Direct and Indirect Detection of Dark Matter
The 2nd DMNet International Symposium
Sep 13 – 15, 2022
Max Planck Institute for Nuclear Physics, Heidelberg, Germany

AMS DM-related results

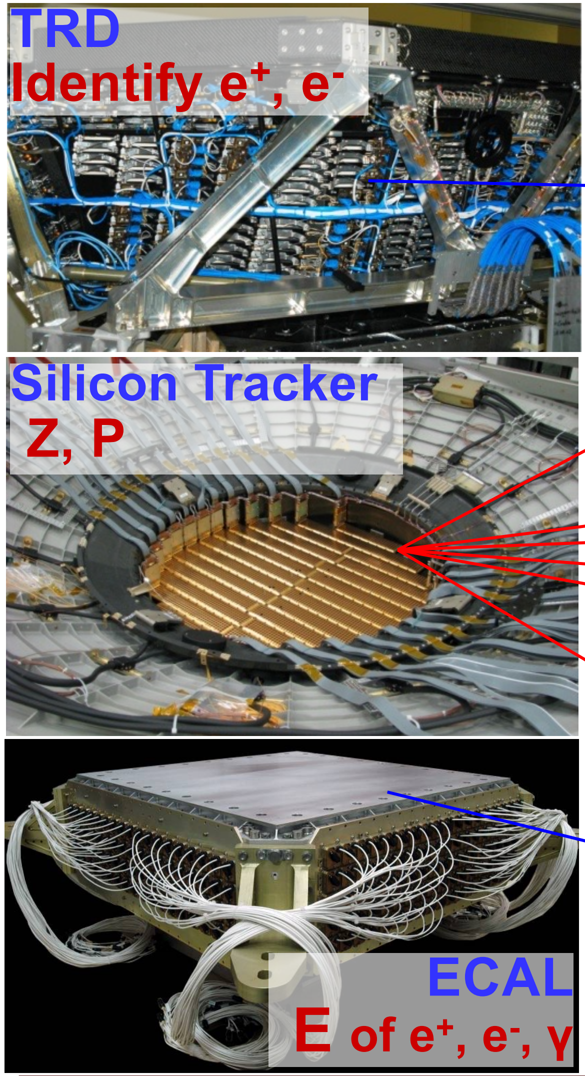
Matteo Duranti
INFN Sez. Perugia
on behalf of the AMS Collaboration

Outline

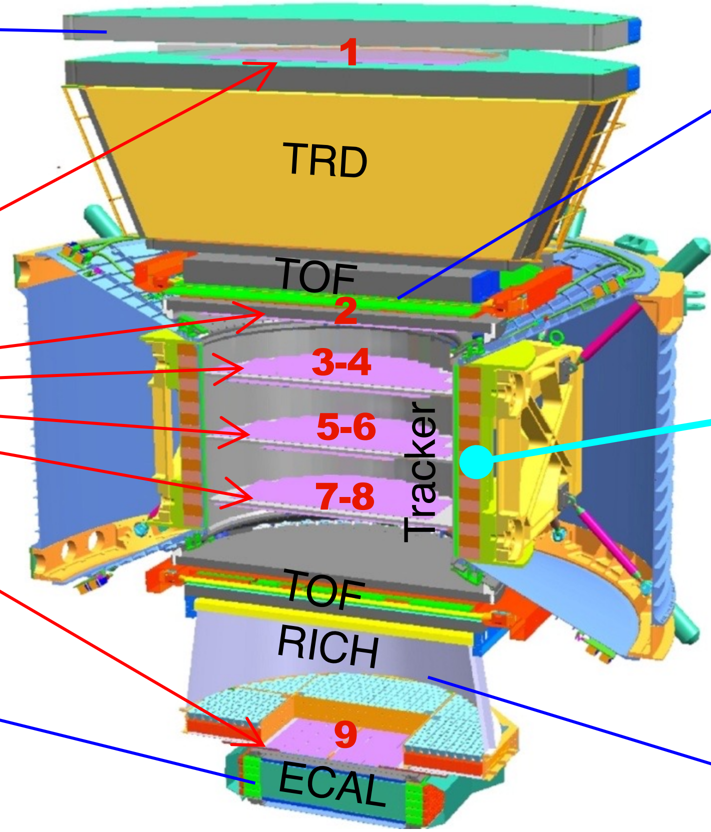
- the instrument
- DM-related physics results
- the future…

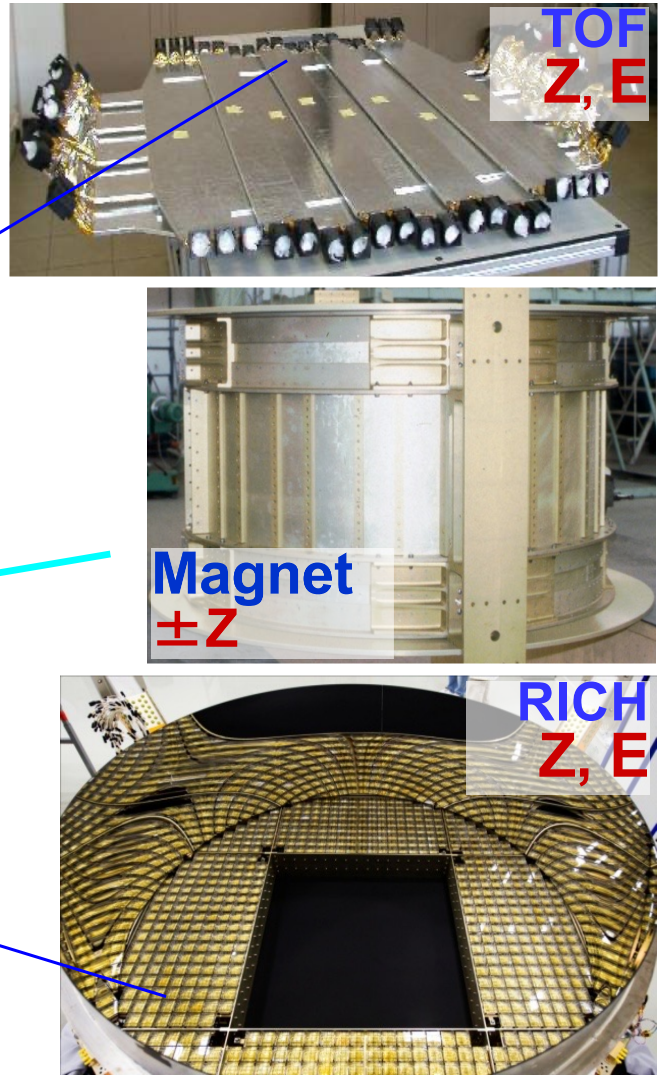
The instrument

A precision, multipurpose, TeV spectrometer



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

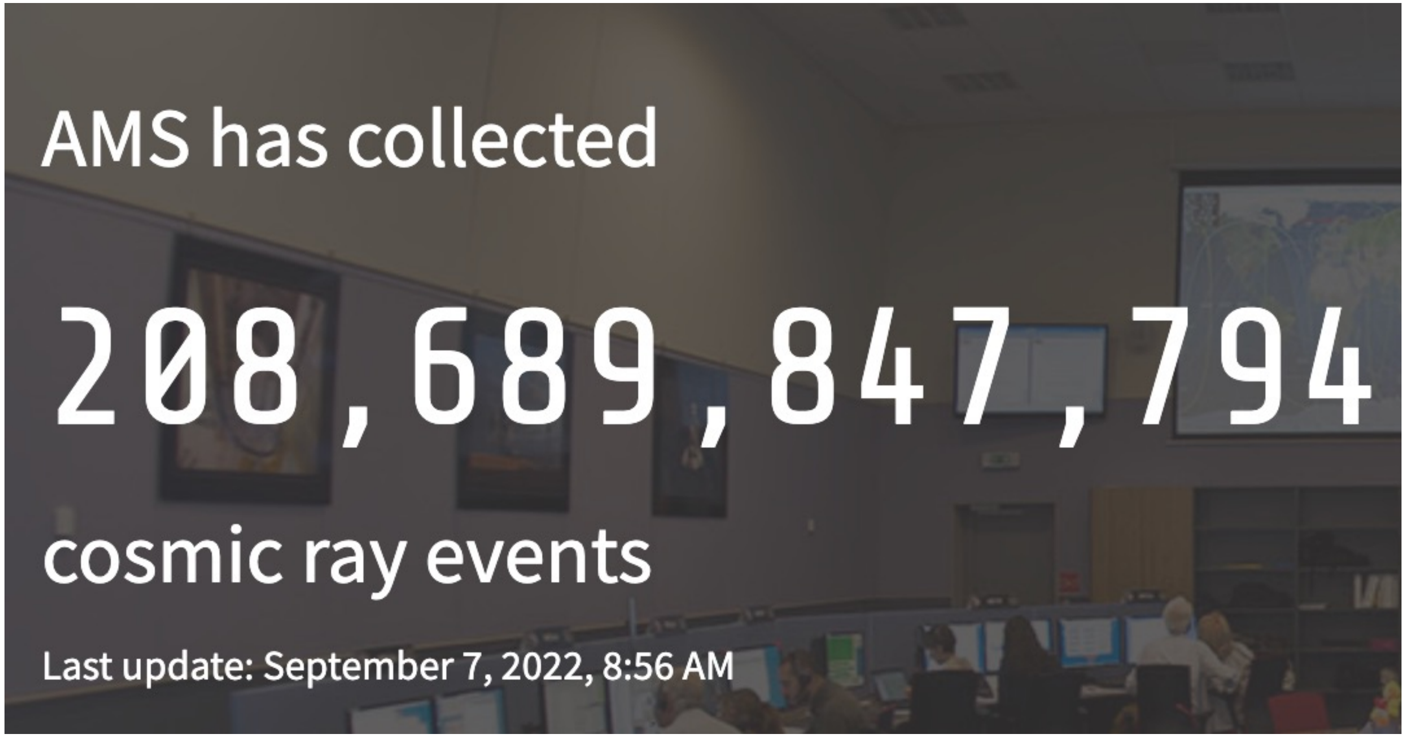




AMS mission

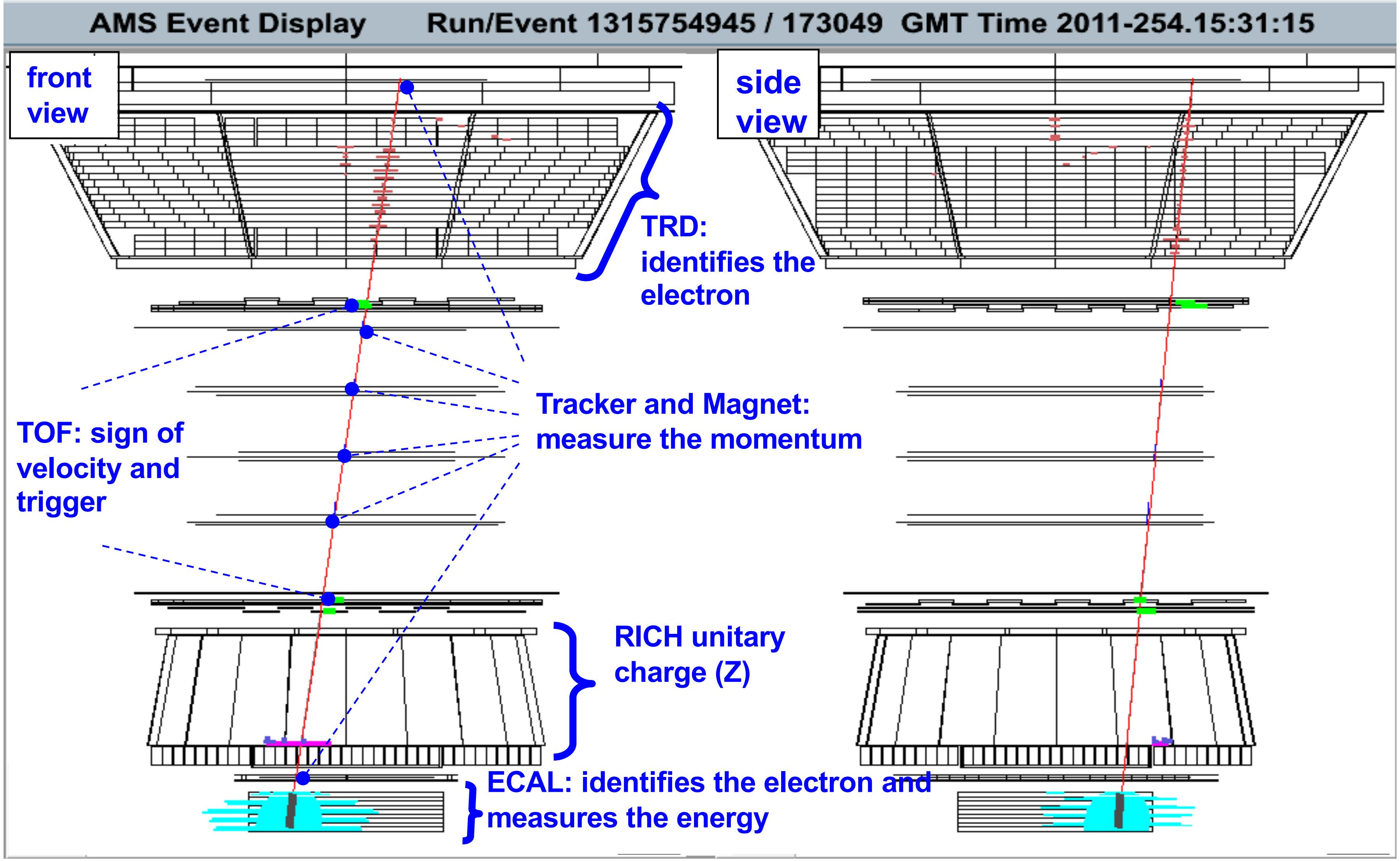

May 16th 2011


AMS
AMS
May 19th 2011

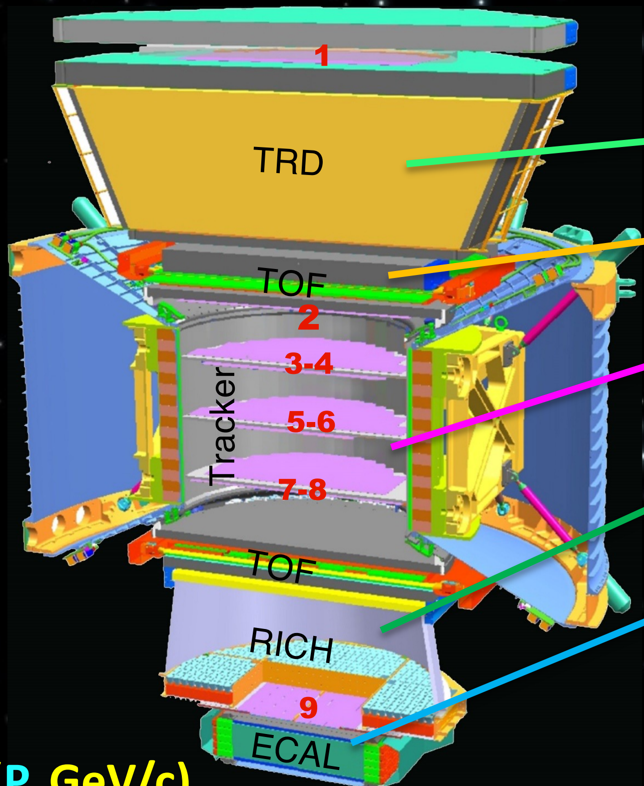

AMS has collected
208,689,847,794
cosmic ray events
Last update: September 7, 2022, 8:56 AM

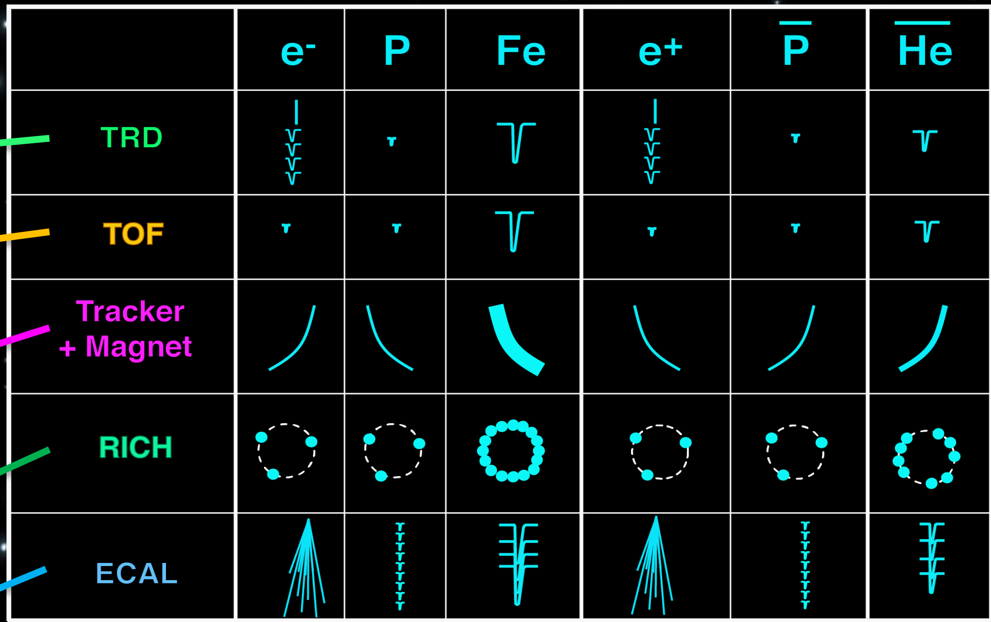

AMS-02 time on ISS since May 19th, 5:46 a.m. EDT:
4128 DAYS 23 HOURS 24 MINUTES 18 SECONDS

ISS Data – 1.03 TeV Electron



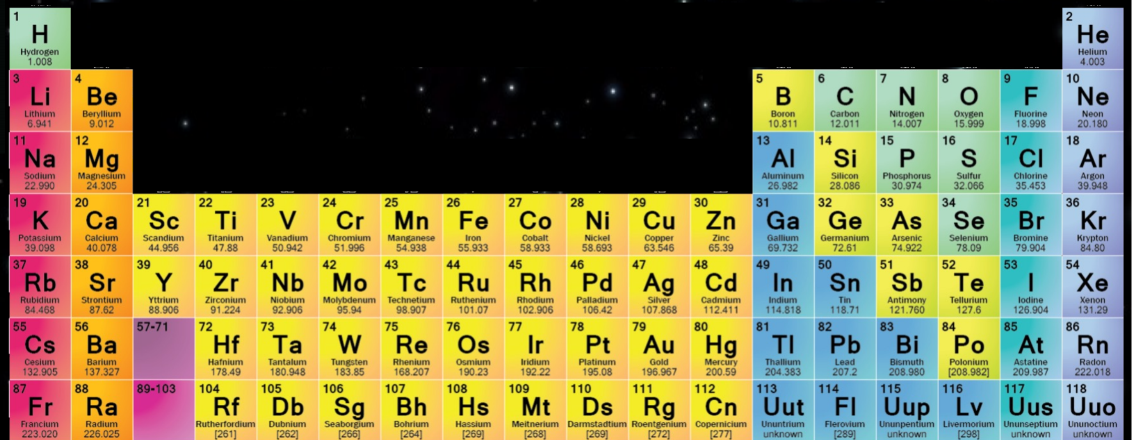
Particle identification





AMS measures :

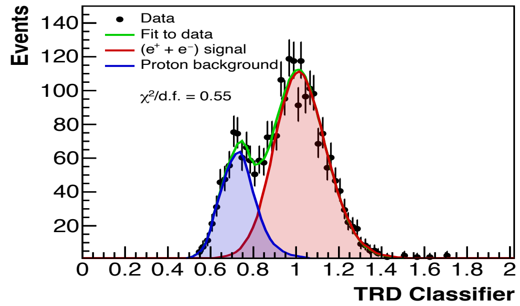
- Momentum (P, GeV/c)
- Charge (Z)
- Rigidity (R=P/Z, GV)
- Energy (E, GeV/A)
- Flux (signals/(s sr m^2 GeV))



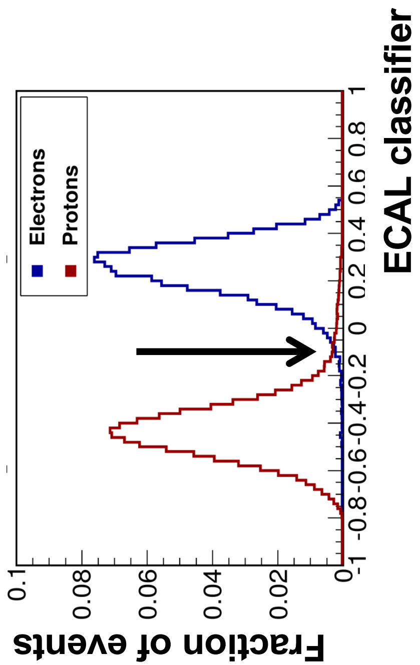
e/p discrimination

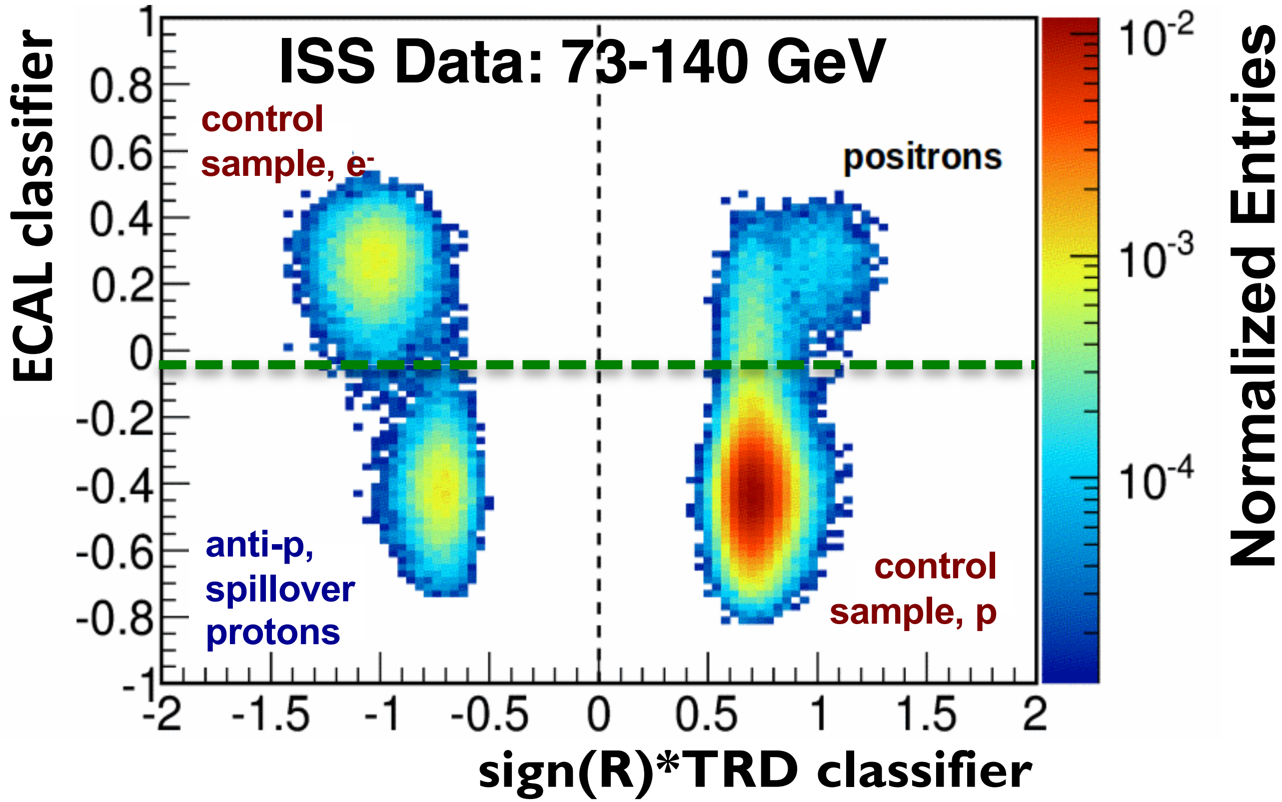
One important lesson from the AMS experiment is the importance of the redundancy: use one detector to create control sample for another one.

Study of the difference (i.e. likelihood) between dE/dx and TR in 20 layers of fleece radiator + straw tubes



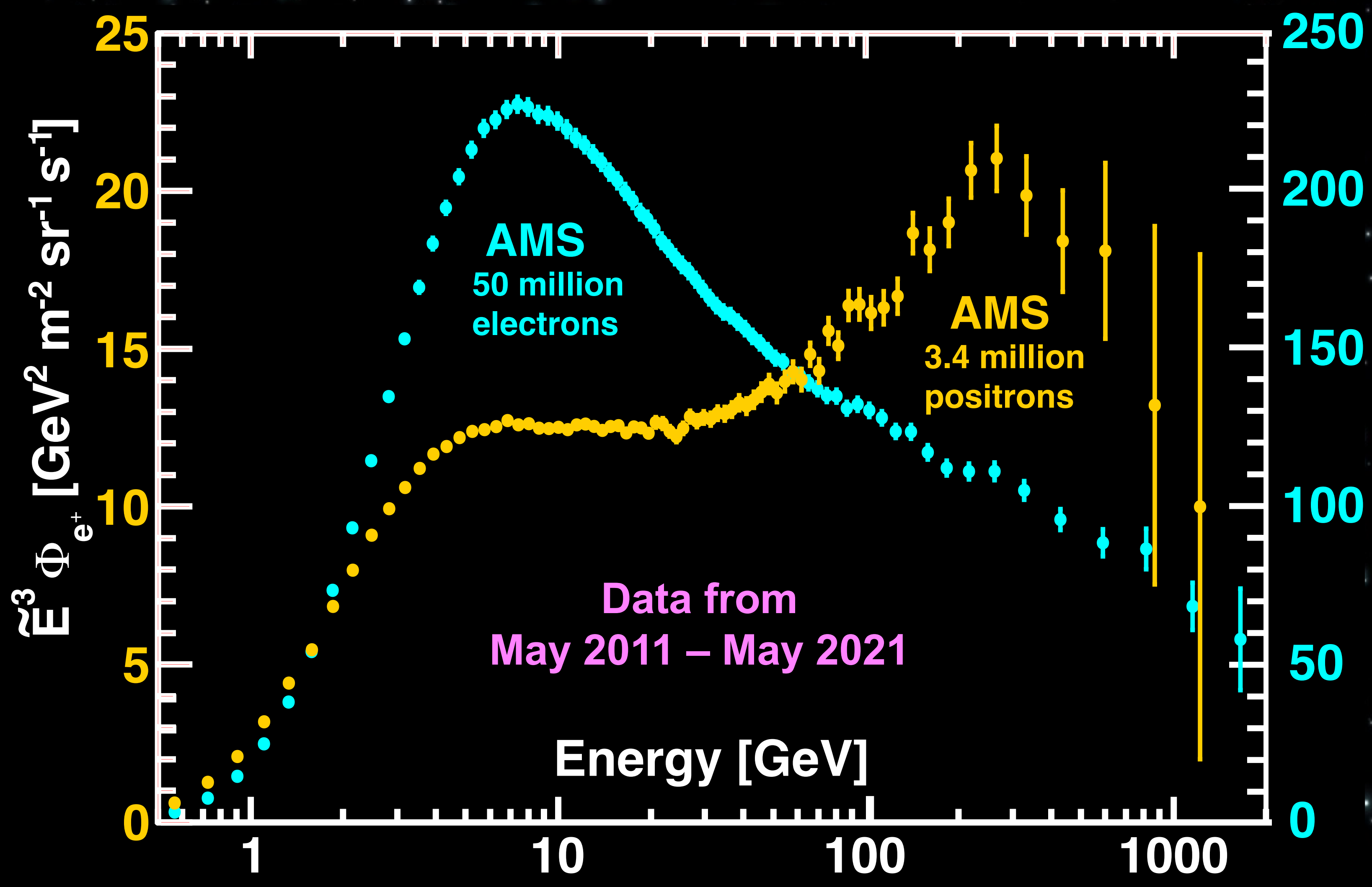
Study of the difference (i.e. Boosted Decision Tree, BDT) between hadrons and EM particles in 19 variables describing 3D shower shape



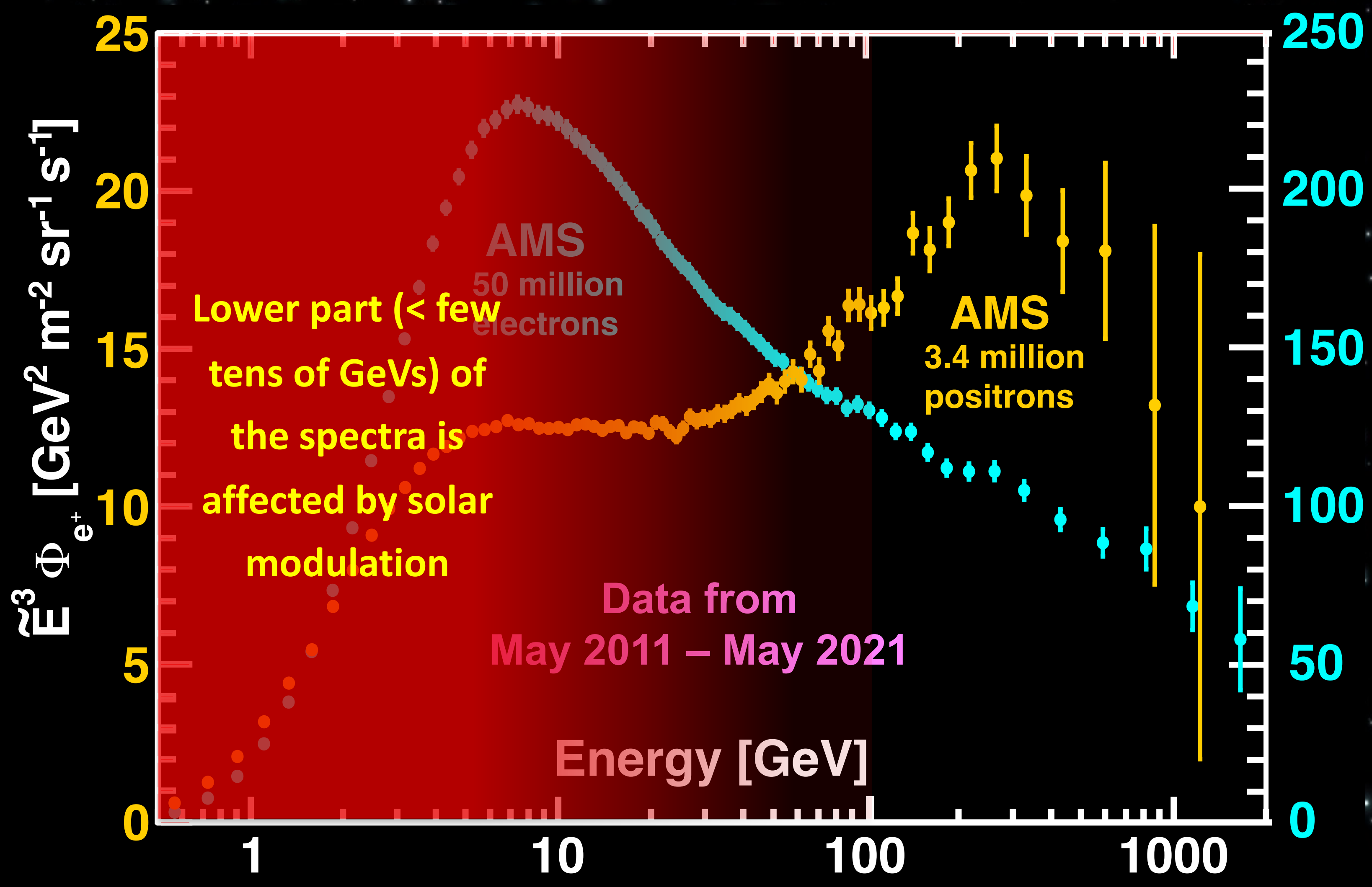


Physics Results

Study of Positrons & Electrons



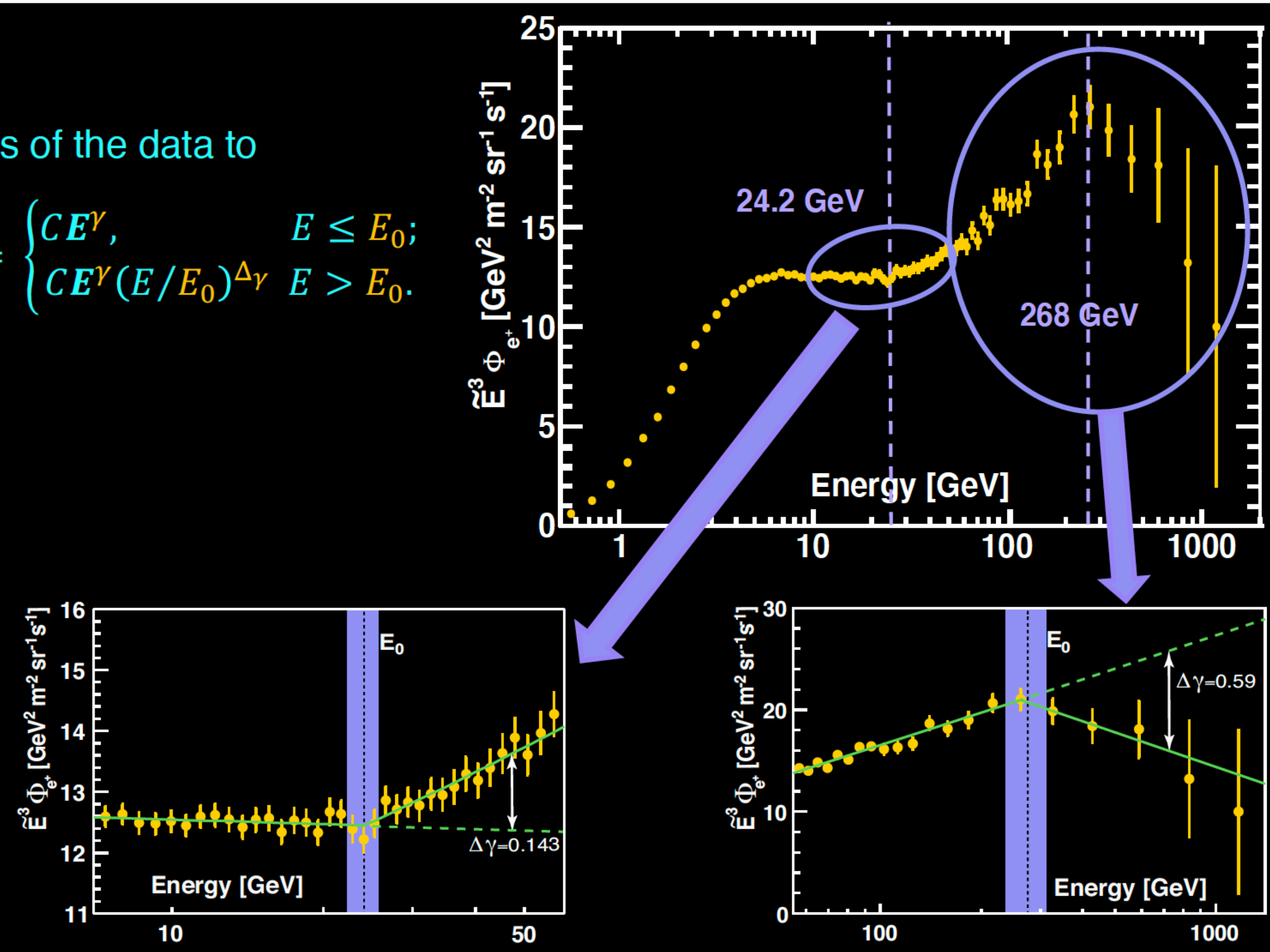
Study of Positrons & Electrons



Positrons

Fits of the data to

$$\Phi_{e^+}(E) = \begin{cases} C E^{\gamma}, & E \le E_0; \\ C E^{\gamma}(E/E_0)^{\Delta\gamma} & E > E_0. \end{cases}$$



7.8σ excess above $E_0 = 24.2 \pm 1.1$ GeV   4.8σ sharp drop-off at $E_0 = 268^{+35}_{-33}$ GeV

Electrons

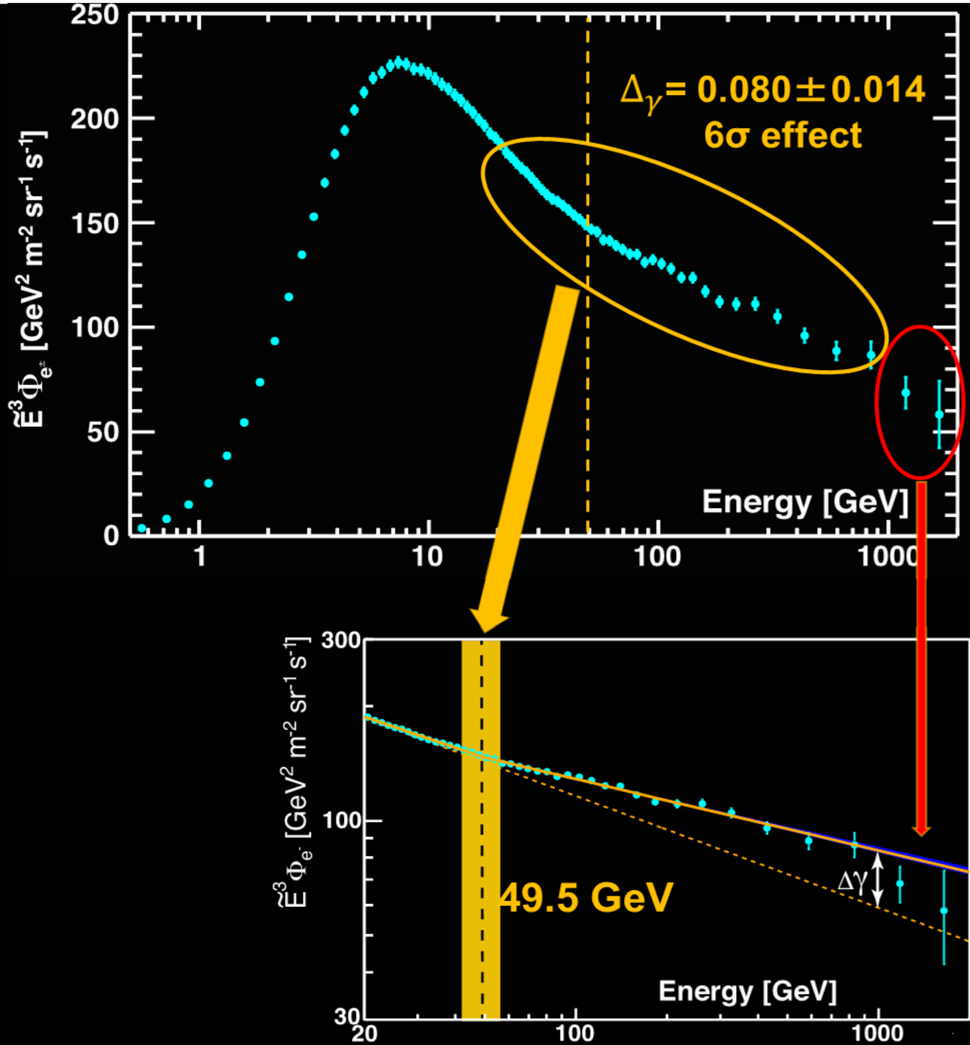
Traditionally, Cosmic Ray spectrum is described **by a power law function.**

Change of the behavior at **~50 GeV** and **at ~1 TeV**

Fit to data

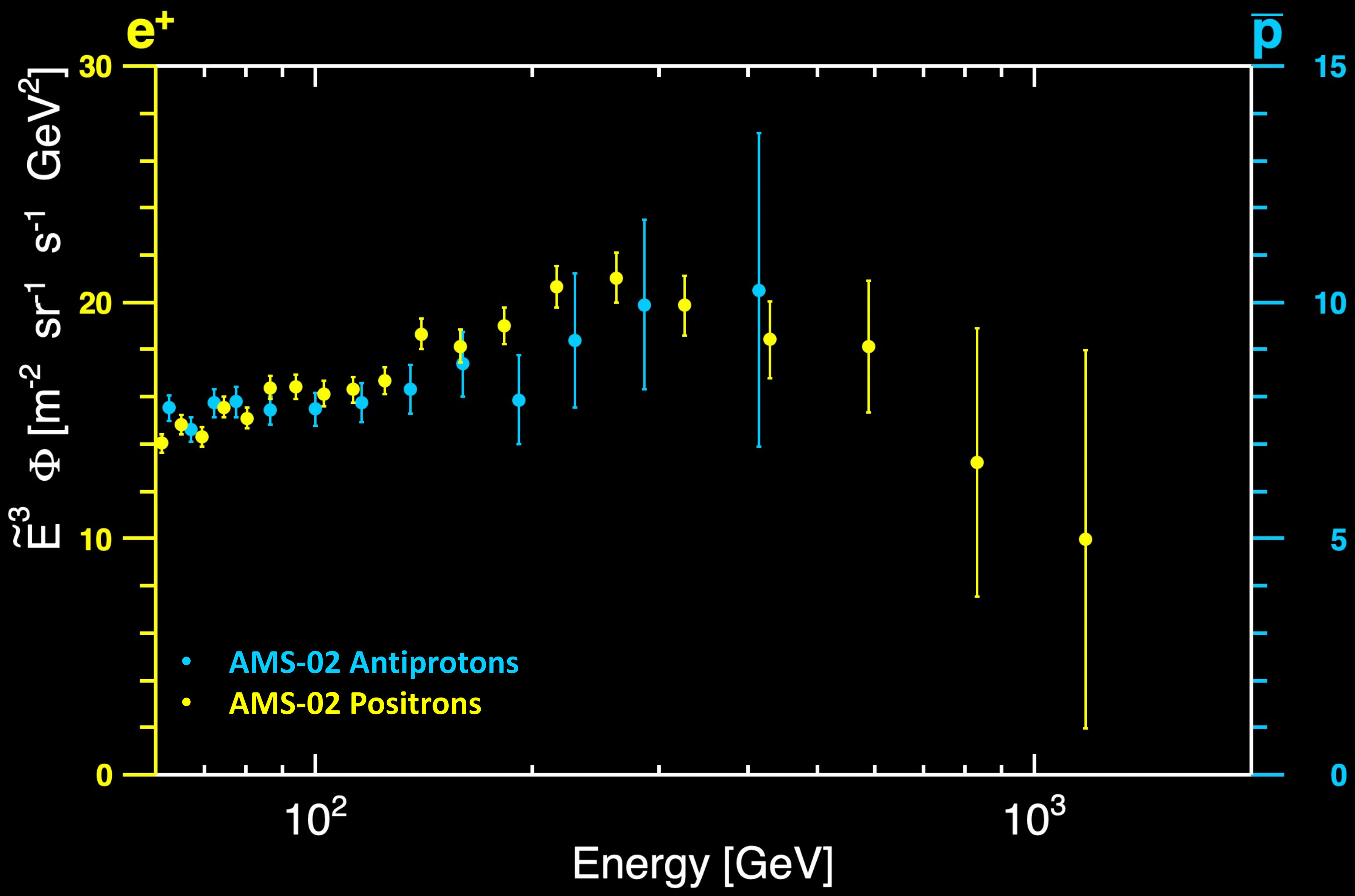
$$\Phi_{e^-}(E) = \begin{cases} CE^{\gamma}, & E \le E_0; \\ CE^{\gamma}(E/E_0)^{\Delta\gamma}, & E > E_0. \end{cases}$$

A significant excess at E_0 = 49.5±5.6 GeV



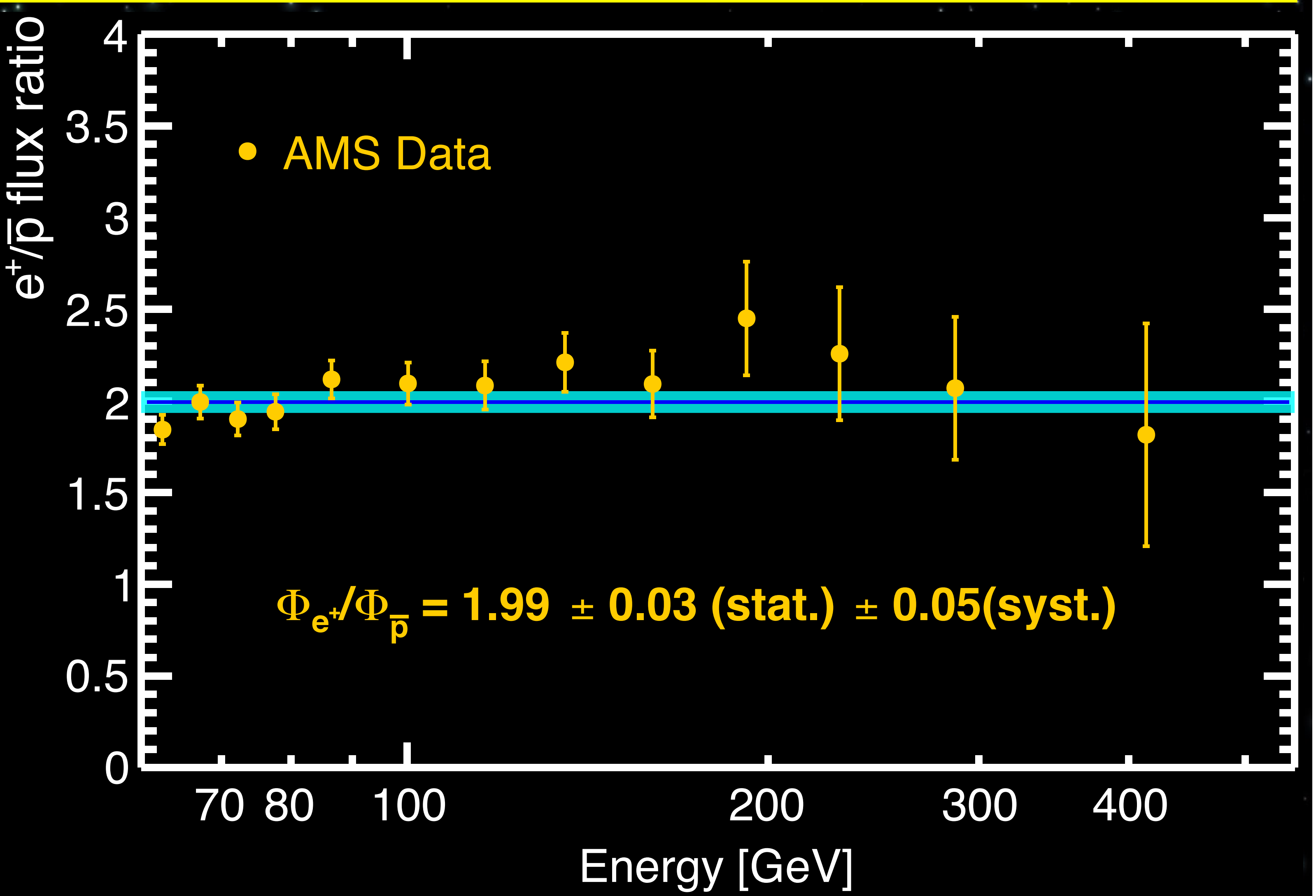
Antiprotons vs positrons

Antiproton data show a similar trend as positrons.



Antiprotons vs positrons

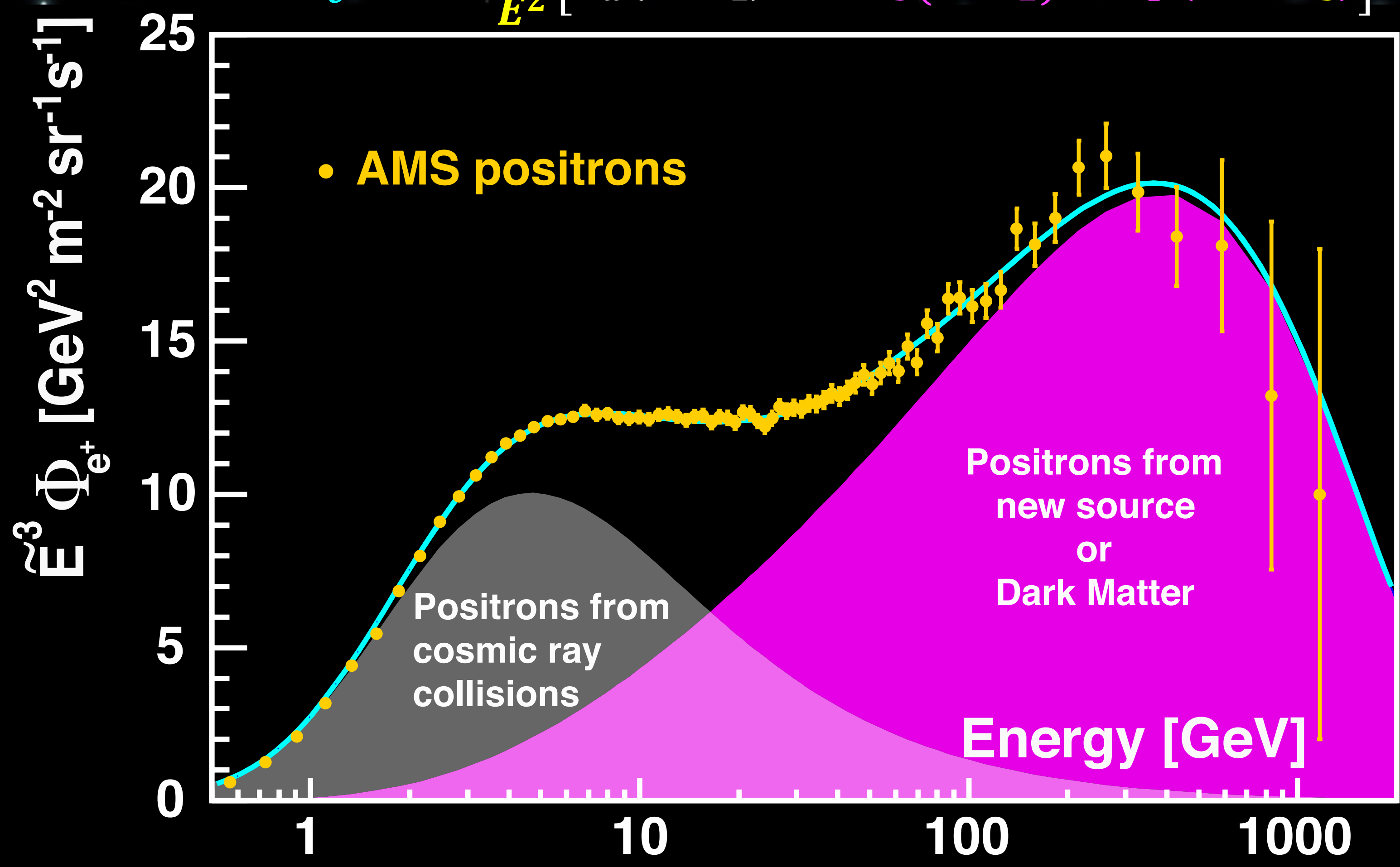
The positron-to-antiproton flux ratio is constant independently of energy. Antiprotons cannot come from pulsars.



Study of Positrons

The positron flux is the sum of low-energy part from cosmic ray collisions plus a high-energy part from a new source or dark matter both with a cutoff energy E_S.

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$

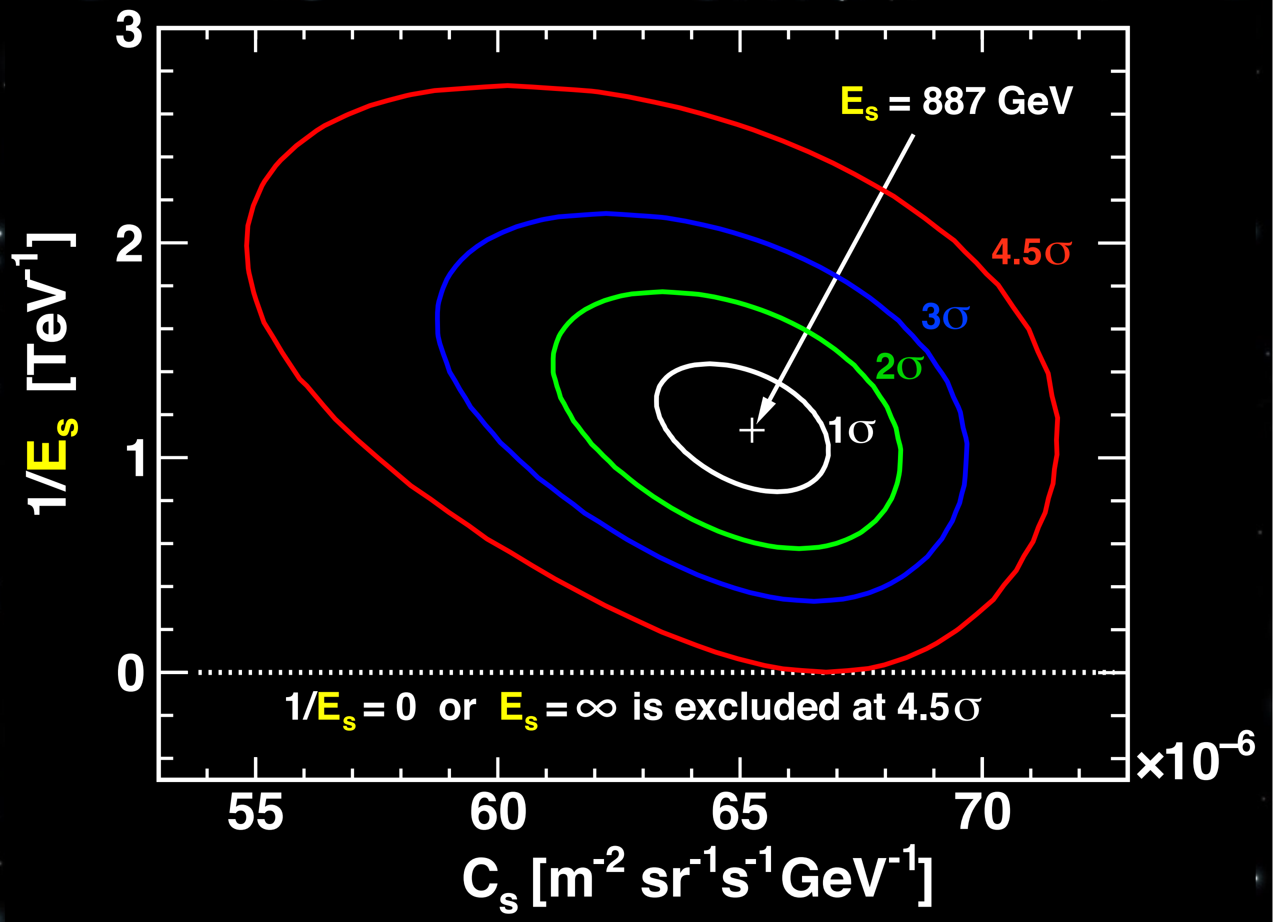


Study of Positrons & Electrons

Collisions — New Source or Dark Matter

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$

The finite cutoff energy E_s is established at 4.5 σ

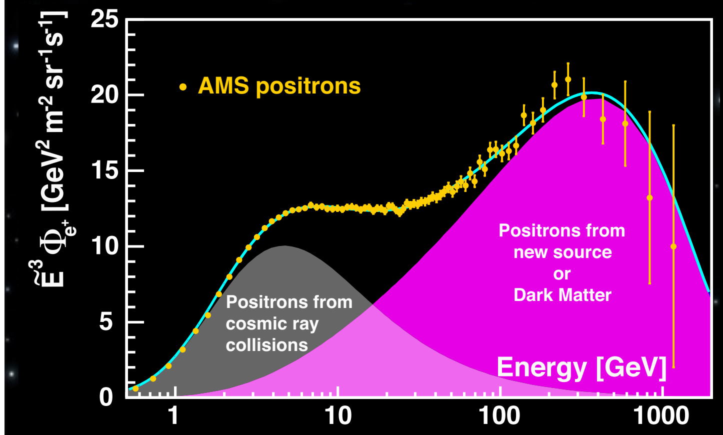


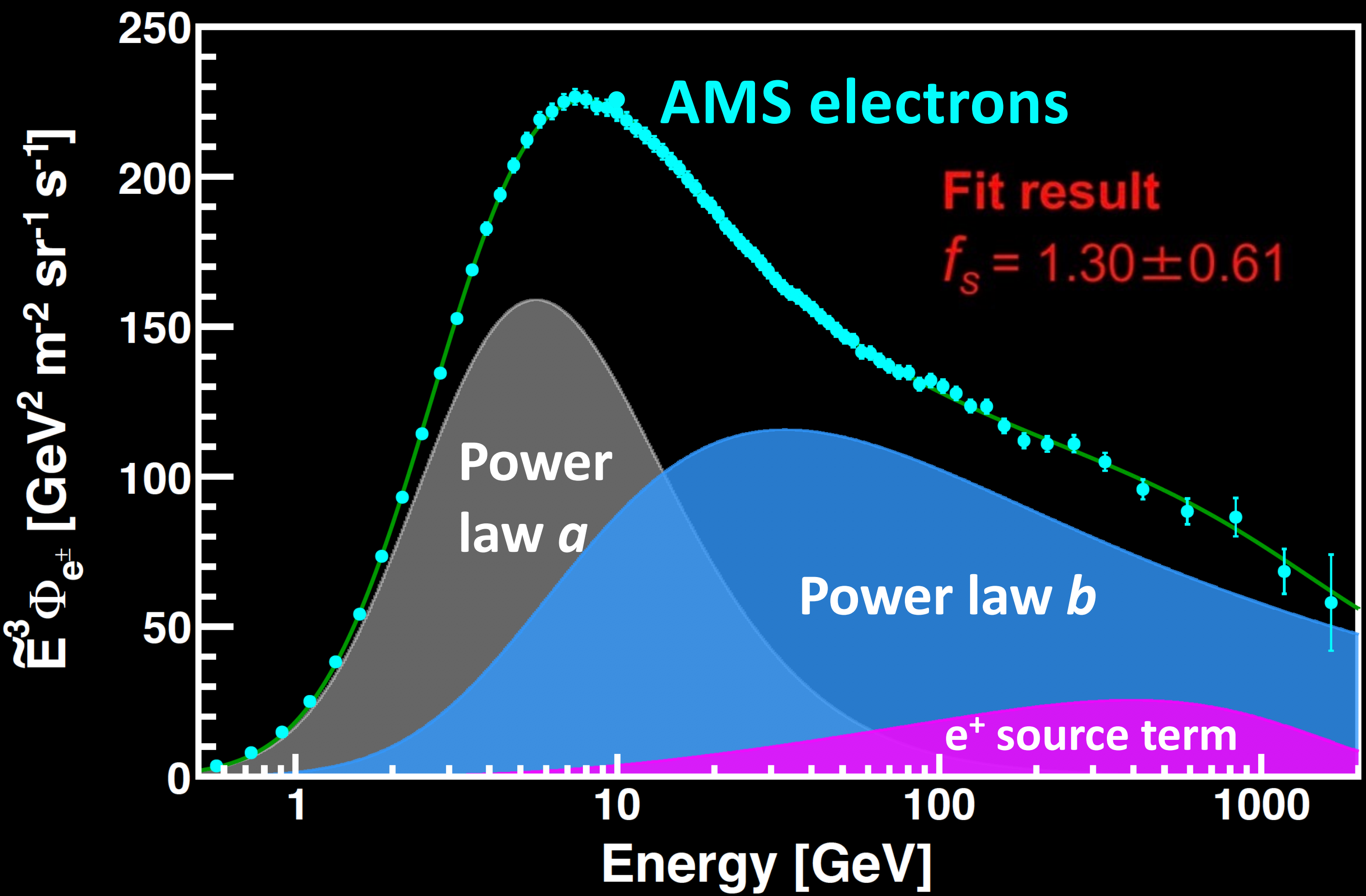
Electrons

$$\Phi_{e^-}(E) = S(E)\left[C_a(\hat{E}/E_a)^{\gamma_a} + C_b(\hat{E}/E_b)^{\gamma_b} + f_s C_s^{e^+}(\hat{E}/E_2)^{\gamma_s^{e^+}} \exp(-E/E_s^{e^+})\right]$$

Solar | Power law *a* | Power law *b* | Positron source term

Electron spectrum favors the contribution of the positron-like source term at 2σ level

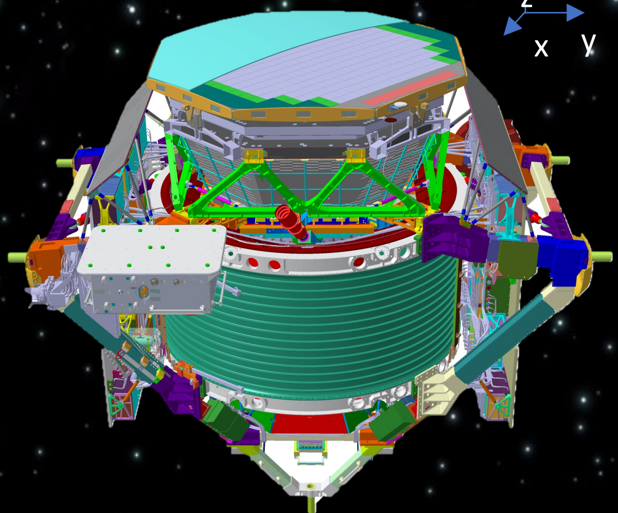




Conclusion

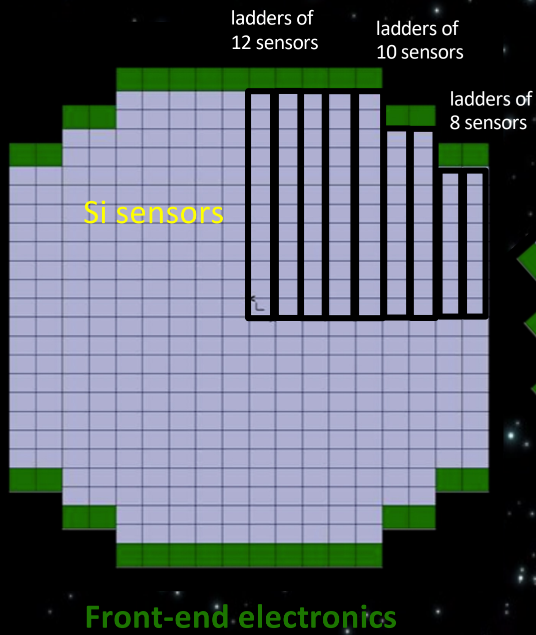
- in the first 10 years AMS-02 produced a wide set of high statistics, high accuracy, unprecedented, cosmic ray measurements
- this set of measurements is challenging the theoretical community for a fully comprehensive model able to explain all the observed features
- AMS will be operated for the full life-time of the ISS (2032?). In case of upgrade, some channels will have a significant boost in statistics/accuracy

New Silicon Tracker Layer: one plane, two layers, each ~ 4m²



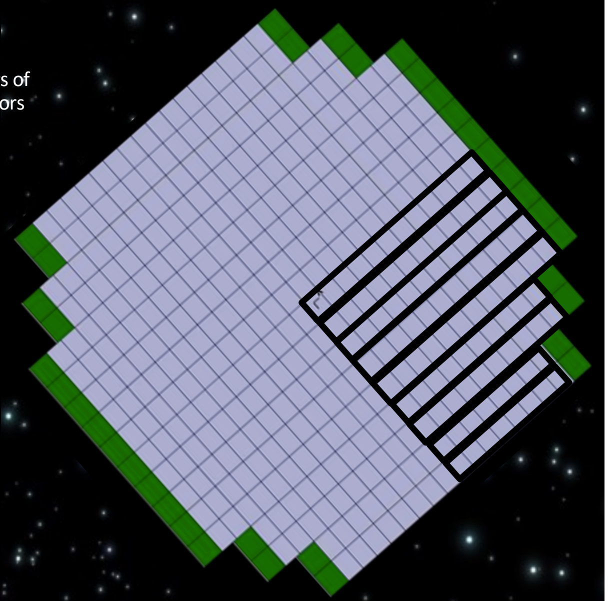
L0-Y

bending direction
7 micron



L0-U

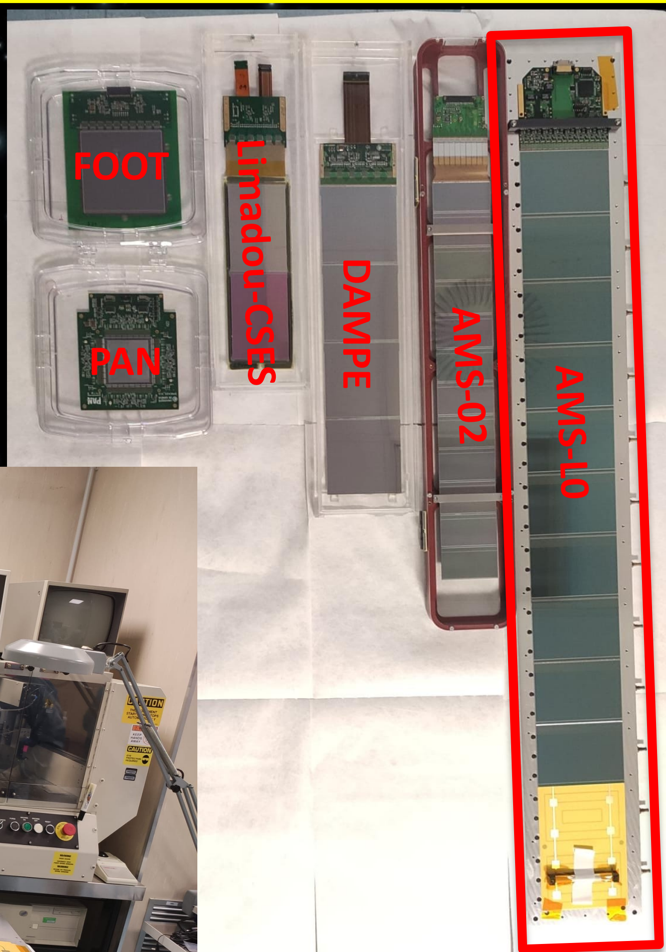
rotated 45°
10 micron bending
10 micron non-bending

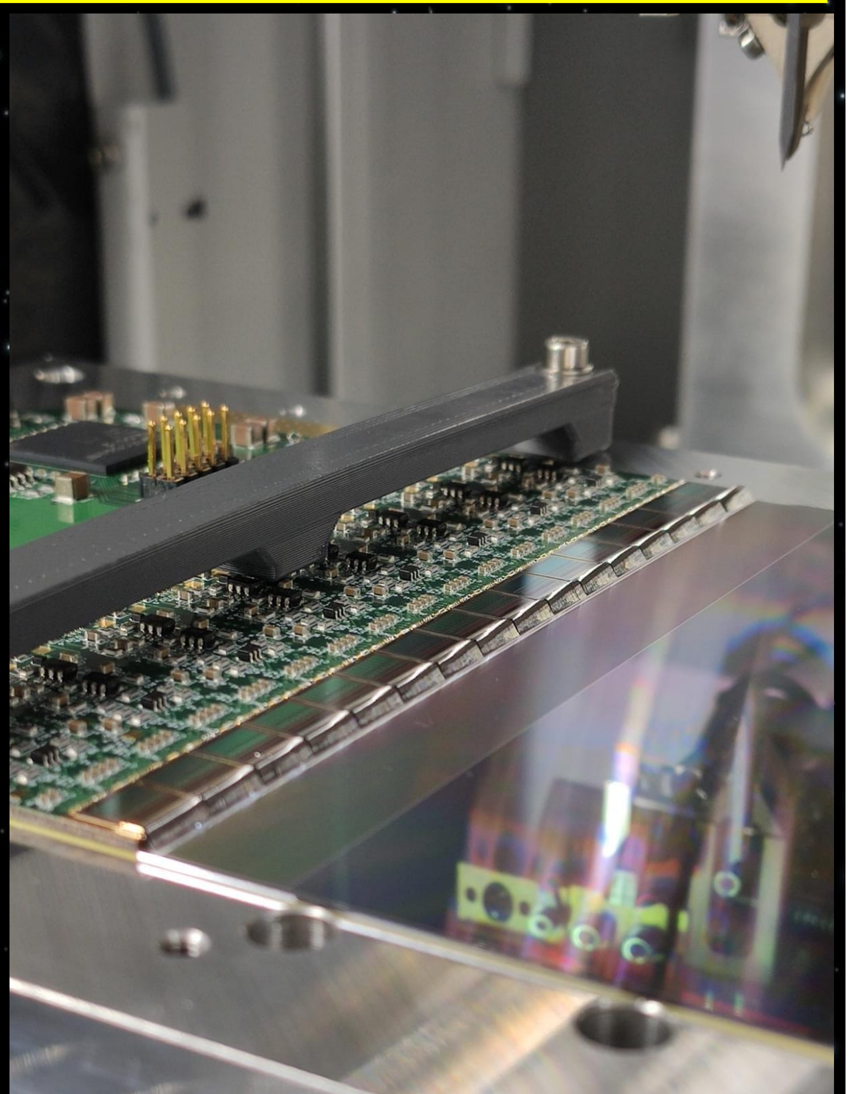


Acceptance increased to 300% (10 years data becomes 30 years data)

AMS-02 upgrade "L0"

10x10 cm^2 sensors
(INFN-Perugia, Italy)





Stay tuned...

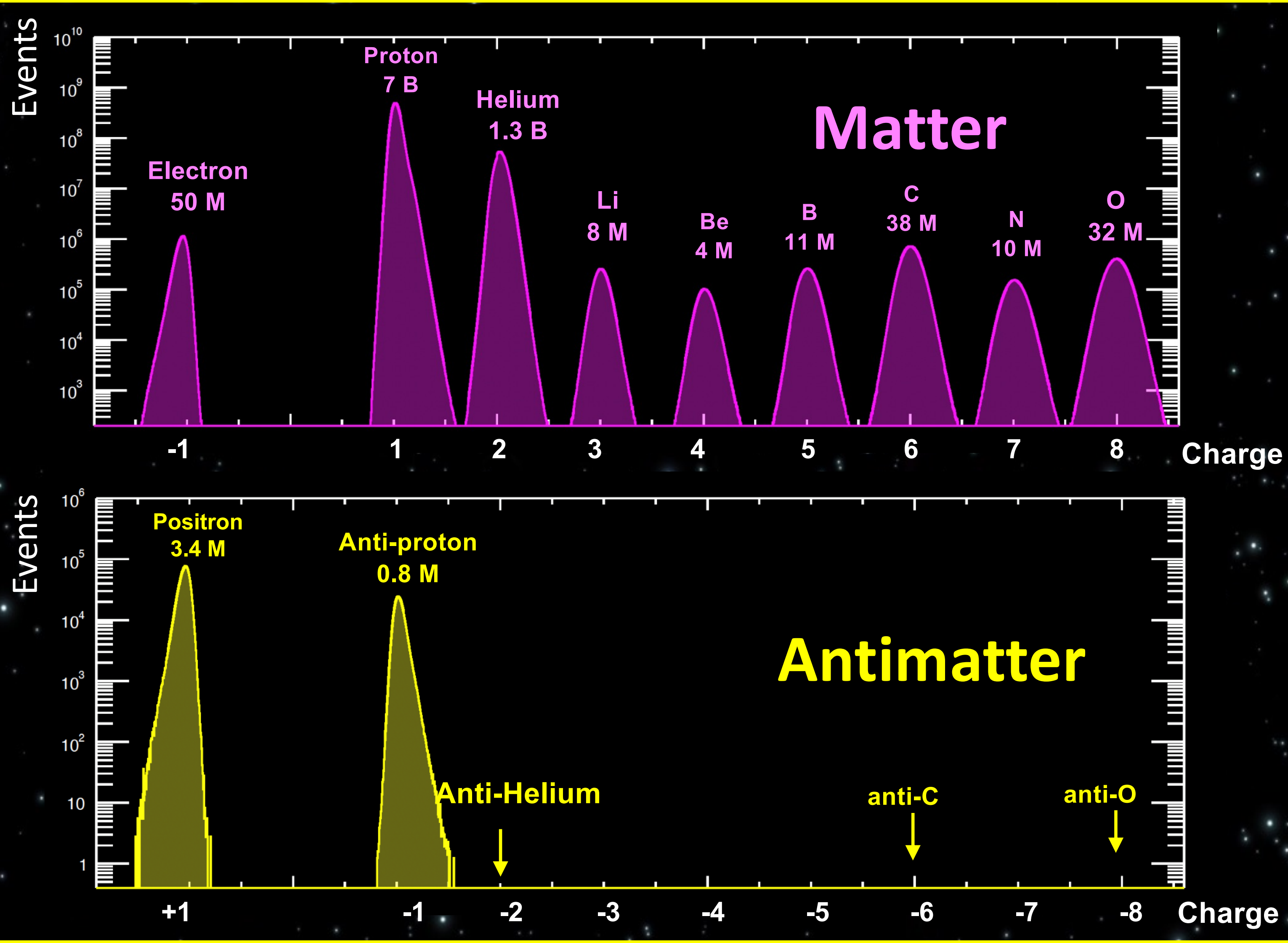
Backup

AMS Publications

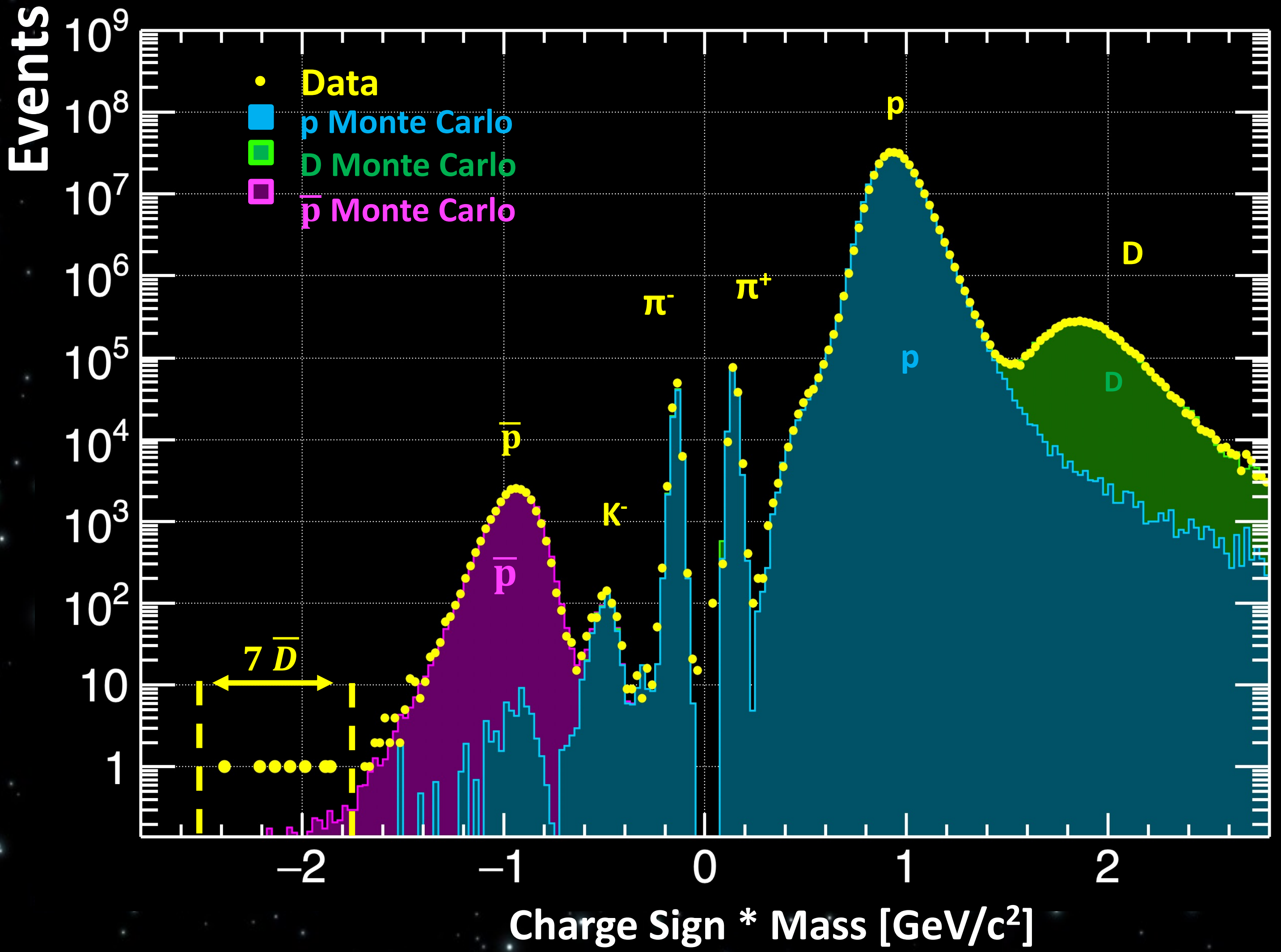
1) e^+/e^++e^- - Phys. Rev. Lett. 110, 141102 (2013). Editors' Suggestion. Viewpoint in *Physics*. Highlight of 2013. Ten-Year retrospective.
2) e^+,e^- - Phys. Rev. Lett. 113, 121101 (2014). Editors' Suggestion
3) e^+/e^++e^- - Phys. Rev. Lett. 113, 121102 (2014). Editors' Suggestion. Featured in *Physics*
4) e^++e^- - Phys. Rev. Lett. 113, 221102 (2014).
5) p - Phys. Rev. Lett. 114, 171103 (2015). Editors' Suggestion
6) He - Phys. Rev. Lett. 115, 211101 (2015). Editors' Suggestion
7) anti-p - Phys. Rev. Lett. 117, 091103 (2016).
8) B/C - Phys. Rev. Lett. 117, 231102 (2016). Editors' Suggestion
9) He, C, O - Phys. Rev. Lett. 119, 251101 (2017).
10) Li, Be, B - Phys. Rev. Lett. 120, 021101 (2018). Editors' Suggestion. Featured in *Physics*.
11) p, He vs t - Phys. Rev. Lett. 121, 051101 (2018).
12) e^+, e^- vs t - Phys. Rev. Lett. 121, 051102 (2018). Editors' Suggestion
13) N - Phys. Rev. Lett. 121, 051103 (2018).
14) e^+ - Phys. Rev. Lett. 122, 041102 (2019). Editor's Suggestion
15) e^- - Phys. Rev. Lett, 122, 101101 (2019).
16) ^{3}He, ^{4}He, vs t - Phys. Rev. Lett. 123, 181102 (2019). Editors' Suggestion
17) Ne, Mg, Si - Phys. Rev. Lett. 124, 211102 (2020). Editors' Suggestion. Featured in *Physics*.
18) Physics Reports 894, 1 (2021),
19) Fe - Phys. Rev. Lett. 126, 041104 (2021). Featured in *Physics*.
20) F - Phys. Rev. Lett. 126, 081102 (2021). Editors' Suggestion
21) Na, Al, N - Phys. Rev. Lett. 127, 021101 (2021).
22) p vs t - Phys. Rev. Lett. 127, 271102 (2021).

> 6000 citations as of today

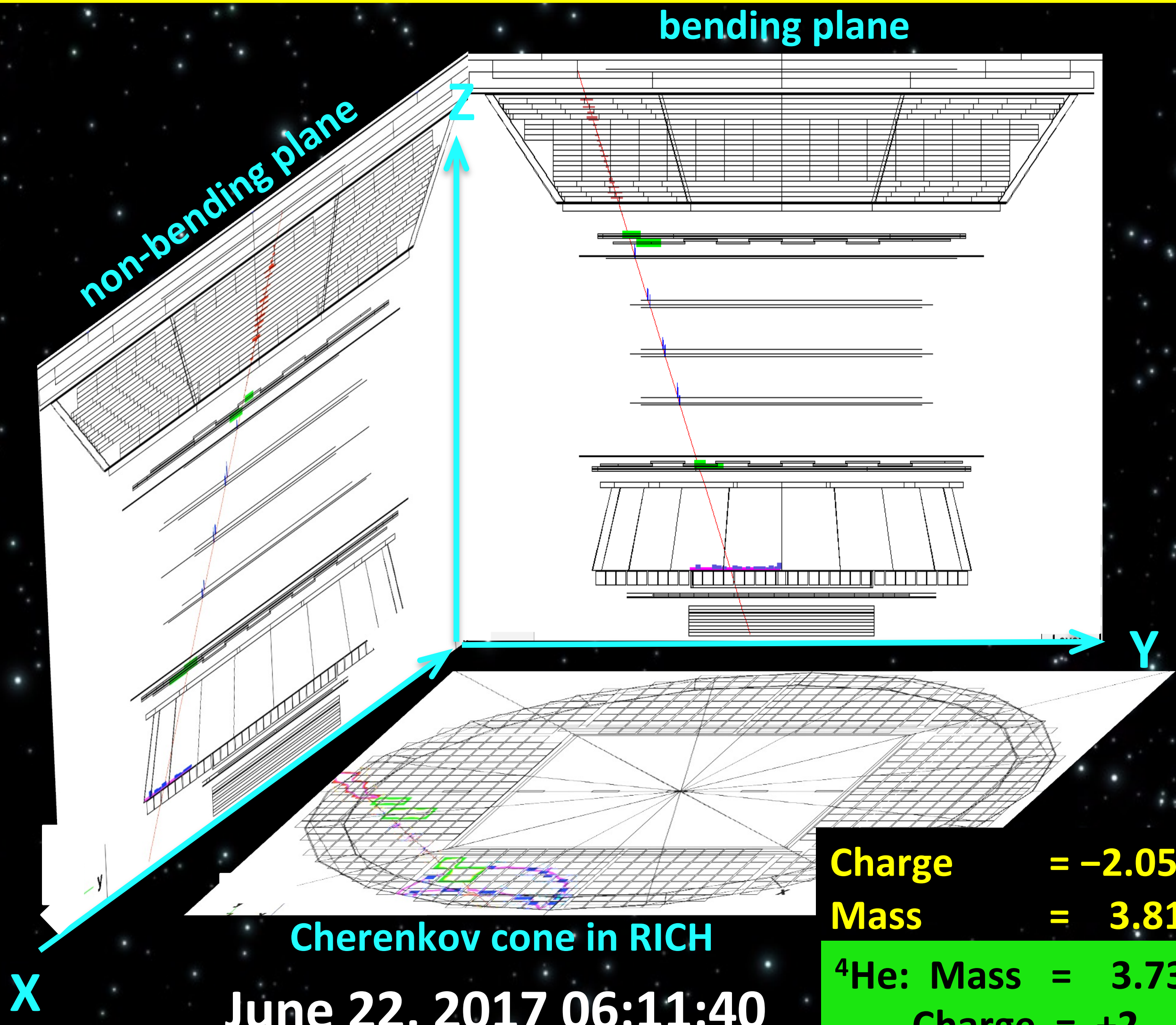
Mstter and Antimatter



Anti-deuterons



Heavy antimatter



June 22, 2017 06:11:40

Charge = −2.05 ± 0.05
Mass = 3.81 ± 0.29 GeV/c^2

^{4}He: Mass = 3.73 GeV/c^2
Charge = +2

Unexpected results from the Study of Positrons & Electrons

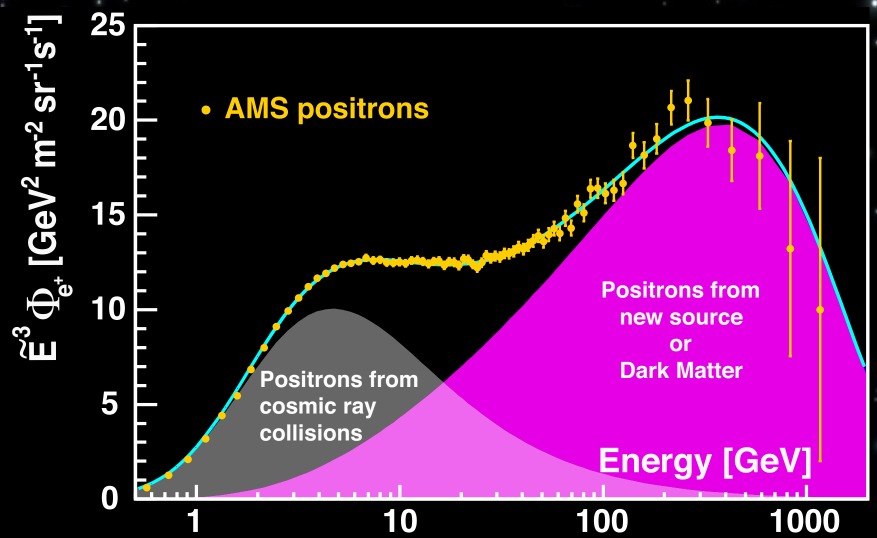
The positron flux is the sum of a low-energy part from cosmic ray collisions
plus a high energy part from pulsars or dark matter.

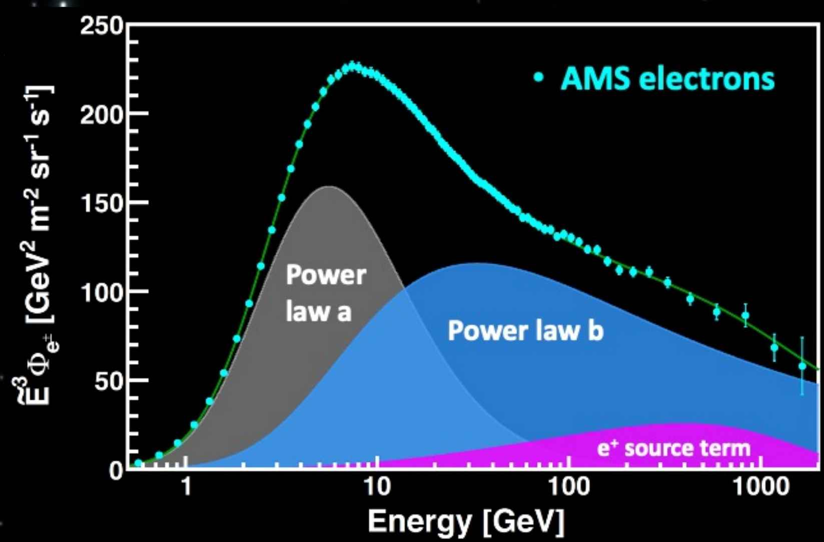
The antiproton spectrum rules out the pulsar origin of positrons.

Bulk of electrons originate from different sources than positrons;
but highest energy electrons show positron-like contribution at 2σ level.

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}\left[C_d(\hat{E}/E_1)^{\gamma_d} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)\right]$$

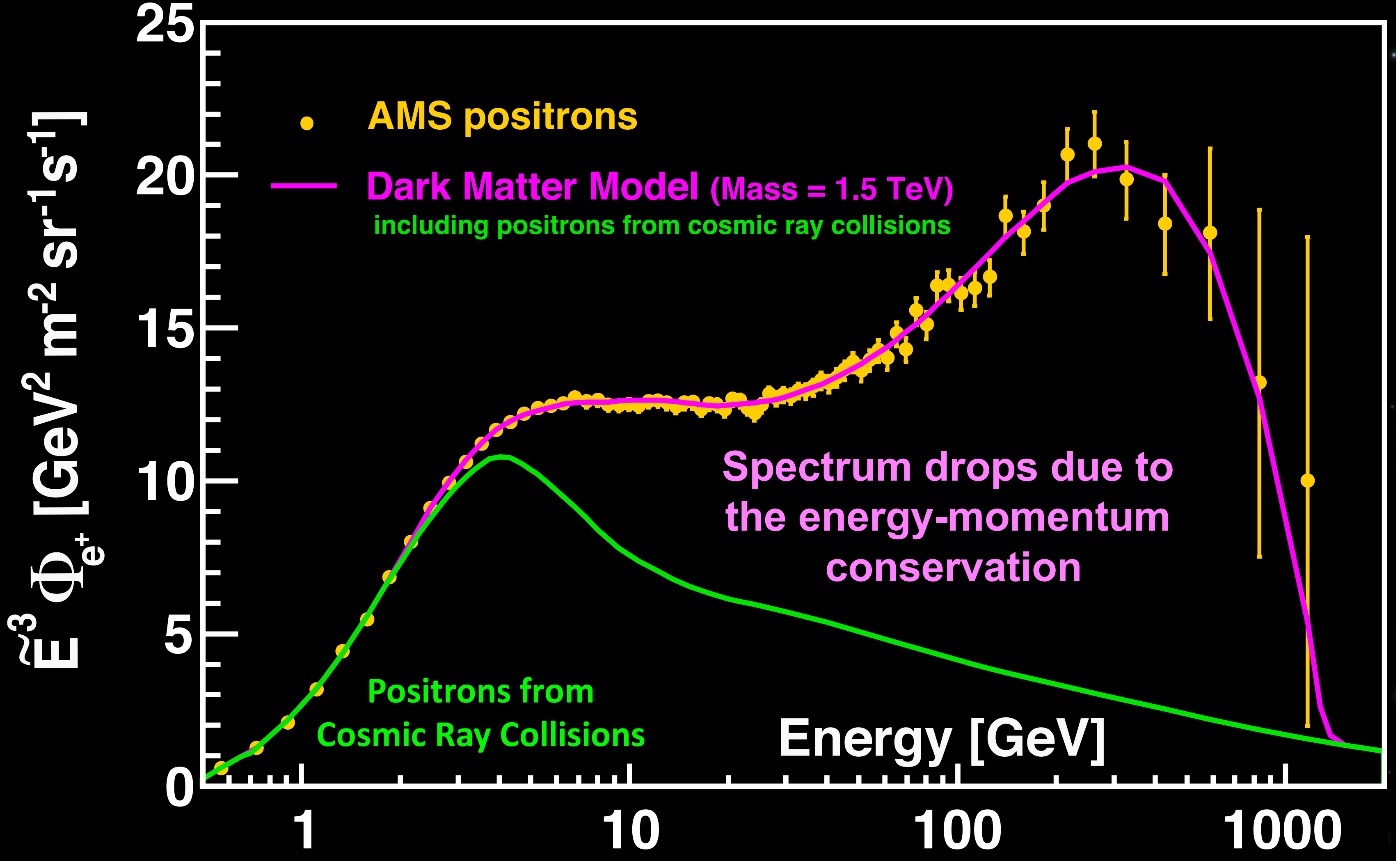
$$\Phi_{e^-}(E) = S(E)\left[C_a(\hat{E}/E_a)^{\gamma_a} + C_b(\hat{E}/E_b)^{\gamma_b} + C_s^{e^+}(\hat{E}/E_2)^{\gamma_s^{e^+}}\exp(-E/E_s^{e^+})\right]$$





Positrons and Dark Matter

Positrons and a Dark Matter Model

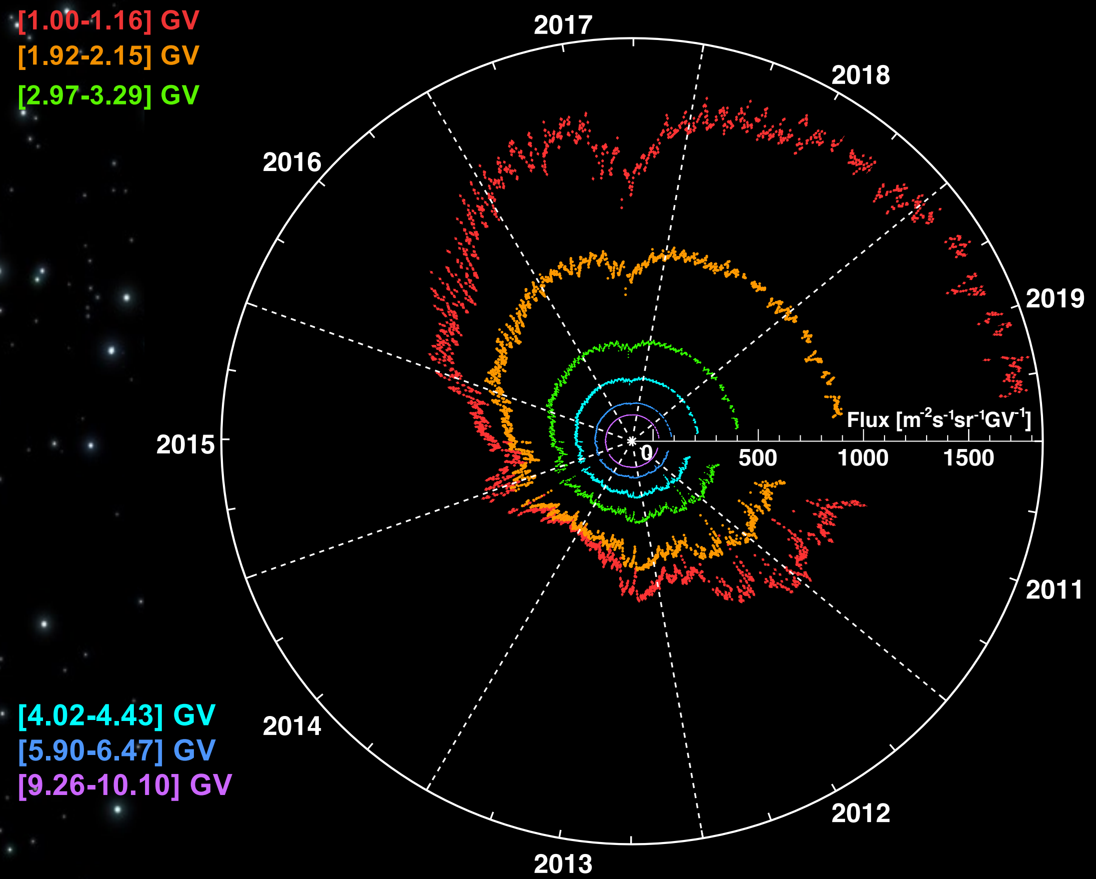


Time variations: protons

Yearly, Monthly, Daily Proton Flux from 5.5 billion events

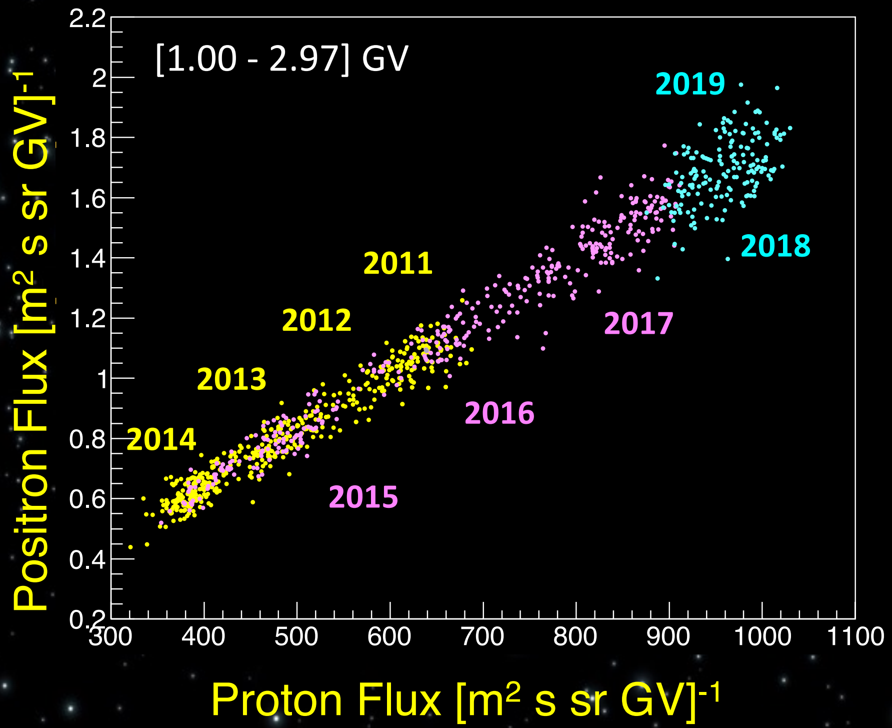
Unexpected observation of periodic structures which are momentum dependent

These are new and unique probes of fundamental properties of solar system and provide safety information for interplanetary travel.

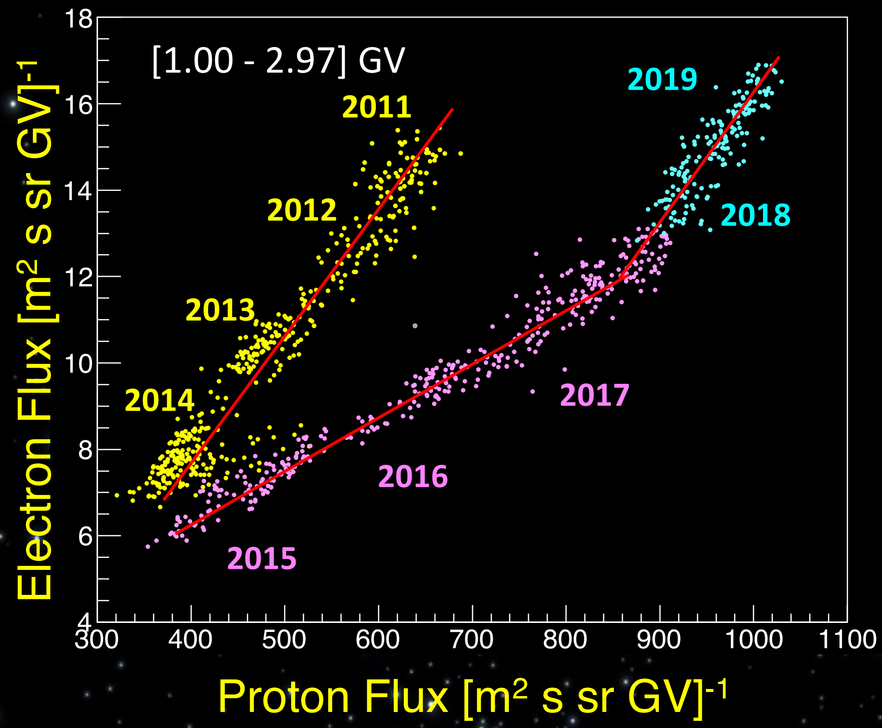


Protons vs electrons and positrons

Positron vs. proton



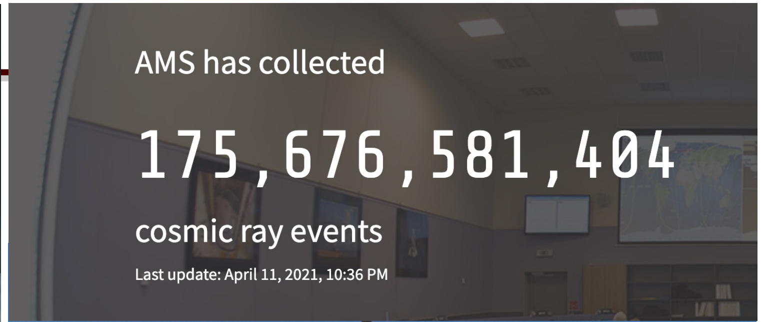
Electron vs. proton

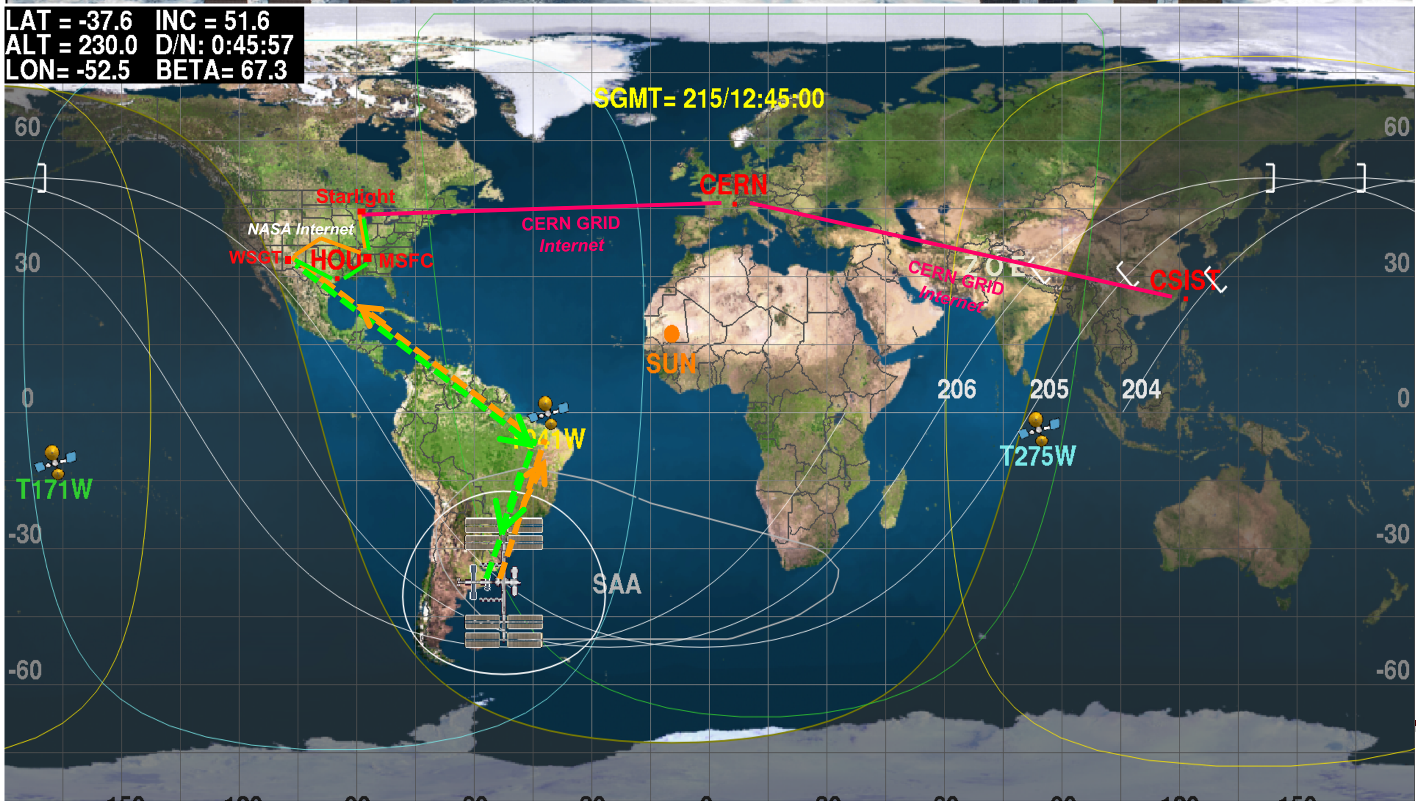


Positrons and protons fluxes have a linear relation

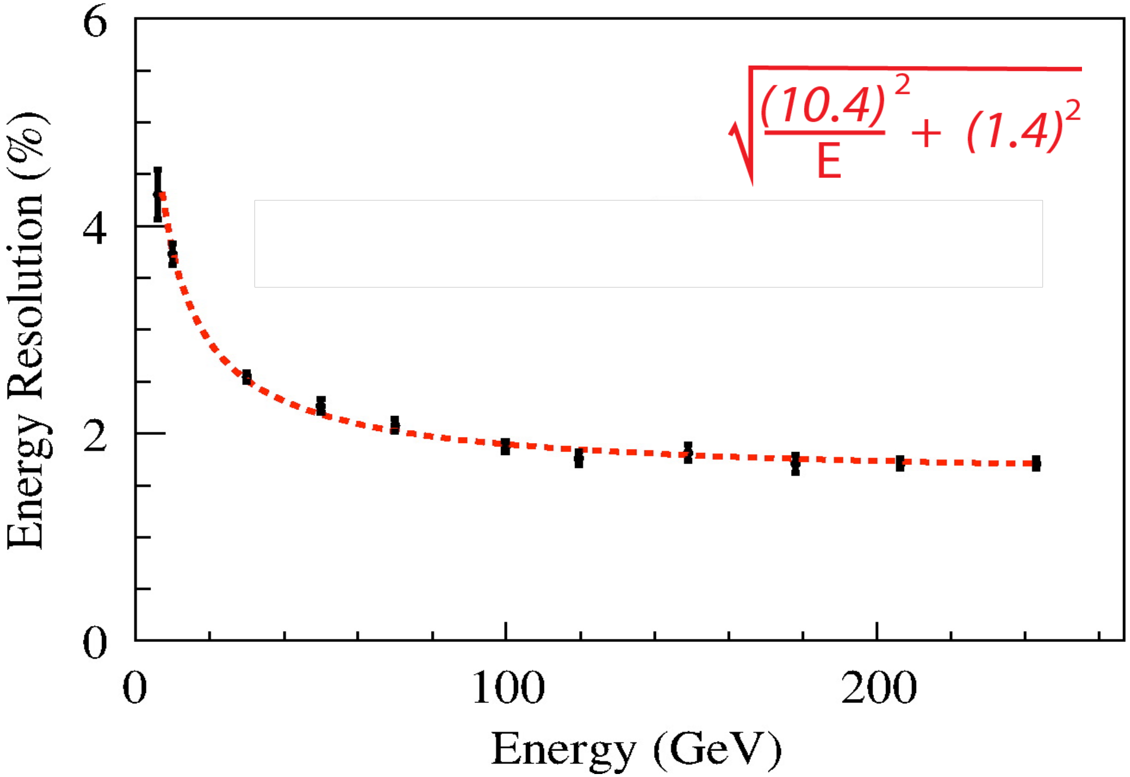
The relation between the electron and proton fluxes is a surprise

A particle physics experiment on ISS





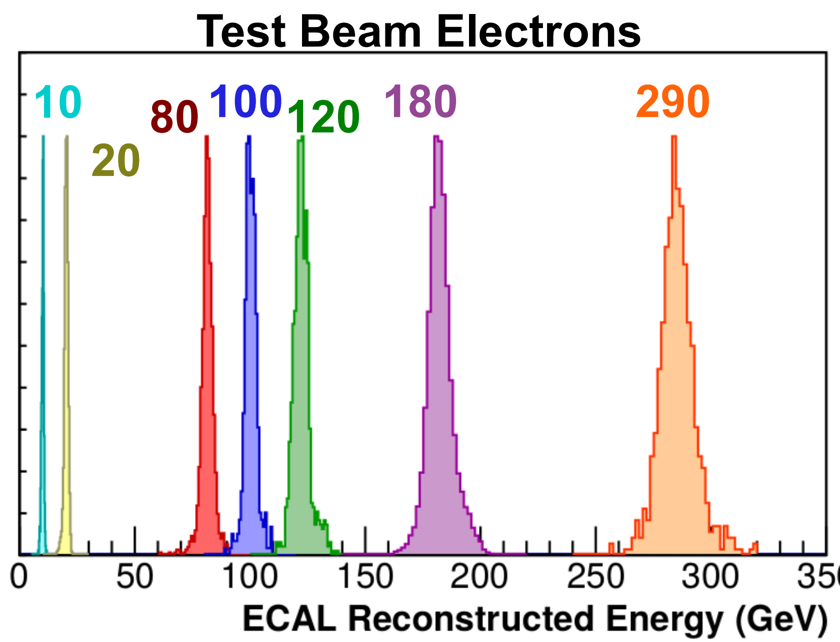
Energy measurement



ECAL energy absolute scale
calibrated and tested during Beam Tests on ground

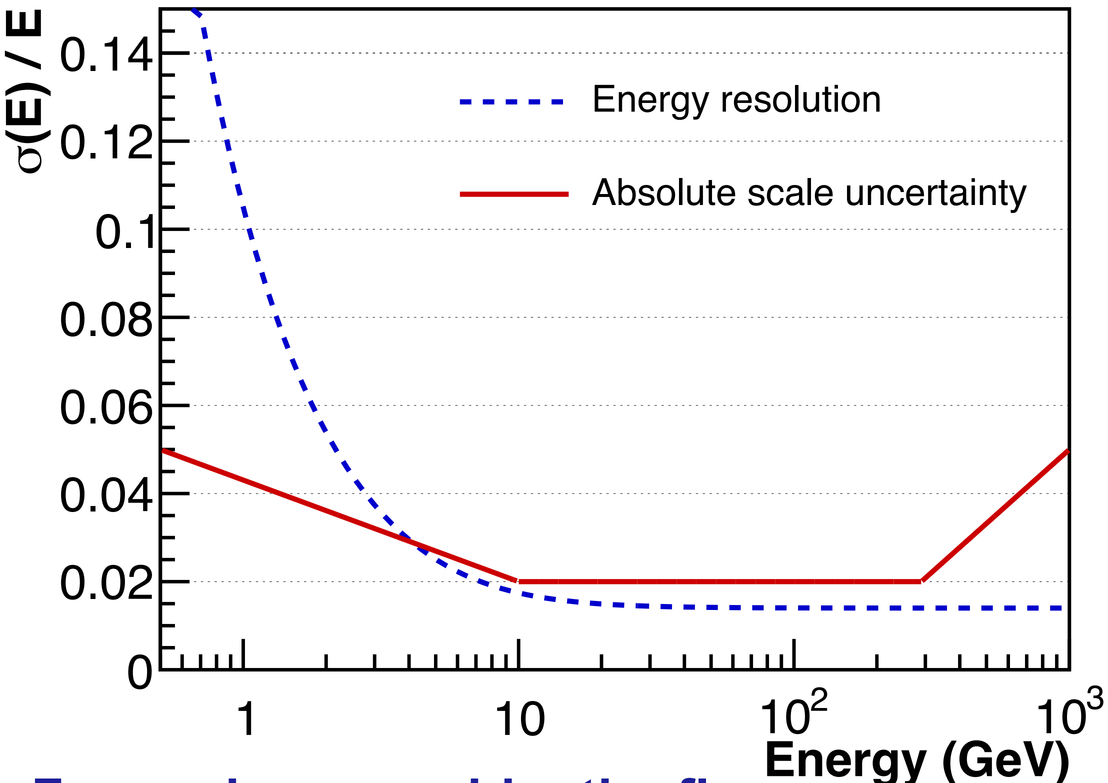
ECAL energy scale known at 2% level in [10.0 – 290.0] GeV

At high energies (>100 GeV), the **energy resolution is better than 2%**.
This has been checked in a large Beam Test campaign and is well predicted by the MC simulation



Energy scale

ECAL energy scale known at 2% level in [10.0 – 290.0] GeV

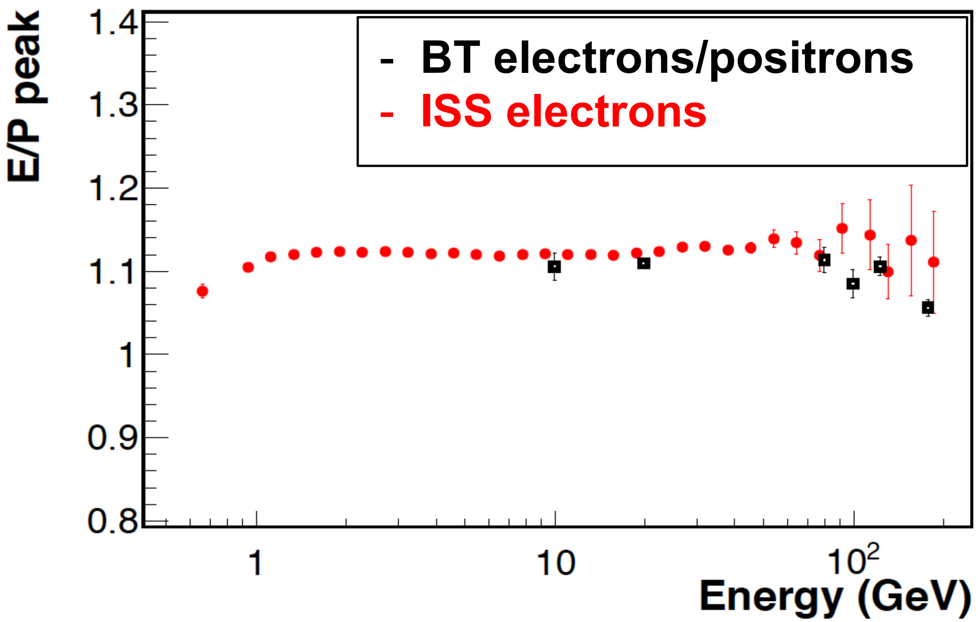


Historically the error on the absolute energy scale is not quoted and not plotted or quoted/plotted as error on the energy (i.e. "on *x*") and not on the flux (i.e. "on *y*"):

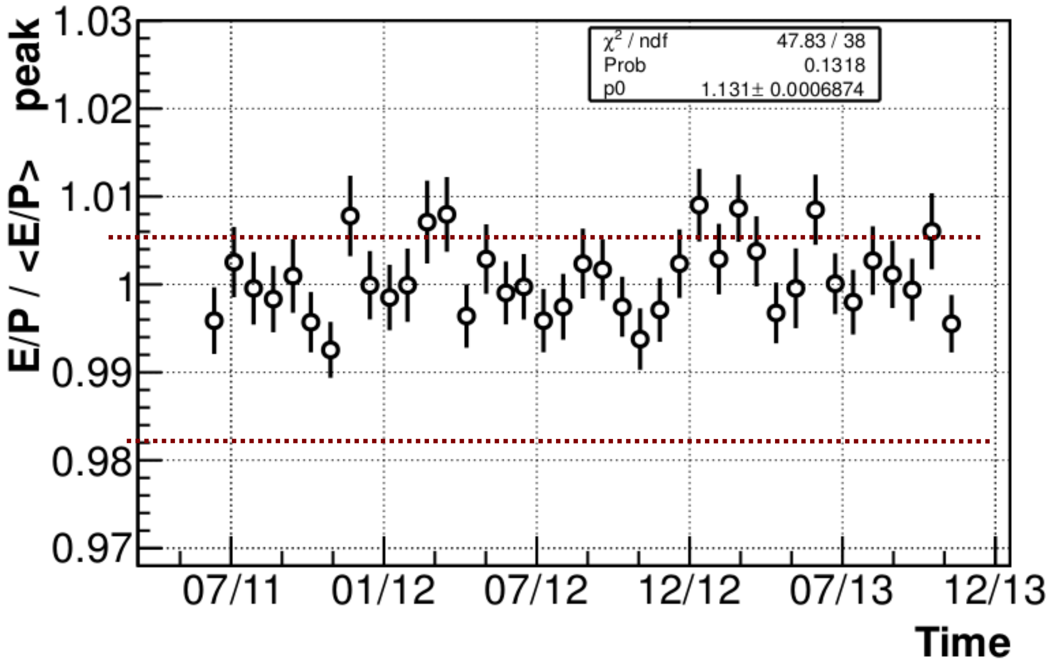
$$\sigma_\Phi \sim (\gamma - 1)\sigma_{abs}$$

- **For each energy bin, the flux measurement is reported to a representative value $\bar{E}$ of the energy in the bin for a flux E^{-3}**
- **the uncertainty on the energy scale is associated as an error to the choosen $\bar{E}$**

Energy absolute scale



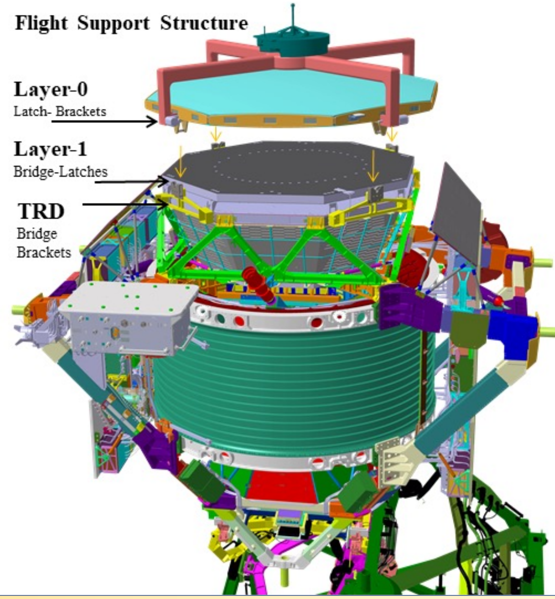
The comparison of the ECAL energy with independent Tracker rigidity measurement used to ensure the correction absolute scale



Stability in time of the calibration **cross-checked, aposteriori**

This is possible thanks to the AMS redundancy and complementarity

- Installation of one additional sylicon tracker layer (~7 m^2): **layer 0 (L0)**
- **Acceptance** X3



2011 AMS-02
InstalledOnISS

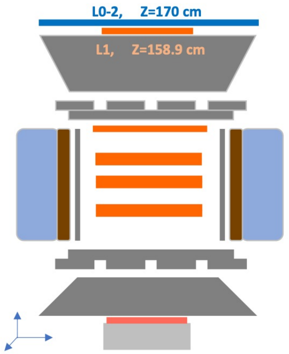
2020 AMS-02.01
1° Upgrade:UTTPS

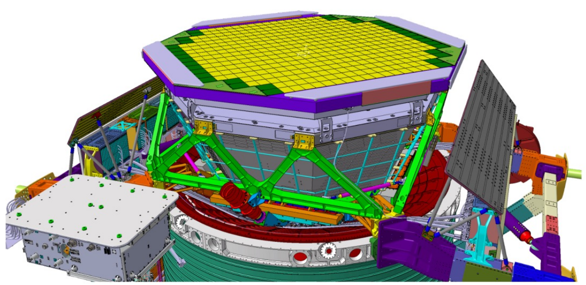
2024 AMS-02.02
2° Upgrade:L0

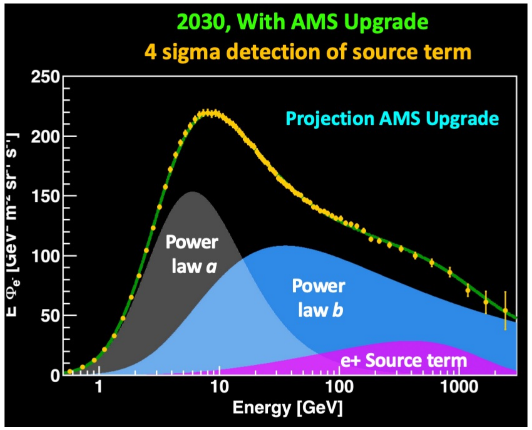
AMS Upgrade

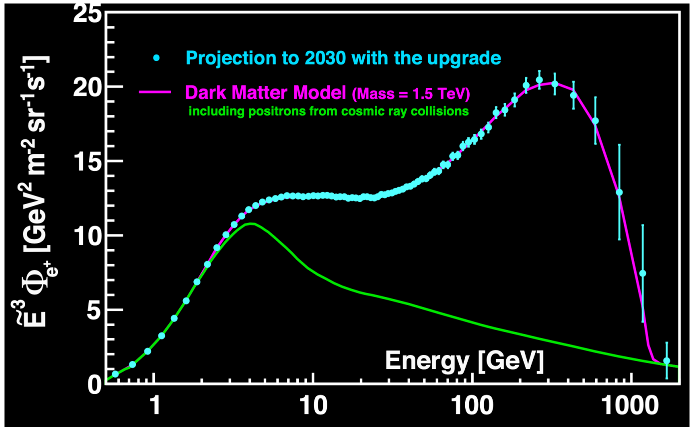
AMS-02 Upgrade

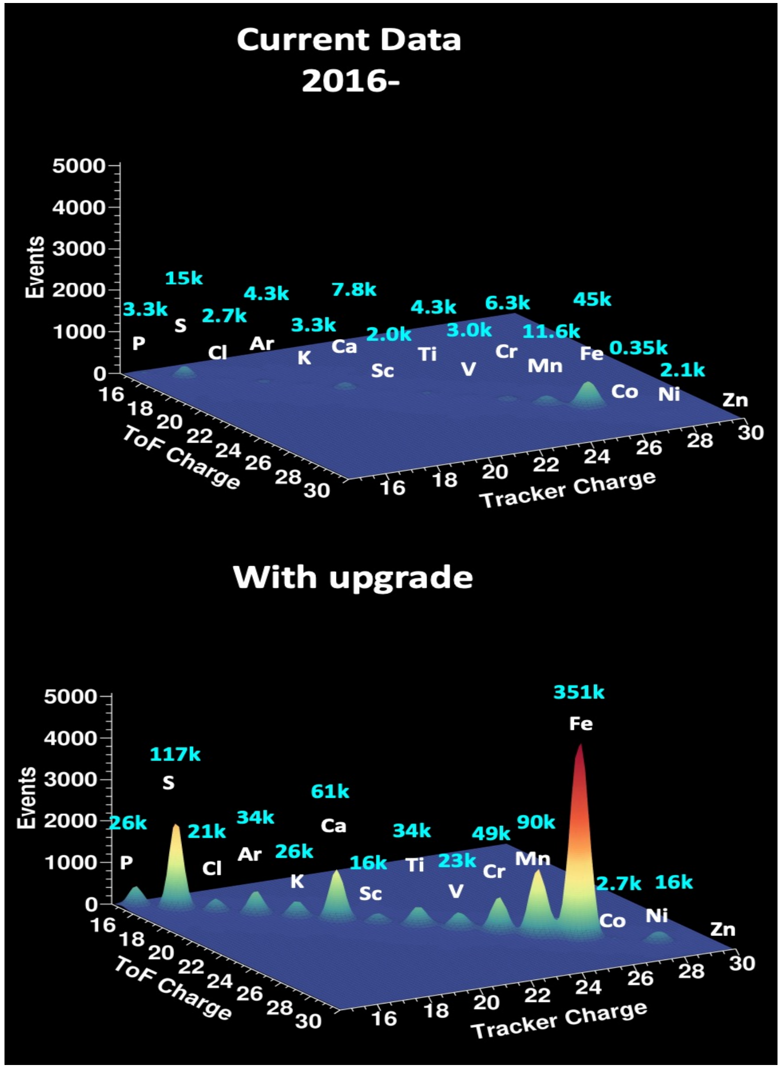
- How ? L0, an additional two side silicon layer (~7 m^2) on top AMS-02
- What you gain? 300% increase in the acceptance for most of the channels
- When? install L0 in 2024, the sooner is L0 installed, the larger is the statistics gain



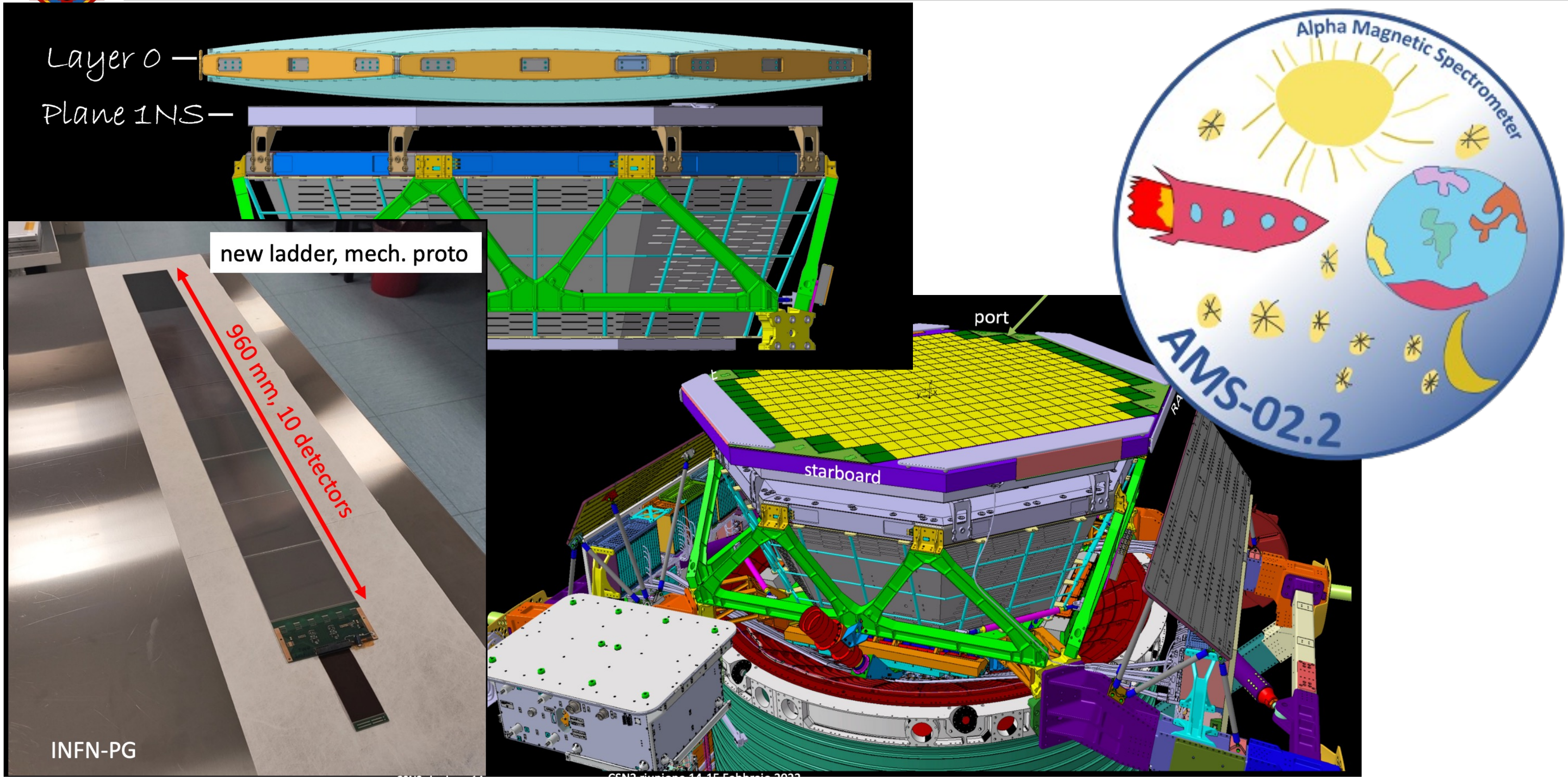








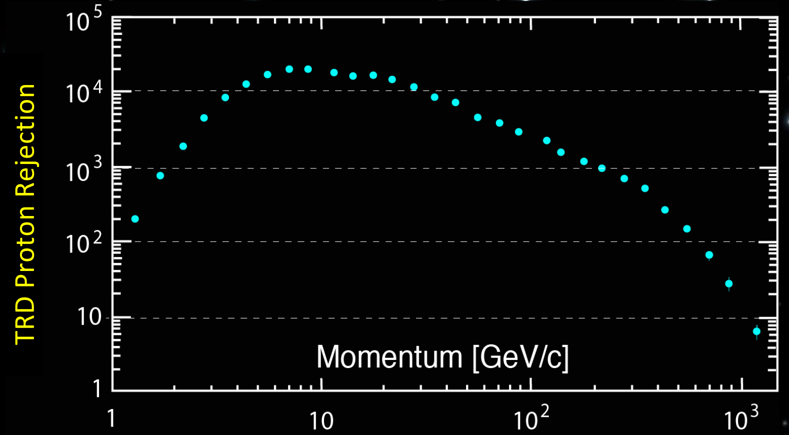
AMS Upgrade


Layer 0
Plane 1NS
new ladder, mech. proto
960 mm, 10 detectors
INFN-PG
port
starboard
Alpha Magnetic Spectrometer
AMS-02.2

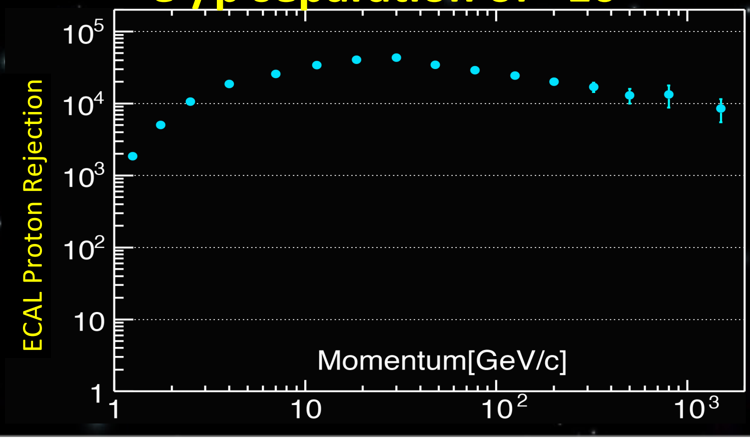
Accurate Measurement of Positrons

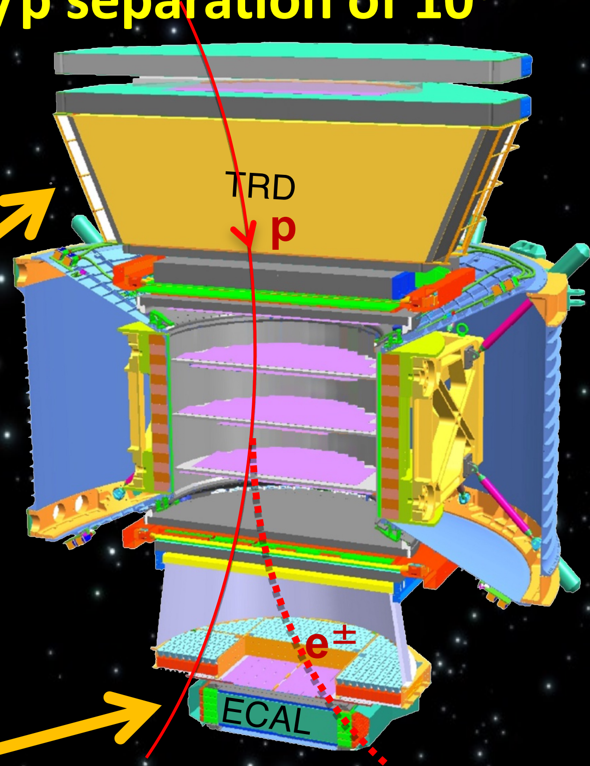
For every cosmic positron there are 10,000 cosmic protons, a 1 % measurement requires a e^+/p separation of 10^6

Transition Radiation Detector (TRD)
e^+/p separation of ~10^3



Electromagnetic Calorimeter (ECAL)
e^+/p separation of ~10^4

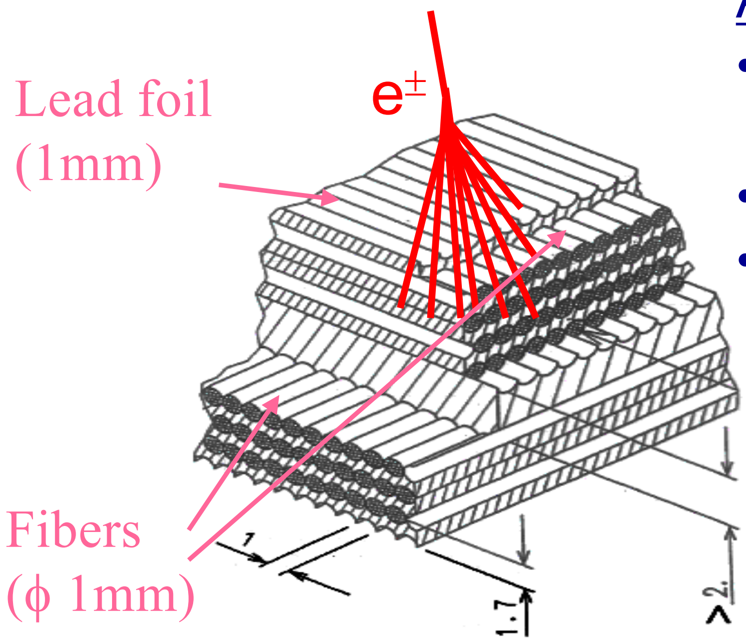




TRD and ECAL are separated by the magnet so that e^+ produced in the spectrometer do not enter the ECAL

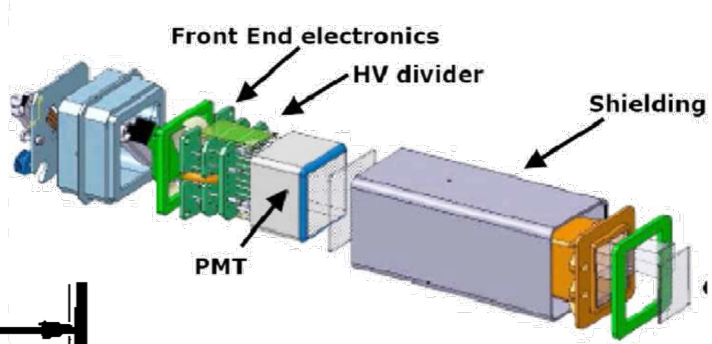
e^+/p separation of > 10^6

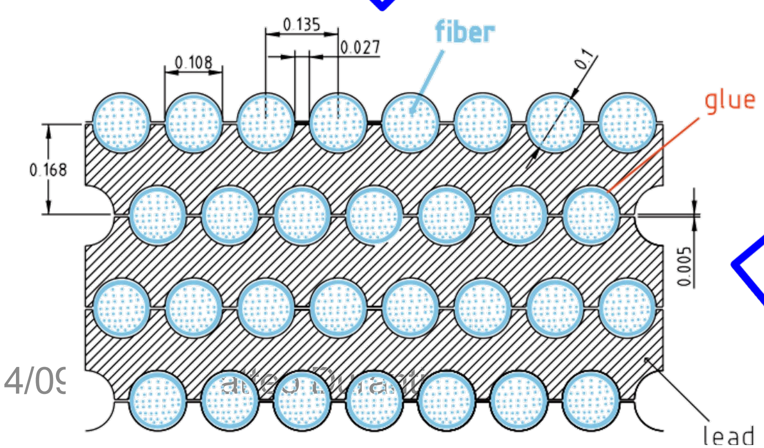
Shower development topology: segmentation

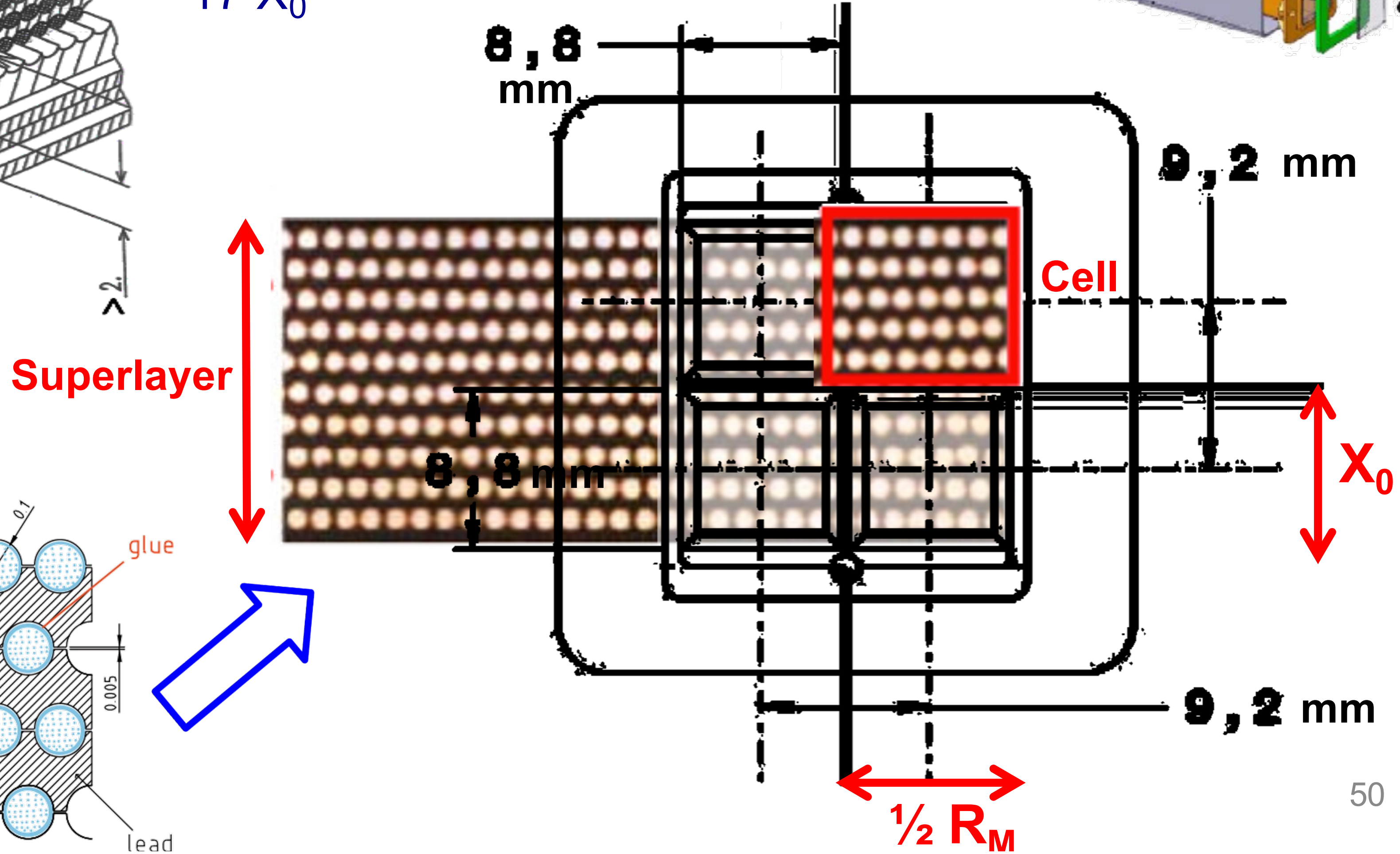


AMS ECAL:

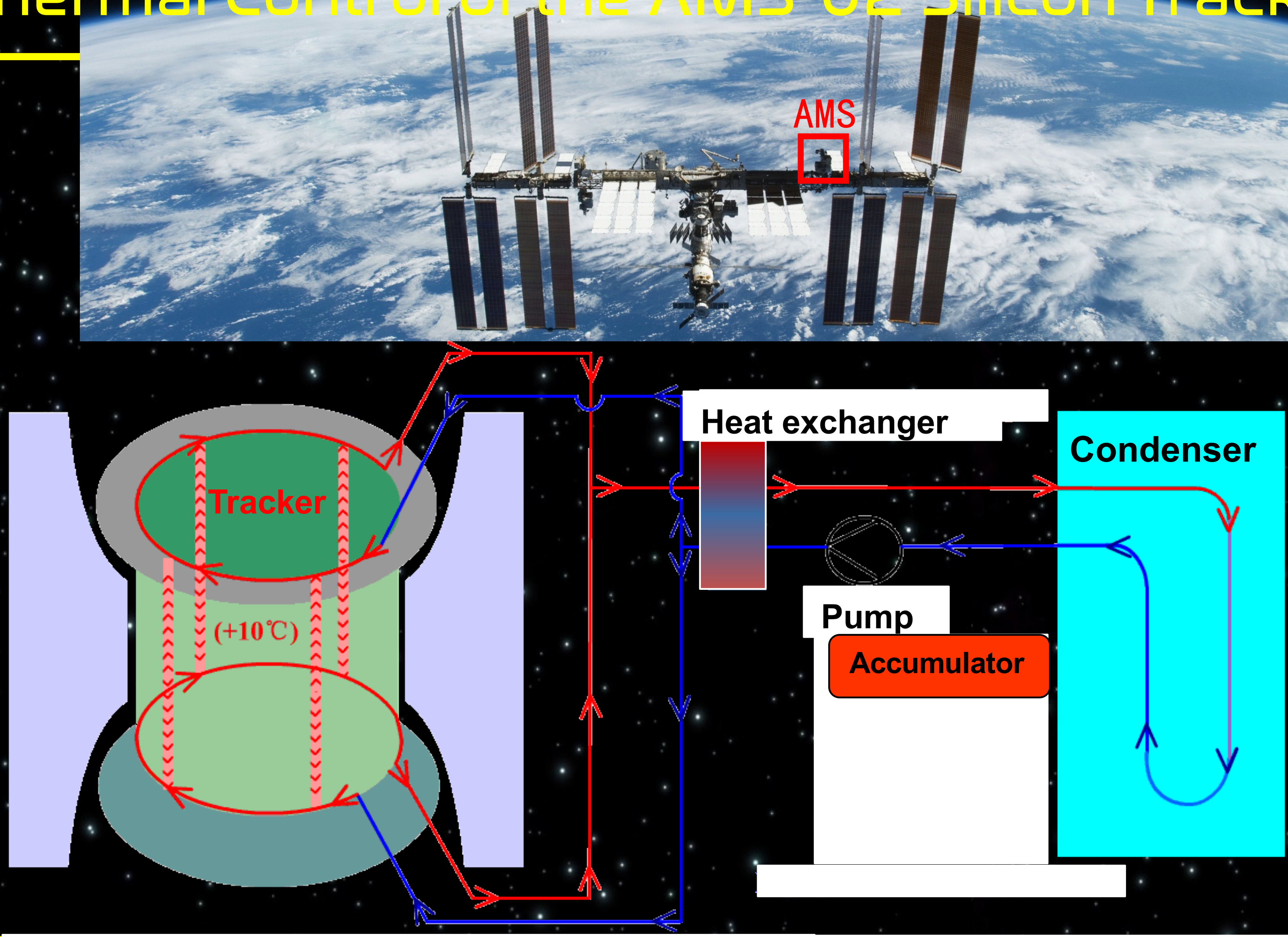
- Lead-SciFi sampling calorimeter
- 18 layers (9 super-layers)
- 17 X_0





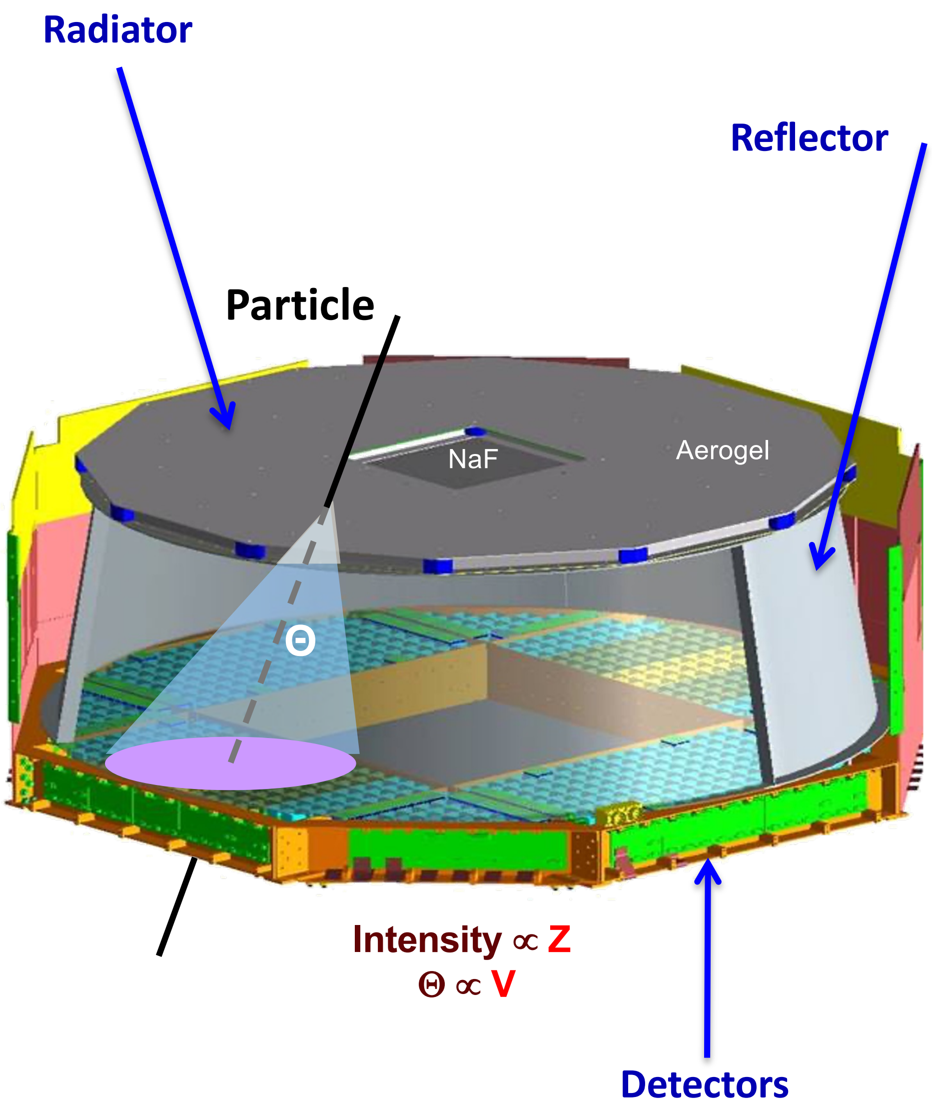


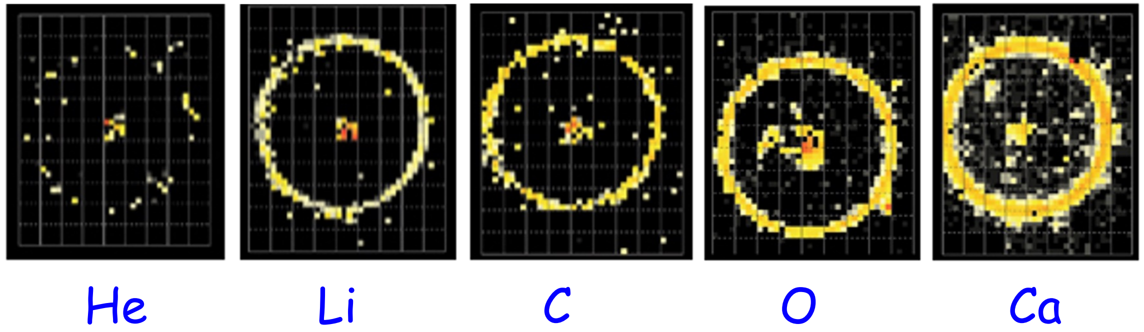
Thermal Control of the AMS-02 Silicon Tracker

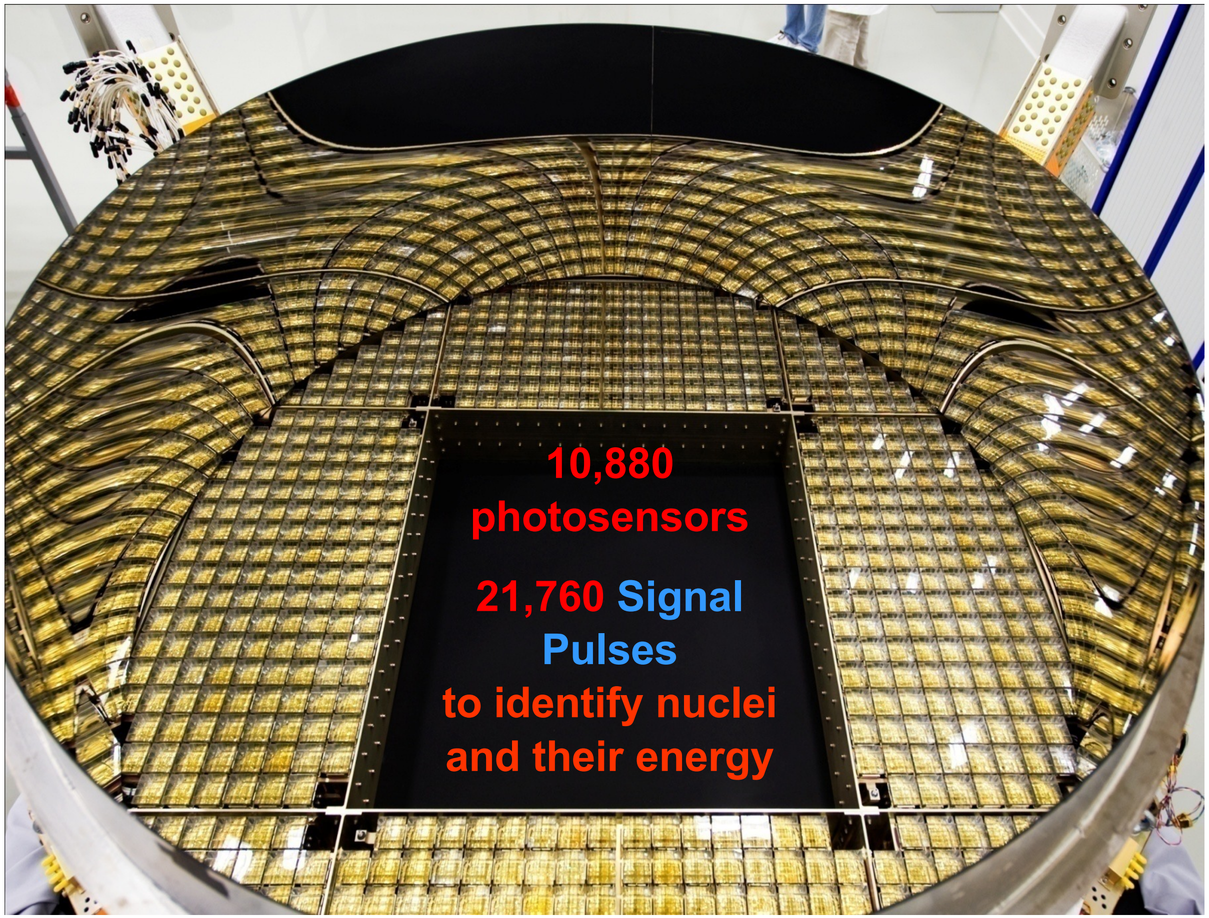


Red line: CO_2 gas/liquid two phase   Blue line: CO_2 liquid phase

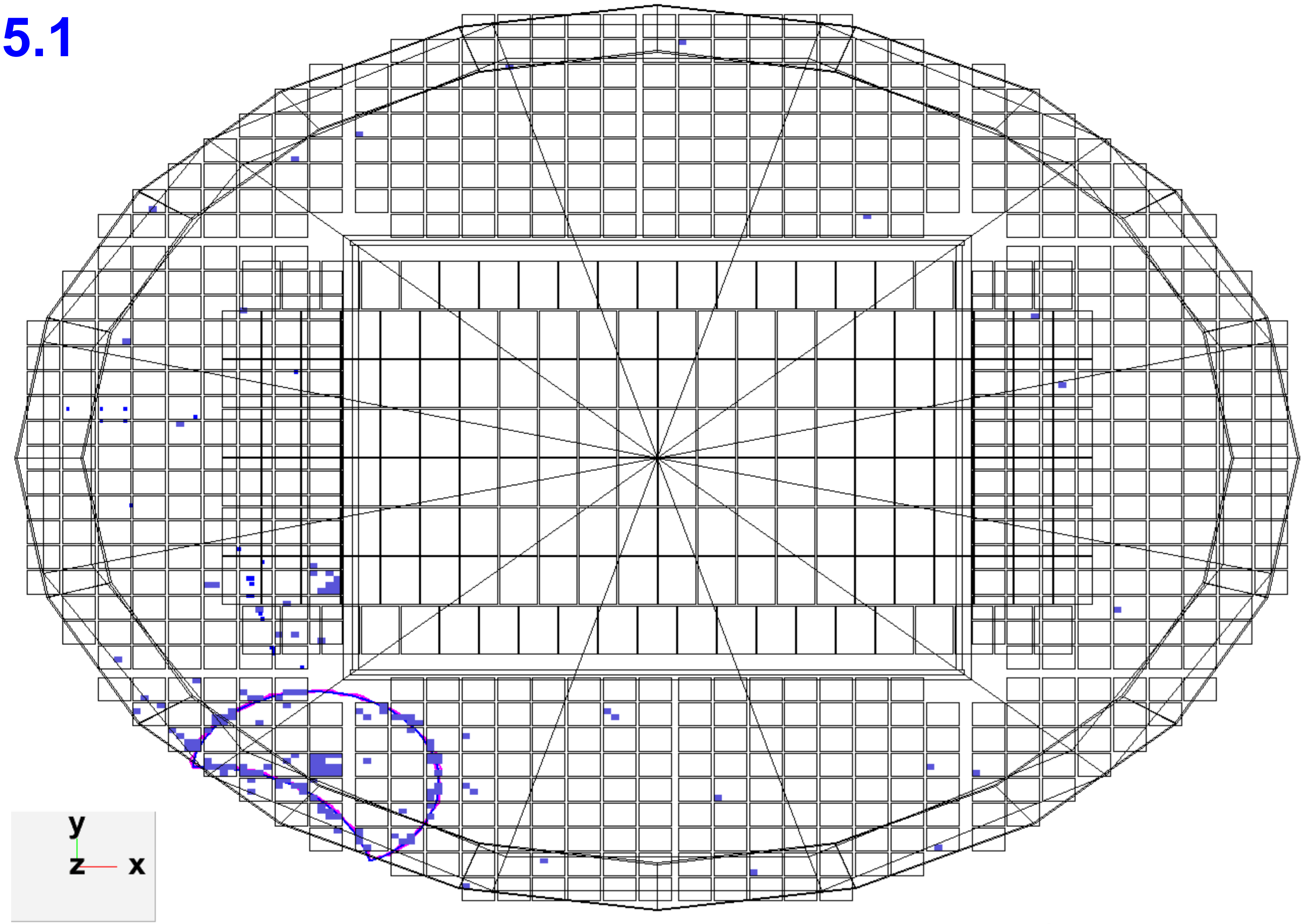
15 November 2019

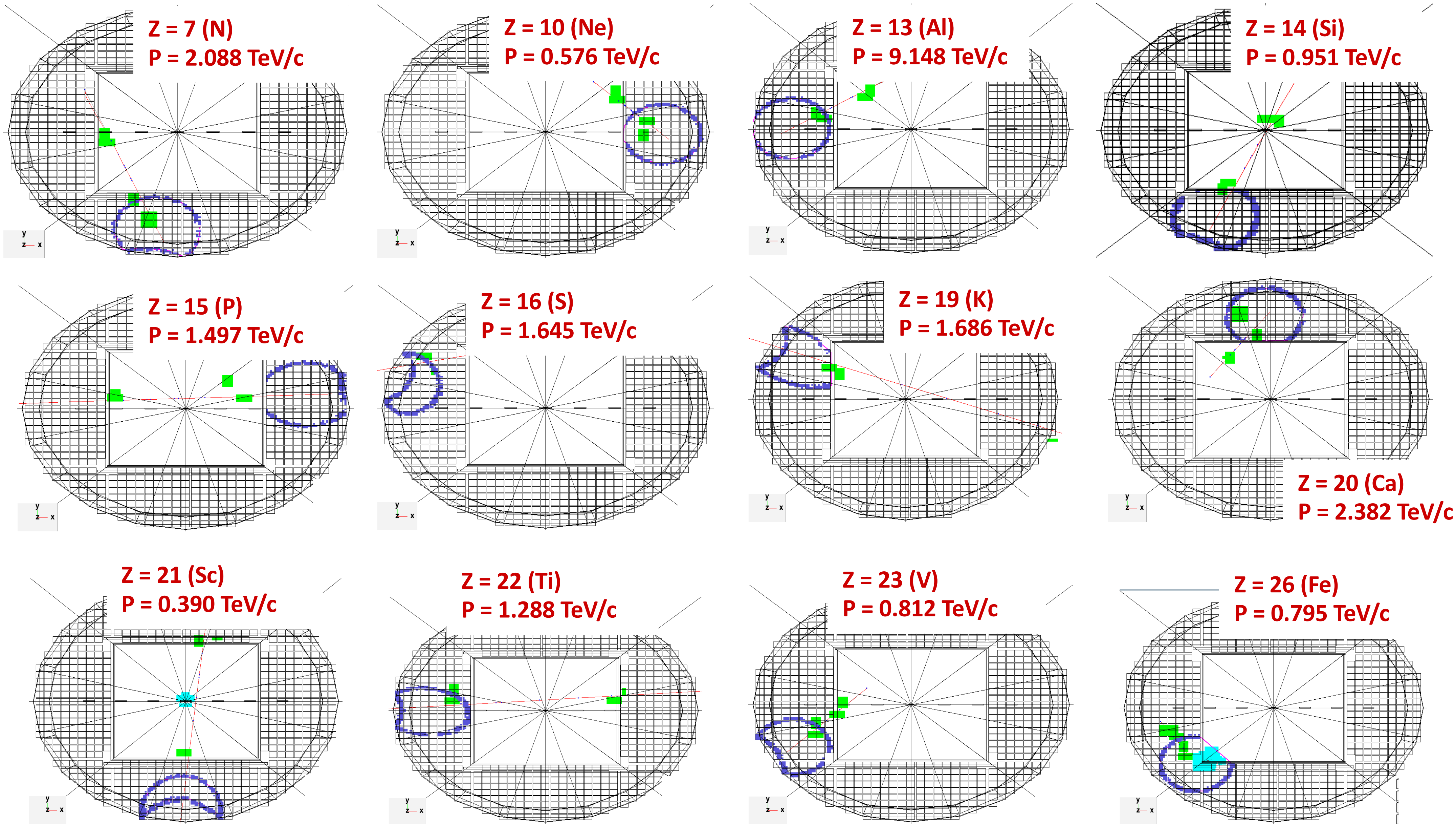

Radiator
Particle
Reflector
NaF
Aerogel
Θ
Intensity ∝ Z
Θ ∝ V
Detectors


He
Li
C
O
Ca

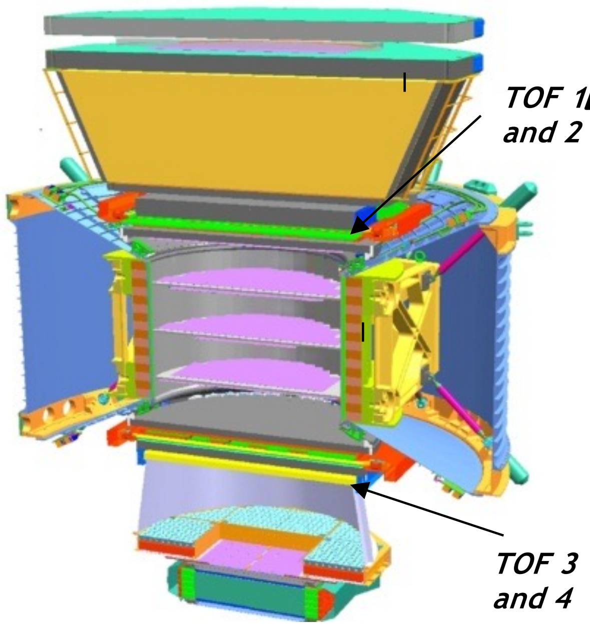

10,880
photosensors
21,760 Signal
Pulses
to identify nuclei
and their energy

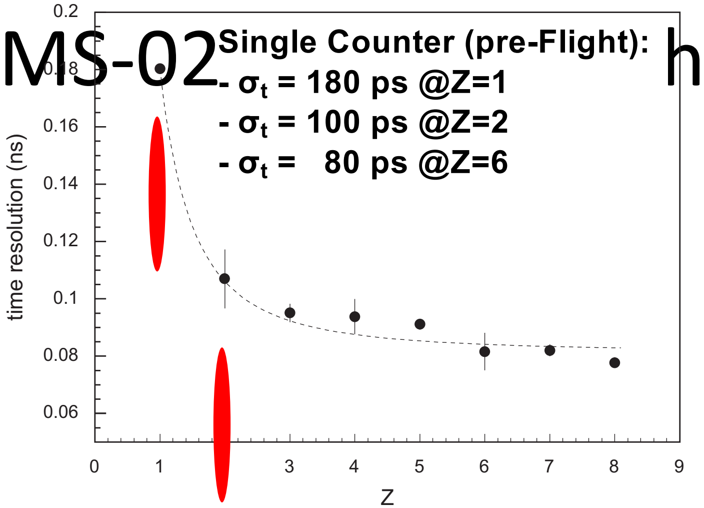
Z_{RICH}= 5.1

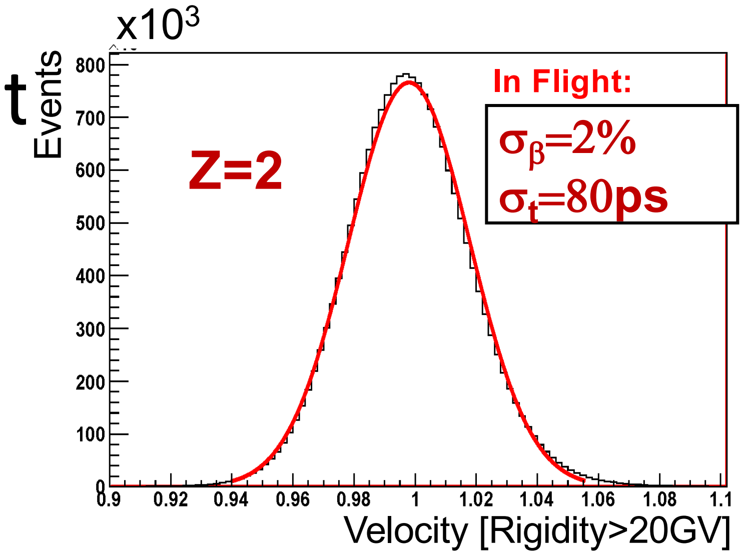



Z = 7 (N)
P = 2.088 TeV/c
Z = 10 (Ne)
P = 0.576 TeV/c
Z = 13 (Al)
P = 9.148 TeV/c
Z = 14 (Si)
P = 0.951 TeV/c
Z = 15 (P)
P = 1.497 TeV/c
Z = 16 (S)
P = 1.645 TeV/c
Z = 19 (K)
P = 1.686 TeV/c
Z = 20 (Ca)
P = 2.382 TeV/c
Z = 21 (Sc)
P = 0.390 TeV/c
Z = 22 (Ti)
P = 1.288 TeV/c
Z = 23 (V)
P = 0.812 TeV/c
Z = 26 (Fe)
P = 0.795 TeV/c

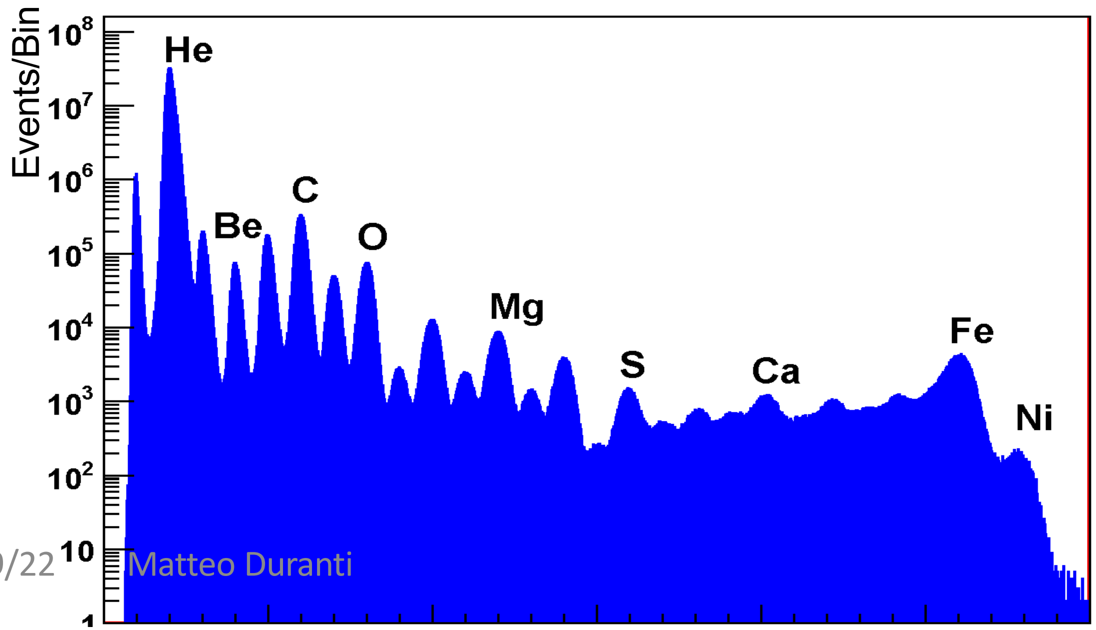
AMS-02 ht

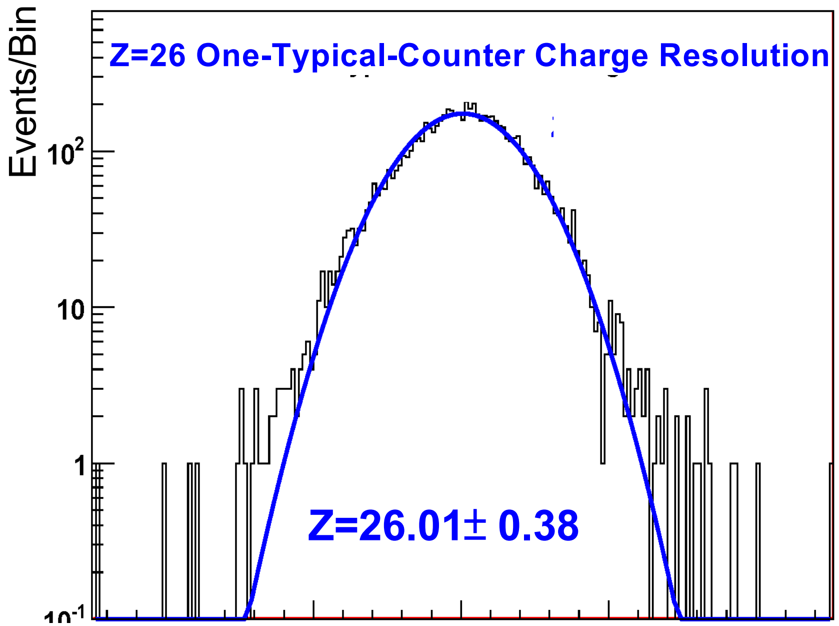




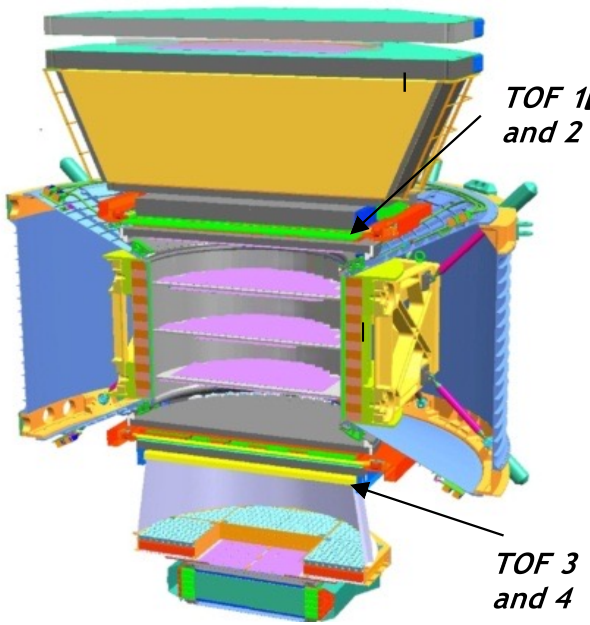


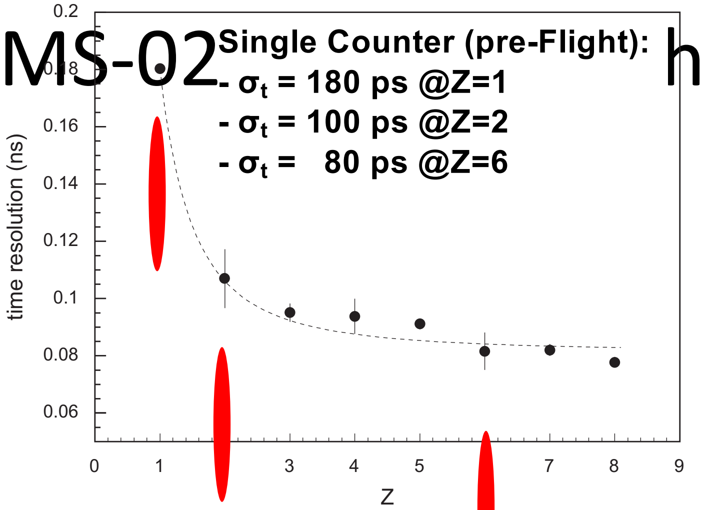
Measures Velocity and Charge of particles

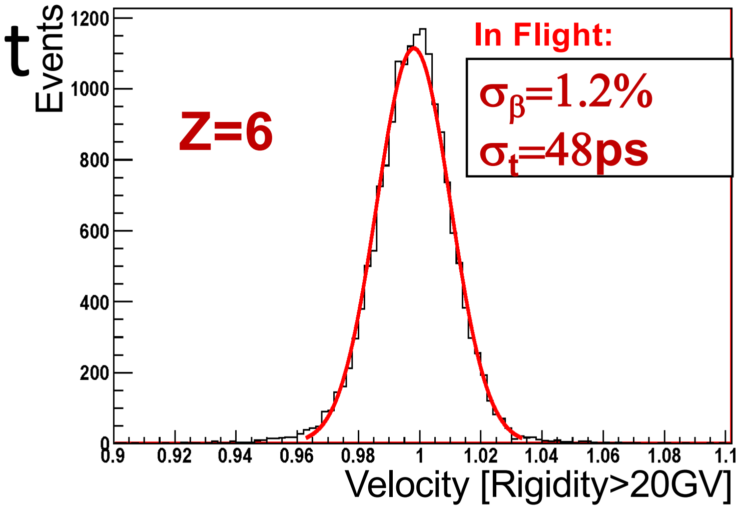




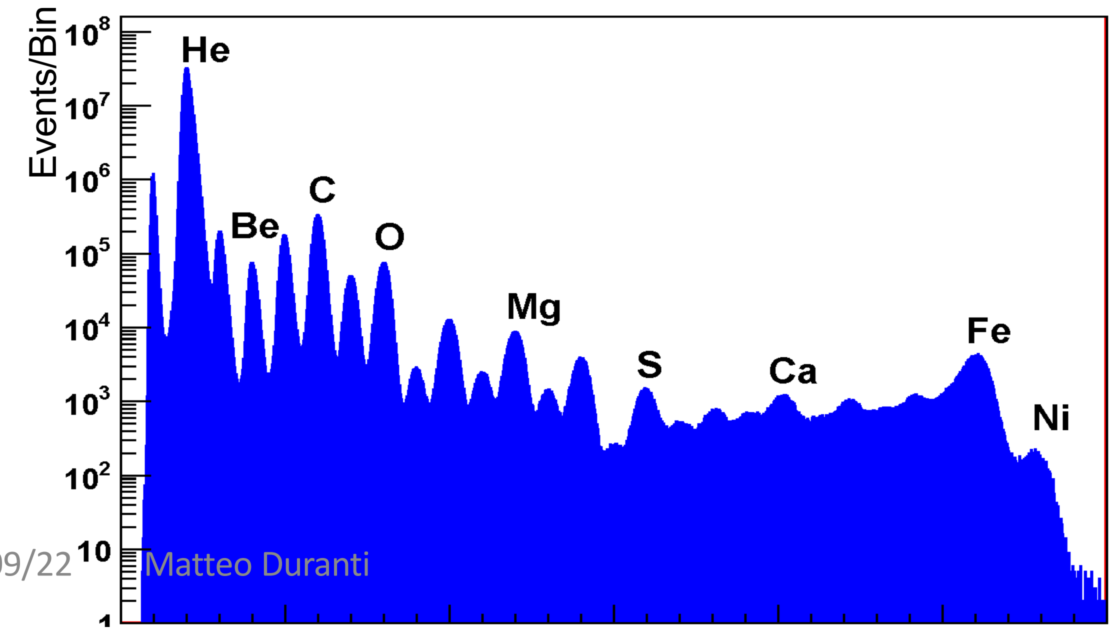
AMS-02 ... ht

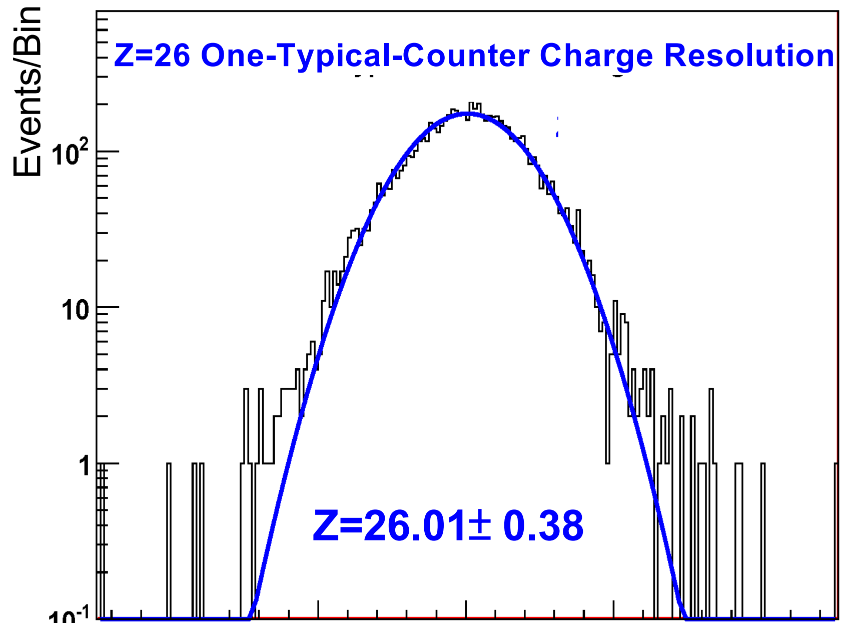


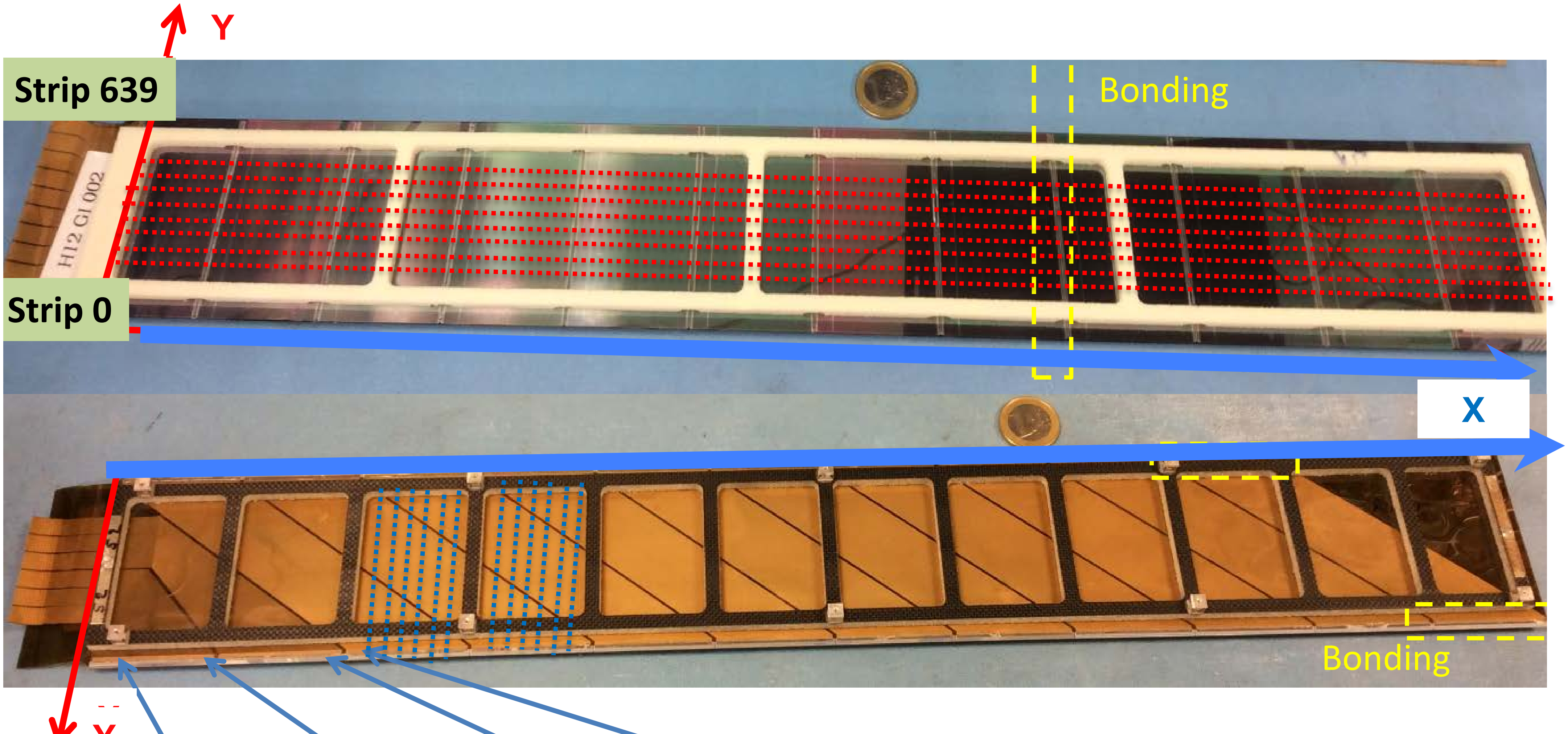


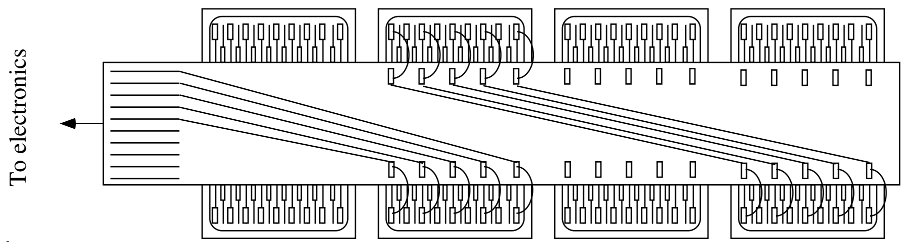


Measures Velocity and Charge of particles









"multiplicity" (or "ambiguity"): the 1500-3000 K-side
channels needed for each ladder are "merged" into 384