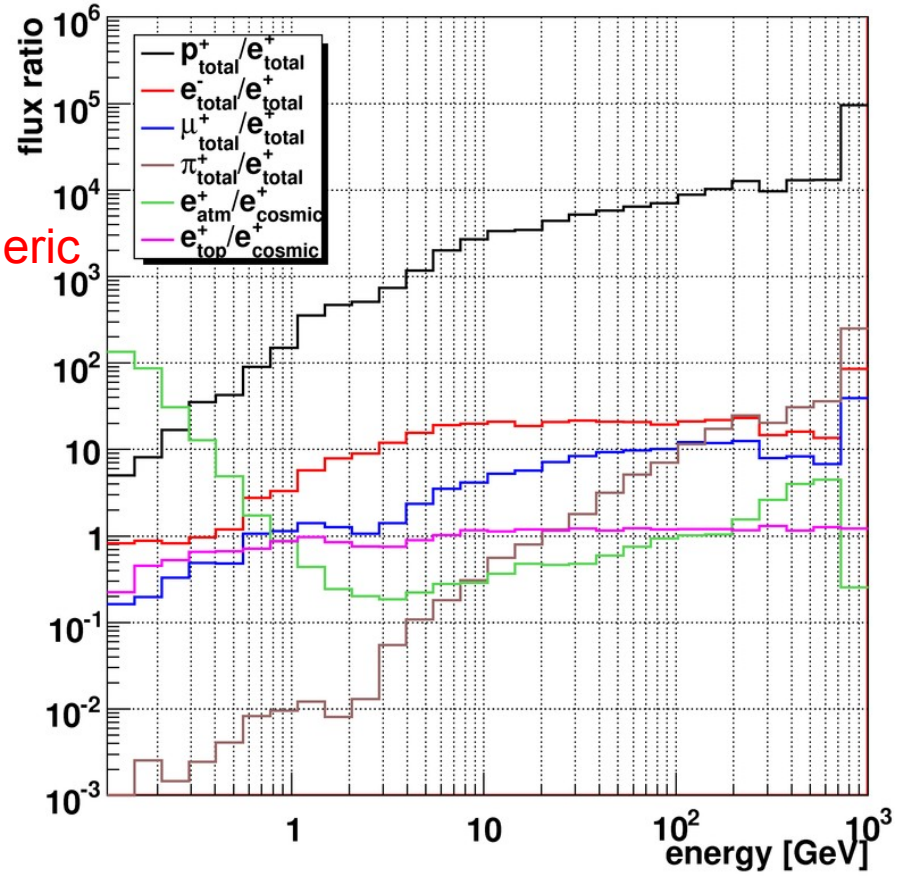
- **good agreement** with secondary muon data of BESS
- **good agreement** with secondary photon data of BETS, ECC, PPB-BETS
- **good agreement** with analytical secondary electron models

Simulation works, now South Pole

Particle Fluxes at the Detector



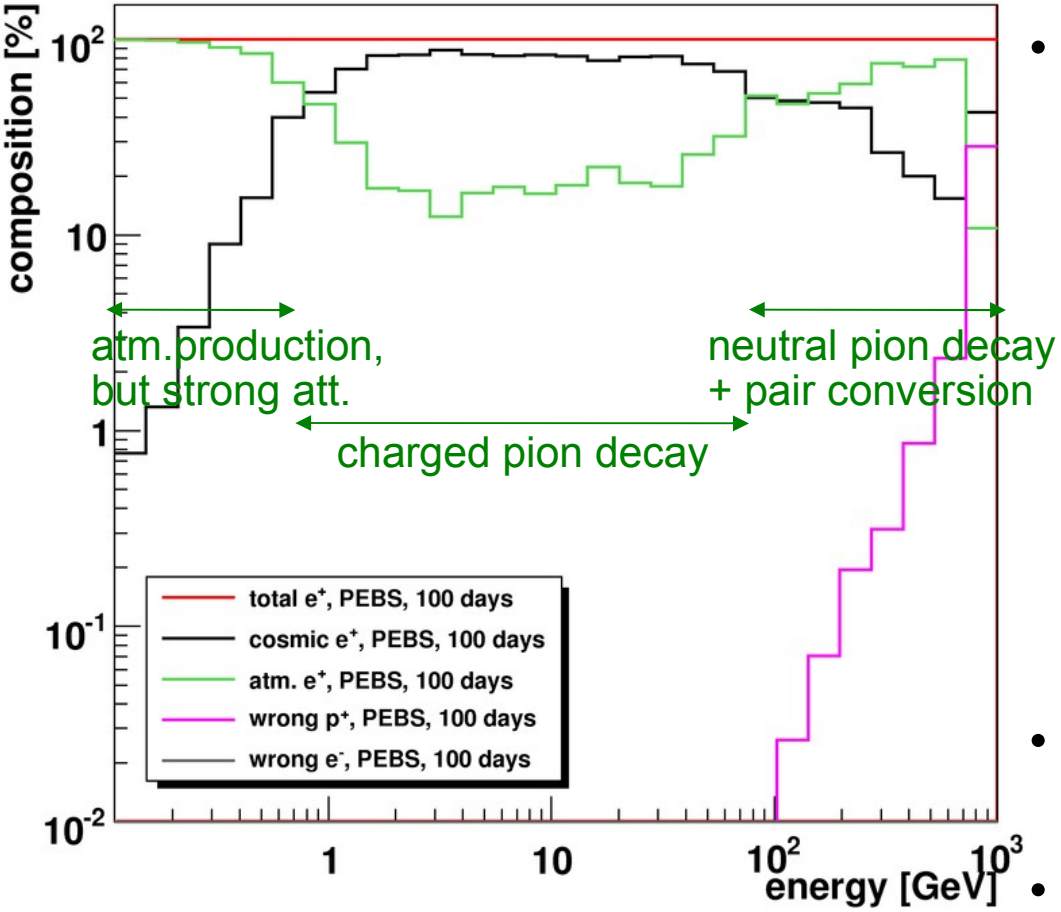
particle fluxes at 40km altitude



particle flux ratios important for the positron measurement at 40km altitude

Composition of "Positrons"

total flux = cosmic + atmospheric + misidentified particles



$$p + n \rightarrow \pi + X \rightarrow \begin{cases} \pi^{\pm} & \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu} \rightarrow e^{\pm} + \overset{(-)}{\nu}_{\mu} + \overset{(-)}{\nu}_{e} \\ \pi^{0} & \rightarrow \gamma + \gamma. \end{cases}$$

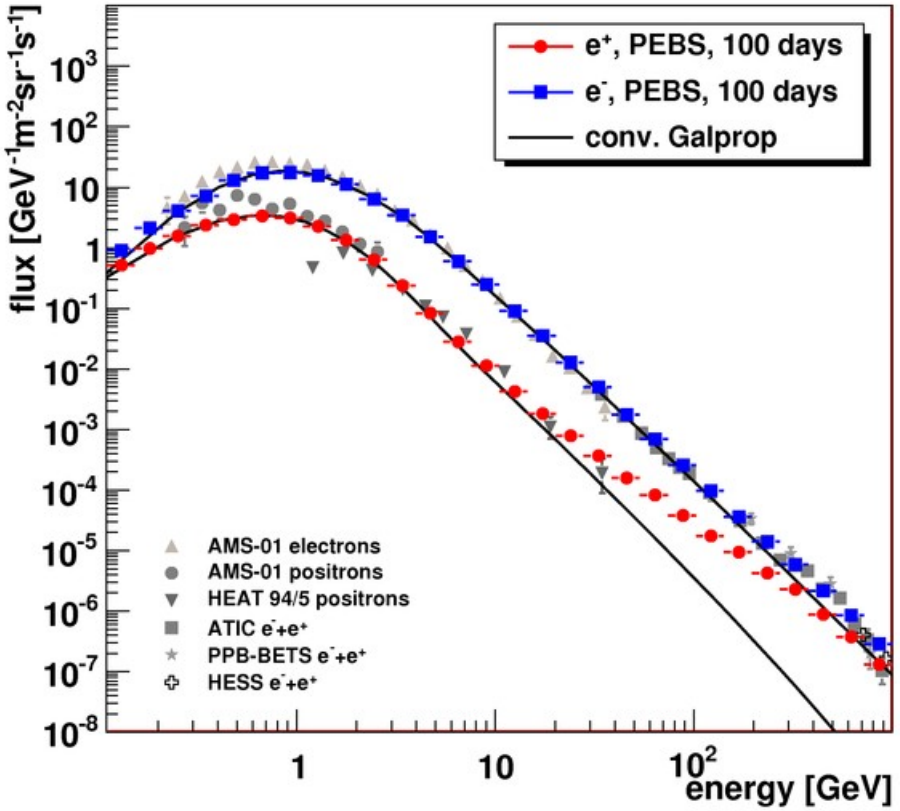
- PEBS uses for the particle identification:
  - TOF: time measurement
  - TRD: transition radiation
  - ECAL: (m,p can be neglected)
  - Tracker momentum resolution:

$$\frac{\sigma_p}{p} = \frac{0.02\,\% \cdot p}{\mathrm{GeV}} \oplus 2.3\,\%$$

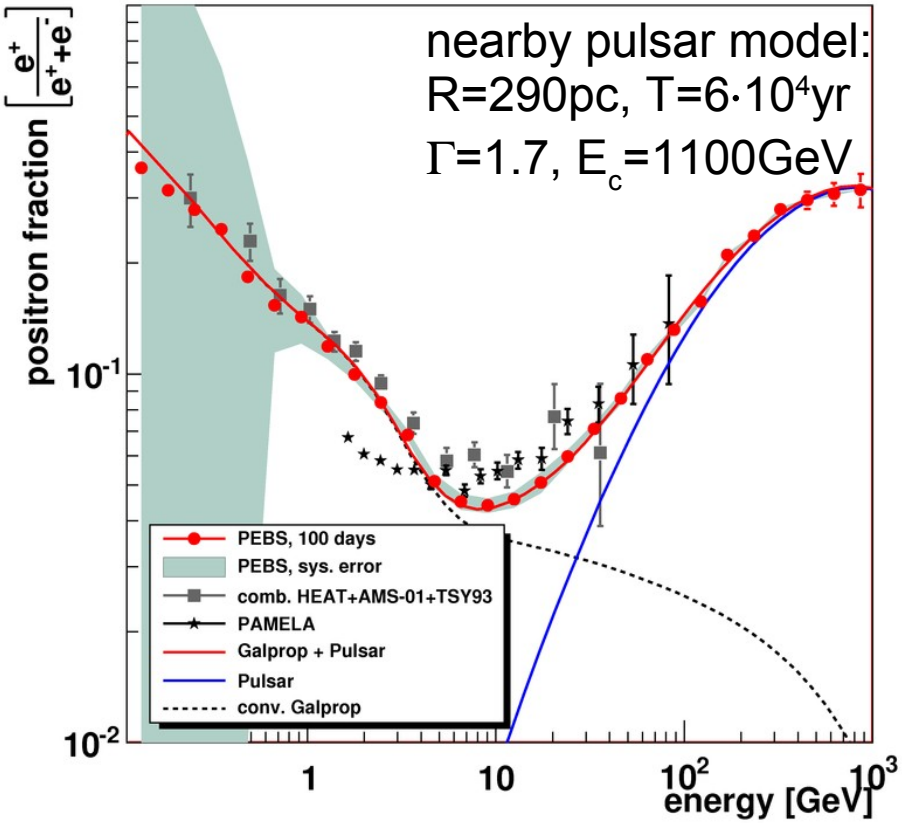
- Positrons must be corrected for attenuation
- **Atmospheric positrons from simulation!**

Positrons: Fluxes and Fraction

fluxes



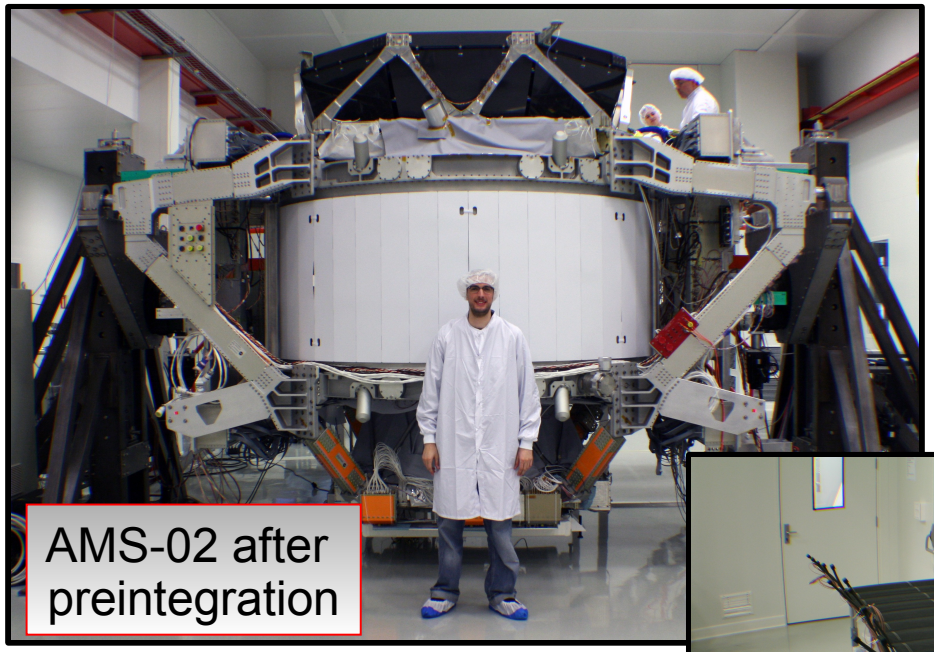
fraction

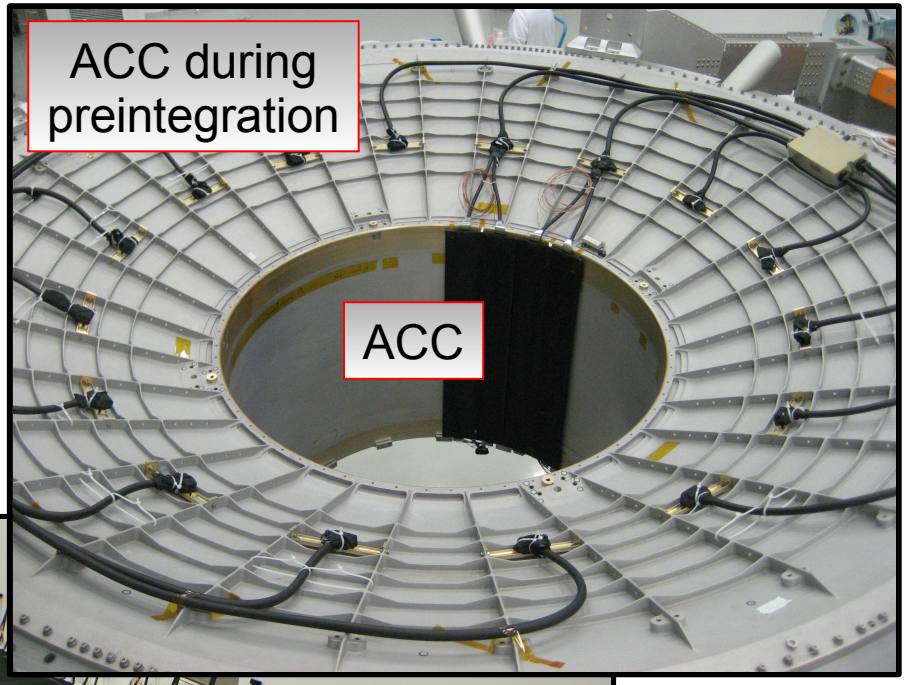


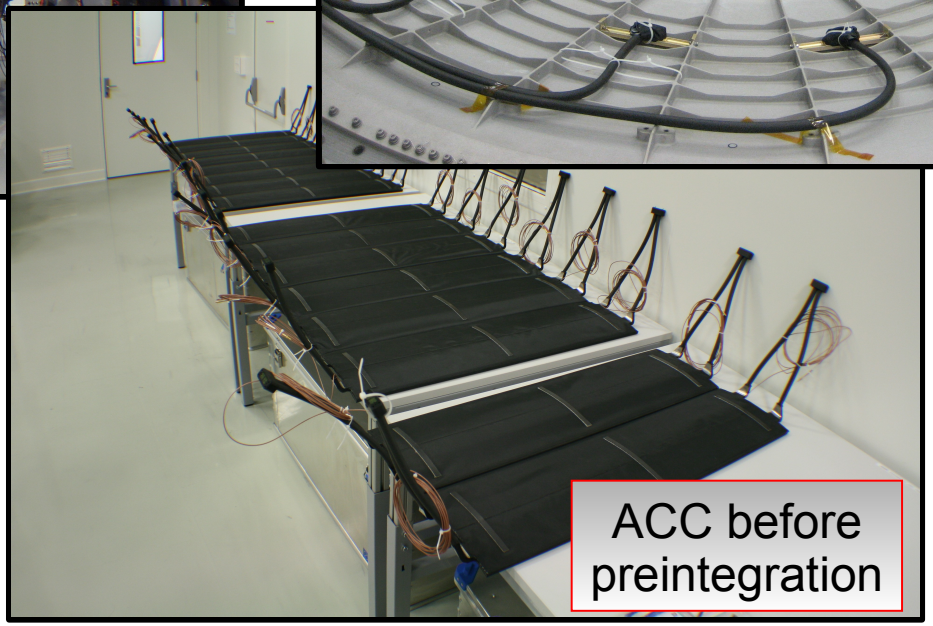
- assuming a total flight time of 100 days
- using systematic errors for detectors of 10% and 15% for the atmosphere

  a reliable positron fraction measurement with PEBS will be possible up to ~2000 GeV

AMS-02: ACC & Antimatter Search



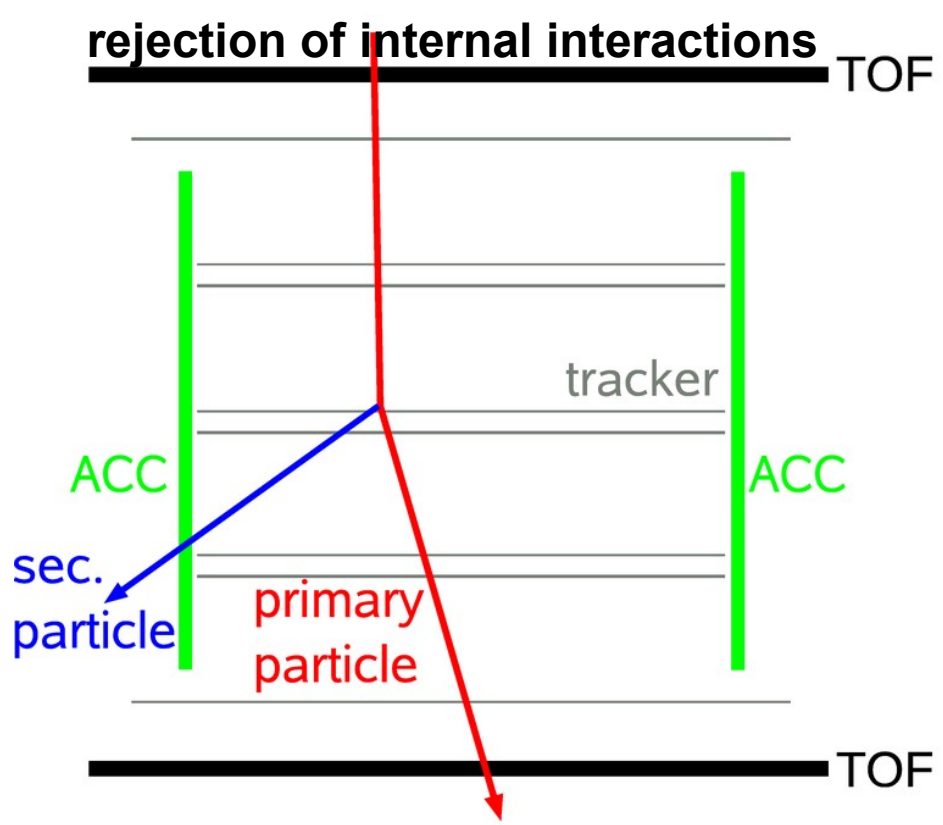


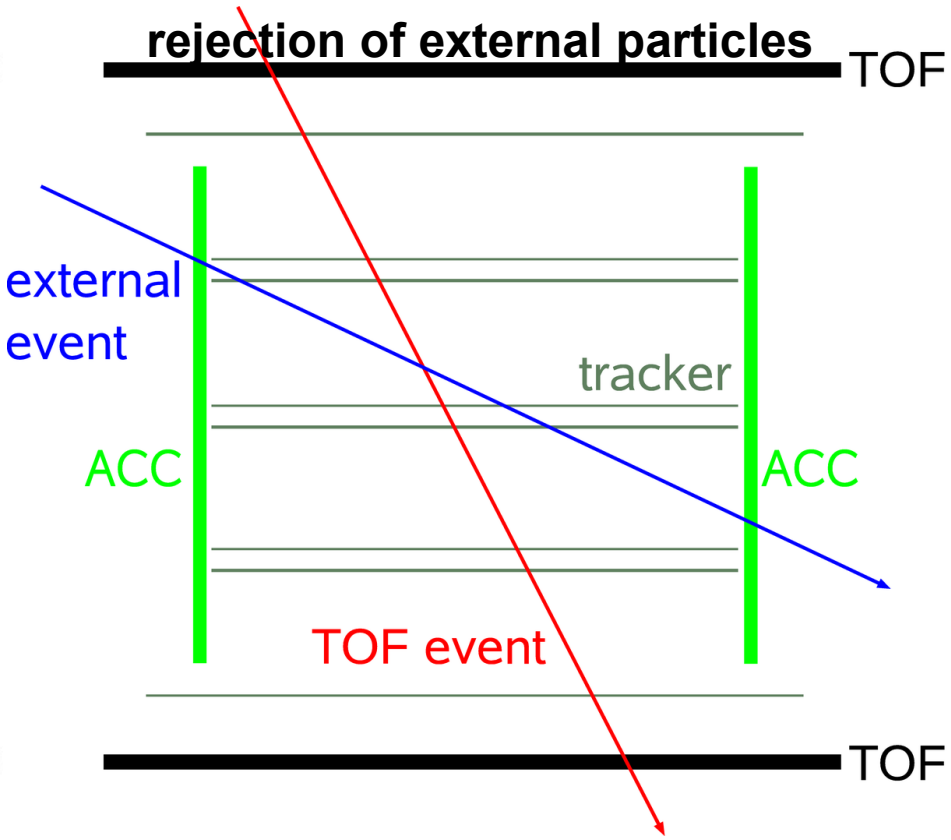


Anticoincidence Counter:

- physics motivation
- detector concept
- detector construction and testing
- detection efficiency analysis

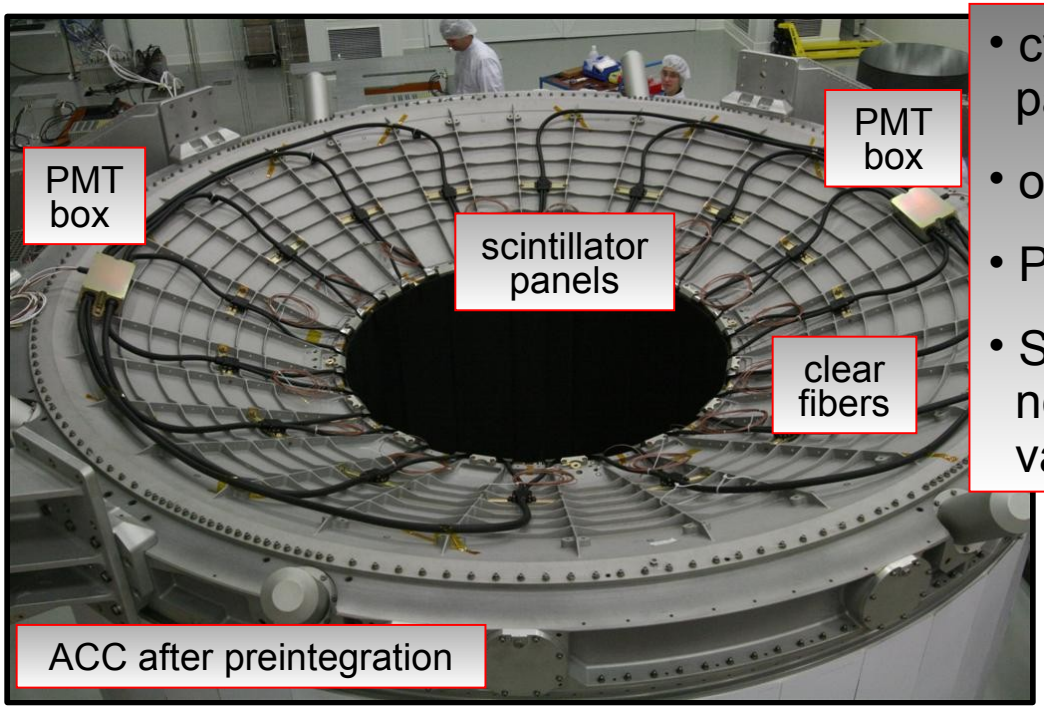
Important Events for the ACC



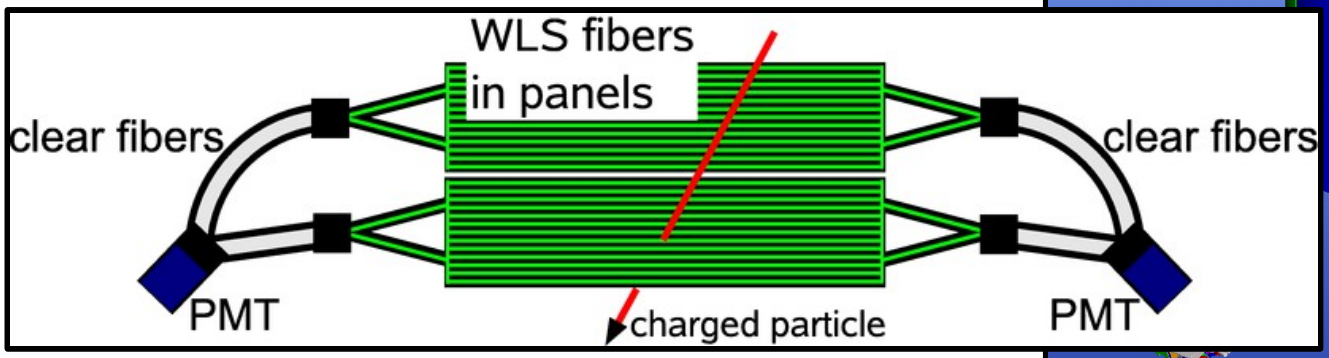


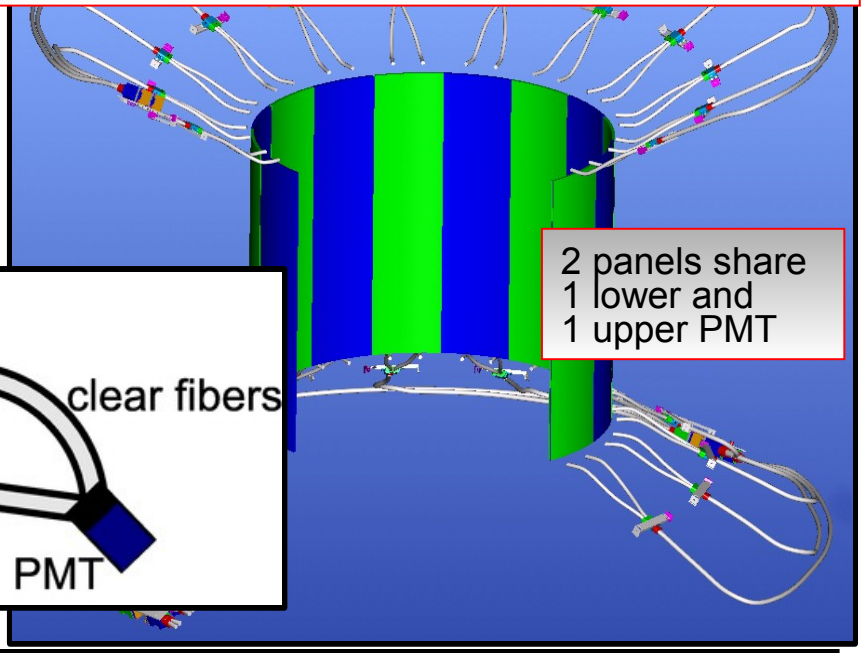
- small ACC inefficiency needed ($<10^{-4}$) for measurement of antimatter with very clean single tracks
- ACC can be included in the level 1 trigger decision as veto (reduce trigger rate: e.g. in the South Atlantic Anomaly)

ACC System

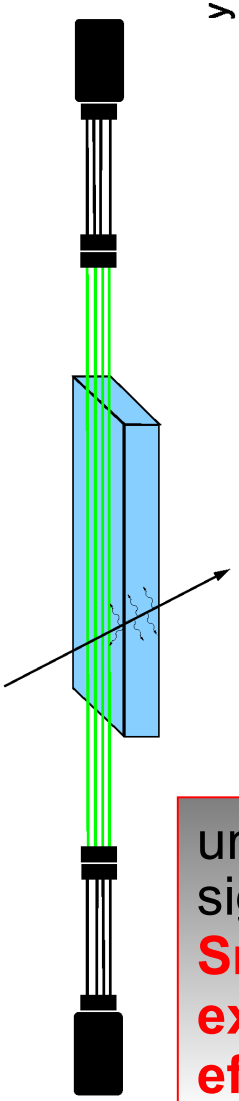


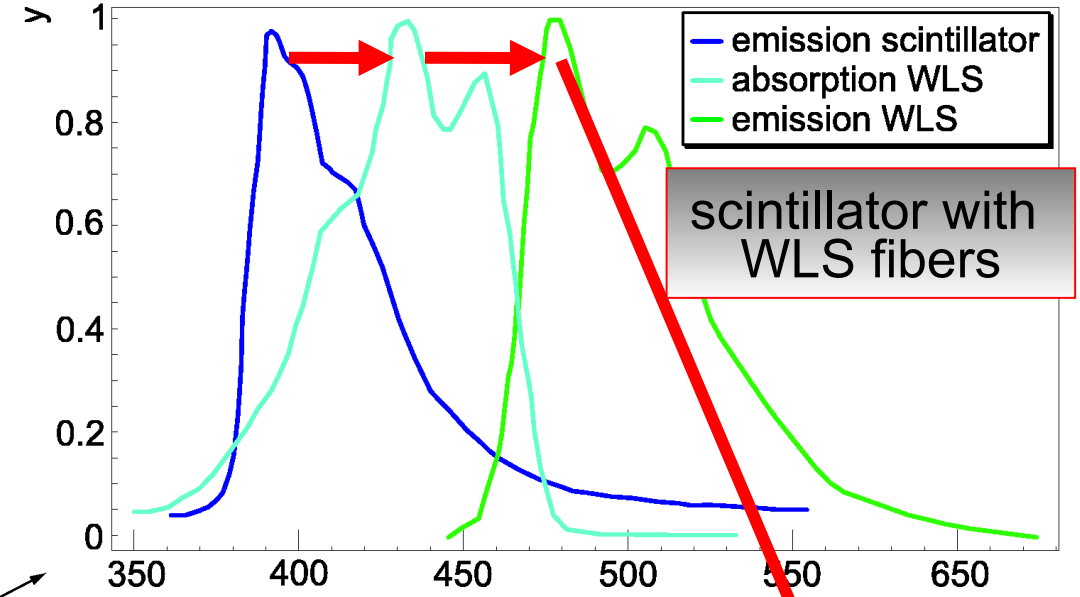
- cylinder made of 16 plastic scintillator panels surrounding the silicon tracker
- operation in magnetic stray field (~0.1T)
- PMT readout for fast response
- Space qualification of all parts is needed (Space Shuttle take-off, vacuum, temperature)



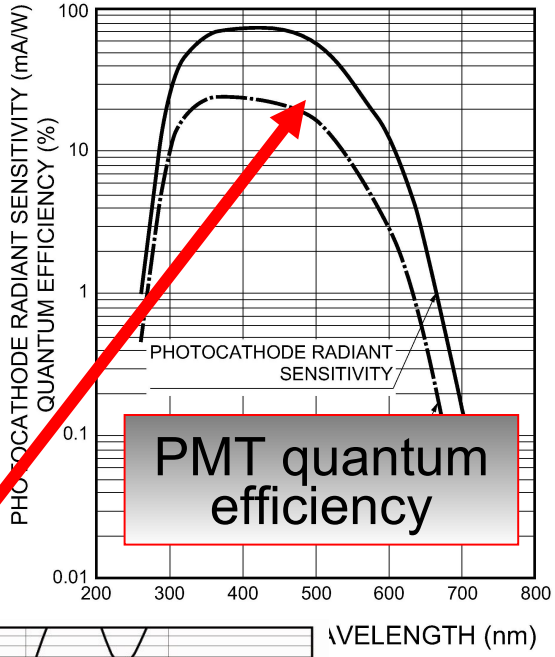


Light Signals



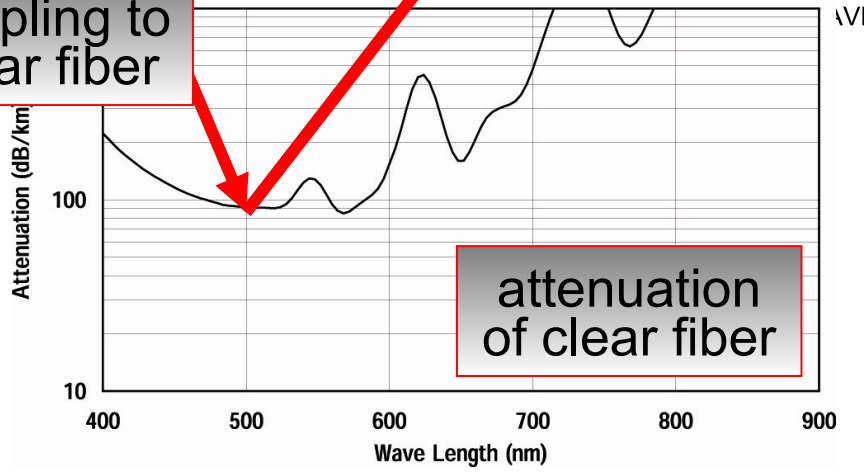


scintillator with WLS fibers



PMT quantum efficiency

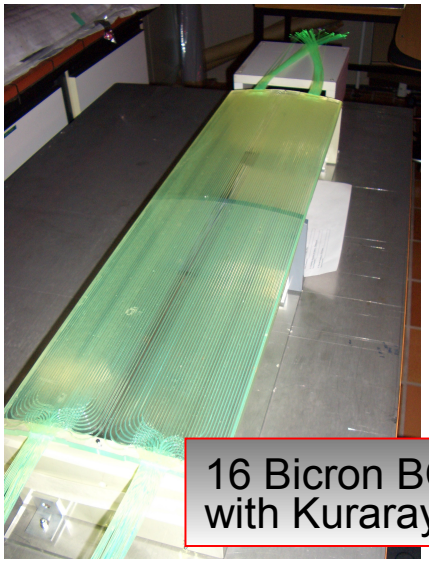
coupling to clear fiber

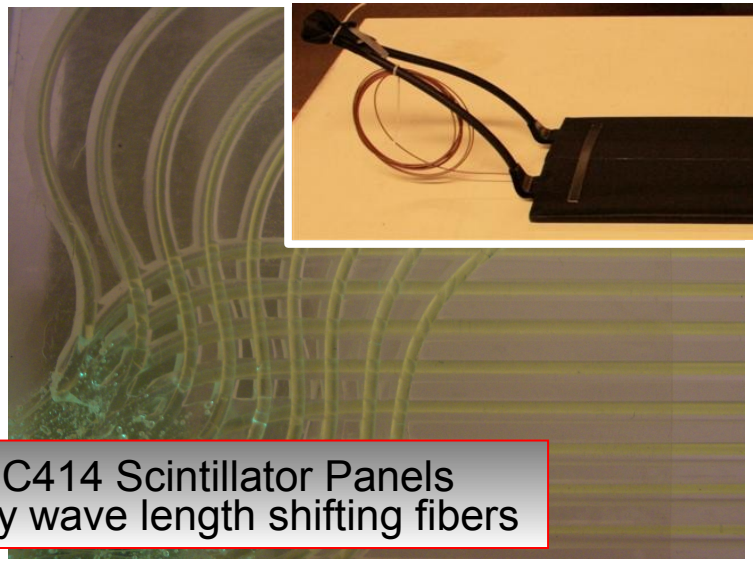


attenuation of clear fiber

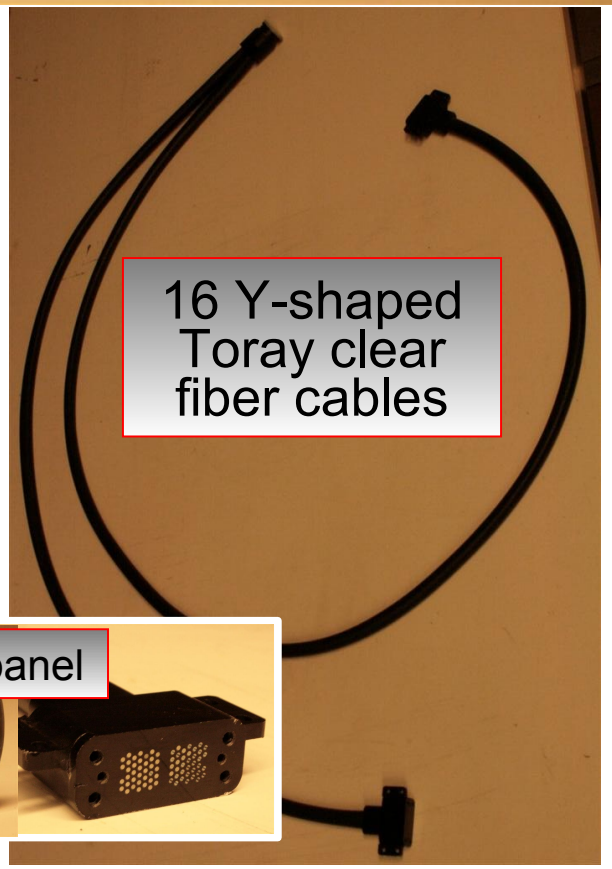
unavoidable complicated signal transport:
Small signals are expected but large efficiency is needed!

Panel and Fiber Production





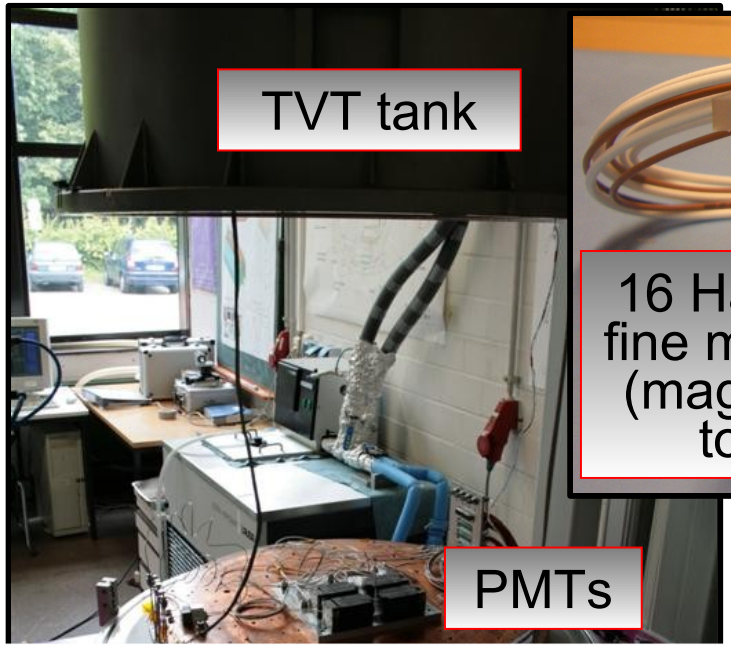
16 Bicron BC414 Scintillator Panels with Kuraray wave length shifting fibers

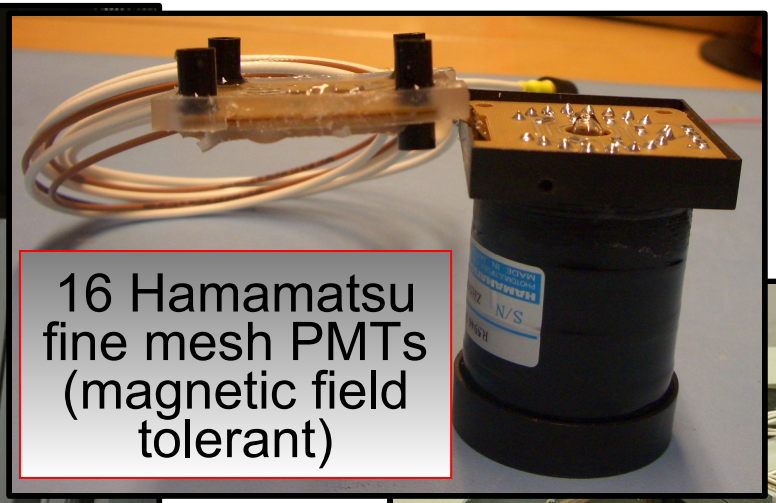


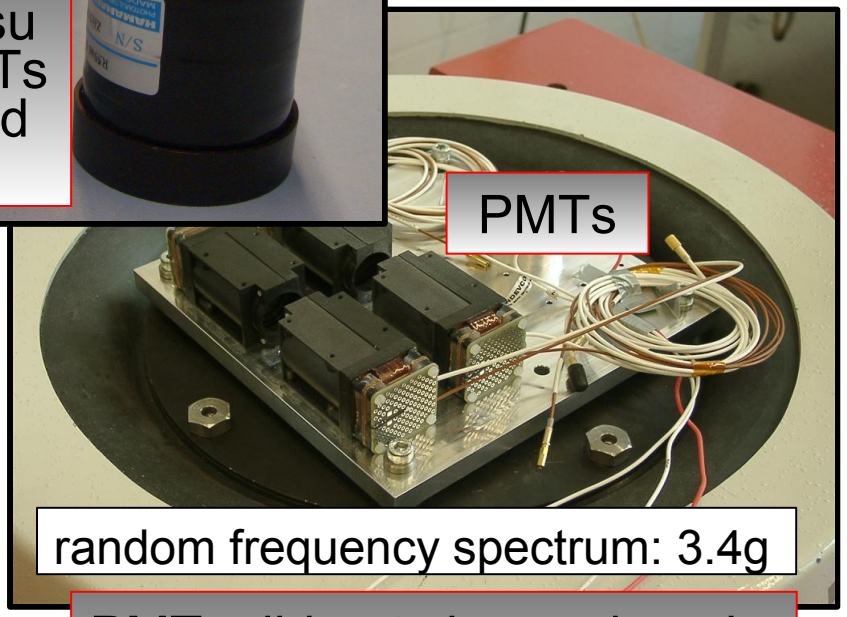
16 Y-shaped Toray clear fiber cables

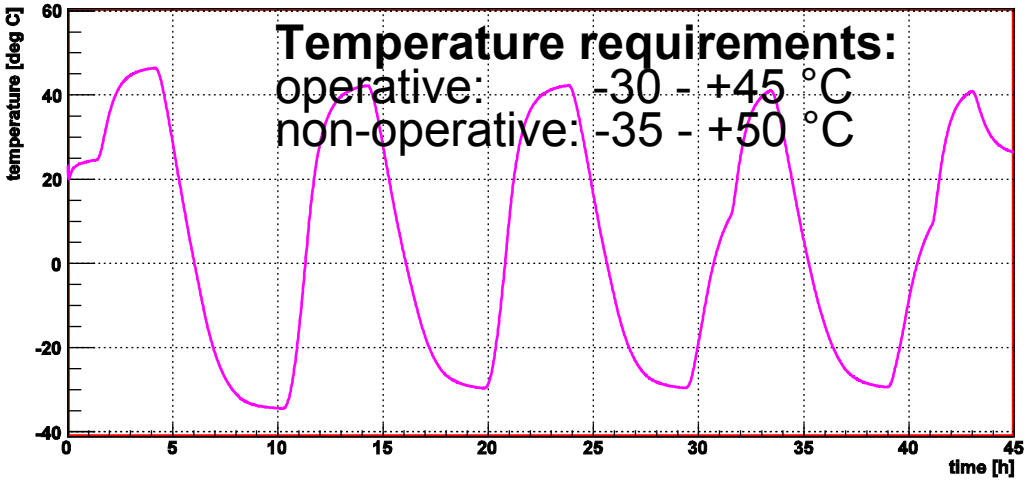
- panel space qualification was done for AMS-01
- acceptance angle matching of wavelength shifting fiber and clear fiber is important to increase light output
- clear fiber matches NASA space qualification requirements

Space Qualification - PMTs



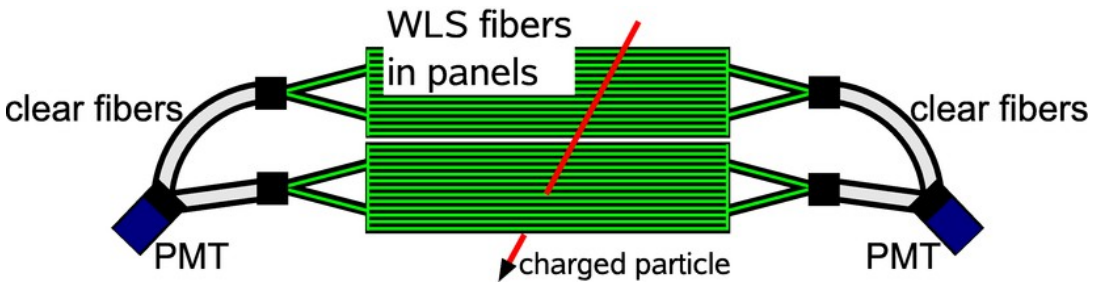




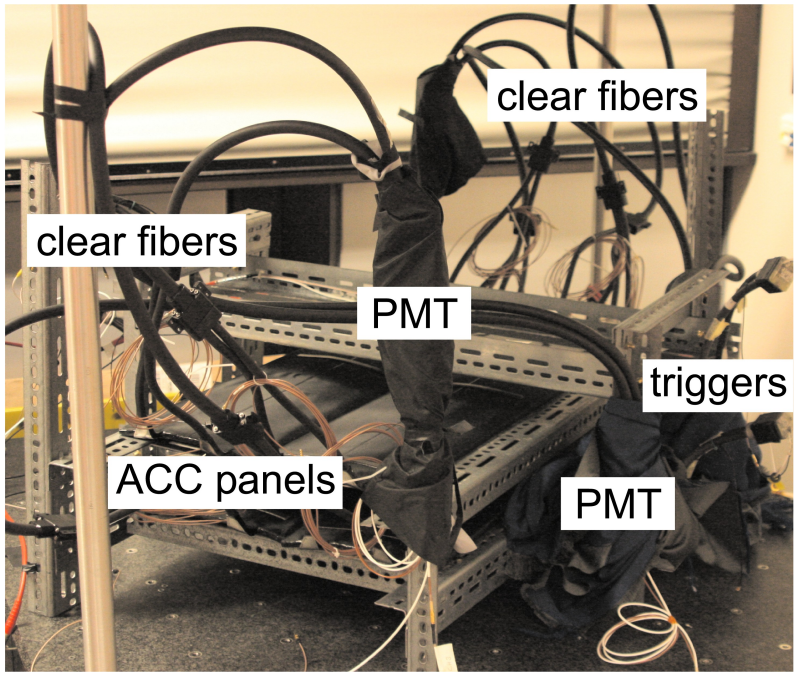


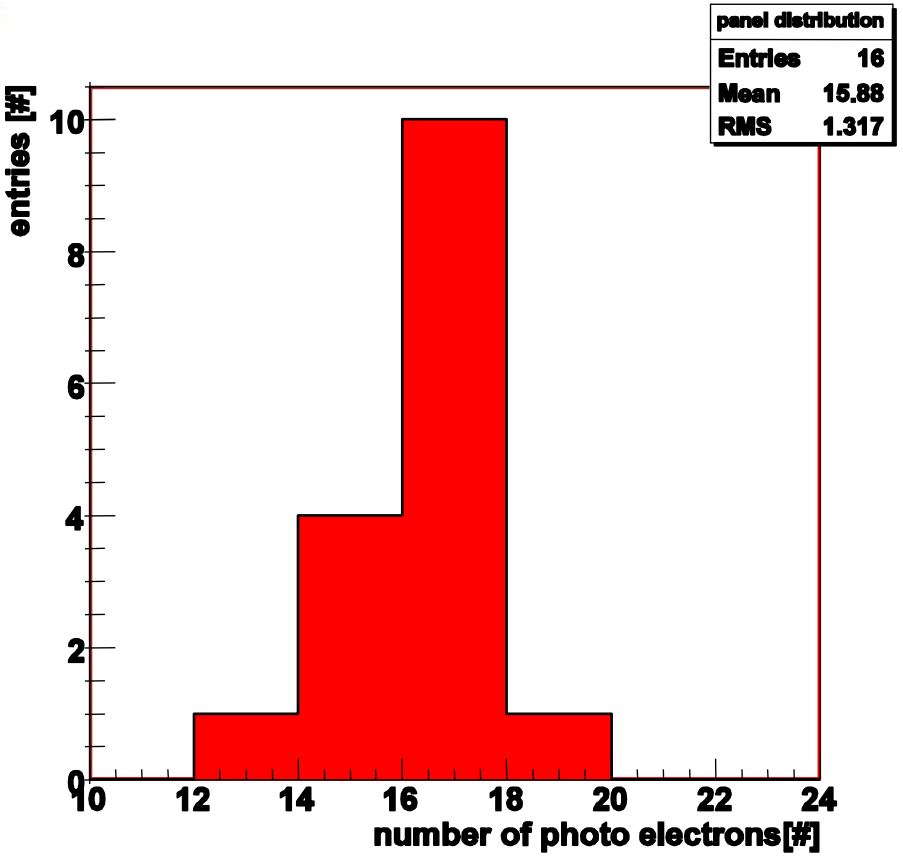
PMTs did not change in gain and photo-electron number within 5% after space qualification

Complete System Test



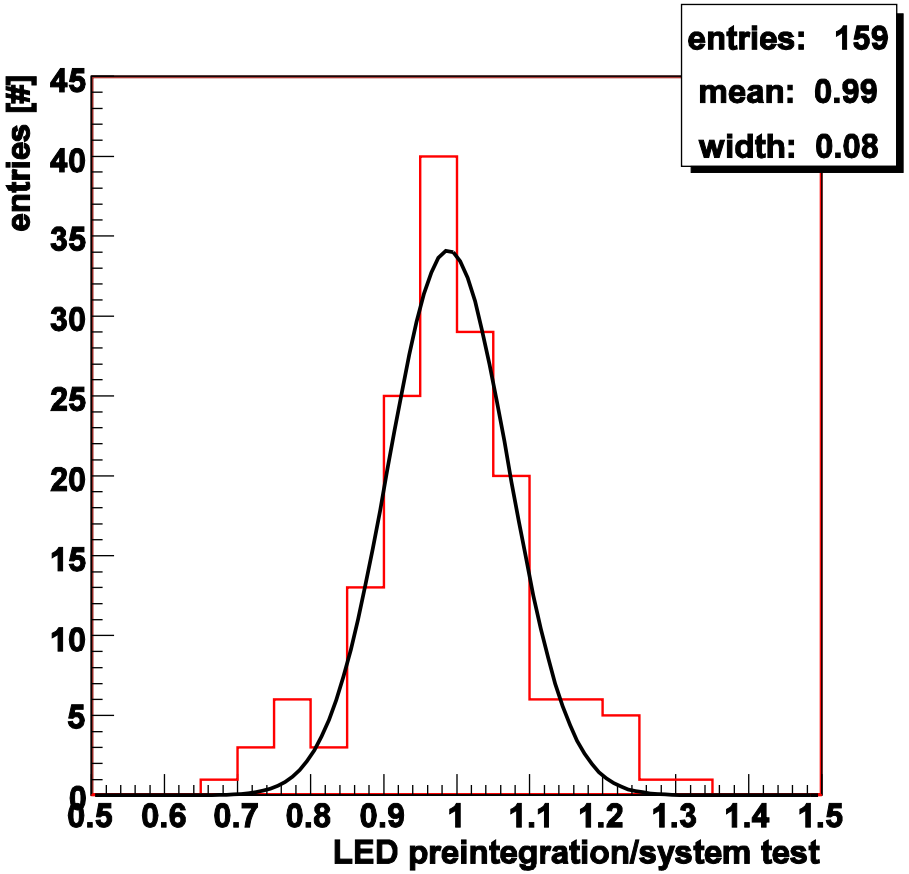
test of complete chain:
panel + clear fiber + PMT
show good results
(mean: 16 photo electrons)





Preintegration (all components, but magnet)

always under supervision of Prof. Ting (Nobel Prize '76)



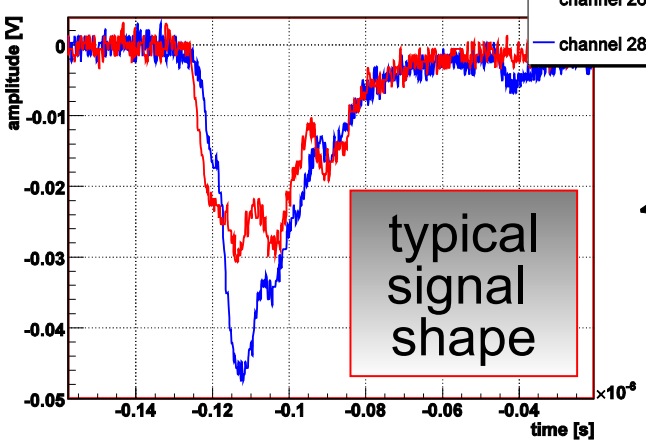
successful preintegration: 99 ± 8 %

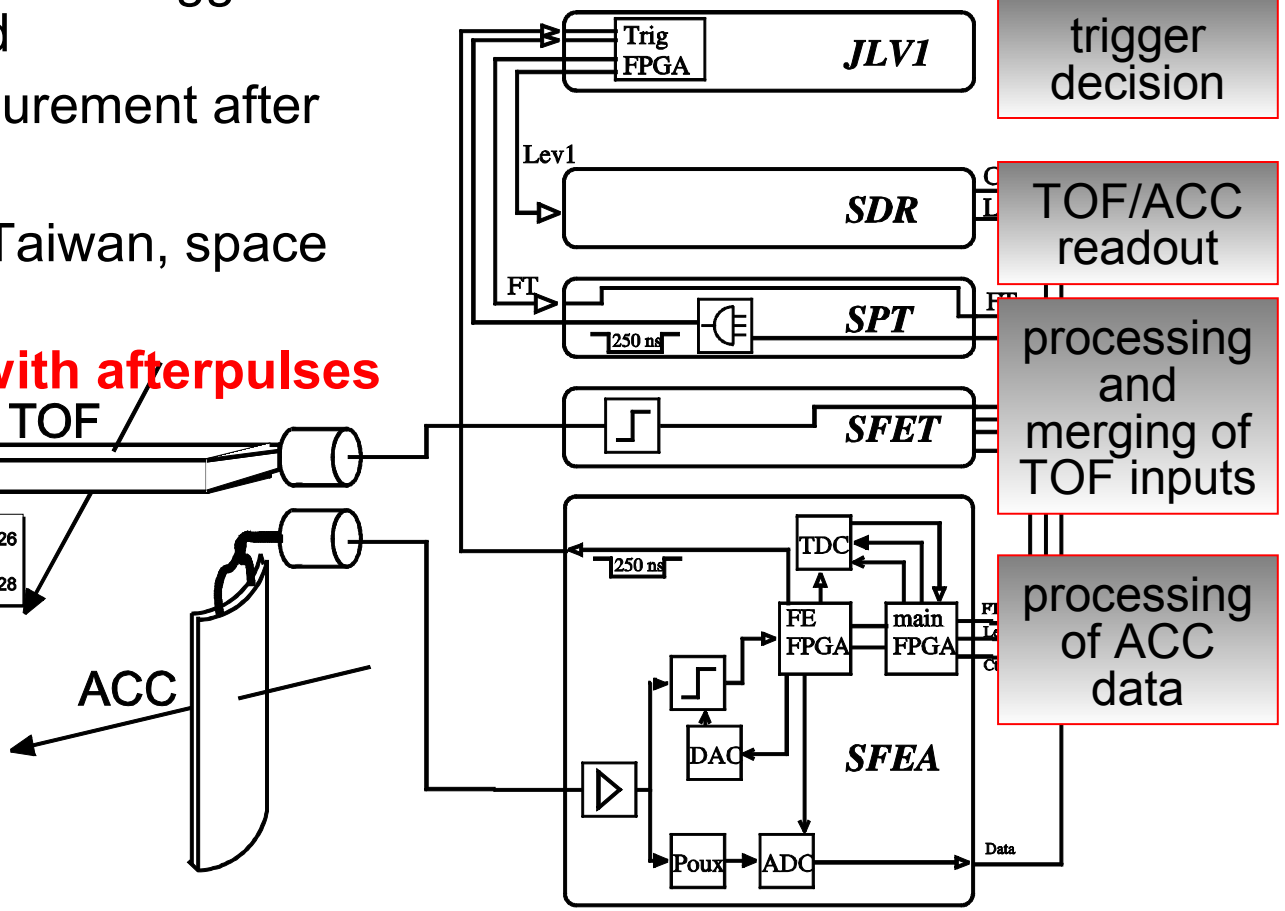
LED test comparison (after/before)

Flight Electronics

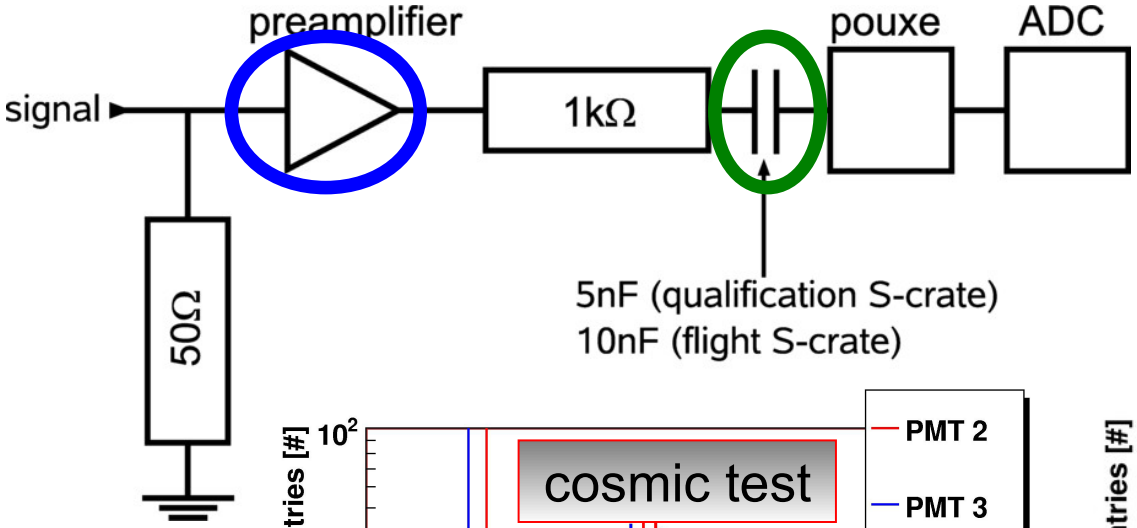
2 branches of signal processing:

- fast veto decision for level1 trigger with discriminator threshold
- charge and time measurement after trigger (ADC, TDC)
- production at CSIST, Taiwan, space qualification in Italy
- **small spiky signals with afterpulses**

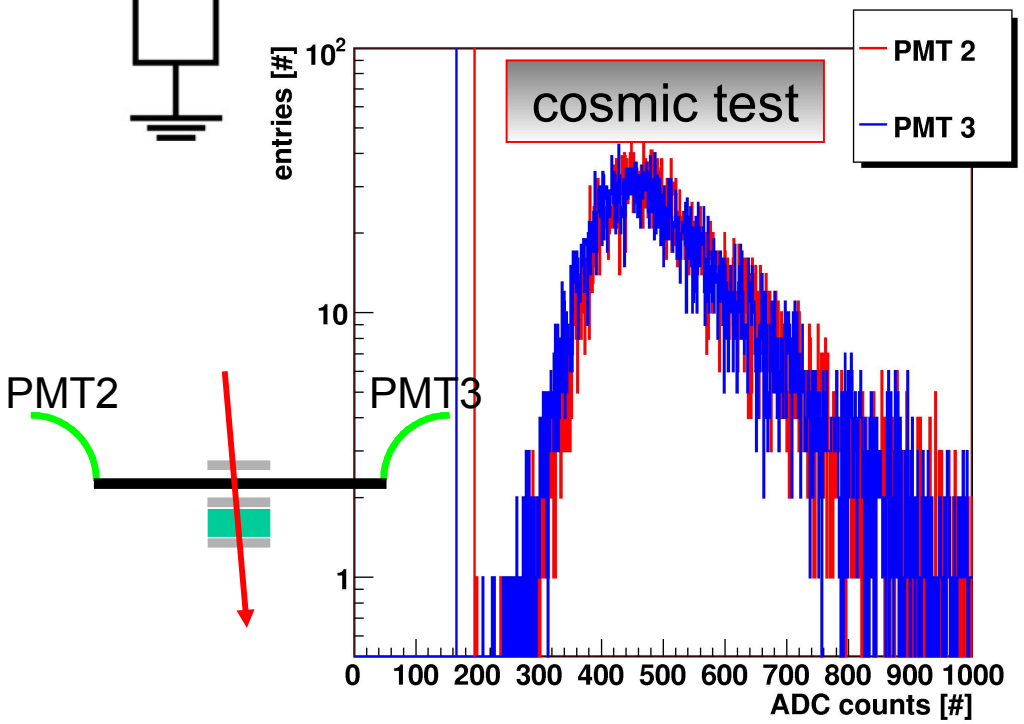


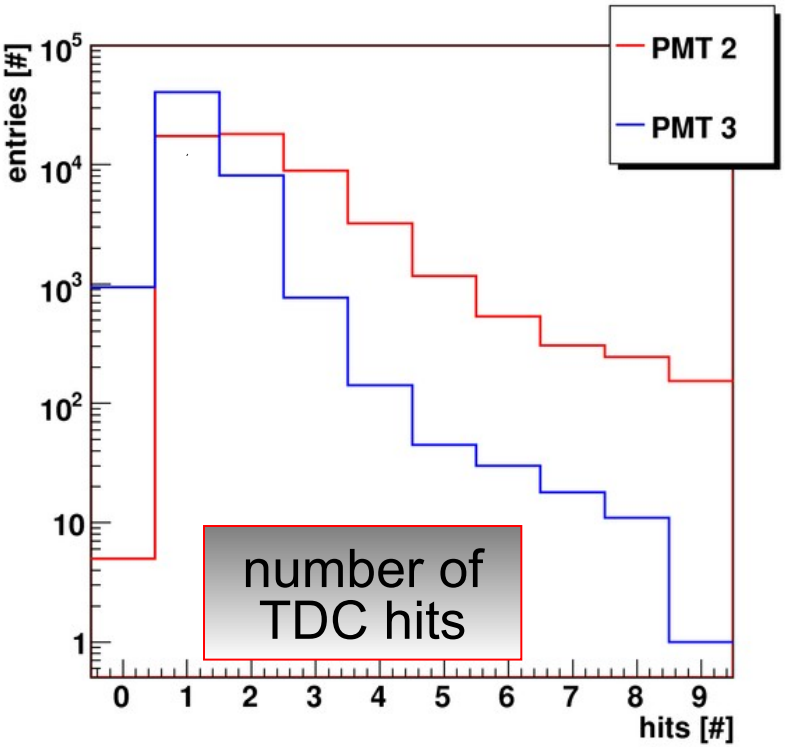


Flight Electronics: ADC & TDC

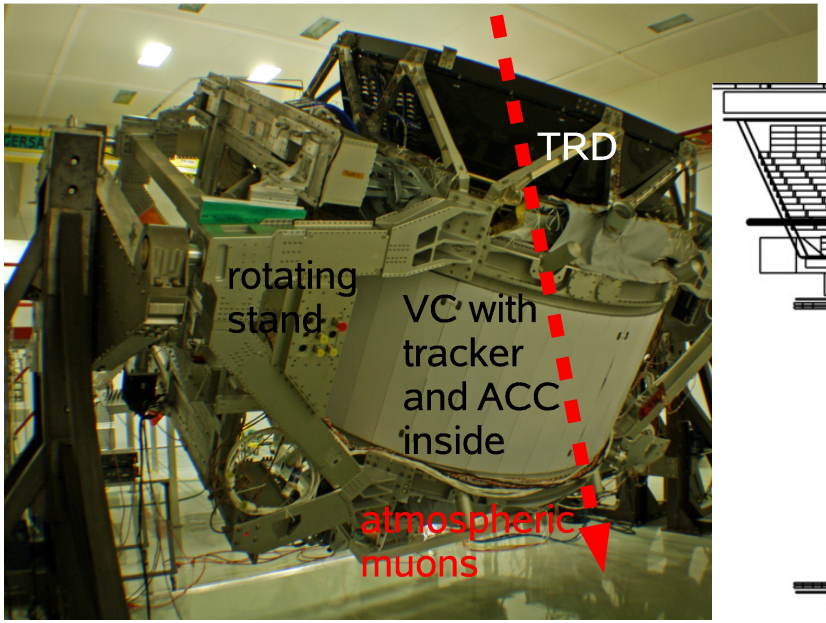


- **ADC** needed for charge digitalization
- **TDC** stores time mark for transitions above discriminator threshold

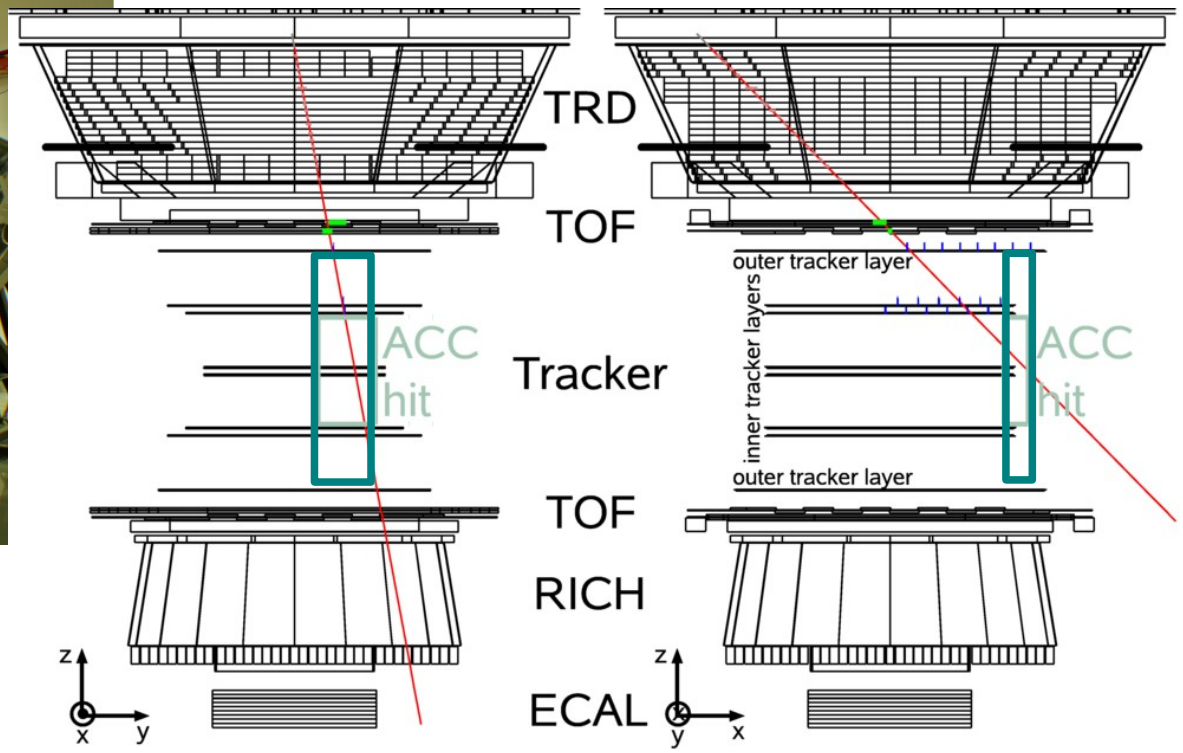




ACC Inefficiency Study with Cosmics



AMS-02 taking data after preintegration

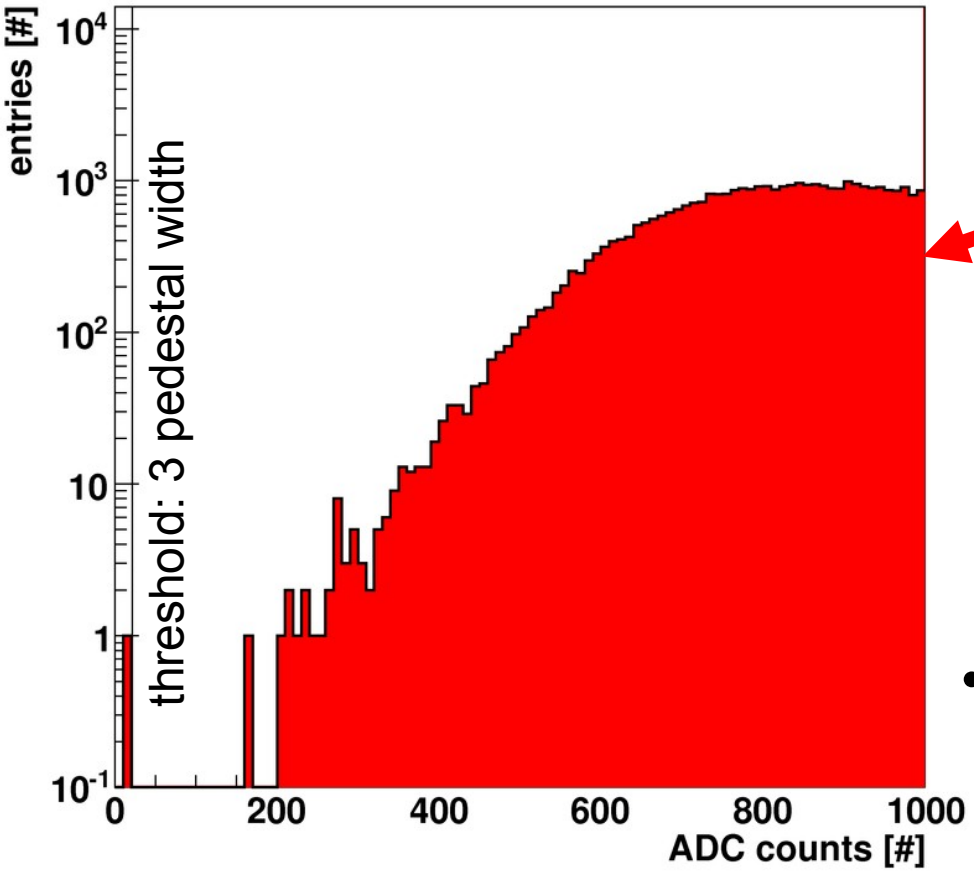


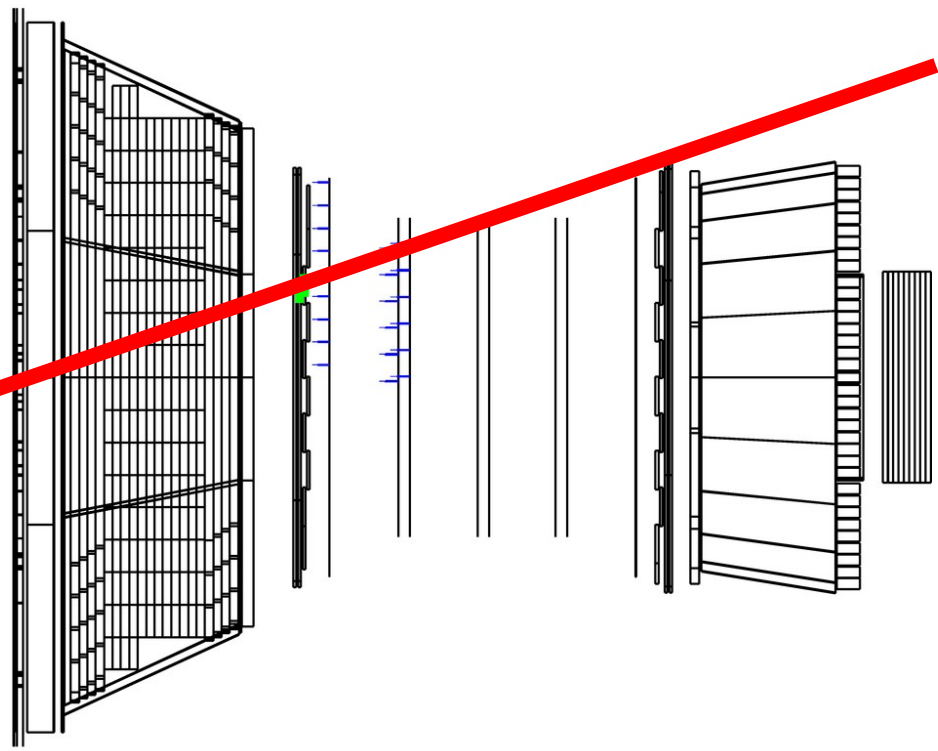
inefficiency study of ACC with TRD and tracker tracks:
Extrapolate clean single tracks and determine ACC inefficiency as function of position!

ACC Inefficiency

ACC inefficiency = $1.5^{+2.3}_{-1.1} \cdot 10^{-5}$

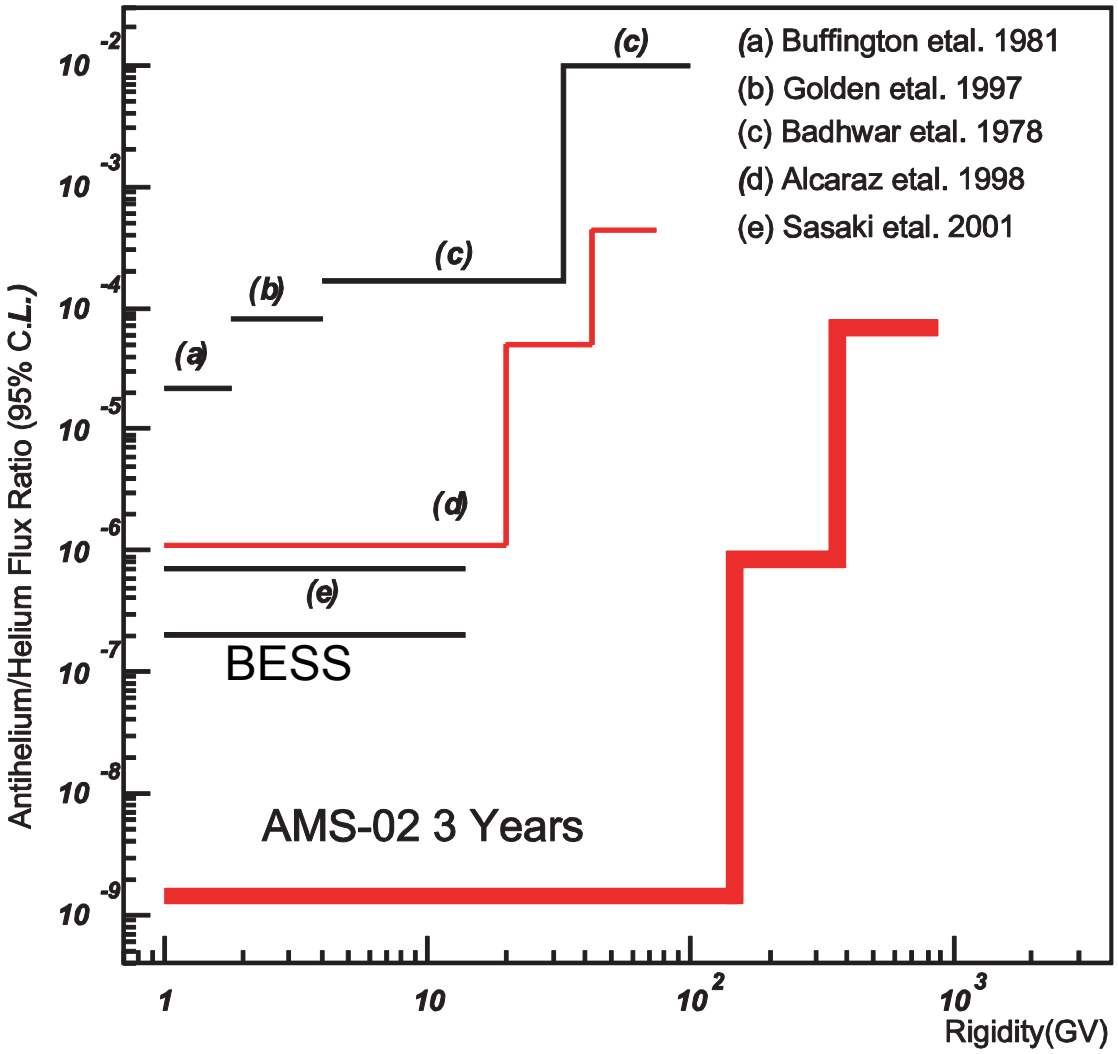
Fermi ACD: 89 tiles: 1-1.2cm, inefficiency: $3 \cdot 10^{-4}$





- only 1 missed event in special run conditions (AMS-02 rotated by -90°)

AMS-02 Prospects for Antihelium



antihelium sensitivity down to $\overline{He}/He=\sim 10^{-9}$

Conclusion & Outlook

- **exciting times in cosmic-ray physics in the GeV-TeV range**
  - positron fraction by PAMELA
  - electron flux by ATIC, Fermi, HESS
- **new experiments are needed to search for new phenomena**
  - **PEBS, balloon:**
    - residual atmosphere
    - extend e.g. the positron fraction with a low cost detector up to ~2TeV
  - **AMS-02, Space (ISS, 09/2010):**
    - construction and Space qualification of the ACC
    - final integration this fall, testbeam, TVT @ ESTEC
    - wide field of physics: antiparticles, antimatter, sky coverage