The AMS-100 experiment:

The next generation magnetic spectrometer in space

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on behalf of the AMS-100 group

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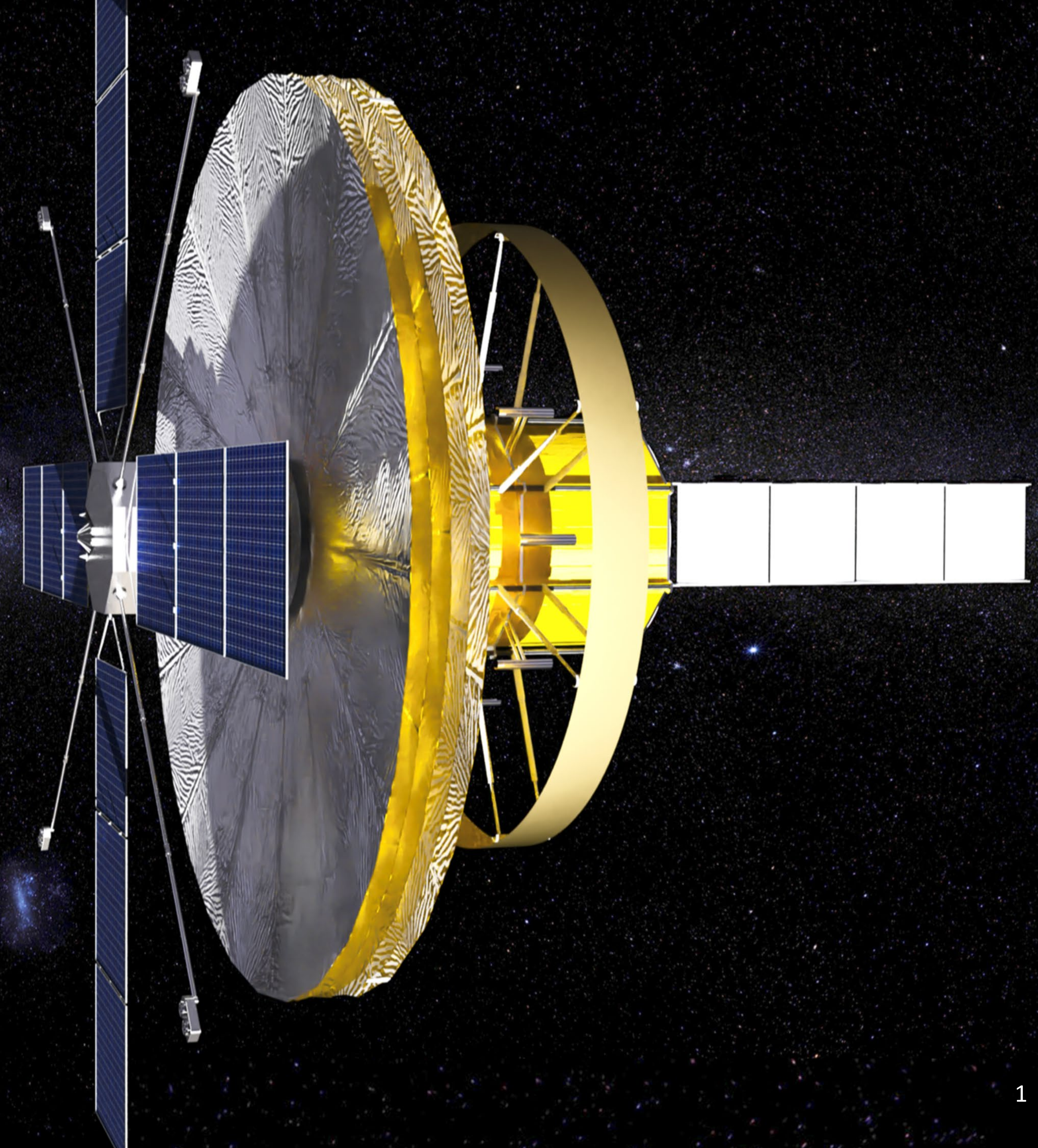
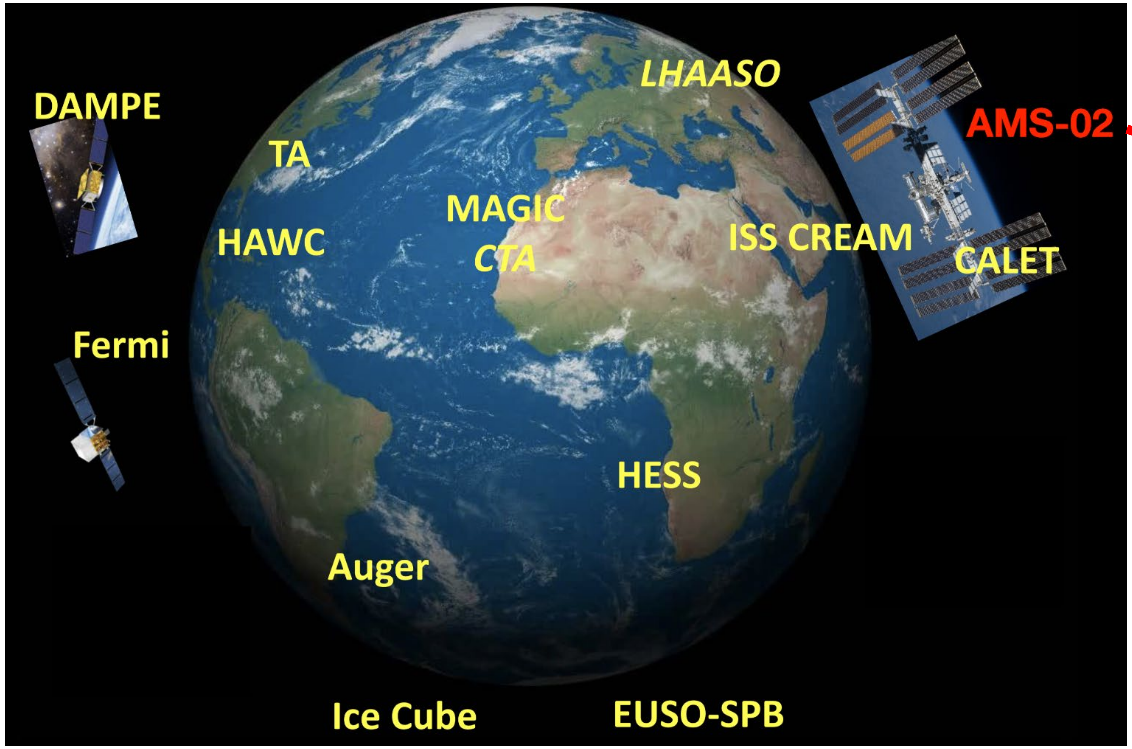
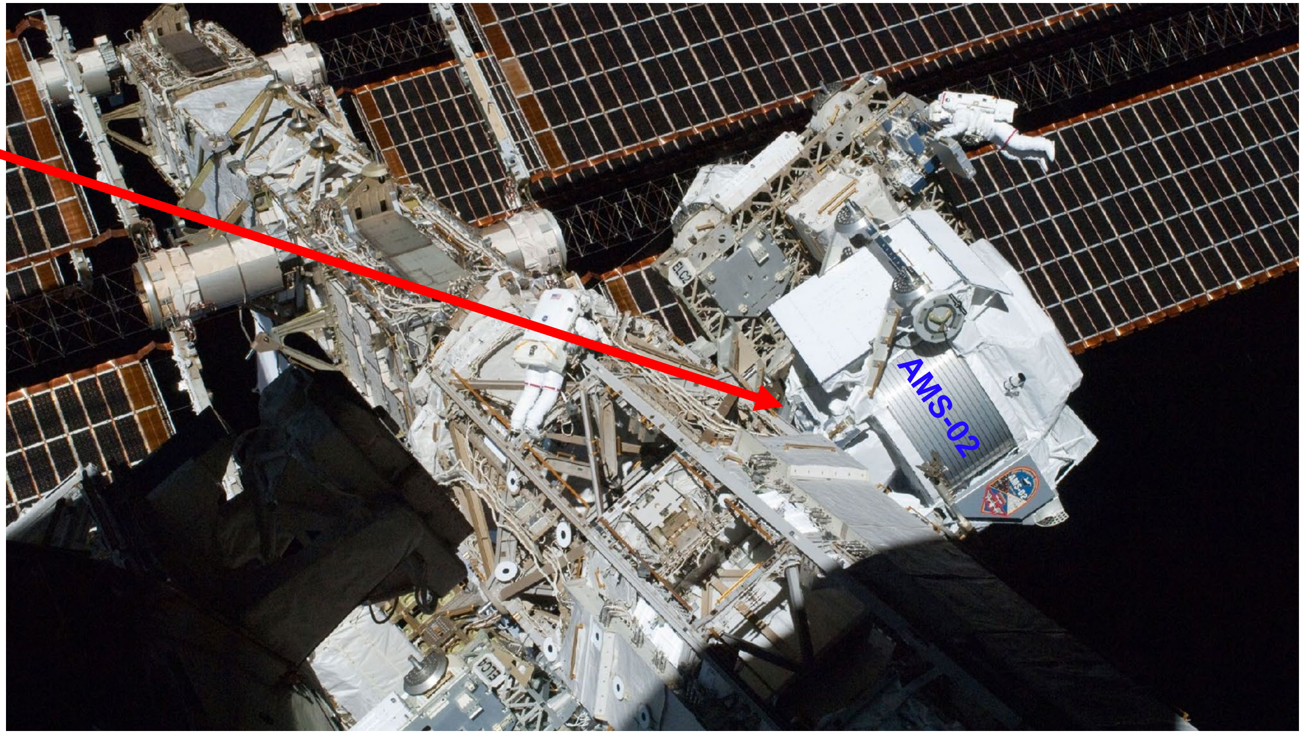


Major Cosmic Ray Experiments





AMS-02 is the only magnetic spectrometer in space:

Operational on the ISS since May 2011

Weight:	7 t
Magnet:	BL^2=0.15 Tm^2
Acceptance:	0.1 m^2sr
MDR:	2 TV
Calorimeter:	17 X_0, 1.7λ

Recorded more than **198 Billion** cosmic rays and will continue through the lifetime of ISS.

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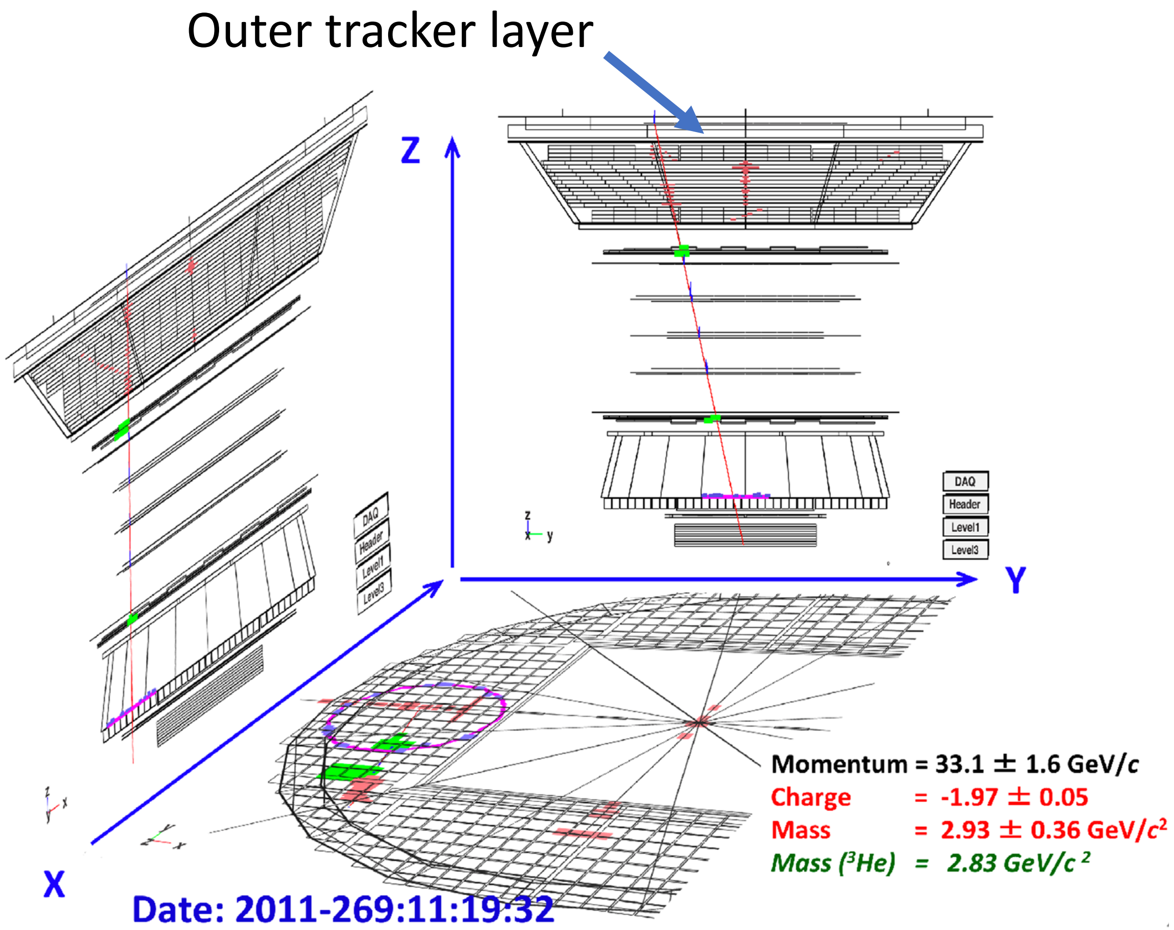
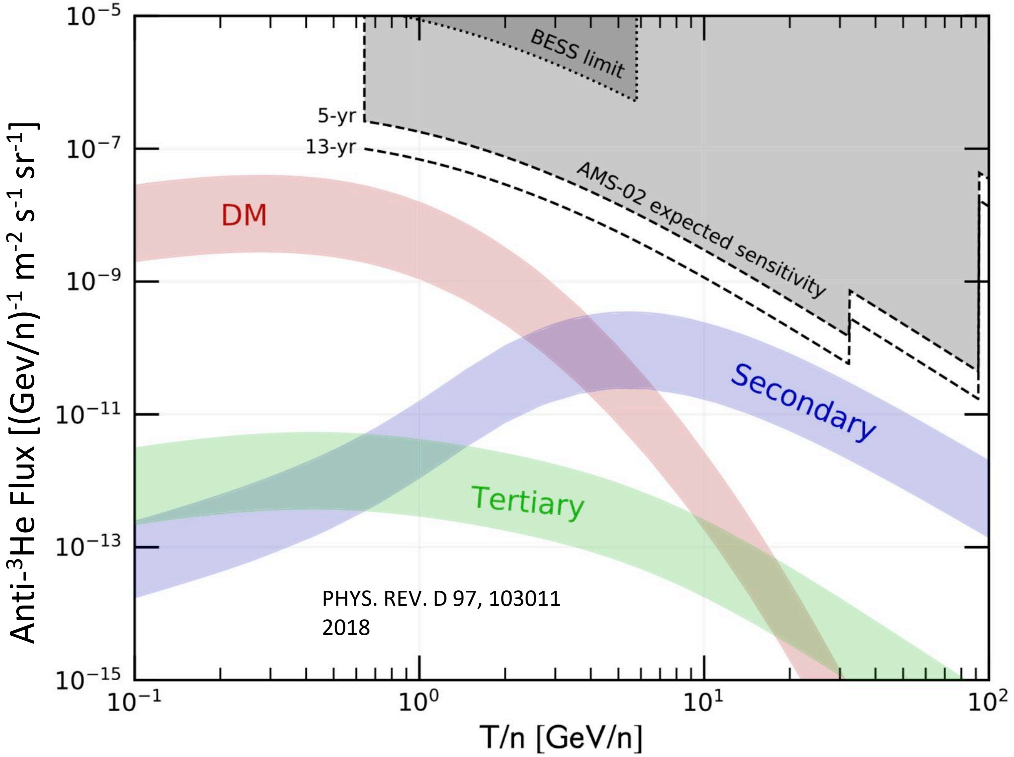
AMS-02: Open Questions: Search for Anti-Helium Nuclei





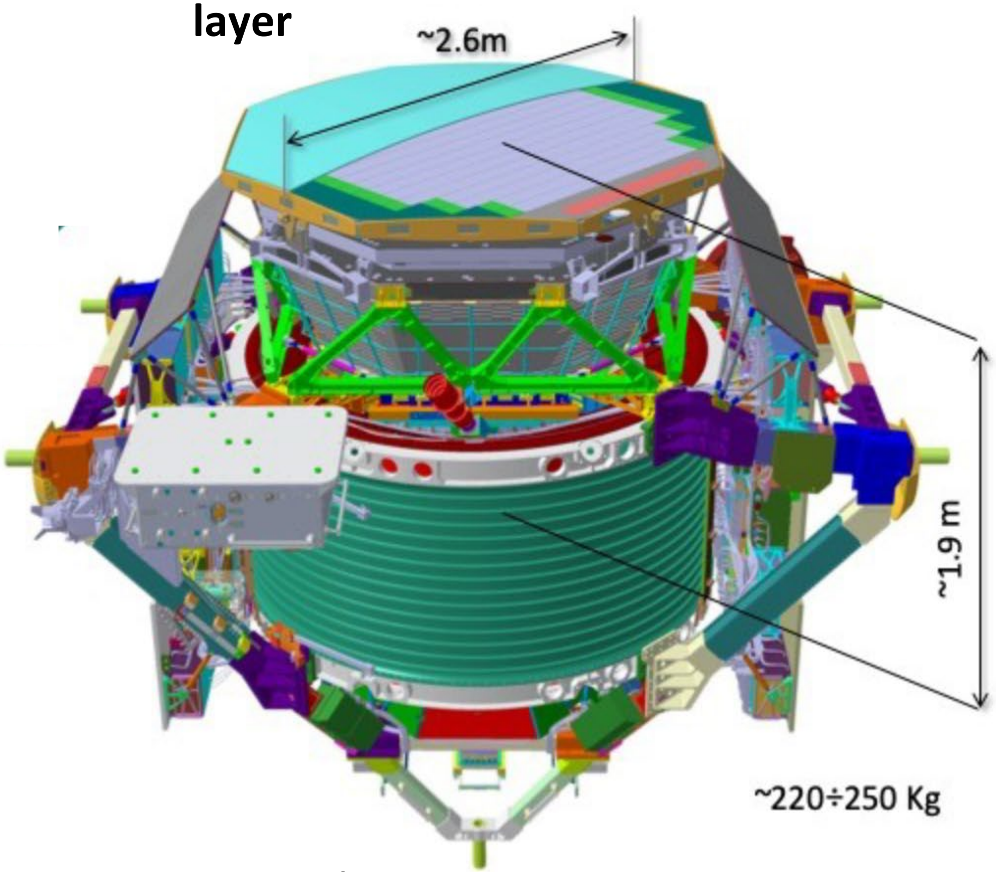
AMS-02 found:

8 $^{3}\overline{He}$ and 2 $^{4}\overline{He}$ candidates,

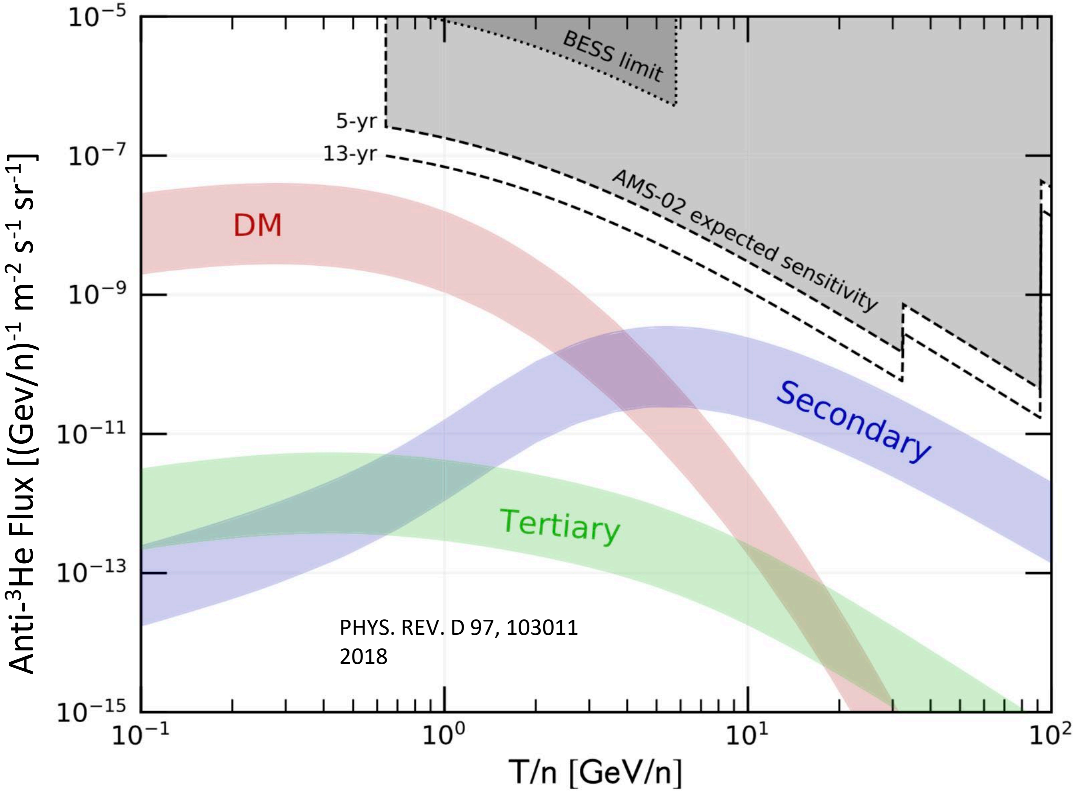
But no hits in outer tracker layer

AMS-02 Upgrade: Search for Anti-Helium Nuclei

AMS-02 Upgrade: New tracker layer

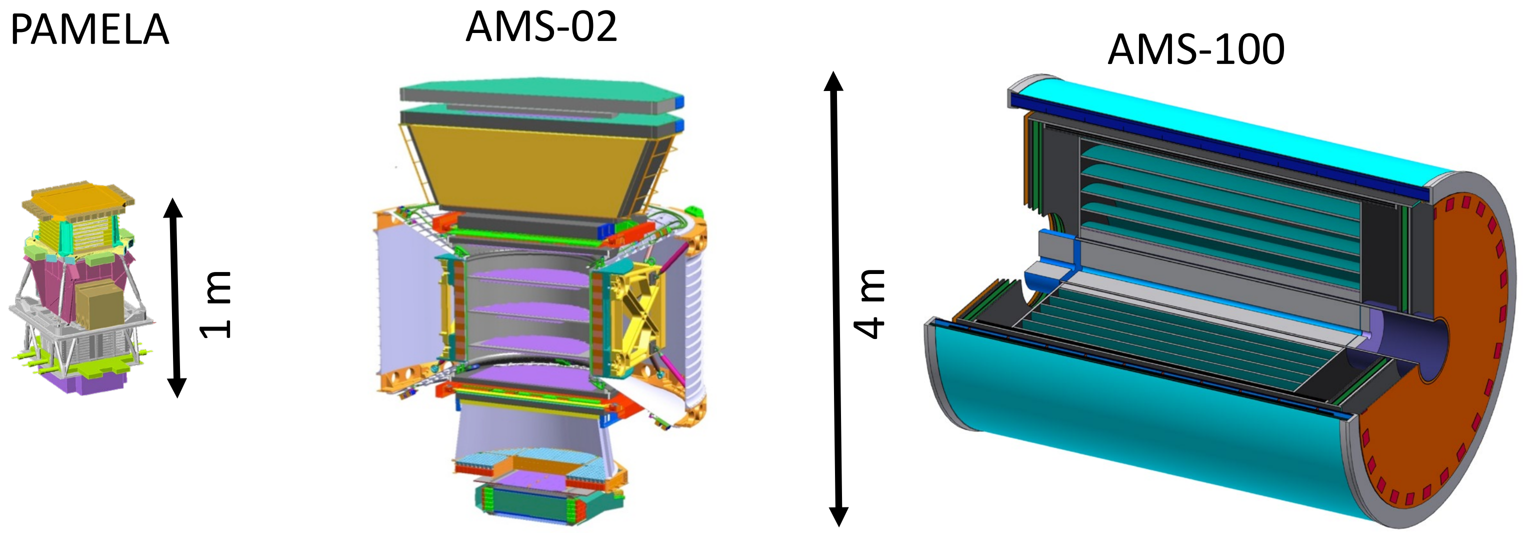


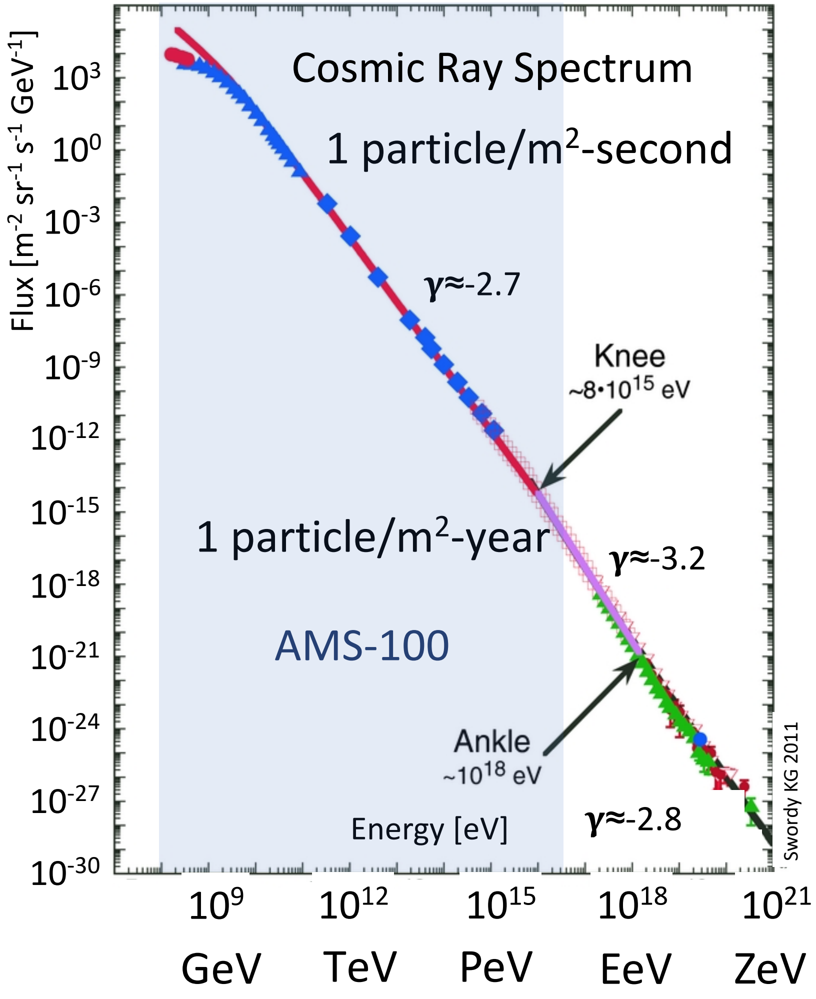
AMS-02 upgrade:
Find Anti-Helium candidates with hits in all tracker layers?



Only a next generation magnetic spectrometer in space will be able to experimentally resolve the questions about Dark Matter signals in cosmic ray anti-matter

Future: AMS-100





The cosmic ray flux follows a power law $\Phi \approx C\, E^{-3}$

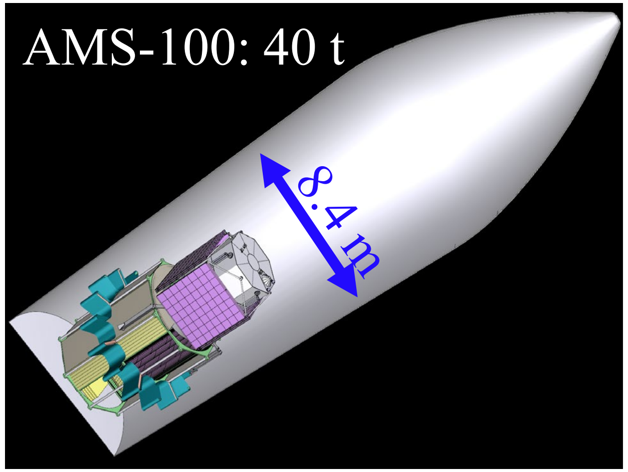
Increase in energy by a factor 10 requires an increase in acceptance by 1000.

Design Requirements for a superconducting magnet spectrometer operated at Lagrange Point 2:

- Max detectable rigidity of 100 TV
- Geometric acceptance of 100 $m^2 sr$ ⟶ 1000 times the acceptance of AMS-02
- Measurement of cosmic nuclei with energies up to the cosmic-ray knee

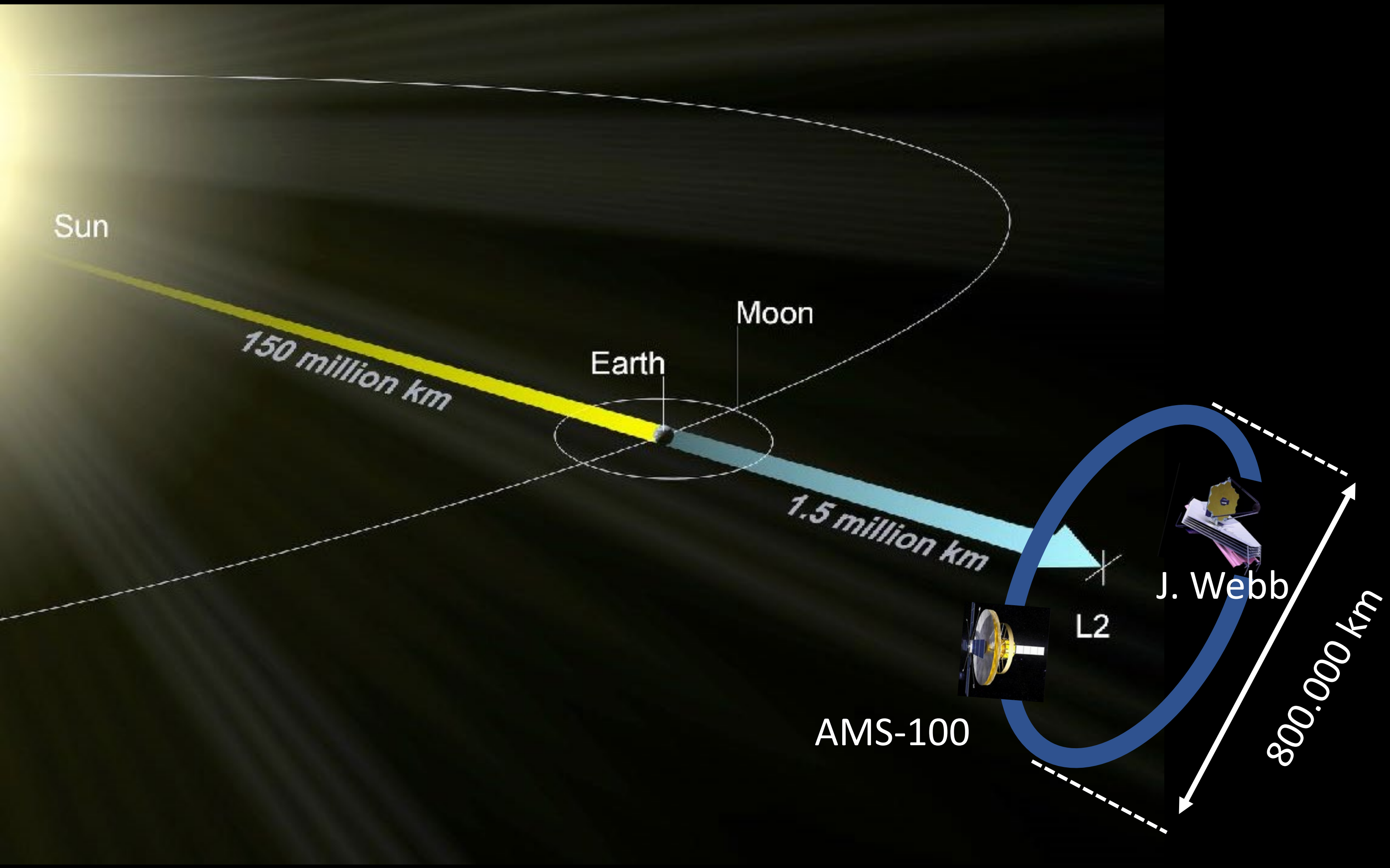
AMS-100: The Expedition to Lagrange Point 2

- Total estimated mass of AMS-100: 40 t
  - Magnet system: 2t
  - Detector equipment: 18 t
  - Auxiliary equipment: 20 t
- Launch with SpaceX's Starship rocket
  - Mass-to-orbit: 100+ t
  - Payload to L2 with refueling on-orbit



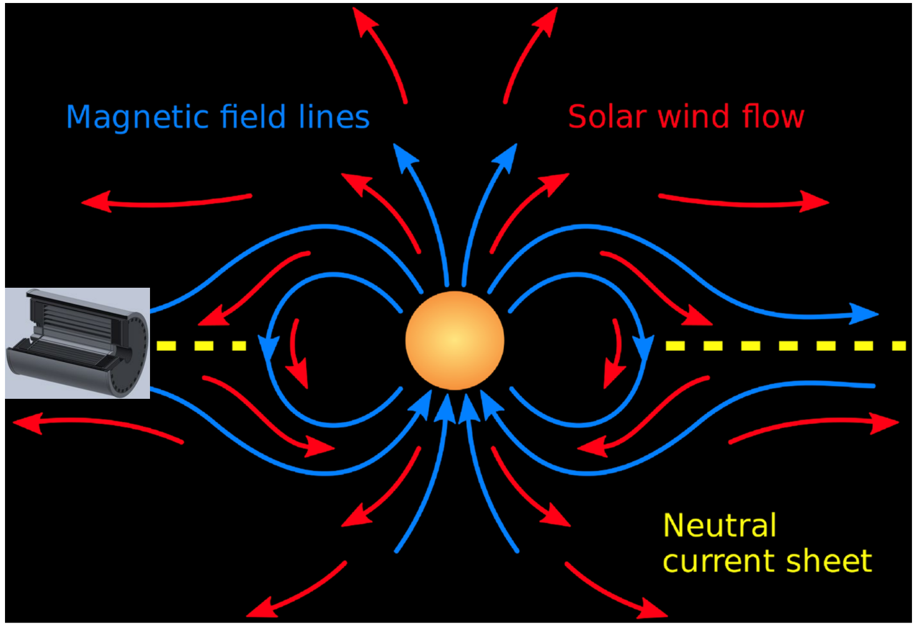
Starship payload deployment sequence

AMS-100: Physics with cosmic rays at Lagrange Point 2



- Position at Sun-Earth Lagrange Point 2
  - No heat radiation from sun or earth
  - Allows cryogenic experiments
  - Gaia, Herschel, Plank, WMAP, James Webb S. Telescope, Queqiao, eRosita
- Starting at around 2035 - 2040
- Collecting data for min. 10 years

AMS-100: High Temperature Superconducting Magnet, Compensation Coil



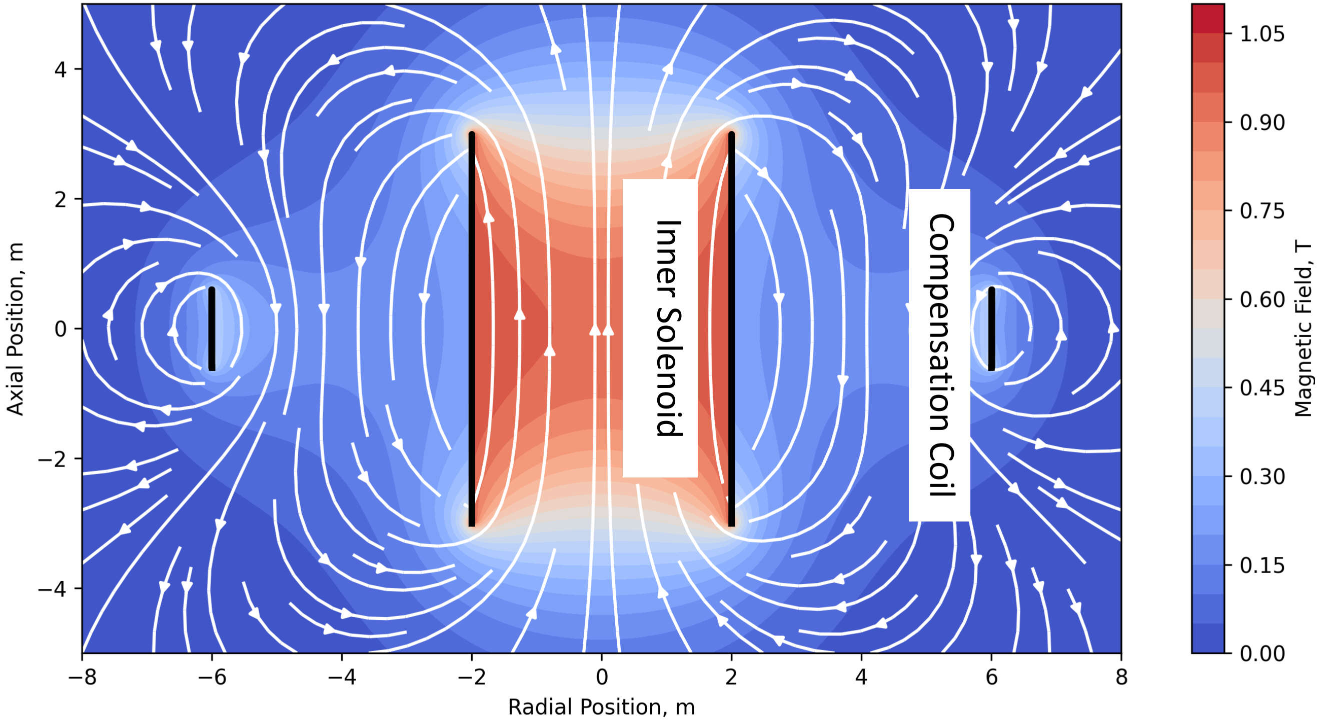
Interplanetary Magnetic Field

<B> = 6 nT, Variation B = 0- 37 nT

⟶ large volume solenoid with a B-Field of 1 Tesla in interplanetary Magnetic Field results in a Torque of 0.4 Nm

⟶ Current in Compensation Coil adjusted such that total magnetic dipole moment of the system is reduced to 1/10000

⟶ Remaining angular momentum is balanced by reaction wheels



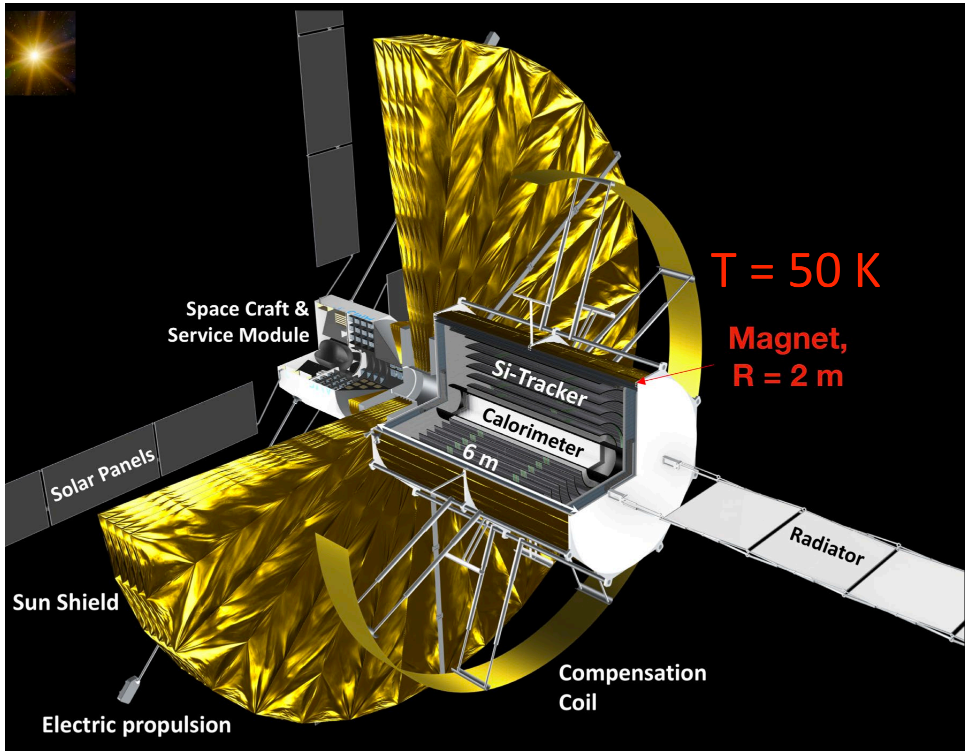
	Main Coil	Dipole Compensation Coil
Length	6.3 m	1 m
Diameter	4.2 m	12.6 m
Number of Turns	450	71
HTS Layers	18 @ 50 – 60 K	3x2 @ 50 K
Current	13500 A	9500 A
B-Field	1 T	-0.06 T @ z=0, R=0

AMS-100:

Planned Design:

- 3 mm high temperature superconducting solenoid (HTS tapes)

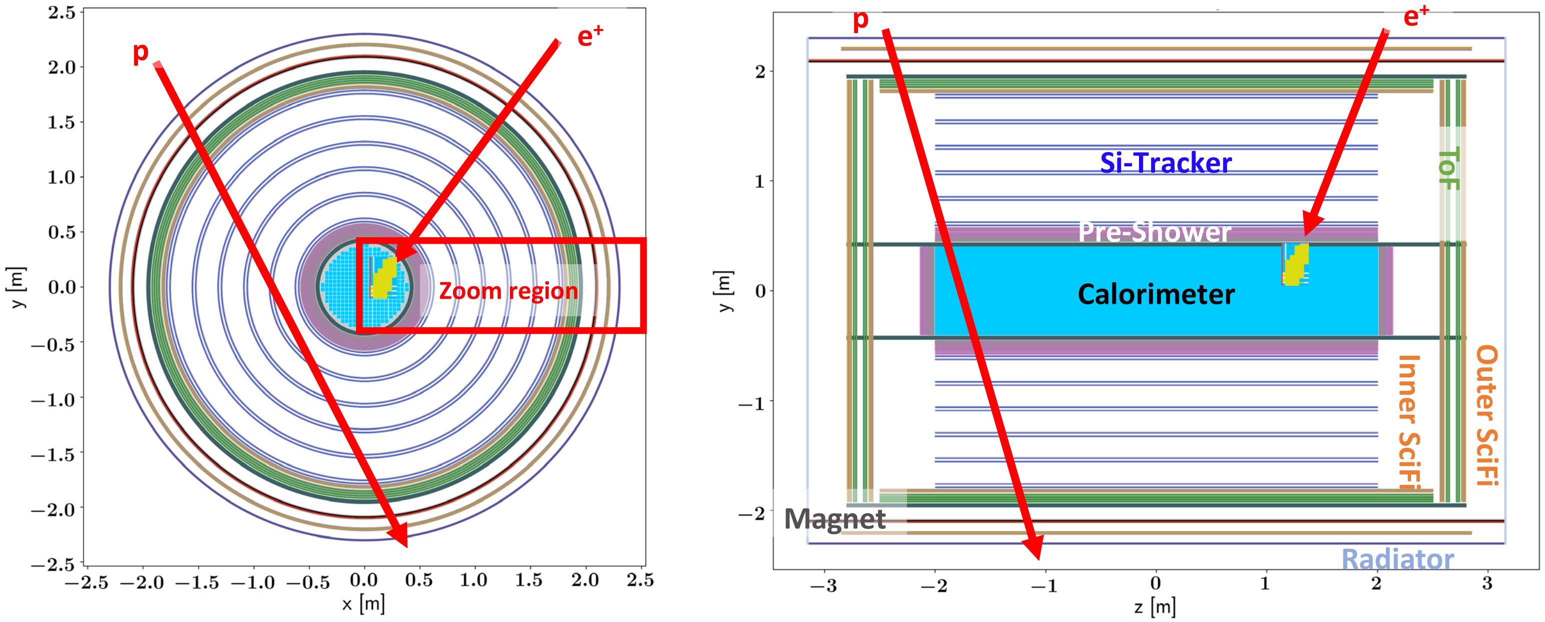
  ⟶ 1 T in a volume of 75 m^3
- Solenoid operated at 50 – 60 K behind the sunshield in thermal equilibrium with the environment
- Expandable high temperature superconducting compensation coil (Ø 12 m) balances magnetic dipole moment of solenoid
- Solenoid is instrumented on the inside with a silicon tracker and a calorimeter system (70 X_0, 4 λ_I)
- SciFi-tracker
- Time-of-flight (ToF) system

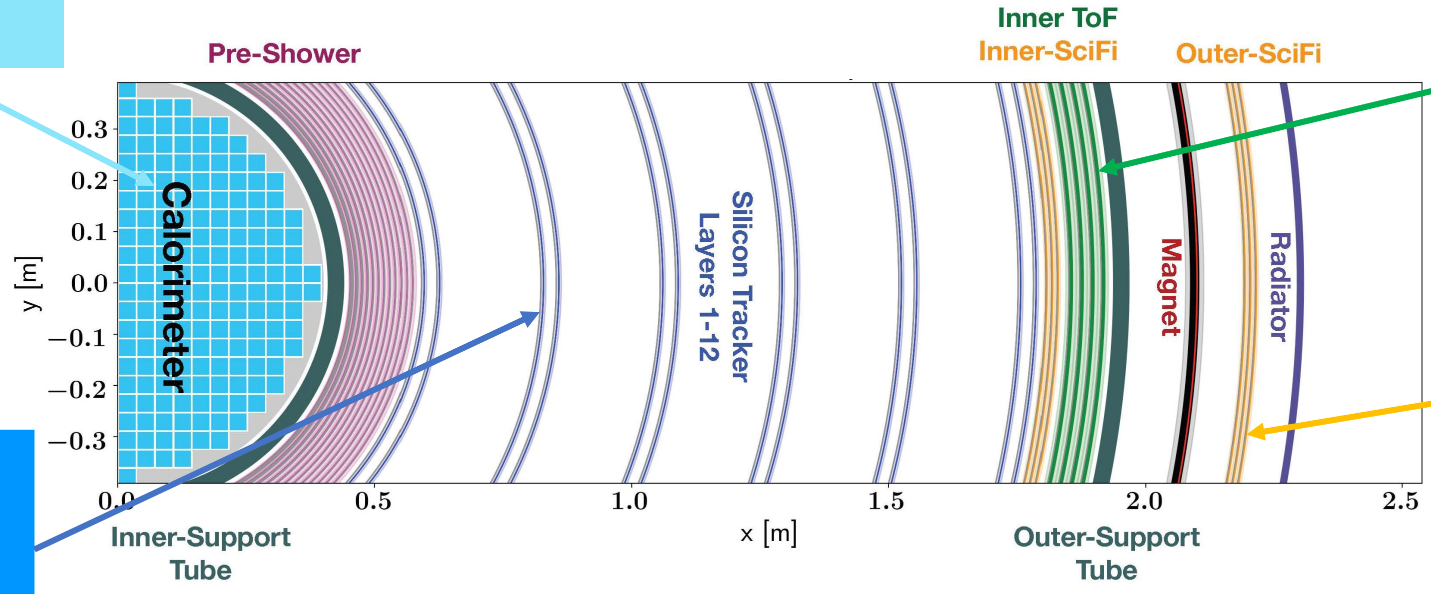


Weight:	40 t
Thin coil Solenoid :	BL^2=15 Tm^2
Acceptance:	100 m^2sr
MDR:	100 TV
Calorimeter:	70 X_0, 4λ
Power Consumption:	15 kW
Incoming Particle Rate:	2 MHz
Number Readout Channels:	8 Million
Mission Flight Time:	10 years

S.Schael et al., https://arxiv.org/pdf/1907.04168.pdf, Nucl. Instrum. Methods Phys. Res. Sect. A 2019, 944, 162561

AMS-100 Detector





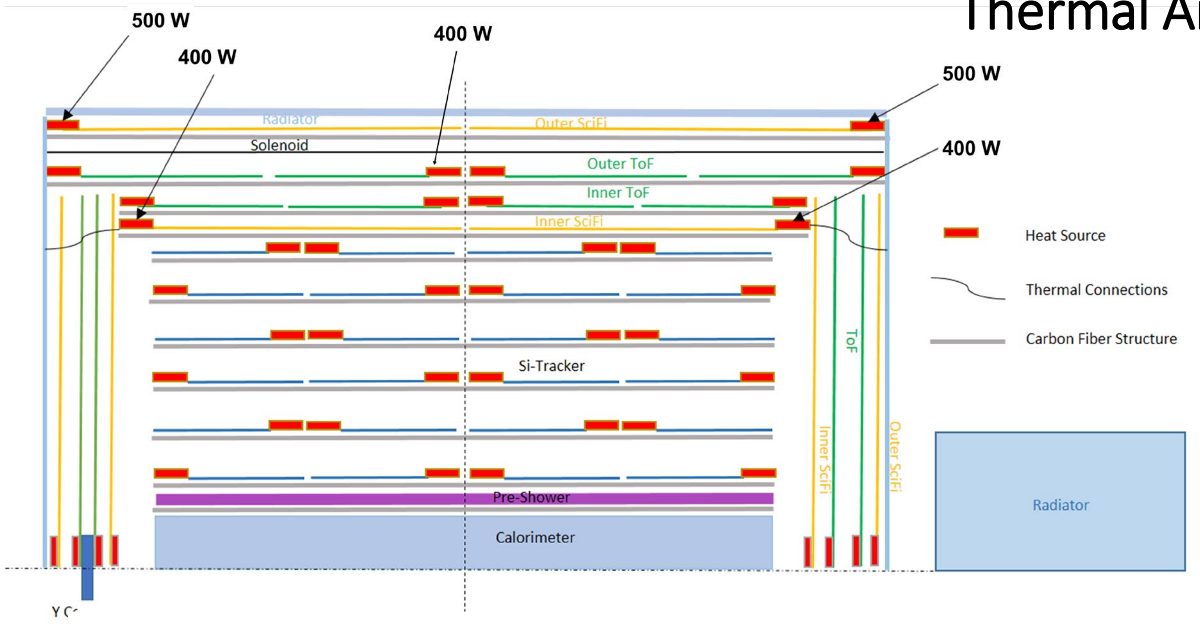
Calorimeter & Pre-Shower:
Measurement of E and Z

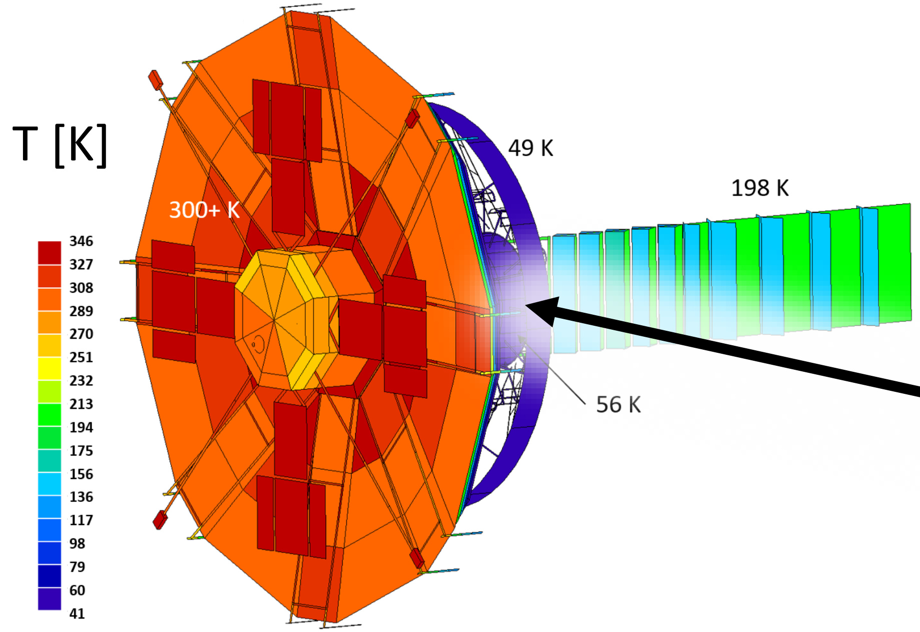
ToF
Measurement of β=P/E and Z
2 x 4 Measurements,
<20 ps resolution.

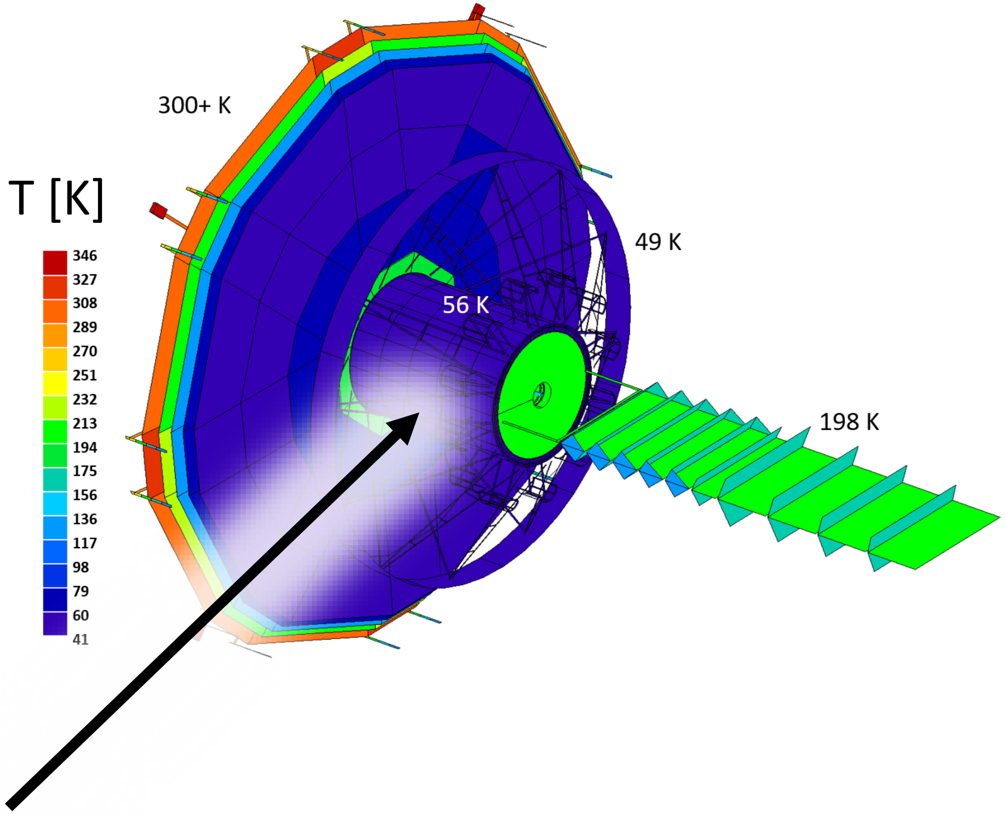
SciFi-Tracker
Measurement of R and Z
2 x 6 Measurements,
40µm or 13µm resolution.

Silicon-Tracker
Measurement of R and Z
2 x 12 Space Points,
5µm resolution.

Thermal Analysis of AMS-100:







Thermal analysis shows:
Magnet-radiator temperature of 50-60 K,
Detector components @ 200 K

AMS-100: High Temperature Superconducting Magnet

AMS-100 magnet system faces many design challenges due to its

Ultra-thin 1T HTS coil,

Design B-field of 1 T in the center of the solenoid.

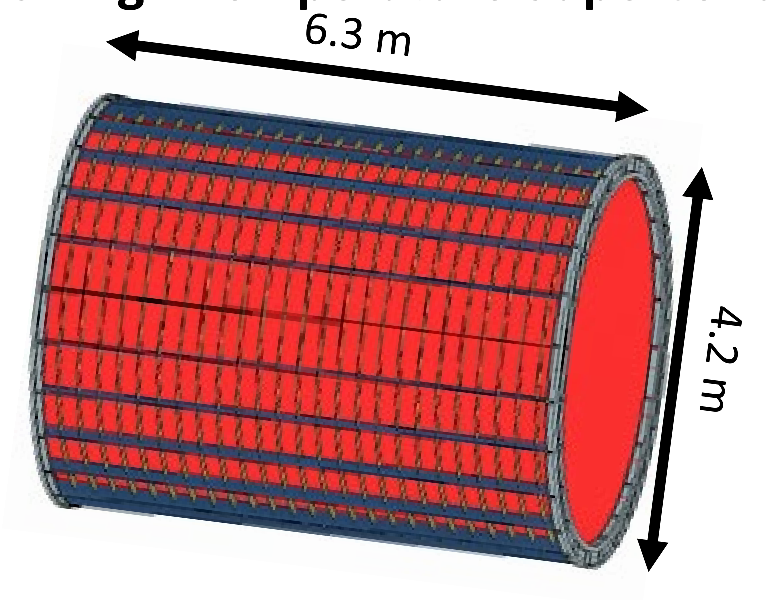
Operating temperature range of 50 to 60 K:

Large temperature margin is important:

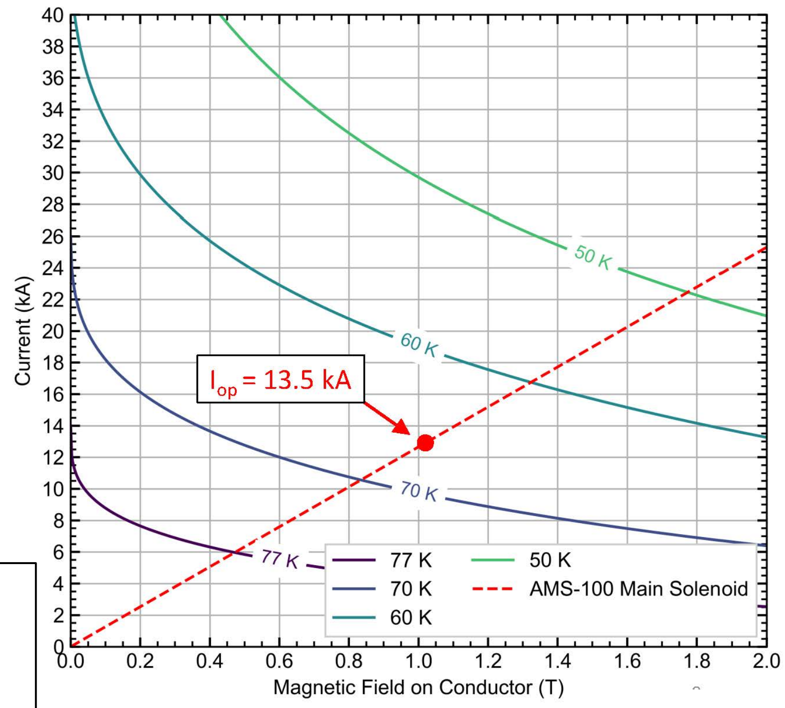
- cooling power is very limited via external radiators,
- large stored energy 39 MJ
- no intervention possible.

Requirement to survive high-vibration launch conditions

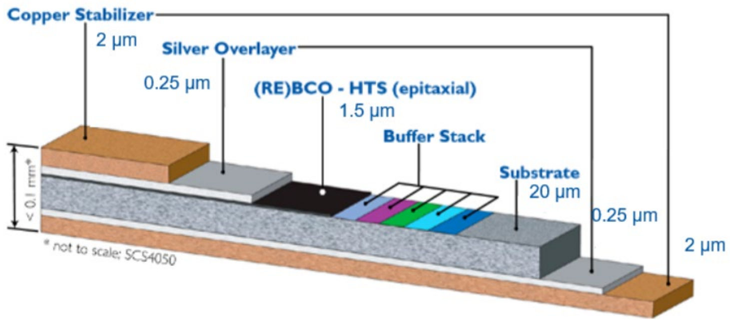
Requirement to fit the magnet and its compensation coil(s) inside a rocket



- Length: 6.3 m, Diameter: 4.2 m
- Number of Turns: 450
- Operating at 50 K – 60 K
- Current: 13500 A
- B-Field: 1 T
- 107 km of HTS Tape
- Thickness: 18x0.04mm = 0.72mm
- Stored Energy 39 MJ
- Radiation Length: 0.11 X_0
- Total Weight: 2200 kg



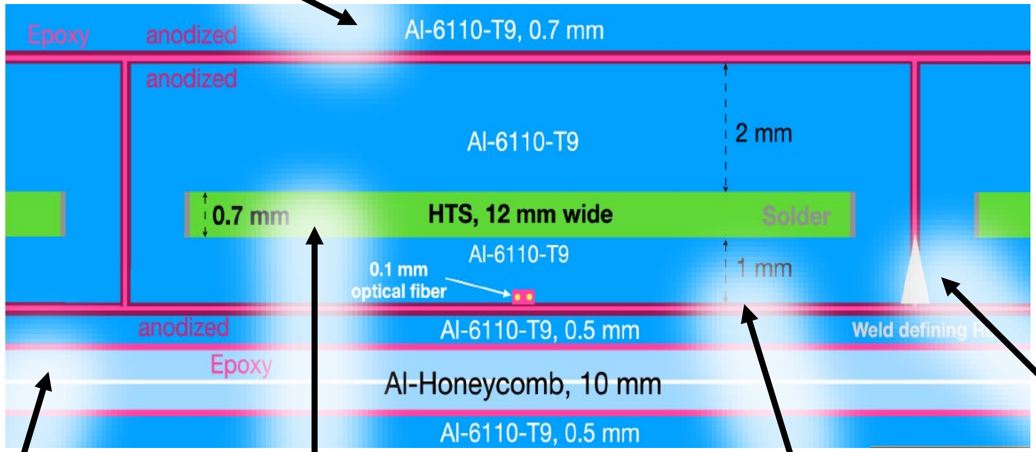
Rare-earth barium copper oxide (REBCO) HTS tapes

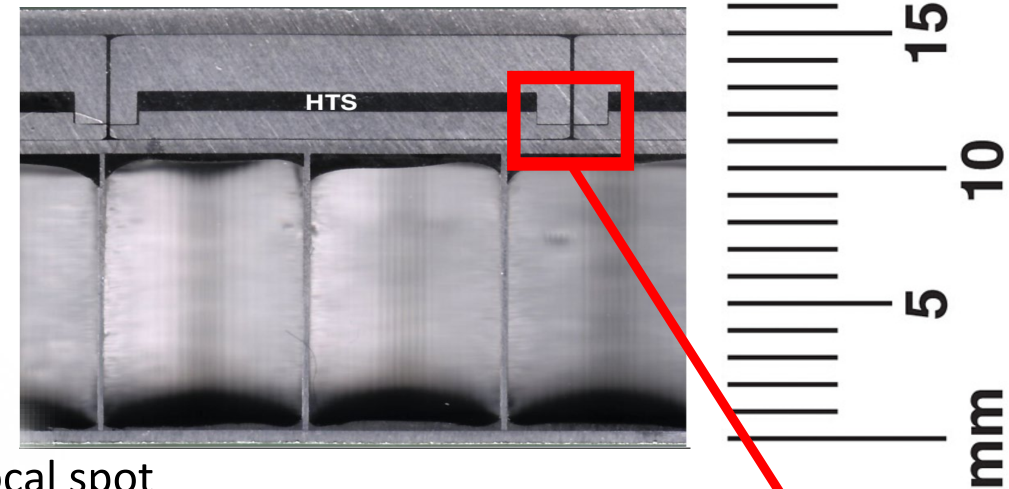


AMS-100: High Temperature Superconducting Magnet, non insulated Coil

Al-alloy skin for mechanical strength and axial thermal conductivity

HTS cable welded in aluminum jacket



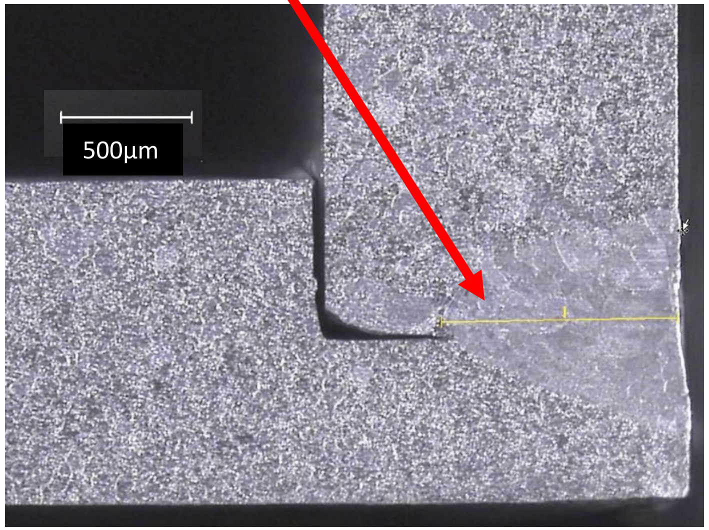


Honeycomb for mechanical stiffness

Stack of HTS tapes

Epoxy (+Kapton) between layers

Local spot welding



Al-6110-T9 skins paired with a honeycomb structure to increase the magnet's stiffness.

- Honeycomb structure increases the effective thickness of the object with minimal increase in radiation length.
- Magnet becomes more resistant to buckling.
- Al-6110-T9 alloy: provides a compromise between mechanical strength (yield stress > 500 MPa) and good thermal conductivity.

AMS-100: High Temperature Superconducting Magnet

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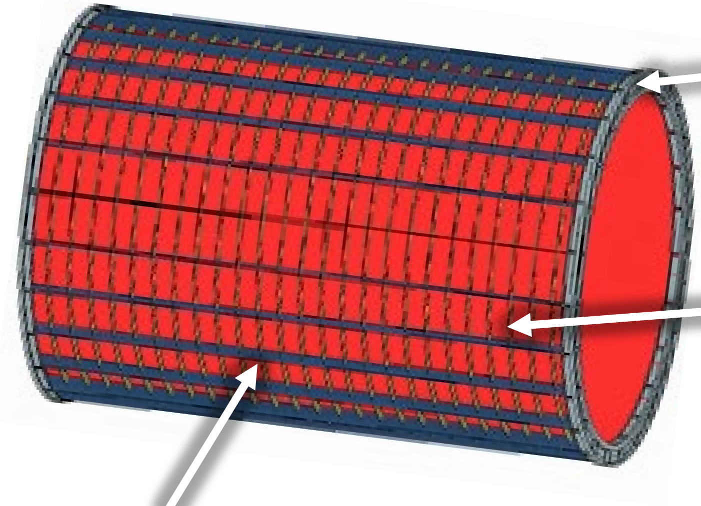


End-Flanges (grey):
Mechanical support of the magnet during manufacturing, launch and operation. Circular, allows quench-back.

Ribs (yellow):
Mechanical support of the magnet during operation and quench events. Circular, allows quench-back.

Stringers (blue):
Mechanical support for during launch.

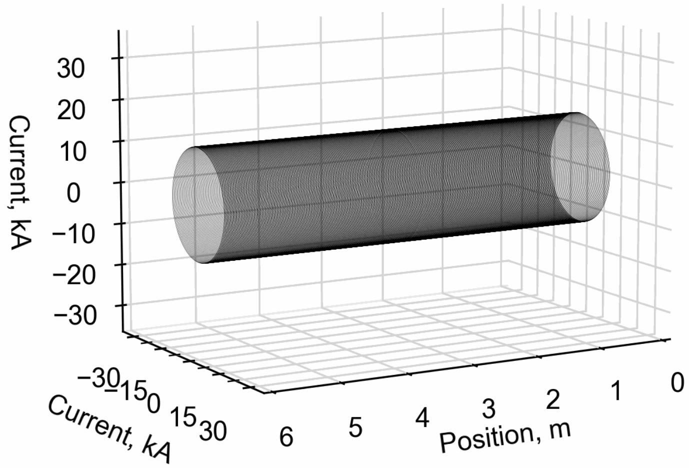
Quench model is under development:

⟶ Predicting quench behavior of main solenoid, resulting hot-spot temperature and mechanical load on conductor are studied for several quench scenarios.

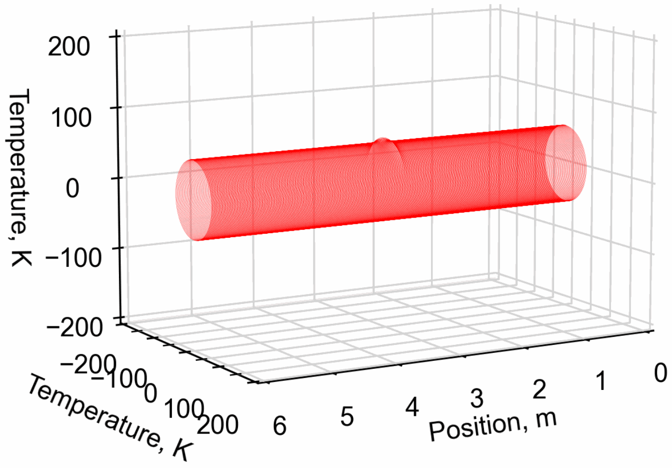
⟶ Quasi 3D thermal, electrical and magnetic nodal-network model is built using python.

⟶ Results from this model are analyzed in ANSYS/Abacus to evaluate the resulting mechanical response.

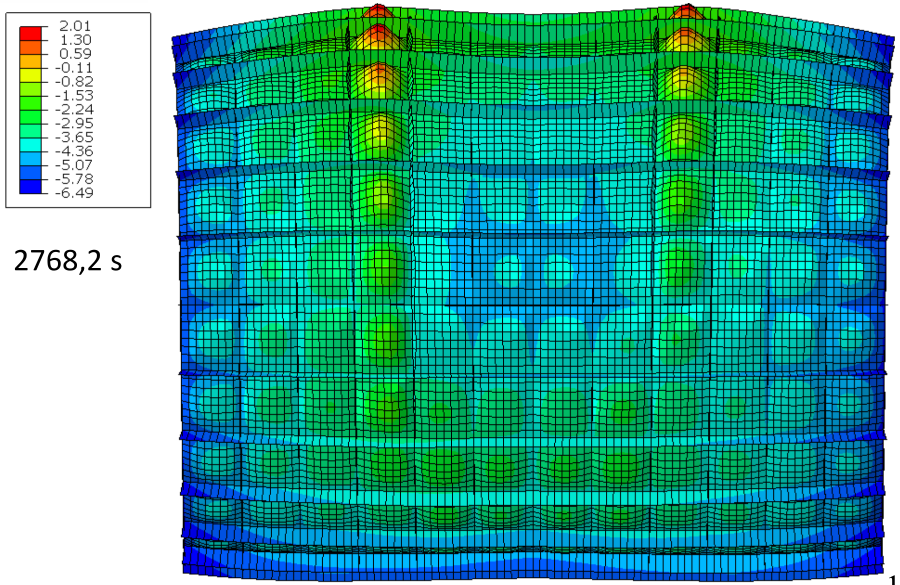
Tim Mulder, CERN   t = 907.7772 s



t = 907.7772 s



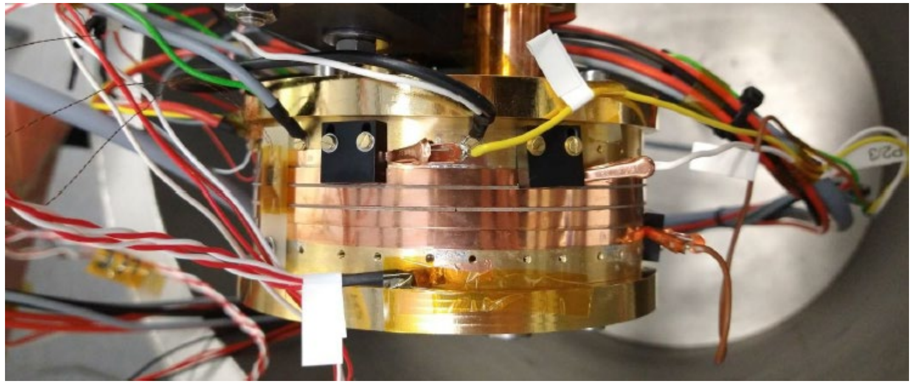
[mm]   Dominik. Pridöhl, Jannik Zimmermann, RWTH Aachen

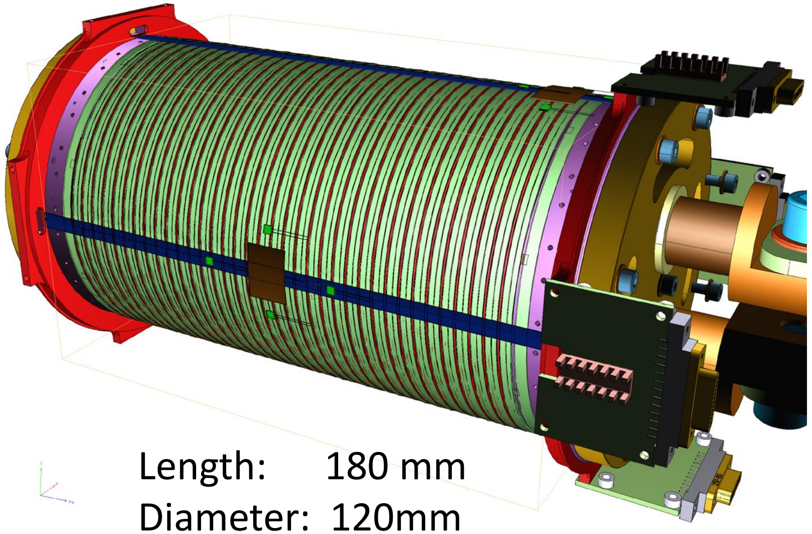


AMS-100: High Temperature Superconducting Magnet

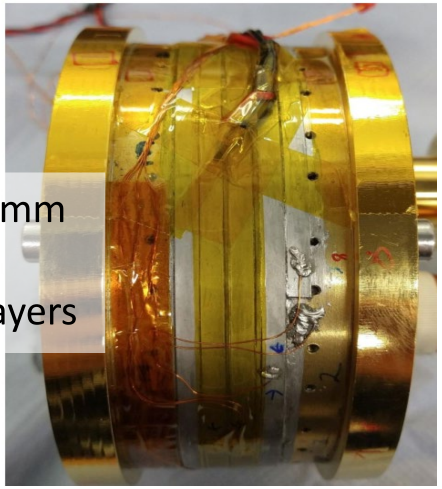
Several compact demonstrator coils are envisioned and in preparation.

- Test of materials and preparation procedures.
- Optimize soldering procedure
- Validate models and results (mechanical, electrical and thermal)
- Starting with small, few turn demonstrator coils, later moving to larger coils.
- Larger Coils will undergo space qualification tests

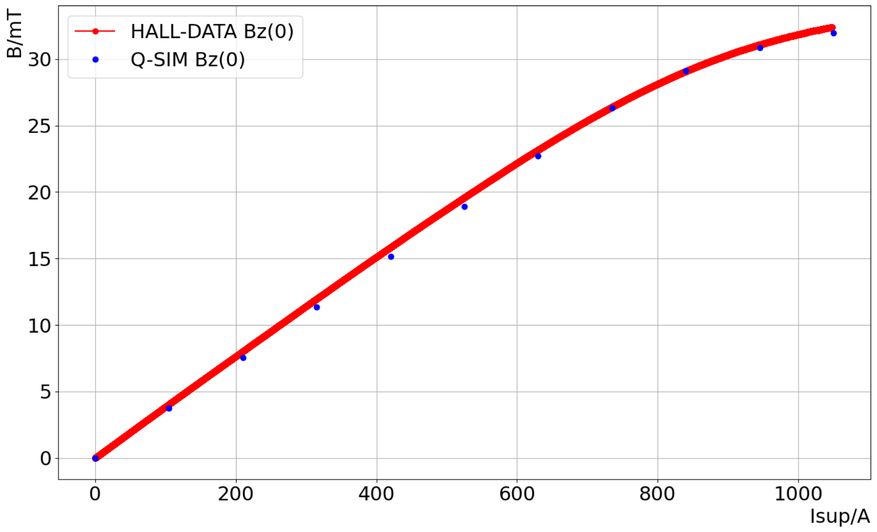




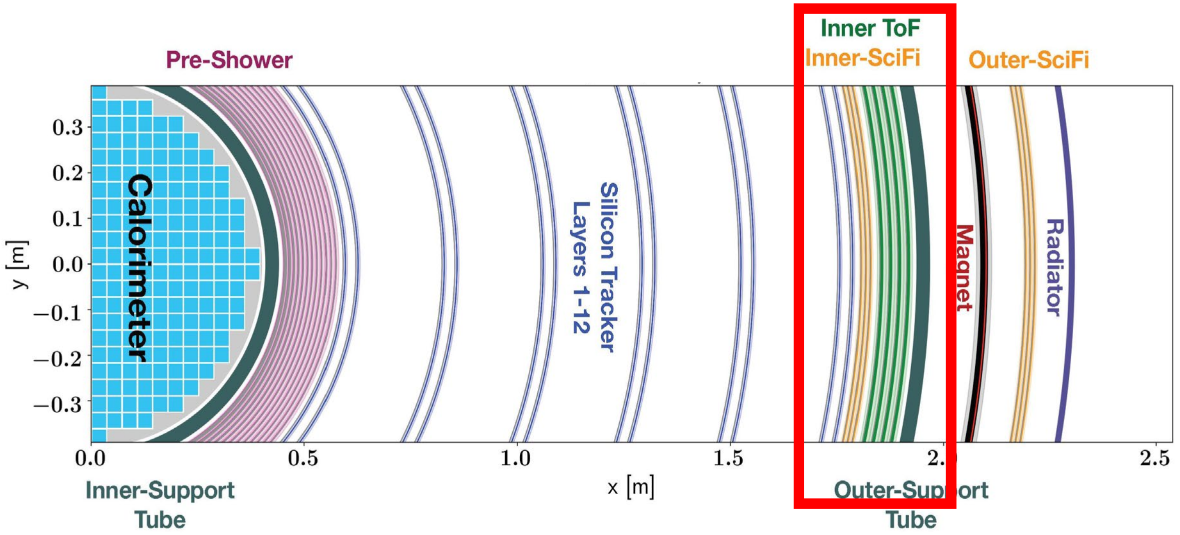
Length: 180 mm
Diameter: 120mm
Turns: 36
HTS 4mm, 8 Layers



Diameter: 120mm
Turns: 3
HTS 4mm, 8 Layers



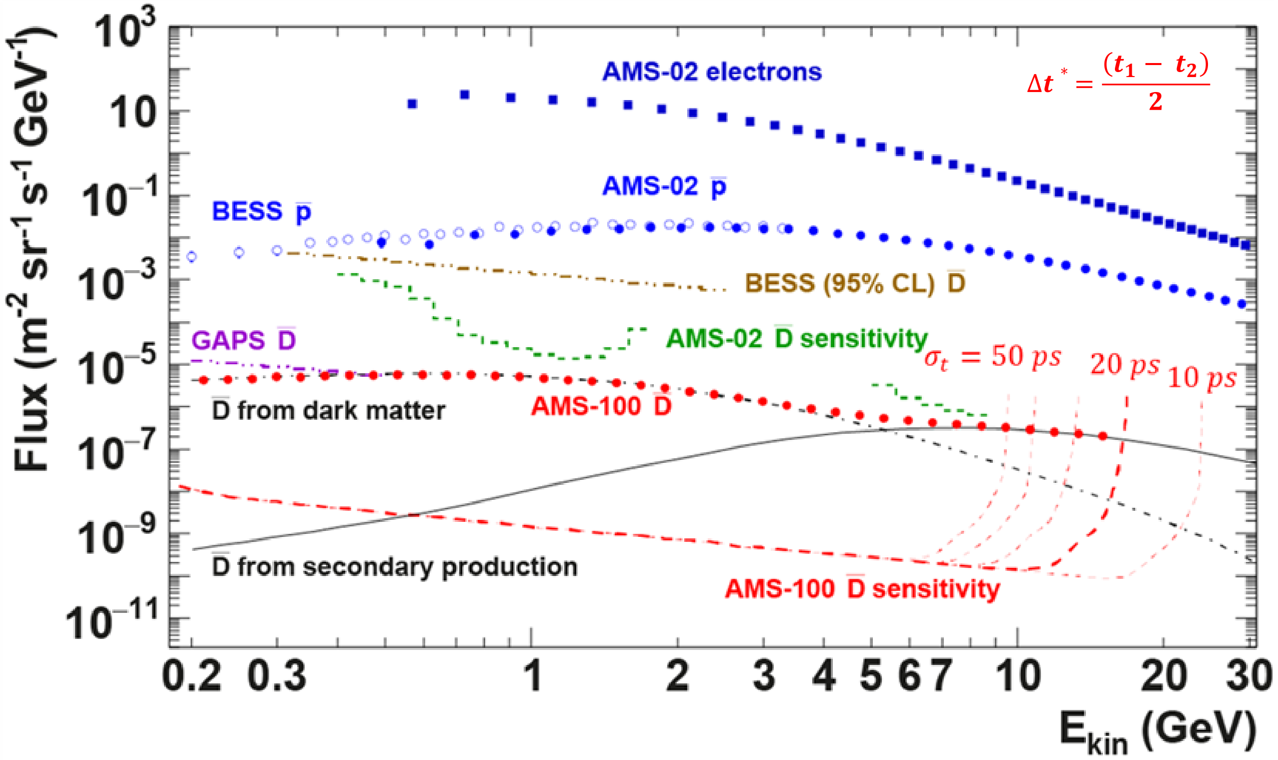
AMS-100: Time of Flight System



Anti-Deuterons are the most sensitive probe for New Physics in Cosmic Rays

AMS-100 would observe thousands of Anti-Deuterons in Cosmic Rays

- Required ToF-Single Counter time resolution : 20 ps
- Z measurements from the signal height
- Provides the trigger and measures **β** = v/c



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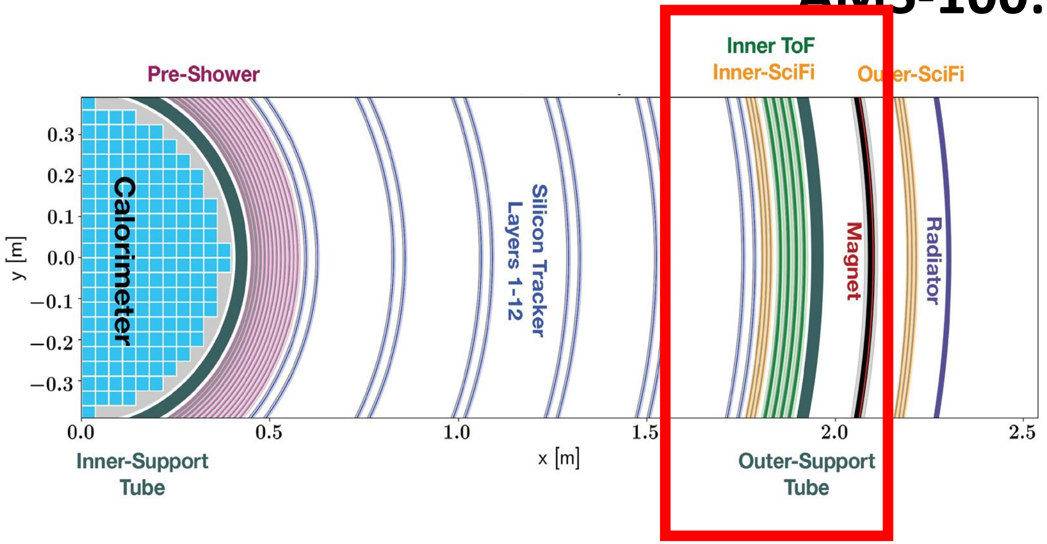
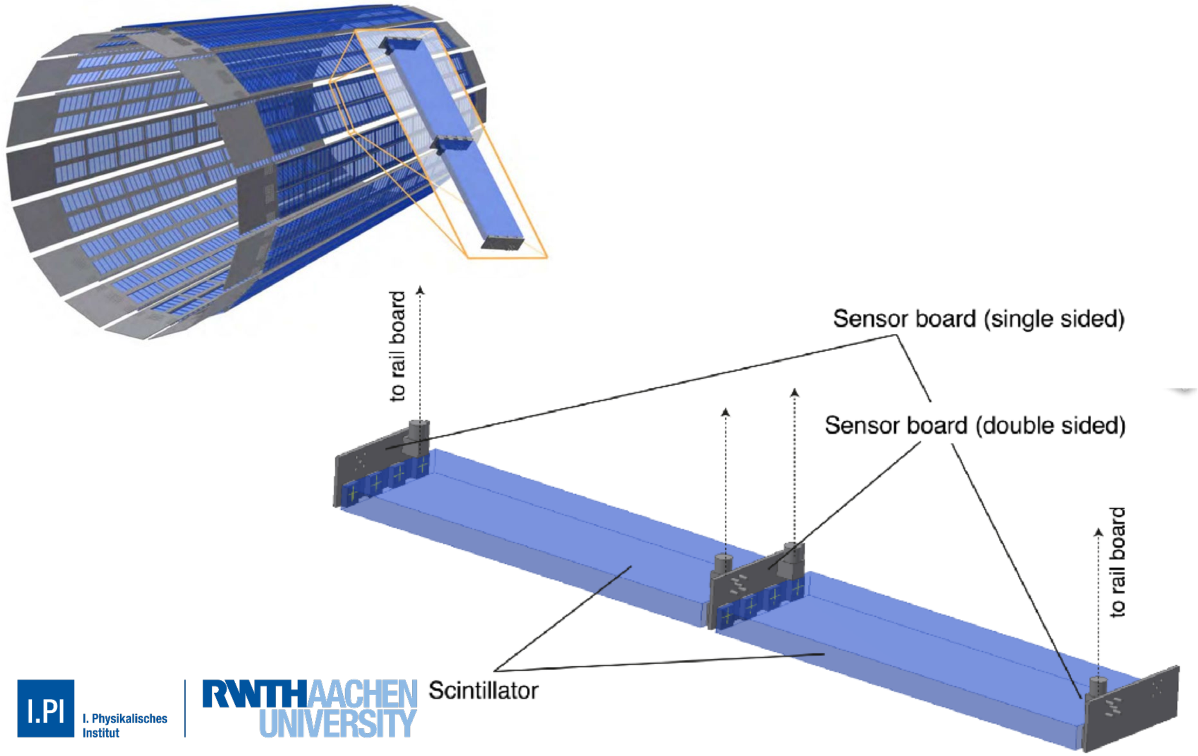


- Scintillator rods with SiPMs operating at 200 K
  - Scintillator dimensions 90 x 25 x 6 mm^3
  - Expected time resolution for one rod: 20 ps
- Similar to the PANDA Barrel TOF

  ⟶ Reached 50ps resolution

  But matching factor ≈ 0.25

The PANDA Barrel-TOF Detector Design



$$\sigma_t = \sqrt{\frac{\sigma_{scint}^2}{k} + \sigma_{SiPM}^2 + \sigma_{elec}^2}$$

σ_{scint} intrinsic time resolution of scintillator with full coverage

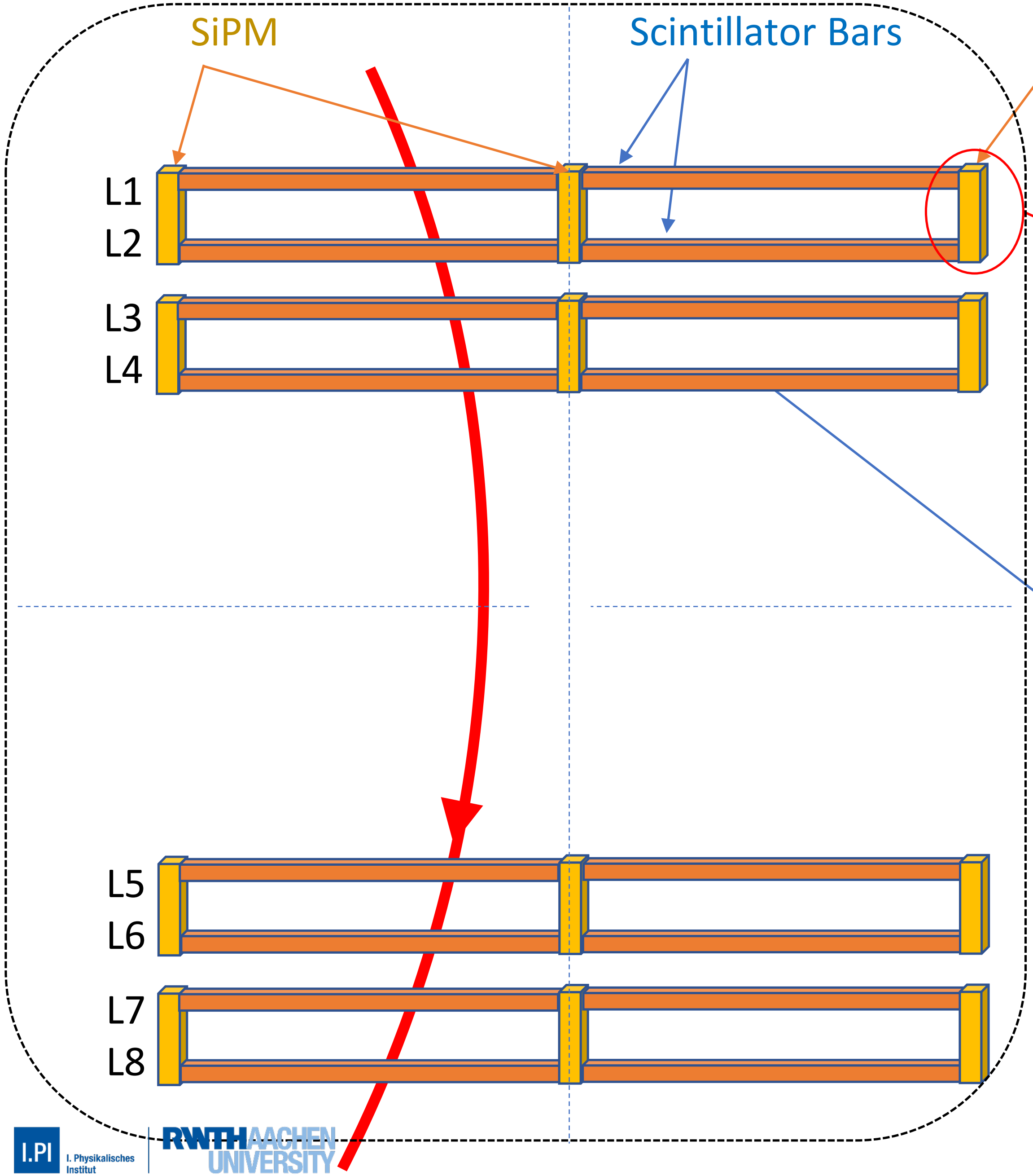
k is the fractional sensor coverage, matching factor

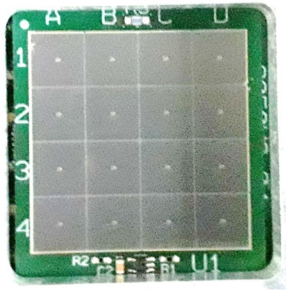
σ_{elec} ~ R_{amp} x C_{SiPM} and intrinsic noise of amplifier

→ full coverage of the frontface of scintillators, k=1

→ serial connection of SiPM cells ⟶ reduce C_{SiPM}

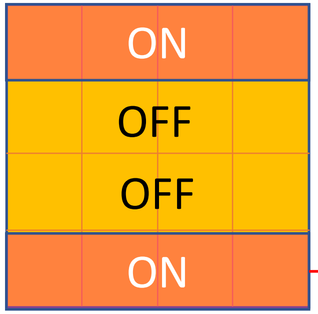
AMS-100: Time of Flight System



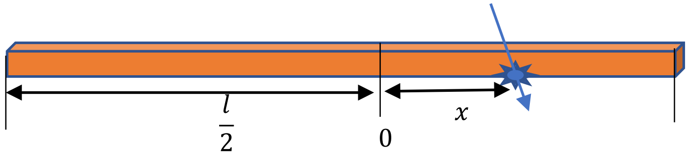


SiPM
(Hamamatsu S14161-6050HS-04)

Single Array Size = 6mm × 6mm
Total Nr. Arrays = 4 × 4
Array Connection : Hybrid
VBR = 38V
Peak Sensitivity (450nm, PDE=50%)
Capacitance C $_{SiPM}$ = 2000 pF



4 Array signals are summed up and fed into one channel



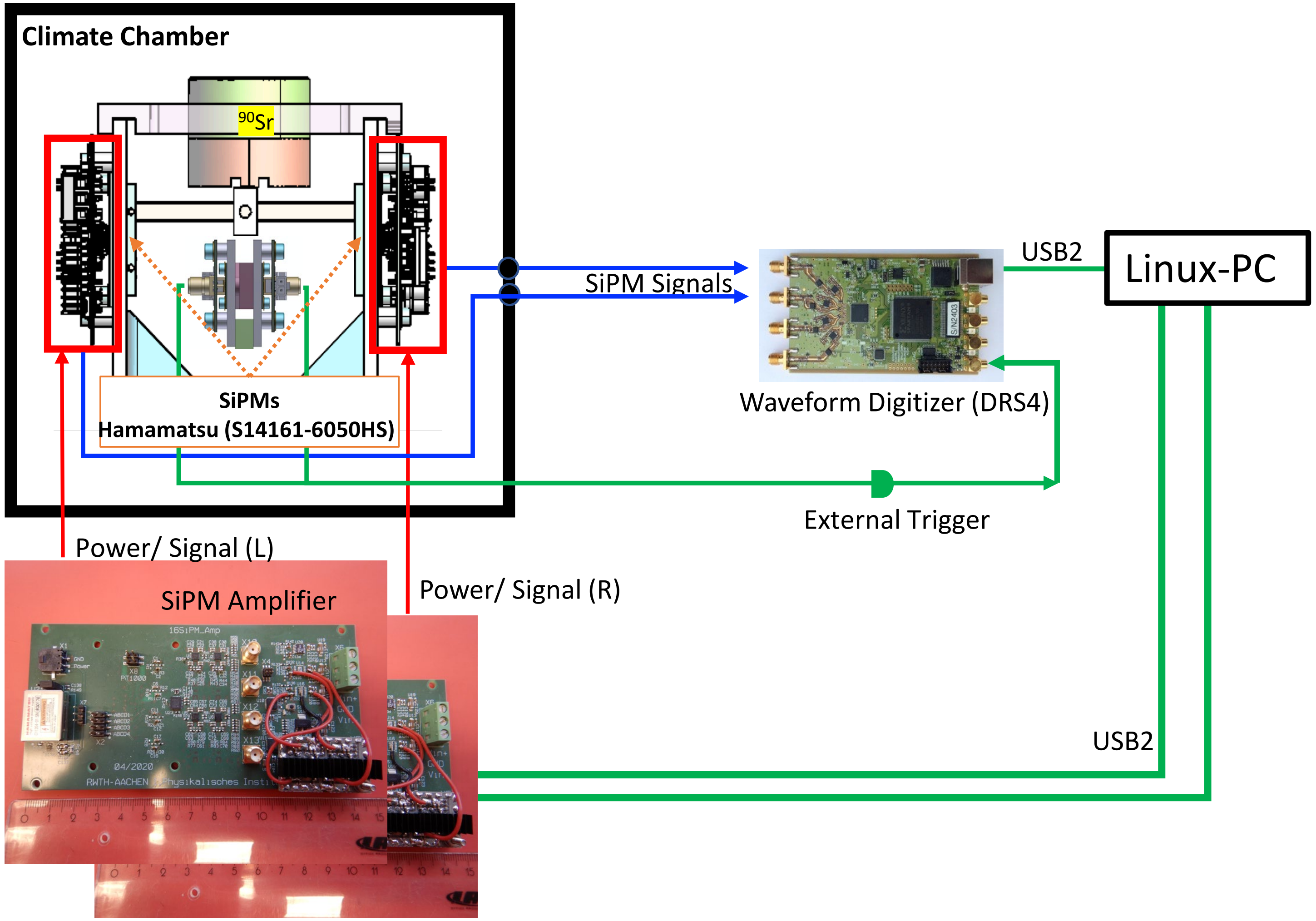
(Eljen 228)

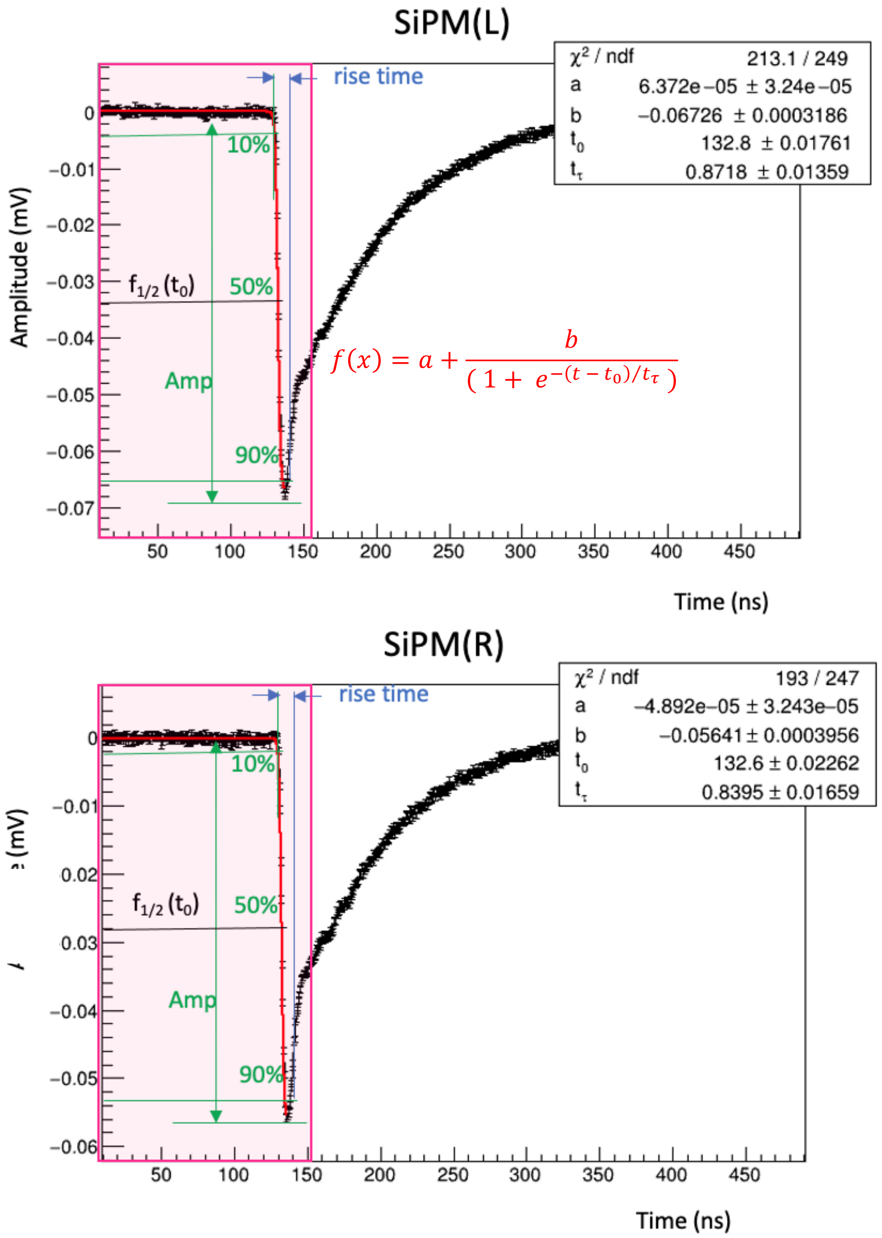
Single Scintillator Size (D×W×L) = 6mm × 25mm × 90 mm
Matching-Factor = 1.0 (fased D×W sides to SiPM)

TOF Time Resolution$(\sigma_t)_{\text{req.}} = 20\ (ps)$

AMS-100: Time of Flight System

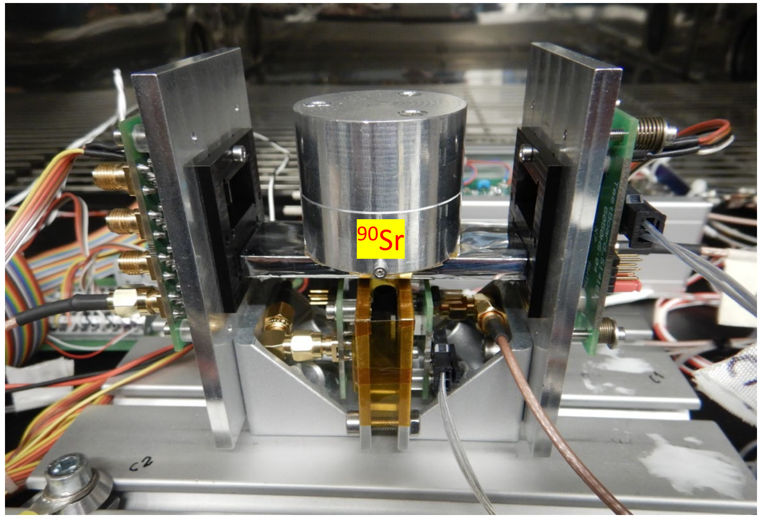
External triggered / Self-triggered Setup:



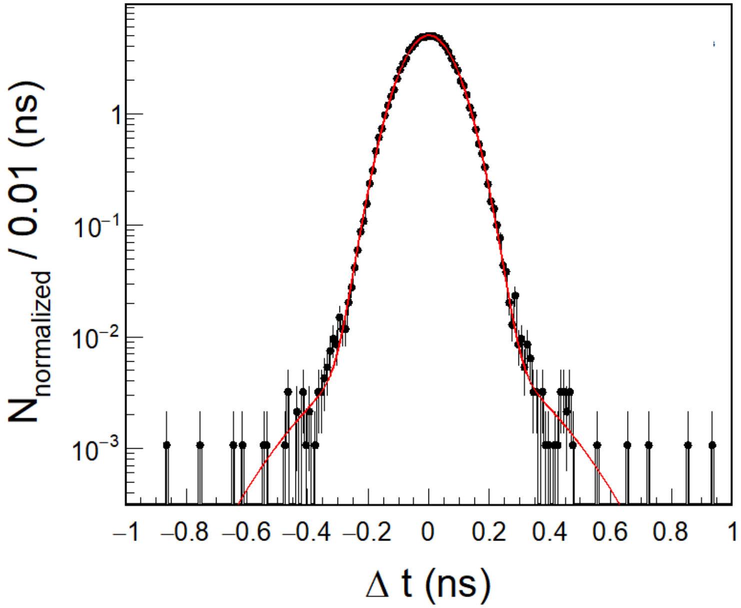


AMS-100: Time of Flight System

External Triggered Events:



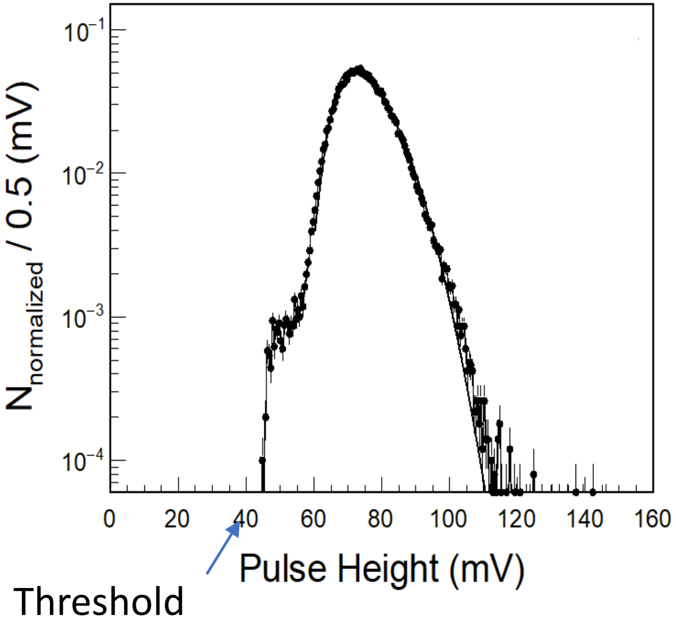
^{90}Sr, EJ-228 (6 mm x 25 mm x 90 mm), PCB-Ch4(Hybrid), T=23°C

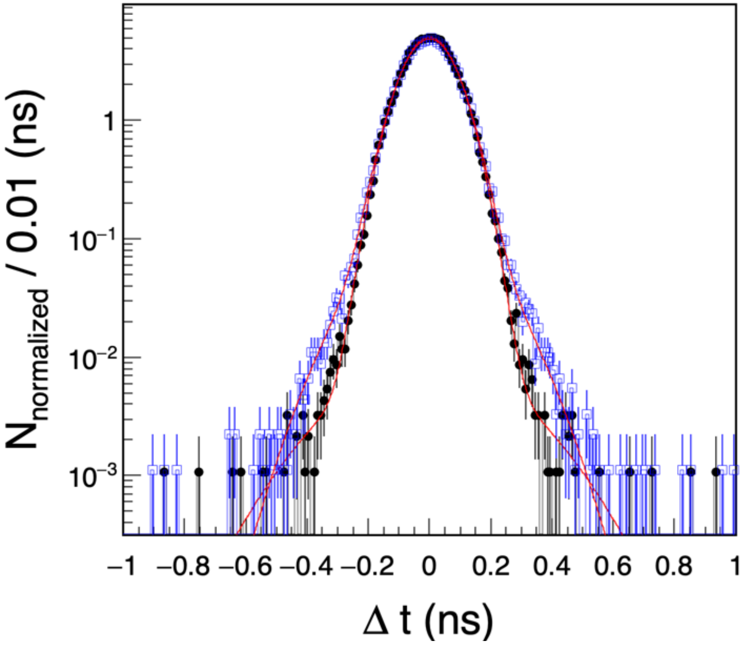


Coincidence Time Resolution (CTR, $\sigma_{\Delta t}$)
For triggered MIP-particles: $\sigma_{\Delta t}$ = 78.7 ps

Time Resolution (σ_t): $\sigma_t = \frac{\sigma_{\Delta t}}{2}$

$$\sigma_t = (39.3 \pm 0.1(stst.) \pm 0.7(syst.))\ ps$$





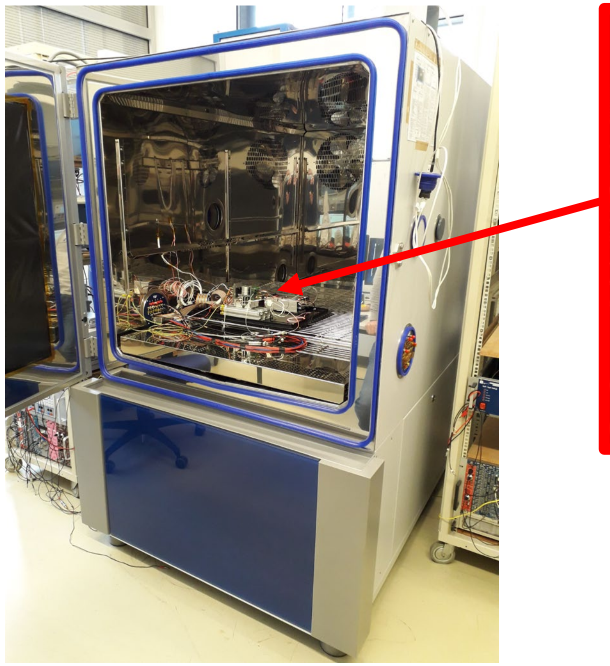
Wrapping/Reflector Studies:

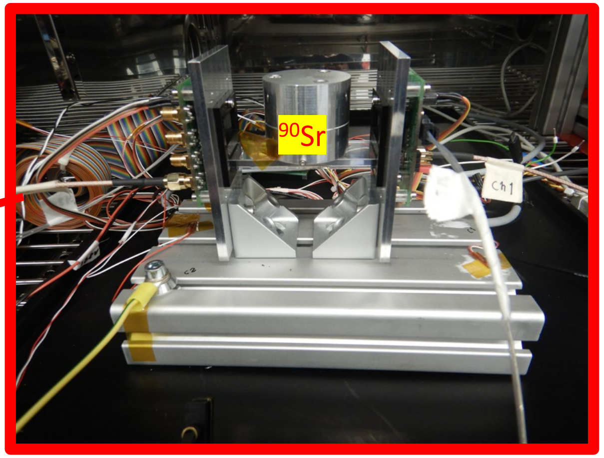
$$\sigma_{t,\,al.Mylar} = 39.3\ ps$$
$$\sigma_{t,PTFE} = 39.9\ ps$$

Next steps: Reduce R_{amp} x C_{SiPM} to improve σ_t

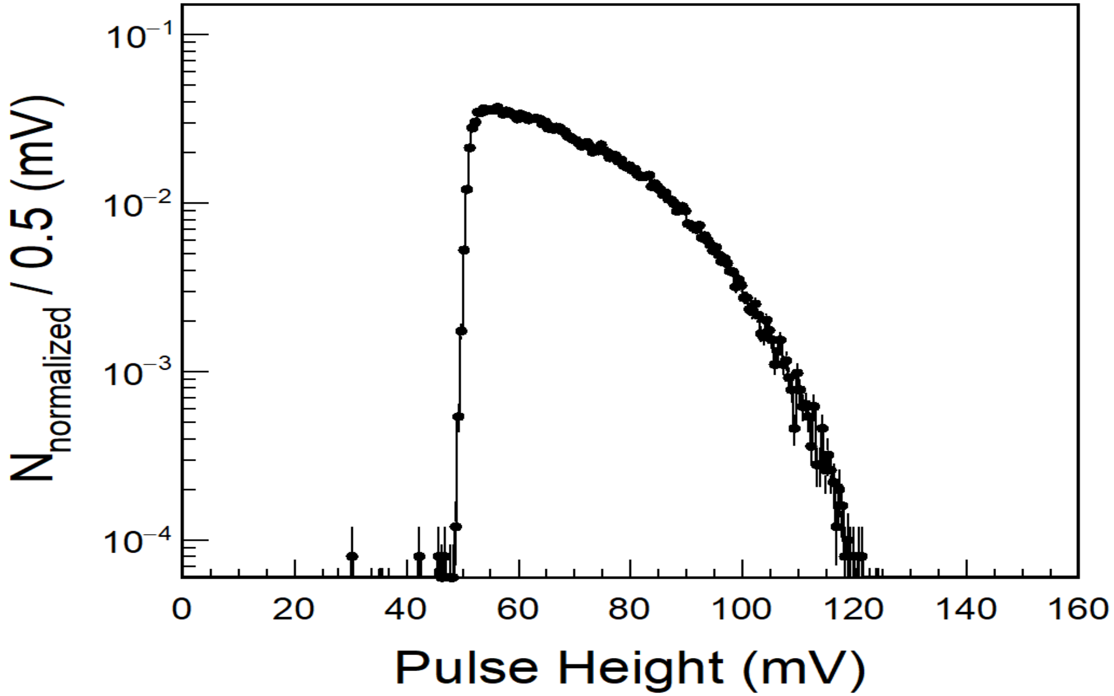
AMS-100: Time of Flight System

Temperature Variation:
Self triggered measurement, threshold 10 mV ⟶ 0.5 MeV e^-

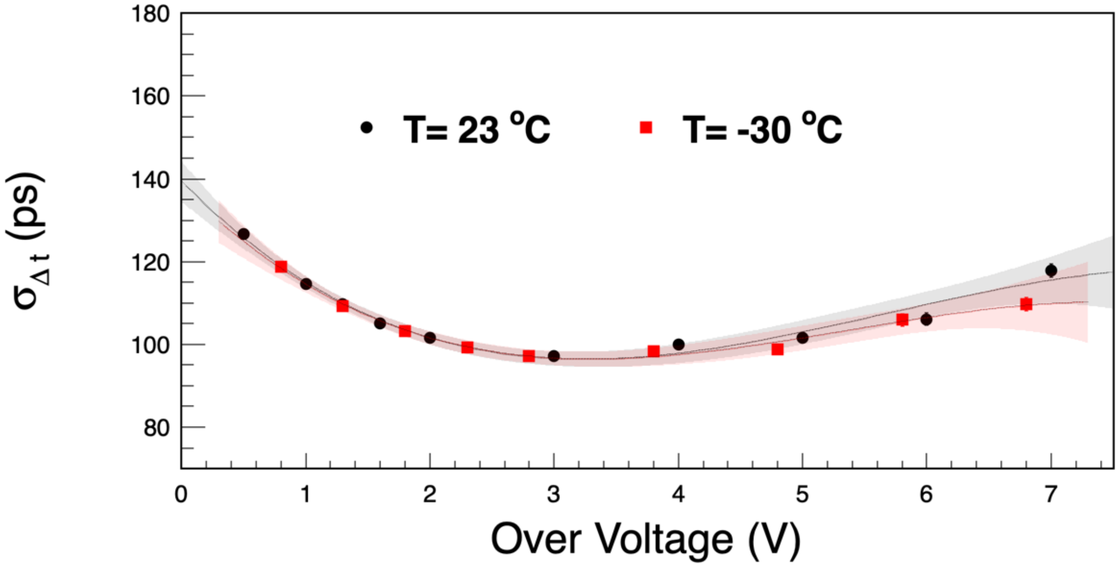




^{90}Sr, EJ-228 (6 mm x 25 mm x 90 mm)

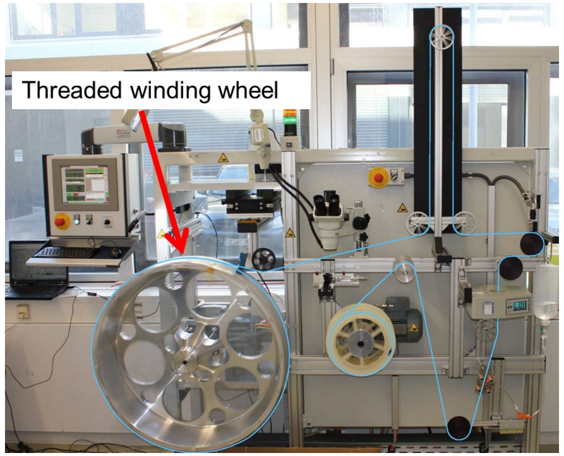


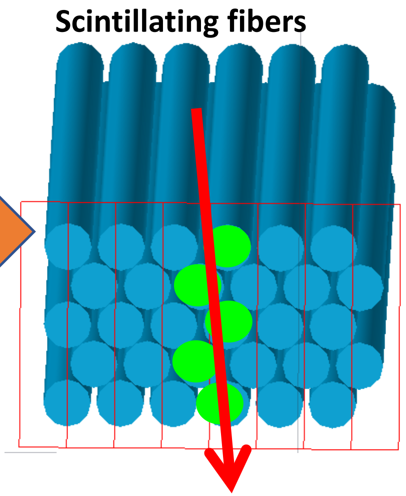
Coincidence Time Resolution (CTR, $\sigma_{\Delta t}$)

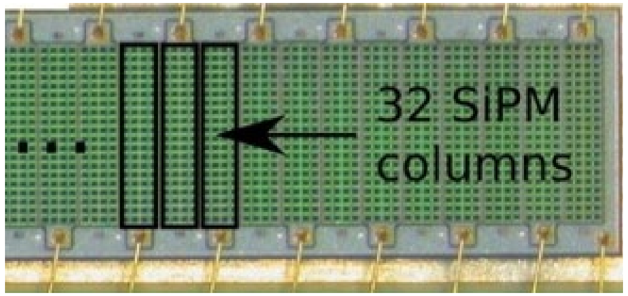


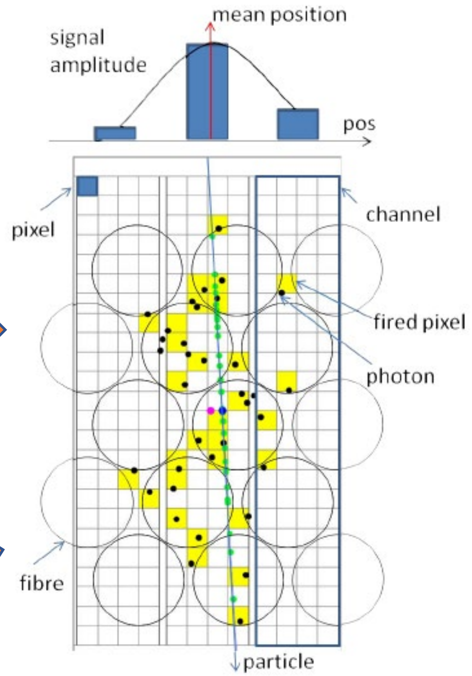
Time Resolution not significantly depending on temperature in the temperature range 23°C to -30°C

AMS-100: Scintillating Fiber Tracker

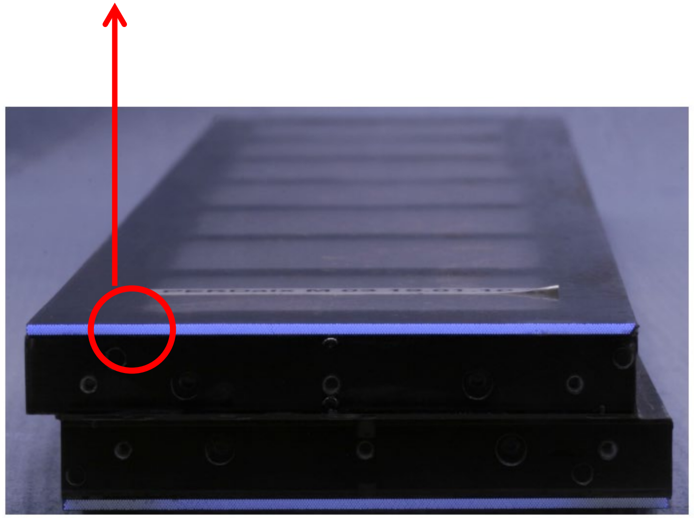


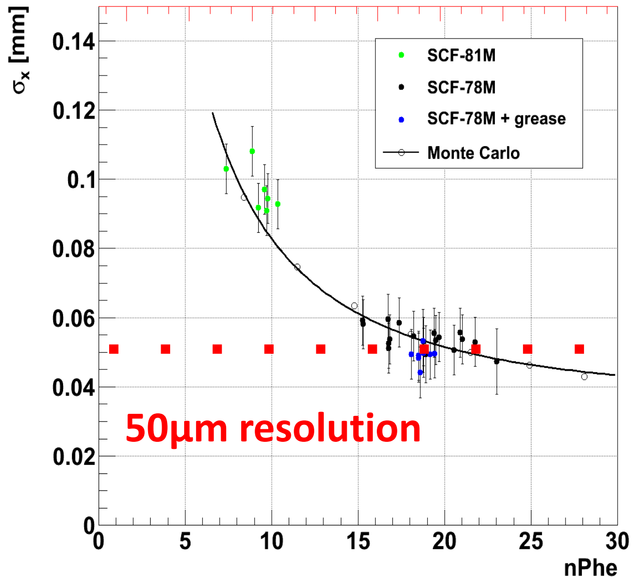






- Staggered layers of Ø250 μm fibres form a fibre mat
- Readout by arrays of SiPMs. 1 SiPM channel extends over the full height of the mat.
- Pitch of SiPM array should be similar to fibre pitch. Light is then spread over few SiPM channels. Centroiding can be used to push the resolution beyond p/sqrt(12).



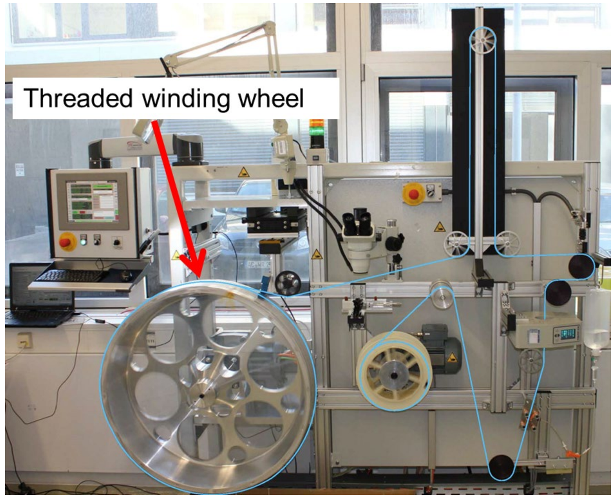


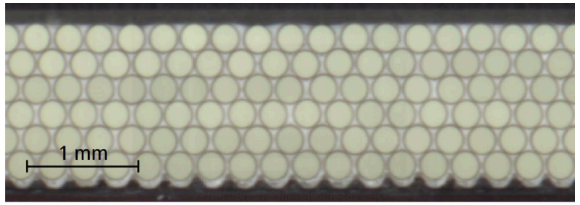
AMS-100: Scintillating Fiber Tracker

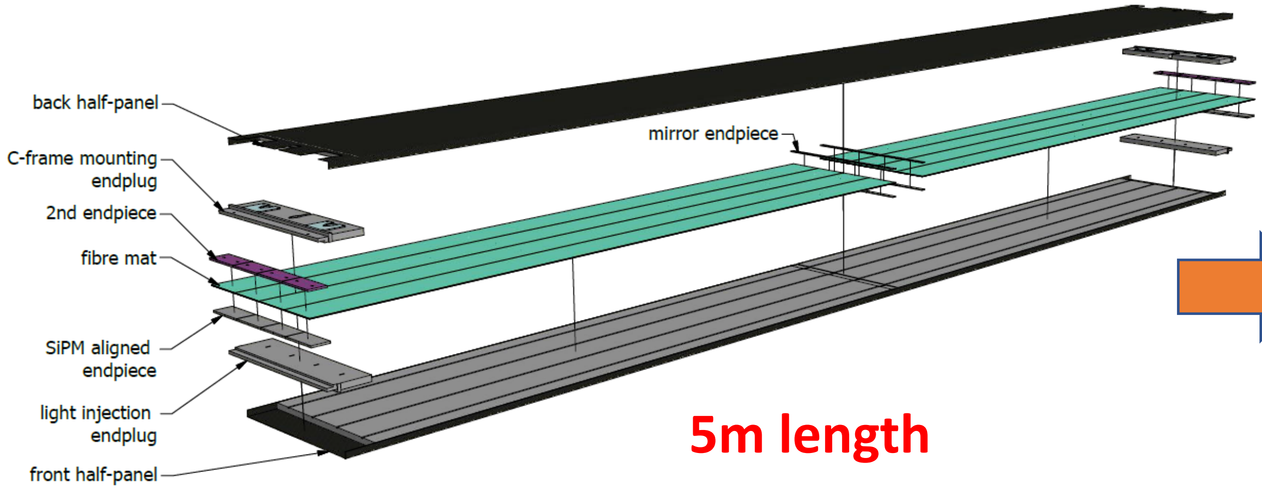
LHCb-SciFi-Tracker:

Fiber Mat Winding

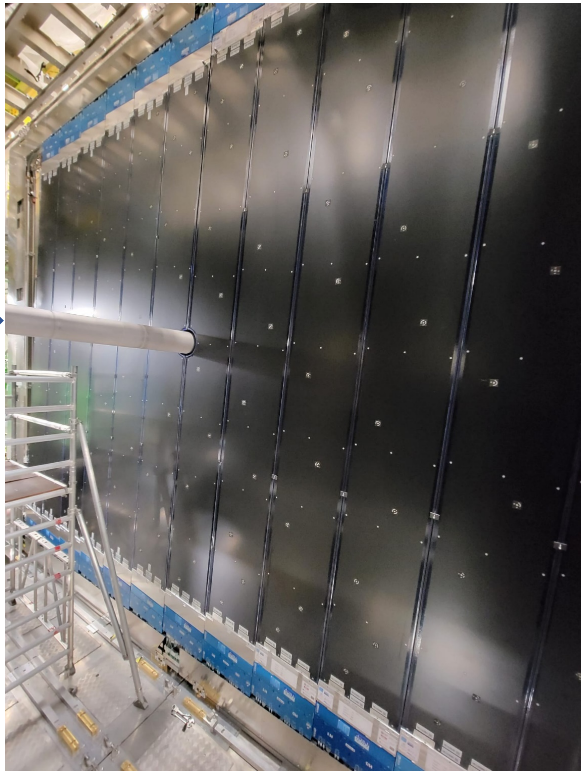
→ 10,000 km of fibre in total







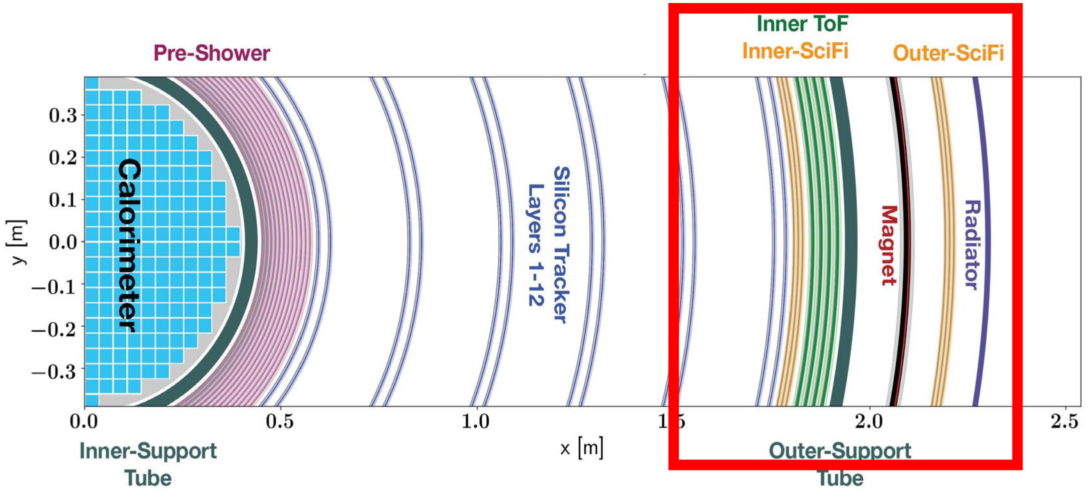
5m length



See talk Lais Soares Lavra: „The Scintillating Fibre Tracker for the LHCb Upgrade"

1152 SciFi mats, 144 Modules, 340 m² total area

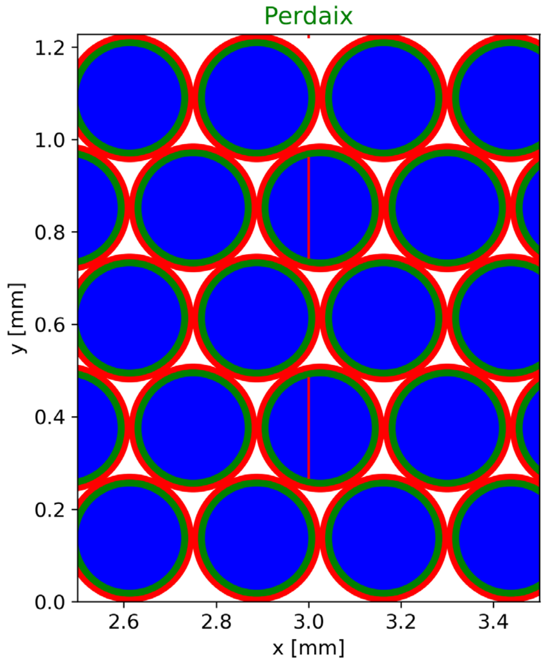
AMS-100: Scintillating Fiber Tracker



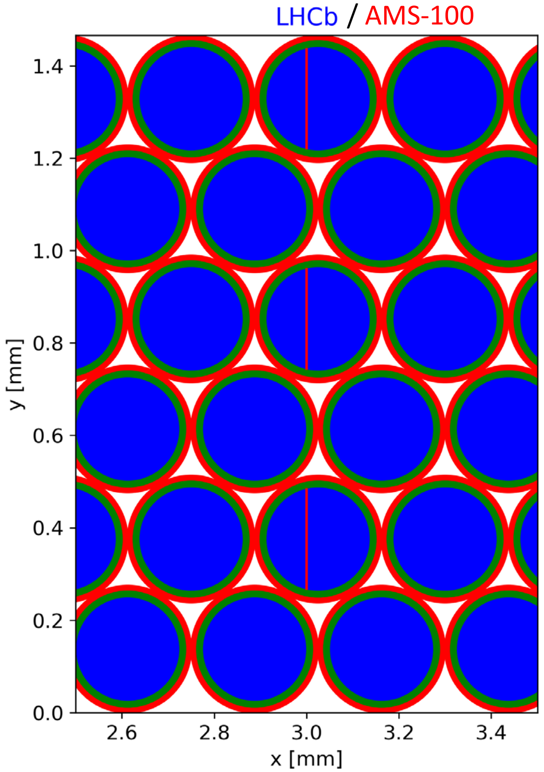
First & Fast Measurement of R and Z; MDR: 3TV
Provides 2x6 Measurements with
40 µm resolution (using 250µm thick fibers), MDR 3TV
or
13 µm resolution (using 125µm thick fibers), MDR 9TV

$$\sigma = FiberWidth/\sqrt{12}/\sqrt{nFiber}$$

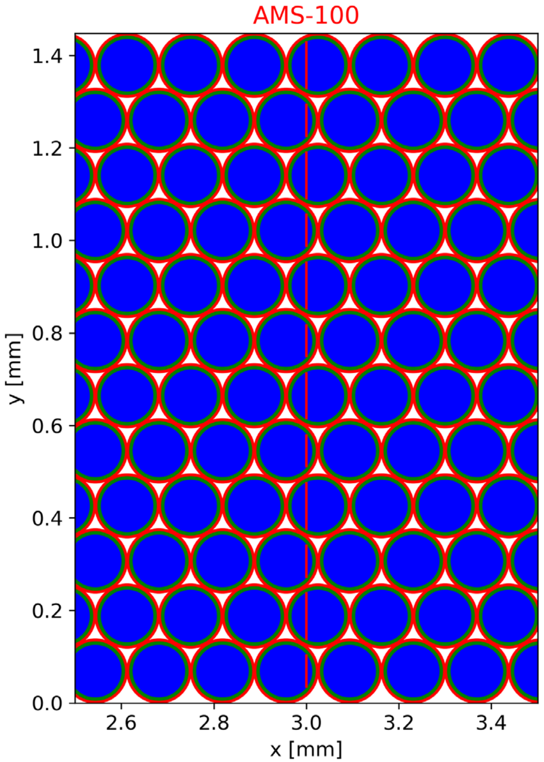
5 Layers, 0.25 mm Fibers



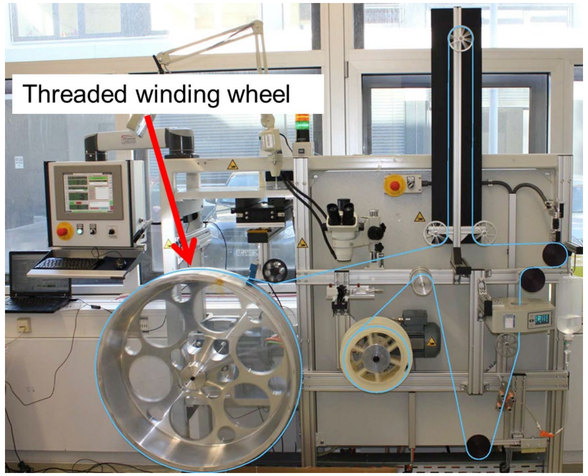
6 Layers, 0.25 mm Fibers



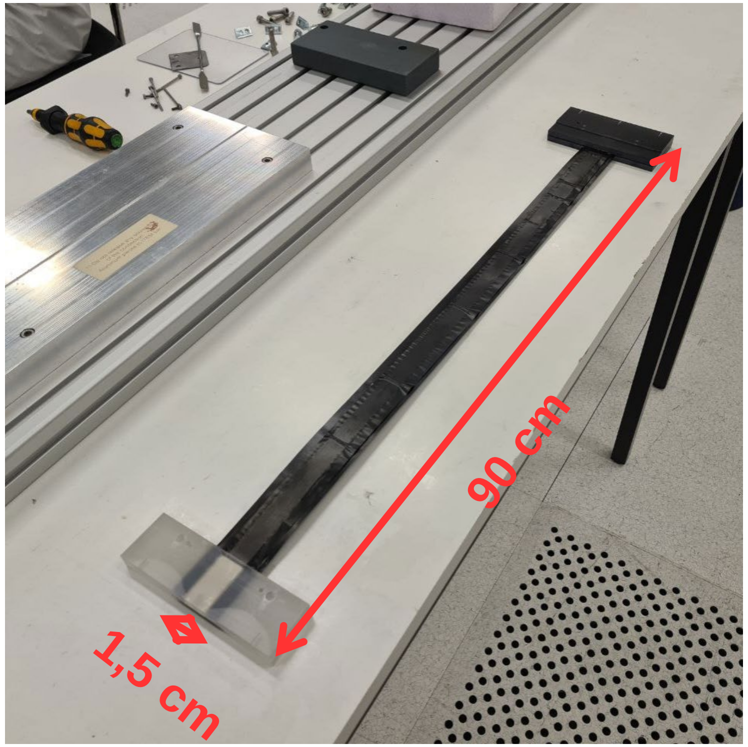
12 Layers, 0.125 mm Fibers



AMS-100: Scintillating Fiber Tracker

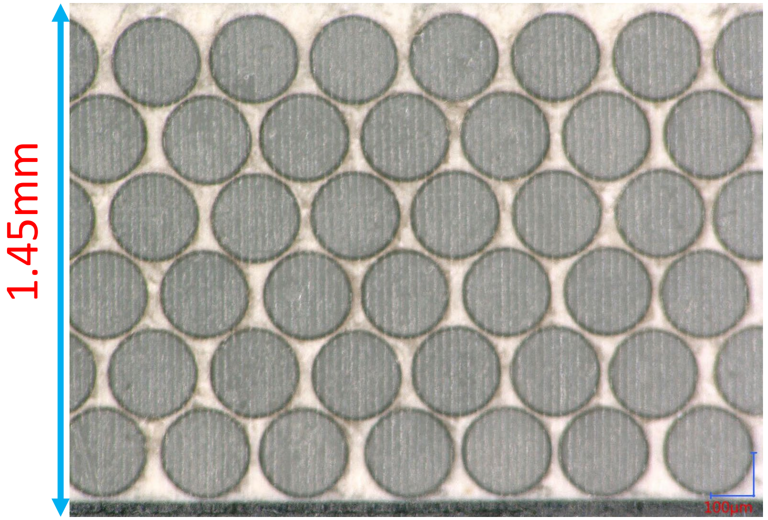


Production of 12 layer fiber mat made out of 125µm thick fibers from Kuraray,
LHCb winding machine @ I. Physics Institute adapted to 125µm fibers,
winding force less then **5cN**.

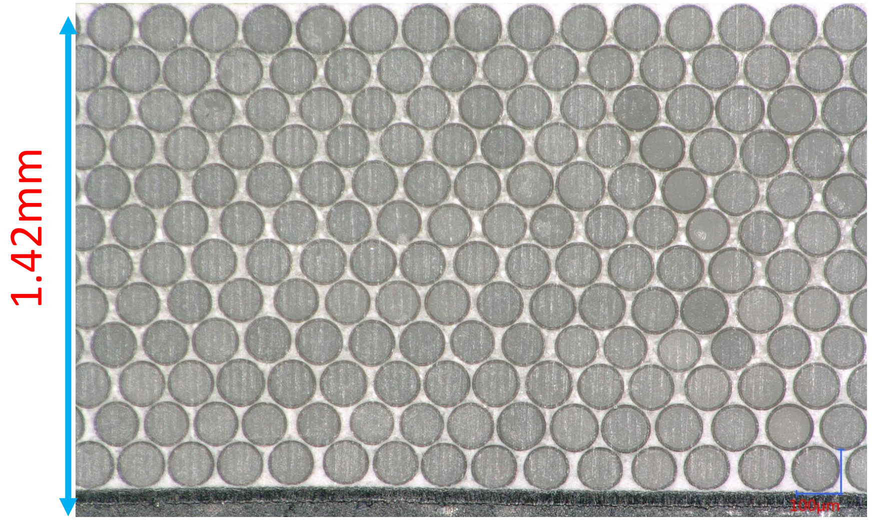


12 Layer fiber mat with 125µm thick fibers produced
L = 90cm, W = 1,5cm, H= 1.42 mm

6 layer 250µm fiber mat



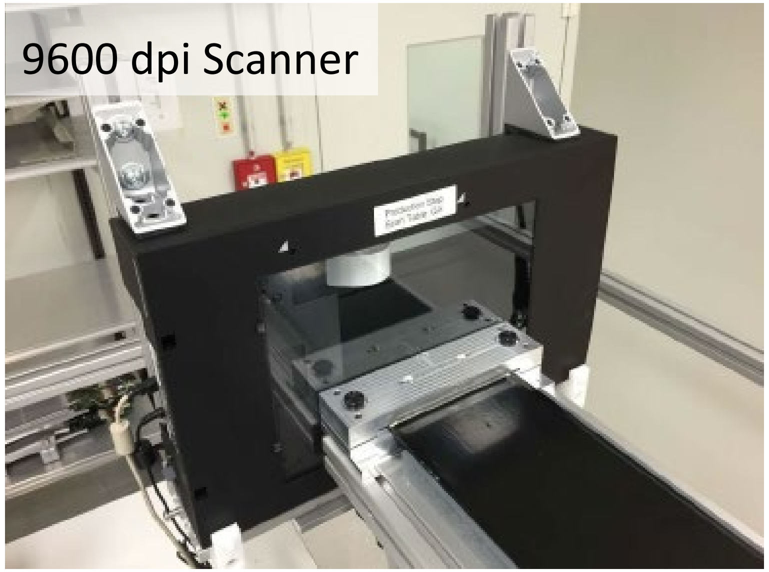
12 layer 125µm fiber mat



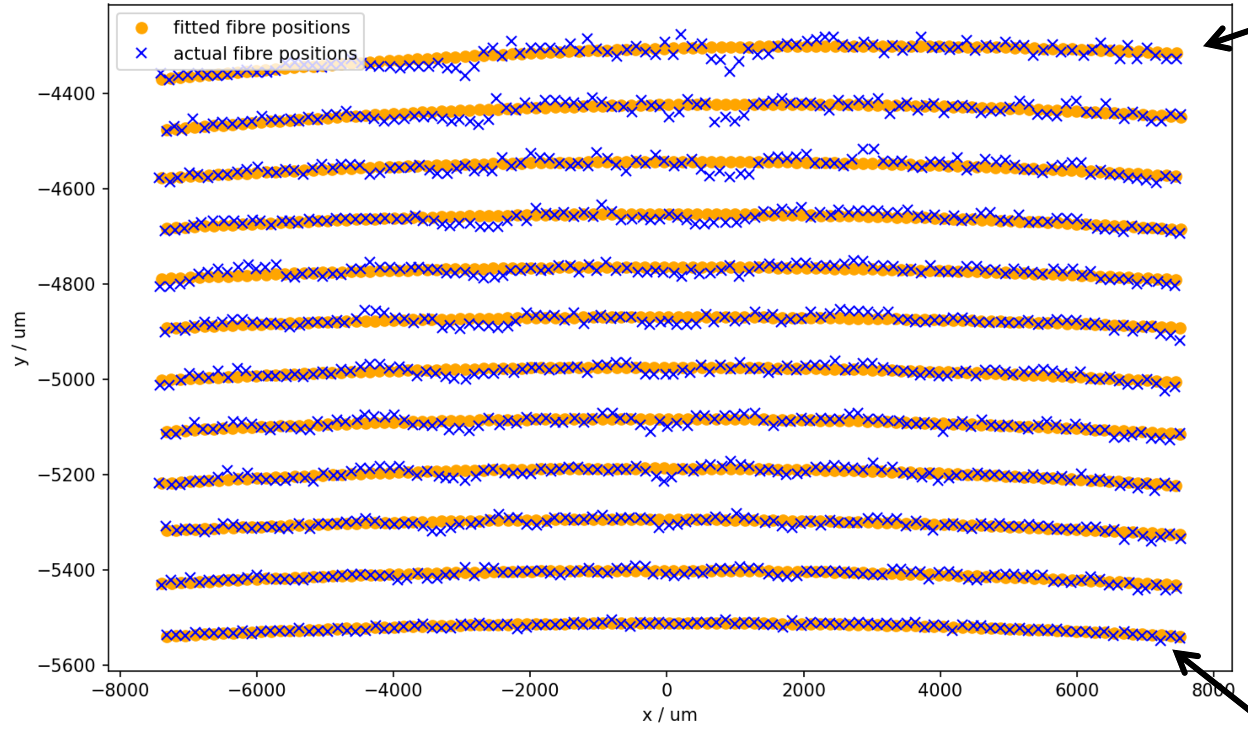
⟶ Production of 1st Fiber mat with 125µm thick fibers successful!

AMS-100: Scintillating Fiber Tracker

Optical Scan of 12 layer fiber mat with 125µm thick fibers



12th wound layer



1st wound layer

Fitted angled quadratic formula per fibre layer:

Distance between fitted and actual fiber position increases from

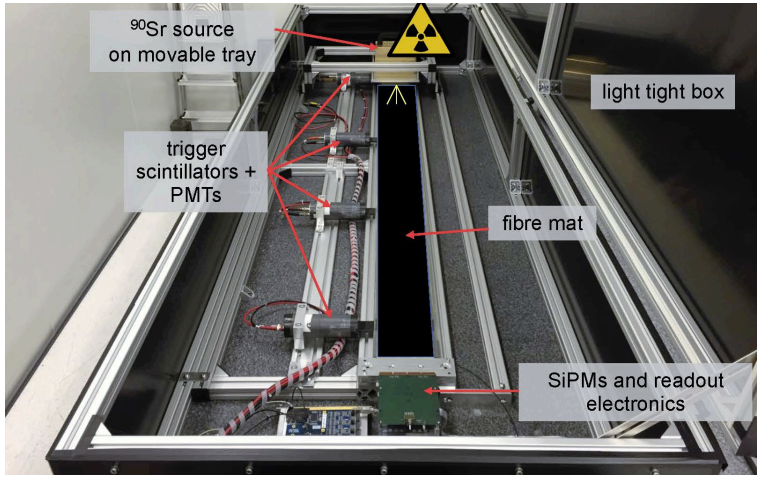
6 µm (1st wound layer) till 17µm (12th wound layer);

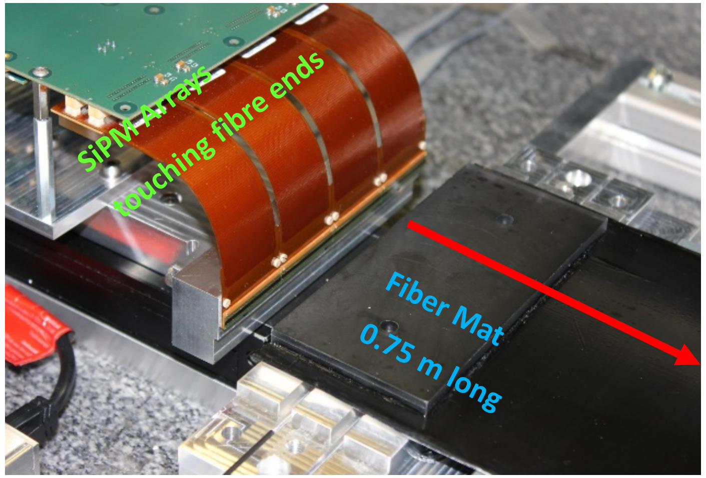
Average distance between fitted and actual fibre position: **13.3 µm**

⟶ Total Position Resolution (σ_x) = 13 µm ⨁ 13.3 µm = 19 µm ⟶ MDR 6TV

AMS-100: Scintillating Fiber Tracker

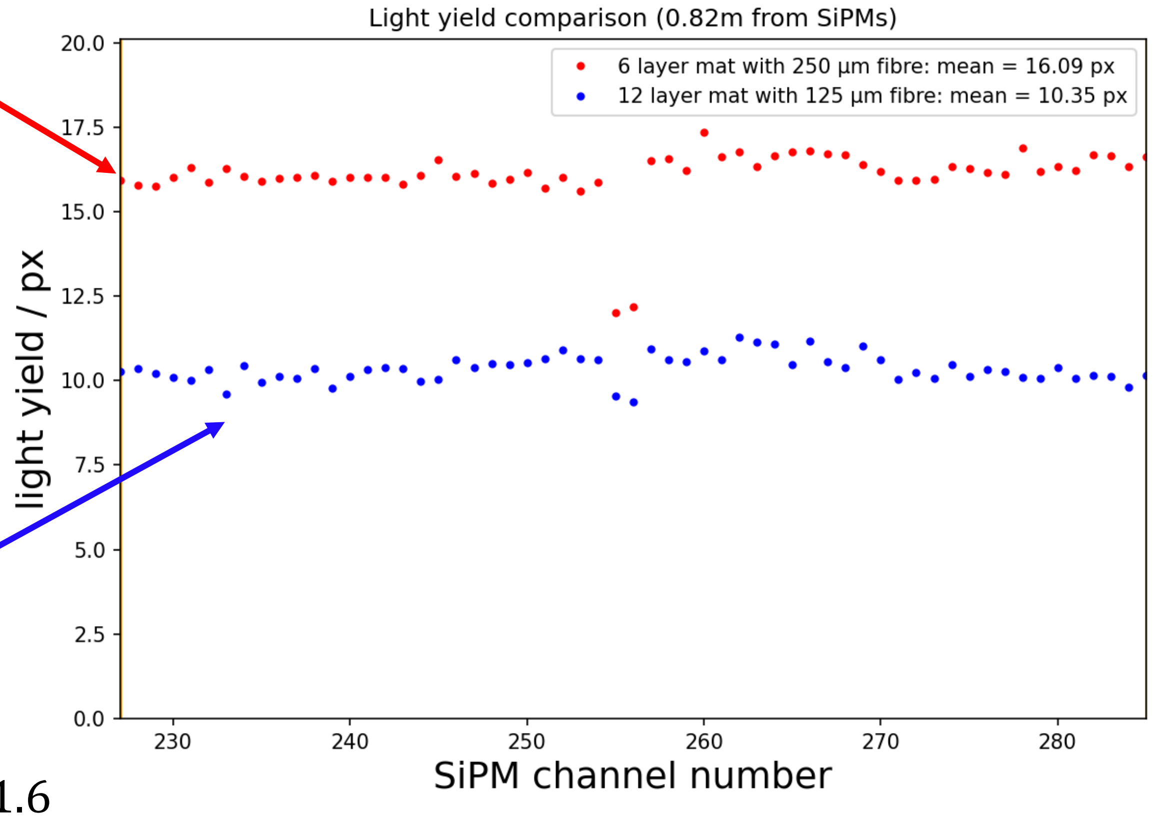
Light yield Measurements using Sr90-radioactive source to excite 12 layer fiber mat with 125µm thick fibers





6-layer Fiber mat with 250 µm thick fibers

12-layer Fiber mat with 125 µm thick fibers



$$R_{LY} = \frac{LY_{250\mu m}}{LY_{125\mu m}} = \frac{16.1}{10.4} = 1.6$$

$$R_{LY}\, exp. @0.8m\ from\ SiPM = 1.11$$

⟶ Lightyield of 12 layer fiber mat with 125µm thick fibers lower than expected!

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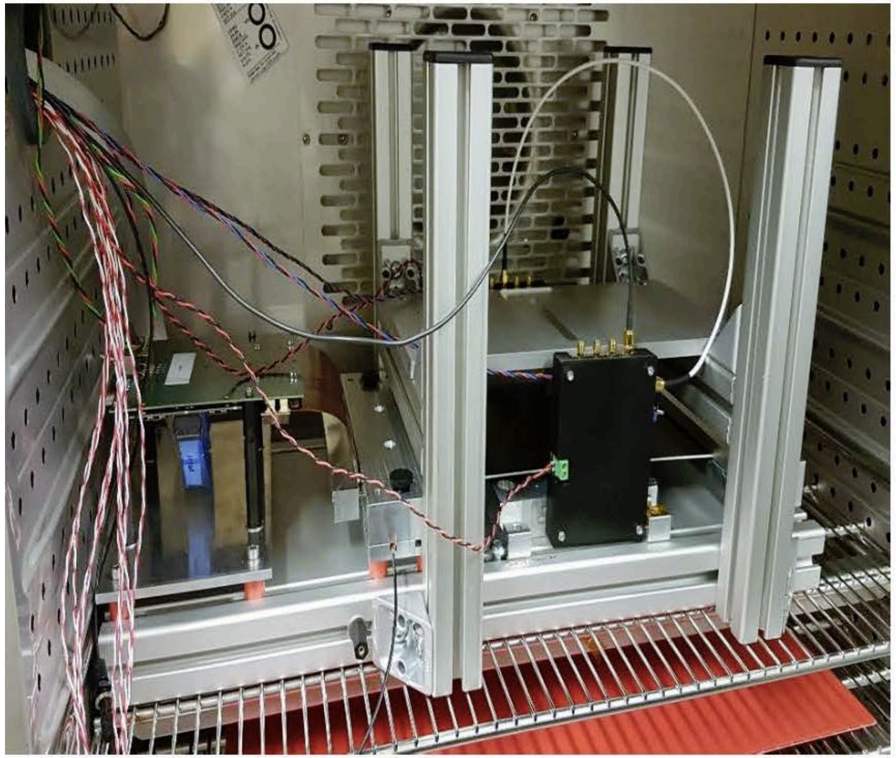
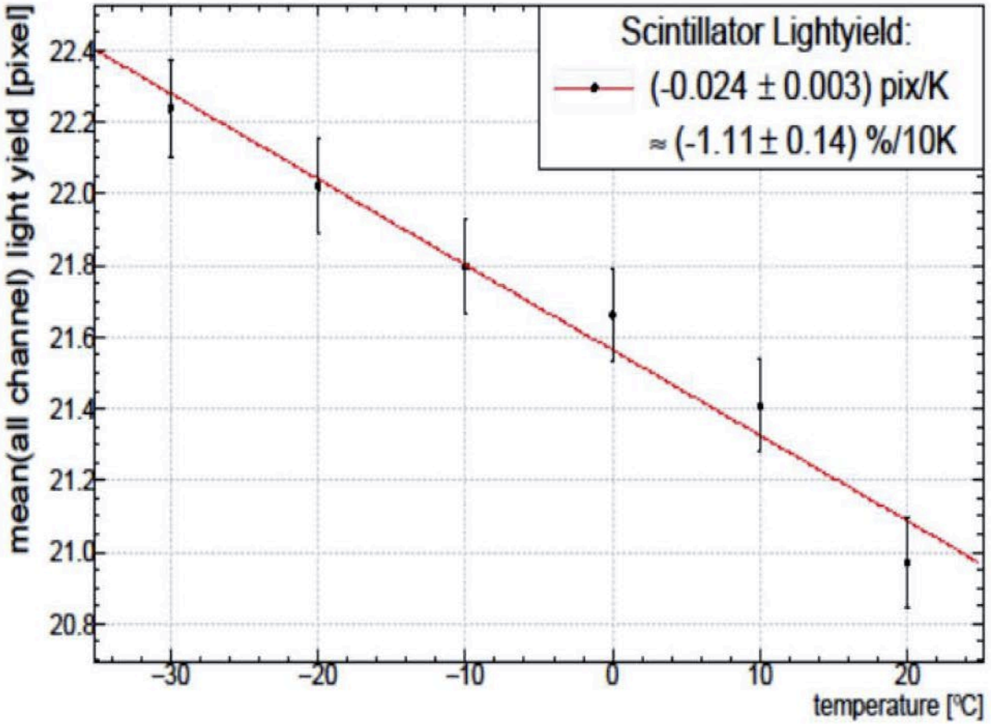
AMS-100: Scintillating Fiber Tracker

Lightyield of 6 Layers SciFi-Mat with 250µm fibers measured at lower temperatures

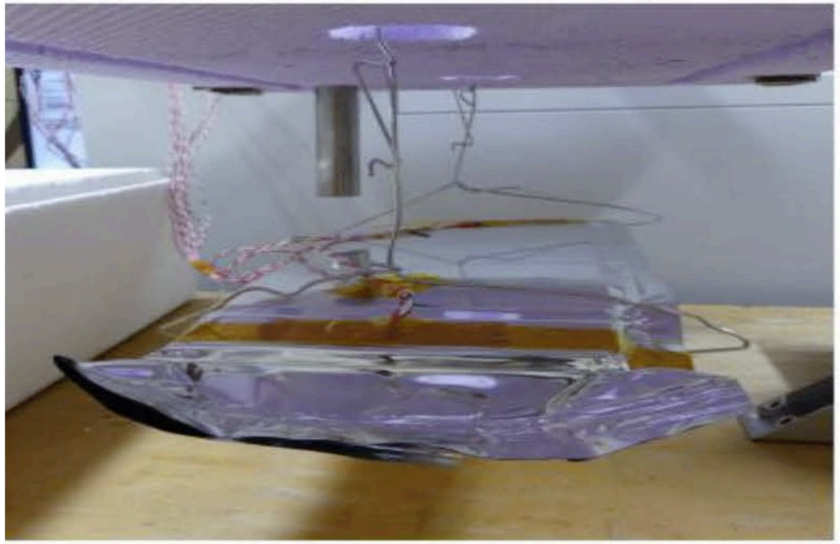


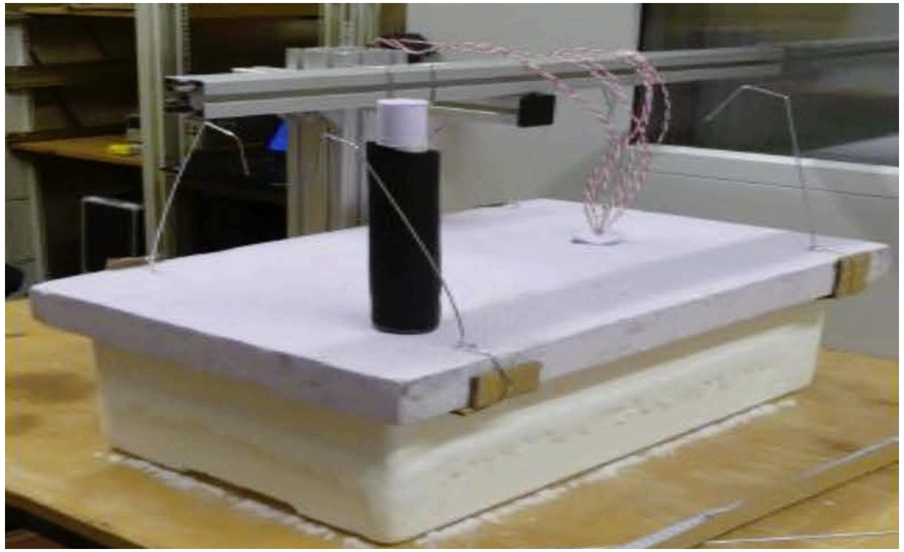


⟶ Lightyield(T) = 0.11 % /K

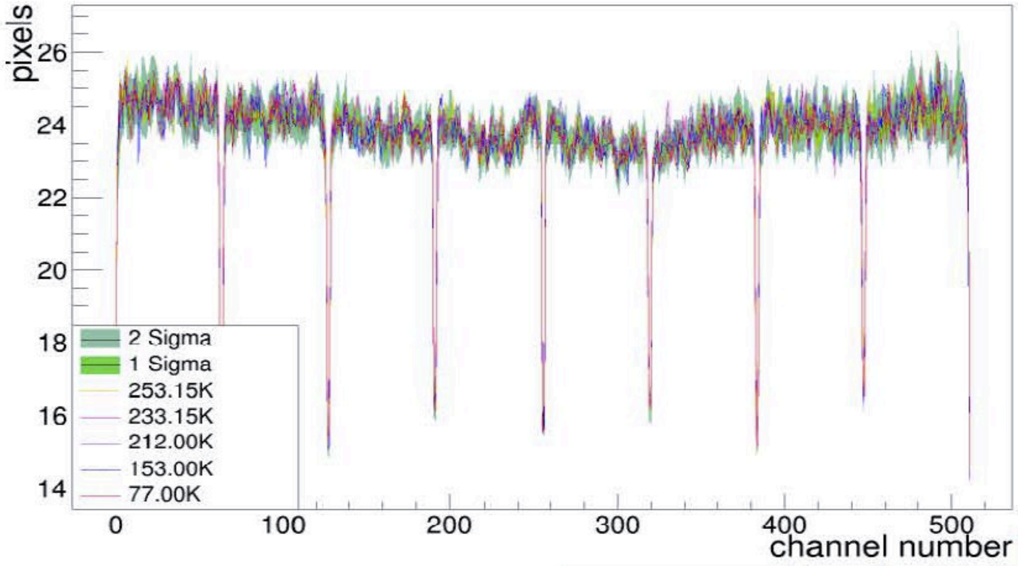
AMS-100: Scintillating Fiber Tracker

6 Layers SciFi-Mat (0.25mm Fibers) @ temperature range 77 K - 253K



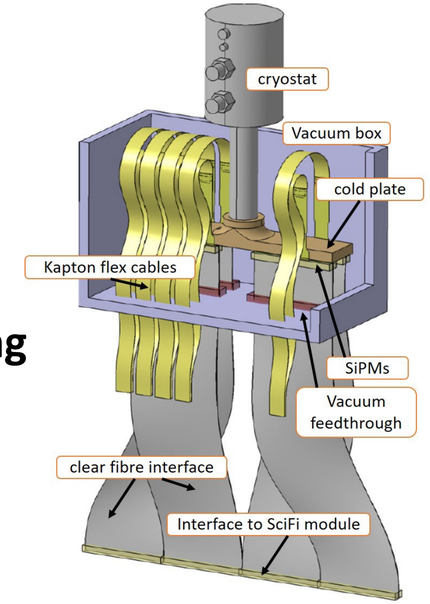


Light yield before and after cryogenic temperatures



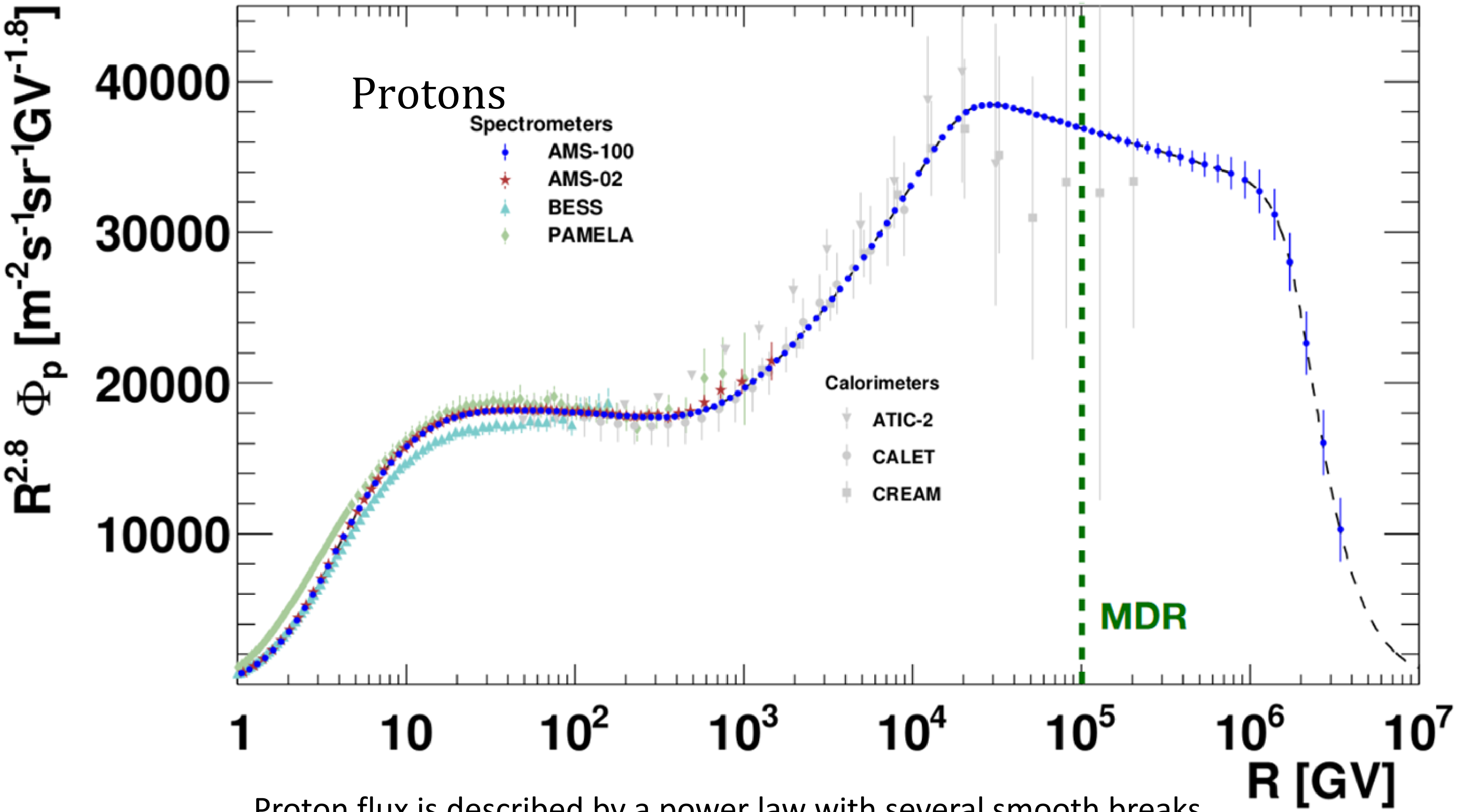
⟶ no significant changes in performance

⟶ LHCb SciFi-Tracker is planning to cool down SiPMs and Fibers to cryogenic temperatures for Upgrade 2



AMS-100

Precise measurements of proton, electron, positron and anti-proton flux at higher energies



Proton flux is described by a power law with several smooth breaks, inserted for the purpose of illustration (dashed curve).

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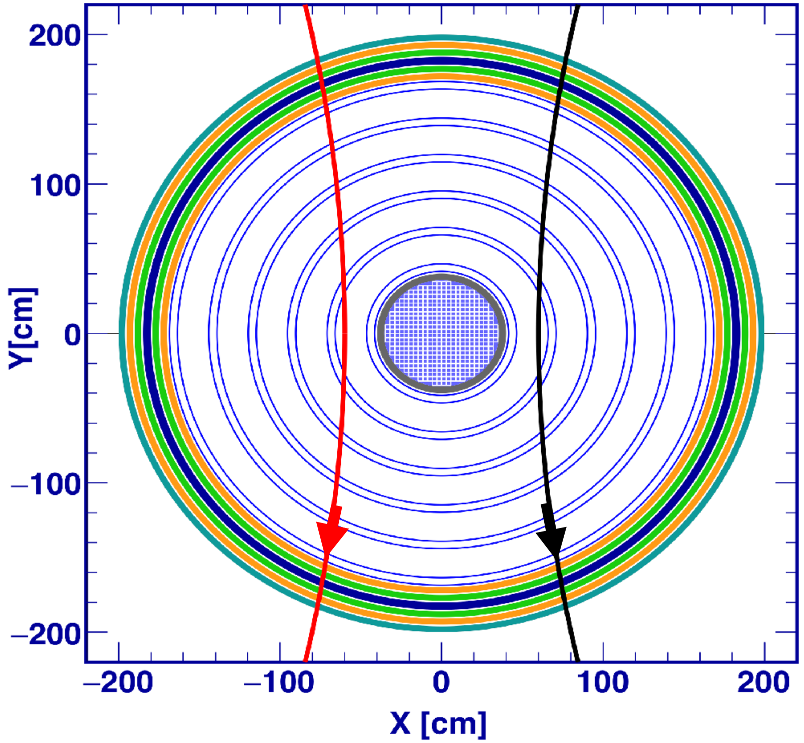
AMS-100

As a Magnetic Spectrometer AMS-100 can separate Anti-Matter from Matter

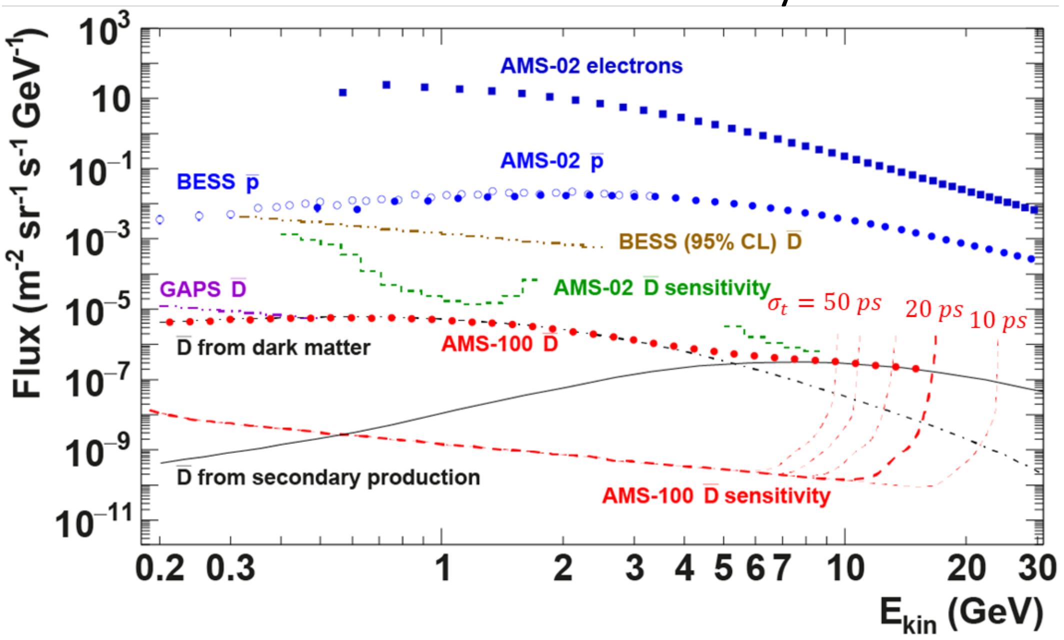


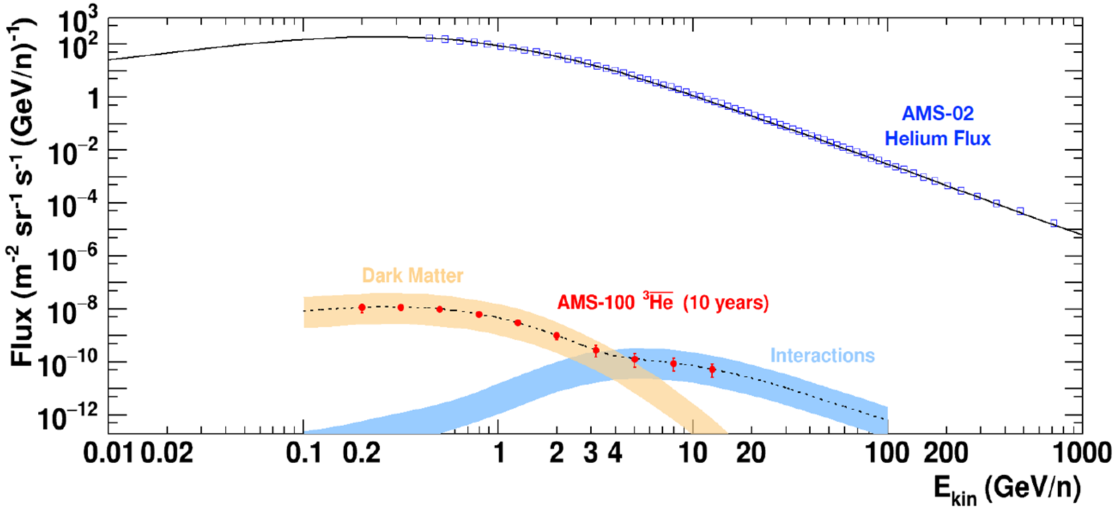
From AMS-02 to AMS-100 Anti Helium Flux:
1 event/year -> 1000 events/year

The resolution is high enough to distinguish between the different sources for Anti-Helium

Anti-Deuterons are the most sensitive probe for New Physics in Cosmic Rays

Z=-1 Particles in Cosmic Rays





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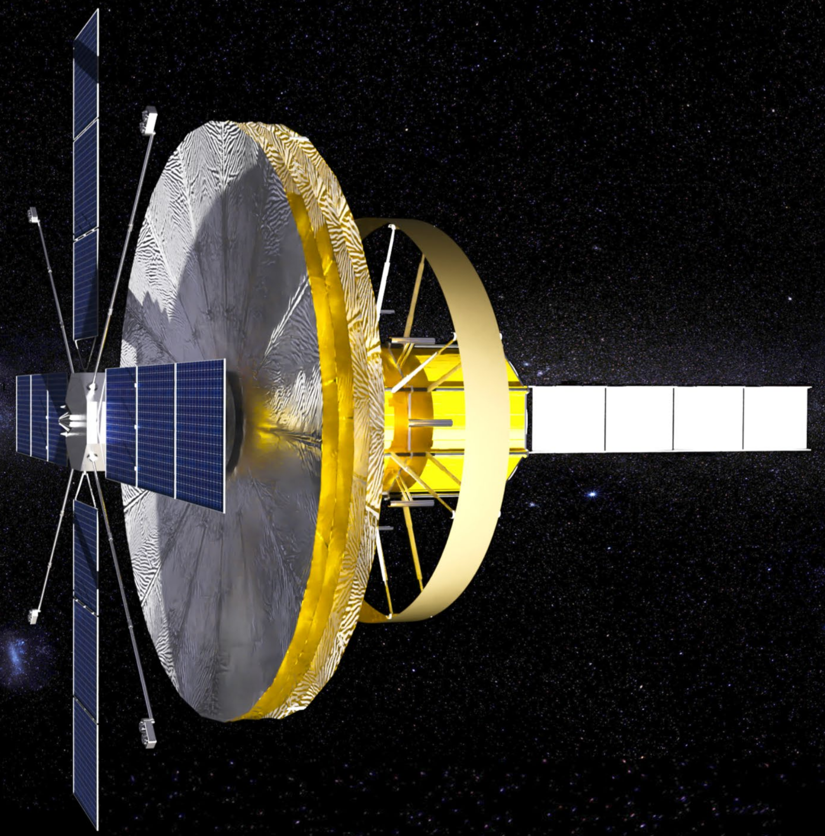
Conclusion

- AMS-100 is a powerful magnetic spectrometer detector concept
    - Acceptance 1000x higher than of AMS-02
    - MDR 100 TV – Calorimetry measurements up to the cosmic knee (PeV)
    - Sensitive to measure Anti-Matter and other rare nuclei in Cosmic Rays
    - High accuracy measurement of the positron spectrum till 10 TV
    - Continous full sky coverage to measure gamma rays with excellent angular resolution
- New technologies
    - High temperature superconducting magnets are becoming very important for accelerators and detectors on earth (LHC. FCC) and in space
    - Detector technologies @ cryogenic temperatures



Weight:	40 t
Thin coil Solenoid :	BL^2=15 Tm^2
Acceptance:	100 m^2sr
MDR:	100 TV
Calorimeter:	70 X_0, 4λ
Power Consumption:	15 kW
Incoming Particle Rate:	2 MHz
Number Readout Channels:	8 Million
Mission Flight Time:	10 years

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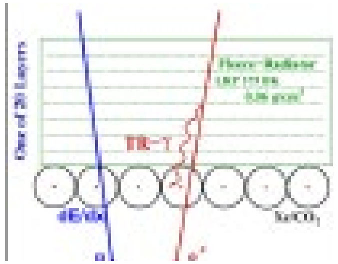
Backup

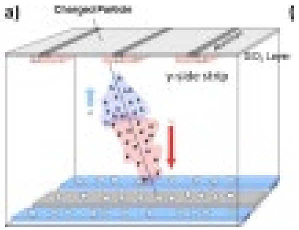
AMS-02 – A TeV Particle Spectrometer

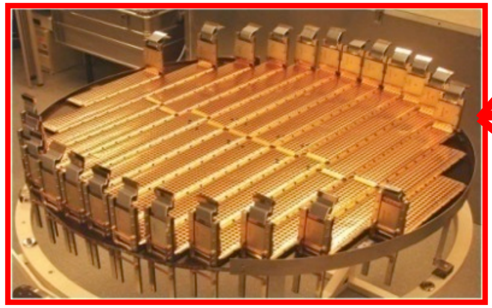
Particles and nuclei are defined by their charge (Z) and energy (E ~ P)

TRD
Separation e±:p

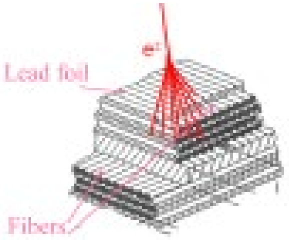


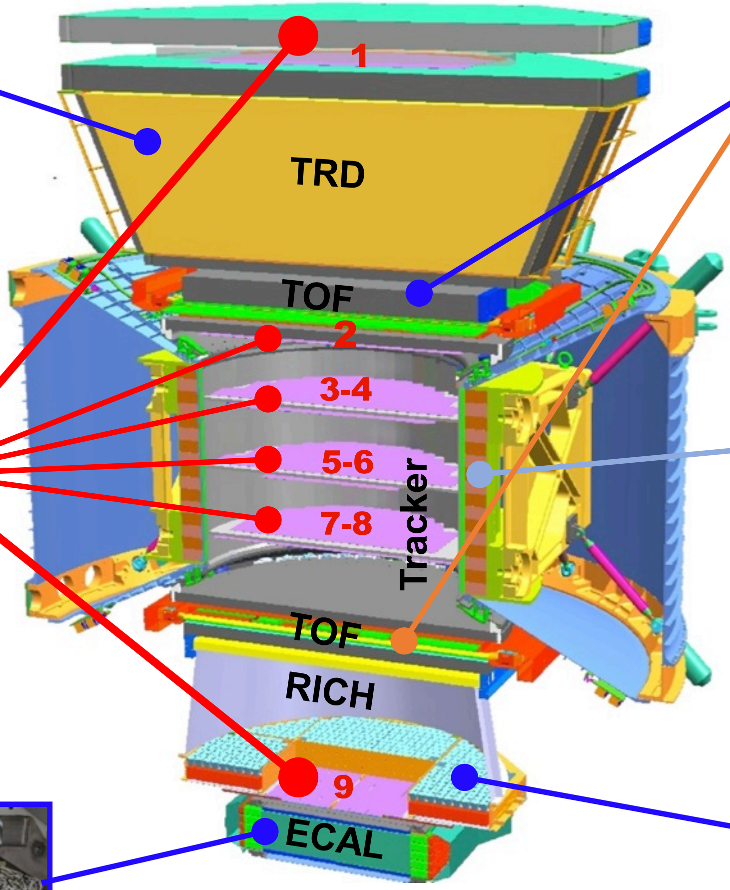
Silicon Tracker
Z, P



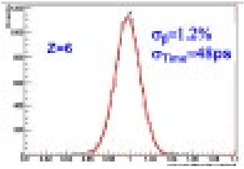


ECAL
E of e±, γ

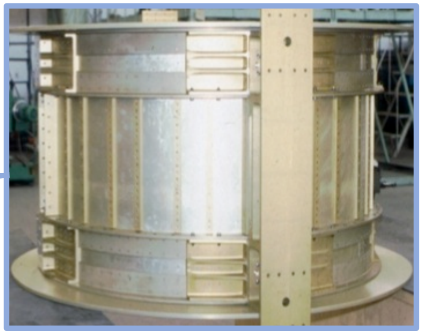


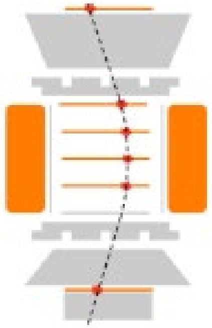


TOF
Z, E

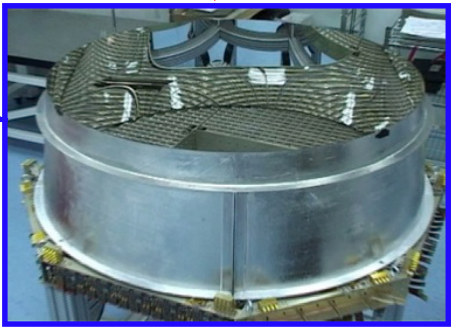


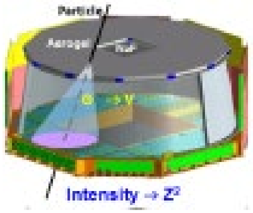
Magnet
± Z





RICH
Z, E





Z, P are measured independently by the Tracker, RICH, TOF and ECAL

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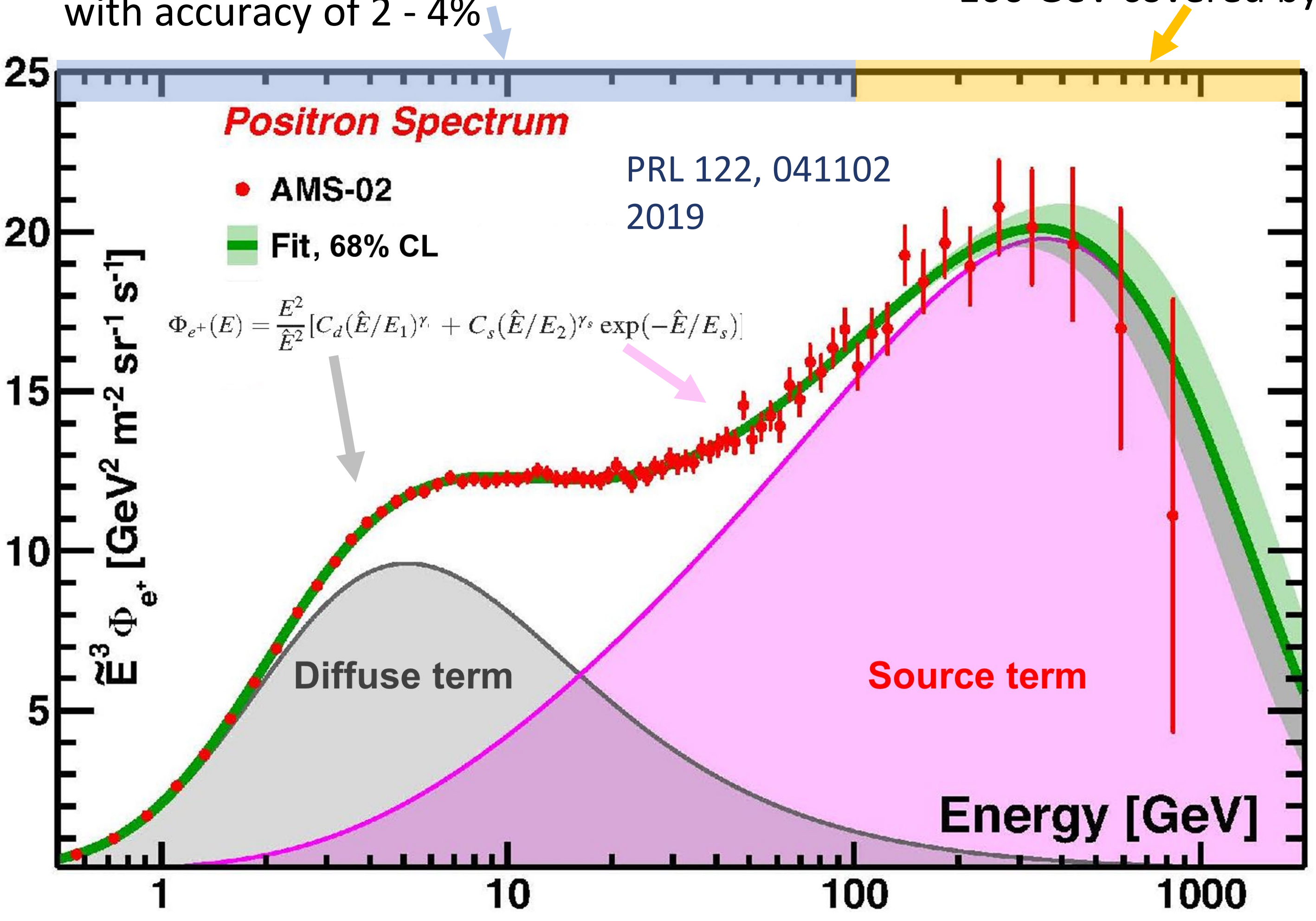
AMS-02 Results & Open Questions: Positron Flux – Search for Dark Matter:

< 100 GeV covered by AMS-02
with accuracy of 2 - 4%

> 100 GeV covered by AMS-100



Diffuse term:
Low-energy part of the flux dominated by the positrons produced in the collisions of ordinary cosmic rays with the interstellar gas

Source term:
Origin through pulsars or dark matter anihilation or an unknown source

Cutoff (≈ 300 GeV):
Gives the maximum energy of the positrons and could therefore represent half the mass of the dark matter particles

⟶ Rigidity range x10,
Increase of acceptance by 1000
to detect enough particles (Flux ≈ $C \cdot E^{-3}$)

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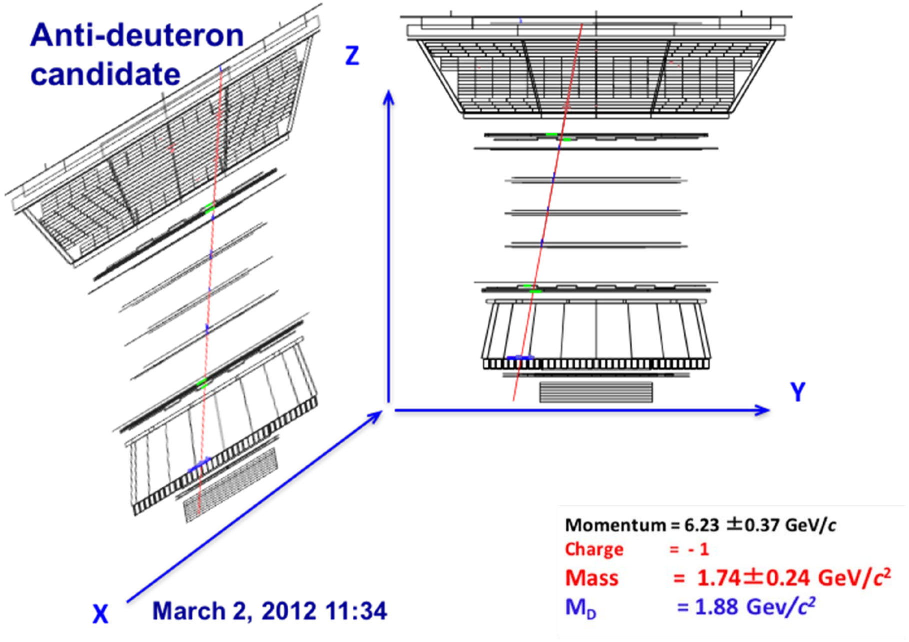
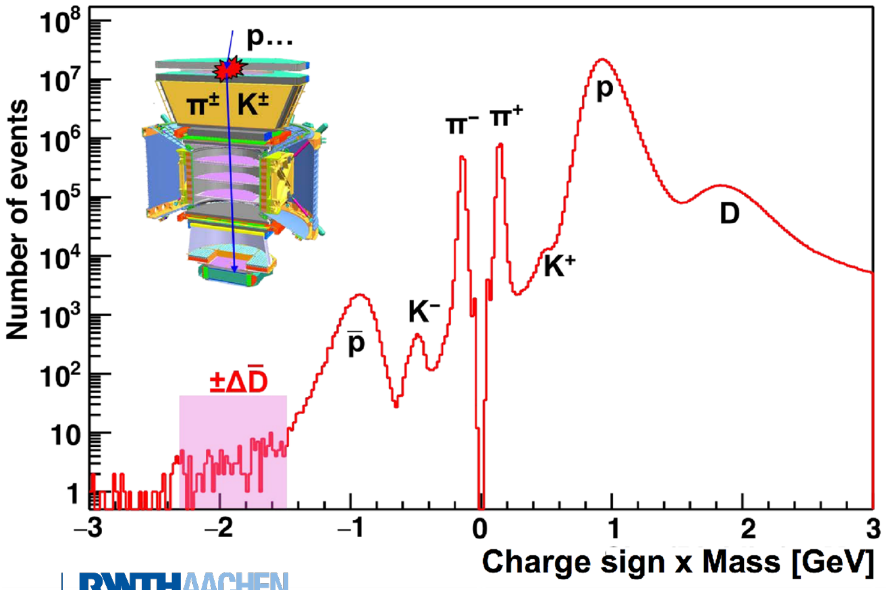
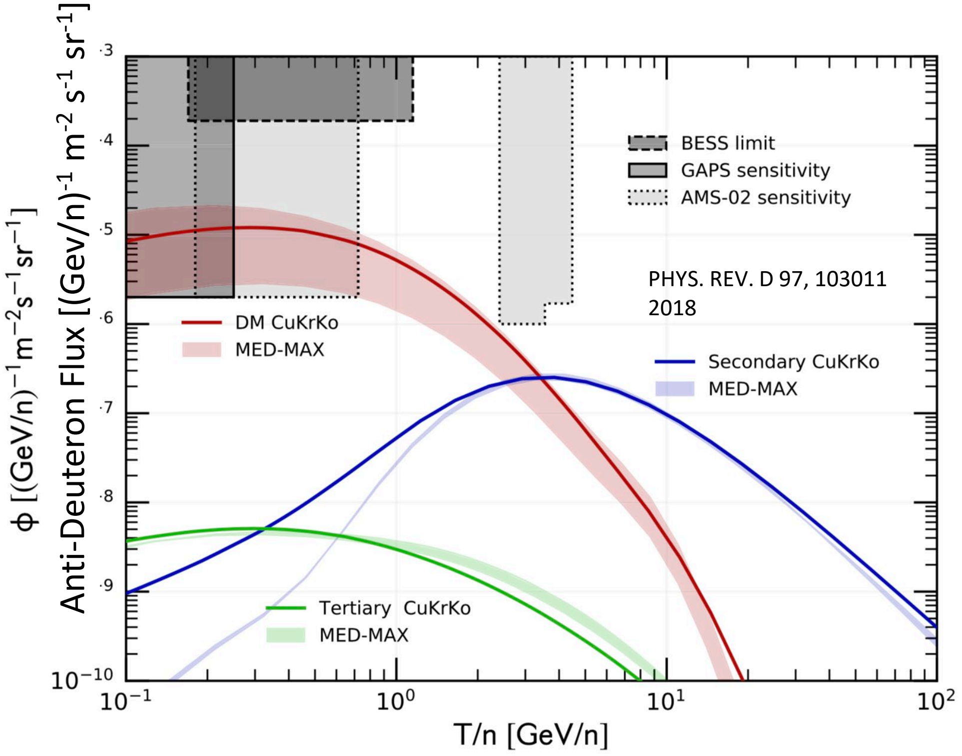
AMS-02 Results & Open Questions: Search for Anti-Deuterons

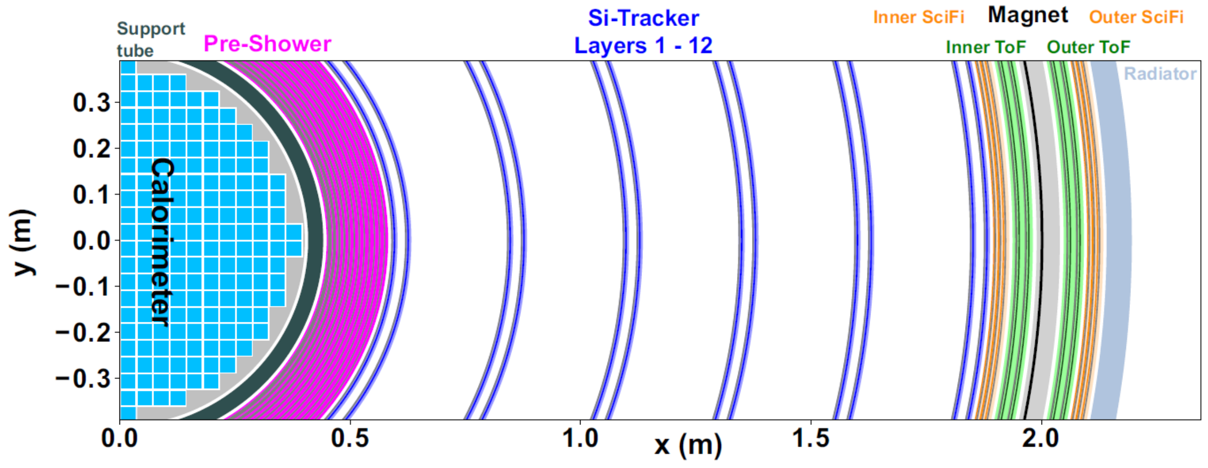


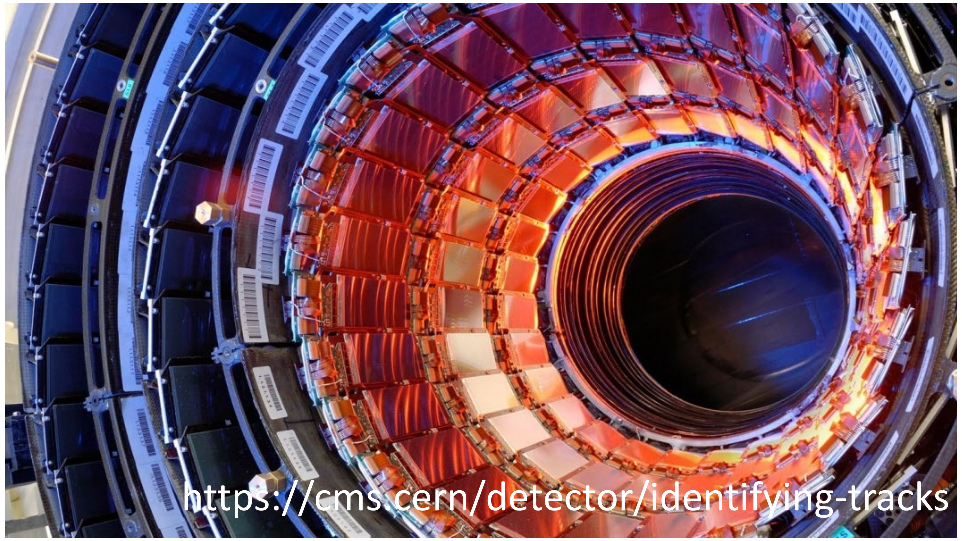




No active or proposed instrument has the sensitivity to exclude low energy Anti-Deuterons from Dark Matter Annihilation by measuring the flux expected from secondary production

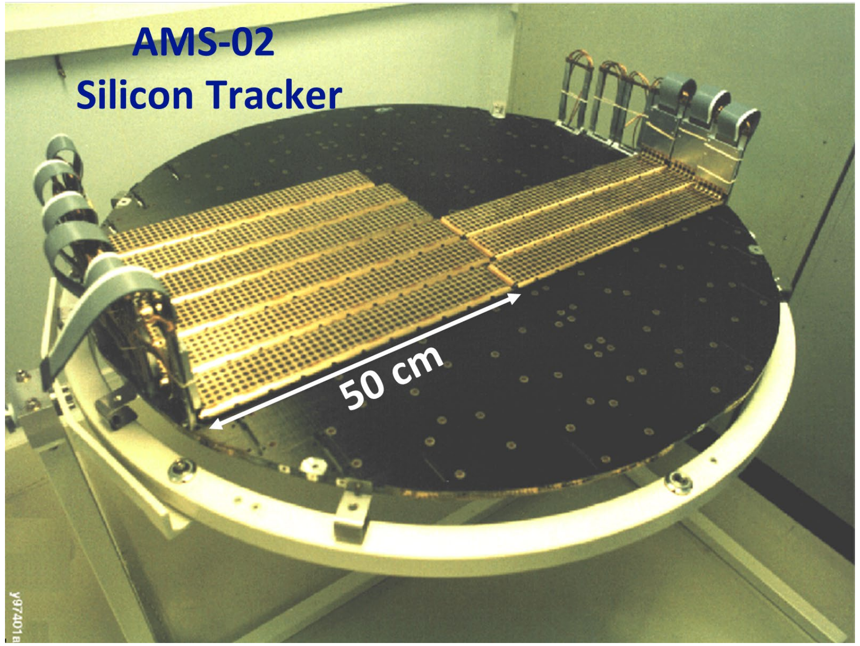
AMS-100: Silicon Tracker





Performance of the Silicon Tracking System:

- Expected: **a single point resolution of 5 µm** in the bending plane for |Z| = 1 particles
- Higher resolution by lowering the temperature to 200 K
- Six double layers arranged in cylindrical geometry leading to a maximum of 24 measurement points for a single track
- With a magnetic field of 1 T, the AMS-100 silicon tracker provides an MDR of 100 TV
- The structure is similar to the CMS silicon strips detectors in the barrel module but with silicon ladders instate of single strips
- Sensitive area 380 m^2
- Readout: VA-140 Chip, 0.35 µm CMOS, 0.3 mW/Channel
- 5.2 10^6 Channels



AMS-100: Tracking System

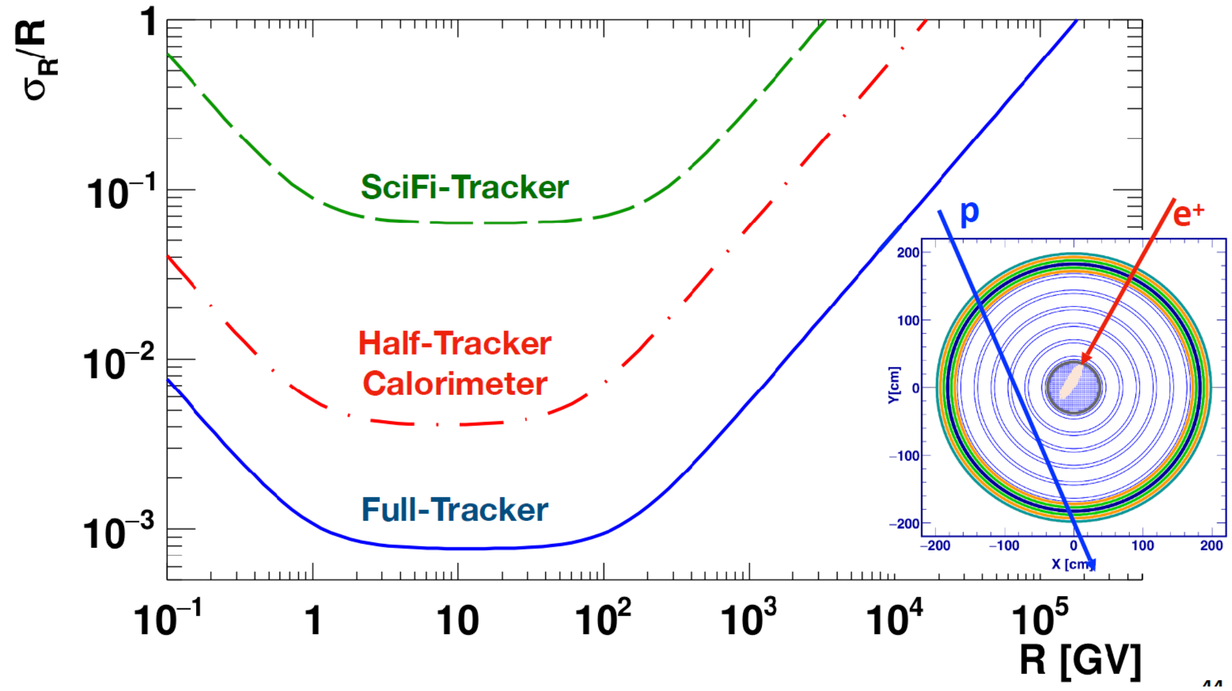
Performance of the Silicon and SciFi Tracking System

Silicon Tracker

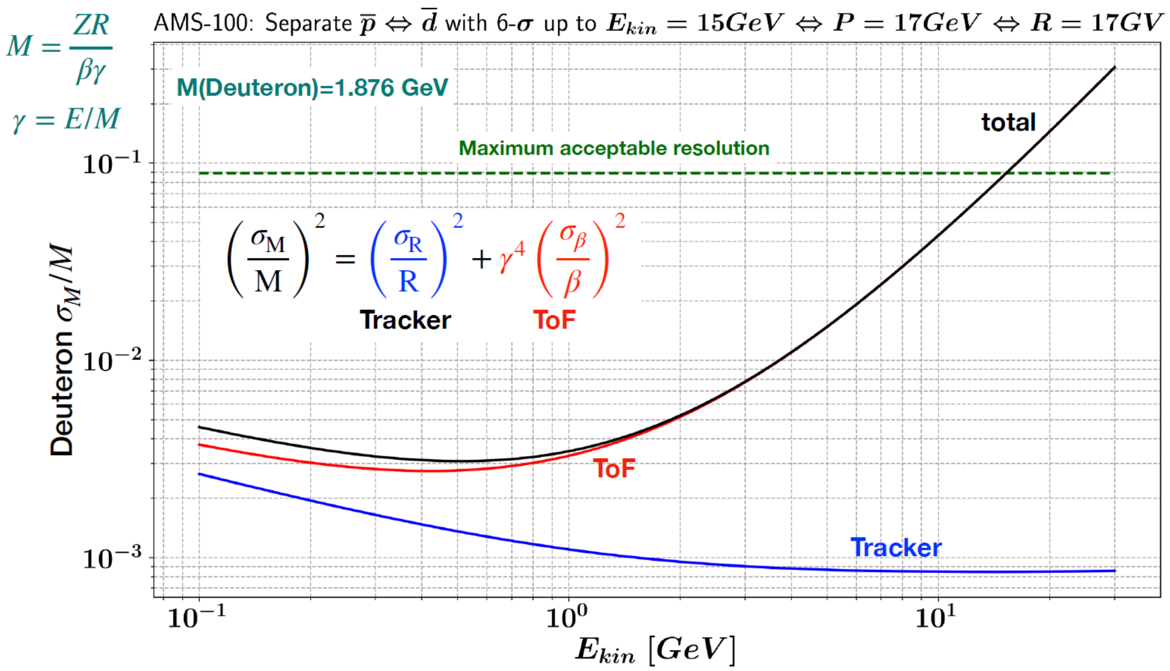
- 2×12 points
- 5 µm resolution

SciFi Tracker

- 2×6 points
- 40 µm resolution



Expected of the Tracker and ToF System

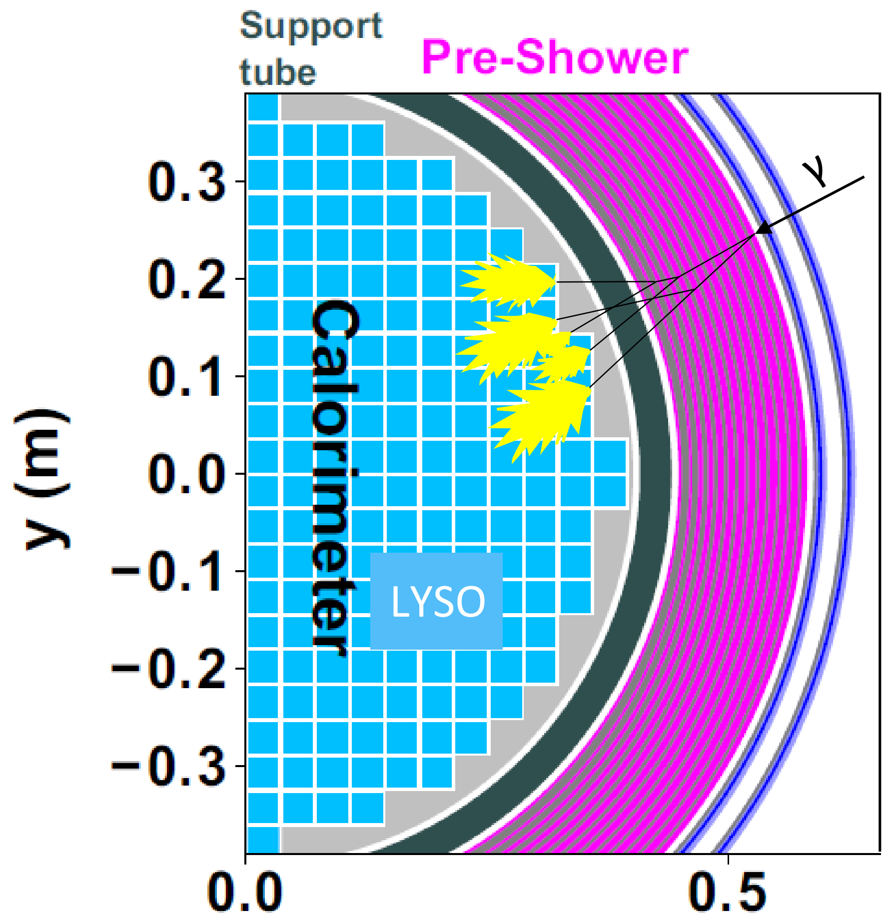


AMS-100: Electromagnetic Calorimeter

Preshower Detektor:
- 12 silicon detector layers interleaved with thin tungsten layers (5 X_0)
- L=400 cm, Weight 4 t
- Measures direction of cosmic gamma rays
- Limit the backsplash of the calorimeter into the silicon tracker

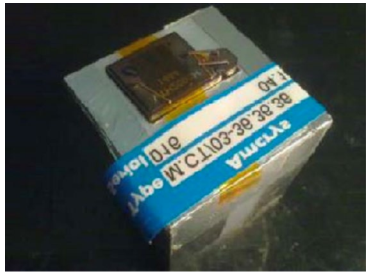
Crystal Calorimeter (inspired by HEARD concept):
- 3-dimensional grid of 37740 LYSO cristal cubes(3 cm x 3 cm x 3cm)
- R=40 cm, L= 400 cm, Weight 8.2 t
- LYSO is a Cerium doped Lutetium based scintillation crystal with a density of 7.1 g/cm3, X_0 = 1.14 cm, each crystal ~ 2.6 X_0
- Readout with large and small area photodiodes glued to one face of the cube.
- Allows reconstruction of the shower shape

Combined detectors:
- Can separate electromagnetic and hadronic showers
- Radiation length of 70X_0
- Nuclear interaction length 4λ_I
- Measurement of cosmic protons and ions with energies above 100 TV up to the cosmic-ray knee (PeV) are possible



LYSO crystal

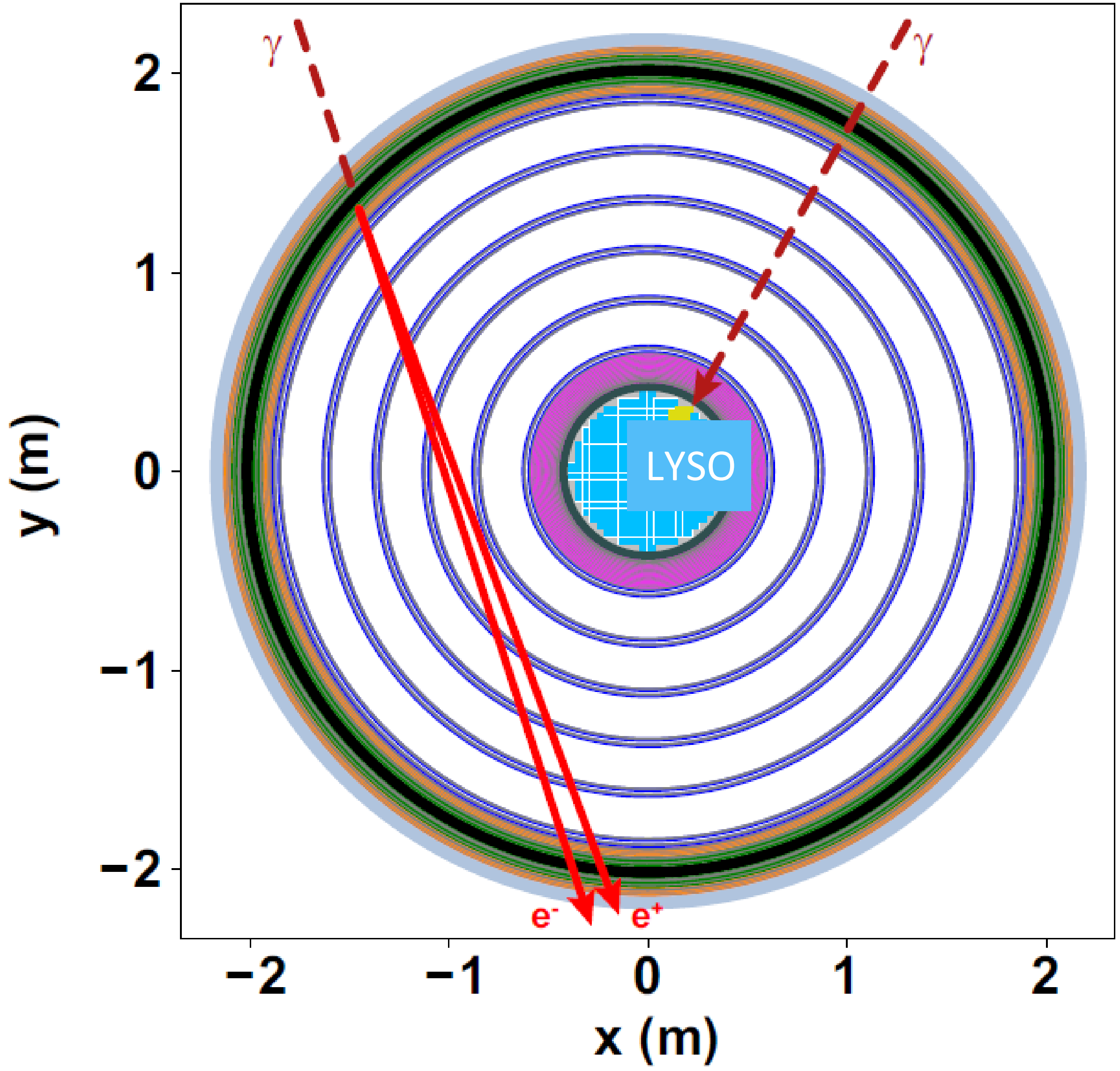
LYSO crystal with photodiodes



AMS-100: Electromagnetic Calorimeter

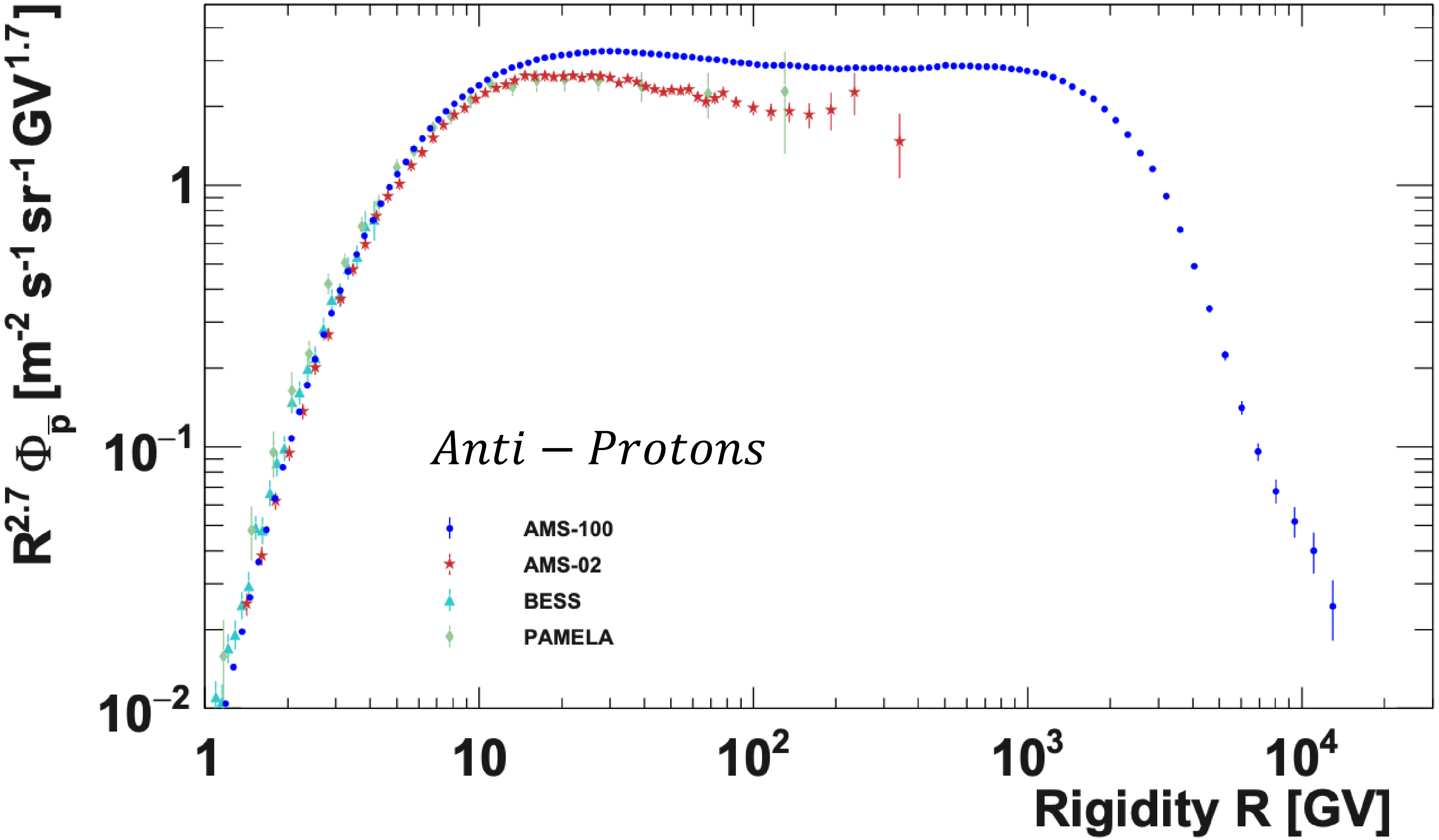
High-Energy Gamma Rays

1. Using the calorimeter to measure directly gamma rays with an acceptance of 30 m^2 sr
2. Measure photons which are converted in the 3 mm thin magnet coil ($0.12X_0$)
3. Measure photons at low energies with the Gamma Converter at the endcap which is inspired by the GAMMA-400 design



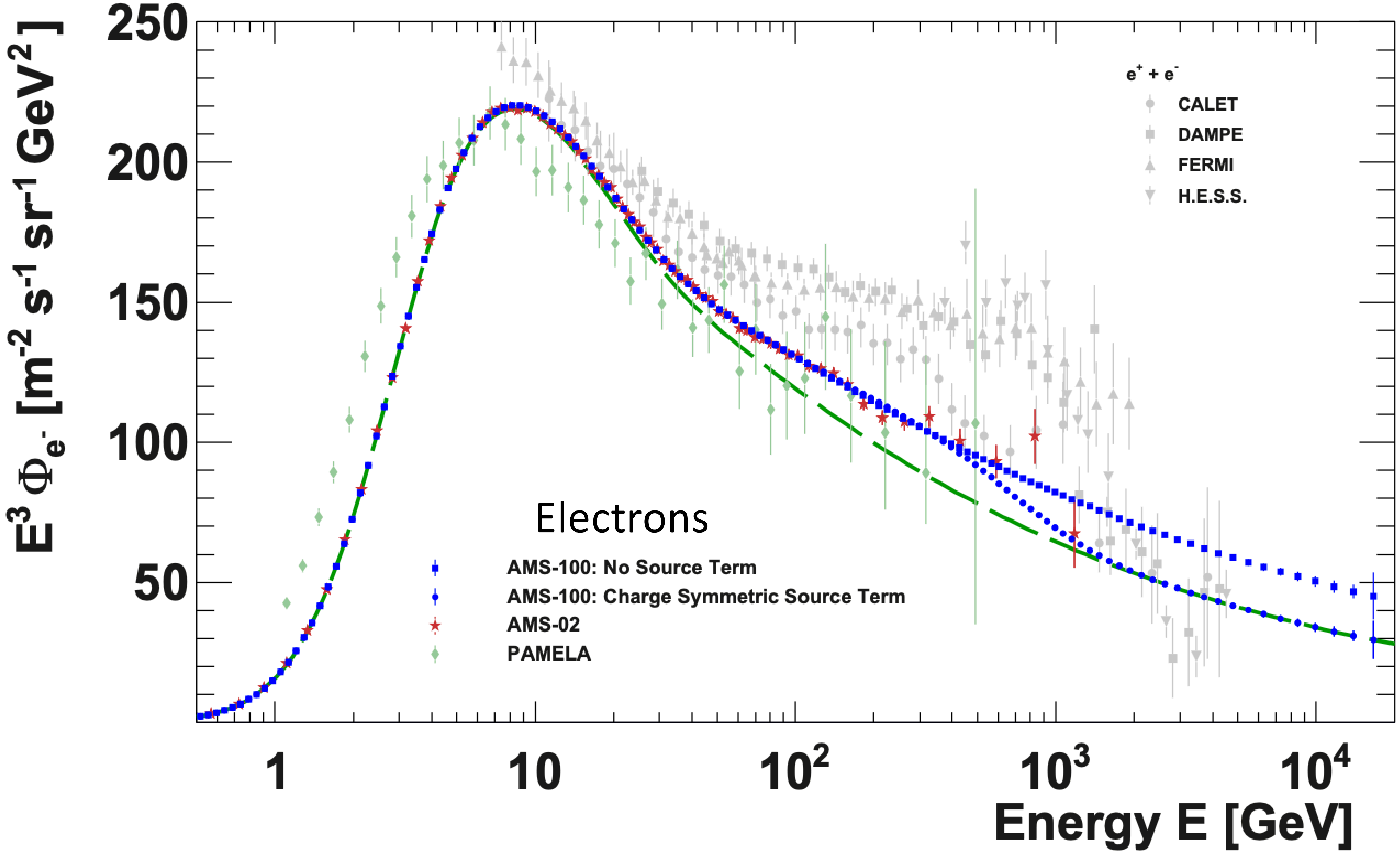
AMS-100

Precise measurements of proton, electron, positron and anti-proton flux at higher energies



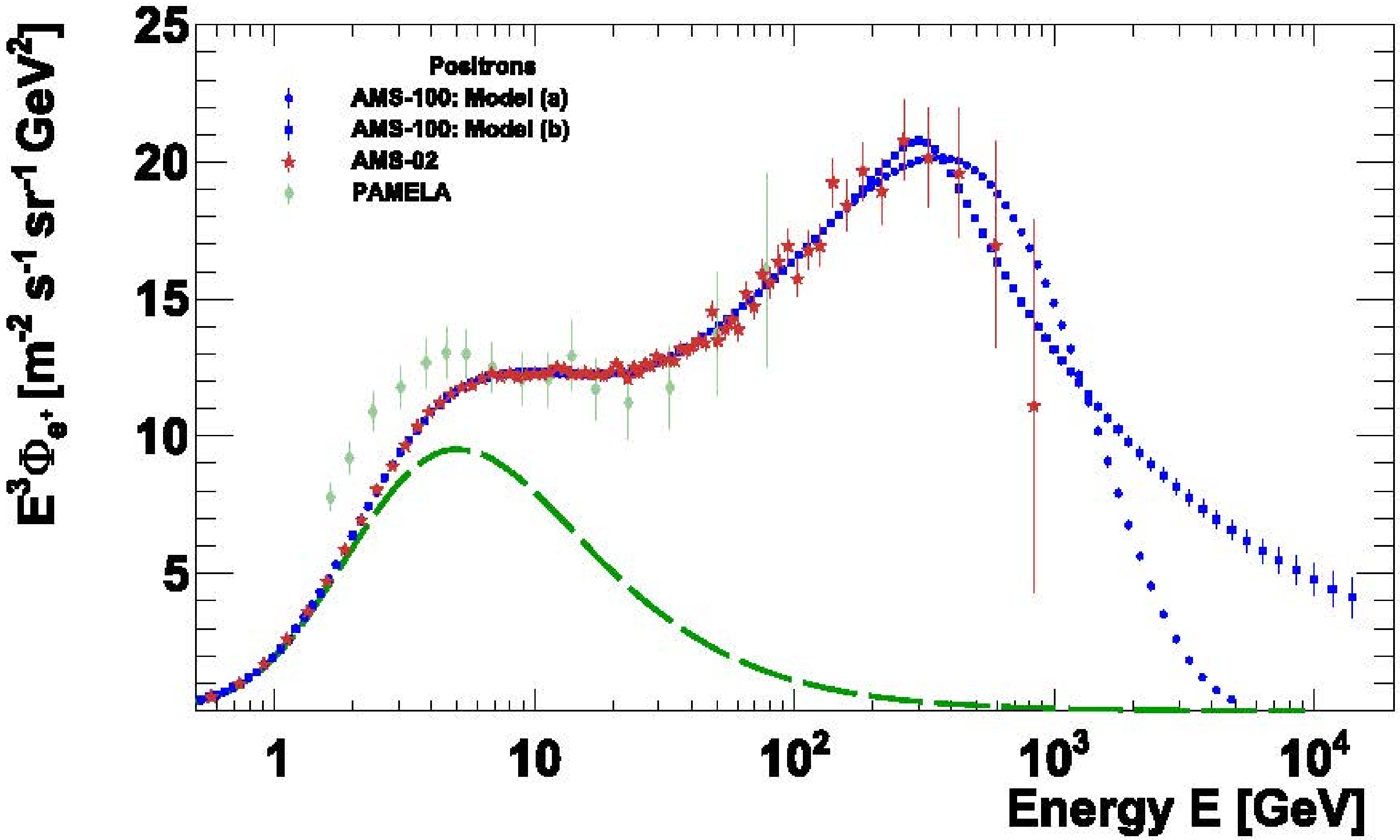
AMS-100

Precise measurements of proton, electron, positron and anti-proton flux at higher energies



AMS-100

Precise measurements of proton, electron, positron and anti-proton flux at higher energies



Model (a): a power law plus a source term with an exponential cutoff (blue circles, lower curve at high energy).
Model (b): power laws with spectral breaks and the last break is at 300 GeV (blue squares, upper curve at high energy).
The dashed green curve shows the contribution as typically expected from secondary production to the spectrum in model