Agenzia Spaziale Italiana

19th SEMINAR ON SOFTWARE FOR NUCLEAR, SUBNUCLEAR AND APPLIED PHYSICS

Particle tracking

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For any questions, doubts and critics
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Disclaimer:

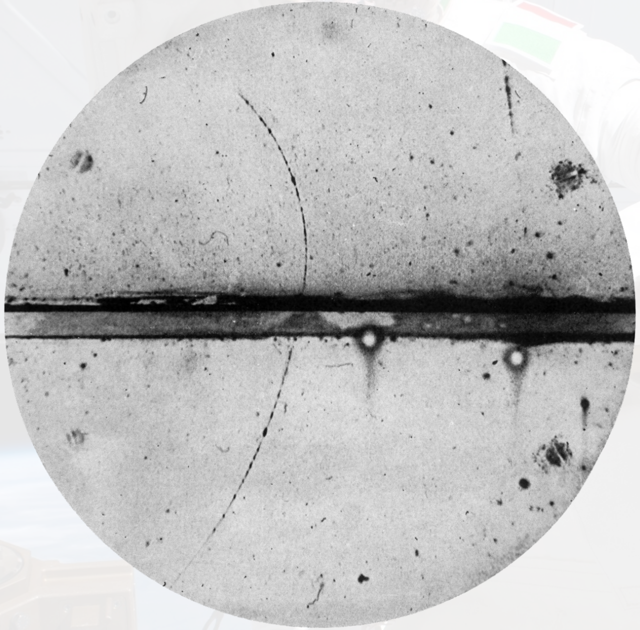
Huge field of technological solutions, applications, data analysis approaches

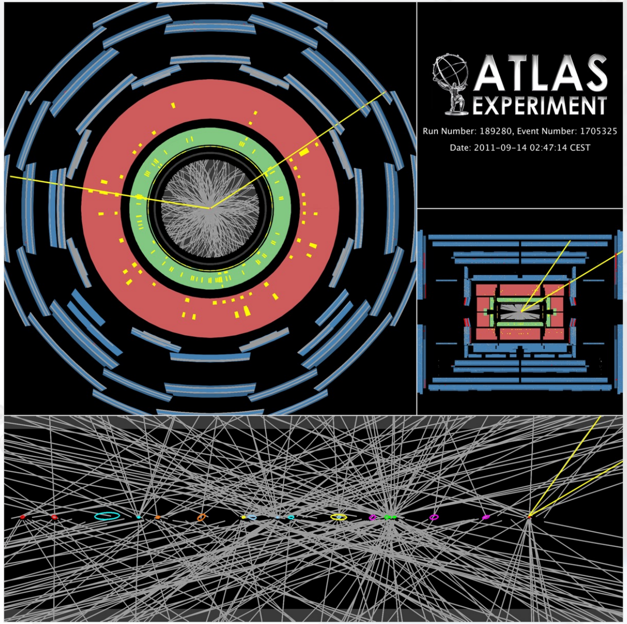
I will cover only a selection of topics and applications, mostly what I have experience with

(Please apologize if your favourite detector is not covered...)

Track visualization in HEP

Track **visualization** to identify: particle trajectories, particle decays points, interaction vertex





Full digital readout → reconstruction of particle trajectories using few sampling points

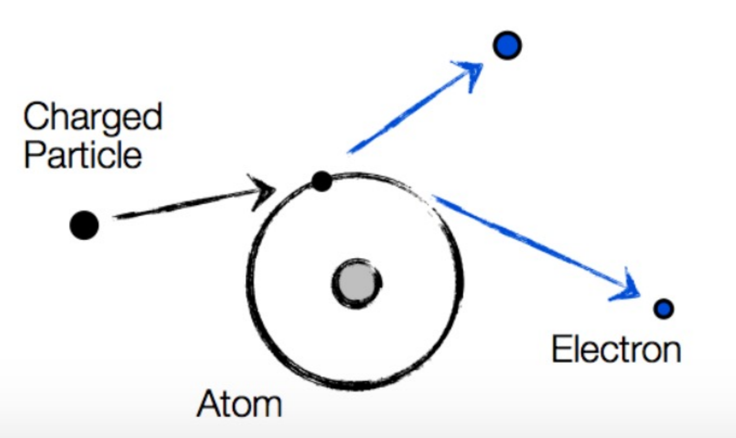
Minimal disruption of particle properties (see calorimeters)

Particle Identification

- Particles are uniquely identified by their **velocity**, **momentum** and **sign of the charge** combining the information from several subdetectors

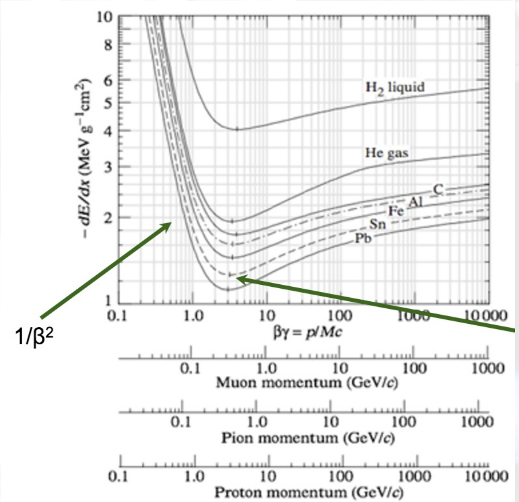
- Curvature in magnetic field $\rho \propto R = \frac{p}{Ze}$
- Velocity after time of flight measurements $\beta \propto \frac{1}{\Delta T}$
- Ionization losses $\frac{\mathrm{d}E}{\mathrm{d}X} = f(z, \beta)$
- Calorimetric measurements $E_{kin} = (\gamma - 1)mc^2$
- Typically, measurements are more than the number of searched parameters → **multiple measurements used to over-constrain the values and to crosscheck systematic effects**
- NB: at high energies (β-->1), the sensitivity of velocity measurements decreases. Complementary techniques used to infer the particle energy.

Ionization energy losses



Main effect of energy loss in materials: **continuous energy losses by ionization from scattering off atomic electrons**

Scattering off electrons: high energy losses, small trajectory deviation
Scattering off nuclei: small energy losses, high scattering angles (multiple scattering)



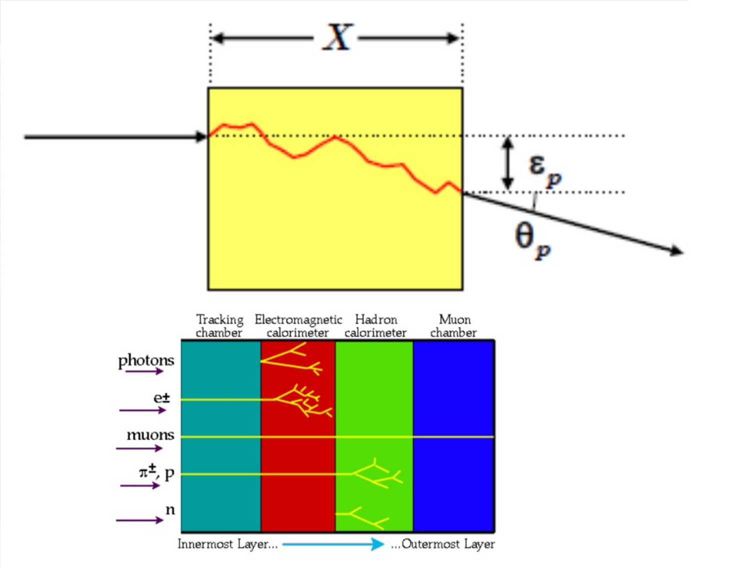
Bethe-Block formula: energy loss per unit of grammage $X = \rho\, x$

$$\frac{\mathrm{d}E}{\mathrm{d}X} = 0.31\,\mathrm{MeV}/(\mathrm{g/cm^2})\, z^2\, \frac{Z}{A}\, \frac{1}{\beta^2} \left[\frac{1}{2}\log(f(\beta)) - \beta^2 - \delta(\beta\gamma)\right]$$

Energy loss depends on particle and medium properties.

$$\frac{\mathrm{d}E}{\mathrm{d}X} \propto z^2$$ **proportionality to particle charge used to identify heavy nuclei**

Coulomb Multiple Scattering



Particles moving through the detector material suffer many e.m. interactions that randomly deviate their trajectory (stochastic process)

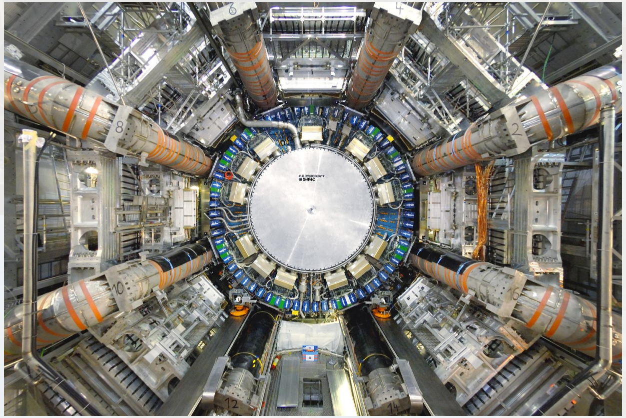
After crossing material with depth *X*, the particle trajectory undergoes:
- an angular deviation
- a trajectory offset (often negligible in thin detectors)

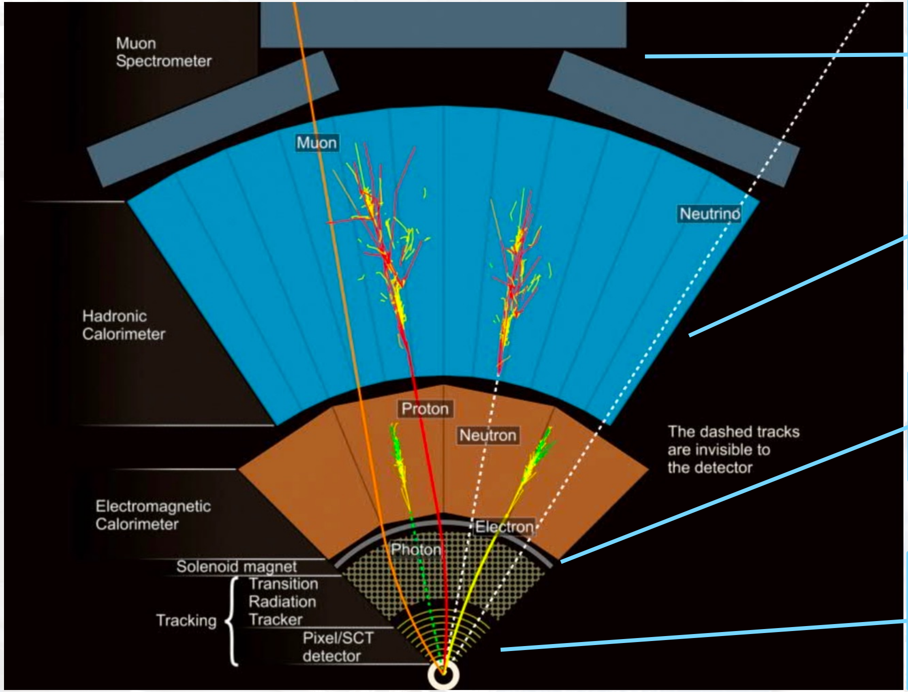
$$\theta_{RMS} = \frac{13.6\,\mathrm{MeV}}{\beta\, c p}\, z \sqrt{X/X_0}\,(1 + 0.038 \ln(X/X_0))$$

At low momentum, position and momentum resolution are dominated by multiple scattering

A typical collider particle detector

ATLAS @ LHC





Meaurement of muons crossing calorimeters (> 2-3 GeV)

Charged hadron absorption
Neutral hadron detection
5-6λ_I

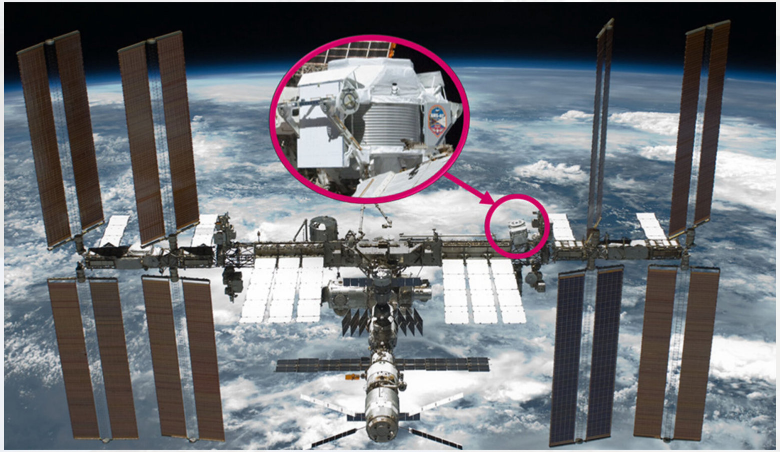
Electron identification
Photon detection
($\sim 20X_0$, 1-2λ_I)

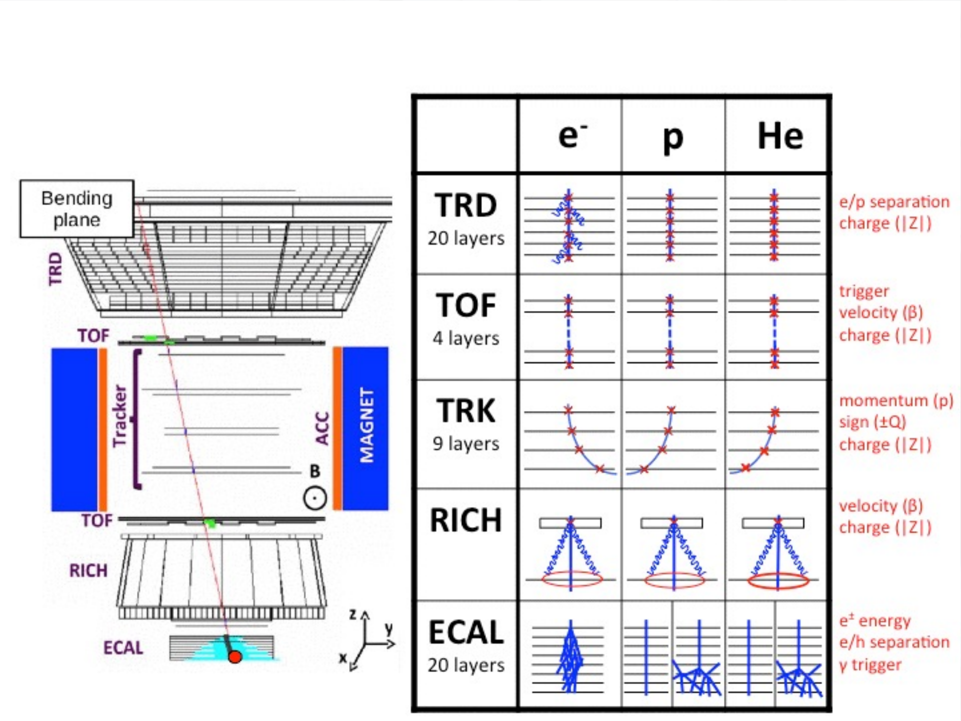
Momentum measurement
decay vertex recon.
Hadron identification
Low material ($\lesssim 1X_0$)

*reference numbers

A typical space particle detector

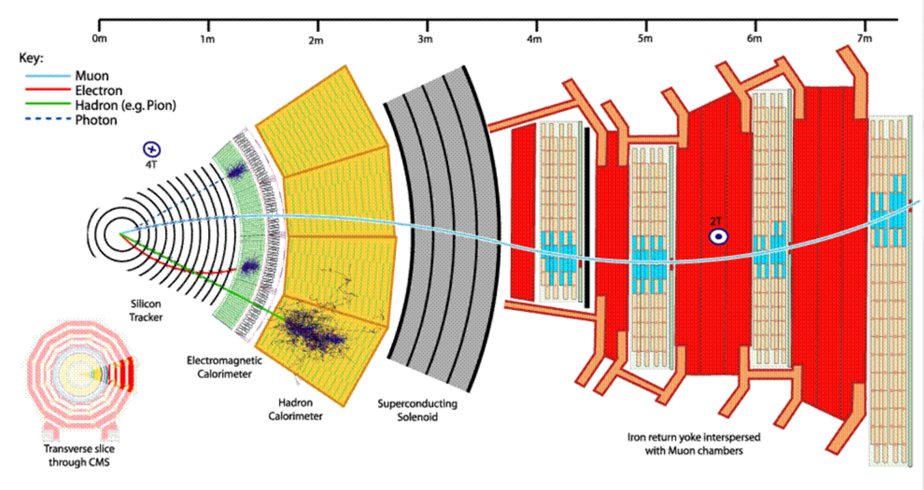
AMS @ ISS





Tracker goals

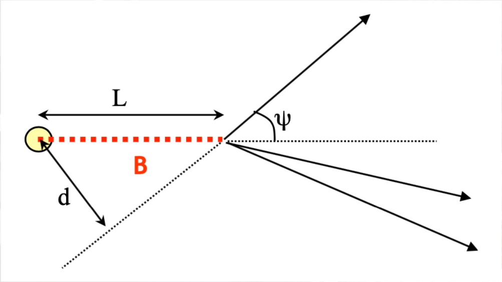
"Particle flow" @ CMS



Reconstruct charged-particle trajectories
- join seed points to create a track ("pattern recognition")
- measure **direction** and **position**
- measure **momentum** and **charge** (with magnetic field)
- two major configurations in colliders: **inner spectrometers** and **external muon systems**

Reconstruct decay and interaction vertices
- primary vertex: collision point
- secondary vertex: decay of unstable particle or interaction with detector material

Vertex detectors



$$d = L\sin\psi = O(\gamma\beta c\tau)\cdot O(\gamma^{-1}) = O(c\tau)$$

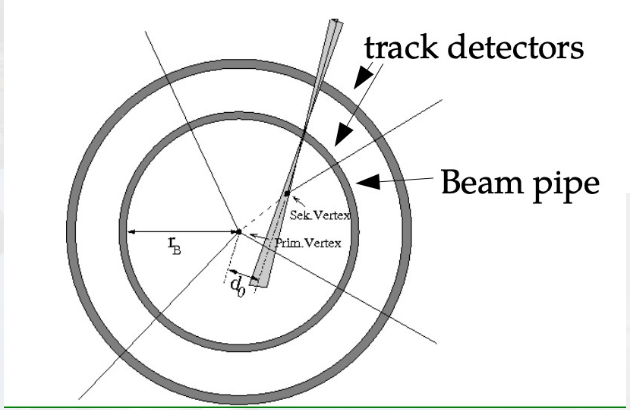
NB: mostly independent on boost for ultrarel.particles

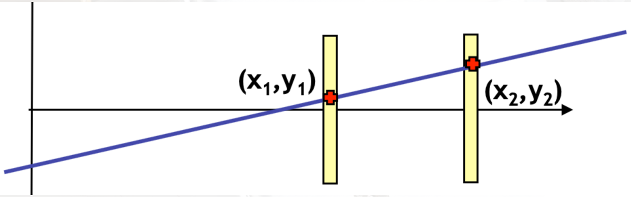
impact parameter d, defined at the distance between the daughter particle trajectory and the mother particle production point

Vertex detectors measure the primary interaction vertex and secondary vertices from secondary decays

An experimental apparatus with decay vertex capabilities must be able to separate the production and decay vertices: σ(*L*) / *L*«1

Uncertainty in *d* depends on detector radii and coordinate resolution





$$\sigma_d^2 = \frac{(r_2\sigma_1)^2 + (r_1\sigma_2)^2}{(r_2 - r_1)^2} + \sigma_{MS}^2$$

Small σ_1 and σ_2: precision coordinate measurement
Small r_1, large r_2
Measurement is degraded by multiple scattering in materials

Tracker technologies

Gaseous detectors

- Based on ionization in gas
- Requires gas amplification O(10^4 or more) to achieve enough S/N

Not covered

Silicon detectors

- based on creation of e/h pair carriers in semiconductor material
- no amplification is needed (~100 carriers/μm)

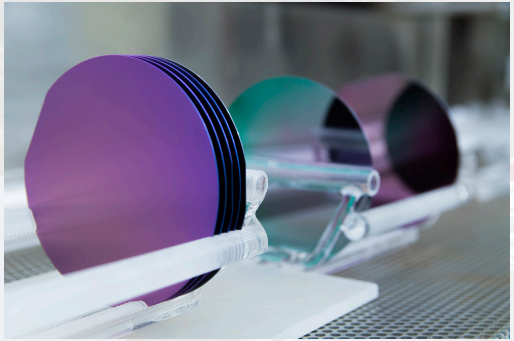
Fiber trackers

- Based on light readout from scintillating fibers
- scintillation light materials with photodetectors sensitive to single electrons

Slightly covered

Silicon sensors

Monocrystalline silicon lingot
(@SUMCO)



Silicon wafer substrate
(@Mi-NET)
(At this stage mostly all detectors look the same)

Moderate energy gap band

E_g = 1.12 eV ⇒ E(e-h pair) = 3.6 eV

≈ 30 eV for e-ion in gas detectors, ≈ 100 eV for photon in scintillators

- High carrier yield
- Improved energy resolution and high signal

High density

~2.33 g/cm^3 -> High specific energy loss

dE/dX (M.I.P.) ≈ 3.8 MeV/cm, ≈ 100 e-h/μm (average)

- Thin detectors
- Reduced range of secondary particles
- Better spatial resolution

High carrier mobility

μ_e=1450 cm^2/Vs, μ_h= 450 cm^2/Vs fast charge collection (<10 ns)

Excellent physical properties

- Can be produced with high purity
- Rigid, allows the use of self-supporting structures
- Industrial technology, relatively low price, small structures workable
- High intrinsic radiation hardness

Position sensitive Silicon sensors

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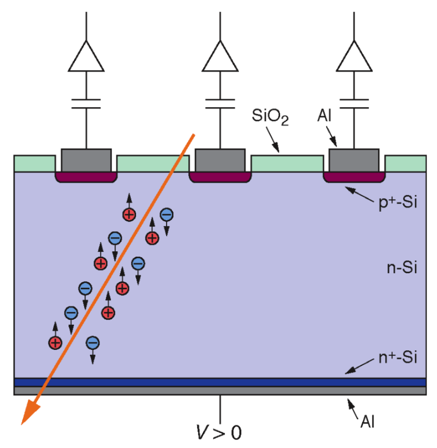
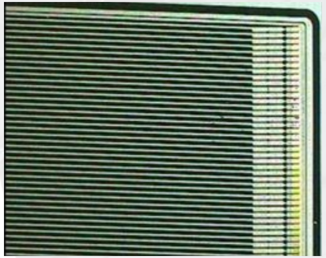
Segmentation of one surface in sensitive elements
strips, pads, pixels

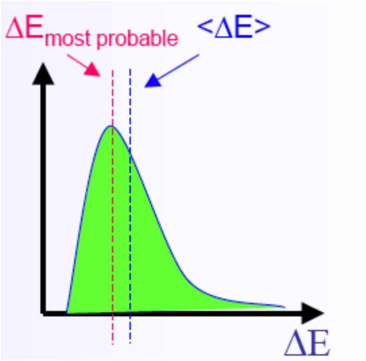
Typical parameters
- Thickness 150µm – 500µm
- Pitch (strip separation): 25µm – 150 µm
- Coordinate resolution down to few µm
- Charge collection O(10ns)
- Charge integration O(100ns)
- Operation voltage < 200V

Signal output
- Average energy loss of MIP in Si
  3.6 eV/pair, ~ 80 pairs/µm (MP)
- 300µm thickness : O(25k) pairs/MIP
- Charge: O(5fC)



Simple layout DC-coupled





Landau energy distribution in thin sensors
Asymmetric probability function with a long "tail" due to large energy deposits

applies in thin O(100µm) Si sensors

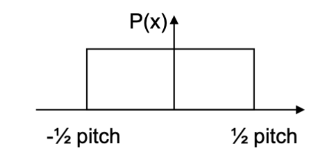
Most probable: ≈ 80 e–h+ pairs per µm
Average value: ≈ 100 e–h+ pairs per µm

NB: Bethe Block describes <ΔE>

Intrinsic resolution

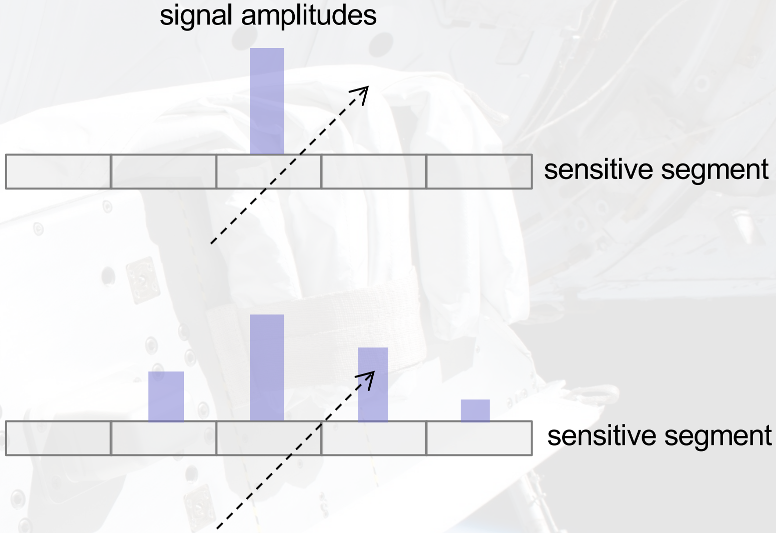
Position measurement comes from segmentation / pitch

Digital resolution:



Position = strip center

Resolution: $p/\sqrt{12}$



Improvement from **signal sharing**:

Assuming signal amplitude prop. to deposited energy

- requires analog signal readout

Position = charge center of gravity

Hits are defined as segments with S/N above threshold

Additional hits generated by:

- secondary charge spread inside the sensor volume
- inclined tracks

Signal sharing allows to achieve improved performances after proper calibration

Double-sided silicon sensors

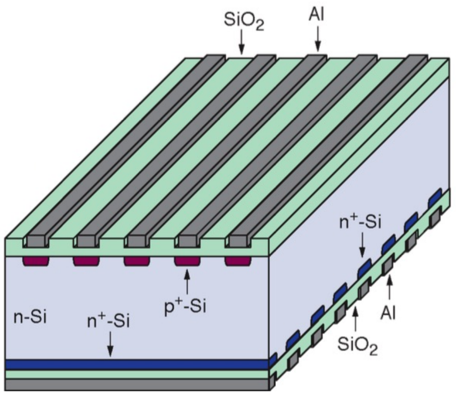
Single sided sensors measure one coordinate only
- use stacks with strips running in different directions to achieve 3D trajectory reconstruction

Double sided sensors measure two coordinates in one layer
- backside implants run perpendicular to top strips

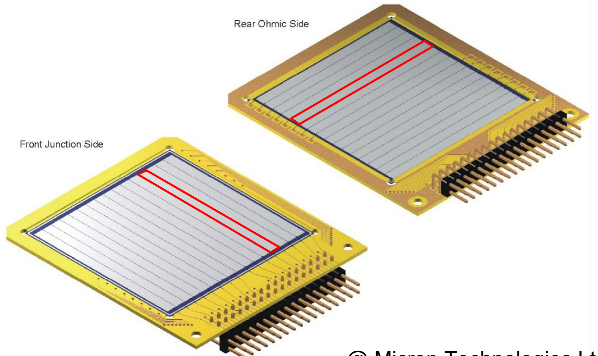
Pros:
- minimize material to measure 3D point in space

Cons:
- Production and handling is more complicated
- Test stations require peculiar modifications
- More expensive

Readout requires dedicated layouts to host FEE on one side only



Scheme of a double-sided microstrip detector (biasing structures not shown):
Holes drift towards p^+ strips
Electrons drift towards n^+ strips



@ Micron Technologies Ltd

Pixel silicon sensors

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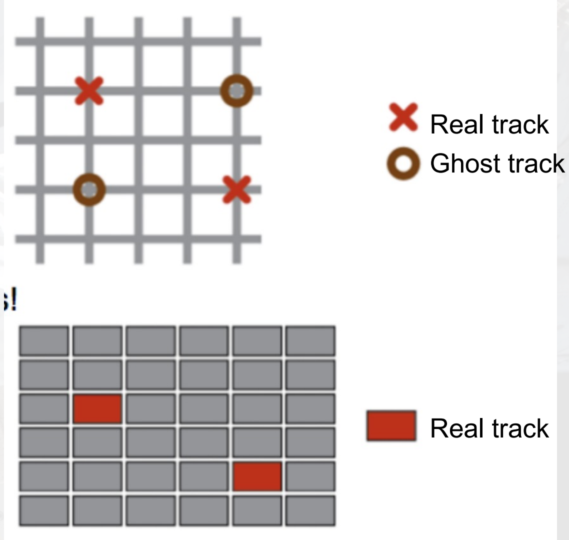
Double sided silicon detectors measure 2D coordinate XY for single tracks crossing the sensor

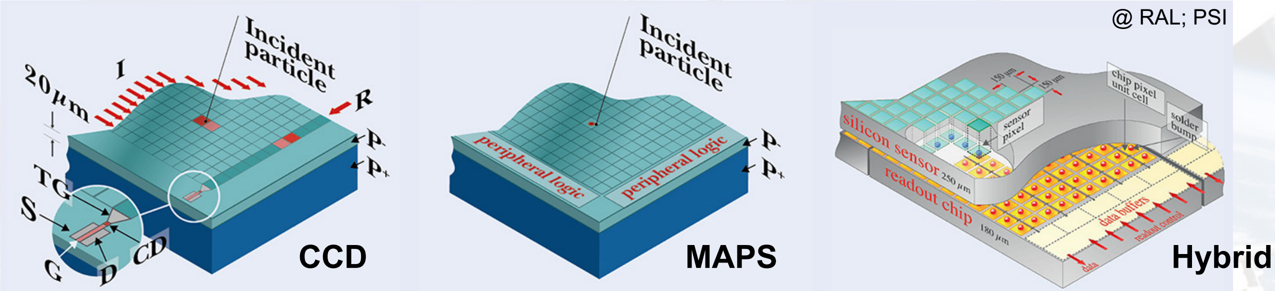
If additional particles cross the sensor during the detector integration time (i.e, "pileup"), we get ambiguity in hit association: "ghost hits"

For N crossing particles
- N^2 combinations
- N^2 - N ghost hits

Peculiar strip geometries may mitigate the problem.

<u>Pixel sensors completely tackle this issue</u>





@ RAL; PSI

Pixel silicon sensors

Pixel size O(50μm x 50μm) or less

If signal amplitude is not recorded (digital readout) resolution $p/\sqrt{12}$ ~ O(10-5 μm)

Pros:

- Small pixel area:
  - √ low detector capacitance O(1fC / pixel)
  - √ large S/N > 100
- Small pixel volume:
  - √ low leakage current O(1pA /pixel)

Cons:

- Large number of readout channels per covered area
- Large number of electrical connections per covered area
- Large power consumption per covered area
- Unaffordable with standard bonding approaches

Half of the SLD vertex detector, consisting of 307 Mpixels, three barrels and a pixel size of 20 × 20 × 20 μm3. Each ladder of 16 cm active length contains two 8 cm-long stitched CCDs

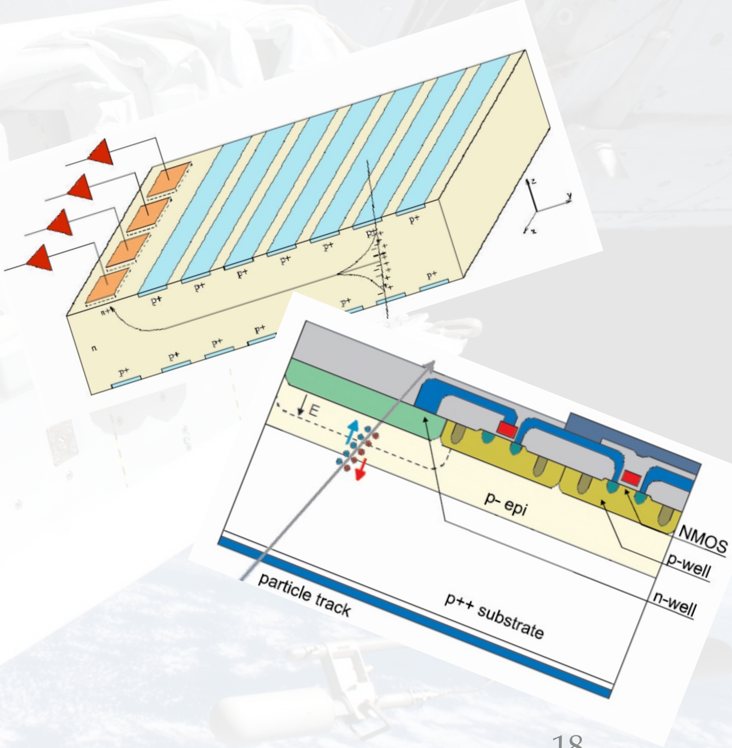
Silicon sensor technology

Strip and hybrid pixel detectors are mature technologies employed in almost every experiment in high energy physics

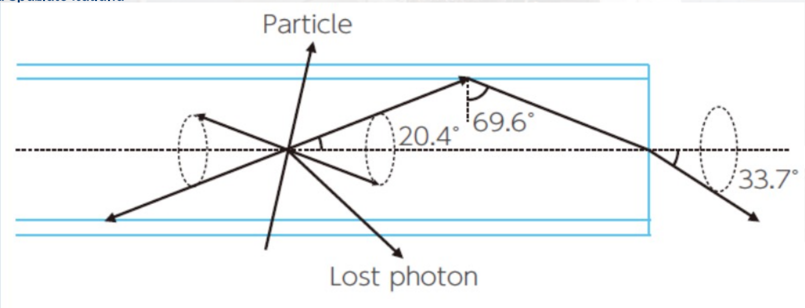
Additional interesting silicon detector structures are:

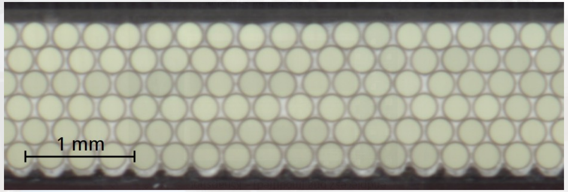
Silicon Drift Detectors (SDD)
Monolithic Active Pixels (MAPS)
3D detectors
Charged Coupled Devices (CCD)
Depleted Field Effect detectors (DEPFET)
Silicon On Oxide (SOI)
Avalanche Photo Diodes (APD) and Silicon Photo Multiplier (SiPM)

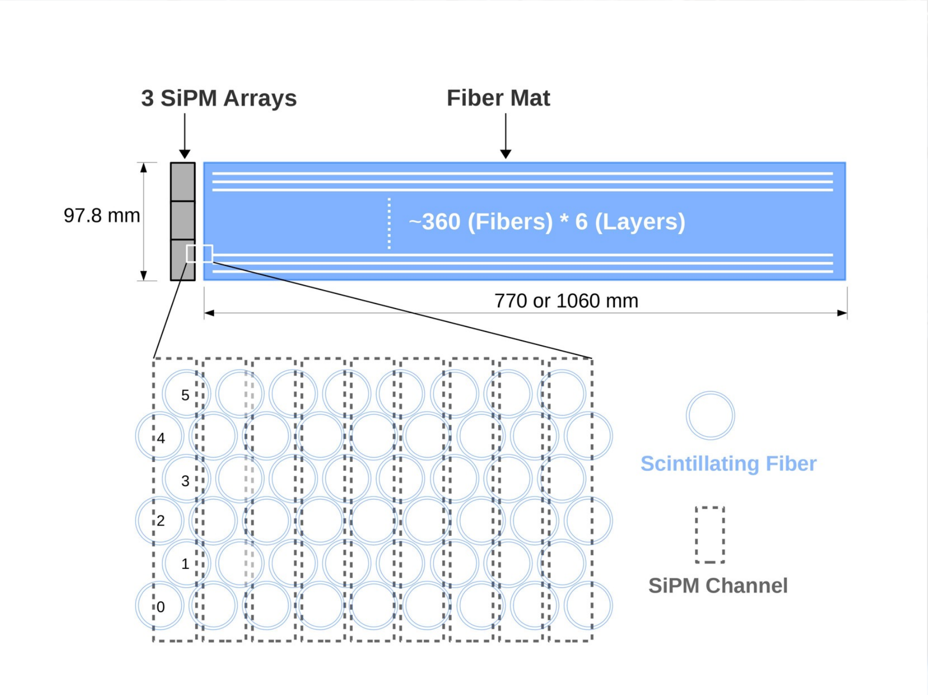
Time performant Si detectors:
Low Gain Avalanche Diodes / Ultra Fast Silicon Detectors
may enable "4D tracking" with Si-detectors with timing performances < 100 ps



Fiber trackers





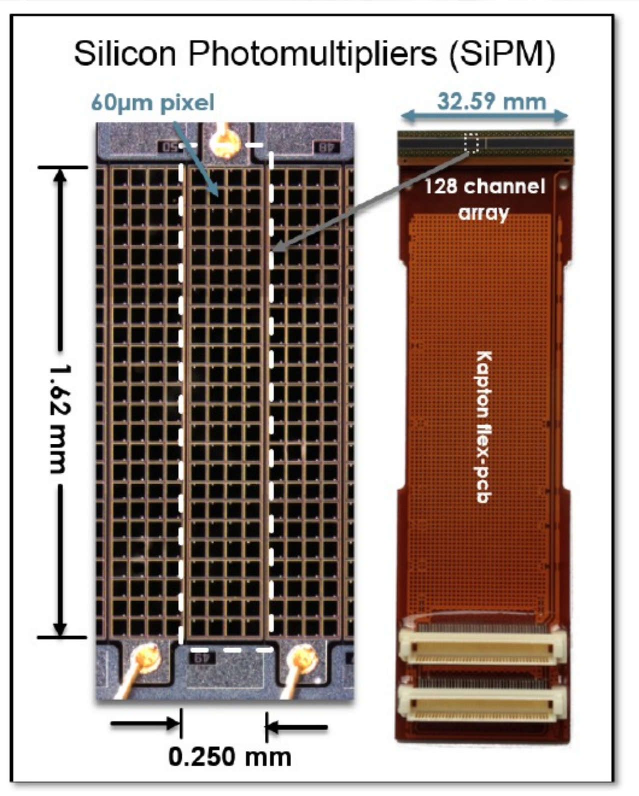


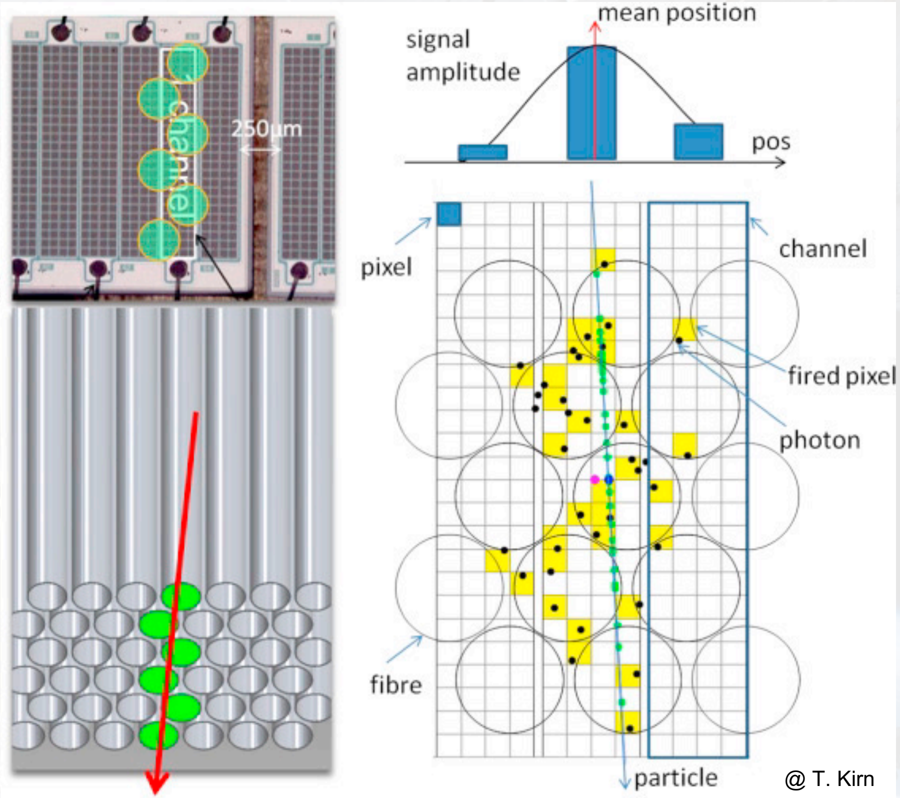
Alternative technology for charge particle tracking based on **SiPM + fiber-boundle coupling**.

- Cheaper cost/area than Si-μstrip
- Mechanical flexibility and adaptability
- Fibers can be up to 2m long without significant light absorption.
- Spatial resolution ~ determined by fiber pitch (with small improvements by SiPM pitch and fiber cross-correlations)

Fiber trackers

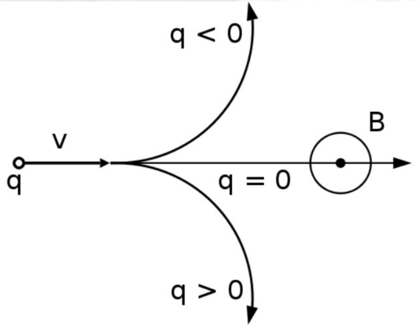
The Sci-Fi tracker for the LHCb detector upgrade





Momentum measurement

Determination of momentum of charged particles by measurement of the bending of a particle track/trajectory inside a magnetic field volume



$$\vec{F} = q\vec{v} \times \vec{B}$$

Lorentz force: is the force on a point charge due to electromagnetic fields

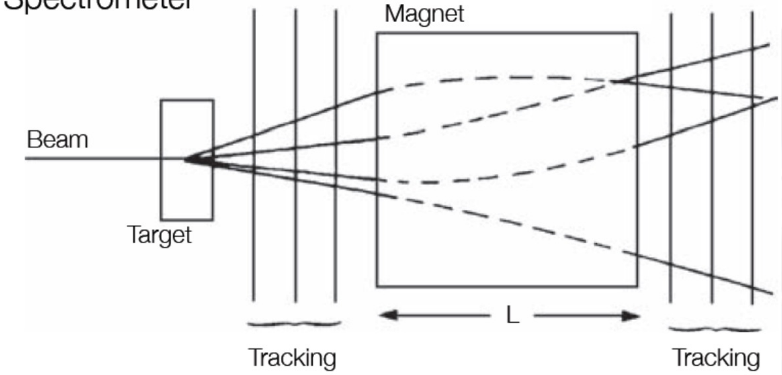
$$\frac{mv^2}{r} = qvB$$

… for a particle in motion perpendicular to a constant B field

In practice:
- use layers of position sensitive detectors before and after (or inside) a magnetic field to measure a trajectory
- determine the bending radius

$$\rho \propto R = \frac{p}{Ze}$$

Schematics of a Spectrometer



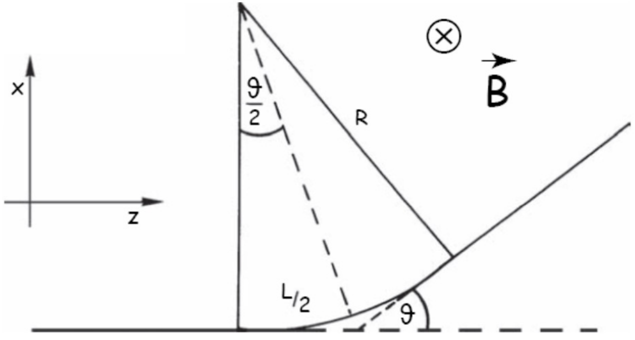
@ E. Garutti

Momentum measurement: fixed target

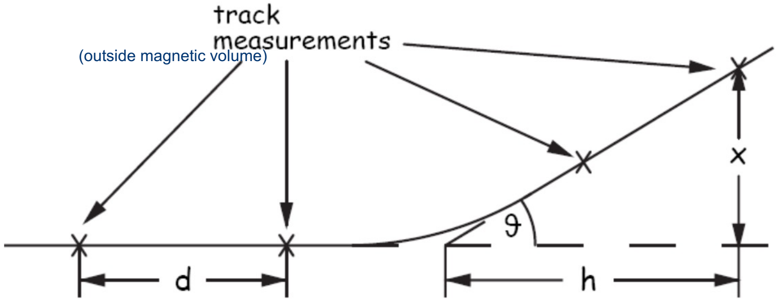
Momentum determination
in fixed target experiments ...

$$p = eRB \qquad \vartheta = {}^{L}/_{R} = {}^{L}/_{p} \cdot eB$$

$$p = eB \cdot {}^{L}/_{\vartheta}$$



Momentum resolution: $\rightarrow \dfrac{\sigma_p}{p} = \dfrac{\sigma_\vartheta}{\vartheta}$ with $\sigma_\vartheta \sim \sigma_x$



Determination of σ_p/p:

$$\vartheta = \frac{x}{h} \qquad \sigma_\vartheta = \frac{\sigma_x}{h}$$

$$\frac{\sigma_p}{p} = \frac{\sigma_\vartheta}{\vartheta} = \frac{\sigma_x}{h} \cdot \frac{p}{eBL}$$

Long lever arm improves momentum resolution ...

@ E. Garutti

Momentum meas. in magnetic volume

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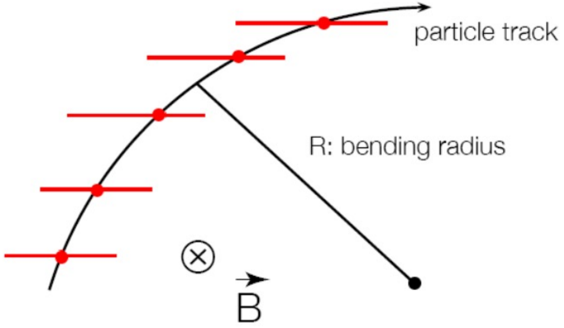
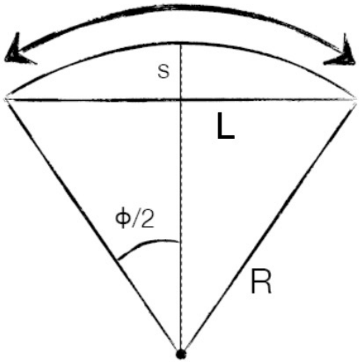
Momentum determination
in a cylindrical drift chamber ...

$$\frac{mv^2}{R} = evB \quad \rightarrow \quad p = eB \cdot R$$

$$\boxed{p\left[\frac{GeV}{c}\right] = 0.3\ B[T]\ R[m]}$$



momentum component perpendicular to the B-field
transverse momentum p_t



For Sagitta s:

$$s = R - R\cos\frac{\phi}{2} \approx R\frac{\phi^2}{8} \qquad \text{with } \phi = \frac{L}{R}$$

$$s = R\frac{L^2}{8R^2} = \frac{L^2}{8R} \quad \text{and} \quad R = \frac{L^2}{8s}$$

➔ radius is obtained by a circle fit through measurement points along the track with point resolution $\sigma_{r\phi}$

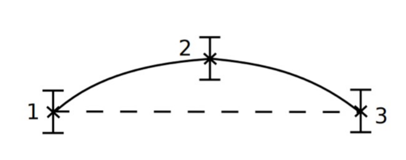
$$\rightarrow \quad \frac{\Delta p}{p} = \frac{\Delta R}{R} = \frac{L^2}{8Rs} \cdot \frac{\Delta s}{s}$$

@ E. Garutti

Momentum meas. in magnetic volume

$$p = 0.3\,B\,R \quad s = \frac{L^2}{8R}$$

$$\frac{\sigma(p)}{p} = \frac{L^2}{8Rs}\cdot\frac{\sigma(s)}{s} = \frac{8R}{L^2}\cdot\sigma(s) = \frac{8\,p}{0.3\,B\,L^2}\cdot\sigma(s)$$



$$s = \frac{x_1 + x_2}{2} + x_3 \quad \sigma^2(s) = \frac{3}{2}\sigma^2(x)$$

$$\frac{\sigma(p)}{p} = \sqrt{\frac{3}{2}}\frac{8\,\sigma(x)}{0.3\,B\,L^2}\cdot p$$

For N equidistant samplings: $\frac{\sigma(p)}{p} \approx \sqrt{\frac{720}{N+4}}\frac{\sigma(x)}{0.3\,B\,L^2}\cdot p$

$$\frac{\sigma(p)}{p}; \propto\ p,\ \sigma(x),\ \frac{1}{B\,L^2}$$ ***BL^2*****: Bending Power**

Spectrometer resolution worsens at high rigidities and can be improved with better coordinate measurement resolution and better bending power

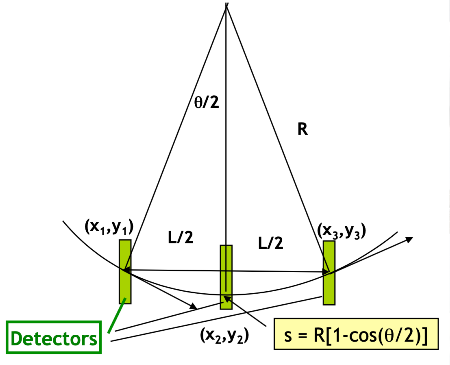
- **L** ~ spectrometer dimensions, limited by space/mechanical constraints
- **B** limited by magnet size and technology (e.g., superconducting magnets in space)
- **σ(x)** position resolution, can be improved to resolutions depending on the application. Tipically O(10μm)

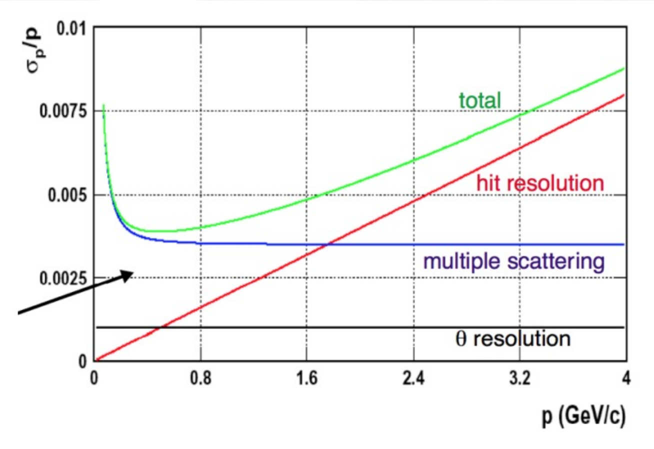
Multiple Scattering effects

Sensors provide material budget to particle crossing that results in deflection of the trajectory

$$\sigma^{MS}(s) \approx L^* \frac{1}{p\beta}\sqrt{L^*}$$

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma^{MS}(s)}{s} \approx \frac{\sqrt{L^*}L^*/(p\beta)}{0.3\,B\,L^2/p_T}$$





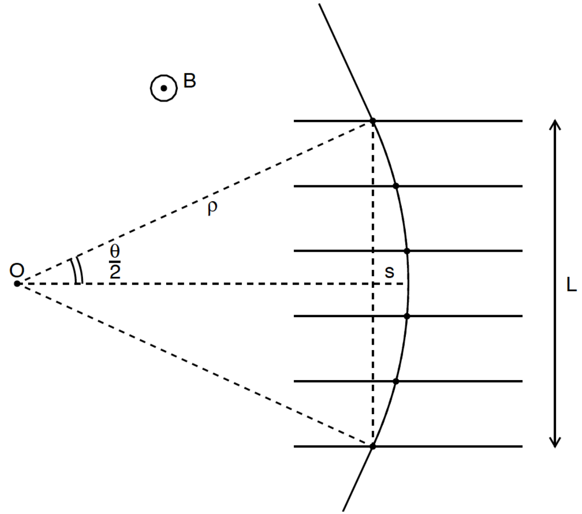
$$\frac{\sigma(p)}{p} \approx \sqrt{\frac{720}{N+4}}\frac{\sigma(x)}{0.3\,B\,L^2}\cdot p\sin\theta \oplus \frac{0.2}{\beta\,B\,\sqrt{L\,X_0\sin\theta}}$$

Low energy momentum resolution is dominated by multiple scattering effects
When β<1 more complicated effects enter in

Spectrometers

Magnetic Spectrometers

Simple 2D sagitta model



- Charged particle bent in magnetic field
- The sagitta is measured by sampling the particle trajectory through different planes
- The particle rigidity is inferred via

$$R(GV/c) = \frac{0.3\,B(T)\,L(m)^2}{8\,s(m)}$$

- Rigidity resolution scale linearly as

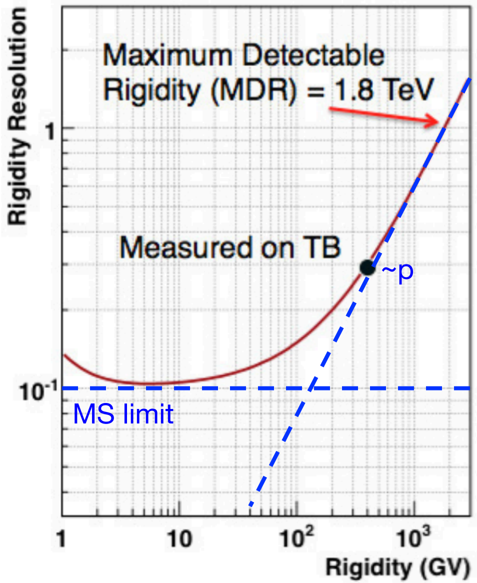
$$\frac{\sigma_R}{R} = \frac{\sigma_s}{s} \propto R$$

- Maximum Detectable Rigidity MDR

$$\boxed{\frac{\sigma_R}{R} = 1 \;\Rightarrow\; R^{(\mathrm{MDR})} \propto \frac{L^2 B}{\sigma_s}}$$

Figure of merit often used to compare spectrometer performances

Spectrometers

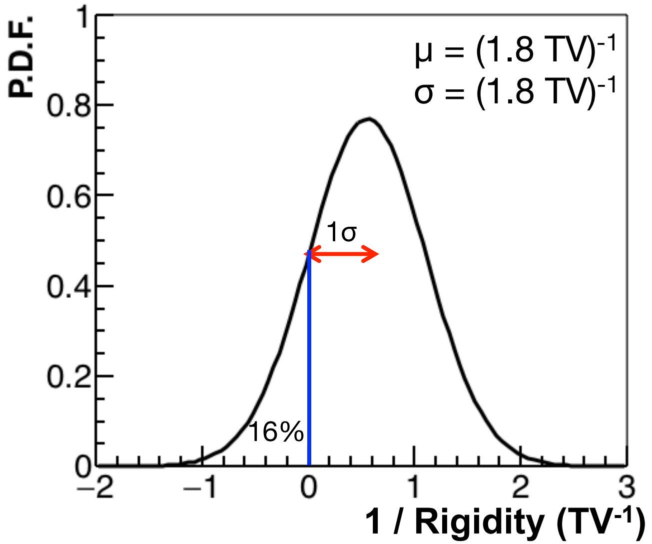


At high energies $\frac{\sigma(p)}{p} \propto p$

At low energies (Multiple scattering) $\frac{\sigma(p)}{p} \approx \text{cost}$

Performance parameter:
Maximum Detectable Rigidity (MDR):

$$\frac{\sigma_R}{R} = 1 \Rightarrow R^{(\text{MDR})} \propto \frac{L^2 B}{\sigma_s}$$

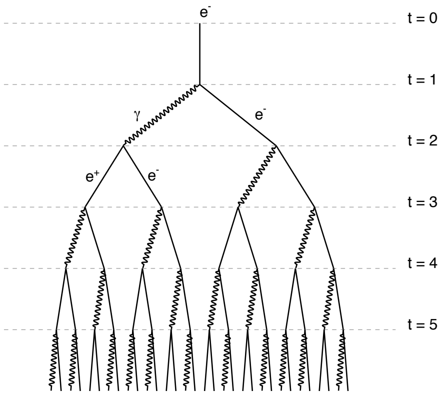


“Spillover”: events that are reconstructed with opposite sign of charge

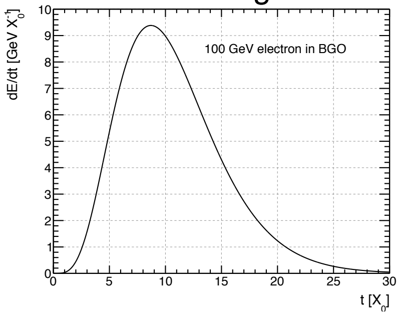
Calorimetry

Calorimeters

Simple electromagnetic shower profile



- Calorimeters measures the energy releases of the particle
  - Homogeneous / Sampling
  - Electromagnetic / Hadronic



$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

- The energy resolution improves as the energy increases

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Statistical fluctuations

Electronics

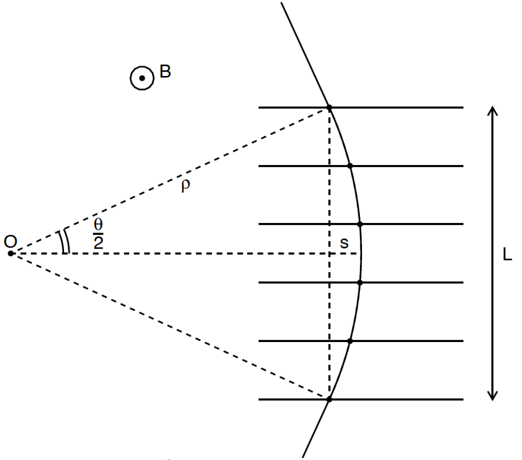
Inhomogenities, calibration, energy leaks,…

BUT: energy resolution is not everything. Tipically the dominant systematic is the knowledge of the energy scale!!

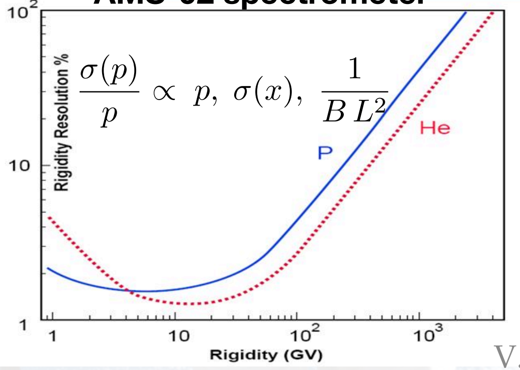
- Resolution → Symmetric smearing of measured energy
- Energy scale → Systematic shift of measured energy

Energy measurements

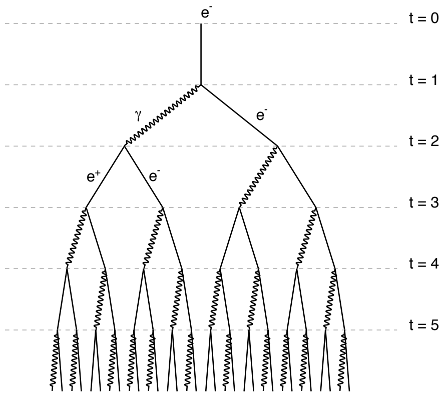
Magnetic Spectrometers



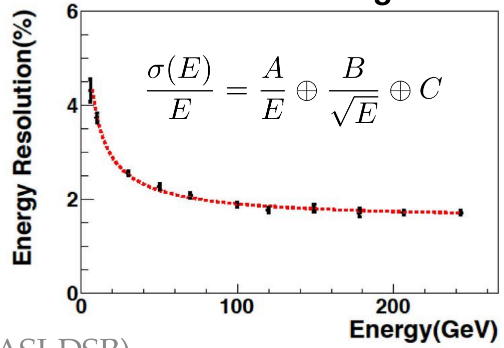
AMS-02 spectrometer



Calorimeters



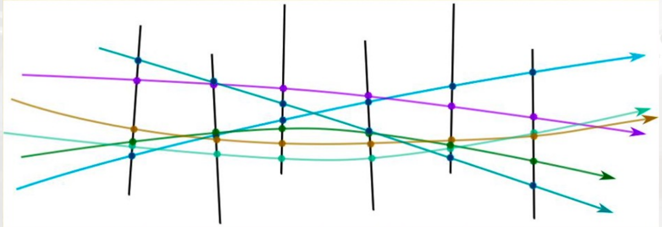
AMS-02 electromagnetic calorimeter



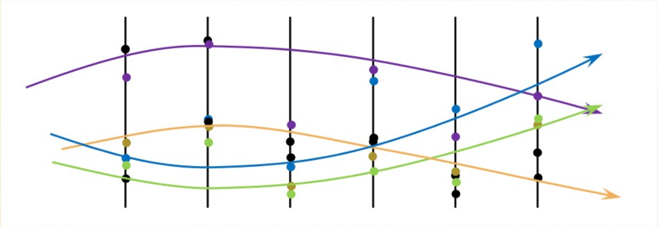
Tracker alignment

Implicit hypothesis: "We know the absolute coordinate of the track sampling"

Tipically WRONG!
- Mechanical uncertainties and instabilities due to magnetic field, temperature etc...
- Drift speed variations (detector inhonogeneities)



True trajectories and True detector layout



Detector layout assumptions and tracks built on this hypothesis

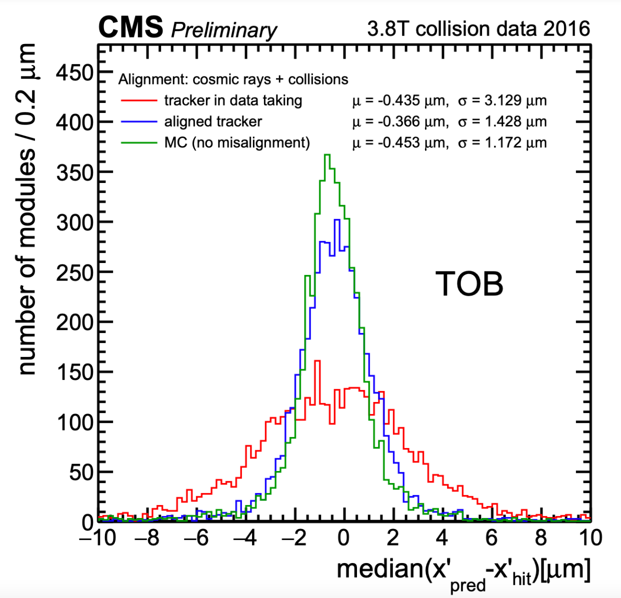
NB: relative point positions along the sensors are correct. Tracks are not.

Solutions in detector design are useful to mitigate this effect. But offline analysis corrections are needed

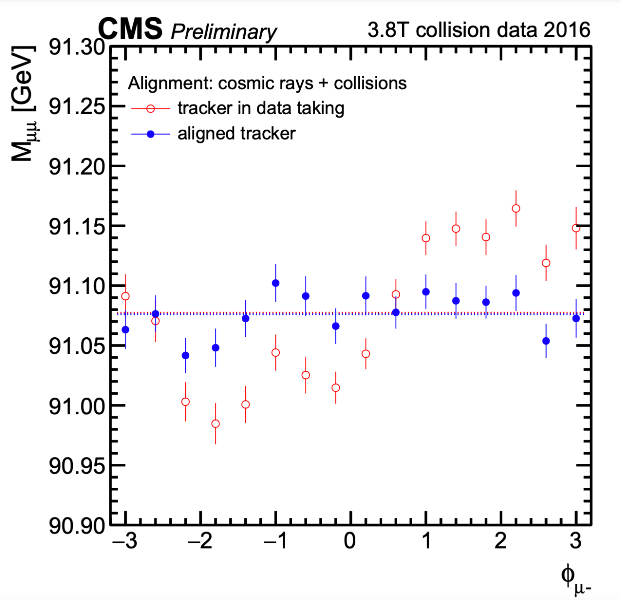
"Alignment"

Tracker alignment

Example: effect of misalignment in CMS tracker systems

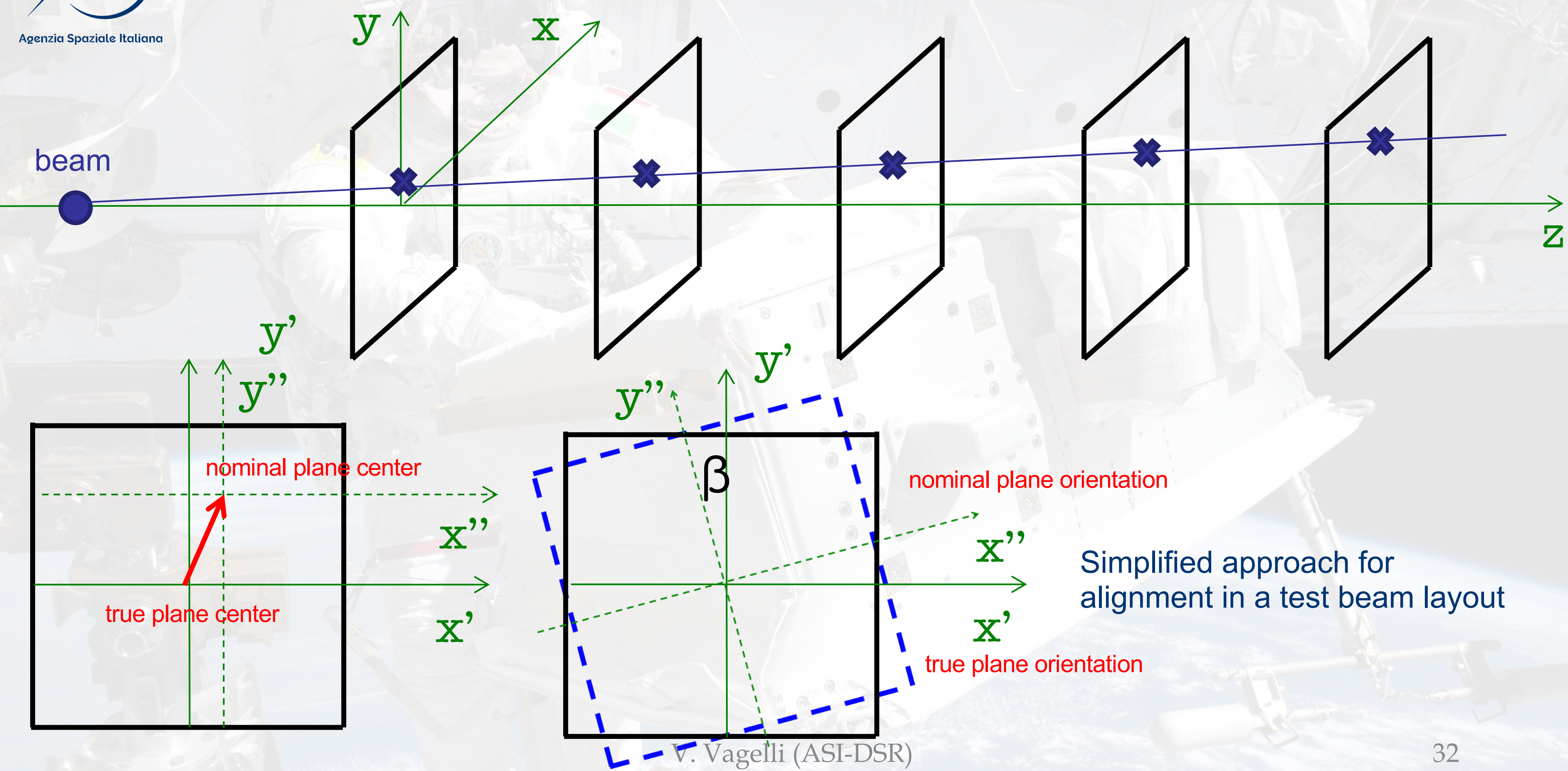


Distribution of median residuals for tracker outer barrel



Reconstructed Z->μμ as function of Φ of μ^-

Simple tracker alignment at test beam



Simplified approach for alignment in a test beam layout

Tracker alignment

Alignment parameters:
the track model depends on additional free factor, i.e. the sensor positions and orientations

Methods:
- **Global alignment**: fit all paramaters to minimize the overall chi2 of a set of tracks (Millipede algo.). Many parameters are involved.
- **Local alignment**: use tracks reconstructed with reference detectors or calibration lasers and align other detectors by using "reference" tracks and minimize the distribution of residuals (track-hit distance)

For all cases, use particle probes in simple data taking environemnts:
- low-multipicity events
- Muons
- High energy particles (no trajectory bending in magnetic field)
- possibly no magnetic field

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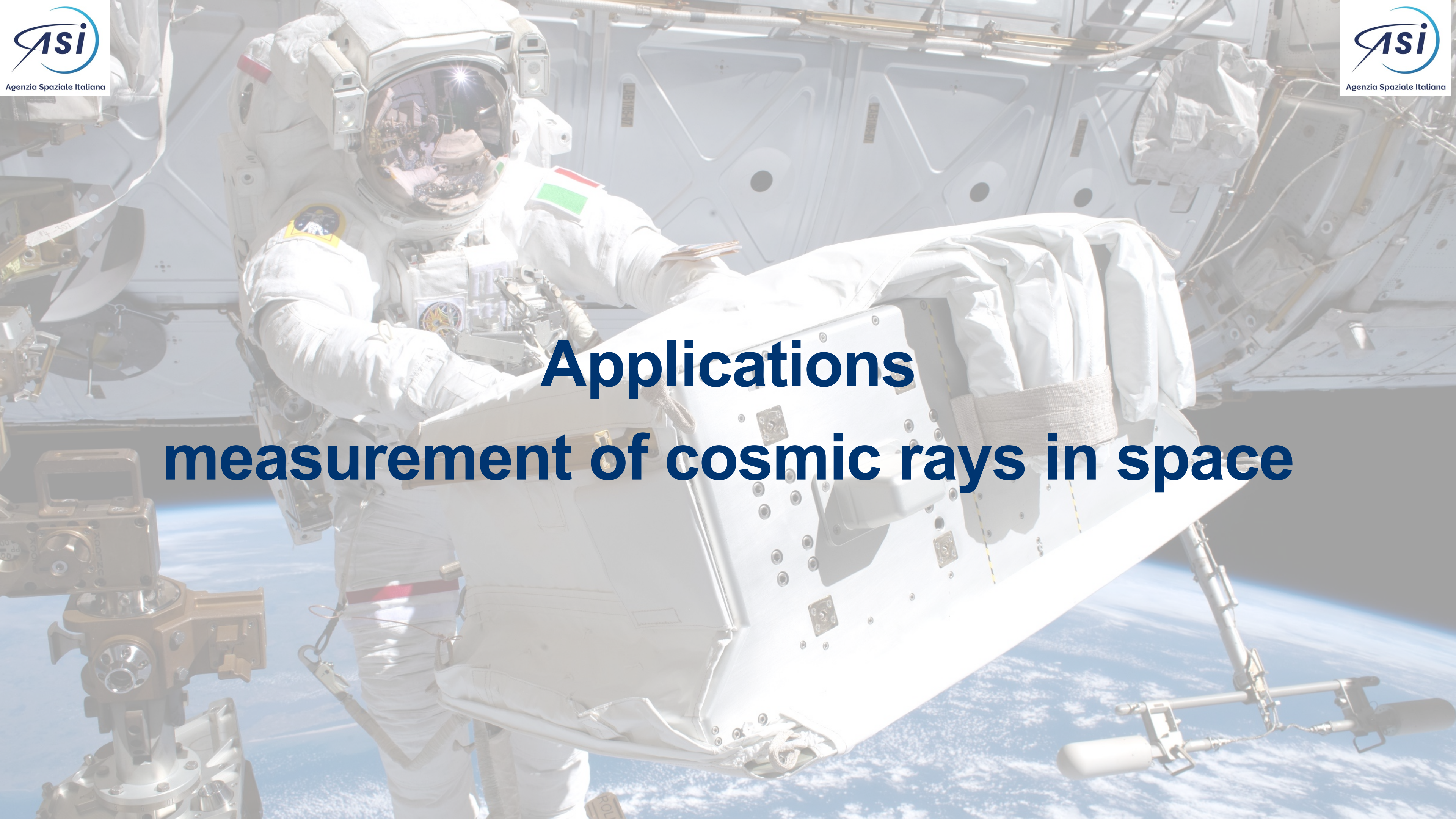

Applications
measurement of cosmic rays in space

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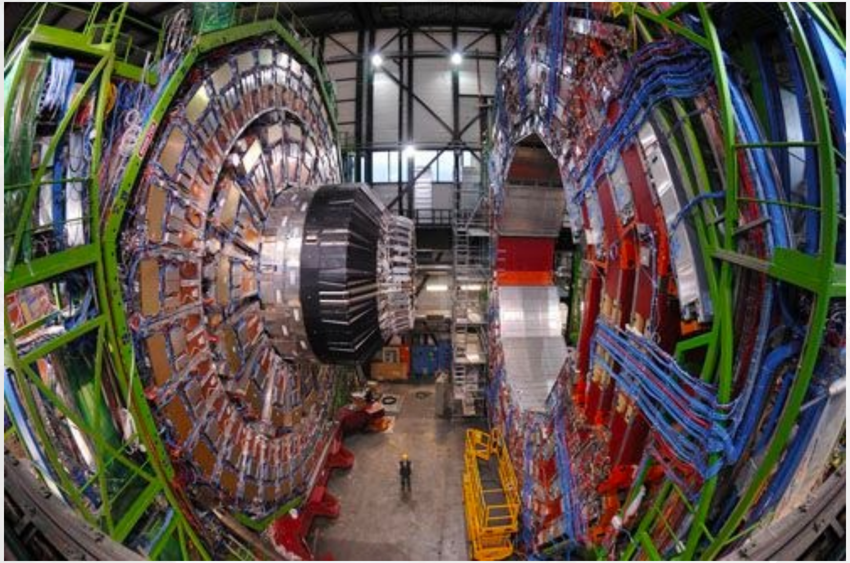
Measurement of Cosmic Rays in Space

Particle physics detectors operated in the "laboratory" of space



CMS detector at LHC (CERN)

Source: particles accelerated in lab

Weigth / Volume: 14'000 tons / 15 x 15 x 21 m^2

Electronics channels: ~ 100 M

Magnetic field: 4 T

Power consumption: ~ 5 MW (only detector, no services)

AMS detector in space (ISS)

Source: particles accelerated in the Cosmos

Weigth / Volume: 8 tons / 3 x 4 x 5 m^2

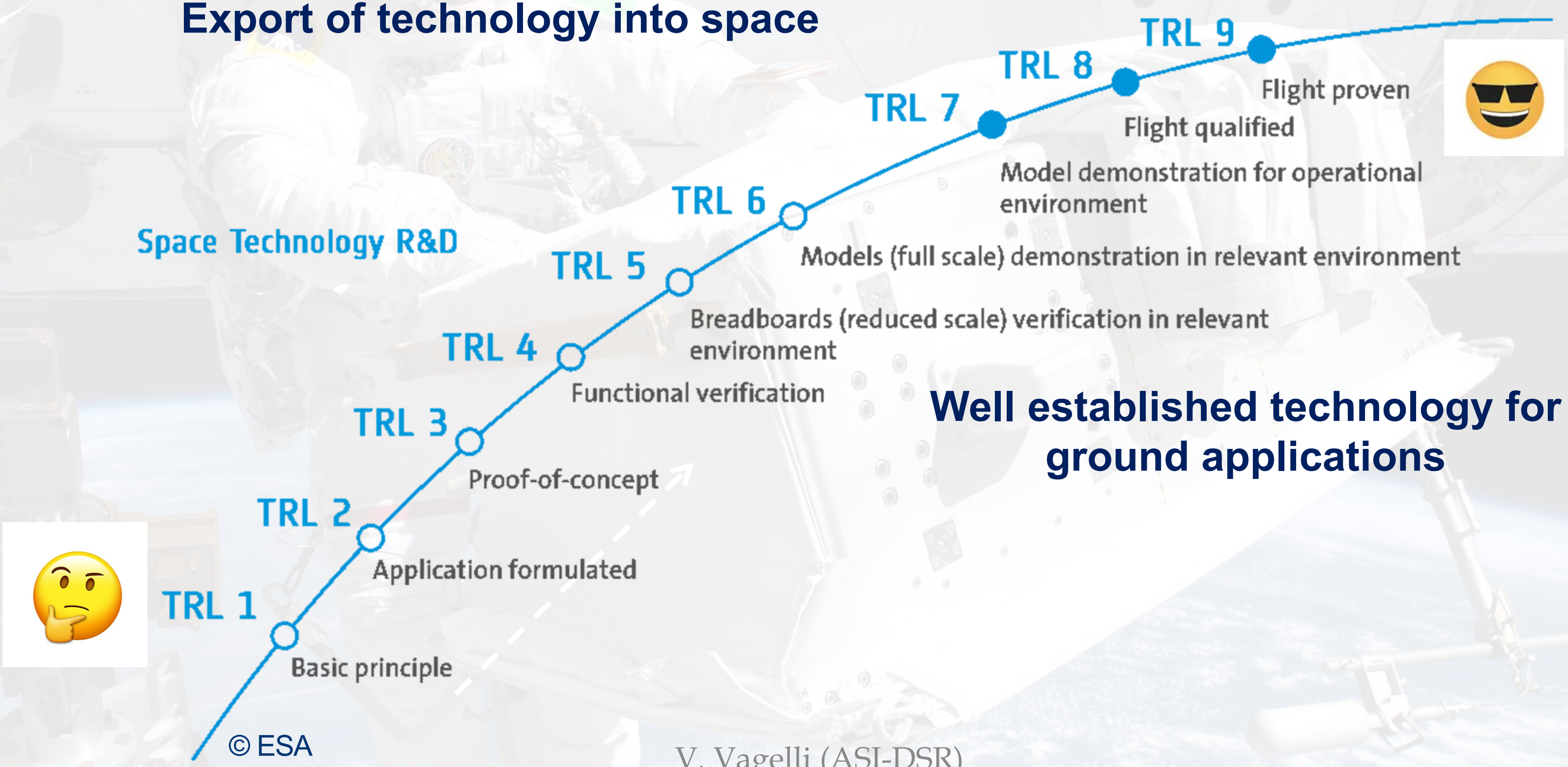
Electronics channels: ~ 300 k

Magnetic field: 0.14 T

Power consumption: ~ 2 kW (whole experiment)

Space technology development

Export of technology into space



Well established technology for ground applications

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Requirements of detectors in space

performance a la ‘particle physics’:
– high resolution measurements of momentum, velocity, charge and energy

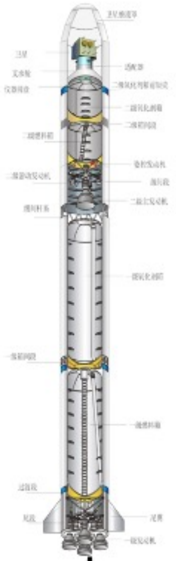
characteristics to properly access and work in space:
– Vibration (6.8 G rms) and acceleration (17 G)
– Temperature variation (day/night $\Delta T = 100^{o}C$)
– Vacuum (10^{-10} Torr)
– Orbital debris and micrometeorites
– Radiation (Single Event Effect)

limitation in
– weight O(tons)
– power (few kW), bandwidth and maintenance

Compliant with EMC (e.m. compatibility) **specs**

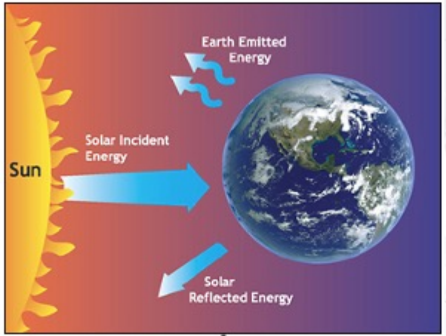
(all stress factors depend on the details of the mission. here AMS-02 reference values are reported)

Operations in space



Mechanical stress at launch:
- Static acceleration
- Random vibration
- Sinusoidal vibration
- Pyroshock

Life in space:
- Thermal stresses due to Sun-light (seasonal / day-night effects)
- Vacuum



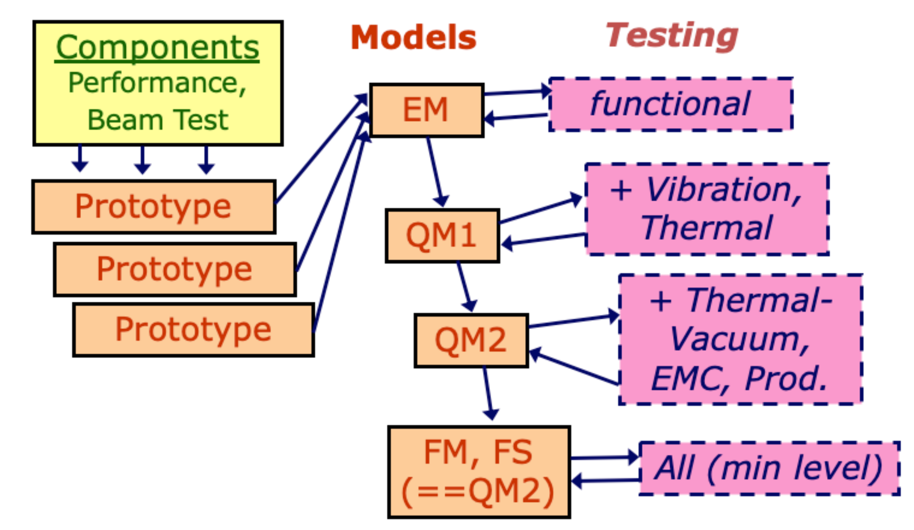
Careful Design, Model validation and Qualification are needed to ensure *highest possible reliability*

Thermal Stress ⇨ Functional check ⇨ Mechanical Stress ⇨ Functional check

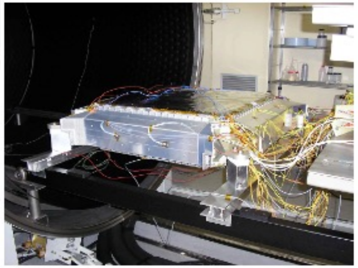
Thermal cycles in Vacuum ⇨ Functional check

➡ EMC

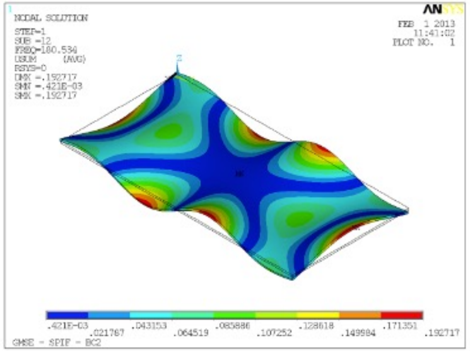
The long process to fly….



THERMO-VACUUM TESTS



VIBRATION TESTS



THERMAL MODELS

The extreme thermal environment

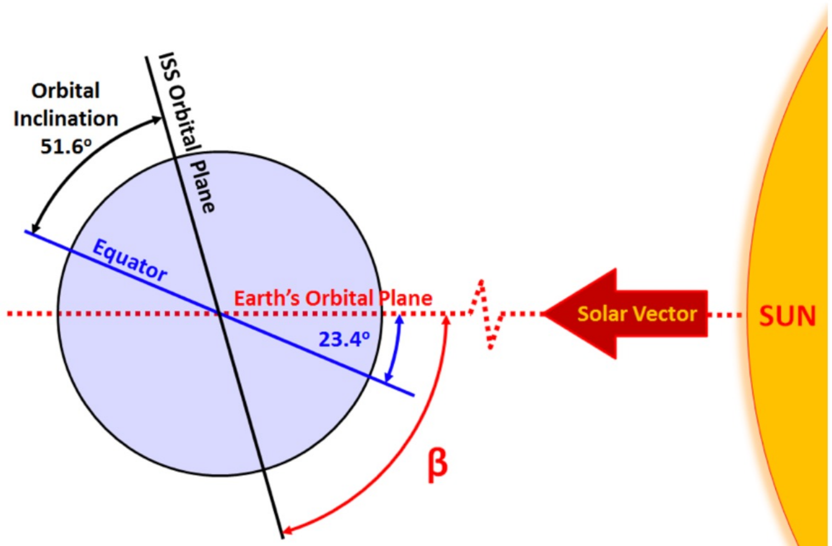


Figure 1. The solar beta angle, β, is the angle between the ISS orbital plane and the solar vector (direction from the Sun to the Earth).

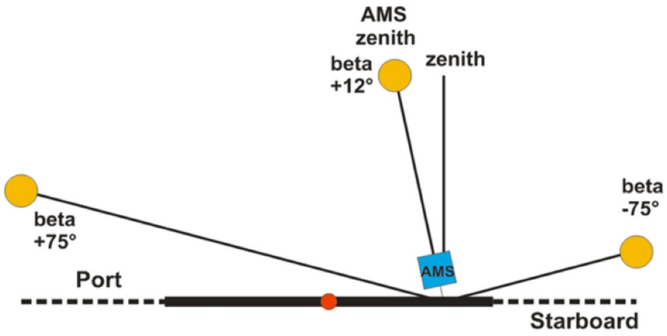


Figure 2. Variation of direction of solar illumination with beta angle. To avoid the rotating ISS solar arrays periodically being in its field of view, AMS is mounted on the ISS with a +12° "roll" to port.

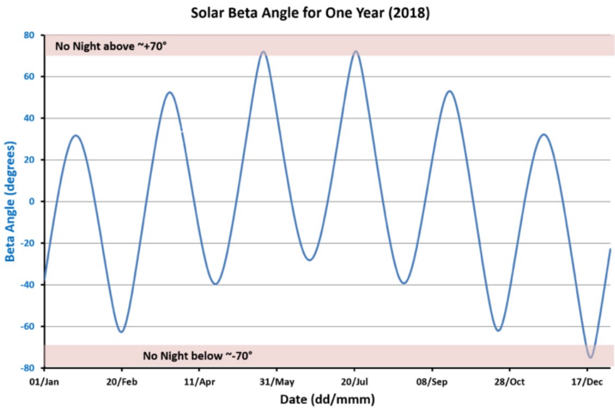
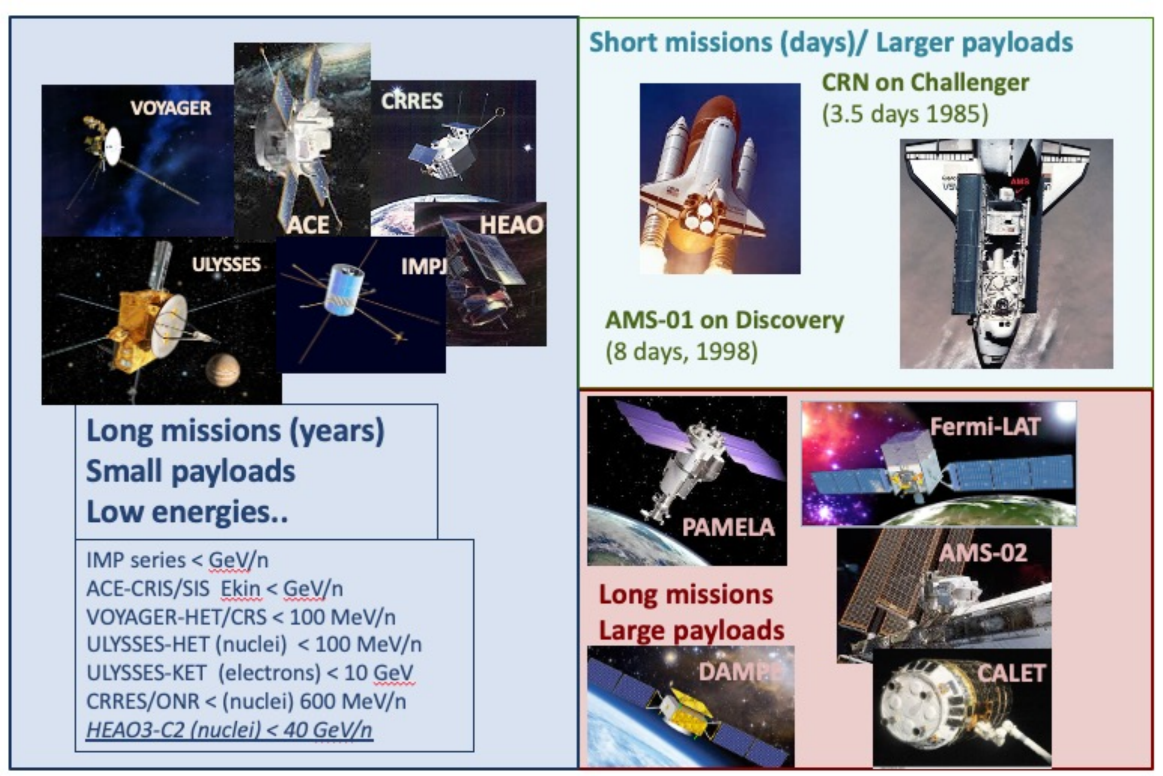
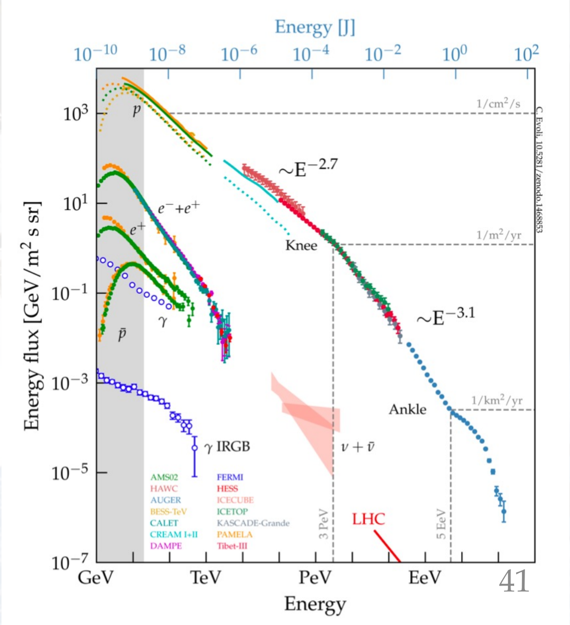


Figure 3. The solar beta angle for the year 2018. The shading indicated the times when there is no night on orbit.

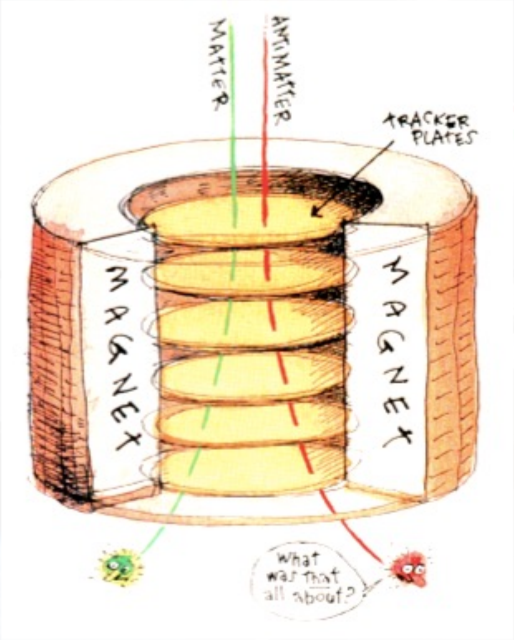
Measurement of Cosmic Rays in Space



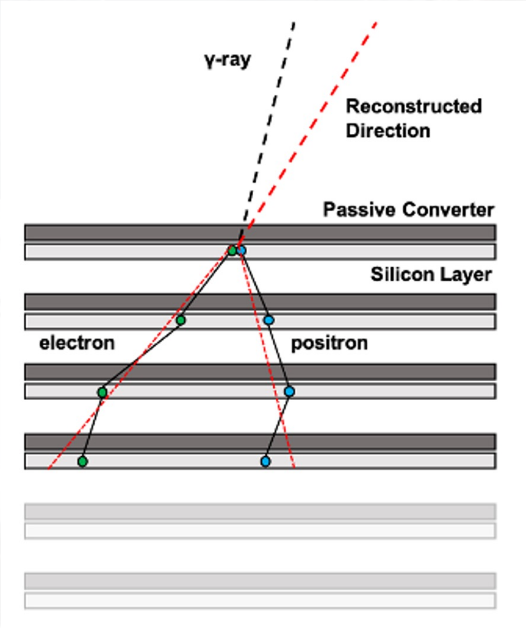
Access to space with **long duration missions** allows **direct measurements of CRs** before the interaction with atmosphere. Limited acceptance prevents investigation at highest energies but allows **measurement of CR spectra and composition**



Trackers for cosmic ray measurements

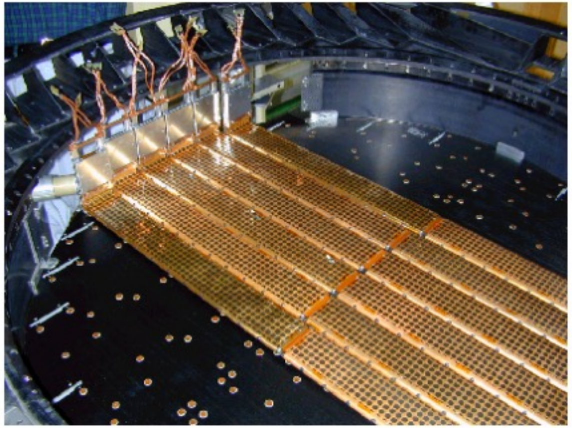


Magnetic Spectrometer
Matter-Antimatter separation
Rigidity measurement
Nuclei Z measurement
Direction reconstruction
(e.g. PAMELA, AMS-02)



Converter Tracker
Photon vertex reconstruction
Nuclei Z measurement
Direction reconstruction
(e.g.: Fermi-LAT, DAMPE)

AMS-01 Silicon Tracker

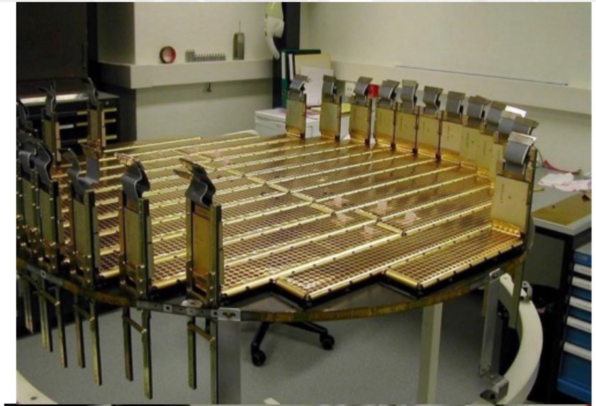


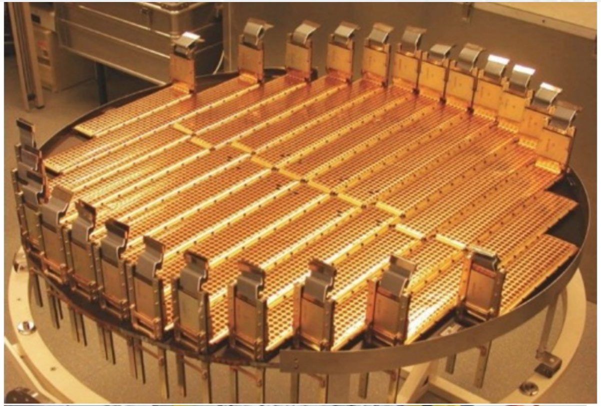
- ✓ Aluminum honeycomb + carbon fiber reinforcement planes
- ✓ Front end electronics disposed vertically on the edge of the plane to save acceptance
- ✓ Thermal bars to dissipate the power on the magnet mass outside

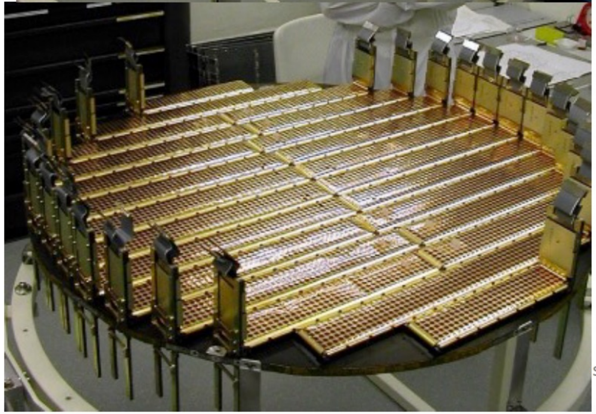
Lightweight carbon fiber shell to hold the planes

First verification of silicon tracker spectrometer in space (1998)

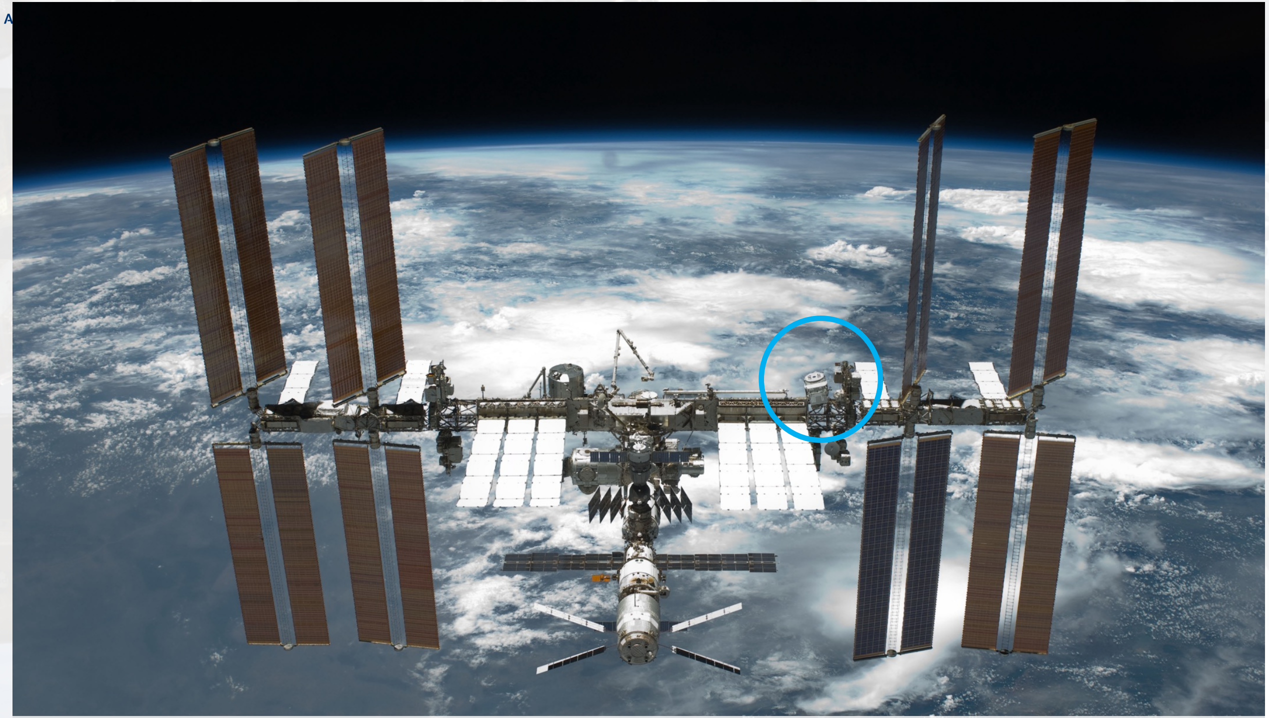
AMS-02 Silicon Tracker







AMS-02 on the ISS



DIRECT MEASUREMENT OF COSMIC RAYS IN SPACE
ONBOARD ISS SINCE 2011

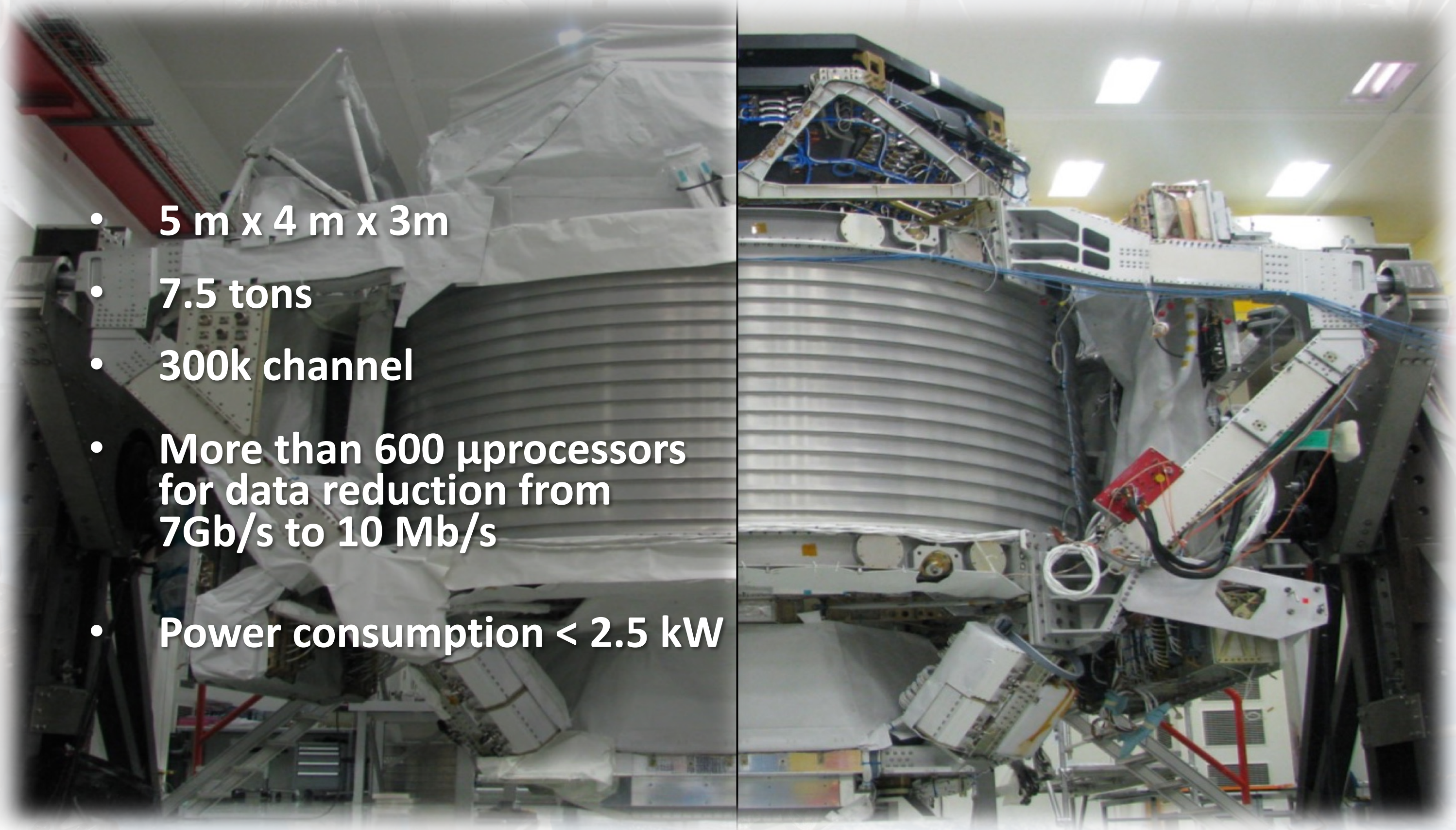
Cosmic ray antimatter

Indirect search for DM

Spectra and composition of cosmic rays

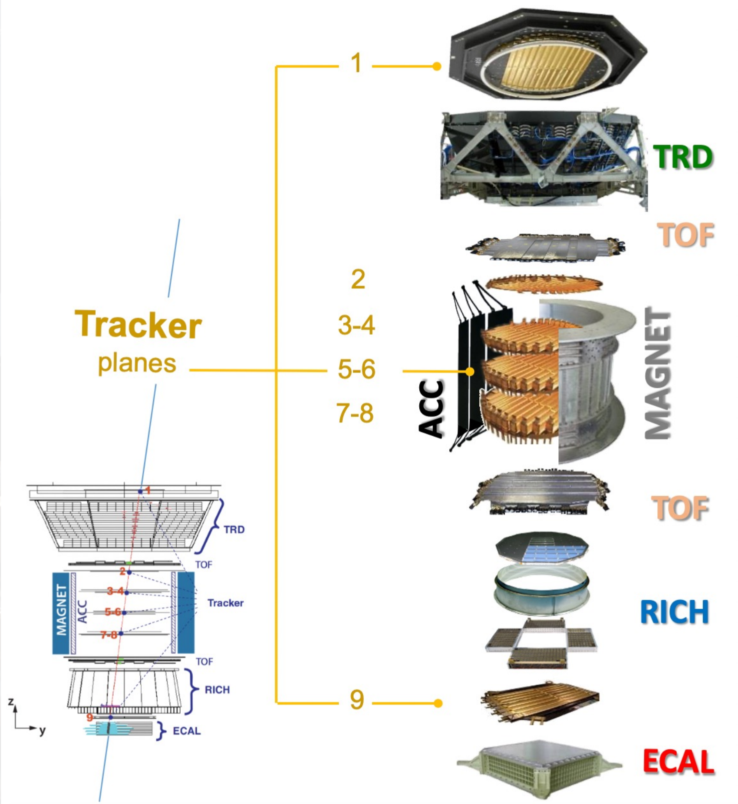
Solar Physics

The AMS-02 detector

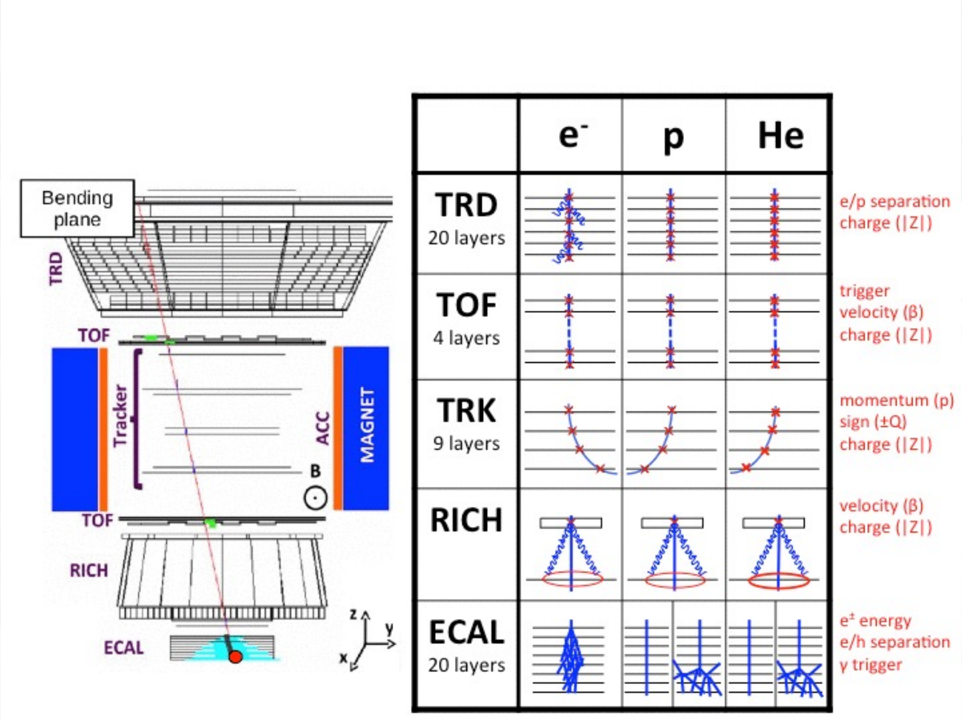


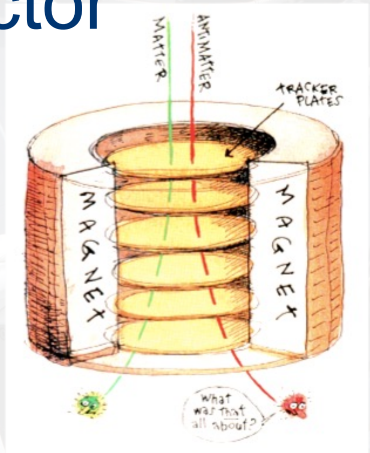
- 5 m x 4 m x 3m
- 7.5 tons
- 300k channel
- More than 600 μprocessors for data reduction from 7Gb/s to 10 Mb/s
- Power consumption < 2.5 kW

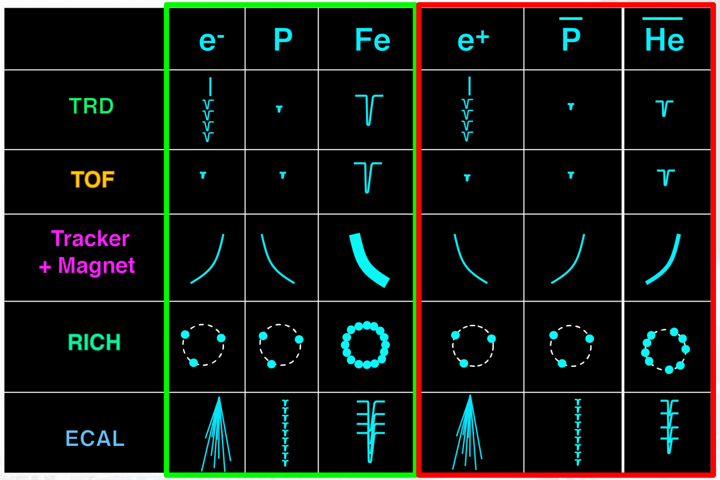
The AMS-02 detector



The AMS-02 detector



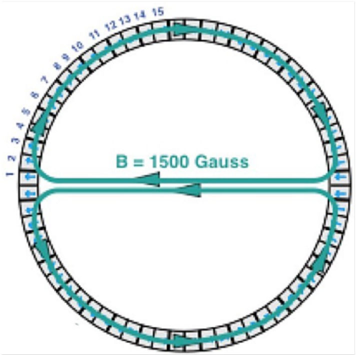


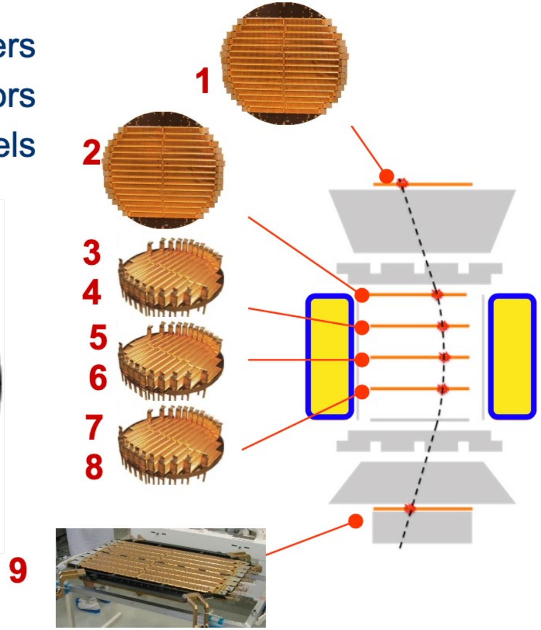


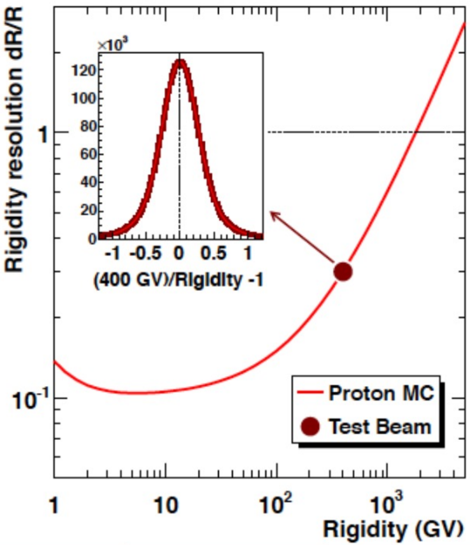
The AMS-02 tracker

9 layers of double sided silicon microstrip detectors inside a 0.14T dipolar magnetic field

192 ladders
2598 sensors
200k readout channels







Charge	Coordinate Resolution	MDR
Z = 1	10 μm	2 TV
2 ≤ Z ≤ 8	5 - 7 μm	3.2 - 3.7 TV
9 ≤ Z ≤ 16	6 - 8 μm	3 - 3.5 TV

BENDING COO
strip pitch: 27.5 μm
readout pitch: 110 μm

NON-BENDING COO
strip pitch: 104 μm
readout pitch: 208 μm

The AMS-02 tracker performances

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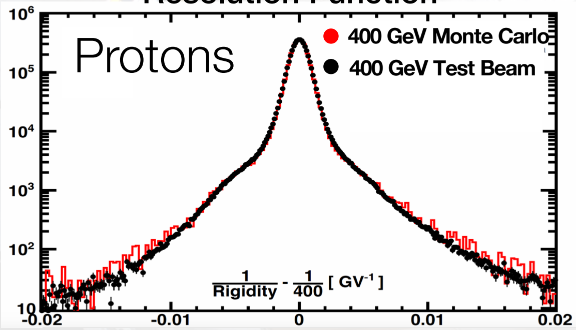
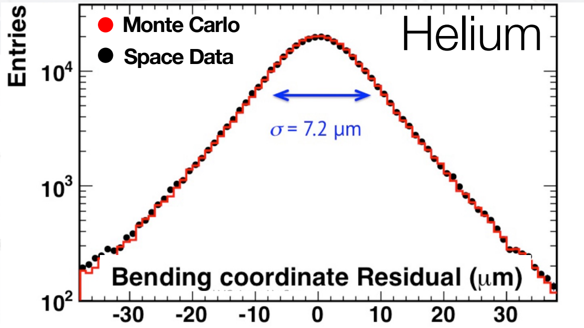
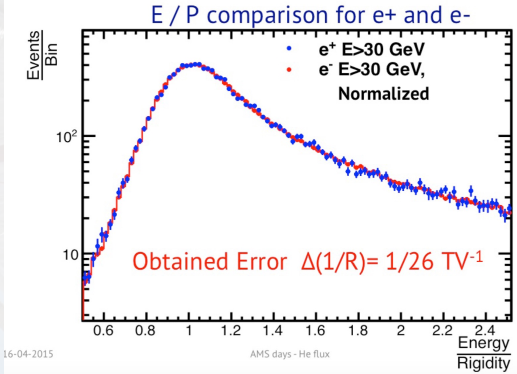
The AMS-02 Tracker Rigidity resolution has been checked comparing Test Beam data and Monte Carlo Simulations to Space data.

Resolution Function



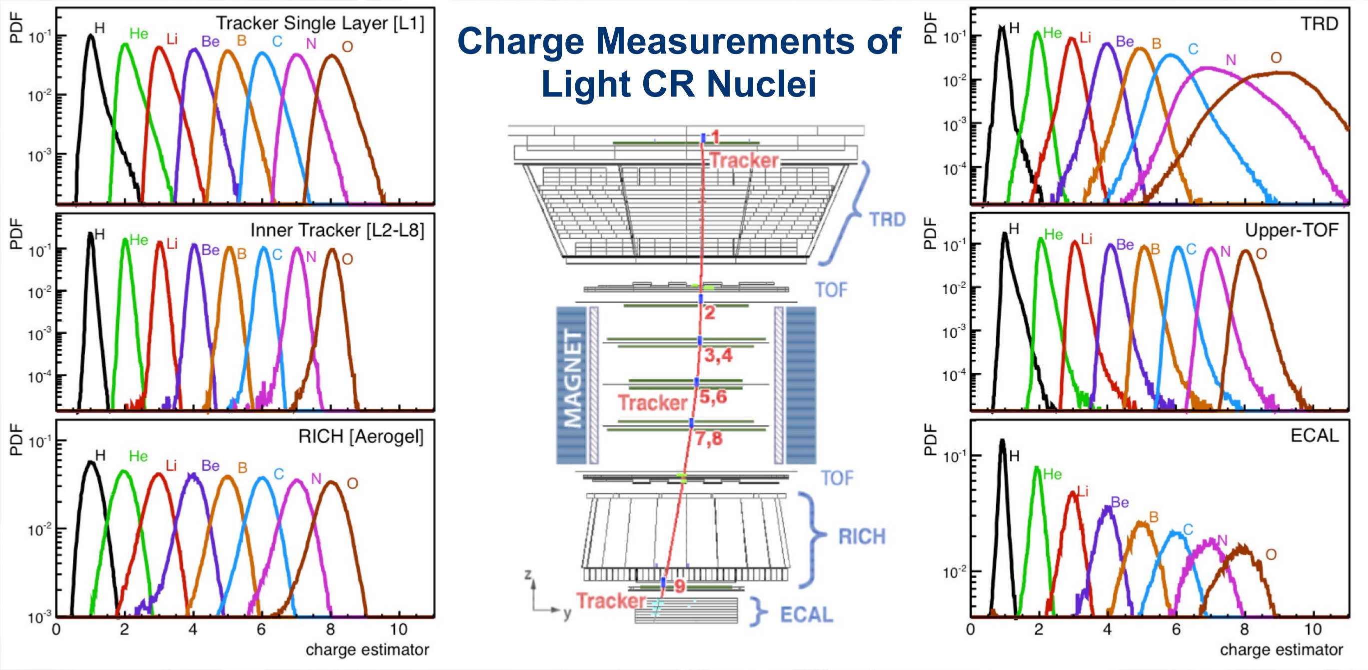
Coordinate resolution





The redundant measurement of the e+/- energy with the ECAL is used to further control the Tracker rigidity scale

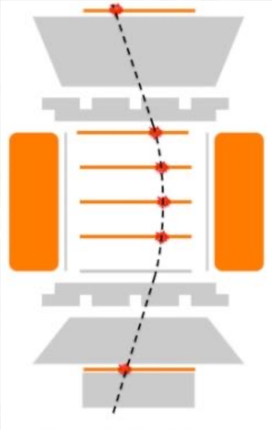
The AMS-02 tracker performances



Redundant measurements of the nuclear charge at different depths of the detector.

Precise understanding of nuclear fragmentation in the materials.

The AMS-02 tracker alignment

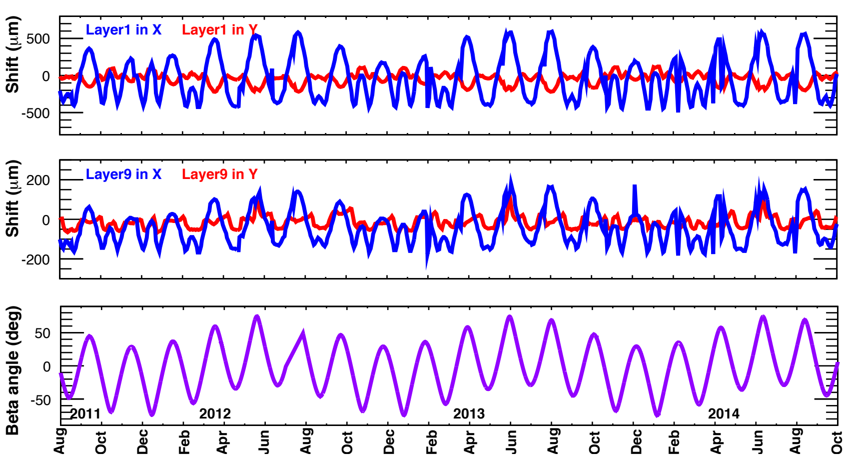


Inner tracker (layers 2 to 8) is arranged in a stiff and lightweight carbon shell and cooled by a mechanically pumped CO2 bi-phase system

- Thermally and mechanically stable within few mm, relative displacements are continuously monitored by 20 laser beams from layer 2 downwards.

External layers (1,9) are mechanically linked to TRD, ECAL and are affected by thermal movements of the structure

Seasonal effects of the space environment on tracker



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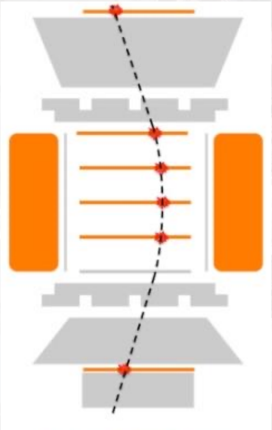
The AMS-02 tracker alignment



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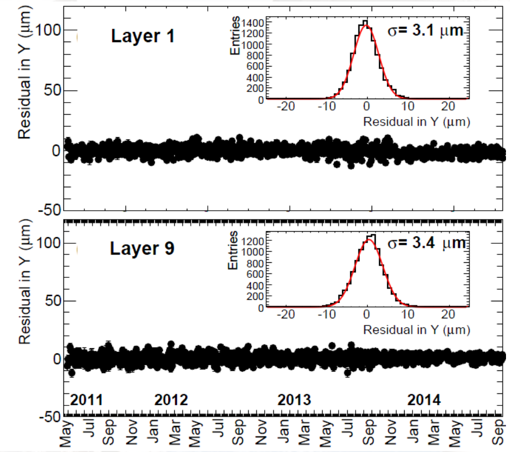
Seasonal effects of the space environment on tracker

Monitor of external layers with CR by means of the study of **Residuals** distance from extrapolated track as reconstructed with the other layers and hit on the layer under study



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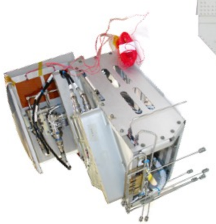
AMS-02 Reloaded

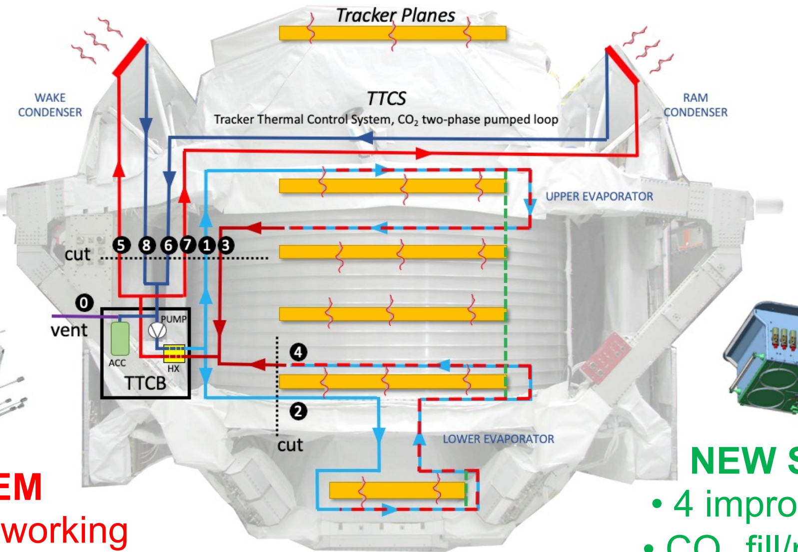
Tracker Thermal Control System initially developed for 3-year operations.
First evidence of defective behavior of the TTCS pumps in 2014.
After 8 years, no more redundancy to guarantee the continuous operations of AMS-02

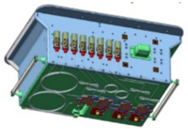
2014: Start of the **UTTPS** program (Upgrade Tracker Thermal Pump System) in collaboration with NASA.

Replacement of the old TTCB box with **new upgraded system**

The intervention requires a set of **EVA with operations outside ISS** involving cutting and handling of 8 gas tubes







OLD SYSTEM
- One only pump working
- Not enough $C0_2$ left on last loop
- No pump health monitor

NEW SYSTEM
- 4 improved pumps
- CO_2 fill/refill system
- Additional sensors for pump monitoring

AMS-02 not developed to be upgraded --> one of the most challenging EVA operations in the last decade

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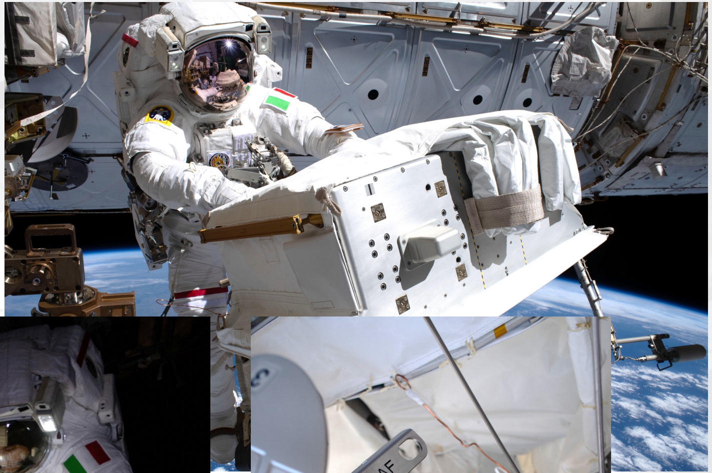
The EVA in pills

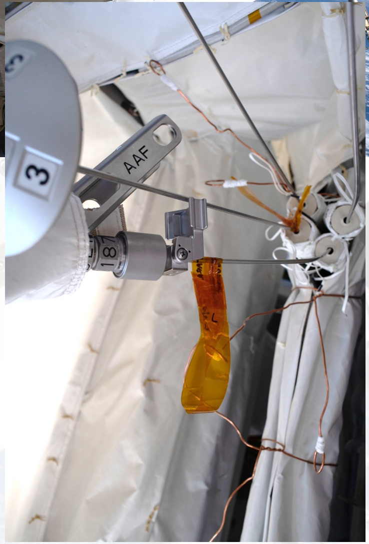
2019/11/15
Removal of AMS debris shield
Toolboxes for next EVAs
Installation of 6 handrails
Removal of MLI and VSB structure to facilitate the access to gas tubes

2019/11/22
Rough cut of 2 tubes to release CO_2 in space
Rough cut of 6 additional tubes
Installation of protection/identification caps

2019/12/03
Transport of UTTPS and installation on AMS-02
Connection of power and data cables

2020/01/25
Optical leak check
Cover AMS with MLI





Anti-Helium candidates in AMS-02

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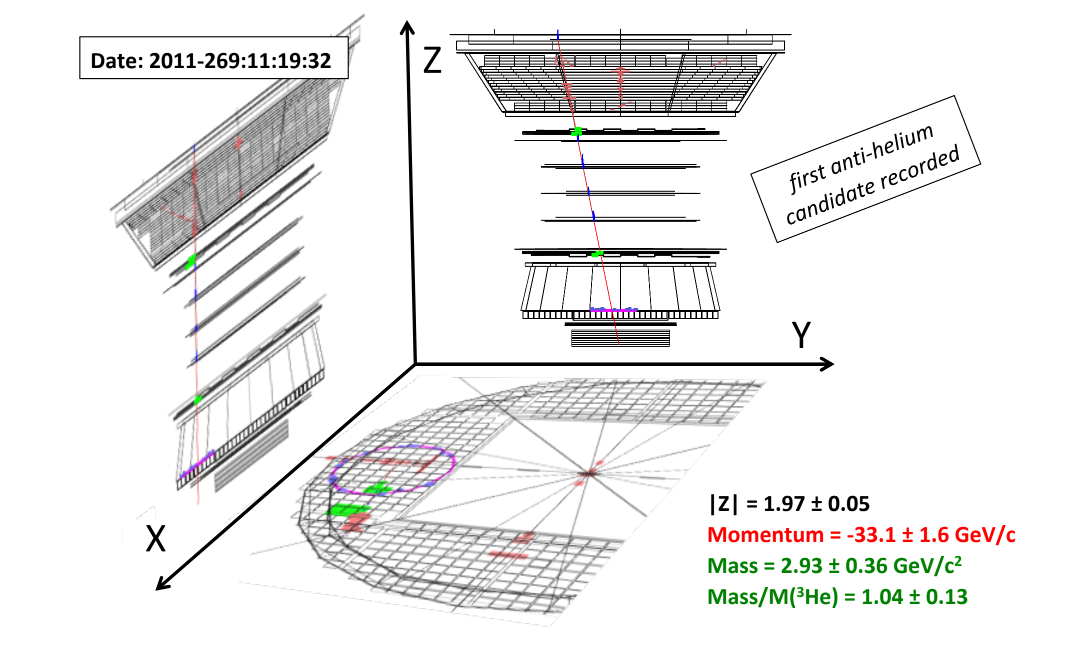
Anti-helium is a "golden"-channel, there is no p,K,π contamination, |Z| is well separated, and rigidity resolution is better than |Z|=1 particles (MDR = 3.2 TV).



S. J. Ting, AMS collab.
AMS Days 2018

Status of the AMS complex antimatter analysis

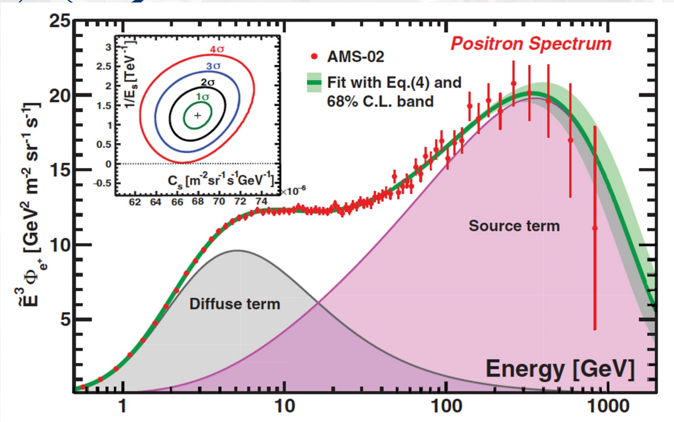
To date we have observed eight Z = -2 events with mass around He.

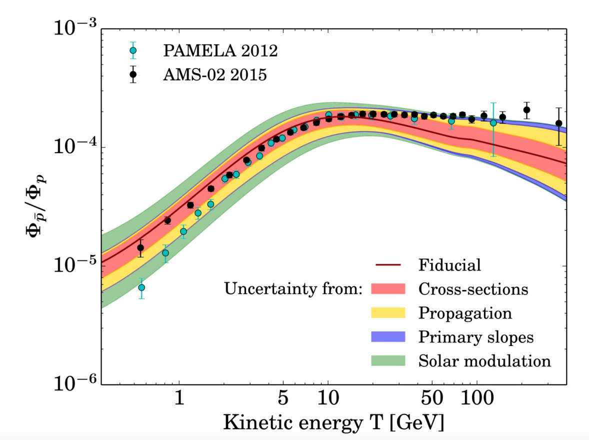
The corresponding sample with Z = +2 amounts to one billion helium events.

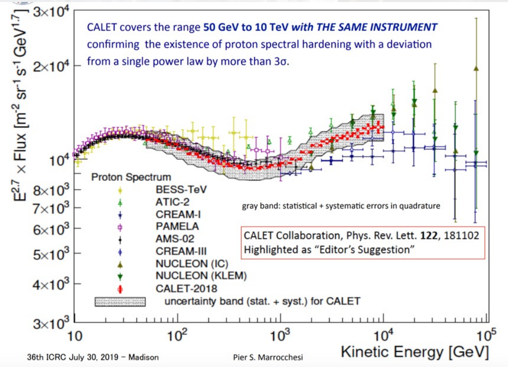
With the anti-Helium to Helium ratio of less than 1 in 100 million, detailed understanding of the instrument is required.

We are performing final detector verifications before announcing the results

Challenges for next-generation





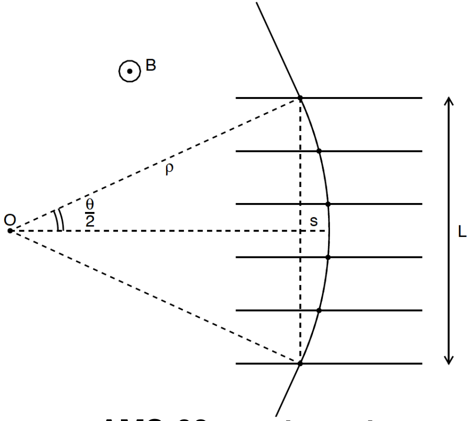


Electron and positron spectra above 1 TeV
Cosmic ray composition up to PeV
Precise determination of low energy abundances and time depencies
Search for rare antimatter components (anti-D, anti-He, …)
…..

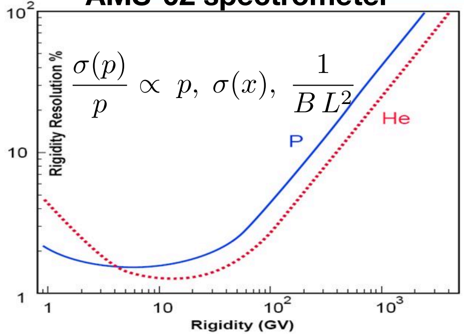
Experimental requirements:
Increasead detector acceptance
Improved detector technology
Novel layouts and idea

Challenges for next-generation

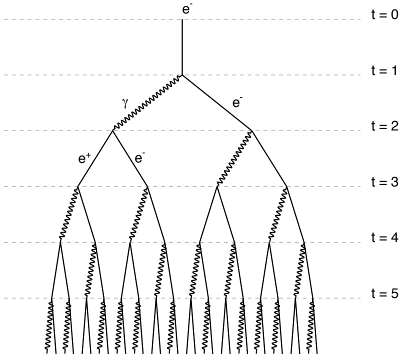
Magnetic Spectrometers



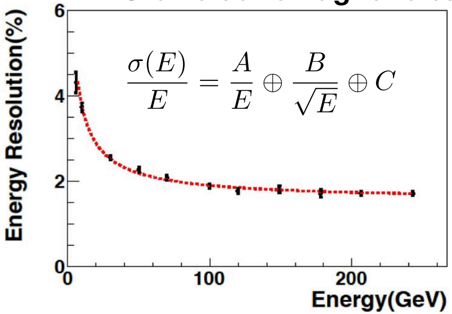
AMS-02 spectrometer



Calorimeters



AMS-02 electromagnetic calorimeter



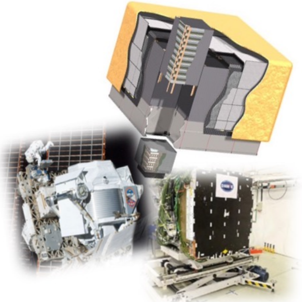
Spectrometer: energy reach limited by MDR

Calorimeter: energy reach limited by statistics

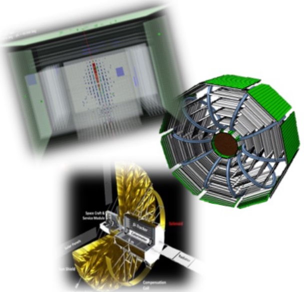
Silicon μstrip detectors in space

Most of space detectors for charged cosmic ray and γ-ray measurements **require solid state tracking systems** based on Si-microstrip (SiMS) sensors.

SiMS detectors are the only solution to instrument large area detectors with larger number of electronics channels coping with the limitations on power consumption in space



Operating Missions						
	Mission Start	Si-sensor area	Strip-length	Readout channels	Readout pitch	Spatial resolution
Fermi-LAT	2008	$\sim 74\,m^2$	38 cm	$\sim 880 \cdot 10^3$	228 μm	$\sim 66\,\mu m$
AMS-02	2011	$\sim 7\,m^2$	29–62 cm	$\sim 200 \cdot 10^3$	110 μm	$\sim 7\,\mu m$
DAMPE	2015	$\sim 7\,m^2$	38 cm	$\sim 70 \cdot 10^3$	242 μm	$\sim 40\,\mu m$



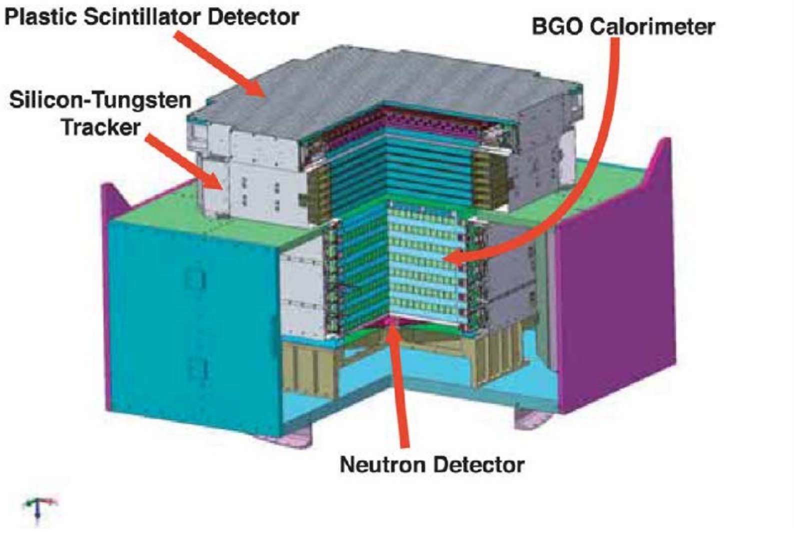
Future Missions						
	Planned operations	Si-sensor area	Strip-length	Readout channels	Readout pitch	Spatial resolution
HERD	2030	$\sim 35\,m^2$	48–67 cm	$\sim 350 \cdot 10^3$	$\sim 242\,\mu m$	$\sim 40\,\mu m$
ALADInO	2050	$\sim$ 80-100 m^2	19–67 cm	$\sim 2.5 \cdot 10^6$	$\sim 100\,\mu m$	$\sim 5\,\mu m$
AMS-100	2050	$\sim$ 180-200 m^2	$\sim$ 100 cm	$\sim 8 \cdot 10^6$	$\sim 100\,\mu m$	$\sim 5\,\mu m$

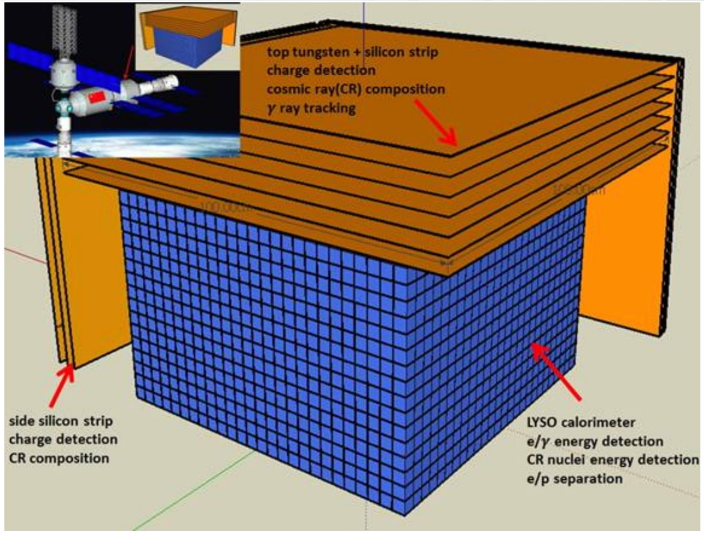
[1] HERD Collaboration. *HERD Proposal, 2018* https://indico.ihep.ac.cn/event/8164/material/1/0.pdf

[2] Battiston, R.; Bertucci, B.; *et al. High precision particle astrophysics as a new window on the universe with an Antimatter Large Acceptance Detector In Orbit (ALADInO)*. Experimental Astronomy 2021. https://doi.org/10.1007/s10686-021-09708-w

[3] Schael, S.; *et al. AMS-100: The next generation magnetic spectrometer in space – An international science platform for physics and astrophysics at Lagrange point 2*. NIM-A 2019, 944, 162561. https://doi.org/10.1016/j.nima.2019.162561

Next generation calorimeter mission: HERD





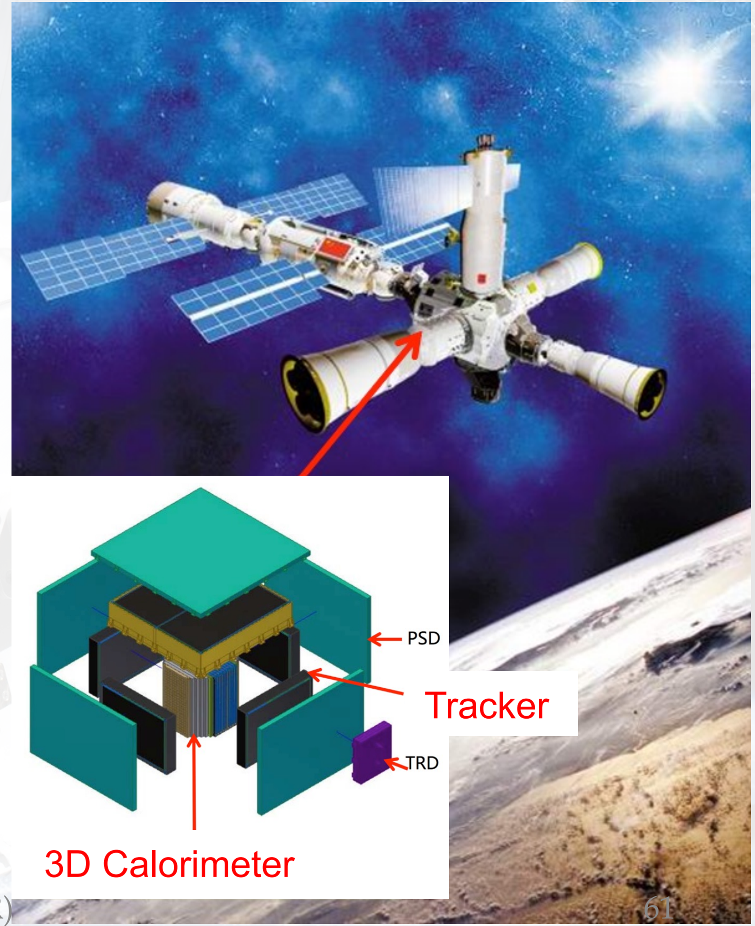
This generation (DAMPE, CALET, AMS-02, …): only CRs from top are detected
Next generation: "**Calocube**" approach: develop a calorimeter that is sensitive also to particles from the side
--> increase statistics without increasing volume and weight

Next generation calorimeter mission: HERD

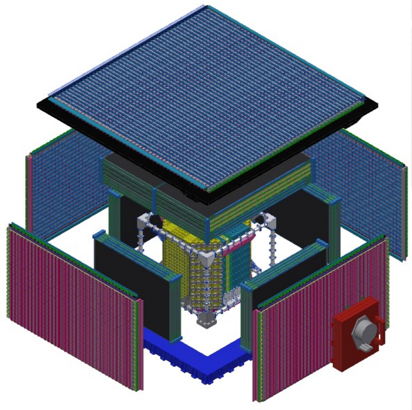
Scientific goals:
- search of dark matter signatures
- investigate origin of cosmic rays
- study of the highest energy particles

Key features:
- **acceptance 10-20 times than existing experiments**
- **weight limited to fit space constraints**

R&D activity to define the best layout of the detector:
- Silicon tracker and Sci-Fi tracker
- Si-based charge detector
- Calorimeter layout optimization
- Deployment of novel detectors in space (SiPM)
- Mechanical structure
- ....



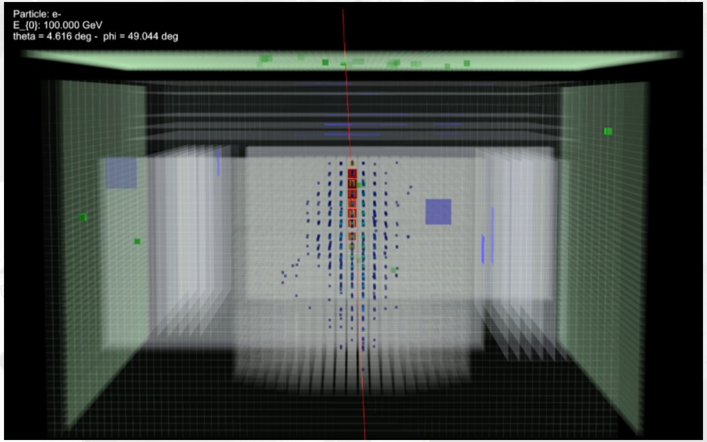
Next generation calorimeter mission: HERD



PSD
Gamma identification
Charge measurement

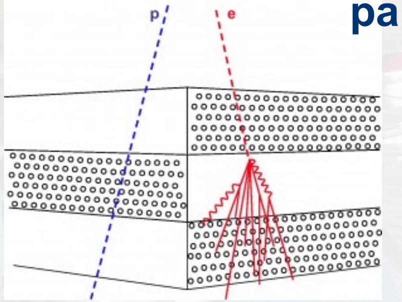
Tracker
Charge measurement
CR trajectory
Gamma converting & tracking

TRD
TeV CR calibration

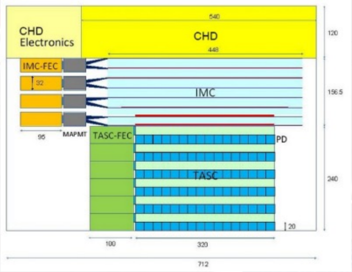


CALO: 3-d imaging calorimeter: Energy measurement & Particle identification

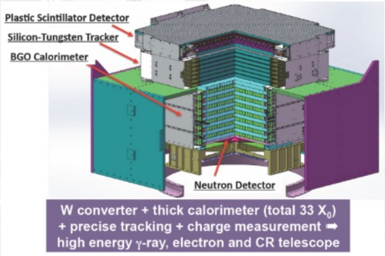
The novel design of 3-d imaging calorimeter could significantly increase GF, improve particle discrimination and reduce systemic error



AMS-02



CALET



DAMPE

HERD

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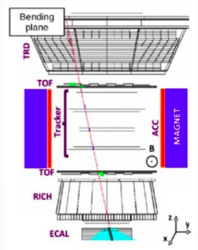
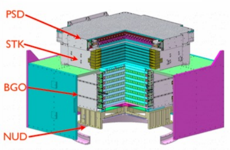
The future of magnetic spectrometers

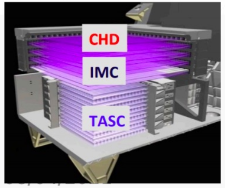
HERD will be the workhorse cosmic ray observatory in space in 2030.
However, without a spectrometer, the legacy of AMS-02 for antimatter physics in space will not be continued.



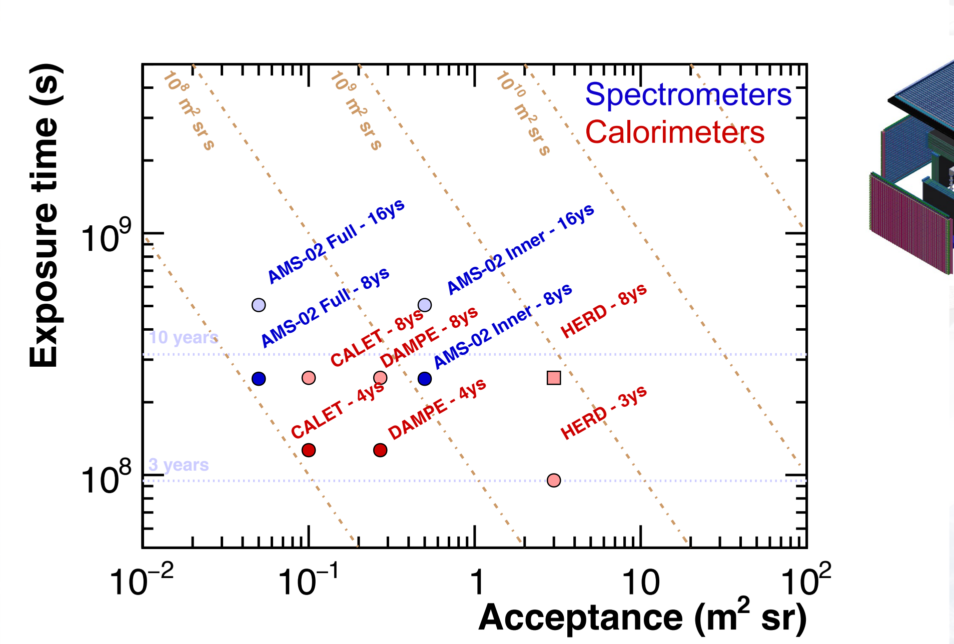
AMS-02 spectrometer

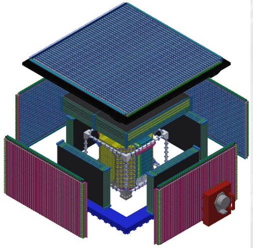


DAMPE calorimeter



CALET calorimeter





HERD calorimeter

AMS is the only magnetic spectrometer that is (so far) planned to be operated in space

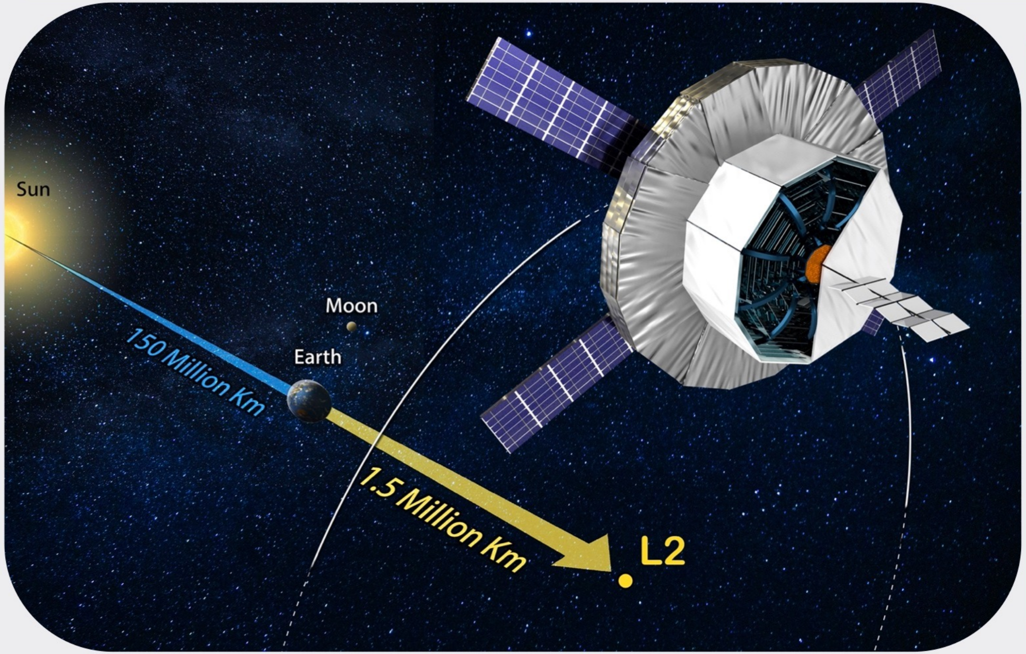
Next-gen spectrometer mission: ALADInO

Agenzia Spaziale Italiana

https://doi.org/10.3390/instruments6020019

Progressing in particle astrophysics with the
Antimatter Large Acceptance Detector In Orbit

ALADInO



High Temperature Superconducting Magnetic Spectrometer in space

Acceptance > 10 m^2sr
Antimatter measurements up to 10 TeV
Established technologies for detection of particles in space

5-year operations in L2

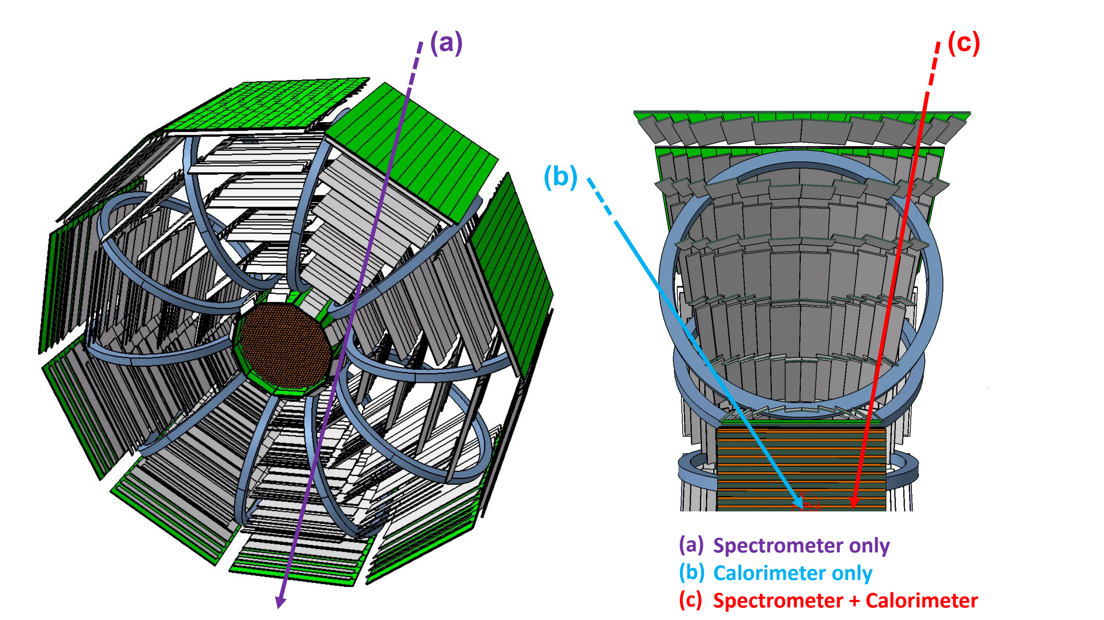
Payload Weight < 6.5 t
Payload power consumption 3 kW
Compact volume (fits Ariane launcher)

Roadmap for mission opportunity

mid 2030s: ALADInO Pathfinder
mid 2040s: Operations in L2
by 2050: Unprecedented results

Next-gen spectrometer mission: ALADInO

An Antimatter Large Acceptance Detector in Orbit



High Temperature Superconducting (HTS) magnetic spectrometer (SMS) to measure the particle rigidity, charge magnitude and sign with MDR>20 TV and acceptance >10 m^2 sr
Time of Flight (ToF) system to measure the particle velocity and charge magnitude;
Large acceptance (~9 m^2 sr) **3D imaging calorimeter (CALO)**

Next-gen spectrometer mission: ALADInO

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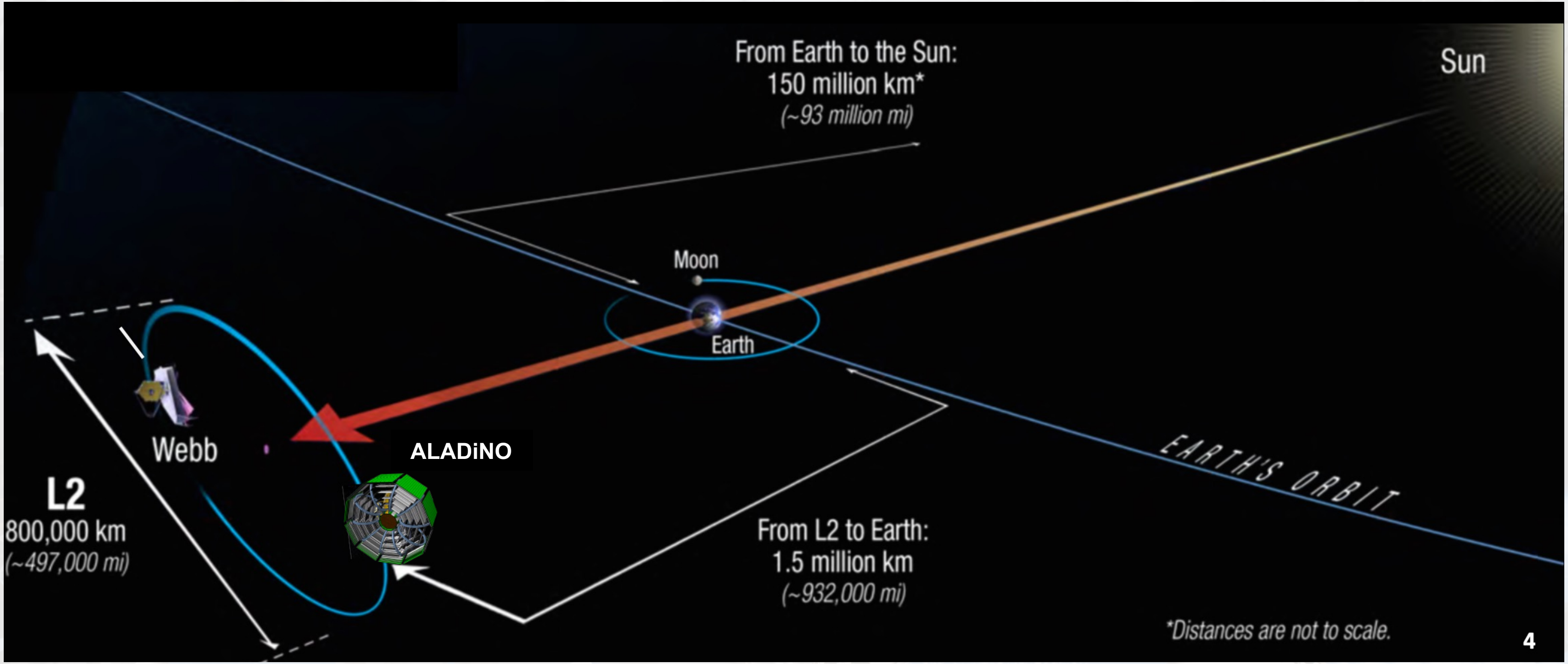
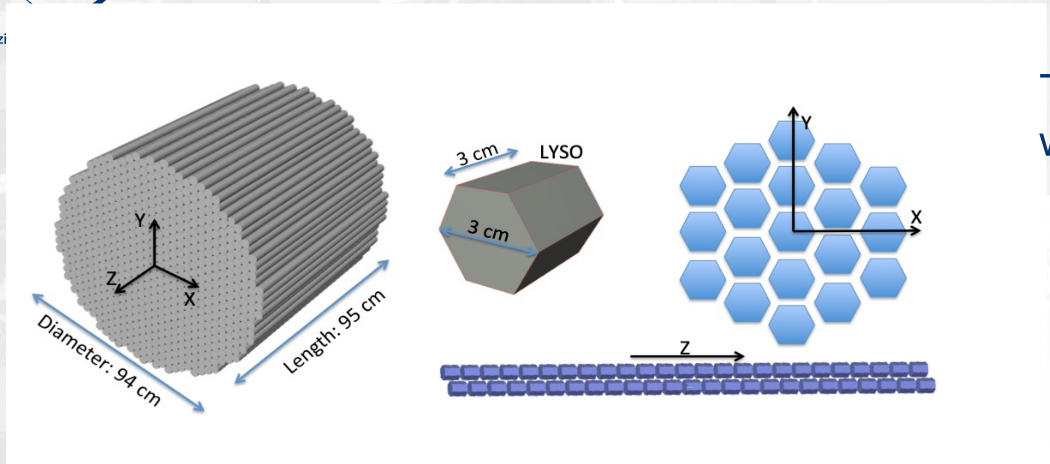
The best place to operate a cryogenic superconducting magnet in space is Lagrangian point L2, like the Webb space telescope, to minimize the active cooling of the cryo-magnet

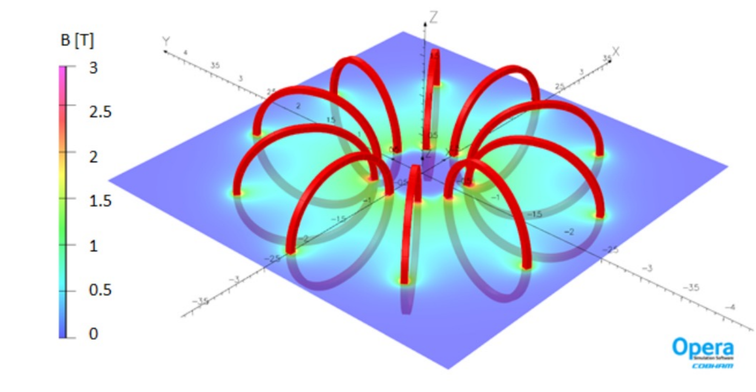


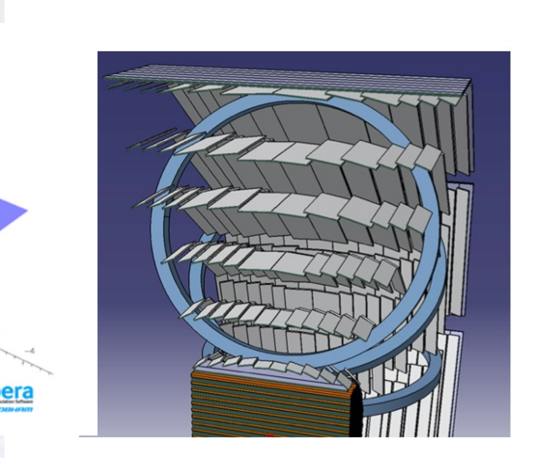
Next-gen spectrometer mission: ALADInO



The core: a symmetric LYSO calorimeter with 61 X_0 depth

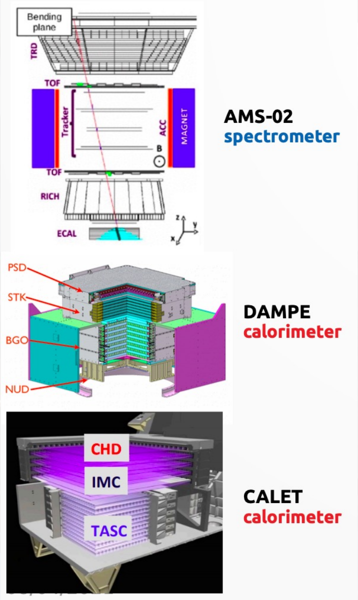
The spectrometer: 0.8T average field generated by HTS coils and silicon tracker system with optmized geometry

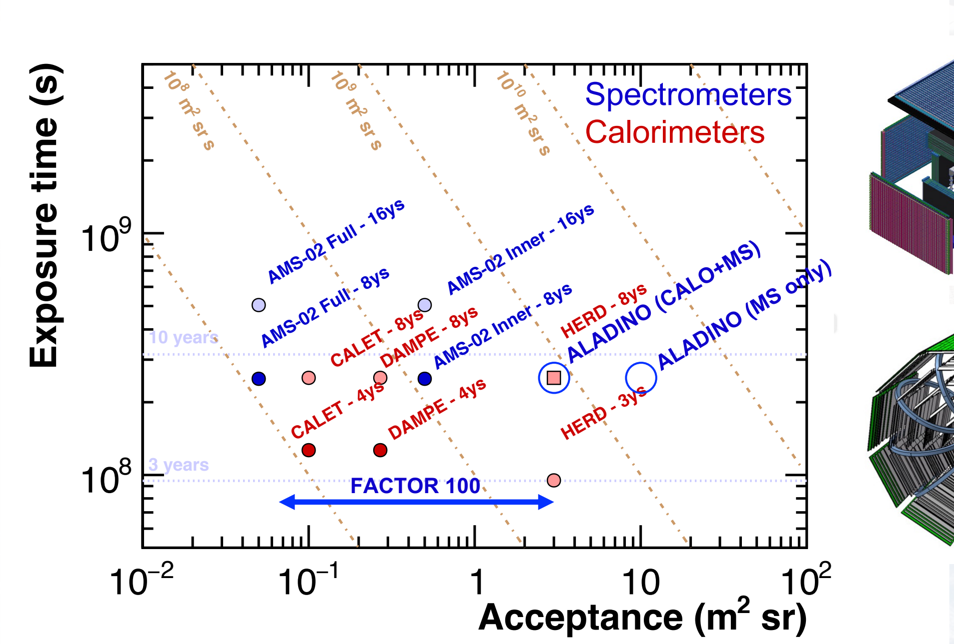


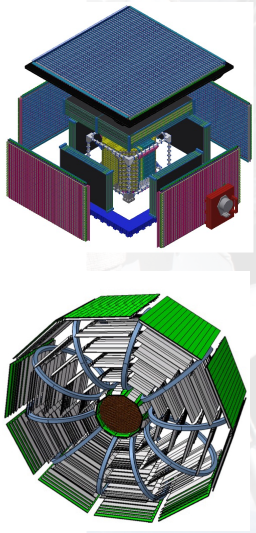


The future of magnetic spectrometers

ALADINO will improve by a factor of 100 the current acceptance of AMS-02







Next-gen spectrometer mission: ALADInO

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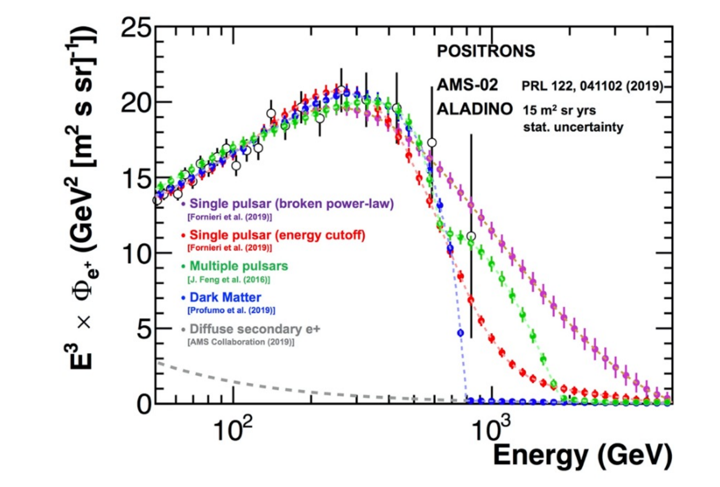
ALADINO with extend the physics of HERD including the capability to separate matter/antimmatter CR in the TeV energy range (which is the current limit of the AMS-02 spectrometer in operation)



Positron and electron spectra at energies > 1TeV will provide unique information to understand the origin of the positron excess observed by AMS-02

Heavy anti-matter CRs (anti-D, anti-He) will be in reach to be measured by ALADInO