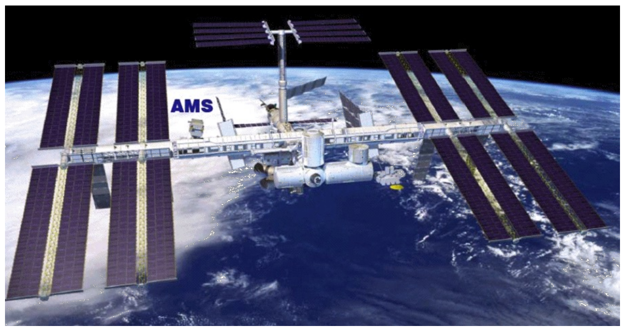
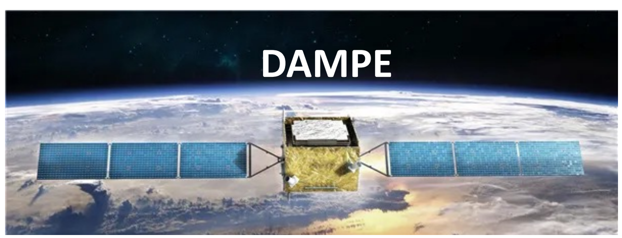
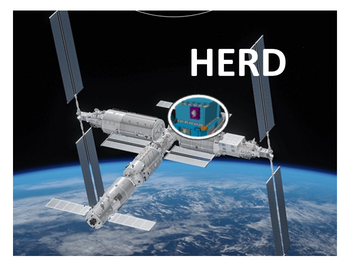
EPFL Physics and Applied Physics master programs - A.Y. 2024-2025

Introduction to astroparticle physics

Part 2 – Lesson 4 – May 16, 2025







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Learning outcomes and goals

Describe the cosmic ray (CR) energy spectrum and composition.
Discuss CR origin, acceleration and propagation.

Explain the relationship between charged CRs, gamma-rays and neutrinos.

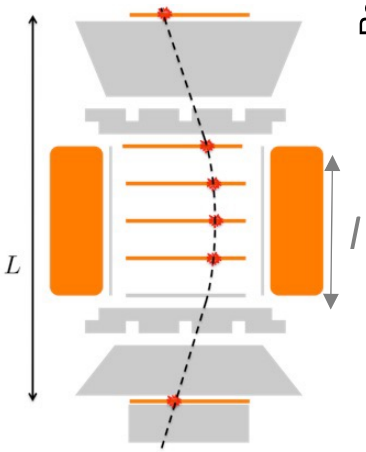
Discuss the detection principles and measured quantities (mass, charge, momentum, rigidity, energy, direction, …) of astroparticle physics experiments.

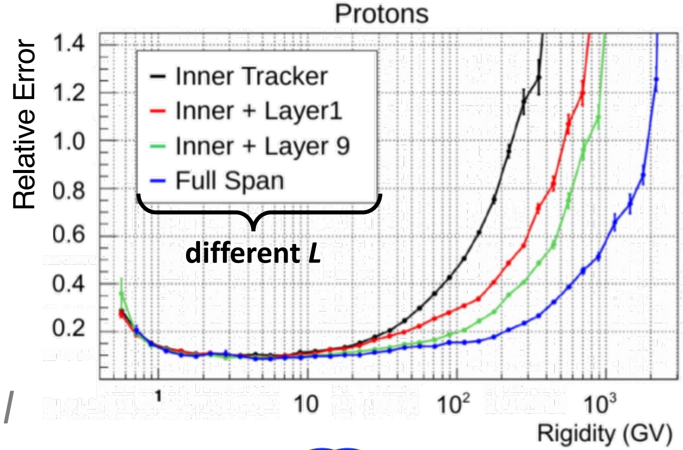
Interpret the main results of selected experiments

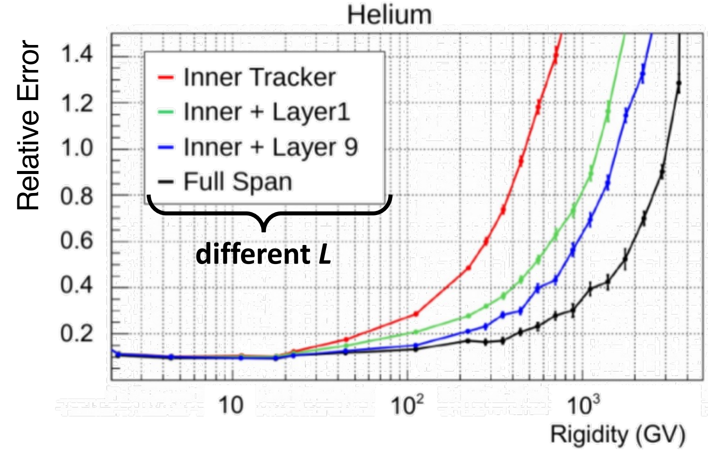
Assess / Evaluate the state of the art of astroparticle physics

AMS Rigidity relative error

$$\frac{\sigma(R)}{R} = \frac{8\,R}{B\,l^2}\sqrt{\frac{3}{2}}\sigma(x)$$







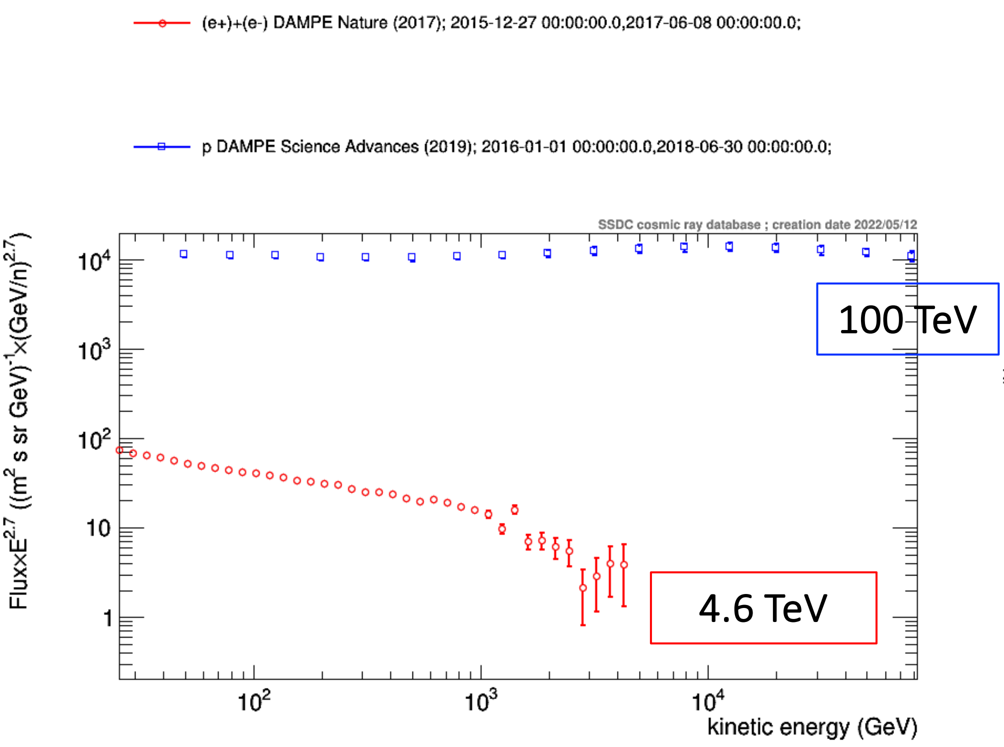
AMS-02 Track reconstruction and rigidity measurement

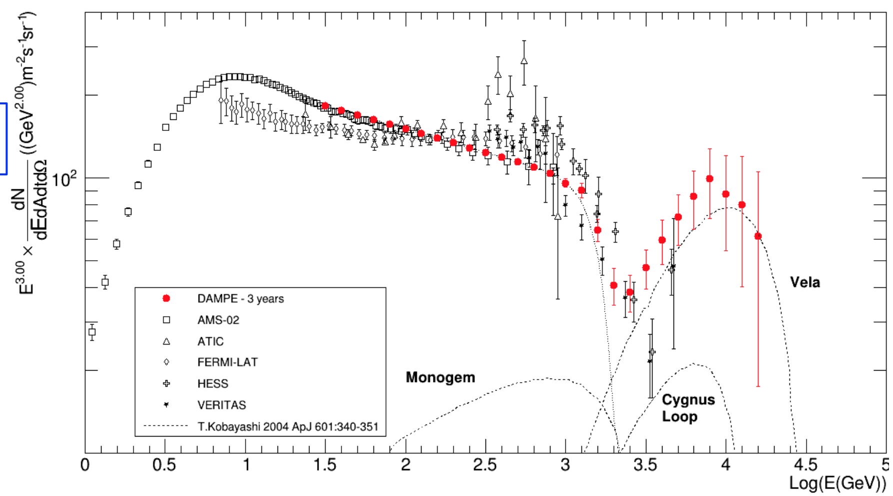
$$\frac{\sigma(R)}{R} \propto \frac{R}{BlL}\sigma(x)$$

- *l* is the total path length immersed in the magnetic field.
- *L* is the distance between the first and last position measurement (different *L* → different «spans»)

- **DEFINITION: The maximum detectable rigidity (MDR) is the rigidity value for which the relative error is 100%.**
- The spatial resolution σ(*x*) is 10.7 μm for protons and 6.5 μm for helium.
  - ➢ **The maximum detectable rigidity (MDR) is 2.0 TV for protons, 3.2 TV for helium.**
- The degradation of *σ(R)/R* at high energies is because the bending of the particle's trajectory by the magnetic field is smaller, therefore the curvature radius is measured with less precision.
- For low rigidities (< 20 GV) *σ(R)/R* is 0.1.
- The degradation of *σ(R)/R* at very low rigidities (< 1 GV) is related to the multiple Coulomb scattering.

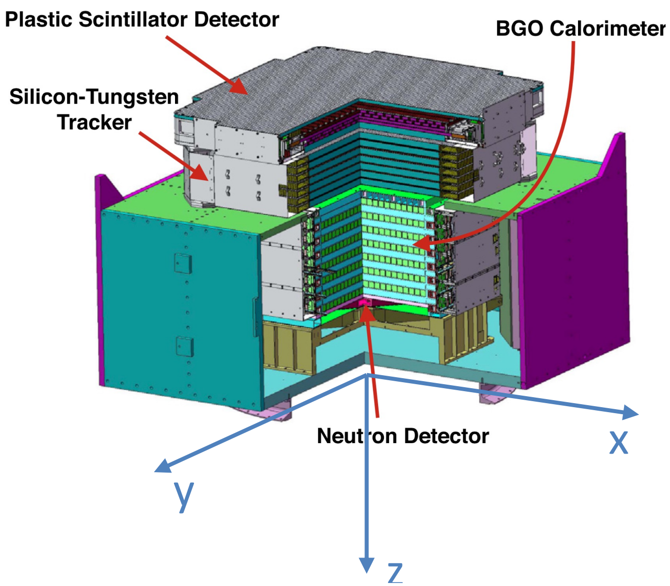
DAMPE spectra



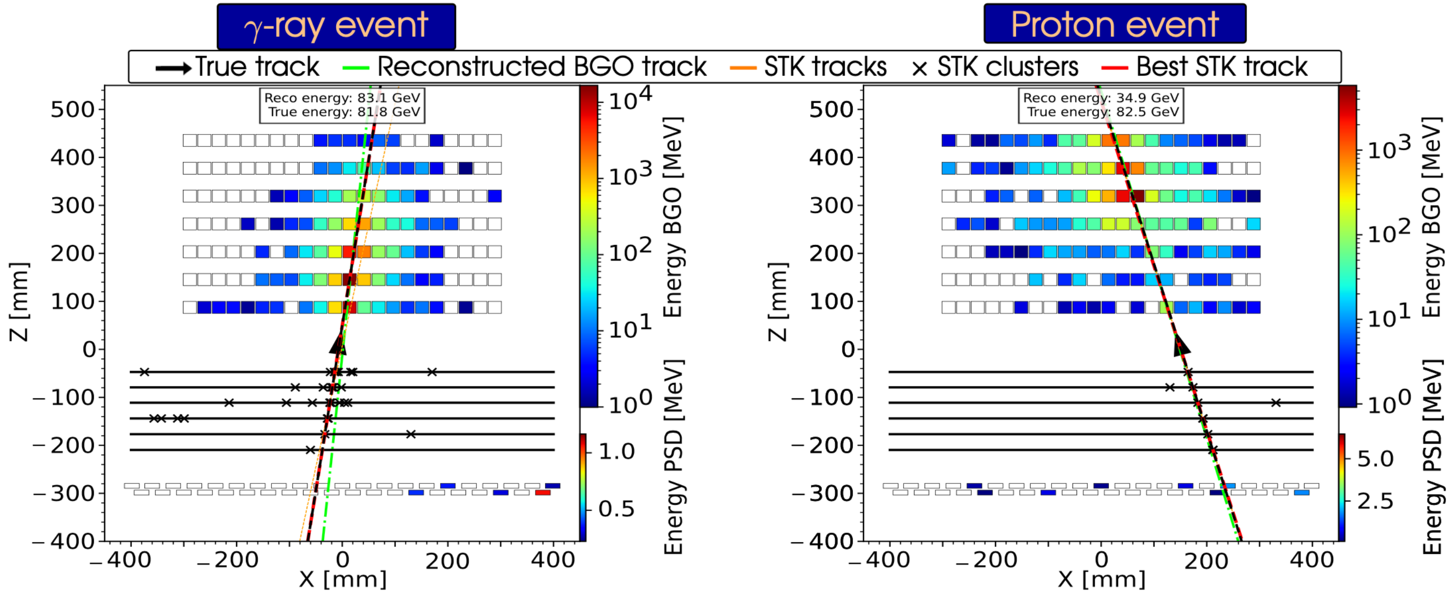


10 TeV

Energy measurement in DAMPE



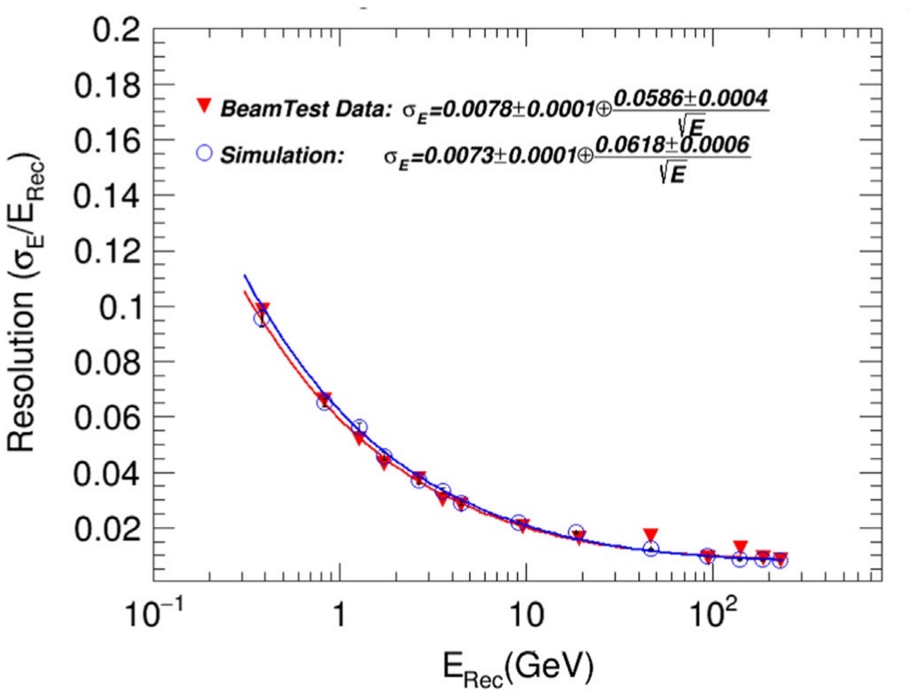
- Made of 14 layers of 22 BGO (bismuth germanium oxide) crystal bars each (size of a bar: 2.5 cm × 2.5 cm × 60 cm) → **calorimeter depth = 31 radiation length** = 31 X_0 Verify.
- Each crystal end is coupled to a photomultiplier tube (PMT)
- Adjacent layers are arranged perpendicularly to reconstruct the shower topology in the calorimeter.
- **We select only «well-contained» showers: i.e., showers with the maximum before the 10th layer.**



Event display by Parzival Nussbaum (PDM 2024)

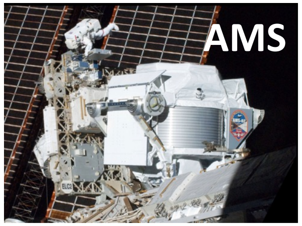
Calorimeter energy resolution

[Z. Zhang et al., NIM A 836 (2016) 98–104](#)

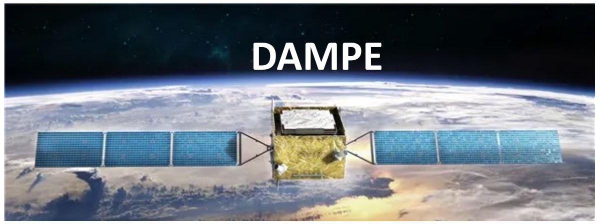


- In **calorimeters** *σ(E)/E* ∝ 1/sqrt(*E*): **energy resolution improves with energy**
- In **magnetic spectrometers** *σ(R)/R* ∝ *R*: the **rigidity resolution deteriorates <u>linearly</u> with rigidity**

Differences between a magnetic spectrometer and a calorimeter



$$\frac{\sigma(R)}{R} \propto \frac{R}{BlL}\sigma(x)$$



Charge measurement
(sign + absolute value)

$\sigma(R)/R \propto R$
the rigidity resolution deteriorates with rigidity

There is a MDR:
Maximum Detectable Rigidity

Solution: stronger magnetic (B) field and larger detector (L)

Only absolute value of the charge

$\sigma(E)/E \propto 1/\mathrm{sqrt}(E)$
energy resolution improves with energy

There is not energy limit in principle but at high energies becomes difficult to contain the shower

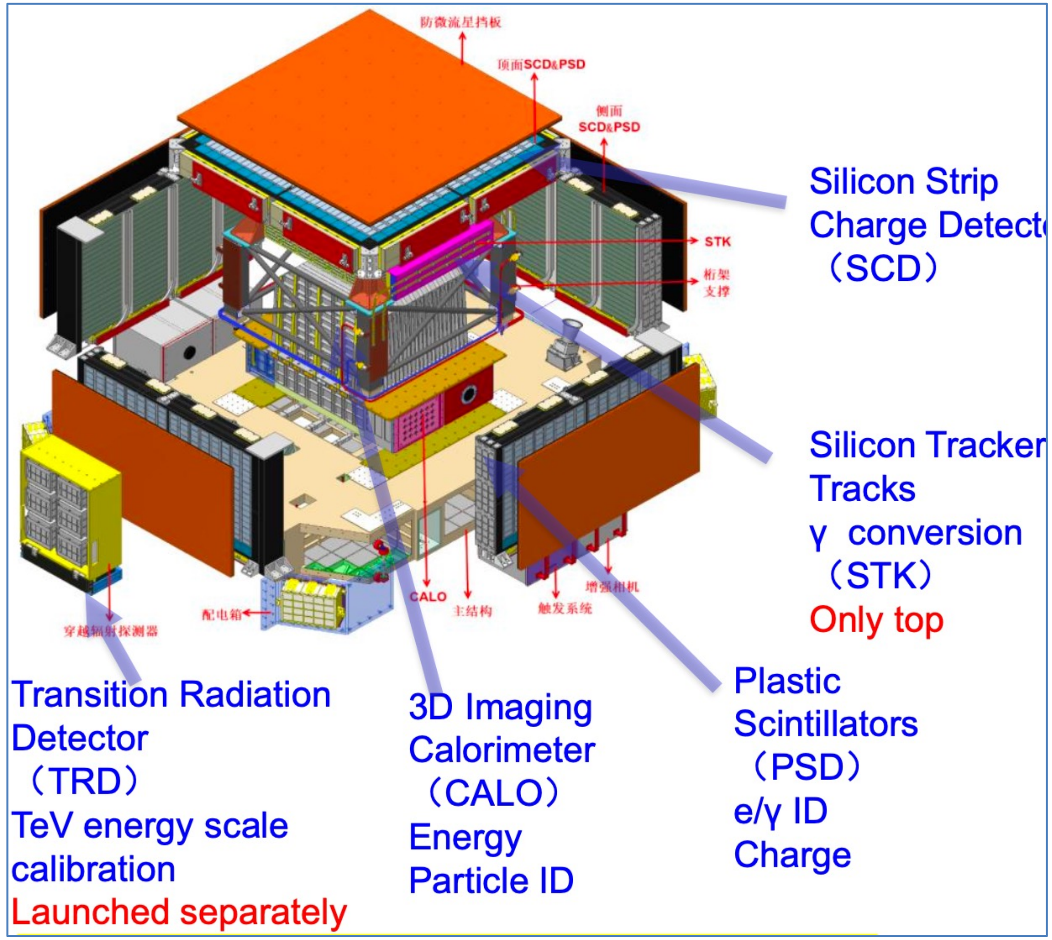
Solution: deeper calorimeter

Future calorimeter: HERD

~ 4 tons
3.6 m × 3.2 m × 2.0 m

The High Energy cosmic-Radiation Detection (HERD) facility is a space-borne CR calorimeter experiment which will be launched and installed onboard the **China Space Station (CSS)** in 2027 and operational for at least 10 years.

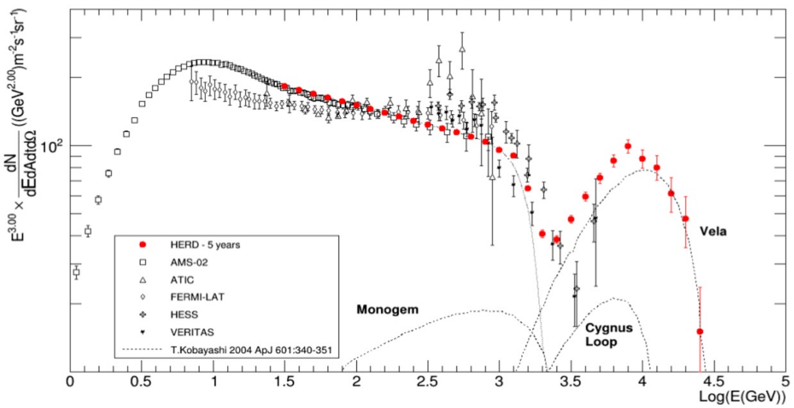
The experiment is based on a homogeneous, isotropic and finely-segmented **calorimeter** that will measure the **cosmic ray** flux up to the *knee* region, search for indirect signals of **dark matter** and monitor the **gamma-ray** sky.



https://indico.cern.ch/event/1463191/contributions/6434058/

The objectives of HERD

Expected $e^+ + e^-$ flux in 5 years

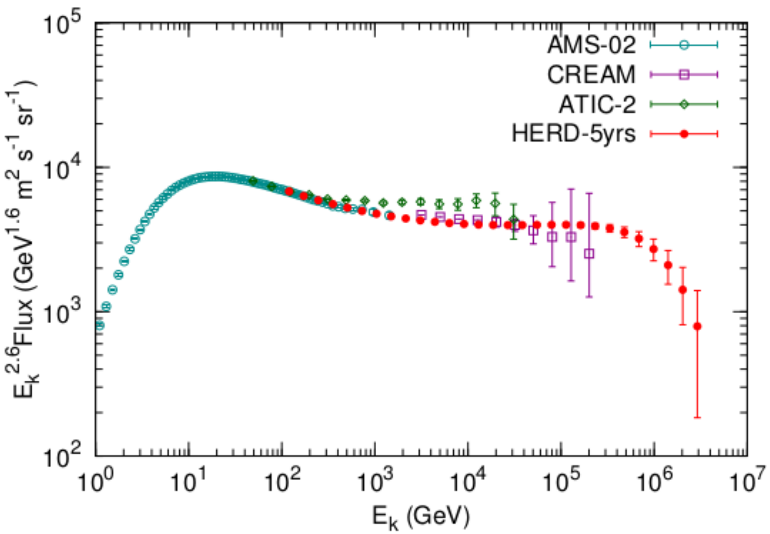


32 TeV

Search for signatures of annihilation/decay products of **dark matter** in the energy spectrum and anisotropy of **high energy electrons+positrons (10 GeV – 100 TeV)**.

Energy spectrum of **p and He up to a few PeV** and heavier nuclei up to a few hundreds of TeV/n.

- The first direct measurement of p and He knees will be very important to understand the physical nature of the knee of cosmic rays.
- The extension of the B/C ratio to higher energy will probe the propagation mechanisms of cosmic rays.



Expected proton flux in 5 years

Question

What will come after HERD?

Question

What will come after HERD?

Solution: stronger magnetic (B) field and larger detector (L)

&

Solution: deeper calorimeter

Hybrid space-borne detectors: MS + deep calo

Detector performance comparison

		Past	Present				Future		
		PAMELA	AMS-02	Fermi	CALET	DAMPE	HERD	ALADInO	AMS-100
Magnetic Spectrometer	Magnetic field [T]	0.43	0.14					0.8 (HTS)	1 (HTS)
	MDR [TV]	1	**2 to 4**					**> 20**	**70**
	Acceptance $[\mathrm{m}^2\mathrm{sr}]$	0.002	0.5					> 10	100
Calorimeters	Energy resolution (e and γ) @100 GeV [%]	5.5	3	10	2	1.5	< 1	2	< 1*
	Angular resolution (e and γ) @100 GeV [%]	0.3	0.3	0.1	0.2	0.1	< 0.1	< 0.1*	<0.01
	e/p discrimination	10^5	10^5	10^3	10^5	10^5	$> 10^6$	$> 10^5$	$> 10^5$*
	Depth $[X_0]$	16.3	**17**	8.6	**27**	**32**	**55**	**61**	**70**
	Acceptance $[\mathrm{m}^2\mathrm{sr}]$	0.06	0.09	1	0.12	0.3	> 3	9	30
Combined	Acceptance $[\mathrm{m}^2\mathrm{sr}]$	0.002	0.09					3	30

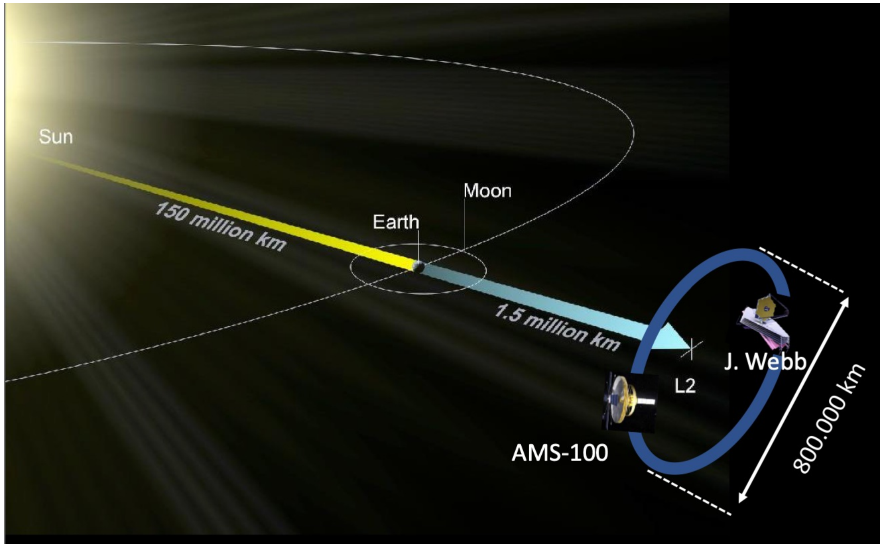
* Educated guess
Courtesy of Alberto.Oliva@bo.infn.it

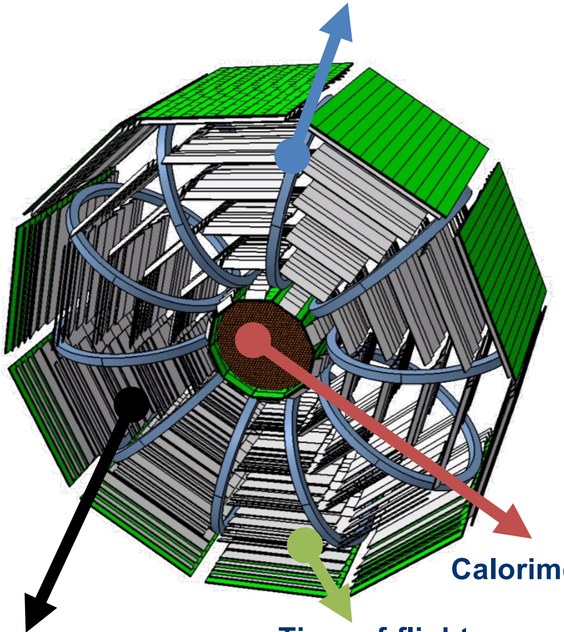
HTS: high temperature superconductive

ALADInO: Antimatter Large Acceptance Detector in Orbit

Physics objectives:
- Anti-nuclei
  - Anti-protons up to 10 TV
  - Anti-D, anti-He in GeV
- Nuclei spectra up to 1 PeV/n

Location	Lagrange Point L_2
Installation	> 2040 (pathfinder in 2030)
Dimensions	4.4 m (diameter) x 2m (length)
Mass	6.5 t
Launcher	Ariane 5 rocket



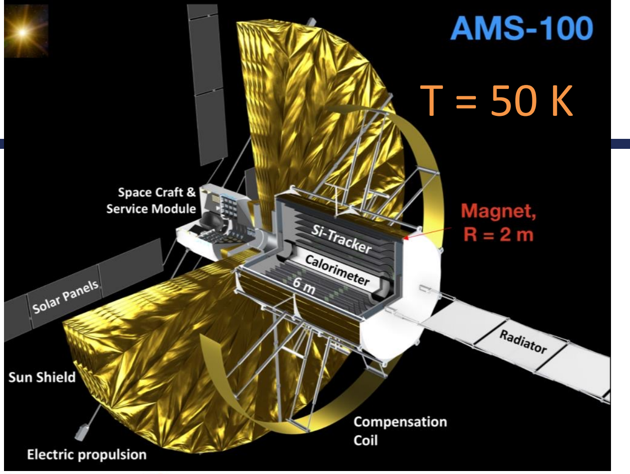


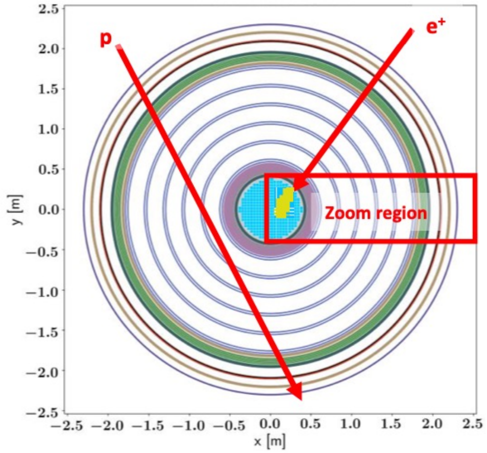
Lagrange Point is the most proper stable orbit to operate a superconducting magnet in space:
- No heat radiation from sun or earth
- Allows cryogenic experiments

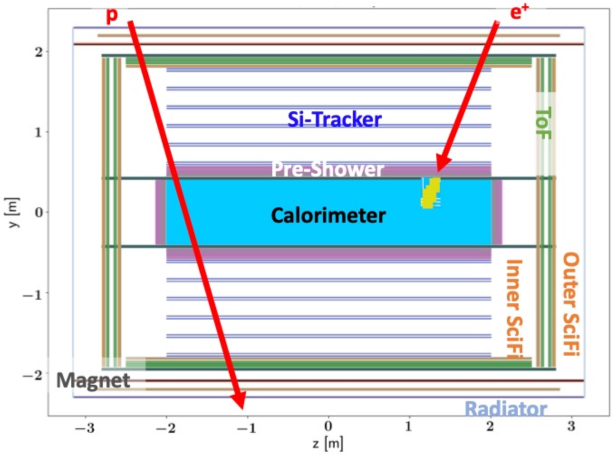
AMS-100

Physics objectives:
- Anti-nuclei
  - Anti-protons up to 10 TV
  - Anti-D, anti-He in GeV
- Nuclei spectra up to 1 PeV/n

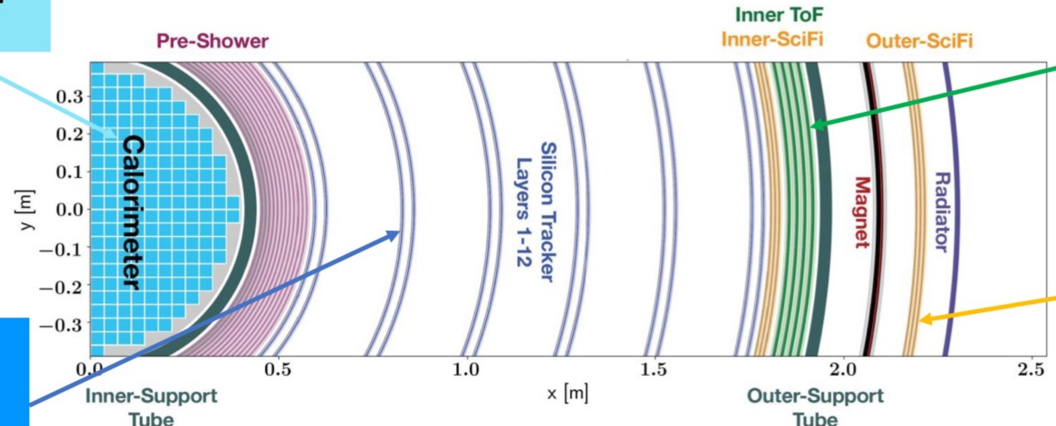
Location	Lagrange Point L_2
Installation	> 2040
Dimensions	4 m (diameter) x 6 m (length)
Mass	40 t
Launcher	SpaceX's starship rocket







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.

Question

Physics objectives:

- Anti-nuclei
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  - Anti-D, anti-He in GeV
- Nuclei spectra up to 1 PeV/n

How AMS-100 and ALADInO could measure nuclei spectra at PeV/n?

Question

Physics objectives:
- Anti-nuclei
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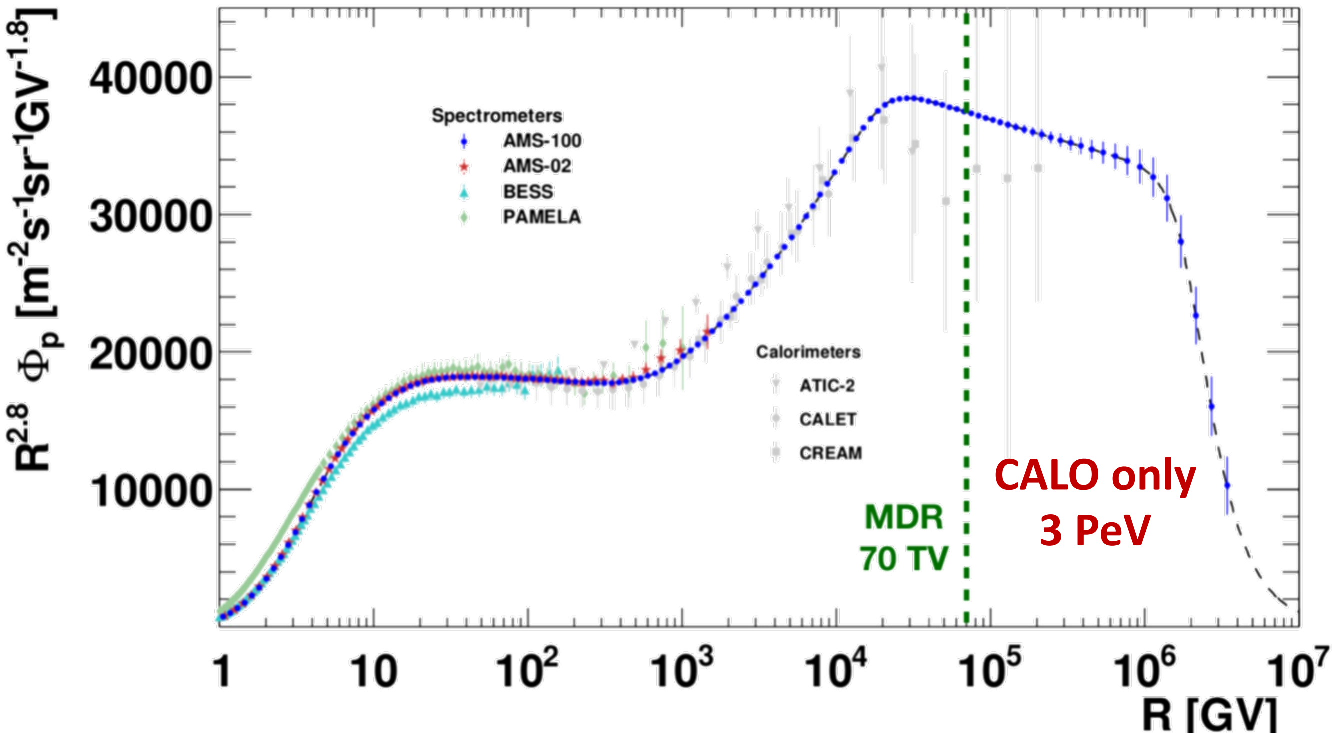
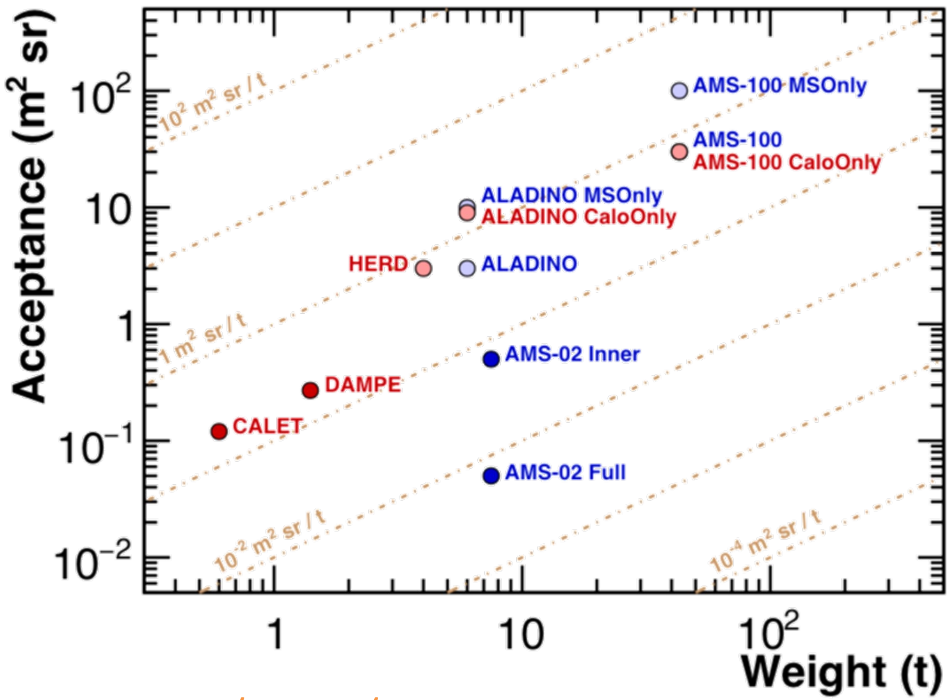
How AMS-100 and ALADInO could measure nuclei spectra at PeV/n?



Detector Acceptance and Mass



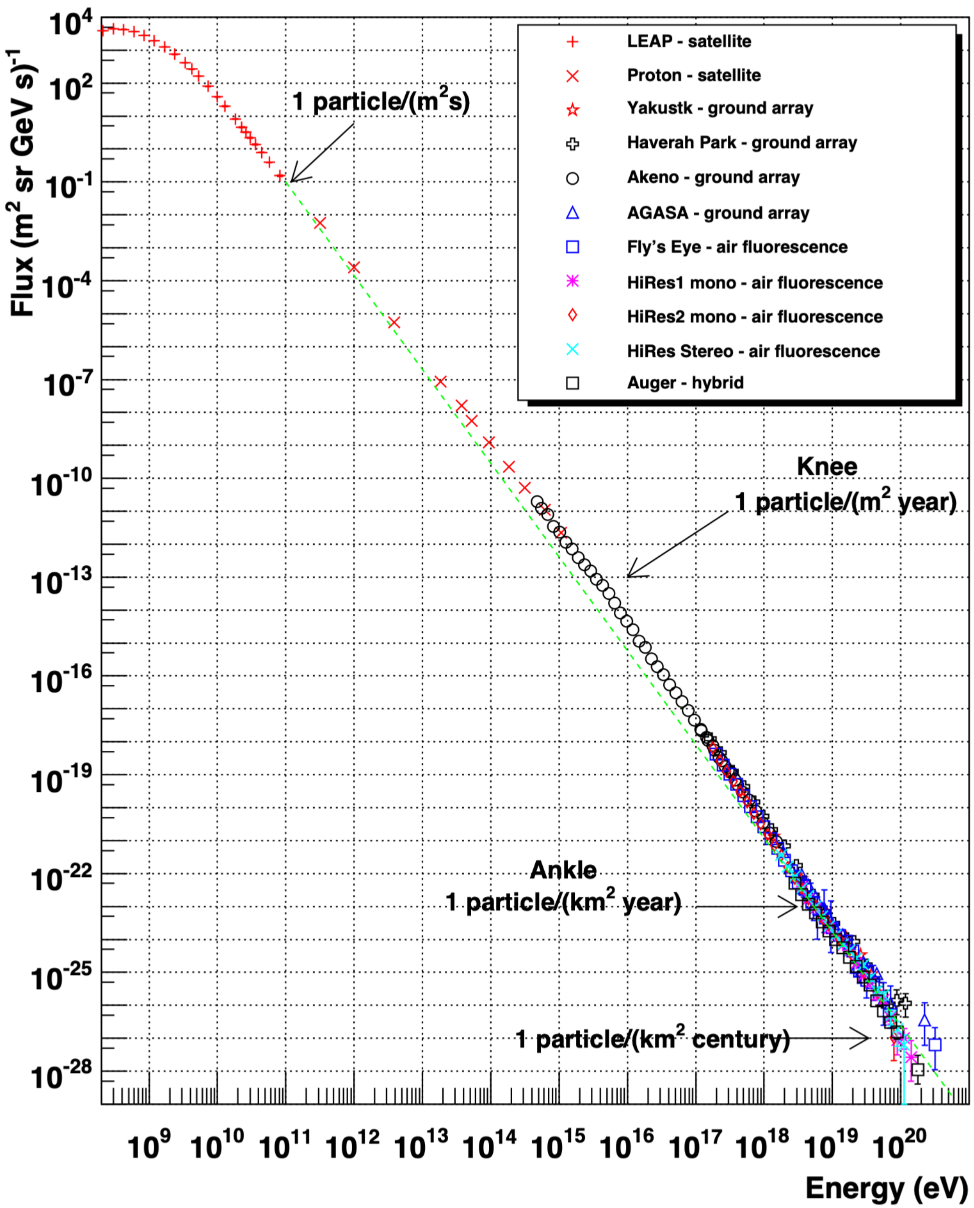
AMS-100 seminar @CERN (Nov 2022): https://indico.cern.ch/event/1210735/

MDR: AMS/ALADInO/AMS-100 = 2 TV / 20 TV / 70 TV

Calorimeter depth: AMS/CALET/DAMPE/HERD/ALADInO/AMS-100 = 17 X_0/27 X_0/31 X_0 /55 X_0 /61 X_0 /70 X_0

CALET @ISS: https://video.desy.de/video/Highlight-New-Results-from-the-first-5-years-of-CALET-observations-on-the-International-Space-Station/062e093a6184b0b1e8c7a3e95b5b0fa2

Direct vs. indirect detection of Cosmic Rays



For energies up to 10^{15} eV:

- **high flux**

→ Possible detection on top of the atmosphere (on balloons) or in space (on space stations or satellites)

For energies from 10^{15} eV:

- **Low flux**

→ Possible only detection on ground or underground.

When a cosmic ray (except for neutrinos) interacts with a nucleus of the high atmosphere many energetic particles are produced.

These particles **interact** with other nuclei or **decay** and a cascade of particles is produced: an Extensive Air Shower (EAS).

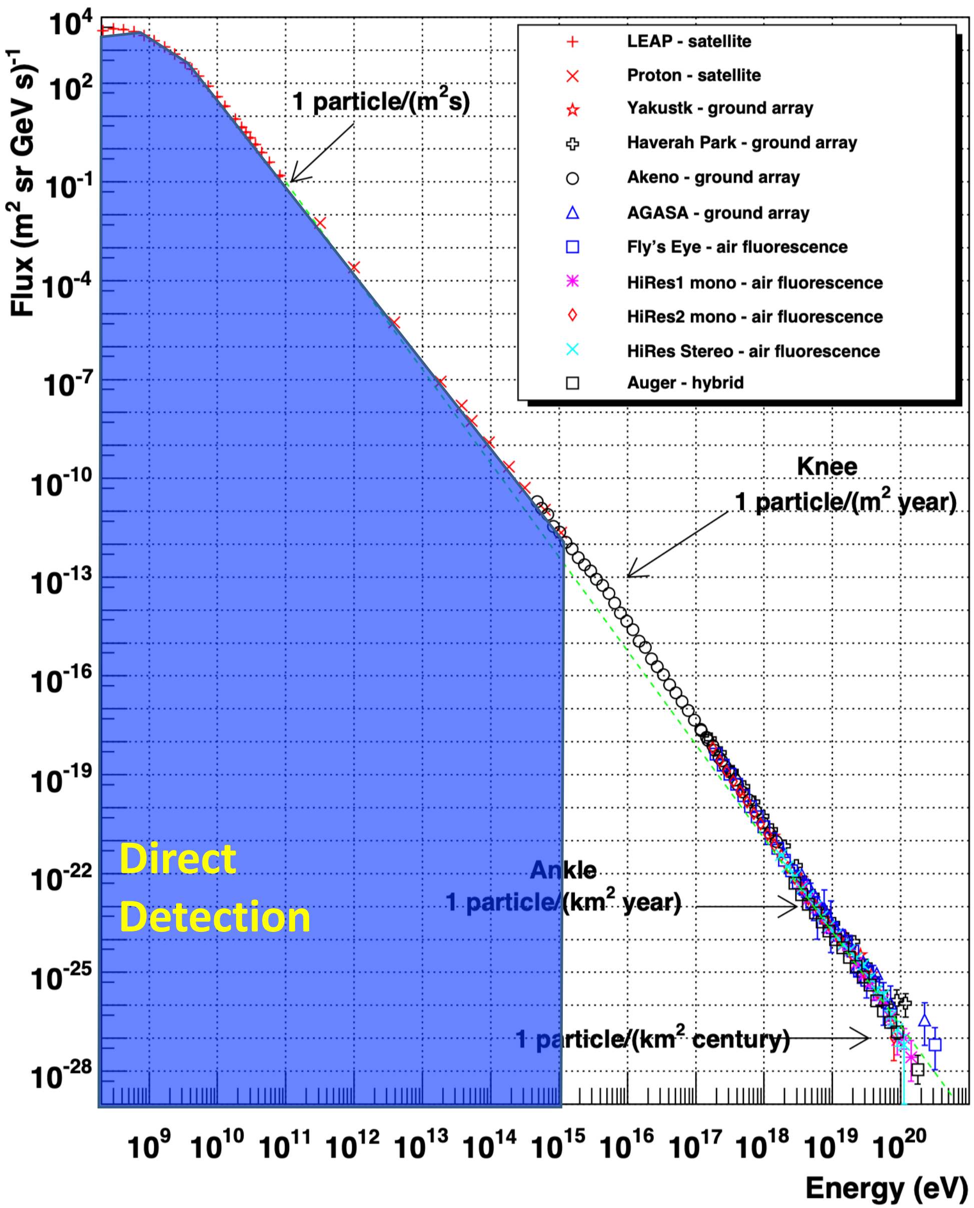
Direct Detection

- With "space-borne" or "direct" detection experiments

Indirect Detection

- With "ground-based" or "indirect" detection experiments or EAS arrays

Direct vs. indirect detection of Cosmic Rays



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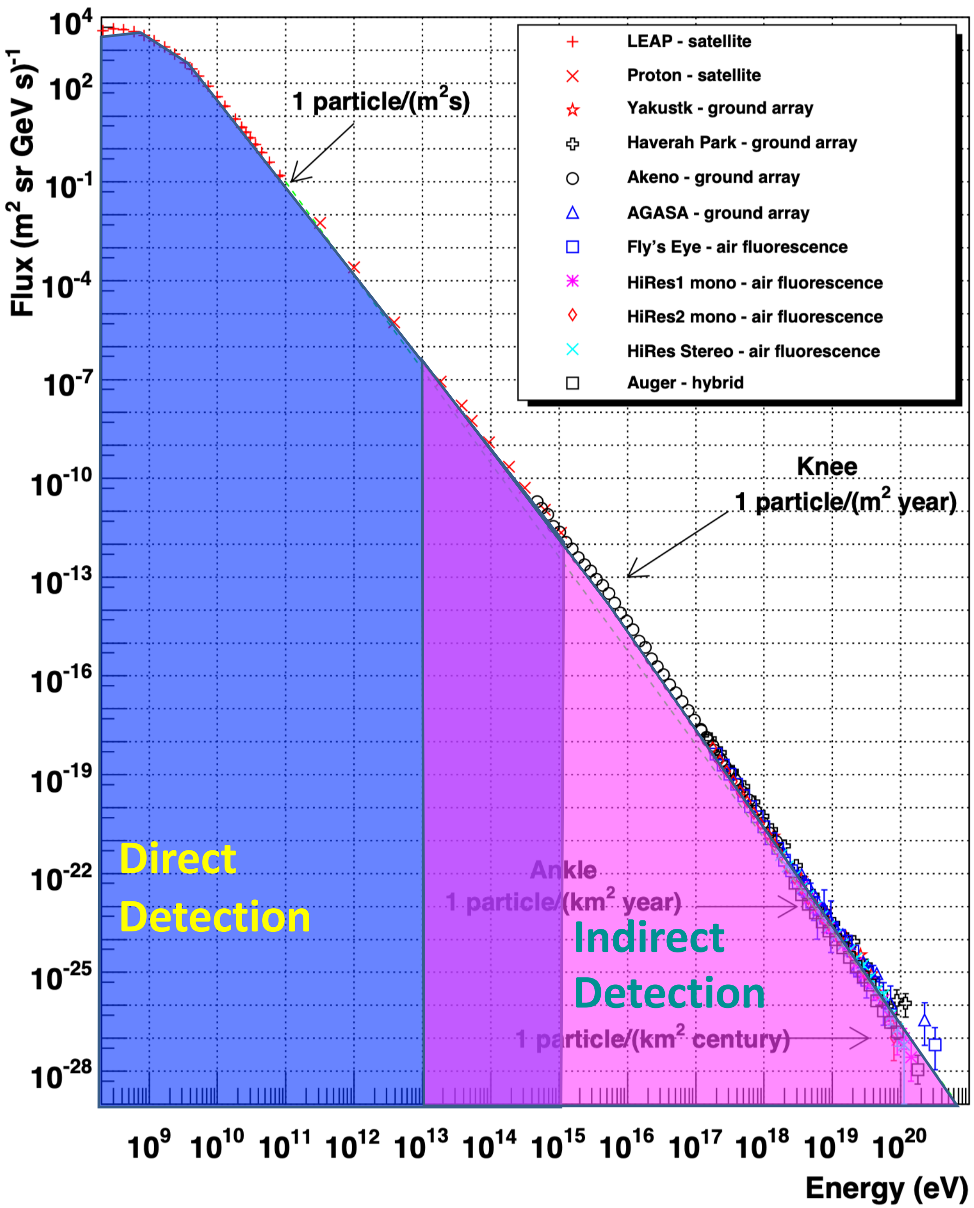

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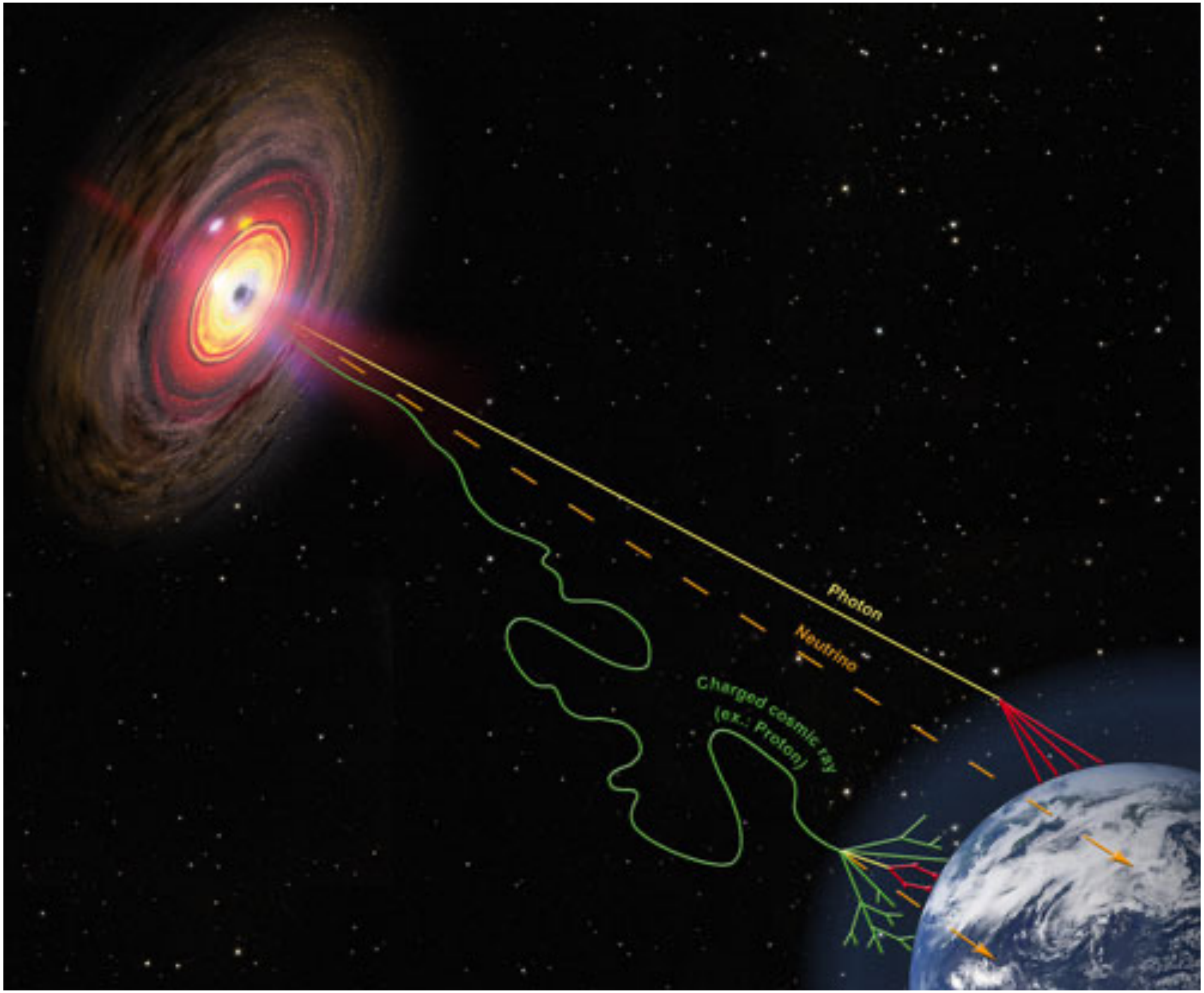
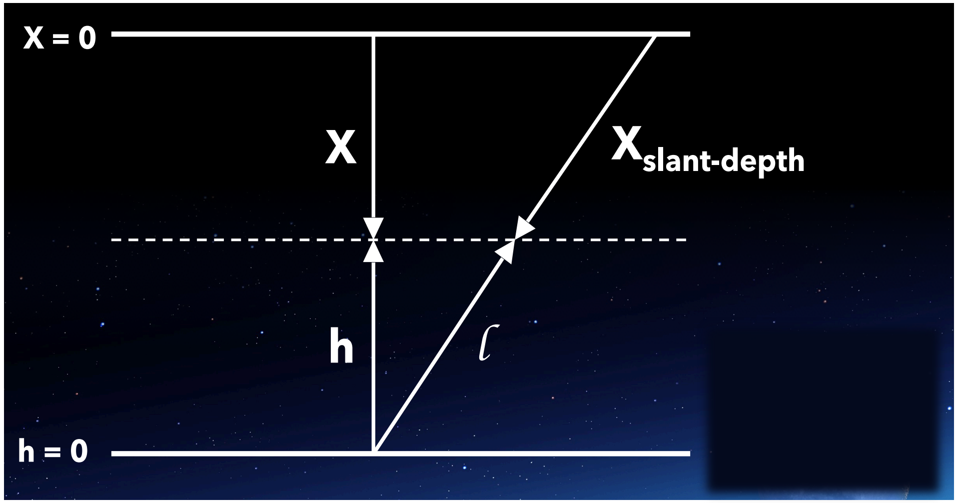
Ground-based experiments



Atmospheric depth and altitude



X: (vertical) atmospheric depth
X = 0: top of the atmosphere

$$X = \int_h^{\infty} \rho(h')\, dh'$$

h: altitude or height
h = 0: sea level

The pressure p (atmospheric weight per unit of area S) at the depth X is:

$$p = \frac{mg}{S} = \frac{g}{S}\int_h^{\infty} \rho(h')\, S\, dh' = gX$$

The atmospheric pressure at sea level, is ***p(h = 0)* = 1 atm = 101’325 Pa**
→ the depth at sea level is ***X(h = 0) = p(h = 0)/g* = 1’033 g/cm²**.

Extensive Air Showers

- https://pdg.lbl.gov/2023/AtomicNuclearProperties/index.html
  →Air (dry, 1 atm)

- The ***nuclear interaction length*** for hadrons in air is λ_{int} = 90.1 g/cm^2.

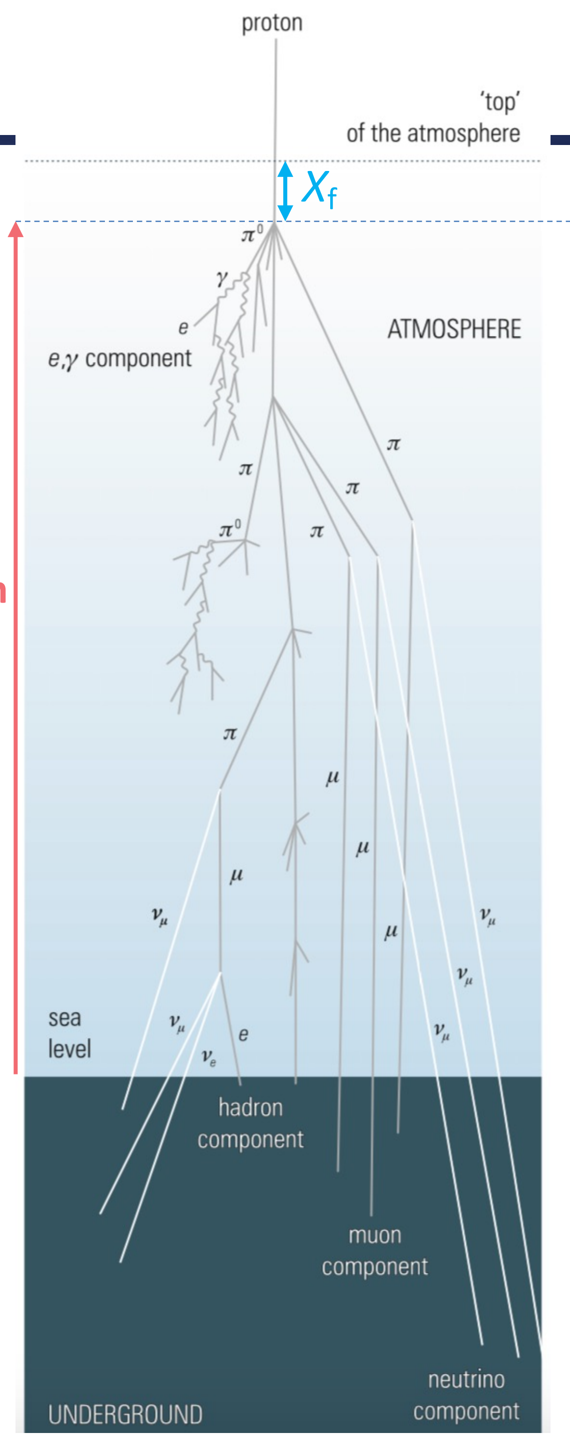
- The ***radiation length*** for photons and electrons in air is X_0 = 36.62 g/cm$^2 \simeq 1/3\ \lambda_{int}$.

The thickness of the atmosphere is ***$X(h = 0)$ = 1’033 g/cm^2***
→ It corresponds to 28 X_0 and 11 λ_{int}.

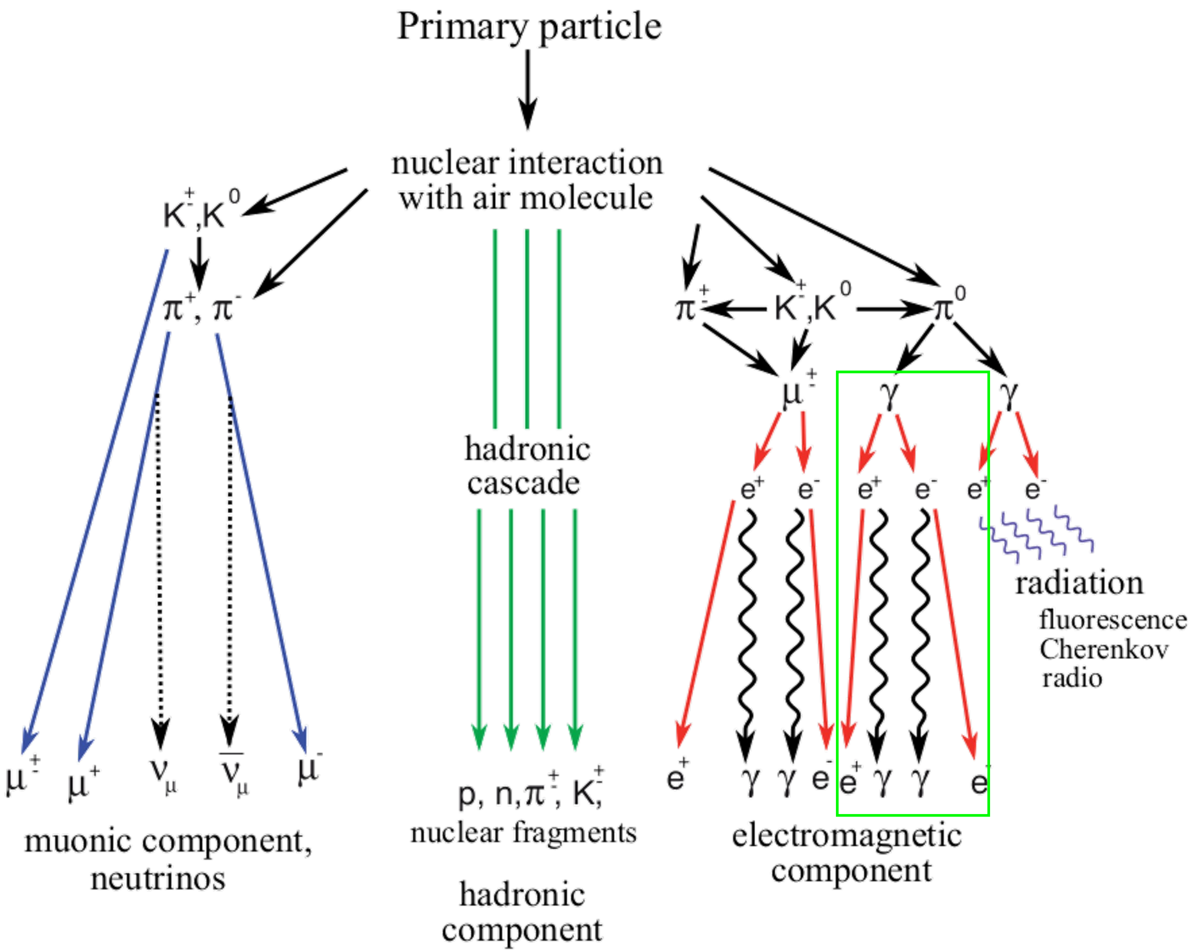
No one “original” cosmic ray arrives at the sea level.

At altitudes of 15 –20 km all cosmic rays interact with atomic nuclei of the air and start an Extensive Air Shower (EAS).

15 – 20 km



Development of an EAS (e.m. component from π^0)

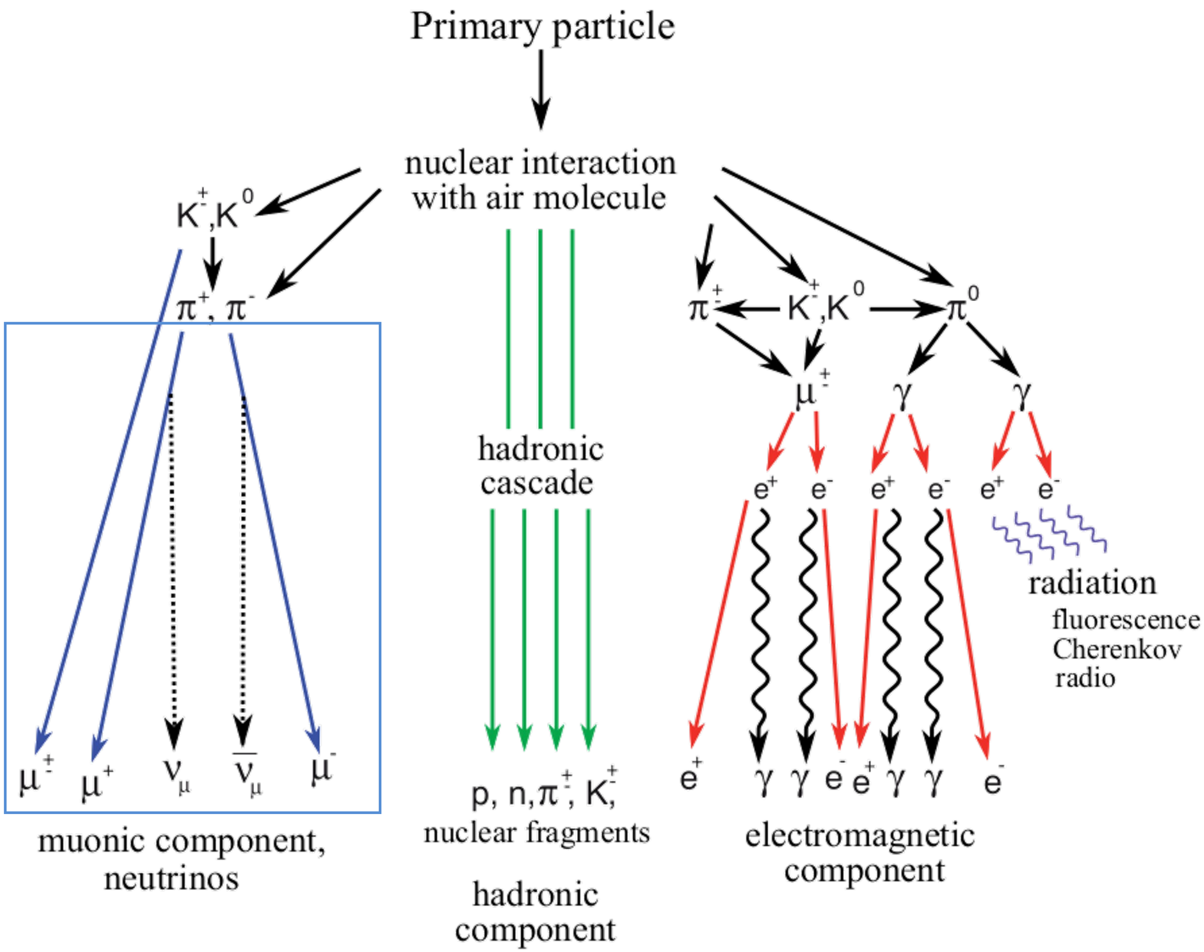


- Protons constitute the largest fraction of **primary** cosmic rays.
- The **secondary** particles most copiously produced are **pions**.
- **Kaons** are also produced but with a probability of 10% – 15% compared to pions.

Neutral pions start electromagnetic (e.m.) showers via the decay

$$\pi^0 \rightarrow \gamma\gamma$$

EAS (μ/ν comp., hadronic comp. & e.m. comp.)



Charged pions and kaons can decay or interact.
The competition between the decay and the interaction probability is a function of energy.

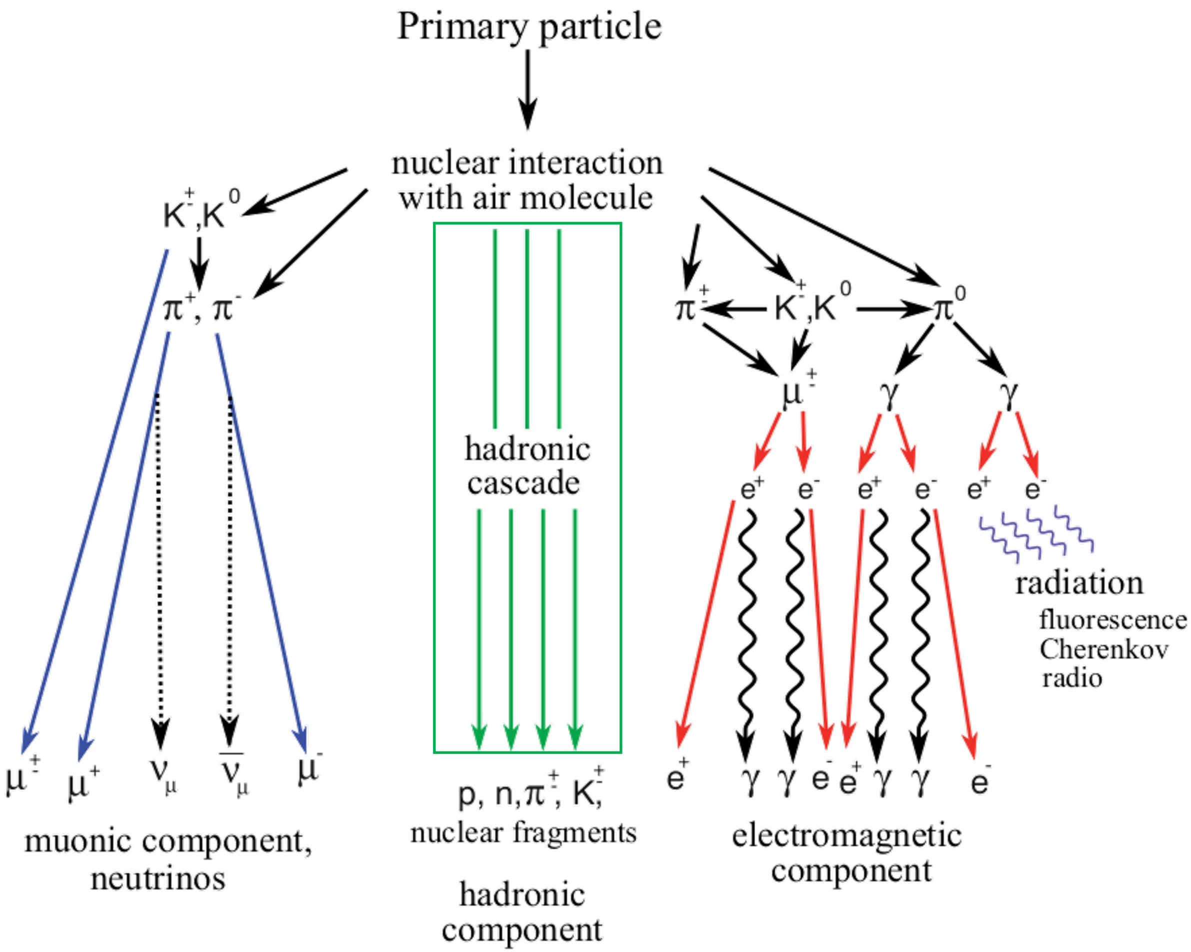
- lifetime (charged kaons) = 12 ns
- lifetime (charged pions) = 26 ns

For the same Lorentz factor: charged kaons have a larger decay probability compared to charged pions.

The leptonic decays of pions and kaons produce the penetrating muon and neutrino components.

The energy loss of relativistic muons not decaying in the atmosphere is low (~ 2 GeV). They constitute with 80% of all charged particles the largest fraction of secondary particles at sea level.

EAS (μ/ν comp., hadronic comp. & e.m. comp.)



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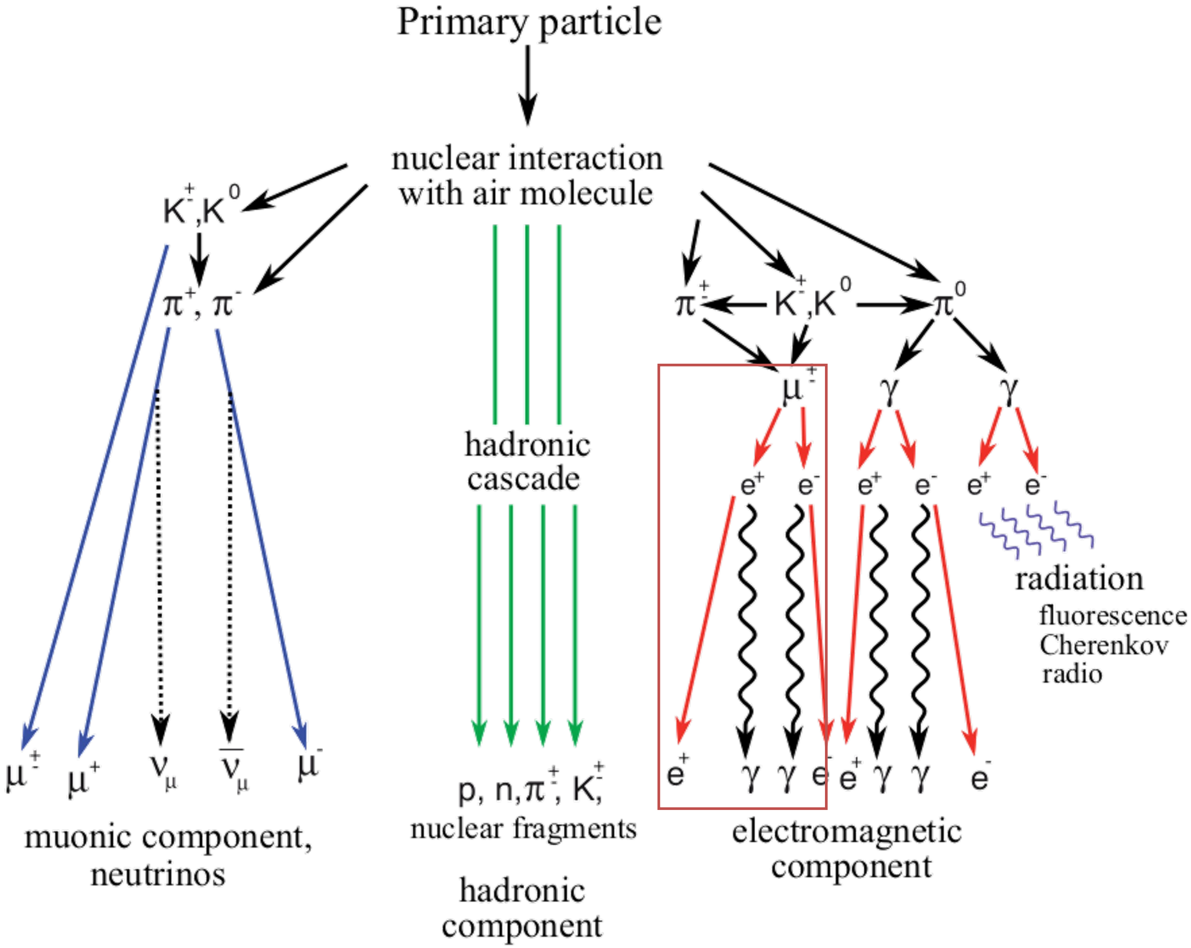

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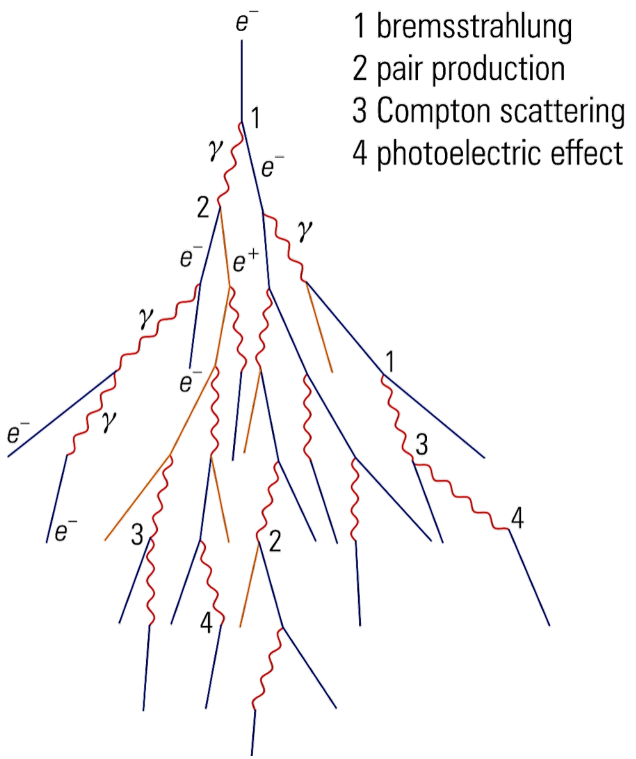
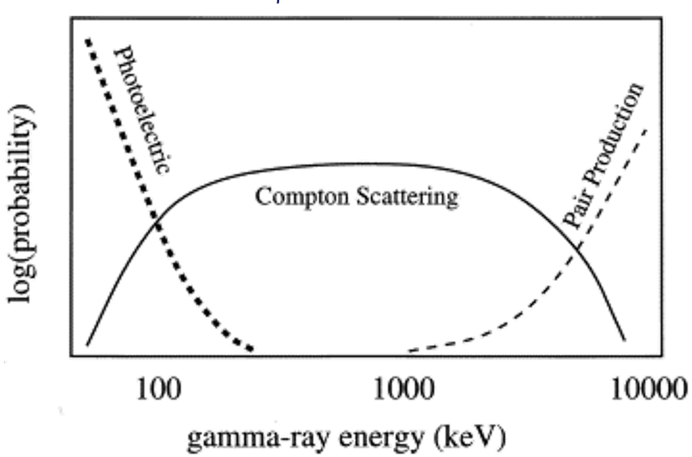
Muons can also decay and contribute via their decay electrons to the e.m. component.

Electromagnetic shower





> 5 MeV
Pair production

$$\gamma + (A,Z) \rightarrow e^+ + e^- + (A,Z)$$

Medium needed because of momentum conservation

100 keV - 5 MeV
Compton scattering

$$\gamma + e^- \rightarrow \gamma + e^-$$

The electron absorbs part of the energy of the incident photon, which therefore varies its frequency.

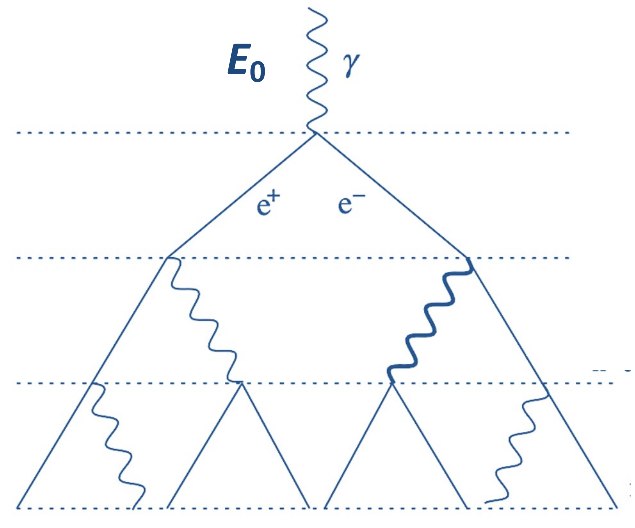
$$E'_\gamma = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos\vartheta)}$$

< 100 keV
Photoelectric effect

$$\gamma + (A,Z) \rightarrow e^- + (A,Z+1)$$

Not possible on a free electron because of momentum conservation

Electromagnetic shower (Heitler model)



1. Bremsstrahlung
2. Pair production
3. ~~Compton scattering~~
4. ~~Photoelectric effect~~

n	N	E	X

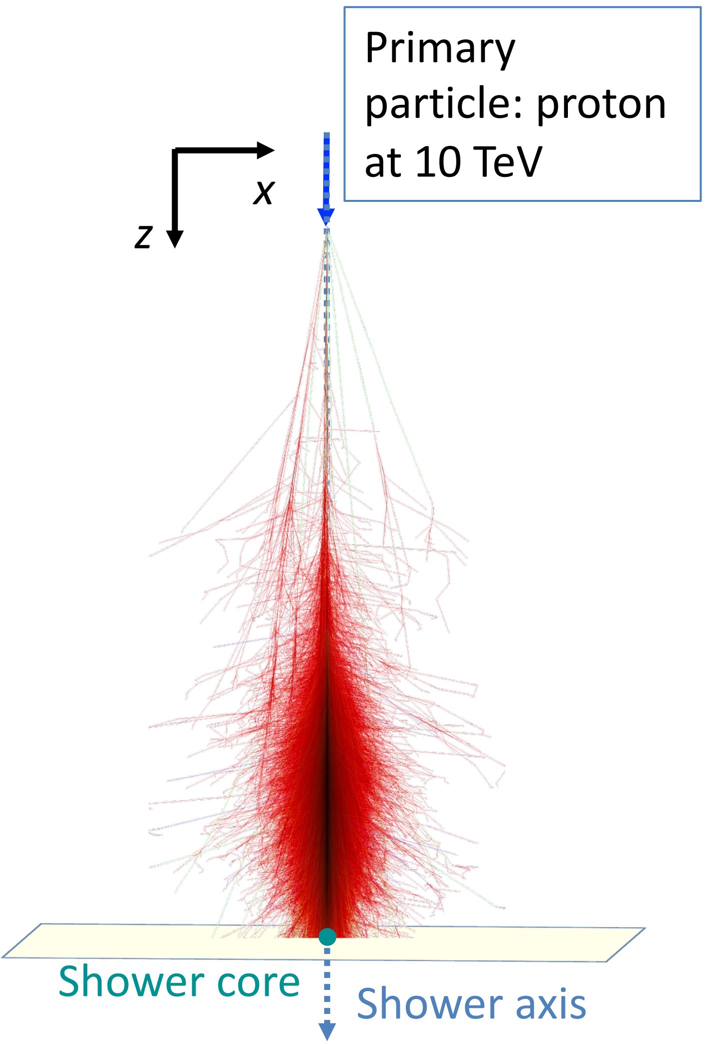
Process continues until the energy of the particles falls below the critical energy, E_c.

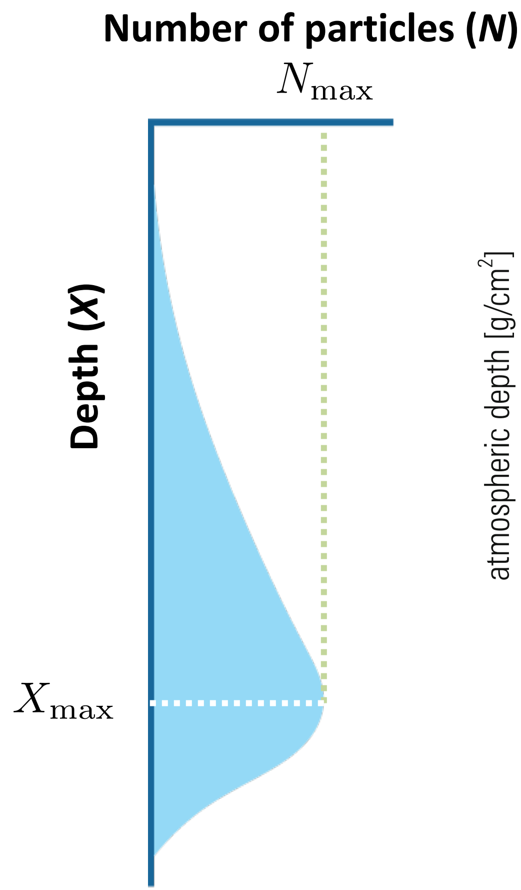
E_c is the value of E for which the losses due to the ionization equal those due to the bremsstrahlung.

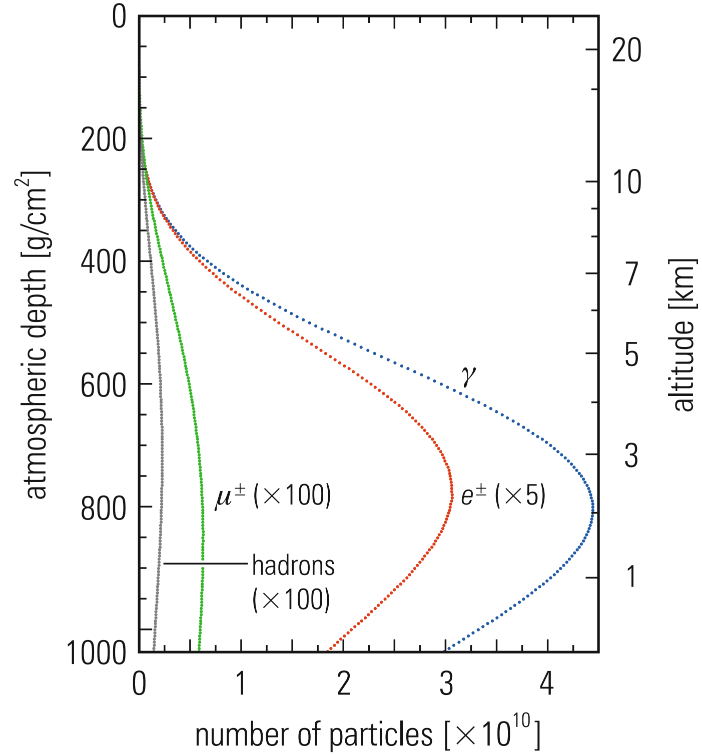
$$N_{\max} = \frac{E_0}{E_c}$$

3. The energy is equally distributed in the interaction products.
4. The mean free path for the bremsstrahlung and pair production process is the same: $X_{1/2} = \ln(2)\, X_0$.

Longitudinal profile







For a proton of 10^{19} eV as primary particle, simulated with CORSIKA-SIBYLL2.1.

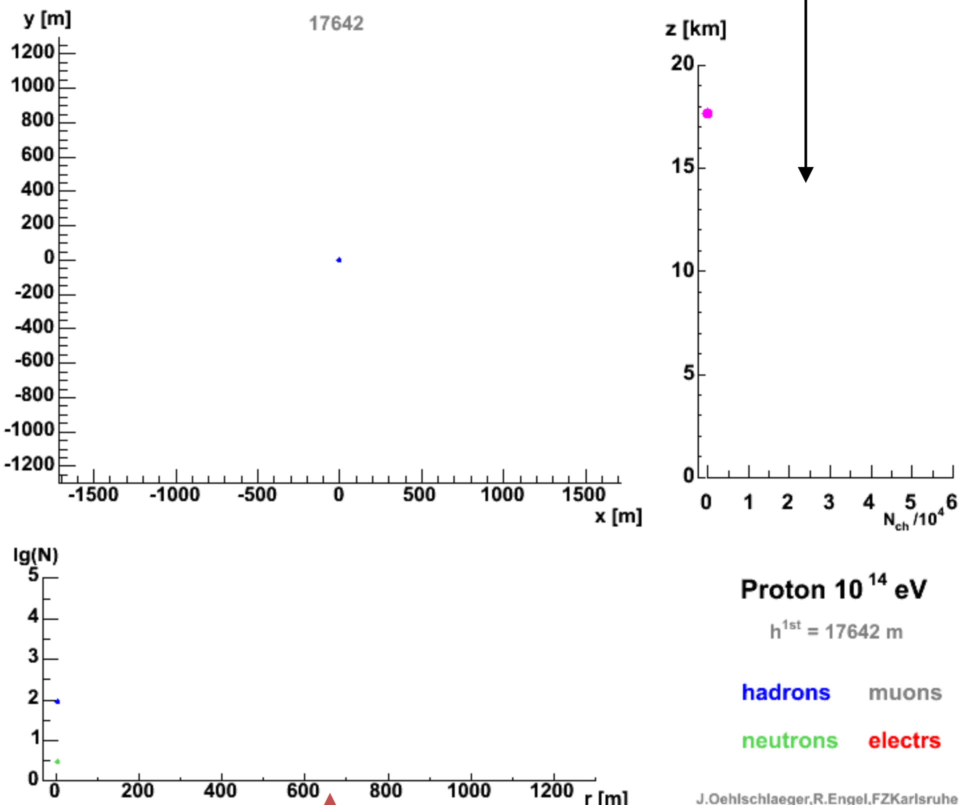
https://www.iap.kit.edu/corsika/index.php

Lateral profile

https://www.iap.kit.edu/corsika/index.php

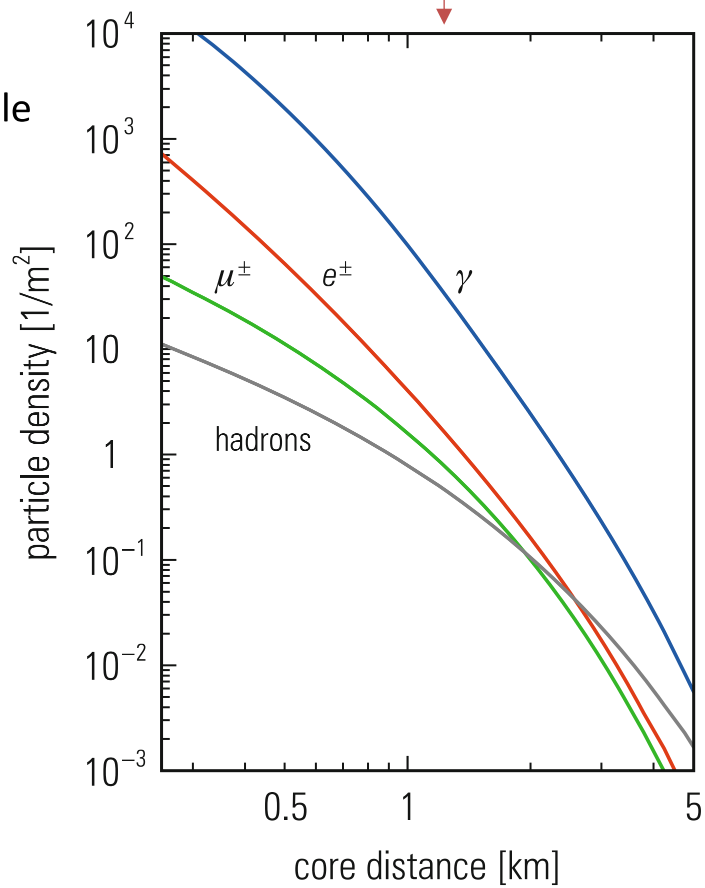
Primary particle: proton at 10 TeV

Longitudinal profile



Lateral profile

Lateral profile:



@ground level (of Auger) for a vertical proton of 10^{19} eV as primary particle, simulated with CORSIKA-SIBYLL2.1.

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