Helium Flux and Antihelium Candidates with AMS-02

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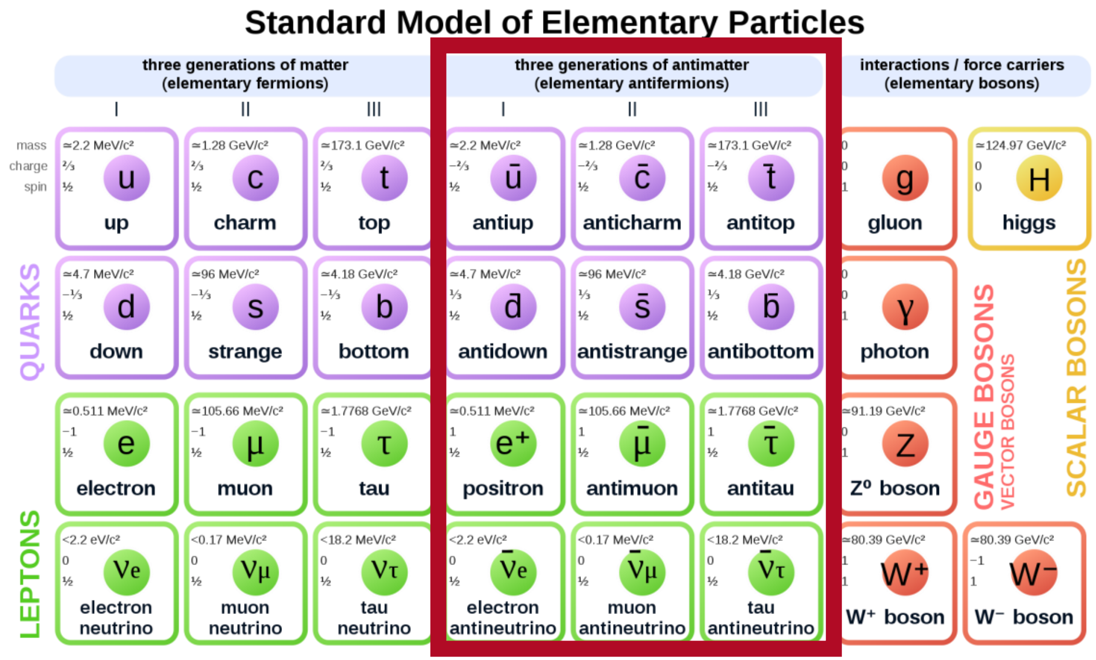
Where is all the Antimatter?

- Dirac equation -> negative energy solutions represent **antiparticle**

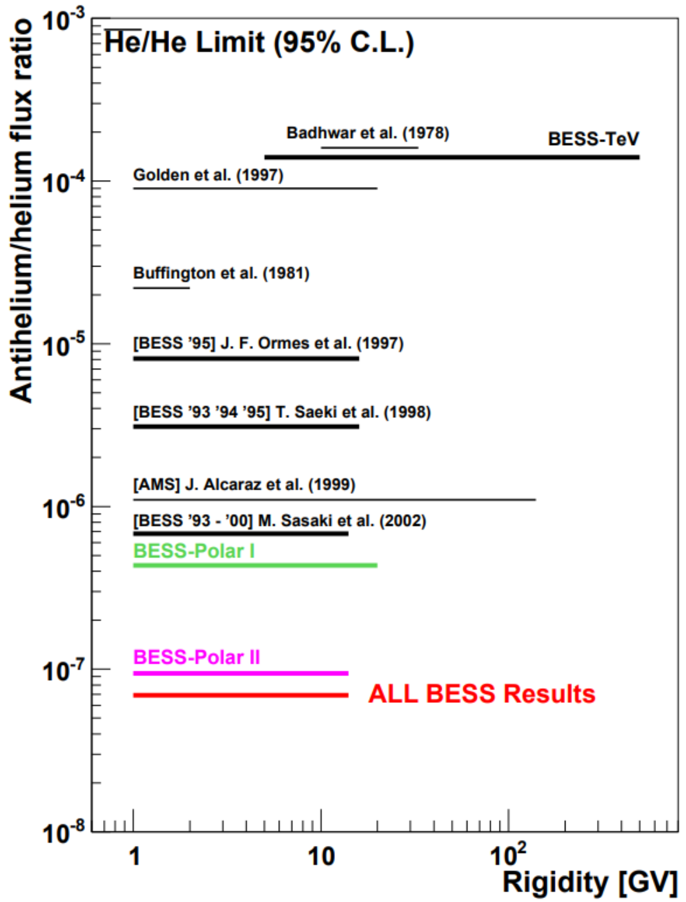
- So far no observation of primordial antimatter with very strong bounds by γ-ray and x-ray observations

- From CMB observations -> $\frac{n_\gamma}{n_b} \sim 10^{10}$



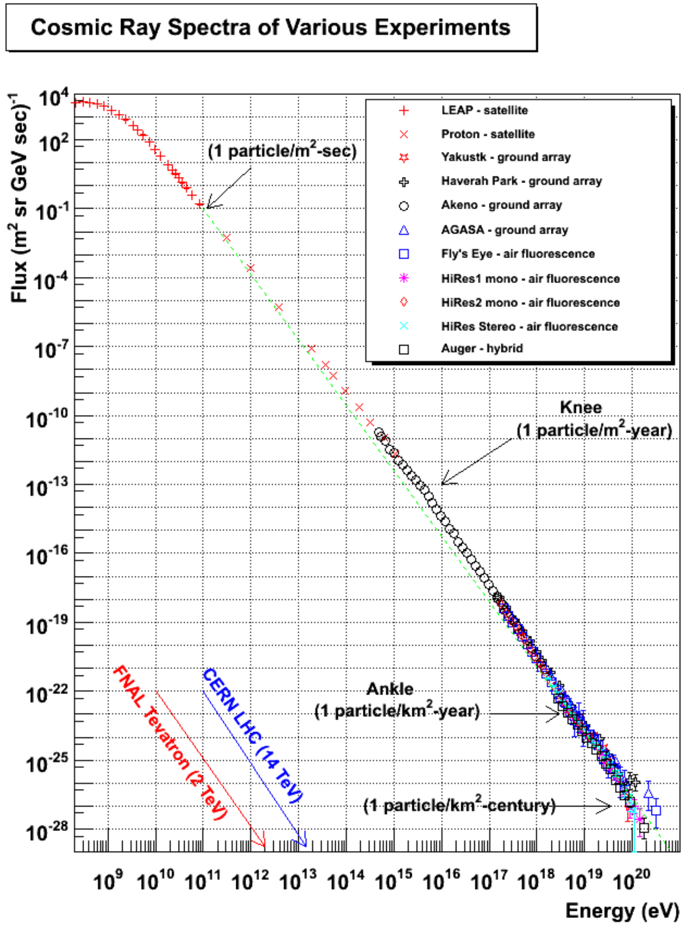
Antihelium search in Cosmic Rays

- Cosmic rays are galactic messengers
- Antihelium is hard to produce as a secondary -> good channel to search for primordial antimatter
- Previous experiments reach $\sim 10^{-7}$ flux ratio, AMS-02 will reach $\sim 10^{-9}$
- Since the start of AMS-02 the collaboration reported **several candidates for antihelium** (rate: $\sim 1/yr$)

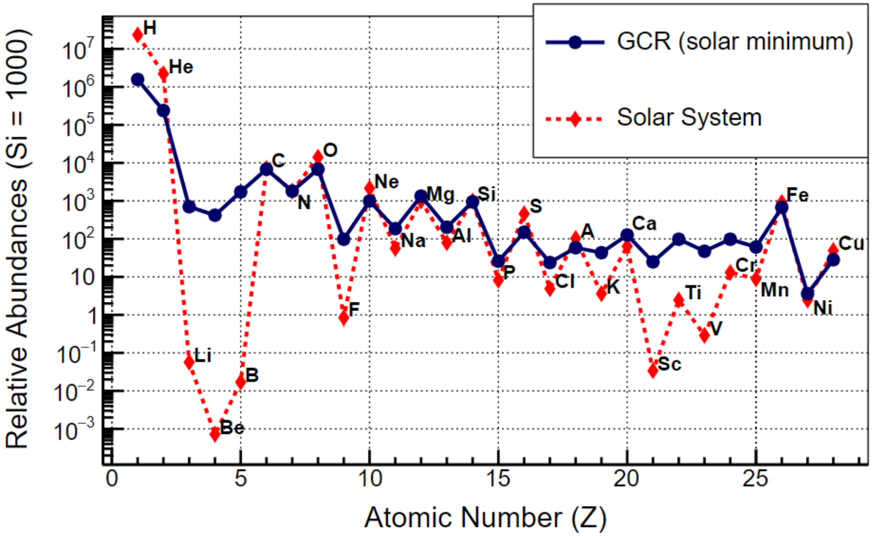


(K. Abe et al. 2012)

Cosmic Rays



- Particles originating from astrophysical sources
- Composition: $\sim$90% H, $\sim$8% He, $\sim$1% C,O,Fe… , $\sim 1\%\ e^-$
- Energies up to 10^{20}eV



Alpha Magnetic Spectrometer 02

- Multipurpose particle detector mounted on the ISS
- Dimensions: $\sim 3 \times 4 \times 3$ m, $\sim$7 t
- Can measure nuclei from hydrogen to iron with momenta ranging from **1 GV to a few TV**
- Since 2011: **>200 billion cosmic** ray events collected
- Sub-detector systems measure: **charge, rigidity (p/z), and velocity**

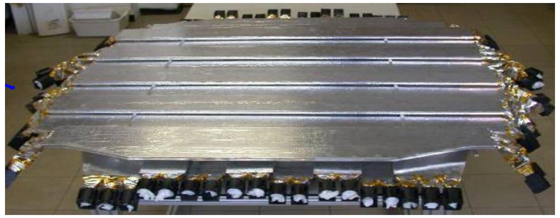
Alpha Magnetic Spectrometer 02

Transistion Radiation Detector

Discriminates p and e

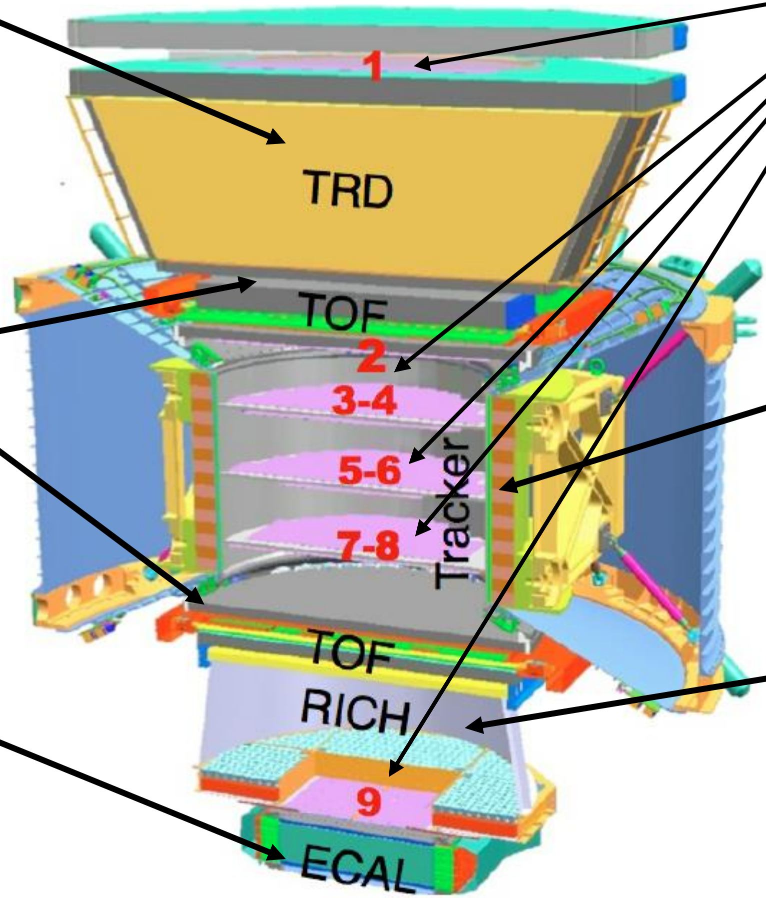
Time of Flight Counters

Z, β



Electromagnetic Calorimeter

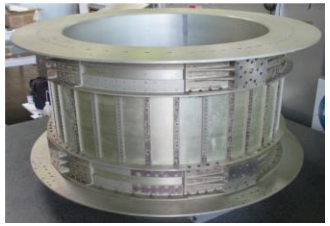
E

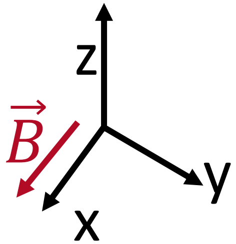


Silicon Tracker

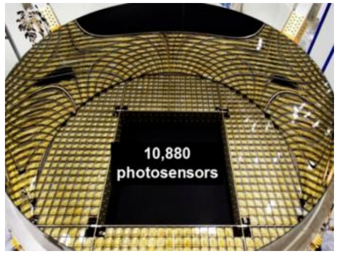
Z, R

Magnet



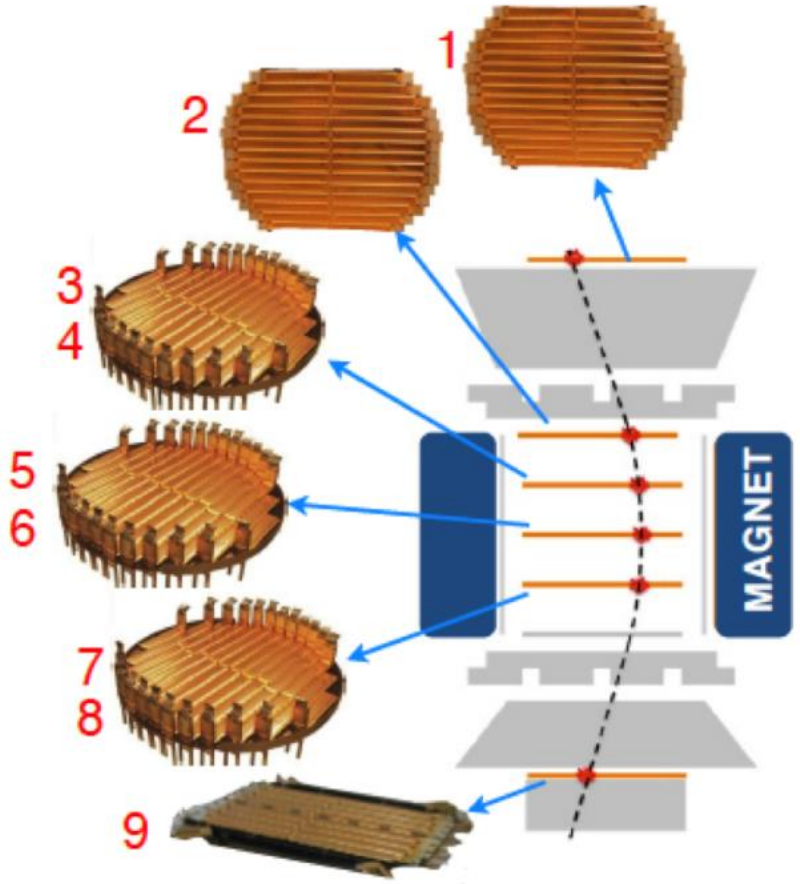


Ring Imaging Cherenkov Detector



Silicon Tracker

- Composed of double sided silicon sensors, each provides x- and y-measurements
- Resolution in bending direction $< 10\ \mu m$
- From multiple position measurements a track can be reconstructed
- Provides also the most precise charge measurement $\Delta Z \approx 0.07$ for $Z = 2$



Silicon Tracker

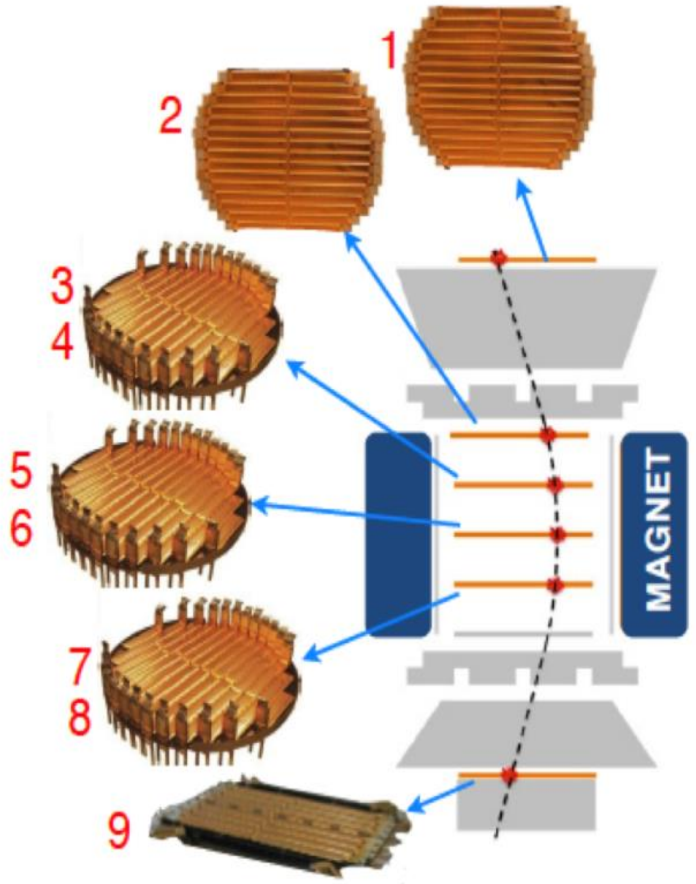
- Different geometries for reconstruction:
  Inner: Layer 2 – Layer 8 (always available)
  Inner + L1: Layer 1 – Layer 8 (chosen for this analysis)
  Inner + L9: Layer 2 – Layer 9
  FullSpan: Layer 1 – Layer 9

- From track and magnetic field -> Rigidity measurement

- Rigidity resolution depends on rigidity:
  - for **low energies**, energy loss worsens the resolution
  - for **high energies**, the positional resolution becomes the limiting factor

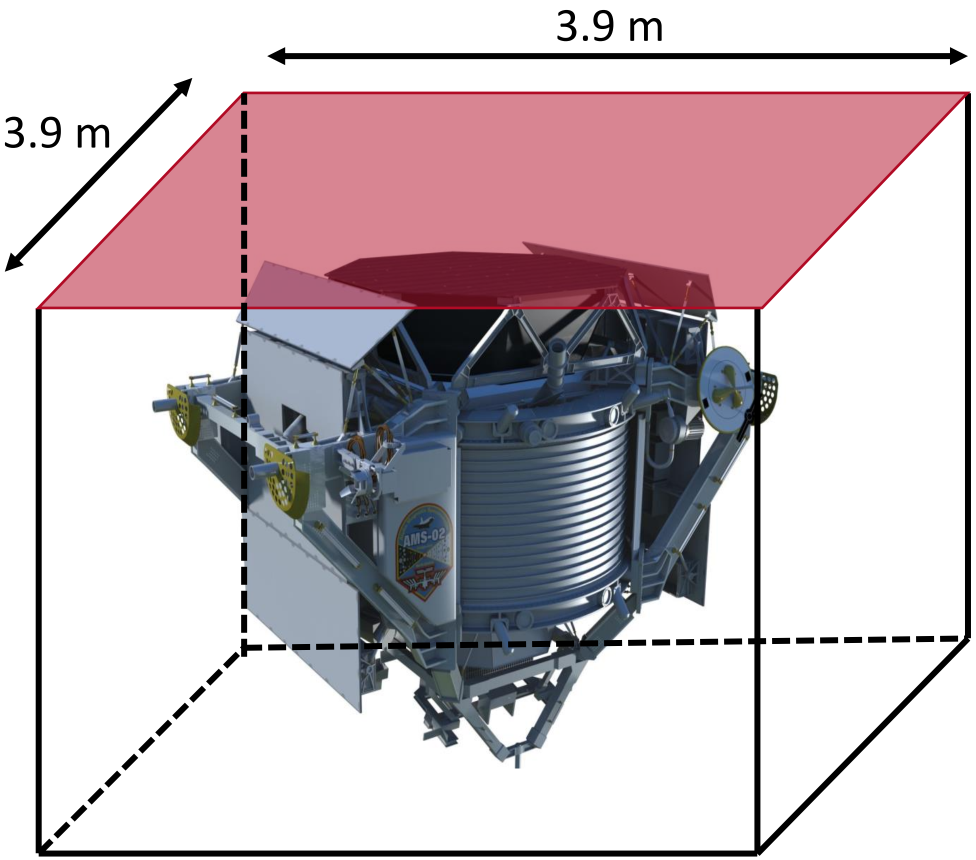
Maximum detectable rigidity (MDR), where $\frac{\Delta R}{R} = 100\%$

Inner	Inner + L1	Inner + L9	Full Span
400 GV	1100 GV	1600 GV	3200 GV



Dataset and Monte Carlo Simulations

- **Data:** first **10 years** of AMS-02
- **MC:** Rigidities 2GV – 500GV
  Generated events: 8.71×10^9, Triggers: 4.7×10^8
- events are produced in a 3.9 x 3.9 square plane above AMS with isotropic angles
- Designated software (based on GEANT4) includes AMS-02's geometry and simulates interactions
- Generated signals are reconstructed the same way as data

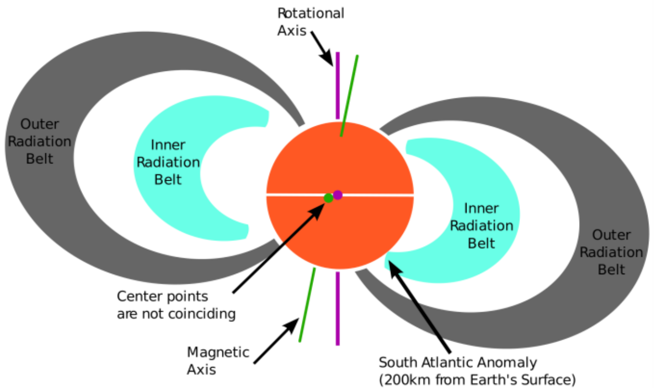


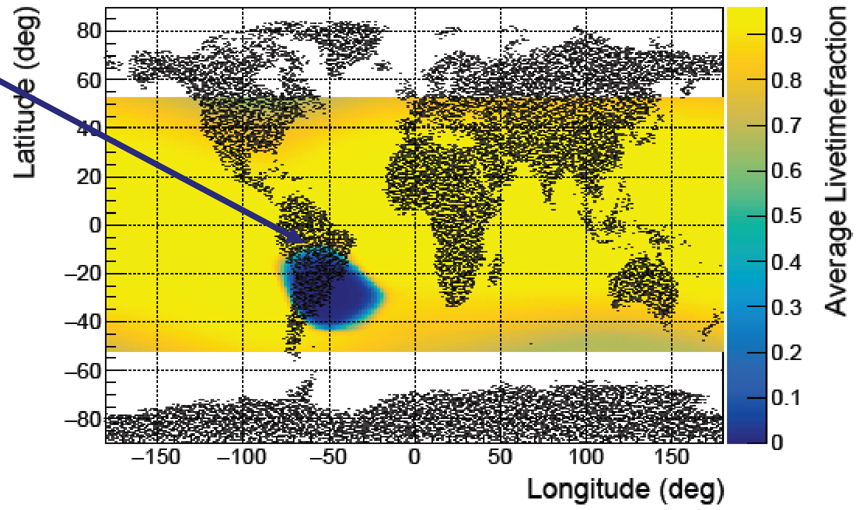
Helium - Selections

AMS in nominal data taking condition

– Good Runtag (4 runs per orbit, ~23 min/run)

– Not in **South Atlantic Anomaly**





Data Acquisition (DAQ) and Trigger Selections

– Good DAQ

– Livetimefraction > 0.5

– Physical Trigger

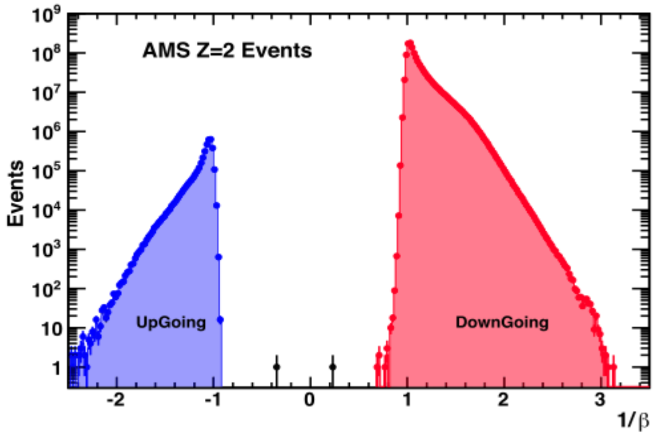
Helium - Selections

Beta Selections

– 4/4 ToF Layer Hits

– Number of Tracks = 1

– Downgoing particle $\beta > 0.6$



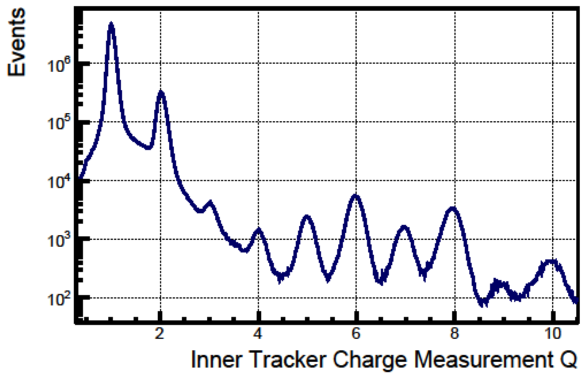
Charge Selections

– Inner Tracker: $1.7 < Q < 2.5$

– Tracker L1: $1.7 < Q < 2.5$

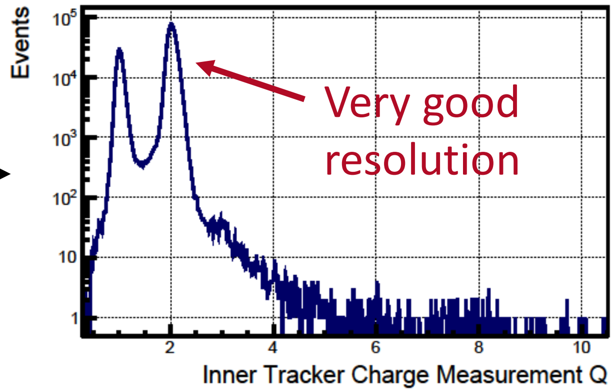
– ToF: $Q > 1.25$

Inner Tracker

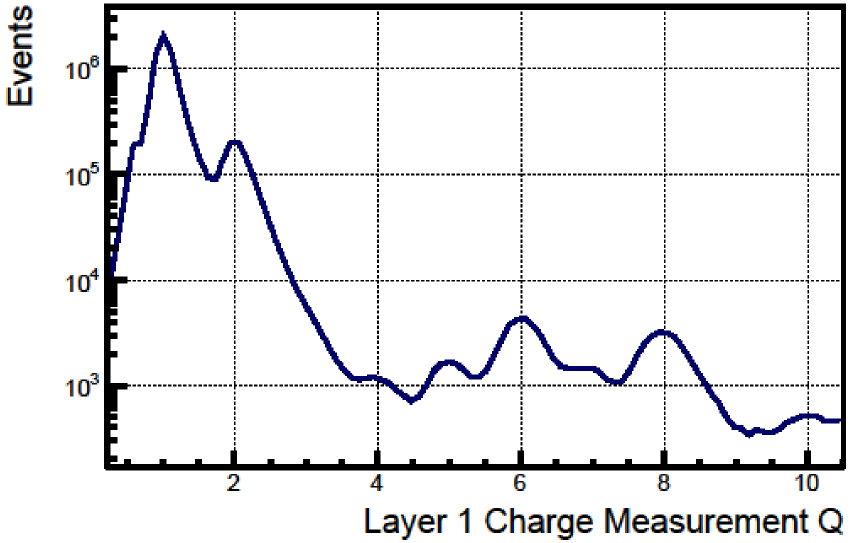


Sel. of Z=2 at Layer 1

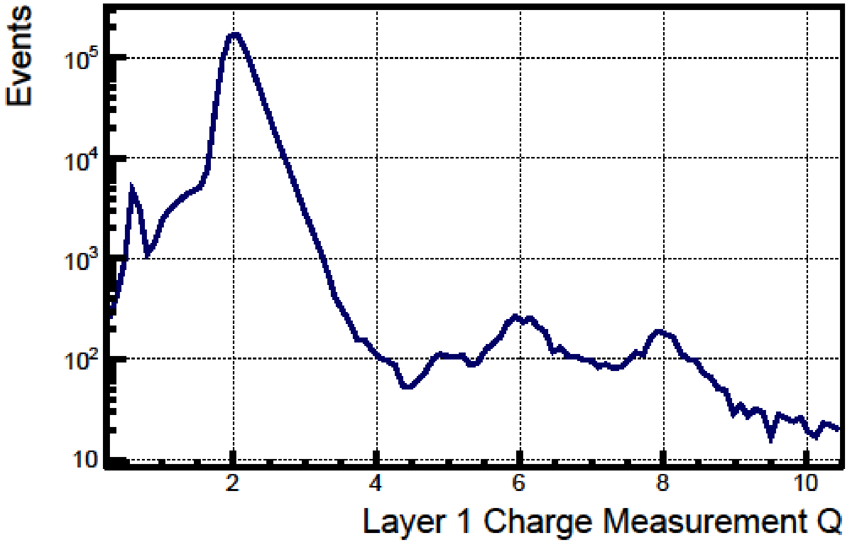
Inner Tracker after L1 selection



Helium - Selections



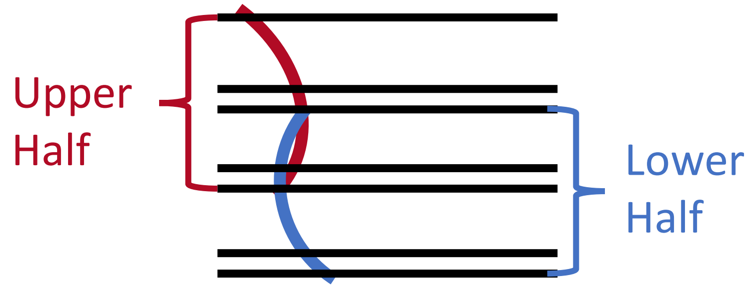
Z=2 selection on Inner Tracker



Helium - Selections

Rigidity Selections

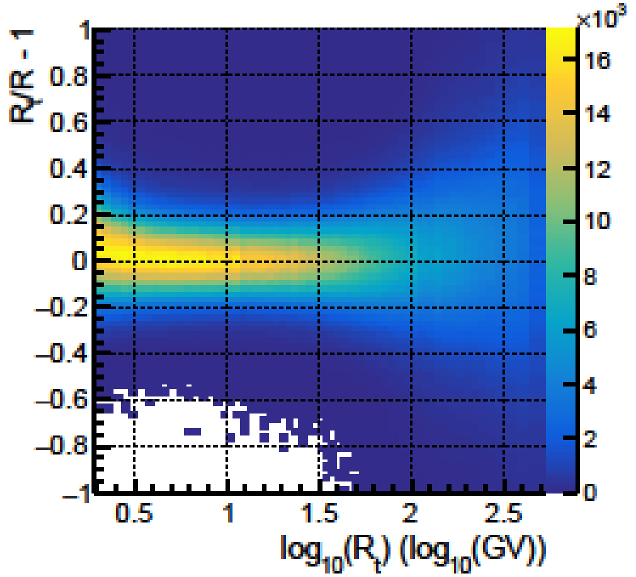
- Number of Inner Tracker Y-Hits > 5
- Track Fit: χ^2/d.o.f. < 10
- $R_{UpperHalf} \times R_{LowerHalf} > 0$

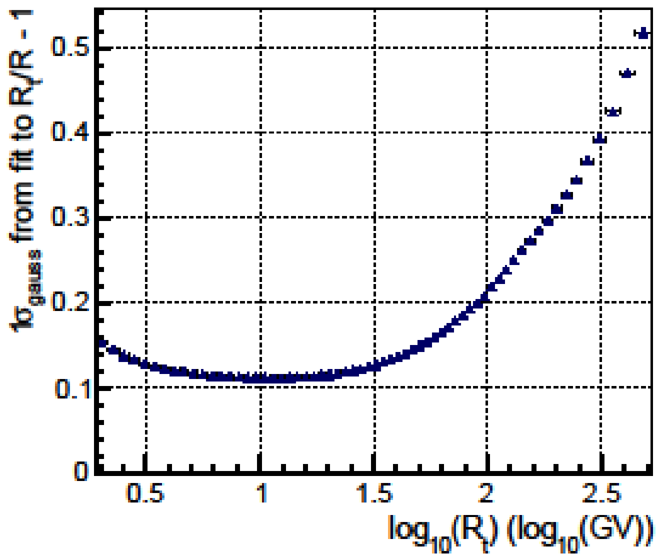


Rigidity Resolution

Is obtained from MC:

$$\frac{\frac{1}{R}-\frac{1}{R_t}}{\frac{1}{R_t}} = \frac{R_t}{R} - 1$$





Helium – Flux Measurement

Flux for rigidity bin i:

$$\phi_i = \frac{N_i}{A_i^{\mathrm{eff}} T_i \Delta R_i}$$

Number of observed He events

Effective acceptance: Combines detector efficiency and geometric acceptance

Exposure Time

Bin width of bin i

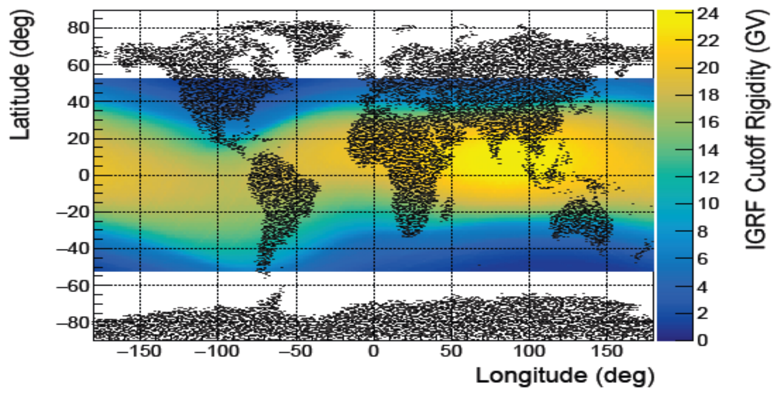
Exposure Time

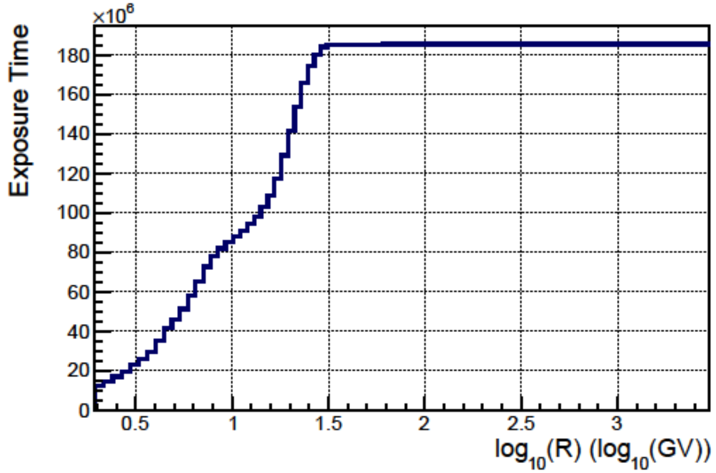
$$\phi_i = \frac{N_i}{A_i^{\mathrm{eff}} \boxed{T_i} \Delta R_i}$$

- Particles can be trapped in Earth' s magnetic field
- It is possible to define a minimum rigidity, where a particle is assumed to be free, i. e. of cosmic origin, using the *Størmer formula:*

$$R_S = \frac{M \cos^4 \lambda}{r^2 \left[1 + \left(1 \mp \cos^3 \lambda \cos \phi \sin \xi\right)^{1/2}\right]^2}$$

- It depends on the direction of the incoming particle and the position in the magnetic dipole field
- Choosing the maximum rigidity obtained in a cone with an opening angle of 35° one gets the cutoff value
- A safety factor of 1.1 is multiplied

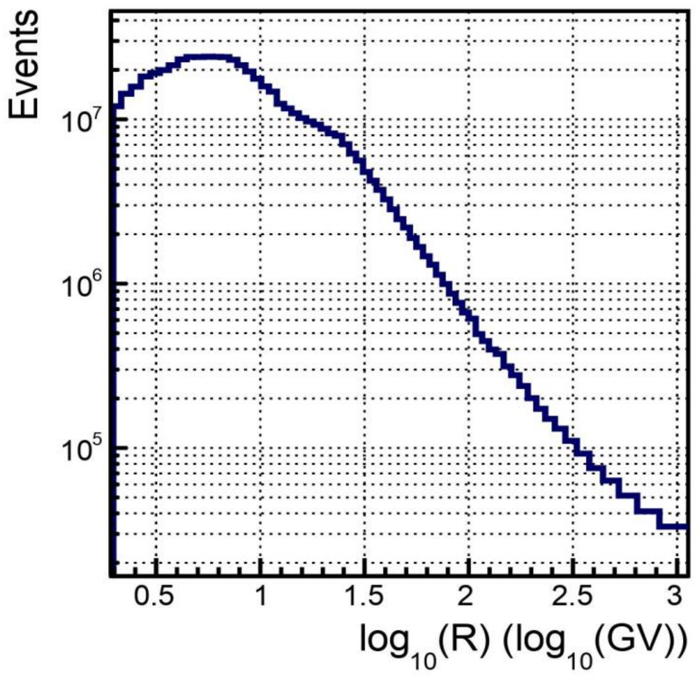




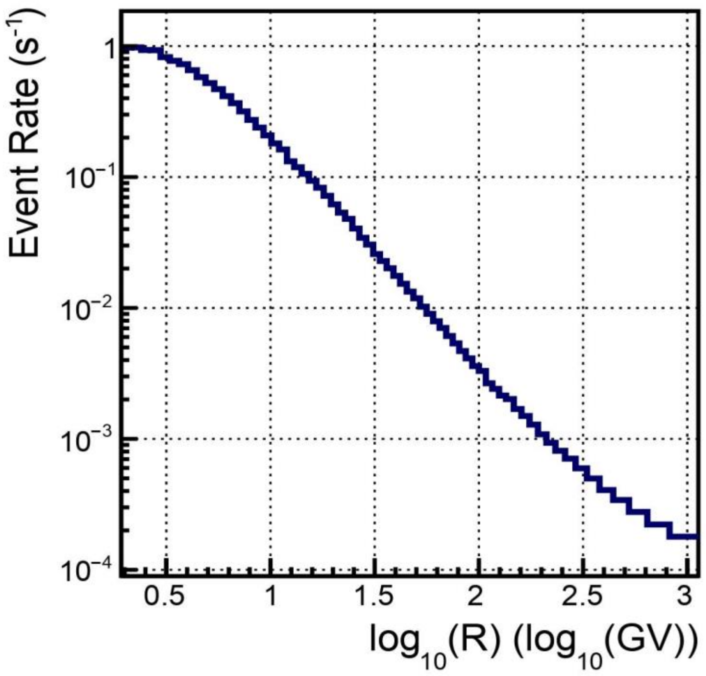
Event Rate

$$\phi_i = \frac{N_i}{A_i^{\text{eff}} T_i \Delta R_i}$$

Number of observed He events



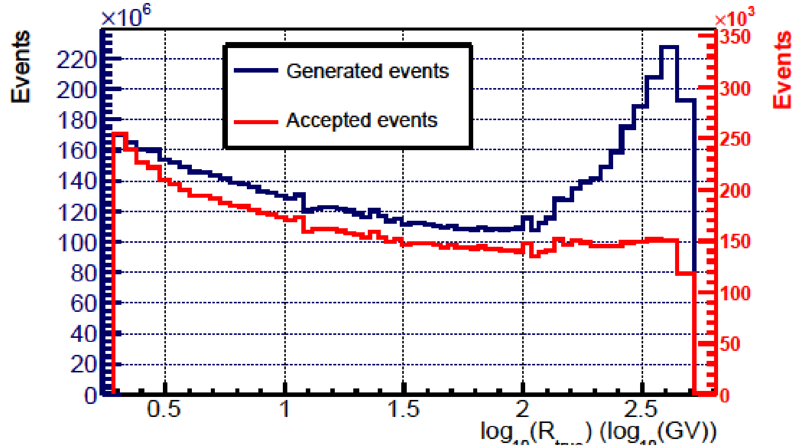
Event rate: $\rho_i = \frac{N_i}{T_i}$



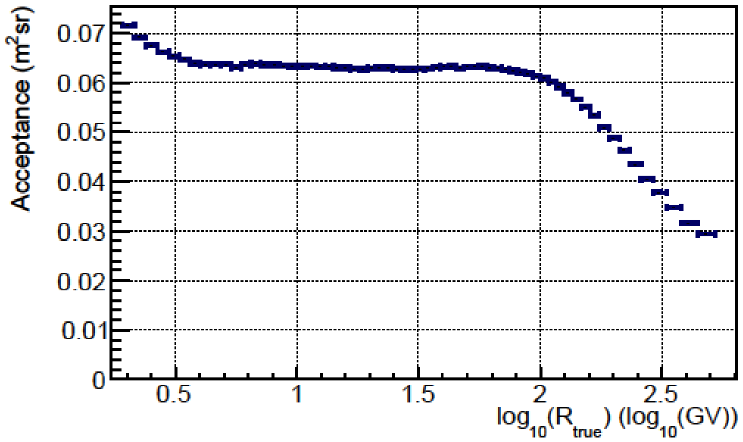
Acceptance and Efficiency (MC)

$$\phi_i = \frac{N_i}{A_i^{\mathrm{eff}} T_i \Delta R_i}$$

– Effective acceptance is calculated using MC
– Same selections applied to MC and data



$$A^{\mathrm{eff}} = 3.9^2\pi \times \frac{N_{\mathrm{acc}}}{N_{\mathrm{gen}}}$$



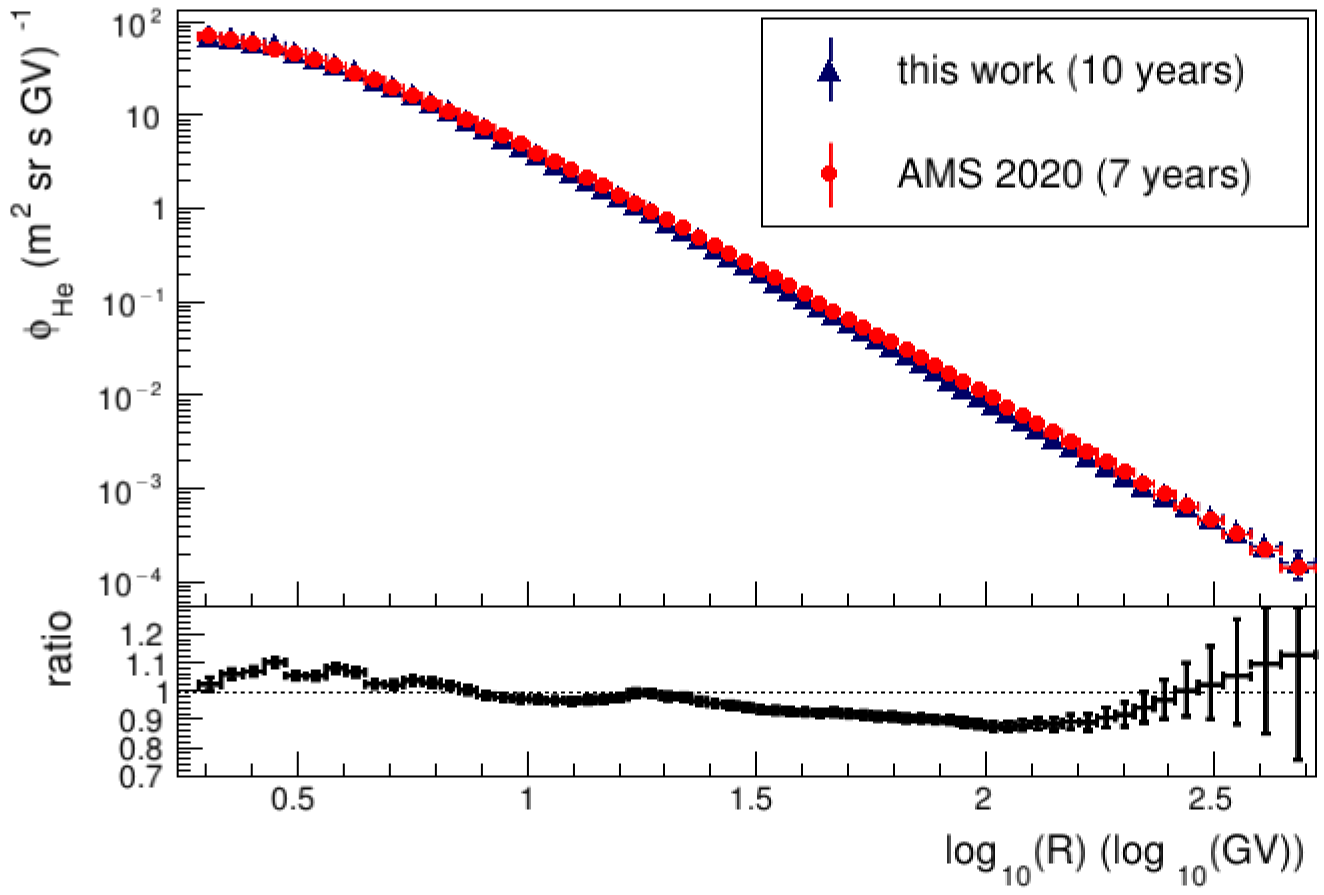
– Drop in acceptance is caused by interactions that get removed on the trigger level

Helium – Flux Measurement

$$\phi_i = \frac{\rho_i}{A_i^{\text{eff}} \Delta R_i}$$

- Differences due to unfolding, data-MC corrections and different time periods (solar cycles)
- Without these expected differences in good agreement

-> Indeed a clean He sample was selected and acceptance and efficiencies are well understood

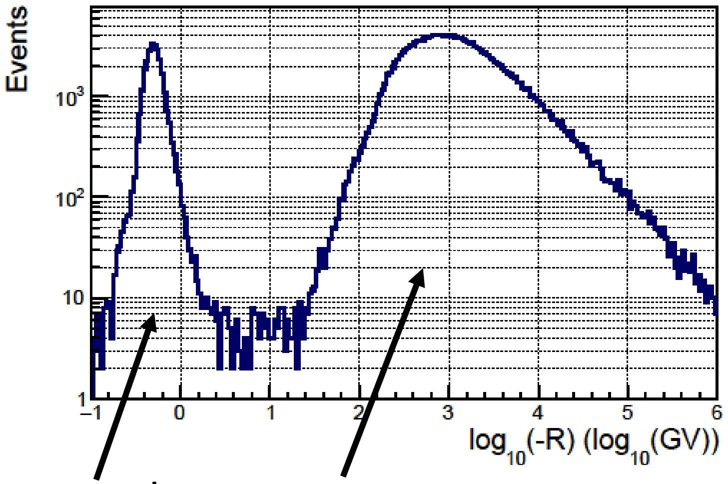


Some He events have negative R!

Antihelium Candidates - Background

- Only way to discriminate He from $\overline{\mathrm{He}}$ is rigidity measurement
- After selections: $\mathbf{6 \times 10^8}$**events with pos. rigidity** and $\mathbf{\sim 80,000}$ **events with neg. rigidity**
- Negative rigidity events are dominated by background from He

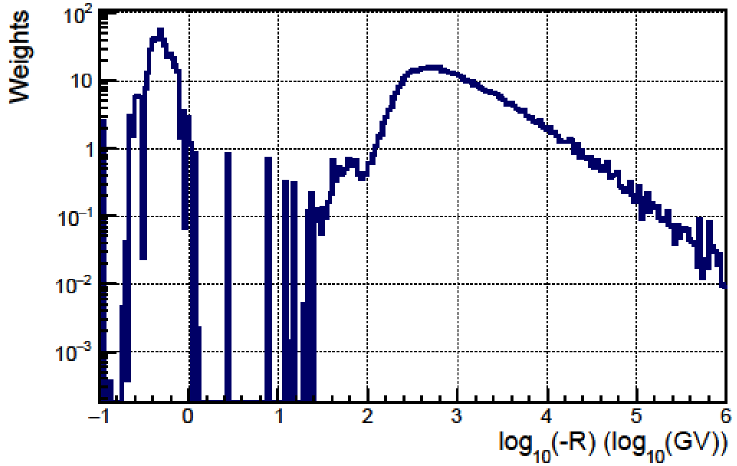
Data:



Large angle Scattering

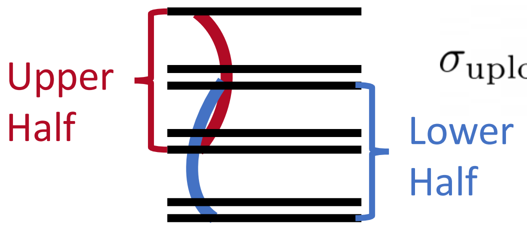
Spillover due to limited resolution

MC:



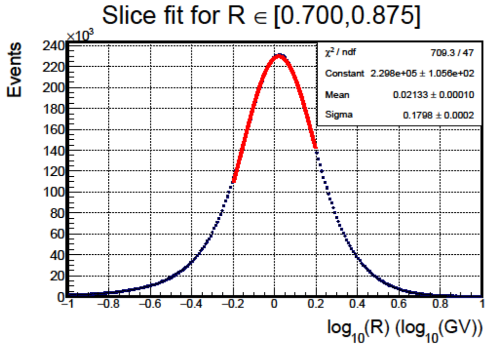
Additional Track Quality Selections

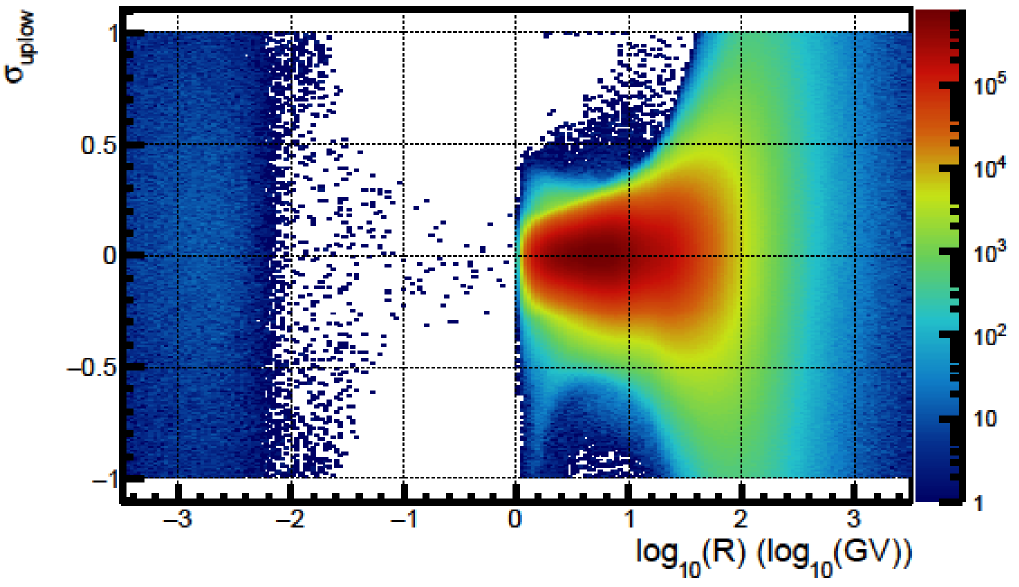
– Compare R obtained from different geometries:

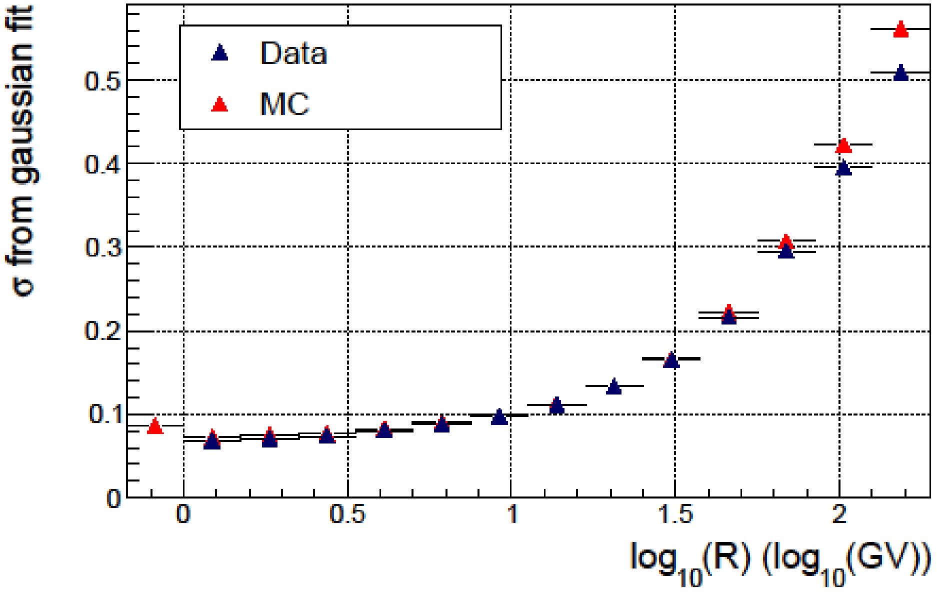


$$\sigma_{\mathrm{uplow}} = \frac{1/R_{\mathrm{up}} - 1/R_{\mathrm{low}}}{1/R_{\mathrm{up}} + 1/R_{\mathrm{low}}} = \frac{R_{\mathrm{low}} - R_{\mathrm{up}}}{R_{\mathrm{up}} + R_{\mathrm{low}}}$$

Exemplary Fit from a slice:

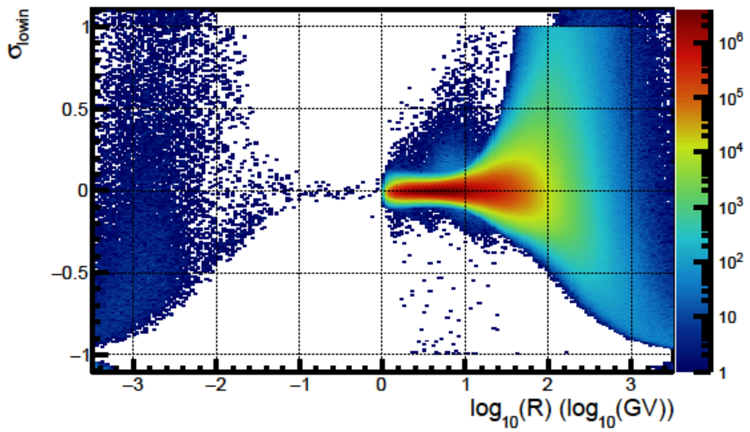




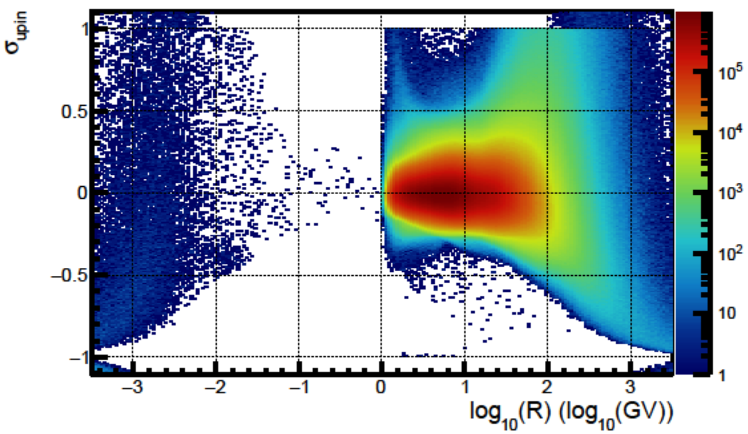


Additional Track Quality Selections

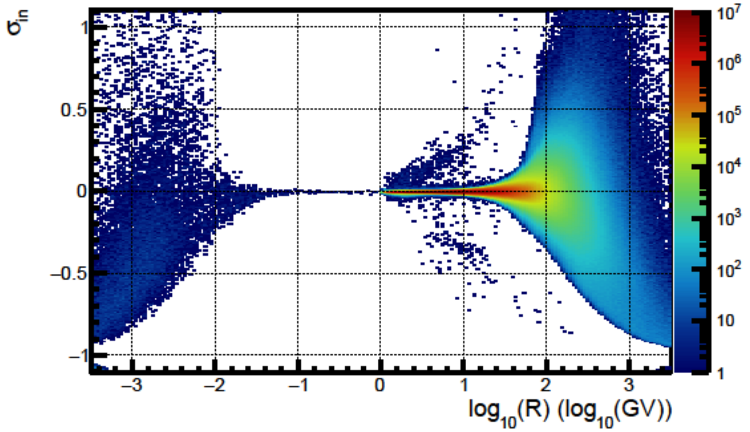
Lower Half vs Inner + L1

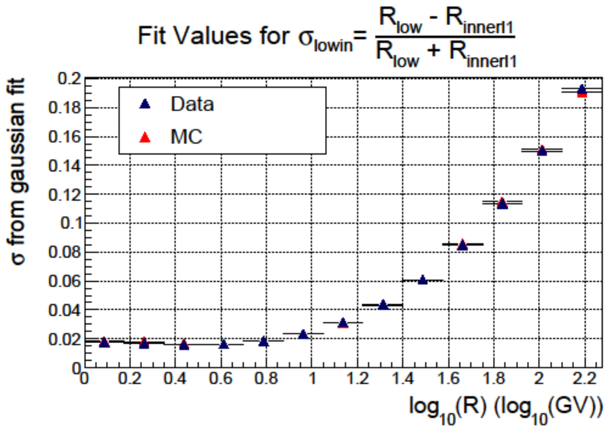


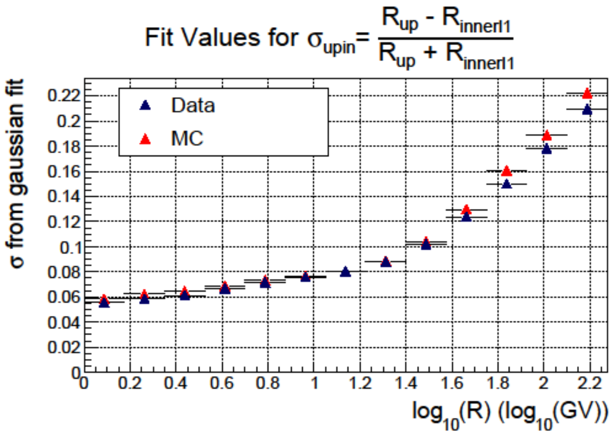
Upper Half vs Inner + L1

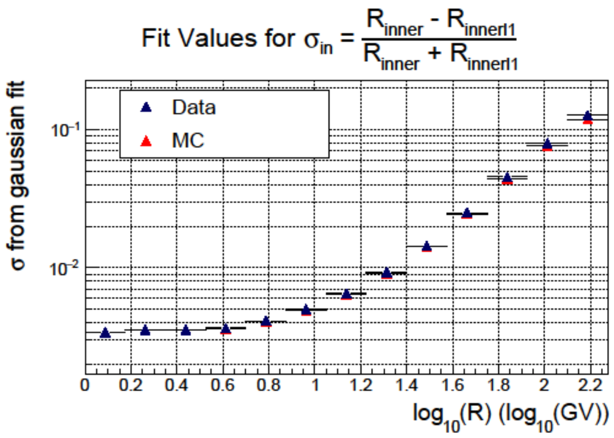


Inner vs Inner + L1



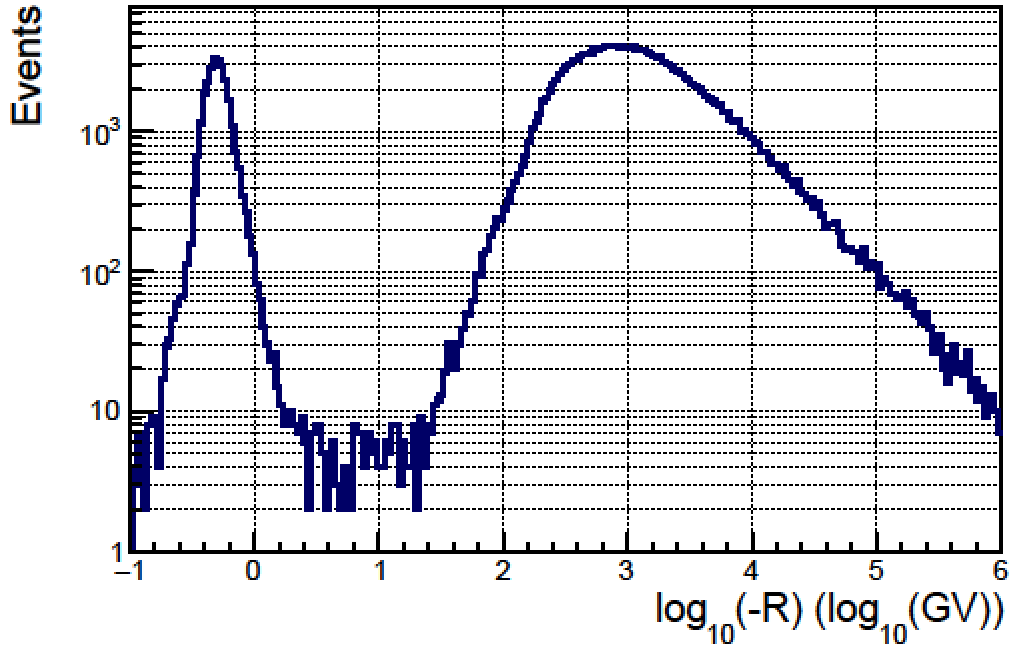




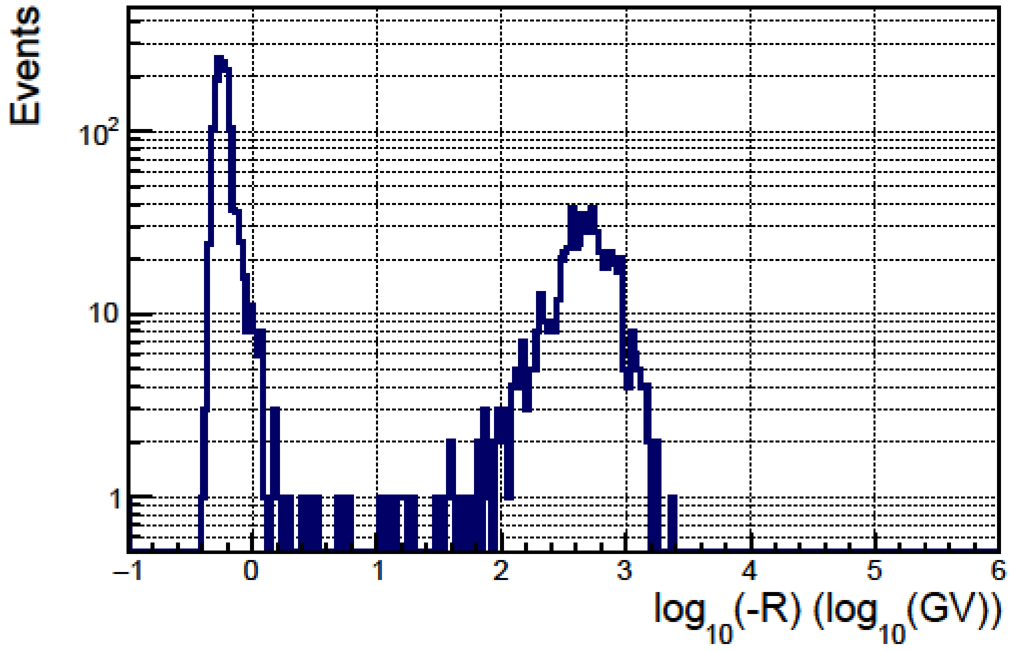


Spectrum after Selections

Before:



After:

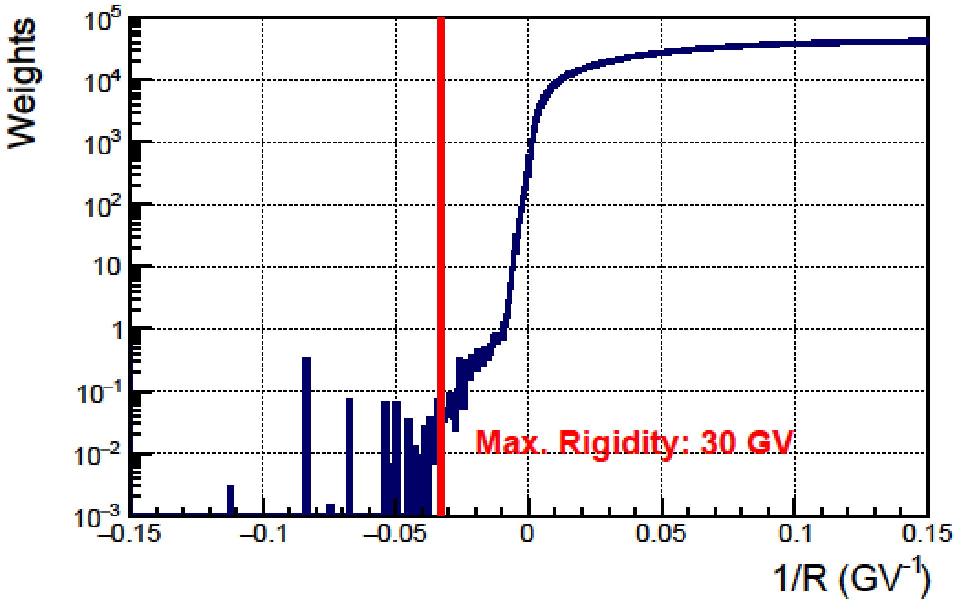


-> Still Background dominated!

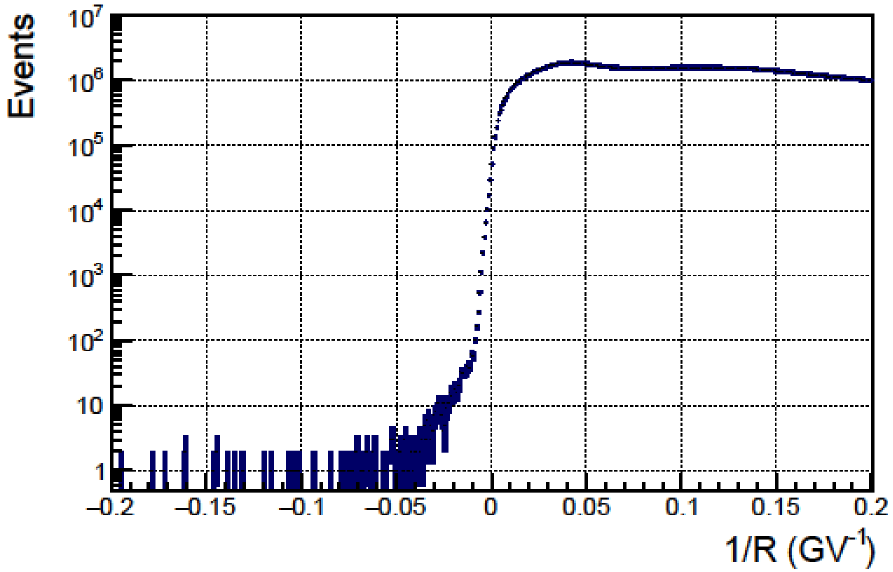
Rigidity Window

- Background from multiple scattering is already effectively removed by the geomagnetic cutoff rigidity, additionally we ask R > 3 GV
- The maximum acceptable rigidity due to spillover was chosen by looking at MC:

MC:



Data:



Mass Measurement

- Mass of remaining events should be compatible with either $^3\overline{\mathrm{He}}$ or $^4\overline{\mathrm{He}}$
- If not rigidity measurement cannot be trusted
- Mass is measured using the β measurement of either ToF or RICH:
- Resolution depends both on R and β resolutions:

$$\boxed{m = \frac{ZR}{\gamma\beta}}$$

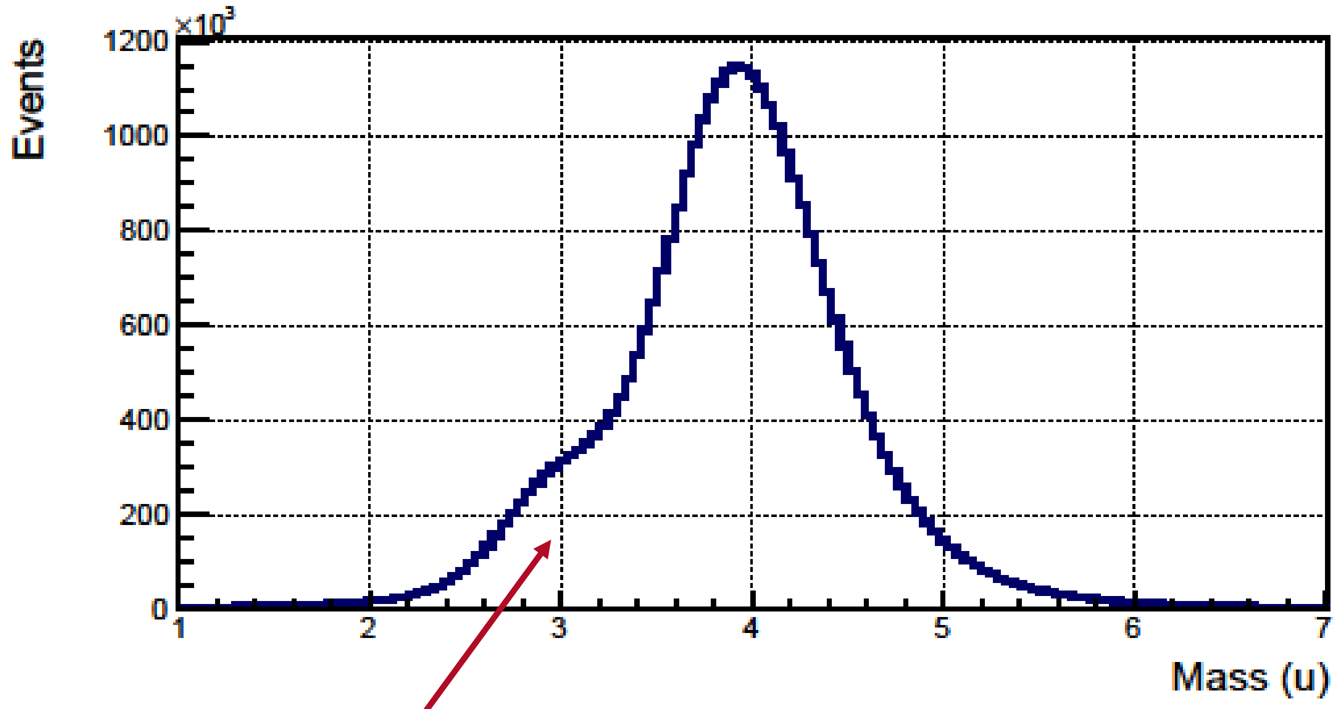
$$\frac{\sigma_m}{m} = \sqrt{\left(\frac{\sigma_{1/R}}{1/R}\right)^2 + \left(\gamma^2 \frac{\sigma_\beta}{\beta}\right)^2}$$

~ 0.1

Quickly diverges for higher energies!

β type	β threshold	R_3 (GV)	R_4 (GV)	σ_β/β
ToF	/	/	/	0.025
NaF	0.75	1.59	2.11	0.0025
Agl	0.953	4.42	5.86	0.0018

He Mass (obtained from RICH β only)

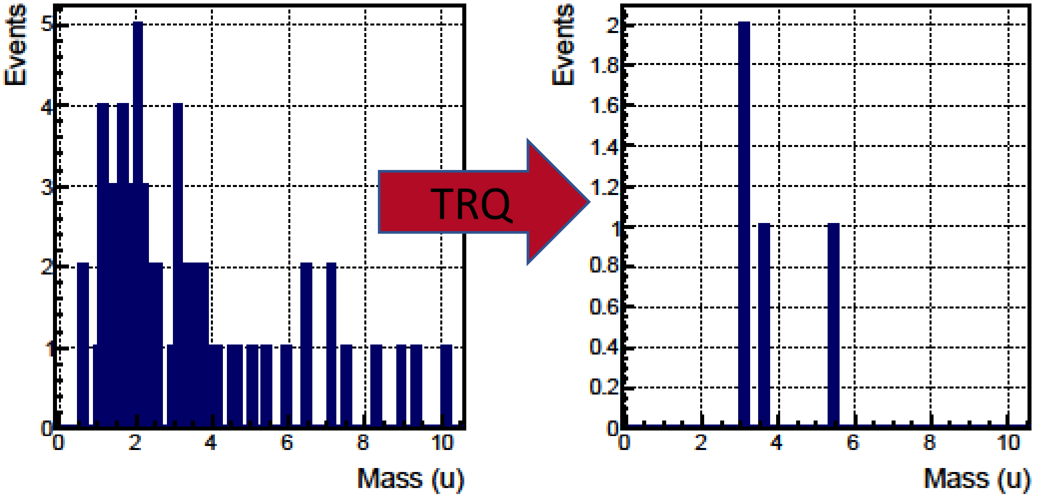


About 15% contribution from $^3\mathrm{He}$

Antihelium Candidates

Data

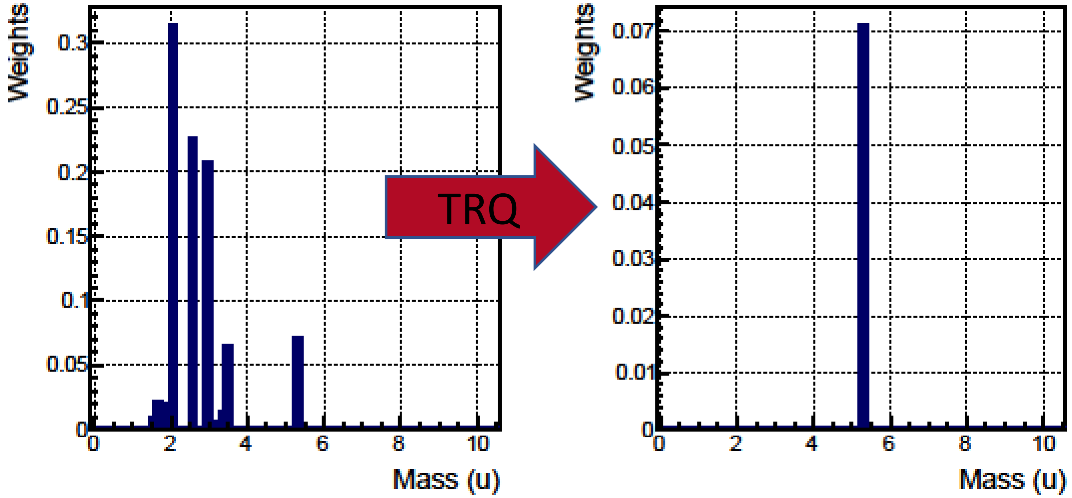
Mass distribution inside R window, before and after **track quality selections (TRQ)**



-> Only events with masses compatible with He survive

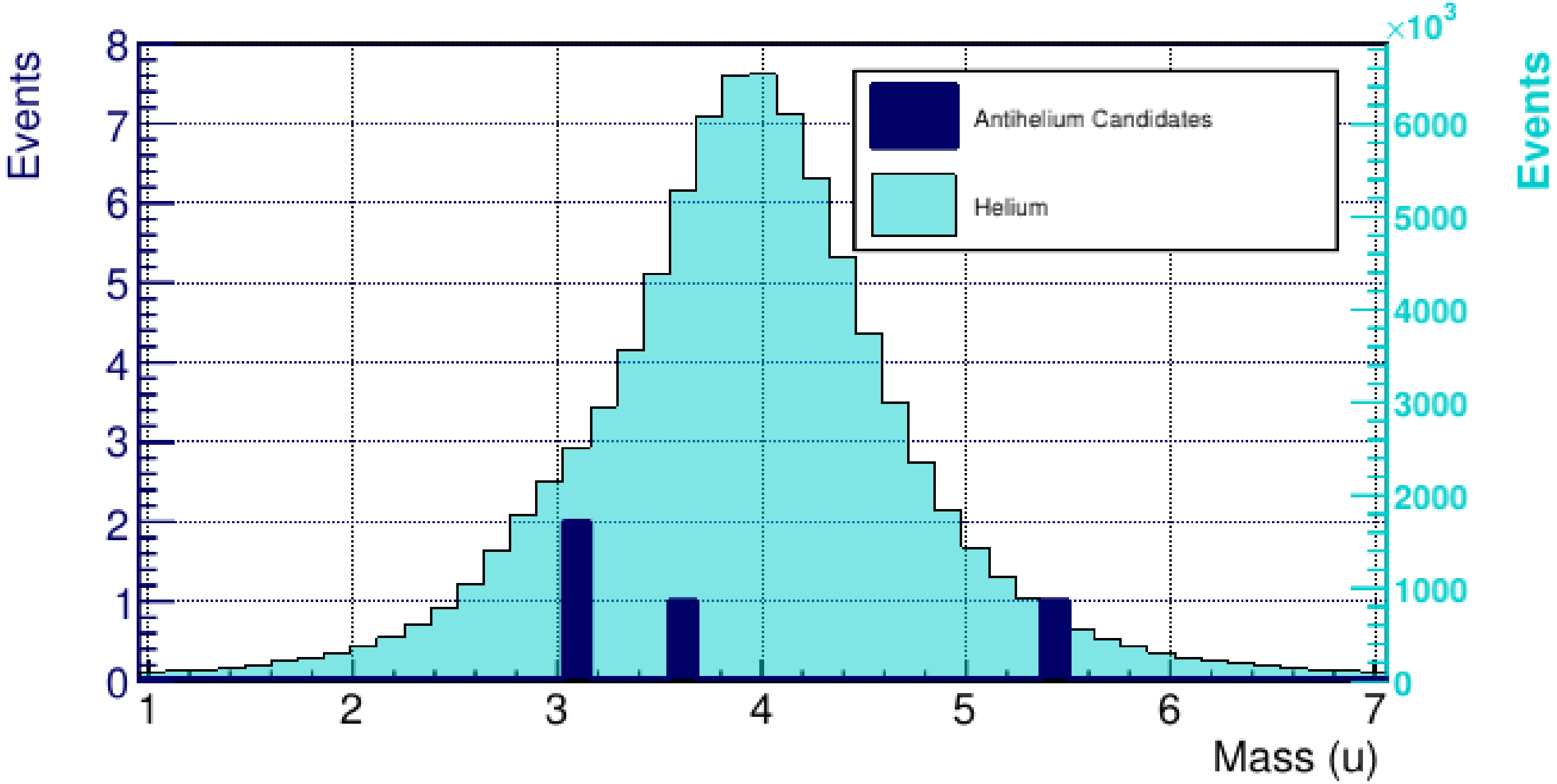
MC

Mass distribution inside R window, before and after **track quality selections (TRQ)**



-> One Background event survives. MC weight corresponds to $\sim 1 - 2$ events in data

Antihelium Candidates



Summary and Conclusion

– Analysing 10 years of data the cosmic He flux was estimated

– The Flux agrees with previous publications

– This clean He sample also contains some events with negative rigidities

– Tight rigidity quality selections were applied to remove the background from ordinary He

– Events with negative rigidities below the geomagnetic cutoff were removed

– Furthermore, events with $R > 30$ GV were rejected, since they originate from spillover

– Finally the velocity measurement was used in combination with the rigidity to estimate the particle mass

Summary and Conclusion

– 4 candidates survive the selections, and they all lie in the expected He mass window

– In MC one event survives, **corresponding to an expected background of 1-2 events**

-> No evidence for antihelium can be claimed!

– The origin of this background is not yet fully understood and should be subject of future works

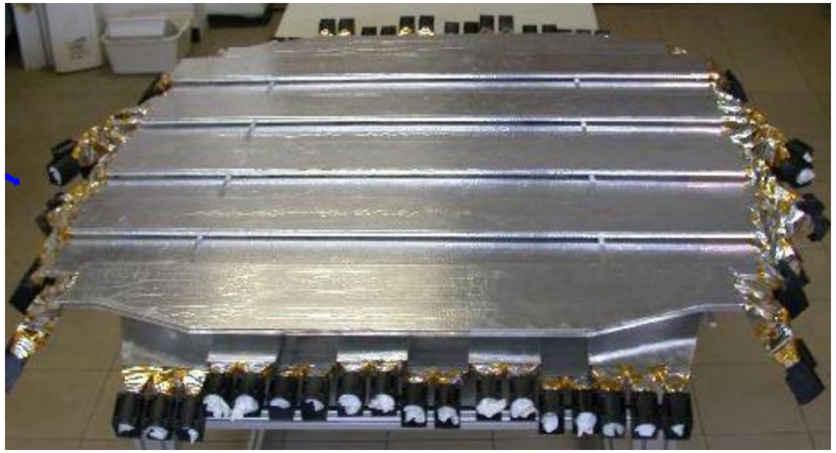
Backup Slides

Time of Flight System (ToF)

- Four scintillator planes (1+2 build *Upper ToF* and 3+4 build *Lower ToF)*
- Used as event trigger
- Average time resolution of $\sim \mathbf{160\ ps}$
- Together with track-> velocity measurement ($\beta = \frac{v}{c}$)
- Velocity resolution for **Z = 2:** $\frac{\Delta\beta}{\beta} \sim 2\%$
- Charge measurement from energy deposition, Bethe-Bloch: $\frac{dE}{dx} \propto z^2$

Upper ToF

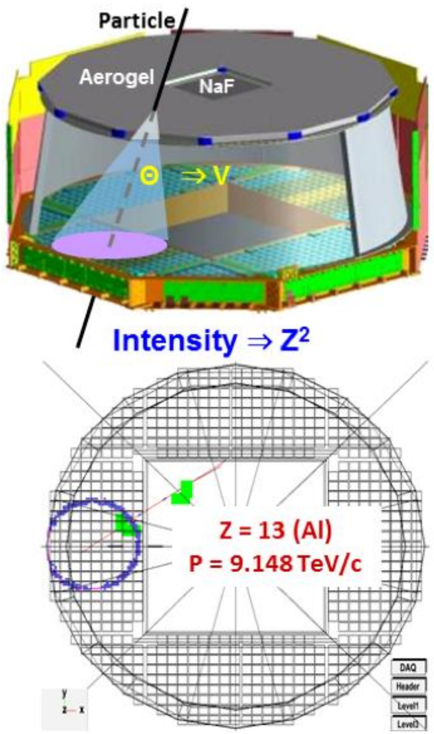
Lower ToF

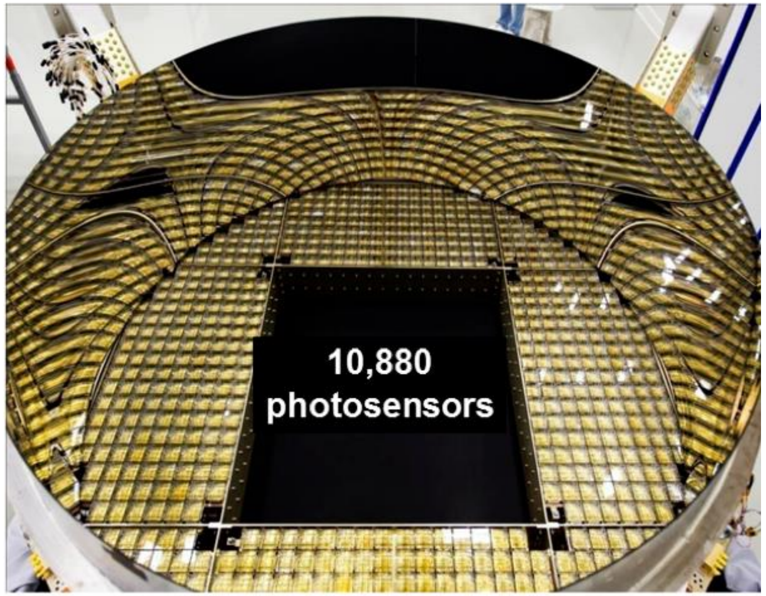


Ring Imaging Cherenkov Detector (RICH)

- Uses Cherenkov effect to measure velocity and charge
- Two different radiators:
  NaF (n = 1.33)
  Aerogel (n = 1.05)
- Detection plane: 680 4 x 4 multi-anode PMTs -> 10,880 photosensors
- Average β resolution:

$$\frac{\Delta\beta}{\beta} \approx 0.1\%$$





MC negative rig events