Particles and the Cosmos

2020/2021

Sascha Caron, Jörg Hörandel

NM109
first semester, 6 ec

28 hrs lecture	Tuesday	8:30 - 10:15
28 hrs problem session	Wednesday	10:30 - 12:15

Lectures:

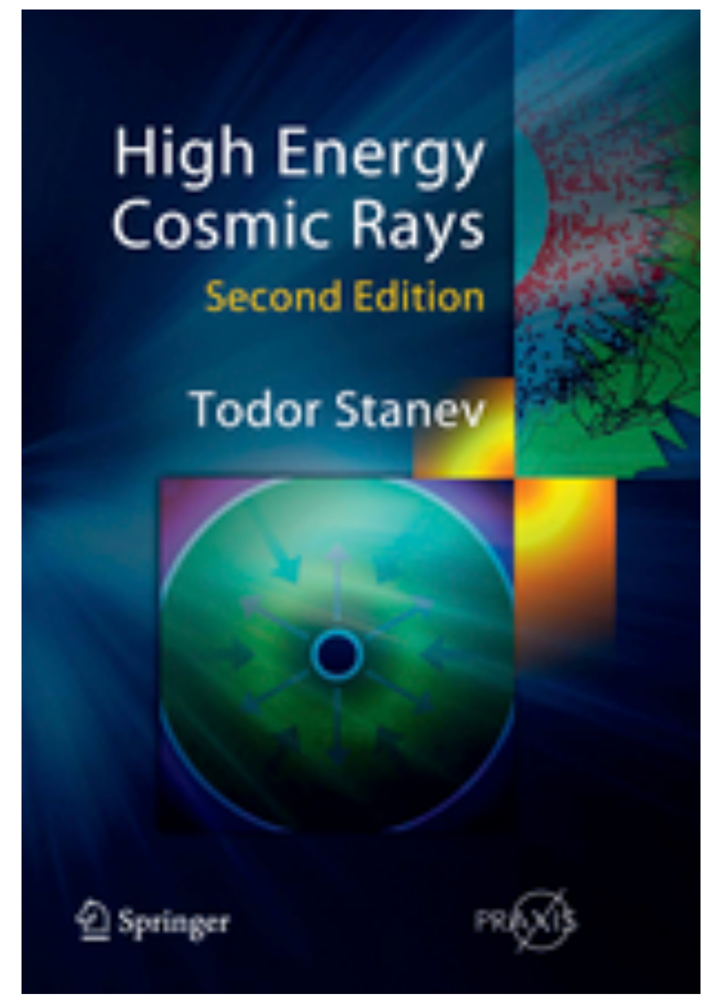
Experimental methods (JRH)
01.09.2020 1. Interactions with matter
08.09.2020 2. Detectors

Standard model (SC)
15.09.2020 3. Particles, QED, Feynman rules
22.09.2020 4. Hadrons and QCD
29.09.2020 5. Hadrons and QCD
06.10.2020 6. Weak interactions, CP violation
13.10.2020 7. Higgs mechanism

Astroparticle physics (JRH)
10.11.2020 8. The birth of cosmic rays
17.11.2020 9. Cosmic rays in the Galaxy, in the heliosphere, and the Earth magnetic field
24.11.2020 10. Cosmic rays at the top of and in the atmosphere
01.12.2020 11. Cosmic rays underground - neutrino oscillations
08.12.2020 12. Neutrino oscillations

Beyond the Standard Model, Dark Matter (SC)
15.12.2020 13. Lambda CDM, Big-bang nucleosynthesis
22.12.2020 14. Dark matter - Beyond-the-standard-model reasons

for Astroparticle Physics



Jörg R. Hörandel
HG 02.728
http://particle.astro.ru.nl

Interactions of particles with matter

electromagnetic processes

- Coulomb scattering
- Ionization loss
- Cherenkov light
- Bremsstrahlung

photon interactions

- Photo effect
- Compton scattering
- pair production

e/m collisions on magnetic and photon fields

- synchrotron radiation
- inverse Compton effect

hadronic interactions

- secondary particles, multiplicity, inelasticity
- nuclear fragmentation

Detectors and Experiments

Resolution

detectors for particles measure
- energy/momentum
- position
- time

the resolution characterizes the quality of a detector

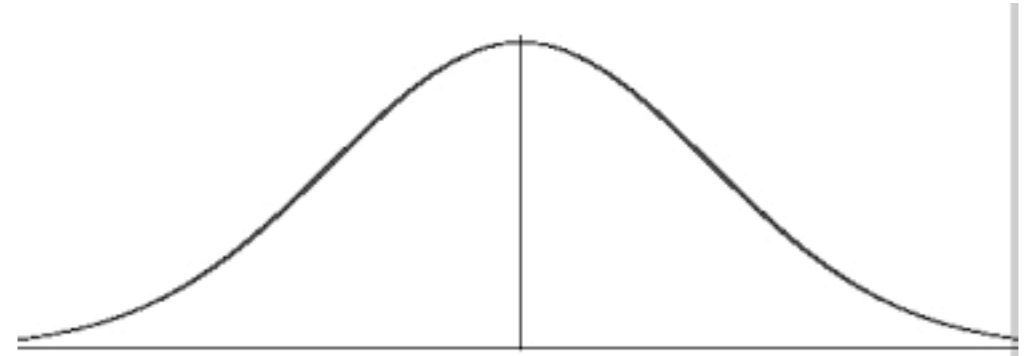
expected value: $\langle z \rangle = \dfrac{\int z \cdot D(z) dz}{\int D(z) dz}$ **distribution function *D(z)***

the variance of the measured value is

$$\sigma_z^2 = \frac{\int (z - \langle z \rangle)^2 D(z) dz}{\int D(z) dz}$$

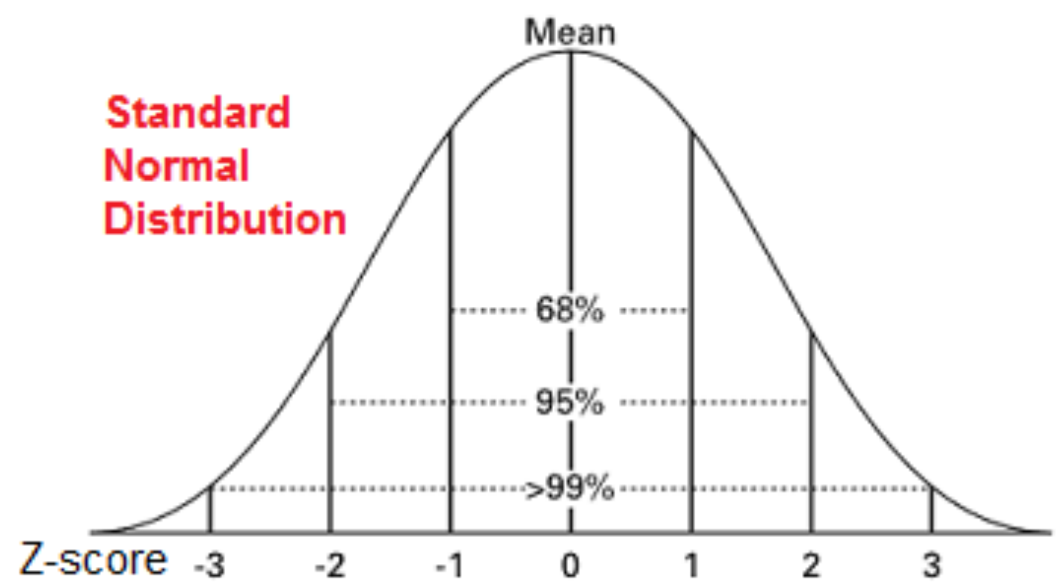
frequently the measured values follow a Gaussian distribution

$$D(z) = \frac{1}{\sigma_z \sqrt{2\pi}} \exp\left(-\frac{(z-z_0)^2}{2\sigma_z^2}\right)$$



the confidence interval gives probability that the measured value is within this interval

$$1 - \alpha = \int_{\langle z \rangle - \delta}^{\langle z \rangle + \delta} D(z) dz$$

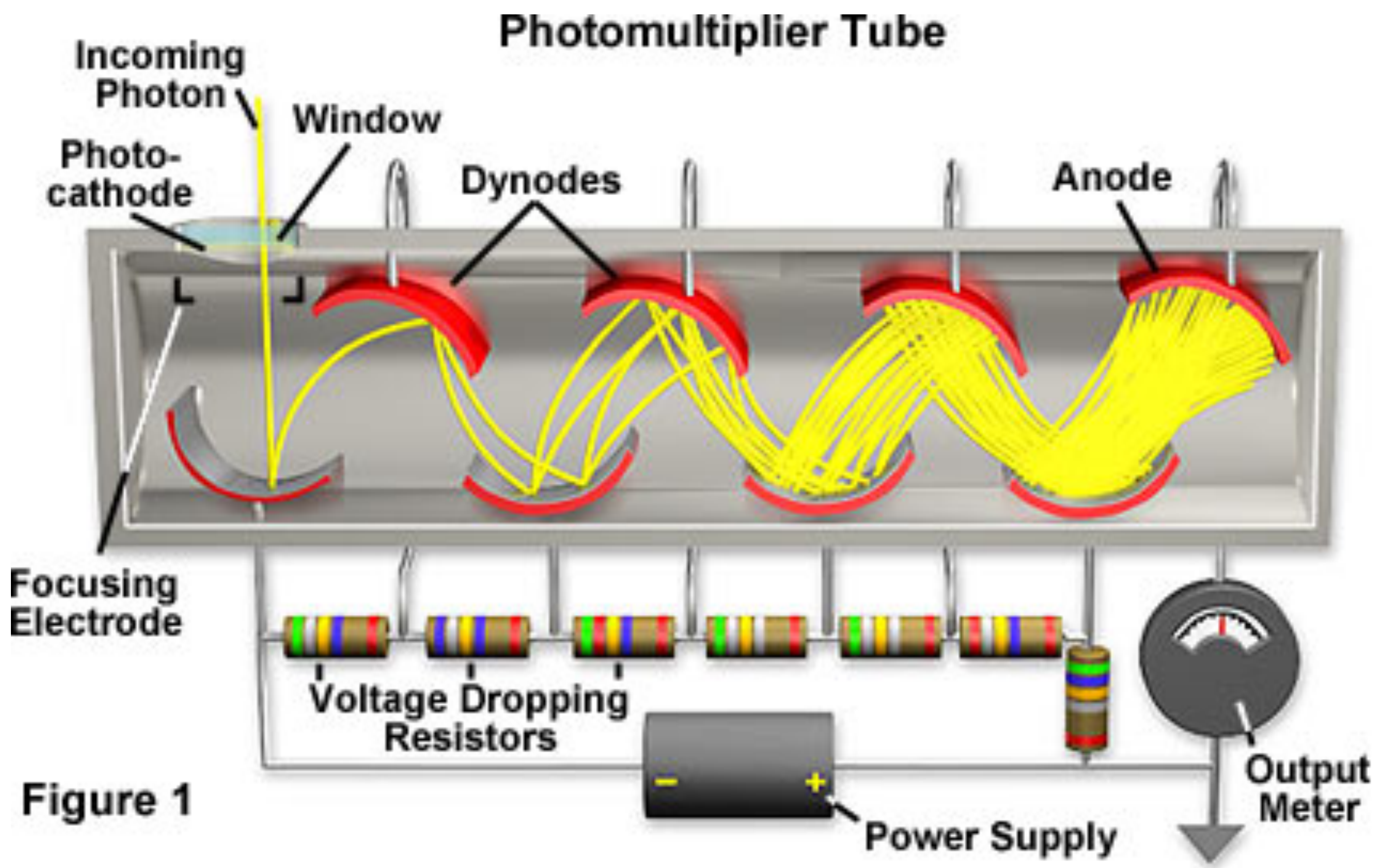


gives the probability that the true value z_0 is in the interval $\pm\delta$ around the measured value $\langle z \rangle$

$100 \cdot (1 - \alpha)\%$ **of the measured values are within** $\pm\delta$

$$1\sigma \rightarrow 1 - \alpha = 68.33\%$$

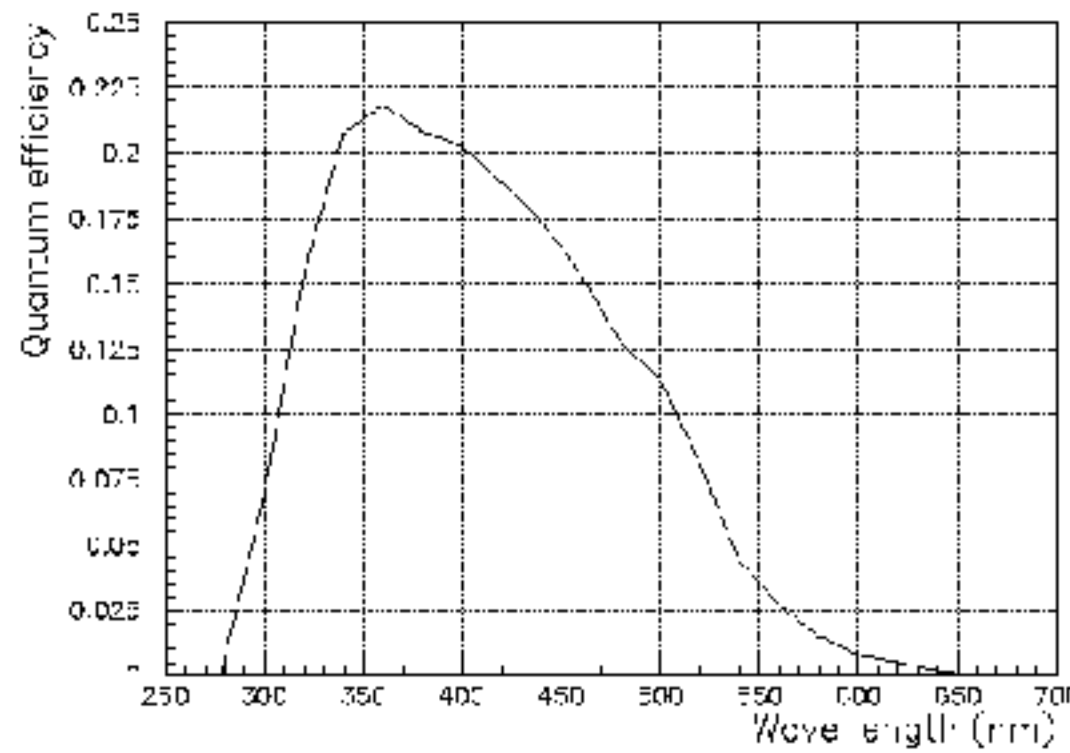
Photomultiplier



commonly used to detect fast signals

incident photons liberate electrons (photoelectric effect)
the electrons initiate an avalanche of secondary electrons --> amplification

quantum efficiency gives the number of photo electrons relative to the incident photons



amplification factor $A = p^{n-1}$

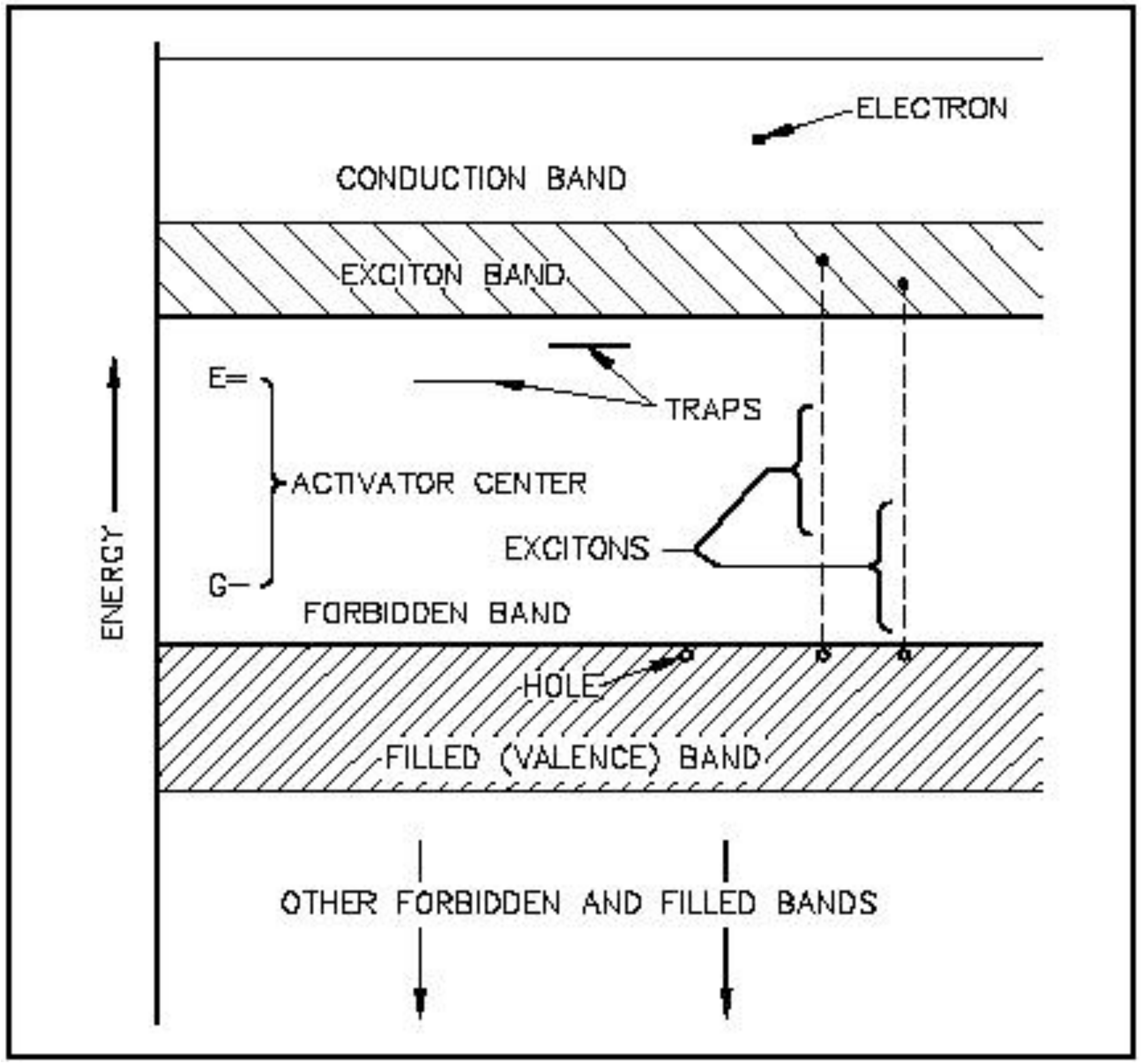
n-1 **dynodes**

p **emission coefficient for secondary electrons**

typical values *p=4, n=14* **-->** *A=7*10^7*

charge at anode: $Q = eA = 1.1 \cdot 10^{-11}\ \mathrm{Cb}$

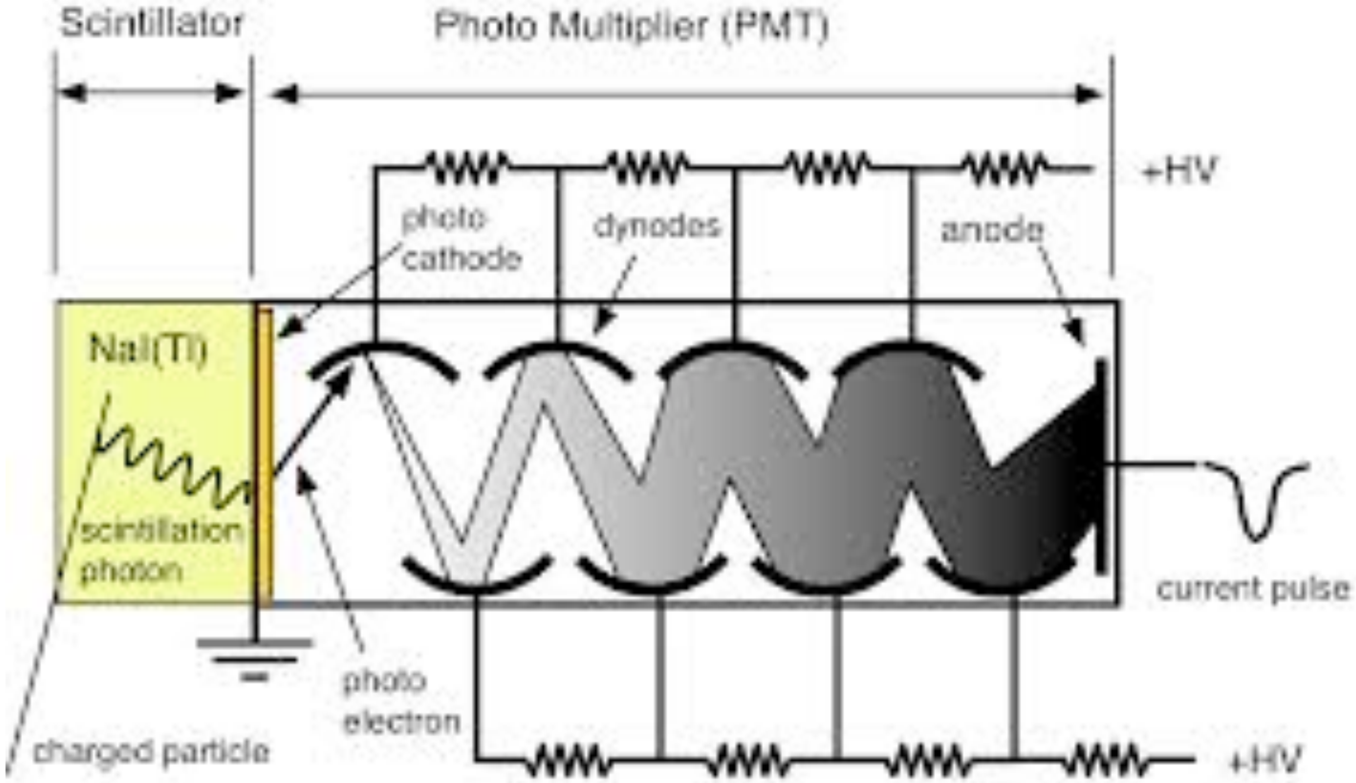
Scintillator



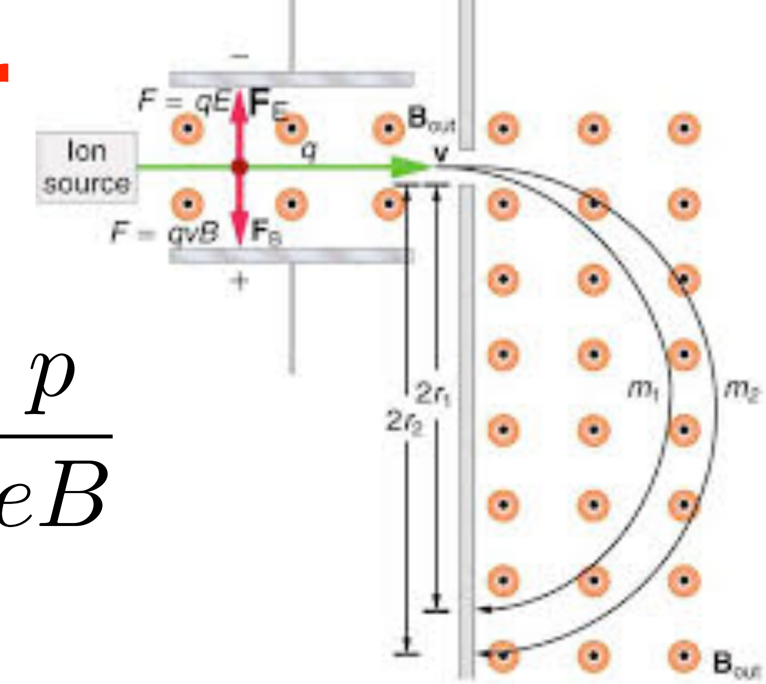
incident particles lift electrons from the valence band to the conduction band

recombination of (free) electron and hole --> emission of photon

typical yield ~10^3 to 10^4 photons/MeV



Magnetic spectrometer



momentum measurement

particle in magnetic field $$\frac{mv^2}{\rho} = evB$$ **and** $$\rho = \frac{p}{eB}$$

deflection angle ($\rho >> L$) $$\theta = \frac{L}{\rho} = \frac{L}{p} eB$$

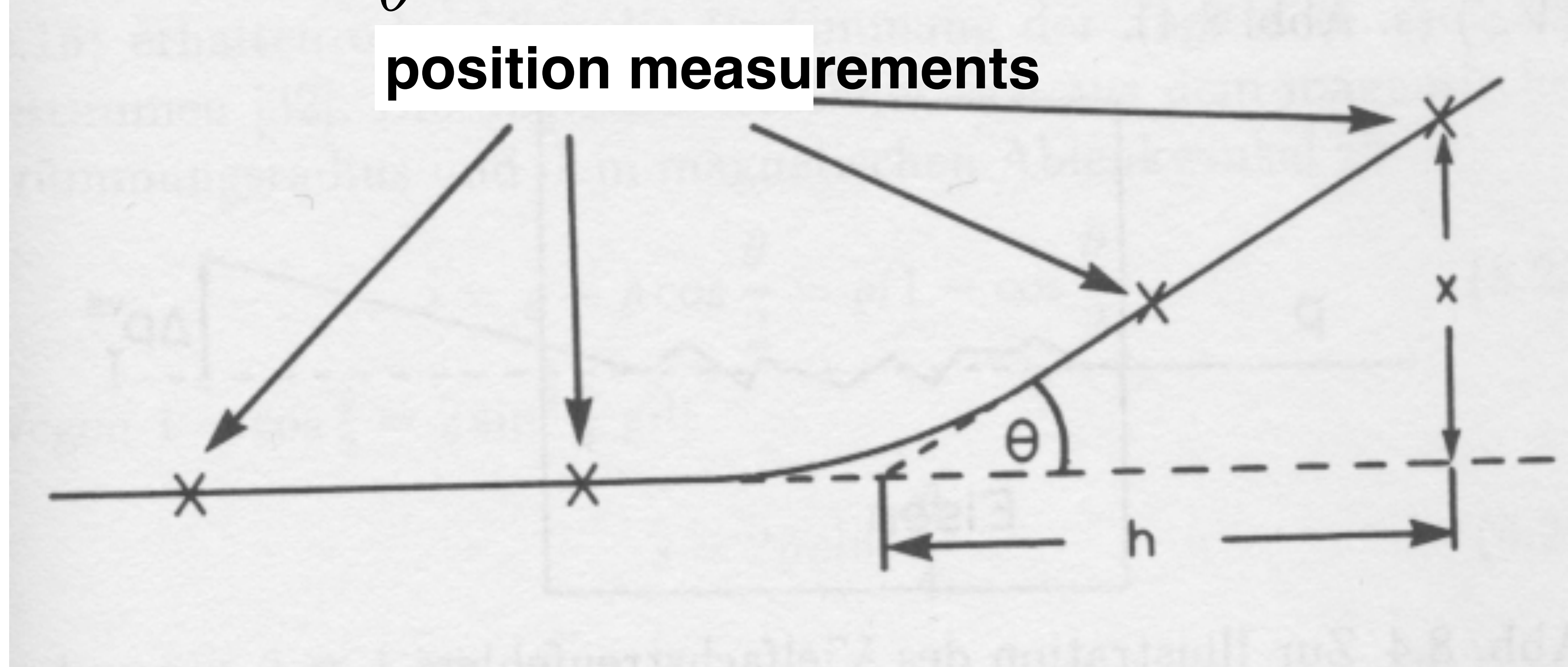
measured momentum $$p = eB\rho = eB\frac{L}{\theta}$$

$$\left|\frac{dp}{d\theta}\right| = eBL\frac{1}{\theta^2} = \frac{p}{\theta}$$

momentum resolution

$$\frac{\sigma(p)}{p} = \frac{2\sigma(x)/h}{eBL}p$$

$$\sigma(p) \propto p^2$$



maximum momentum: $$\frac{\sigma(p_{max})}{p_{max}} = 1$$

Cherenkov detector

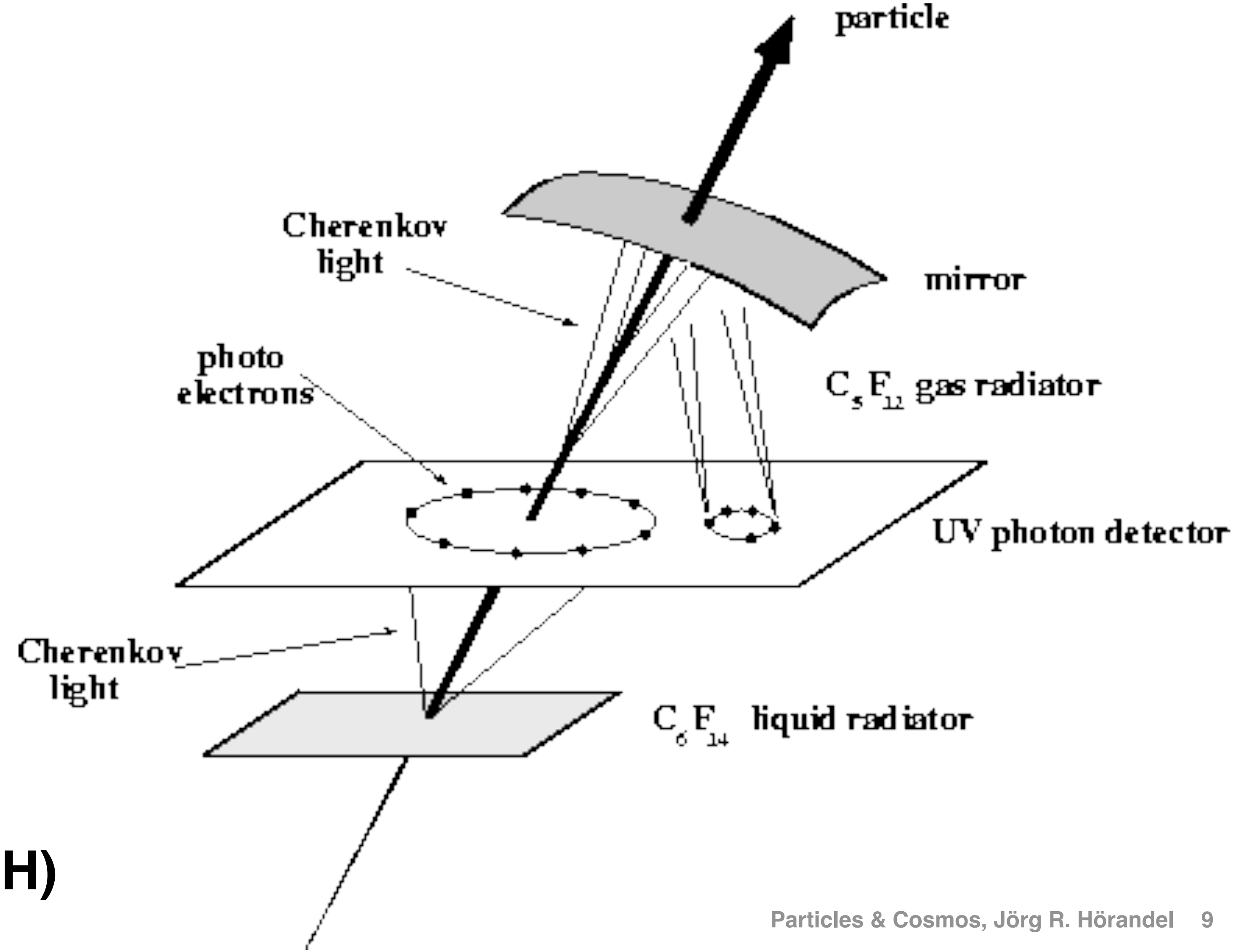
- **particle identification**
  threshold detector

$$\gamma_{th} = \frac{1}{\sqrt{1-\frac{1}{n^2}}} = \frac{E_{th}}{m_o c^2}$$

select material with appropriate *n*
--> light particles radiate

- **measurement of velocity**
  (kinetic energy)

$$\cos\theta_c = \frac{c}{n\beta c} = \frac{1}{n\beta}$$



ring imaging Cherenkov detector (RICH)

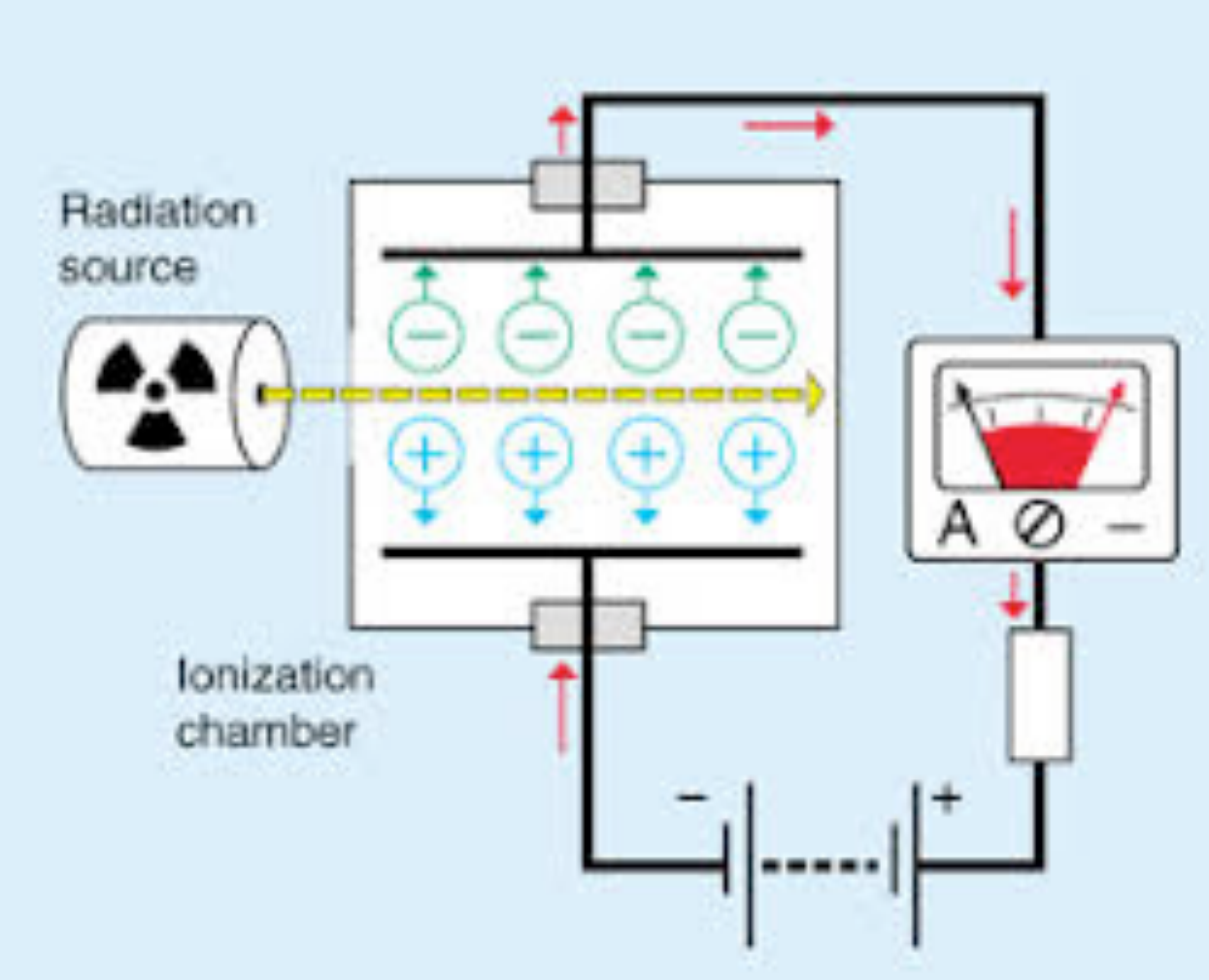
Ionization chamber

traversing particle liberates electrons (ionization)

electrons and (positive) ions drift in electric field

--> electric signal proportional to energy loss

thin chamber --> dE/dx
thick chamber --> total E
(particle completely absorbed)



energy in electric field reduced through free charge carriers

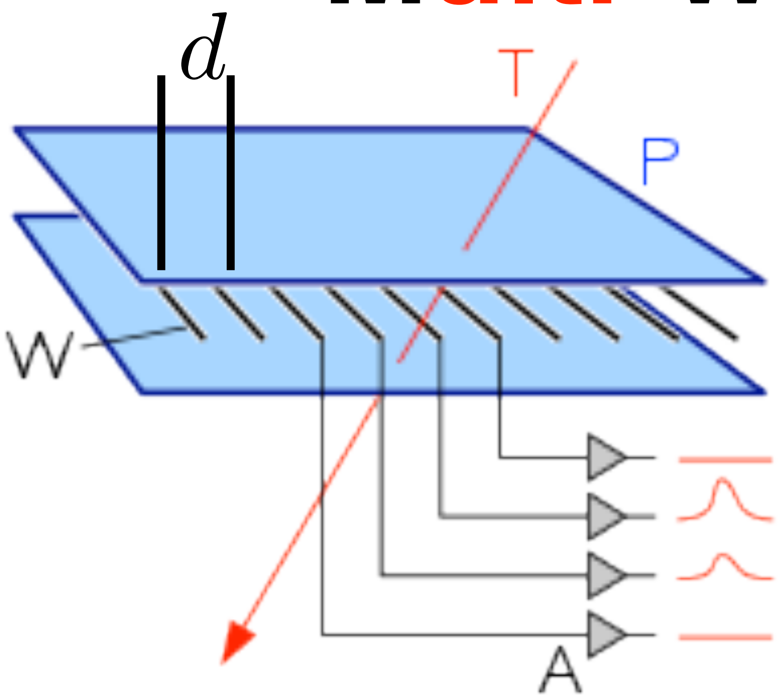
$$\frac{1}{2}CU^2 = \frac{1}{2}CU_0^2 - N\int_{x_0}^{x} qE dx$$

capacitor charged to U_0
N charge carrier pairs

only small voltage change $U + U_0 = 2U_0 \quad \text{and} \quad U - U_0 = \Delta U \quad \text{and} \quad E = U_0/d$

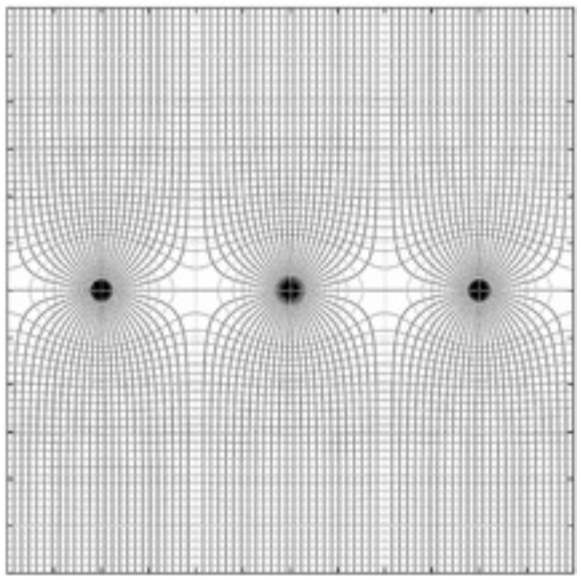
signal amplitude $\Delta U = -\frac{Nq}{Cd}(x - x_0)$ proportional to liberated charge and deposited energy

Multi-Wire Proportional Chamber



spatial resolution

$$\sigma(x) = \frac{d}{\sqrt{12}}$$

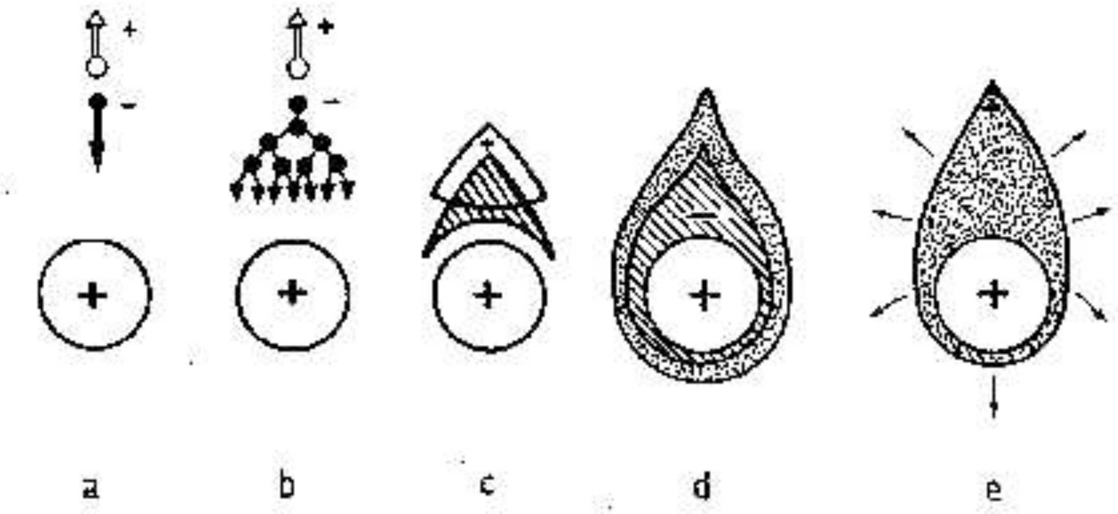


electric field

ionization liberates electrons
--> acceleration in electric field

energy gain between to electron collisions

$$\Delta E_{kin} = -e \int_{r_1}^{r_2} E(r) dr$$



if energy gain is larger than ionization energy

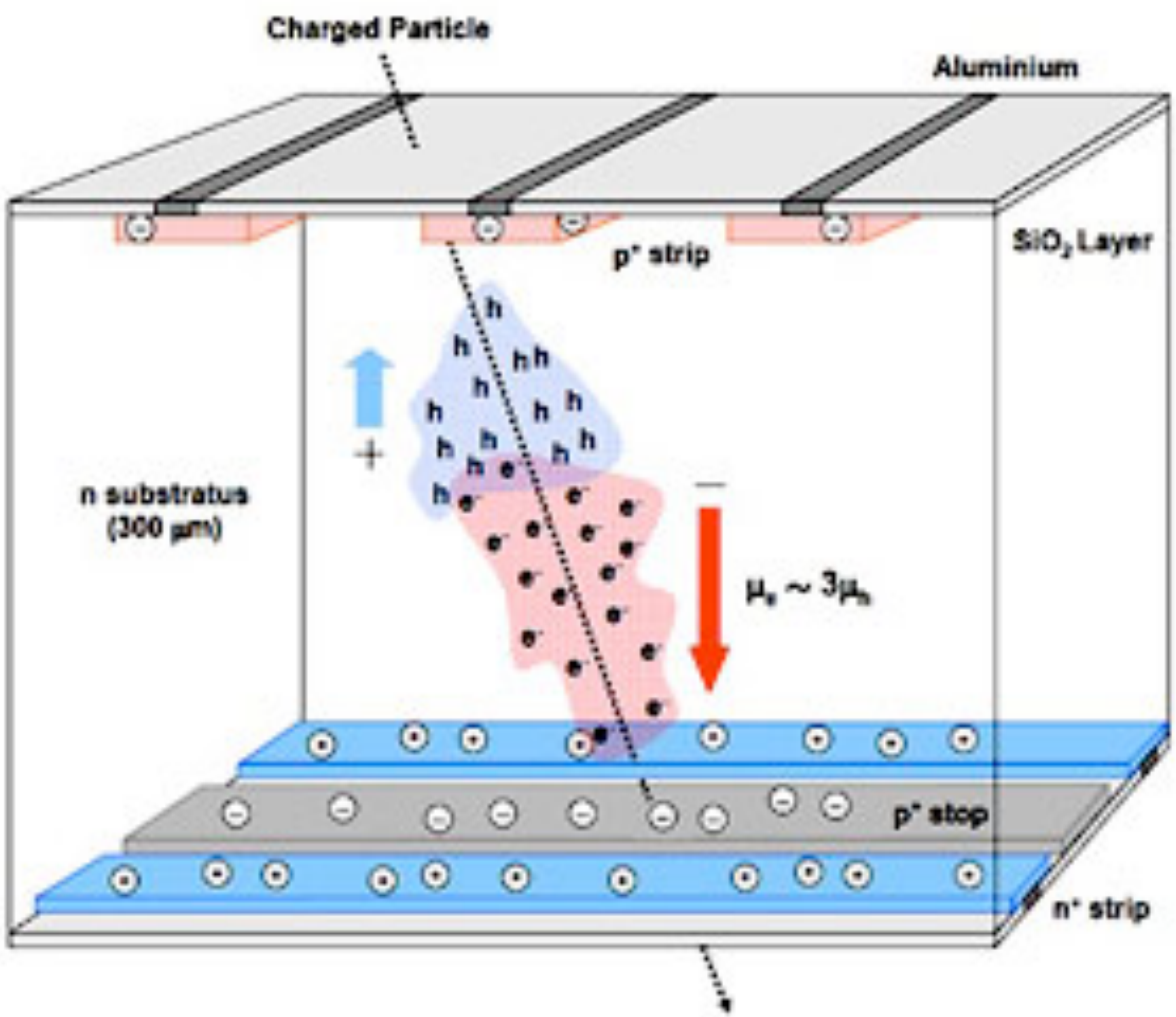
--> development of electron avalanche

voltage signal $\Delta U = -\frac{eN}{C} A$

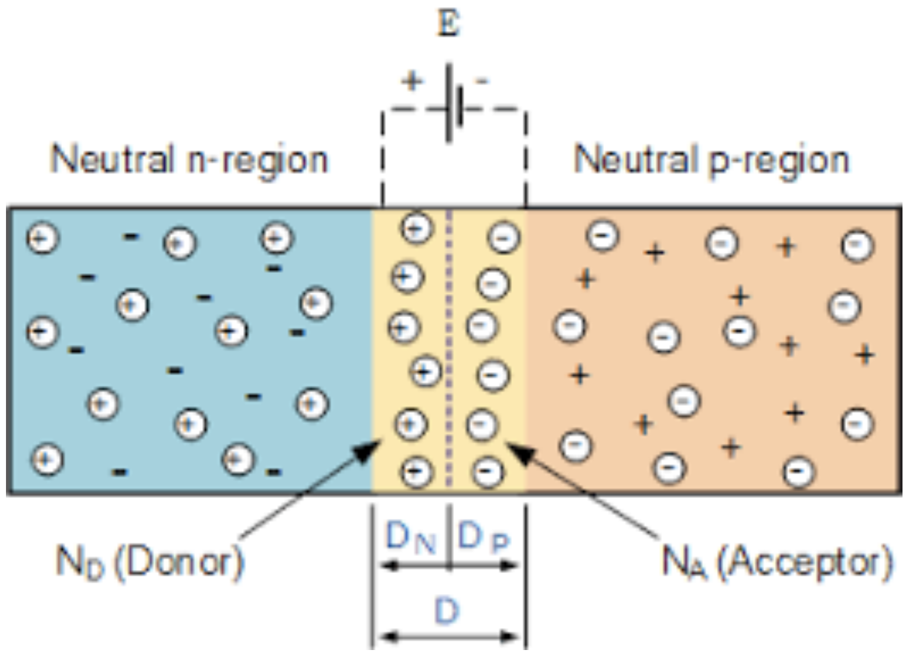
A **gas amplification factor**
N **charge carrier pairs**
C **capacity**

Energy measurement - silicon detector

for particles with MeV energies



p-n semiconductor



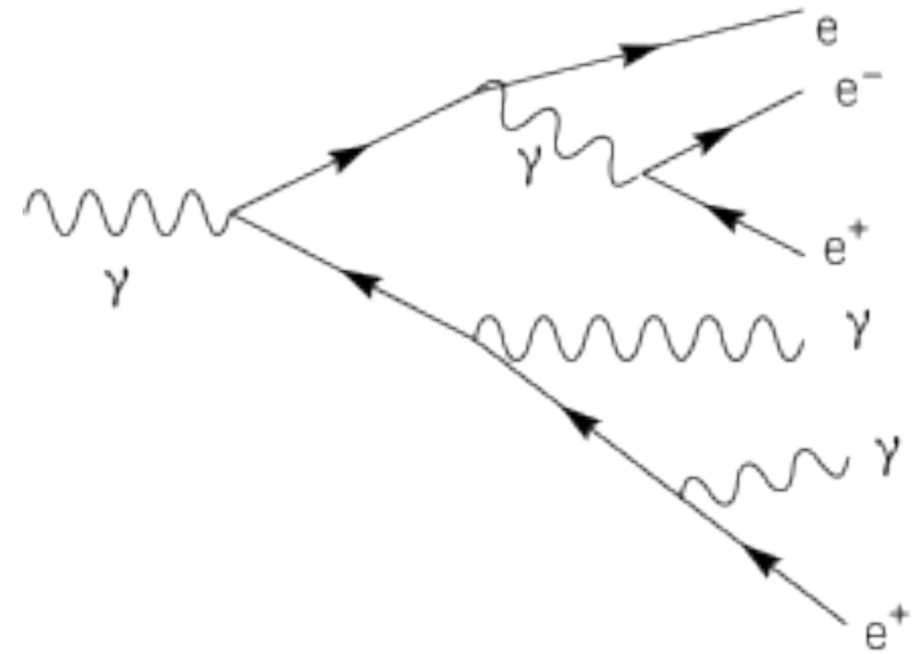
an incident particle generates a series of electron-hole pairs

--> in secondary processes further electron-hole pairs are generated and phonons are excited

--> high charge density along trajectory of 10^{15} to 10^{17} electrons/cm^3

Energy measurement - calorimeter

electron-photon calorimeter



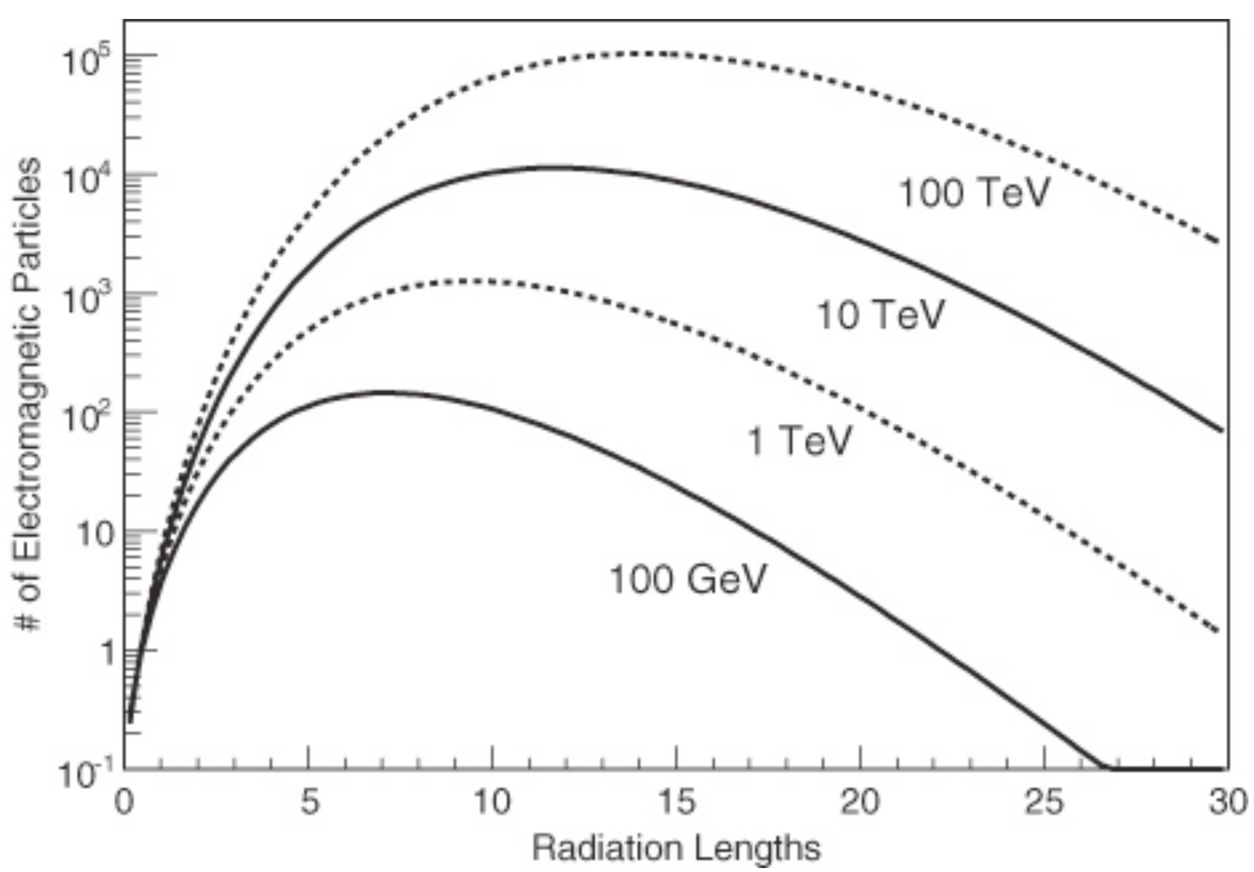
at high energies (>GeV):
electrons loose energy through Bremsstrahung
photons loose energy through pair production
--> electromagnetic cascade

longitudinal shower development/energy loss

$$\frac{dE}{dt} = const \cdot t^a e^{-bt}$$

$$t = x/X_0$$

depth in material in units of the radiation length



depth of maximum depends on energy as

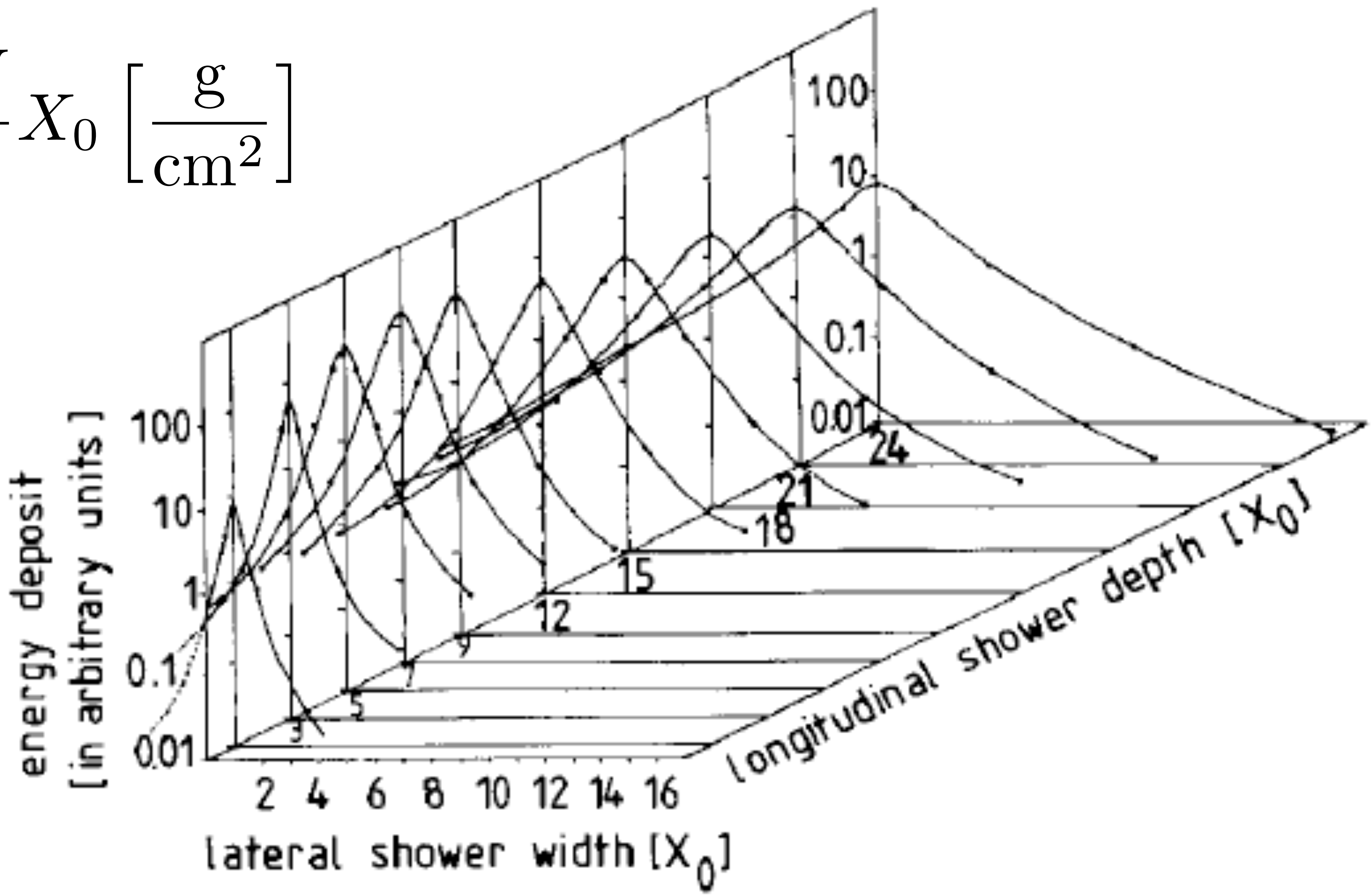
$$t_{max} \propto \ln \frac{E}{E_c}$$

Energy measurement - calorimeter

electromagnetic cascade

lateral extension of the cascade mostly caused by multiple scattering and characterized by Molière radius

$$R_m = \frac{21\ \mathrm{MeV}}{E_c} X_0 \left[\frac{\mathrm{g}}{\mathrm{cm}^2}\right]$$



Electromagnetic calorimetry

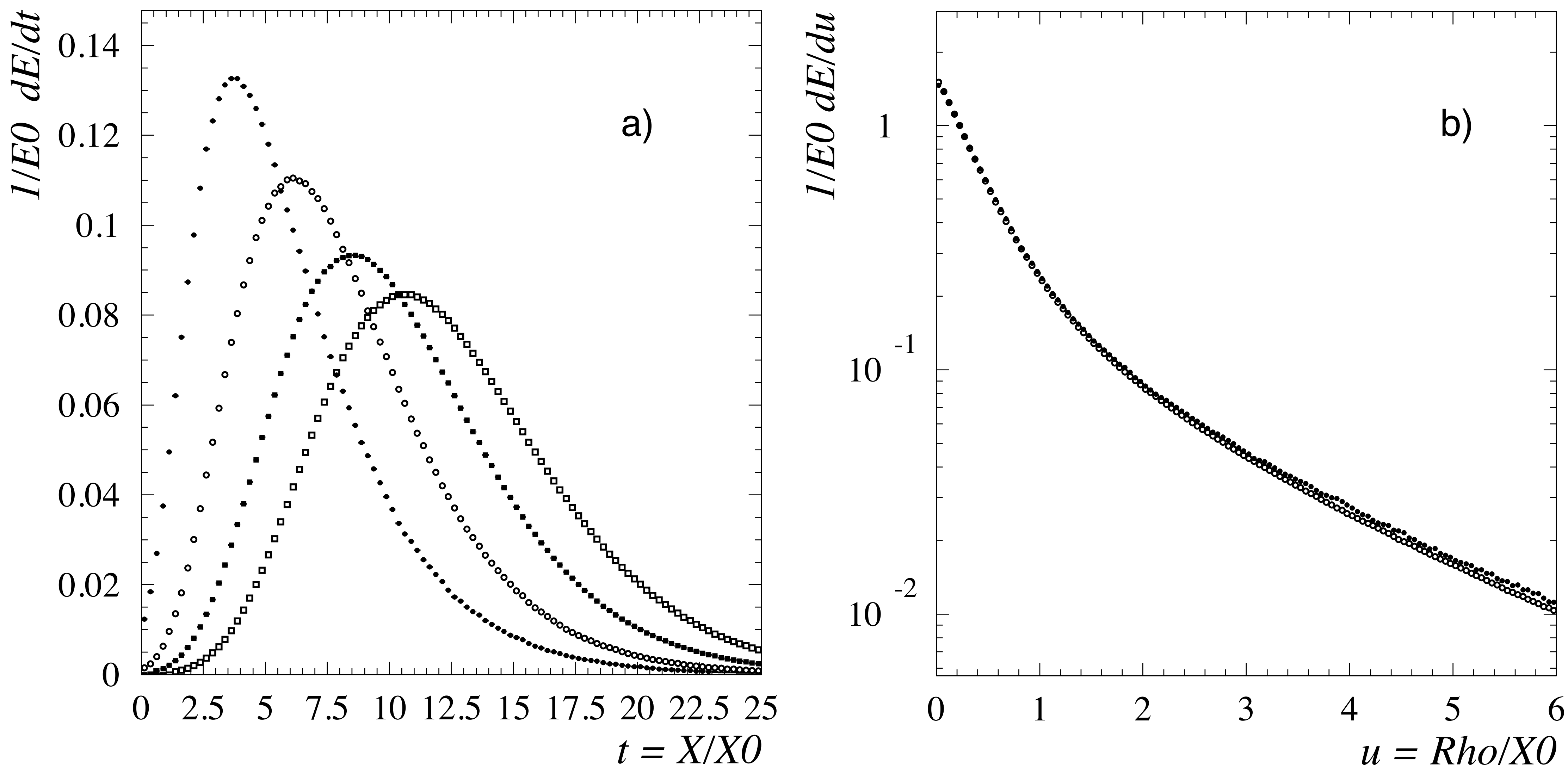


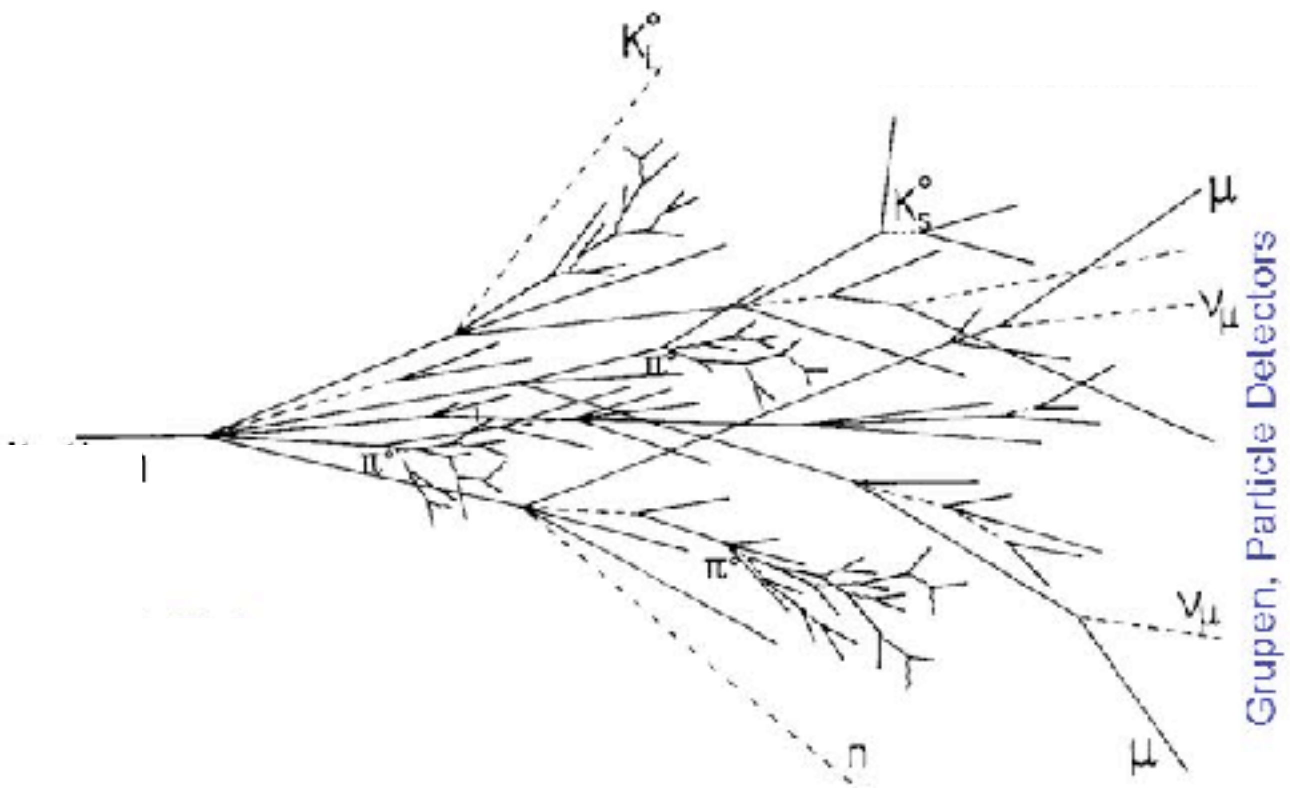
FIG. 2 (a): Simulated shower longitudinal profiles in $PbWO_4$, as a function of the material thickness (expressed in radiation lengths), for incident electrons of energy (from left to right) 1 GeV, 10 GeV, 100 GeV, 1 TeV. (b): Simulated radial shower profiles in $PbWO_4$, as a function of the radial distance from the shower axis (expressed in radiation lengths), for 1 GeV (closed circles) and 1 TeV (open circles) incident electrons. From Maire (2001).

Fabjan, Rev. Mod. Phys. 75 (2003) 1243

Energy measurement - calorimeter

hadron calorimeter

high-energy hadrons (> GeV) undergo inelastic processes
--> production of secondary particles
--> hadronic shower, characterized by hadronic interaction length λ



a fraction of the energy
- escapes from the calorimeter (leakage)
- is invisible (nuclear excitation, neutrinos, ...)

Energy measurement - calorimeter

hadron calorimeter

longitudinal shower development

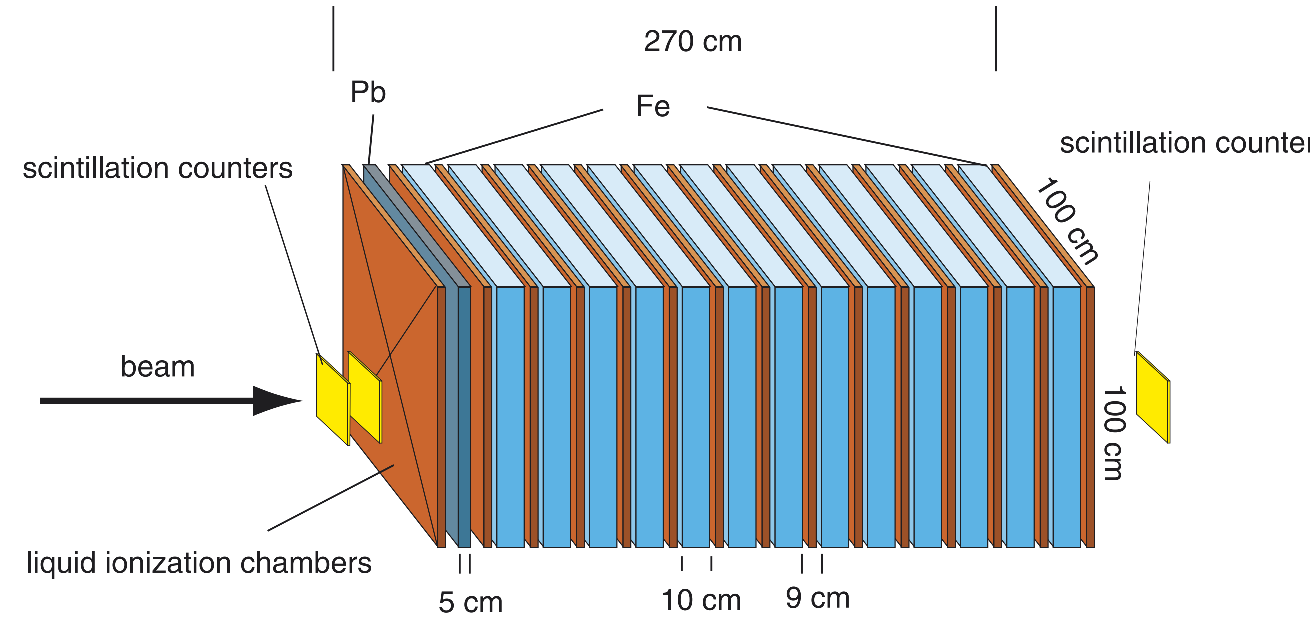


Fig. 2. Schematic view of the sampling calorimeter.

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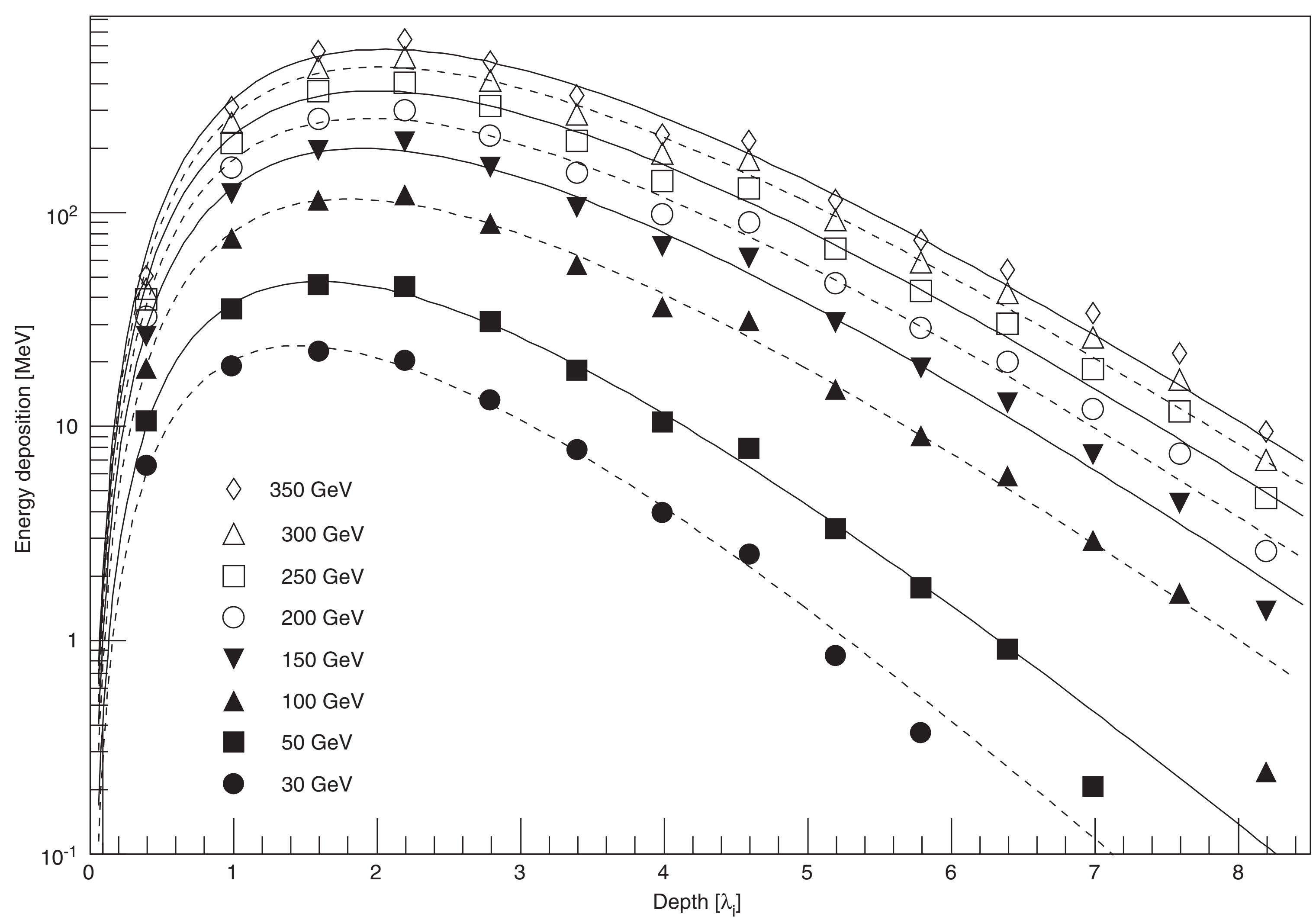

Fig. 13. Measured energy deposition as function of depth in the calorimeter for hadrons with energies from 30 to 350 GeV. The lines represent fits according to Eq. (7).

sampling calorimeter

alternating layers of absorber material and detectors

energy resolution

$$\frac{\sigma(e)}{E} = A + B\frac{1}{\sqrt{E}}$$

$$E_{\mathrm{dep}}(t) = A \cdot t^B \cdot \exp(-t/C)$$

Energy measurement - calorimeter

hadron calorimeter

lateral shower development

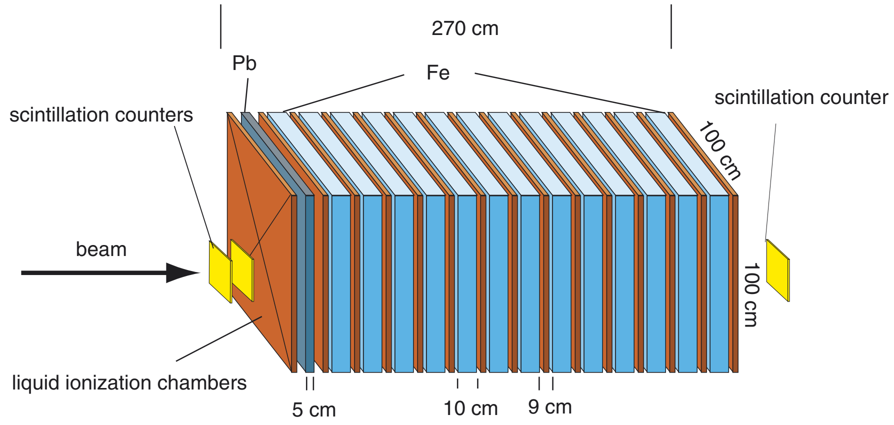

Fig. 2. Schematic view of the sampling calorimeter.

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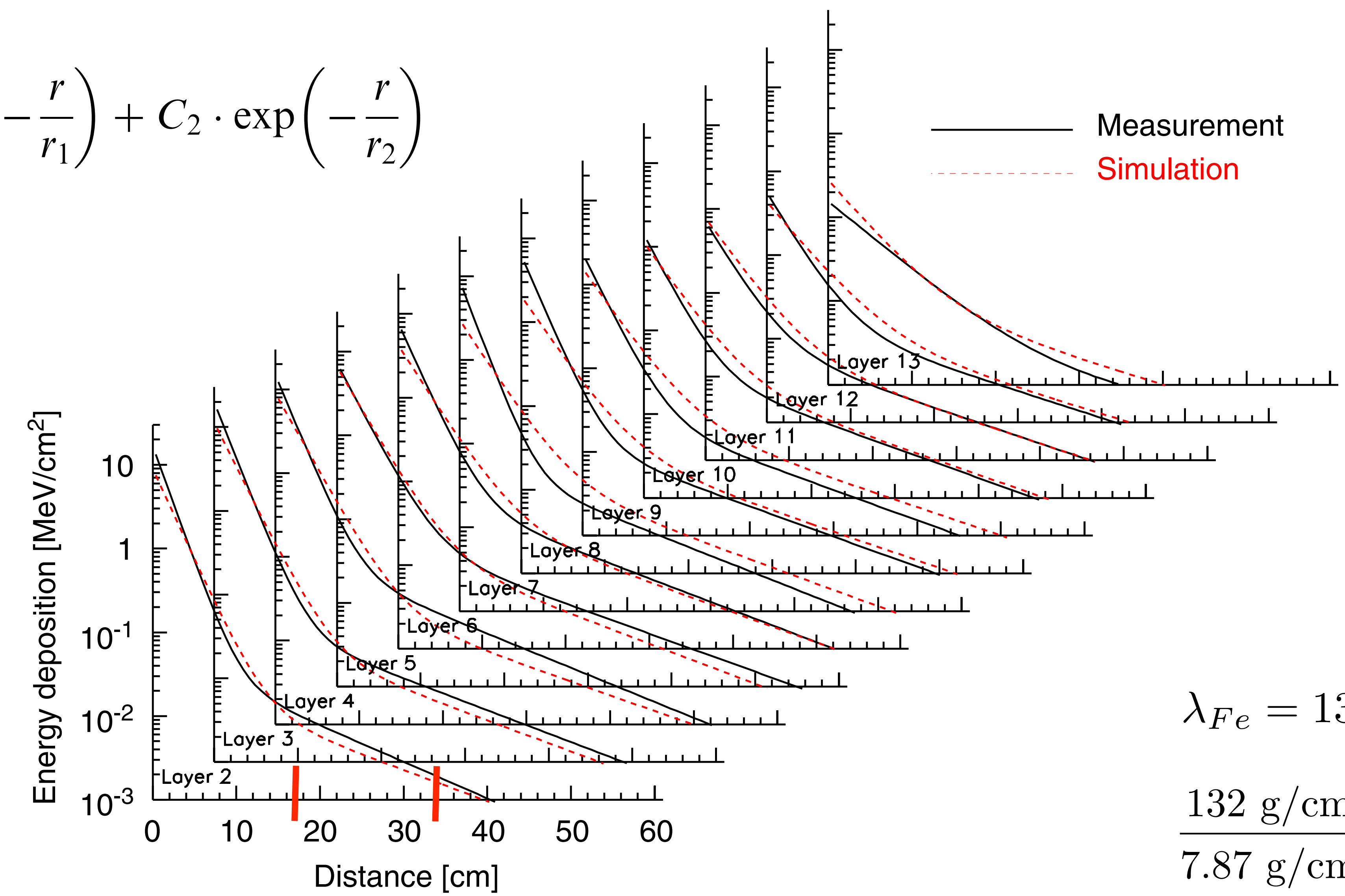
$$\delta E(r) = C_1 \cdot \exp\left(-\frac{r}{r_1}\right) + C_2 \cdot \exp\left(-\frac{r}{r_2}\right)$$



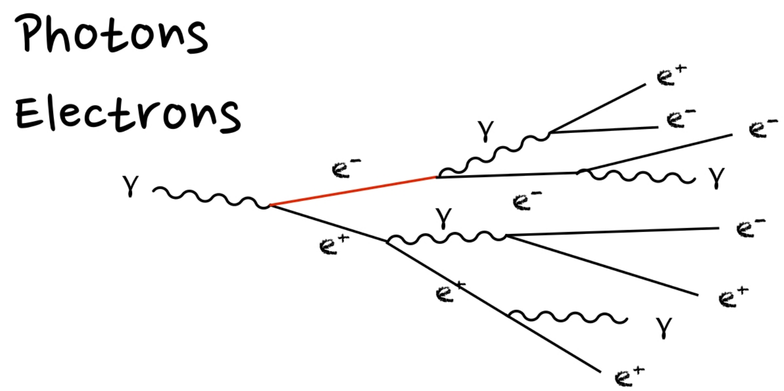
$$\lambda_{Fe} = 132 \text{ g/cm}^2$$

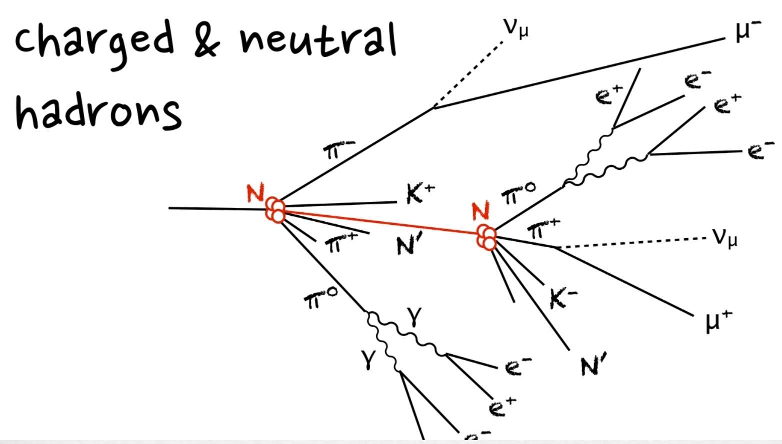
$$\frac{132 \text{ g/cm}^2}{7.87 \text{ g/cm}^3} \approx 16.8 \text{ cm}$$

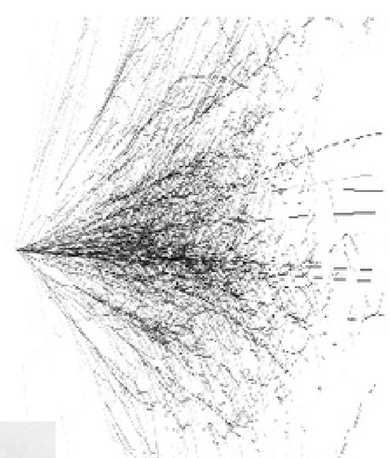
Fig. 9. Lateral distribution of the energy deposition in different layers of the calorimeter for 300 GeV hadrons. Measurements (solid lines) and simulations (dashed lines) are represented by parameterizations according to Eq. (5).

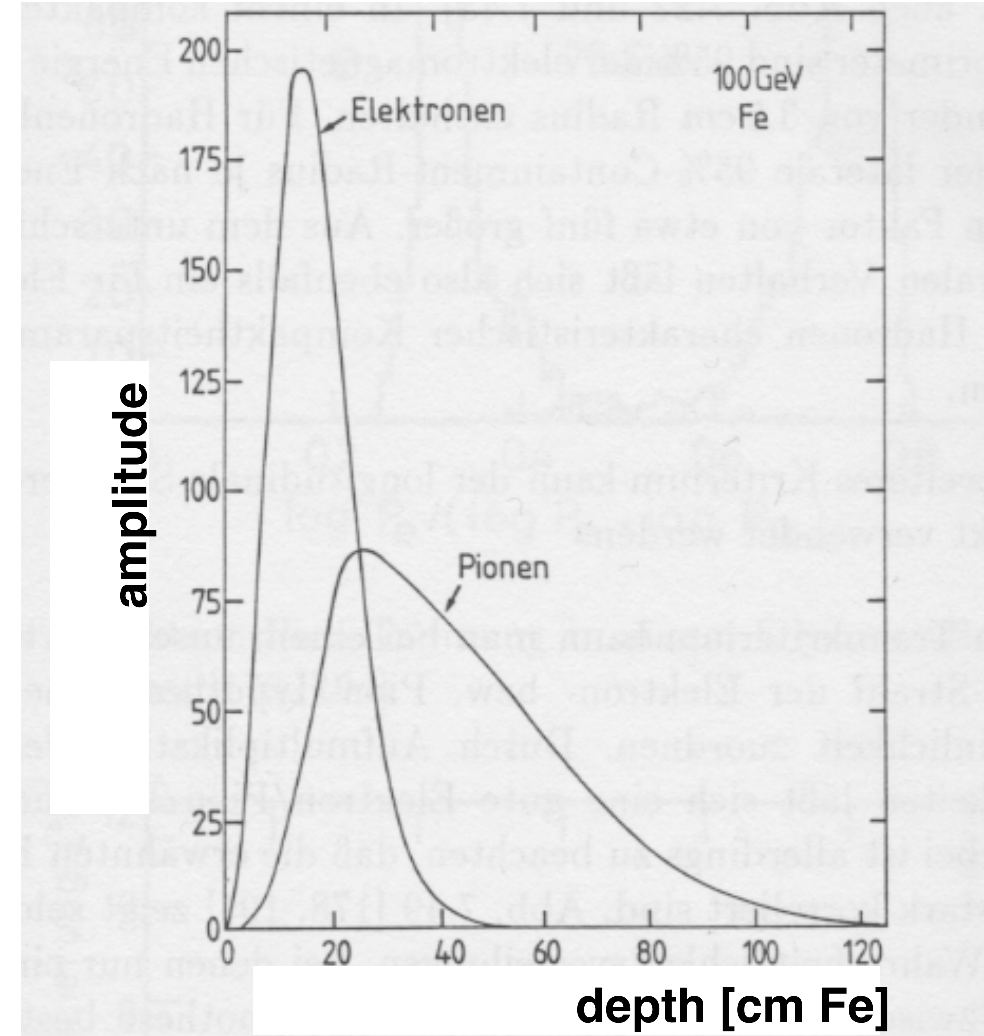
Particle identification - calorimeter

in calorimeters there are different shower responses for electrons and hadrons

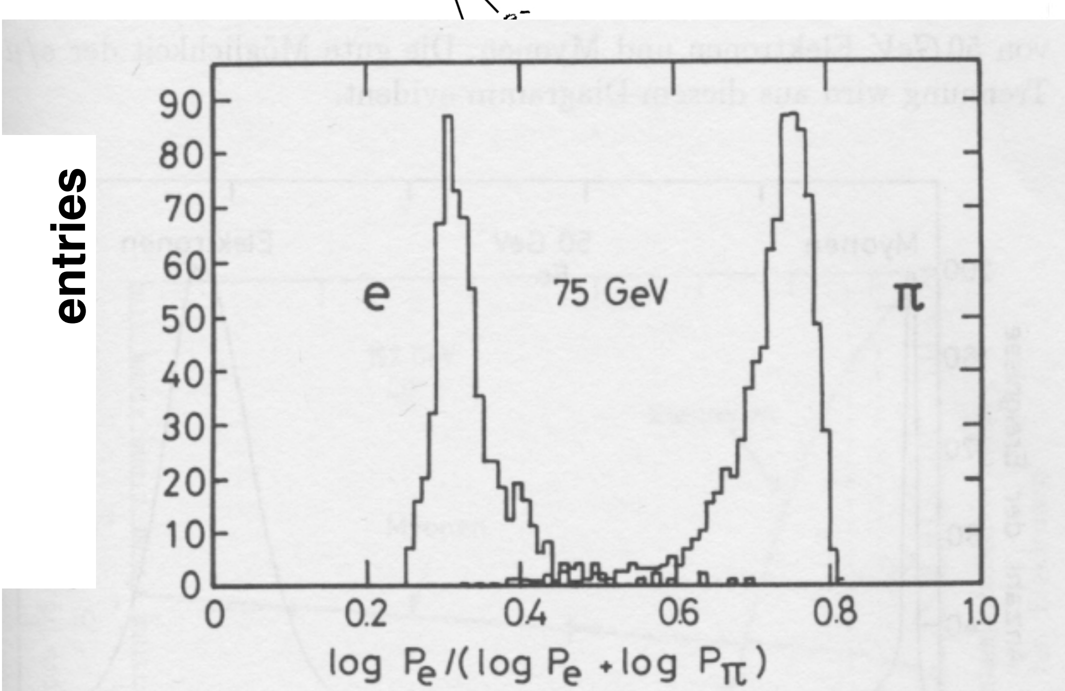




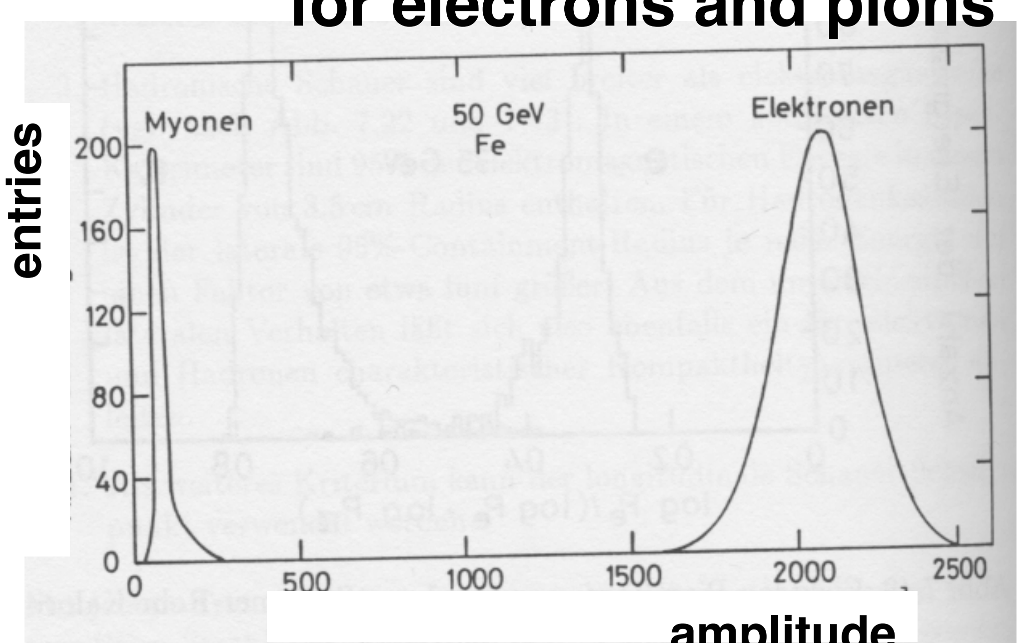




longitudinal shower development for electrons and pions



energy deposit for electrons and pions



energy deposit for muons and electrons

Transition radiation

particles traversing a boundary of media with different dielectric properties
--> emission of transition radiation (below Cherenkov threshold)

differential energy spectrum of emitted x-ray photons

$$\frac{\mathrm{d}^2 W_0}{\mathrm{d}\omega\,\mathrm{d}\theta} = \frac{2\alpha\hbar\theta^3 Z^2}{\pi} \left| \frac{1}{\gamma^{-2}+\theta^2+\xi_1^2} - \frac{1}{\gamma^{-2}+\theta^2+\xi_2^2} \right|^2$$

$$\xi_i \equiv \omega_i/\omega$$

ratio of material's plasma frequency to the emitted photon frequency

$$\epsilon_i \approx 1 - \xi_i^2$$

dielectric constant

emission of photons sharply peaked in forward direction $\theta \approx 1/\gamma$

total radiation yield (integrated over all angles and frequencies)

$$W_0 = \frac{\alpha\hbar Z^2}{3}\frac{(\omega_1-\omega_2)^2}{\omega_1+\omega_2}\gamma.$$

Transition radiation

interference effects between the emission amplitudes of all media boundaries of a radiator

for N-foil regular stack with constant spacing l_2 and foil thickness l_1

$$\frac{d^2 W_N}{d\omega\, d\theta} = \frac{d^2 W_0}{d\omega\, d\theta} 4 \sin^2\left(\frac{l_1}{z_1}\right) \frac{\sin^2[N(l_1/z_1 + l_2/z_2)]}{\sin^2(l_1/z_1 + l_2/z_2)}.$$

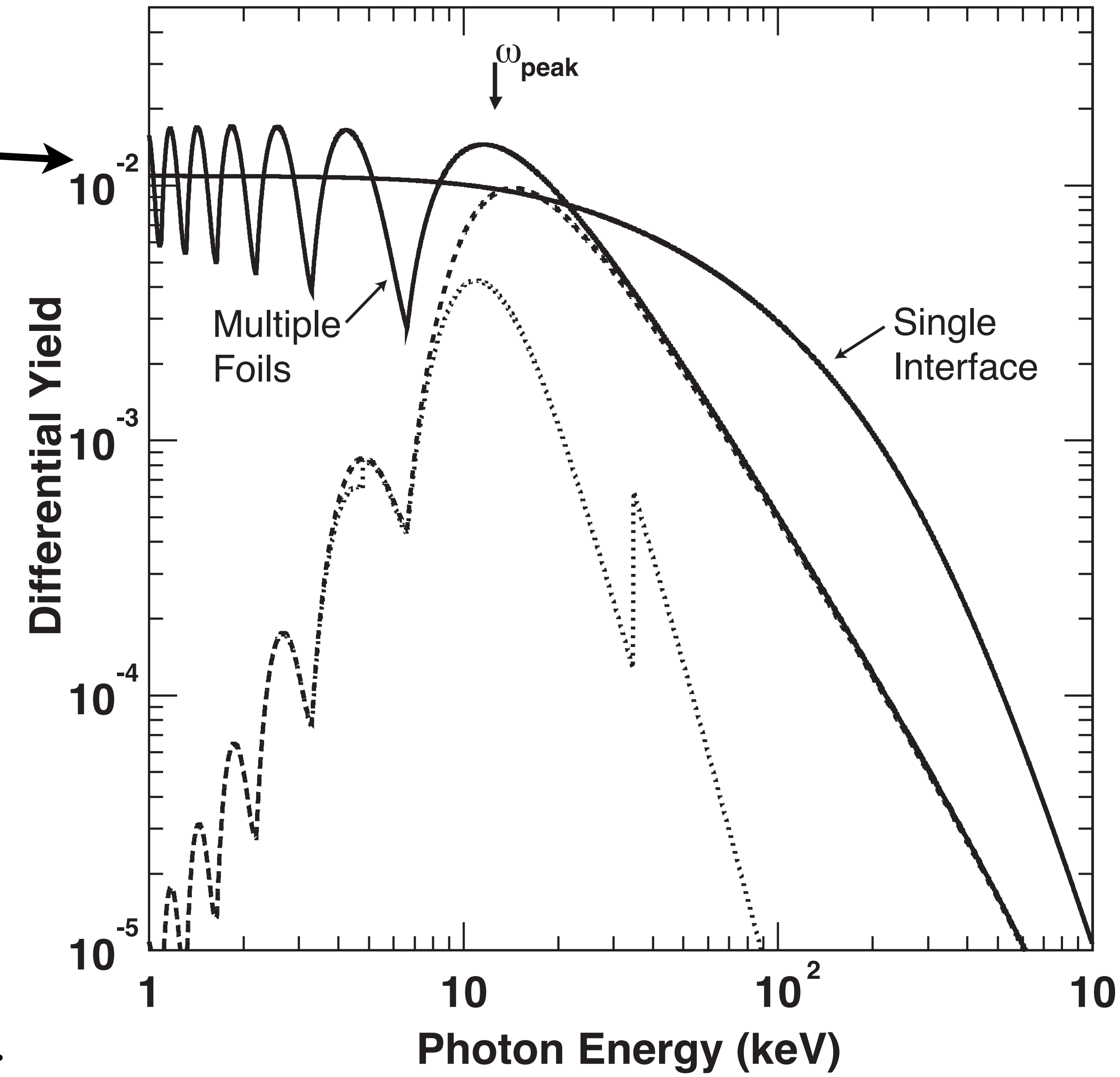


Fig. 1. Differential TR yield ($dW/d\omega$) versus Lorentz factor for several configurations. Shown are the single-interface (smooth line) and approximate multi-foil (oscillating line) energy spectra, as well as the multi-foil spectrum modified by self-absorption processes in the foil (dashed line). The dotted line shows the yield which would be captured in a single 1 cm thick layer of xenon. The characteristic peak emission energy ω_{peak} is also indicated. All spectra are normalized to a single-interface yield. The relevant parameters are $\gamma = 2 \times 10^4$, $l_1 = 35$ μm, $l_2 = 1000$ μm, $\omega_1 = 21.2$ eV, and $\omega_2 = 0.75$ eV.

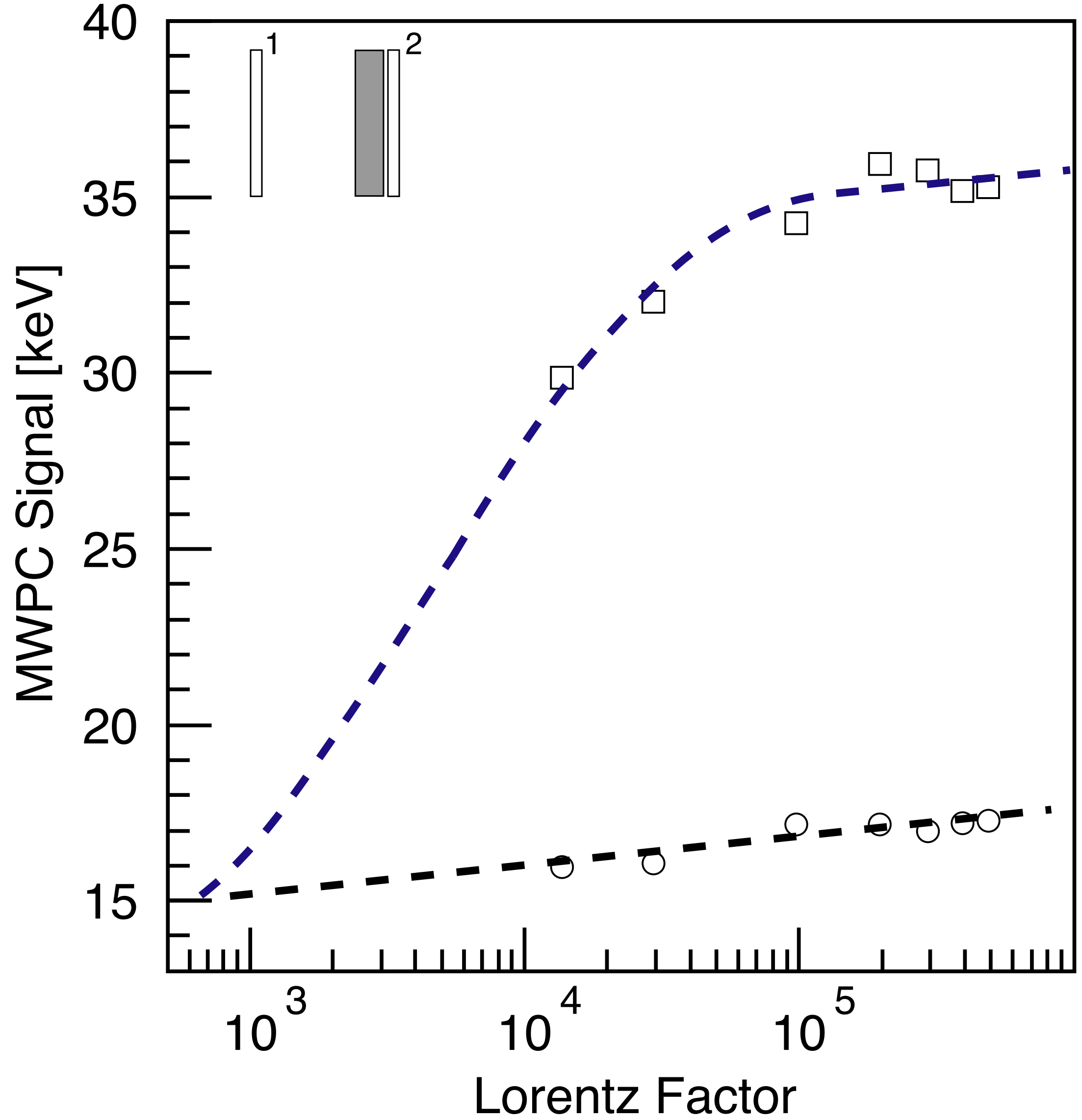
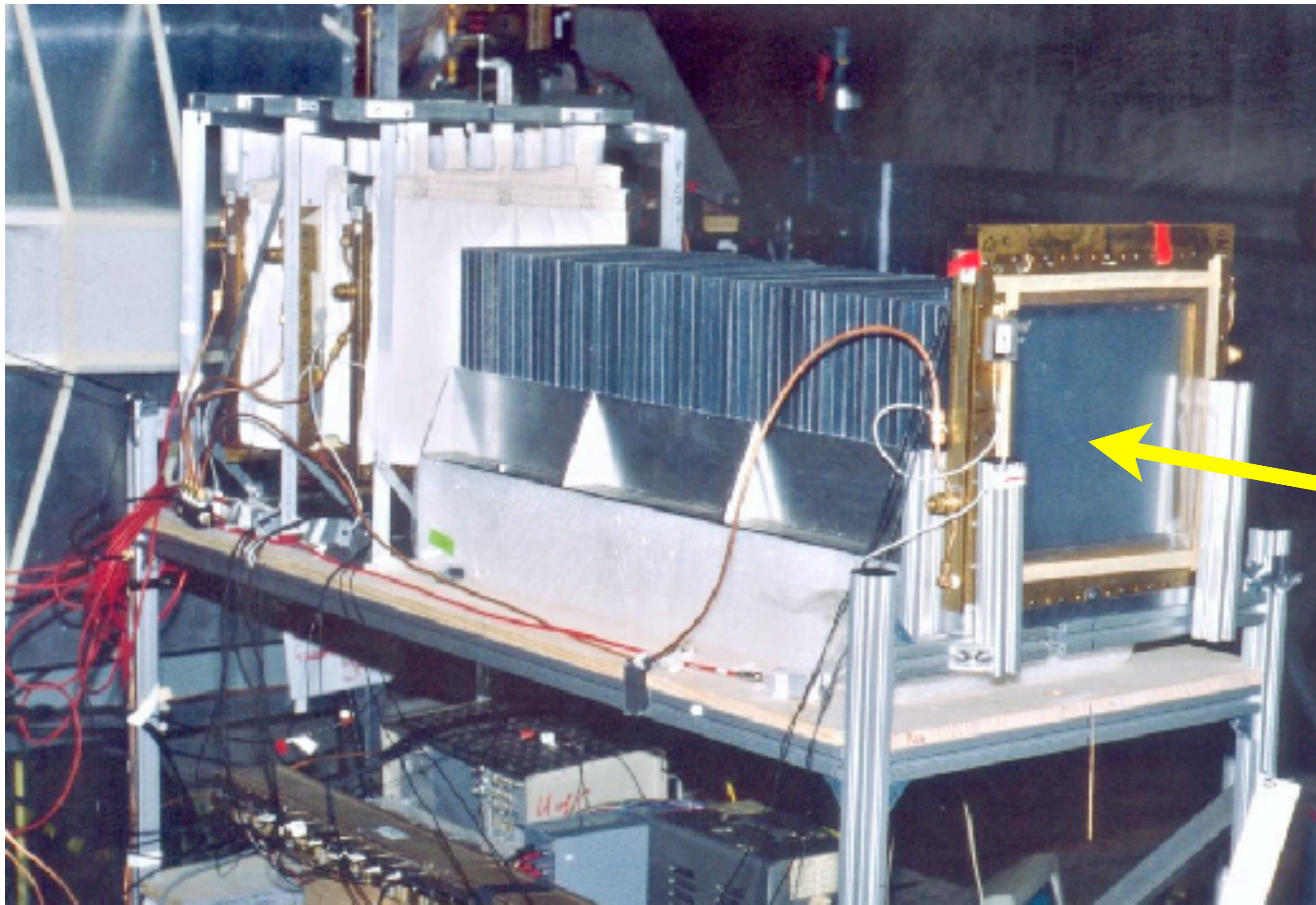


Fig. 8. Average detector signal versus Lorentz factor for a CRN-like radiator configuration. The open circles are data from MWPC 1, and the open squares are from MWPC 2, as shown in the inset schematic. The dashed lines serve to guide the eye.

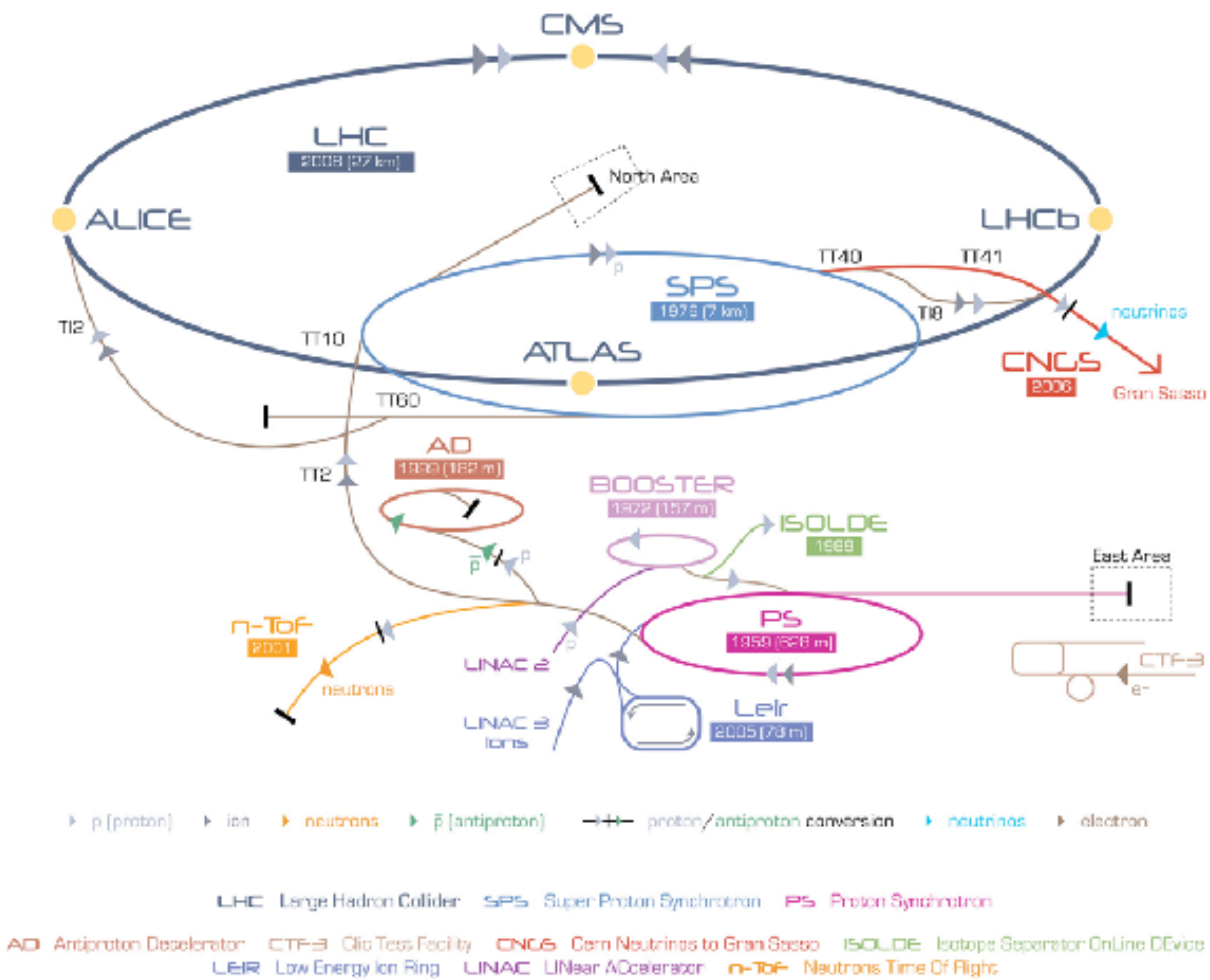
Transition Radiation Detector

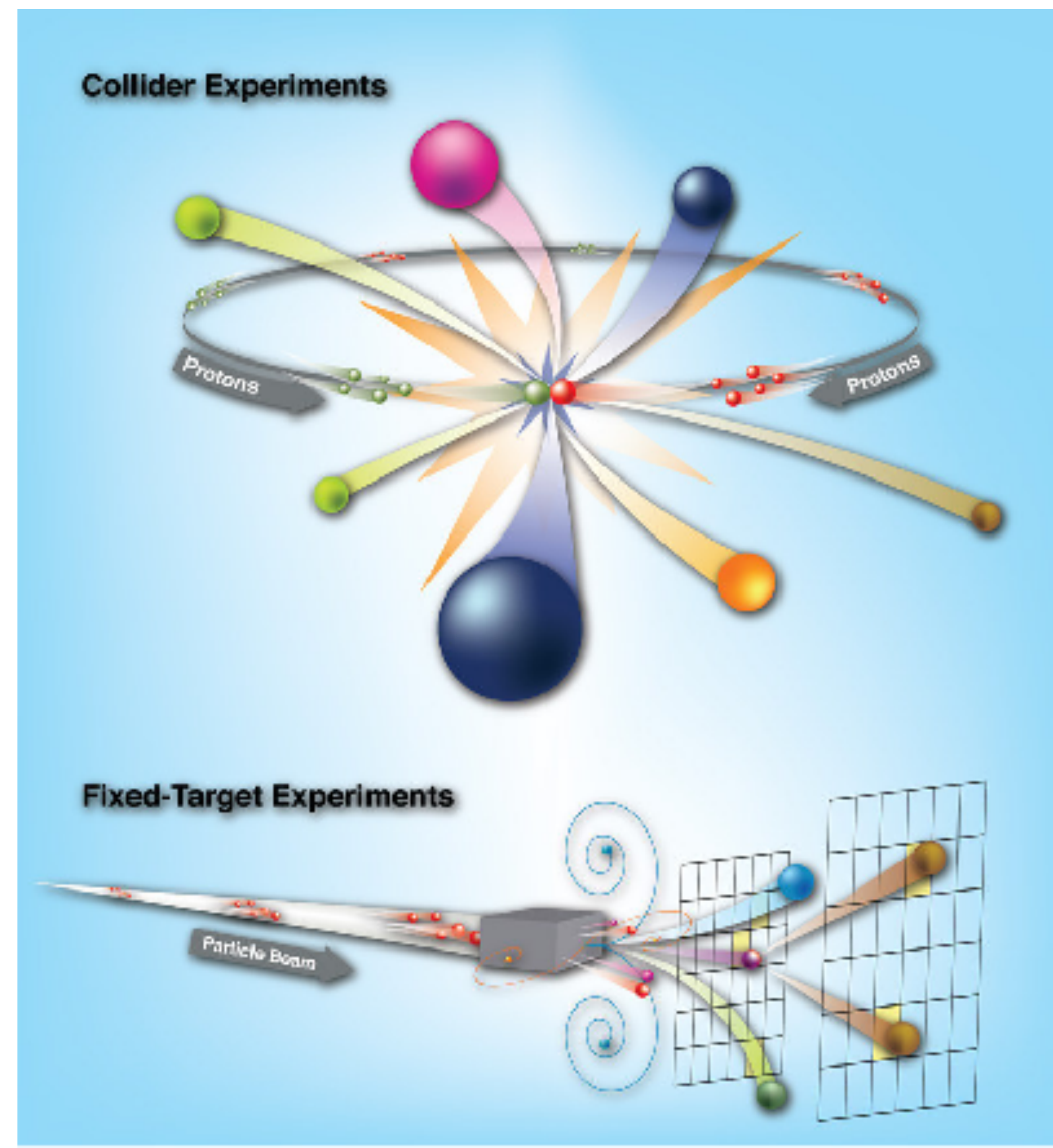
- particle identification (threshold detector)
- energy measurement (Lorentz factor)

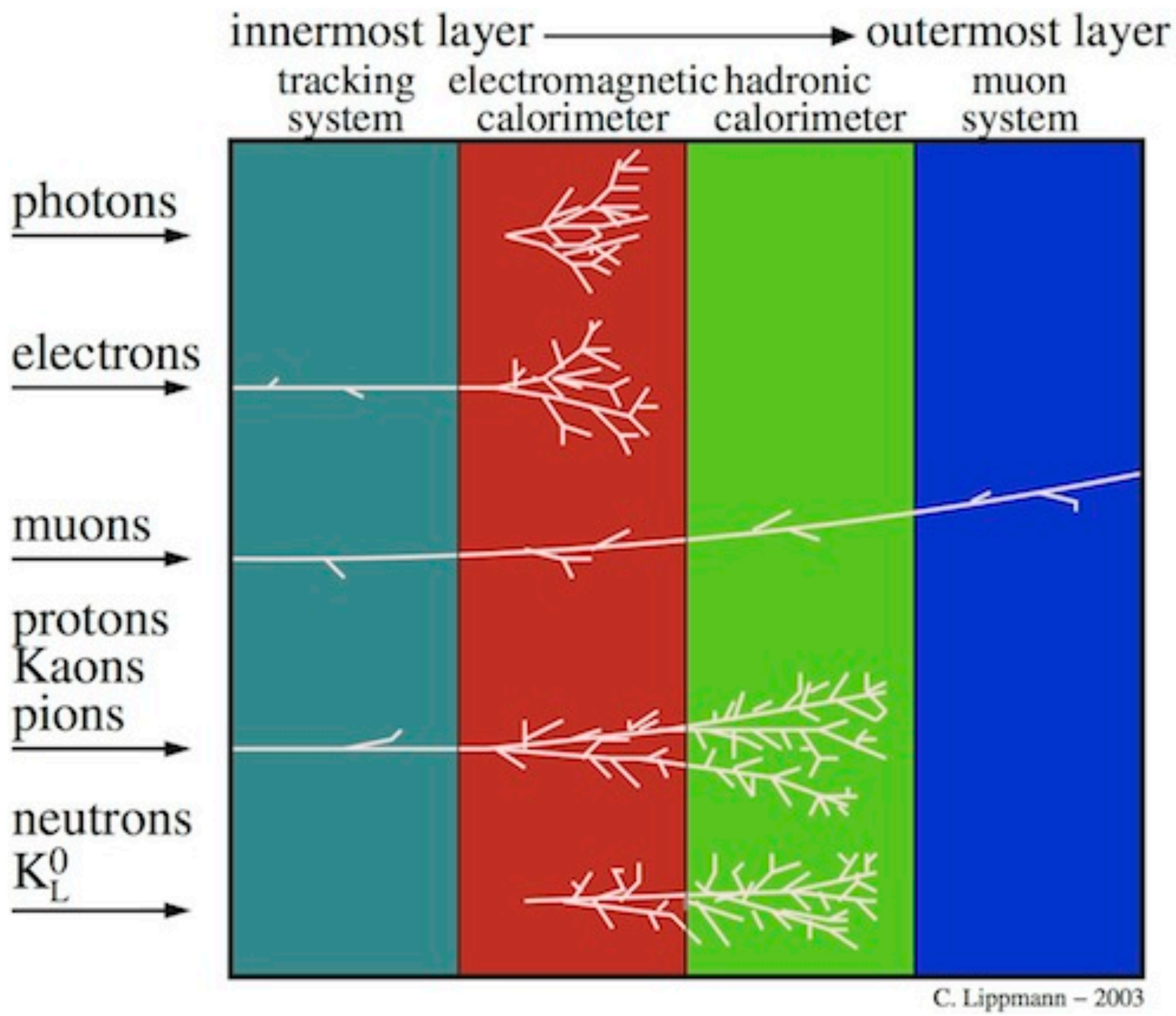
TRD test at CERN



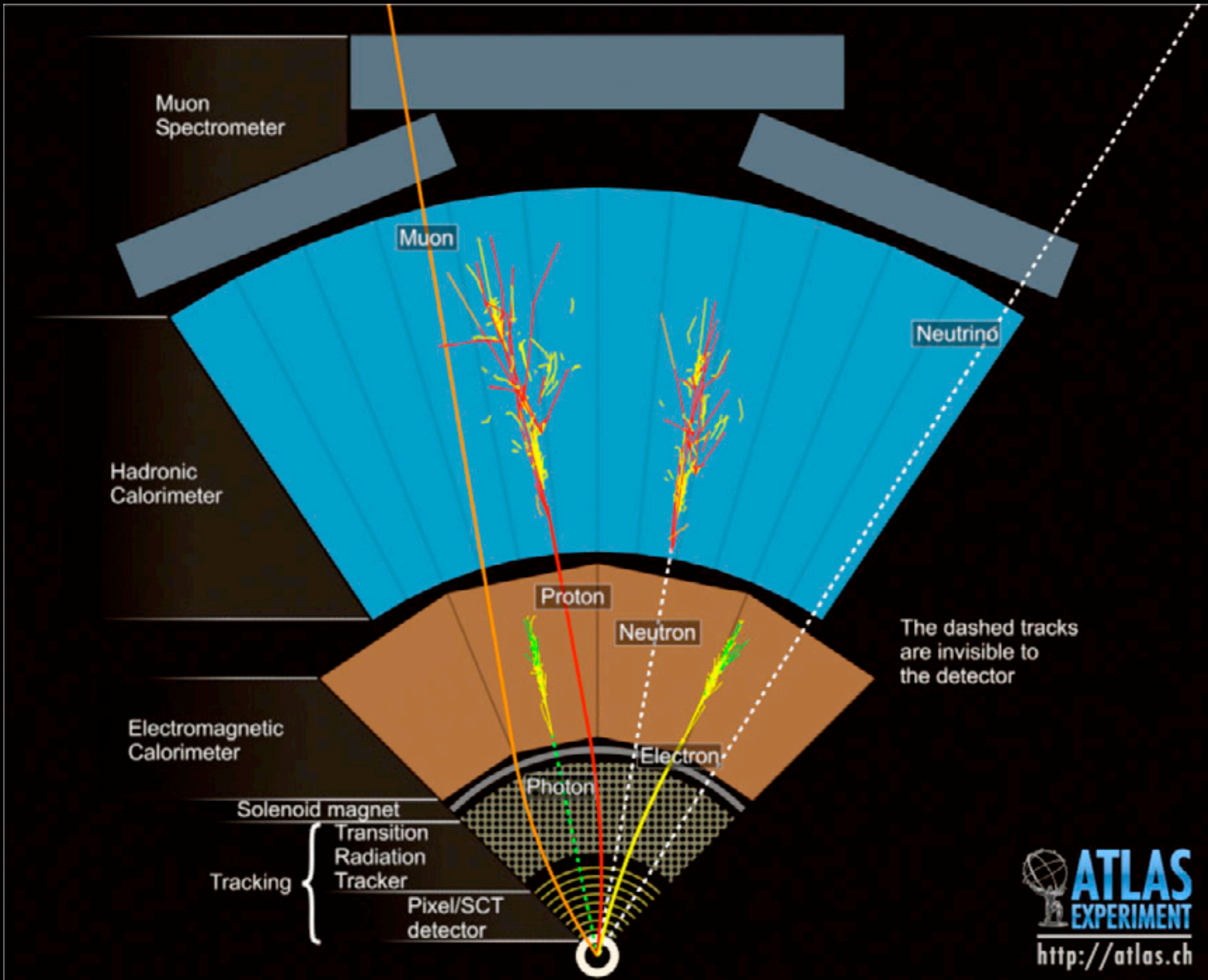
Detectors at accelerators



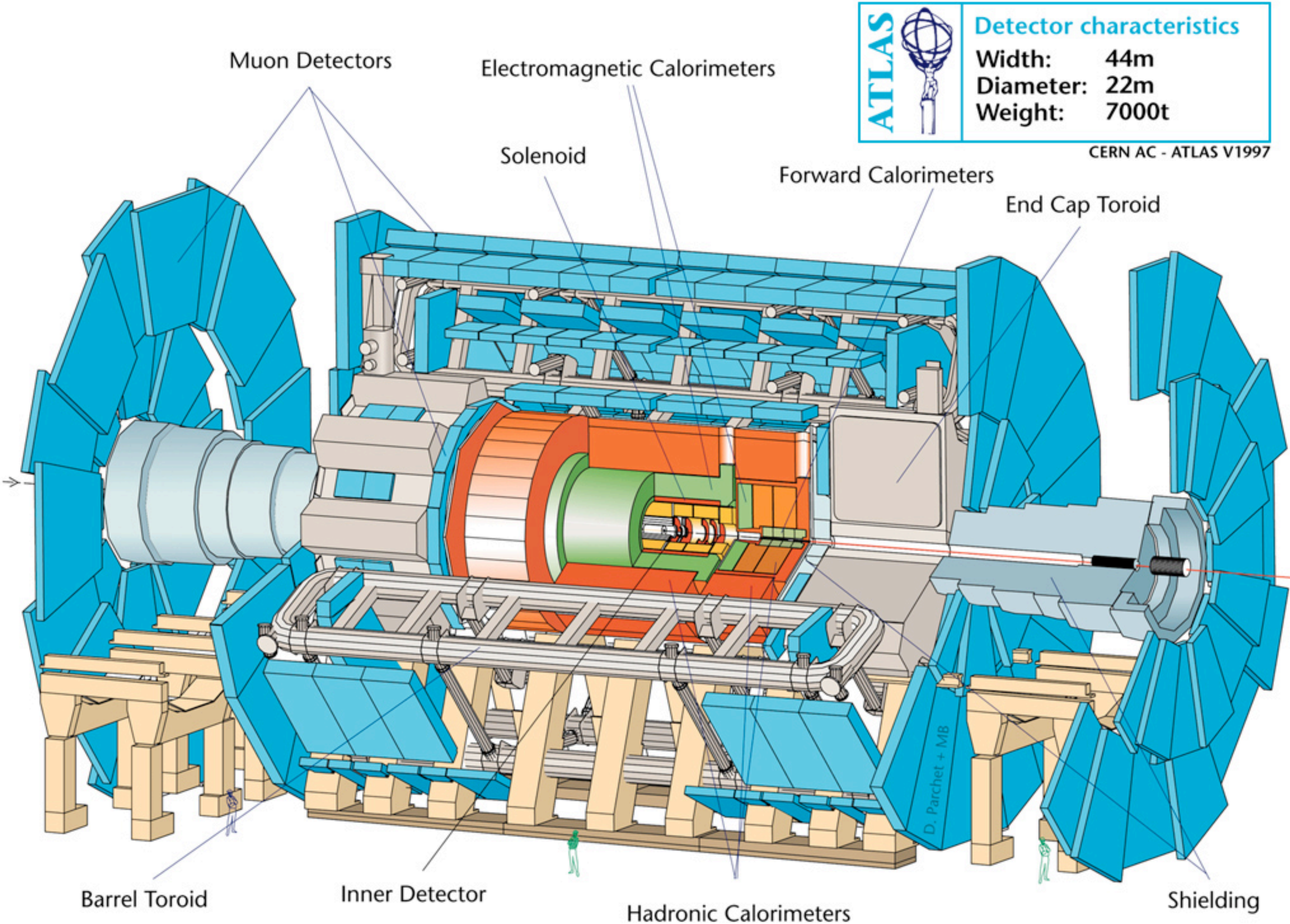


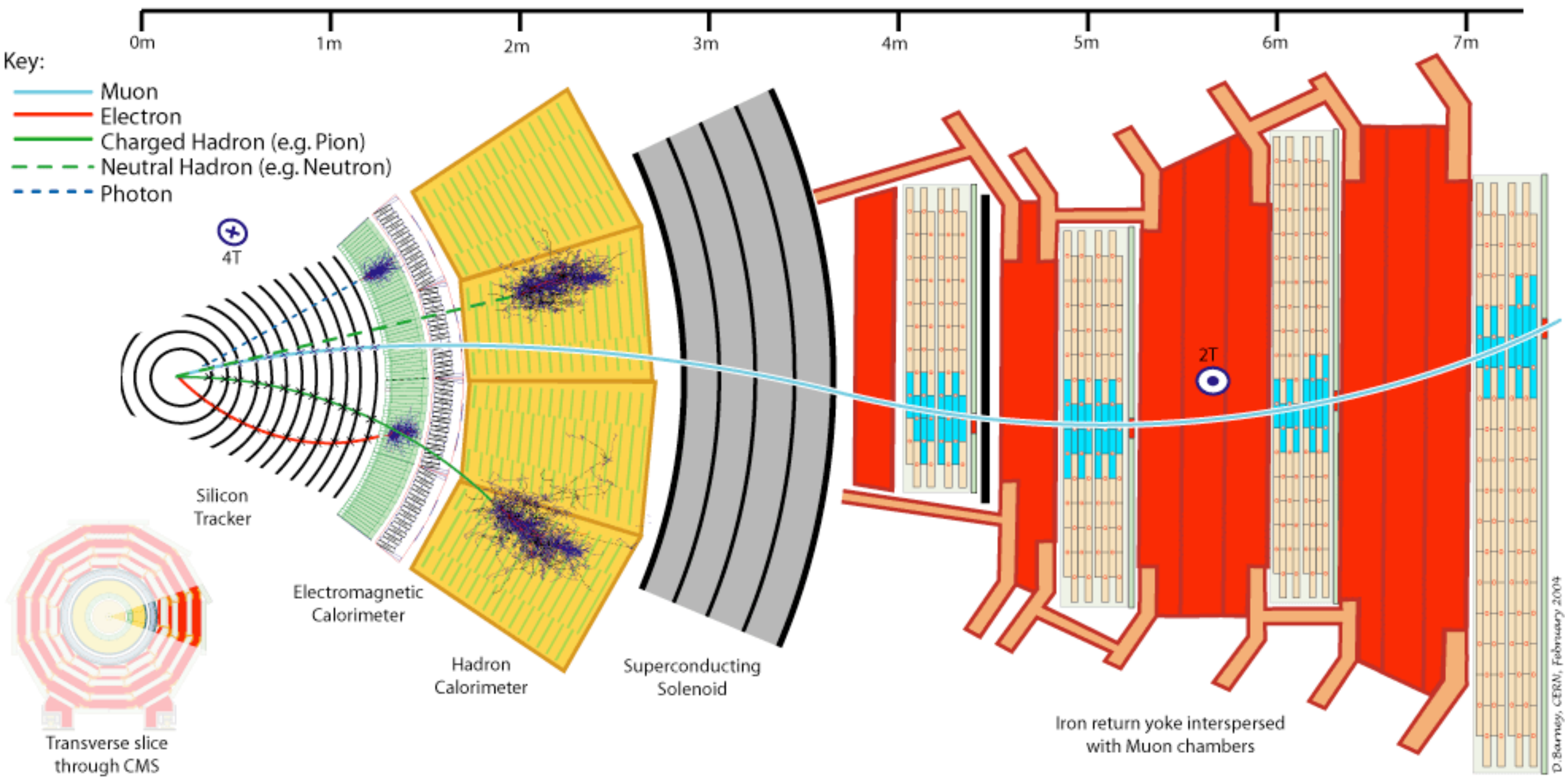


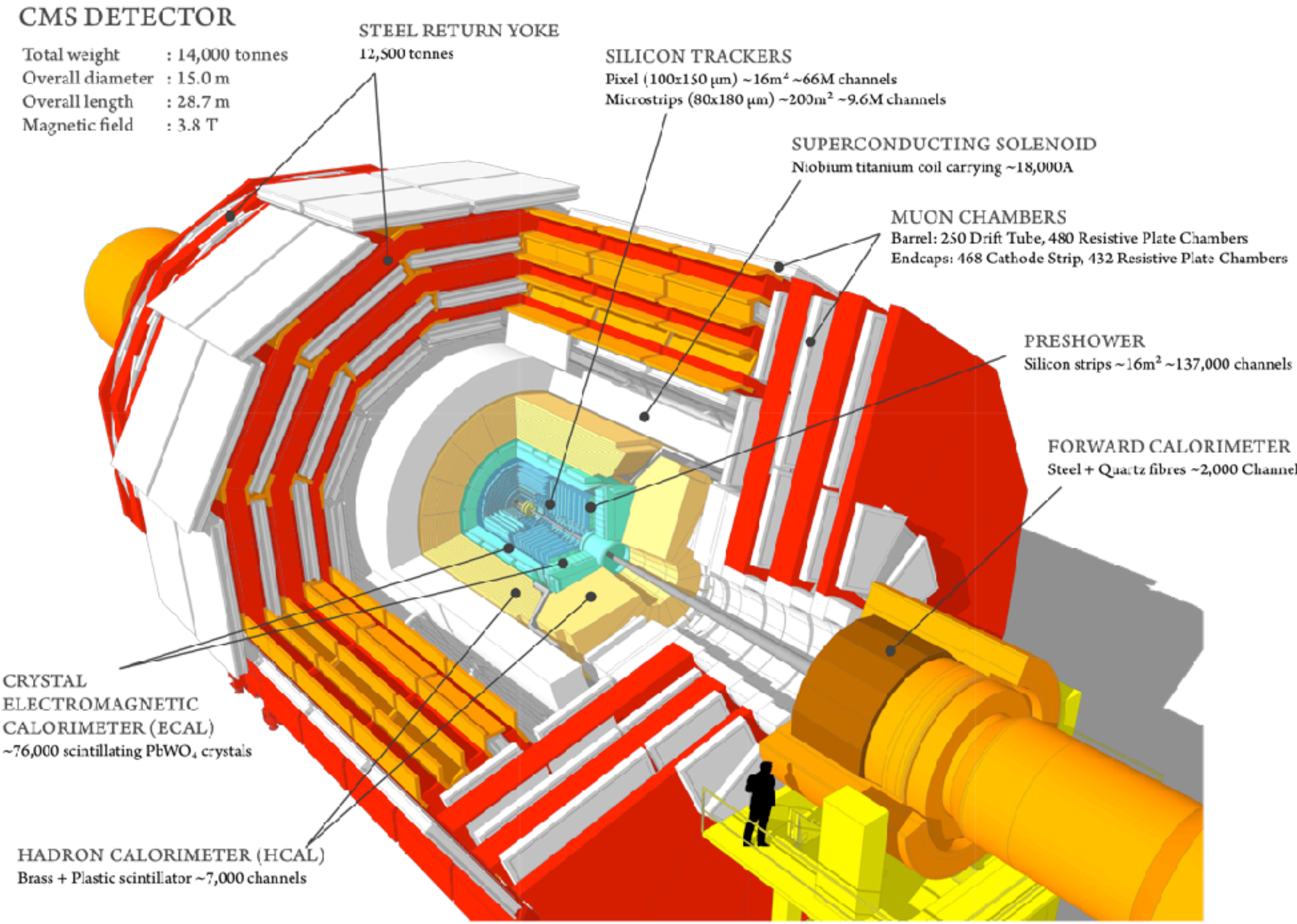
Components of a "traditional" particle physics experiment. Each particle type has its own signature in the detector. For example, if a particle is detected only in the electromagnetic calorimeter, it is fairly certain that it is a photon.



Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT
detector
Muon
Neutrino
Proton
Neutron
Electron
Photon
The dashed tracks
are invisible to
the detector
ATLAS
EXPERIMENT
http://atlas.ch


Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
D. Parchet + MB

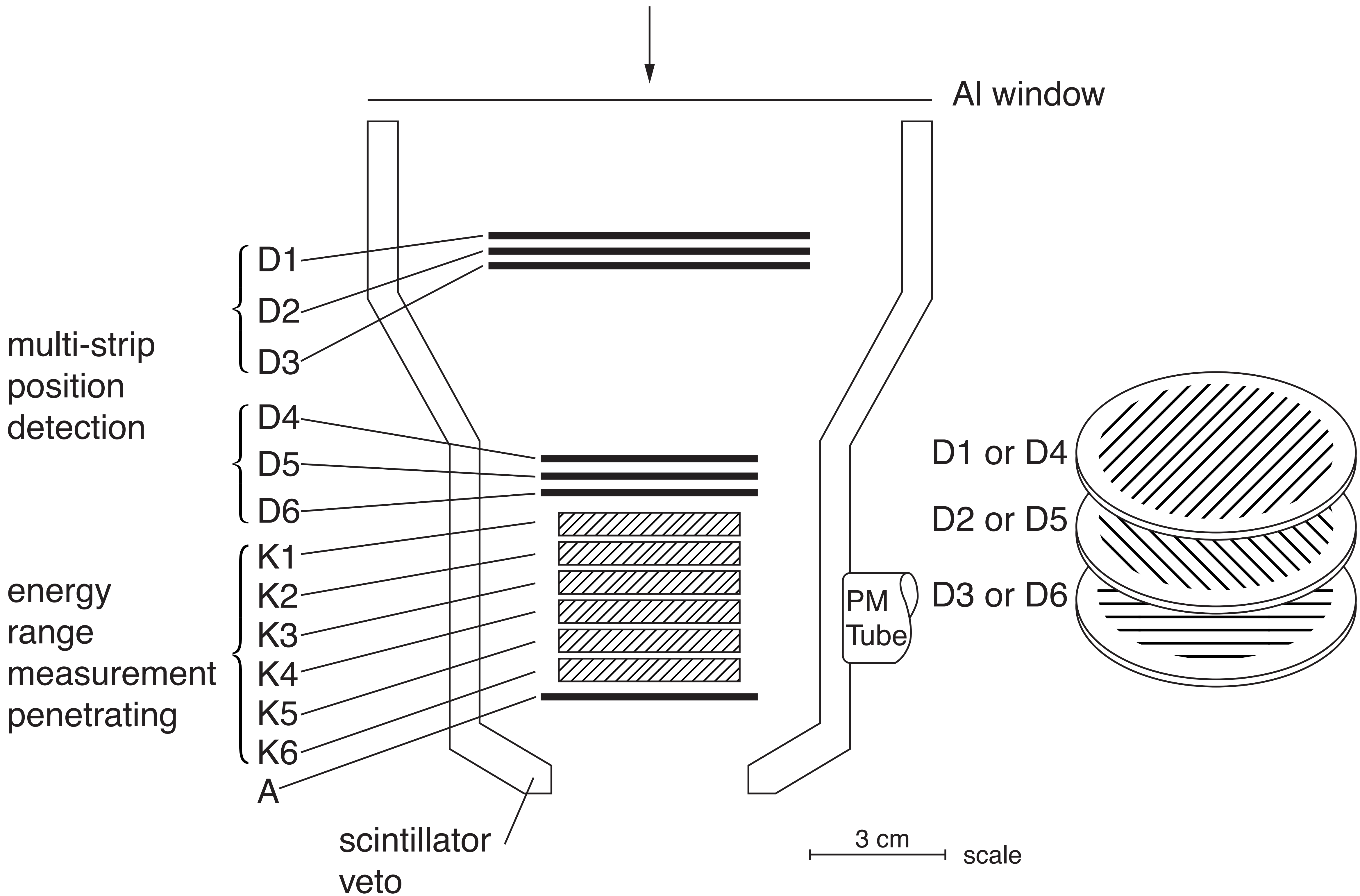

0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

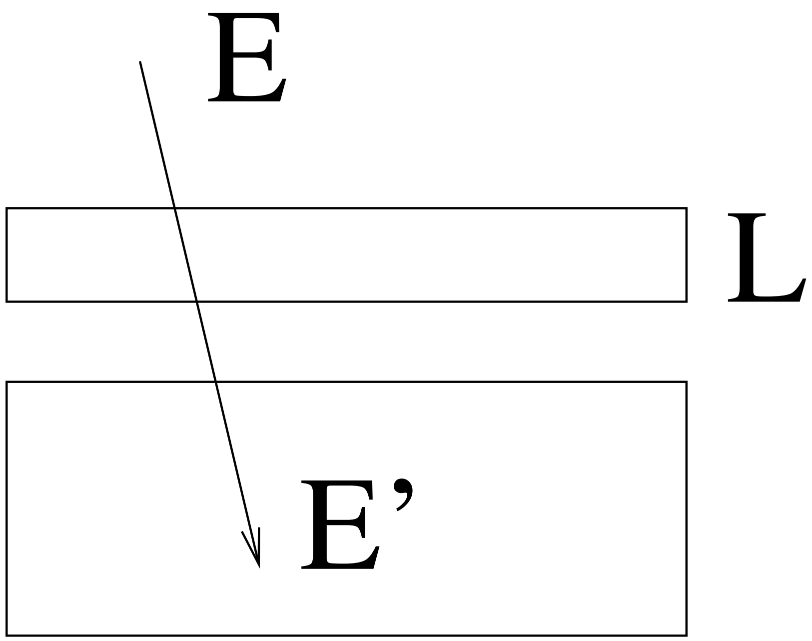
Detectors for direct measurements of Cosmic Rays above the atmosphere

•Silicon detector	IZI, A, E	isotopes
•Magnet spectrometer	+/- Z, E	anti-particles
•Calorimeter	IZI, E	elements
•Cherencov detector	IZI, E	elements
•Transition radiation detector	IZI, E	elements

Ulysses High Energy Telescope (HET)



silicon detector telescope



particles with energy E loose ΔE in thin layer
E' remaining energy

particles with energy E and mass M and charge Z penetrate a distance R into the material

$$R_{Z,M}(E/M) = k\frac{M}{Z^2}\left(\frac{E}{M}\right)^{\alpha}$$

the thickness of the thinn layer can be expressed as $L = R_{Z,M}(E/M) - R_{Z,M}(E'/M)$

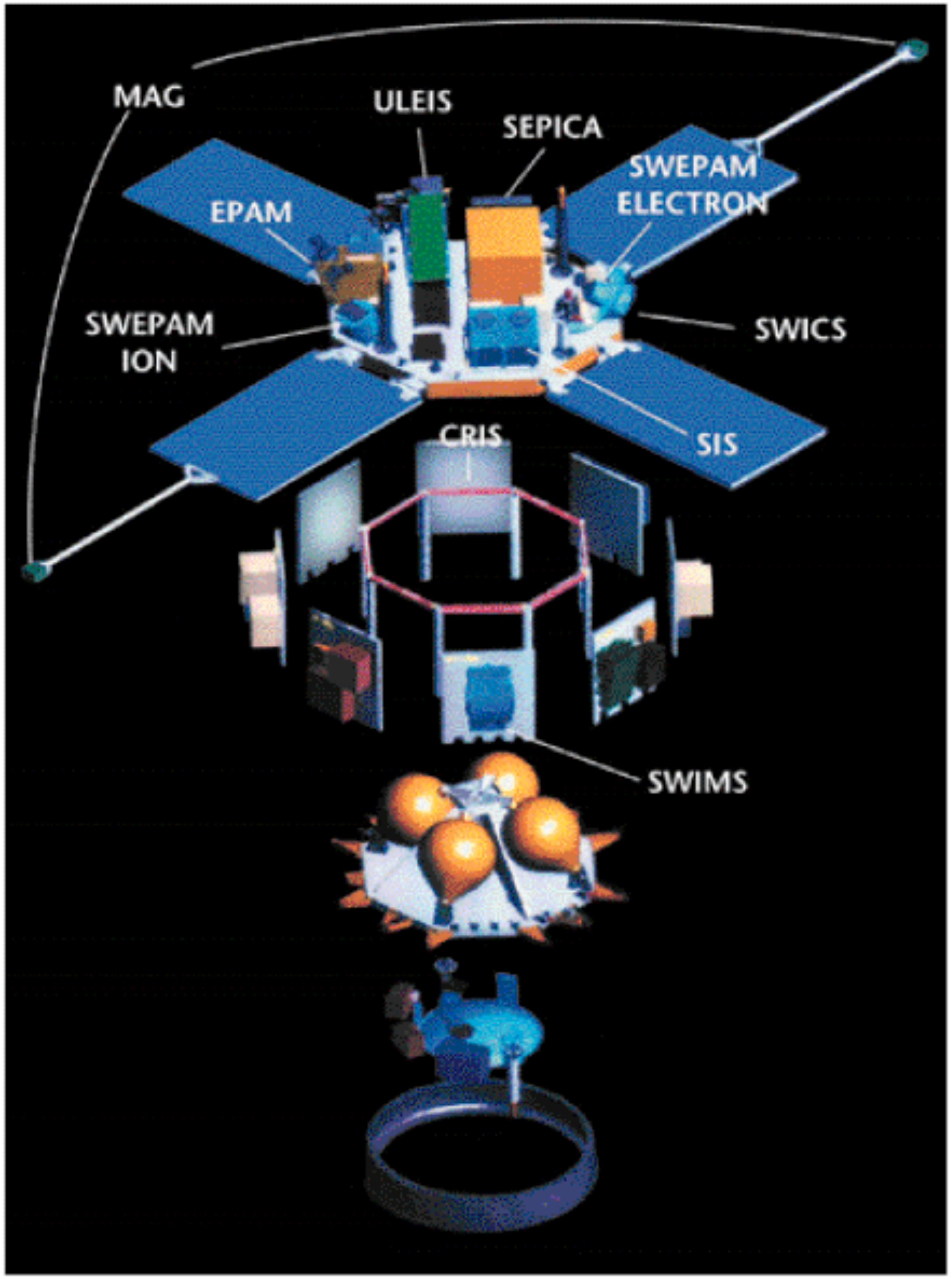
with such an set-up the charge Z and mass M of an incident particle is measured

$$Z = \left(\frac{k}{L(2+\epsilon)^{\alpha-1}}\right)^{1/(\alpha+1)} (E^{\alpha} - E'^{\alpha})^{1/(\alpha+1)}$$

$$M = \left(\frac{k}{Z^2 L}\right)^{1/(\alpha-1)} (E^{\alpha} - E'^{\alpha})^{1/(\alpha-1)}$$

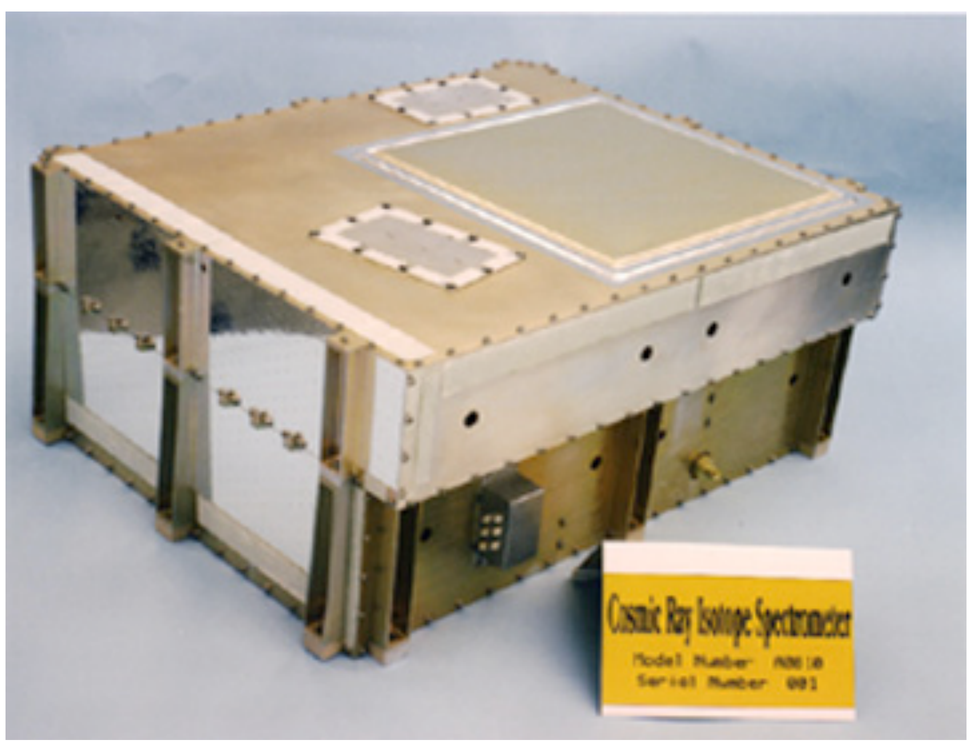
incident cosmic-ray nuclei are fully characterized (Z,A)

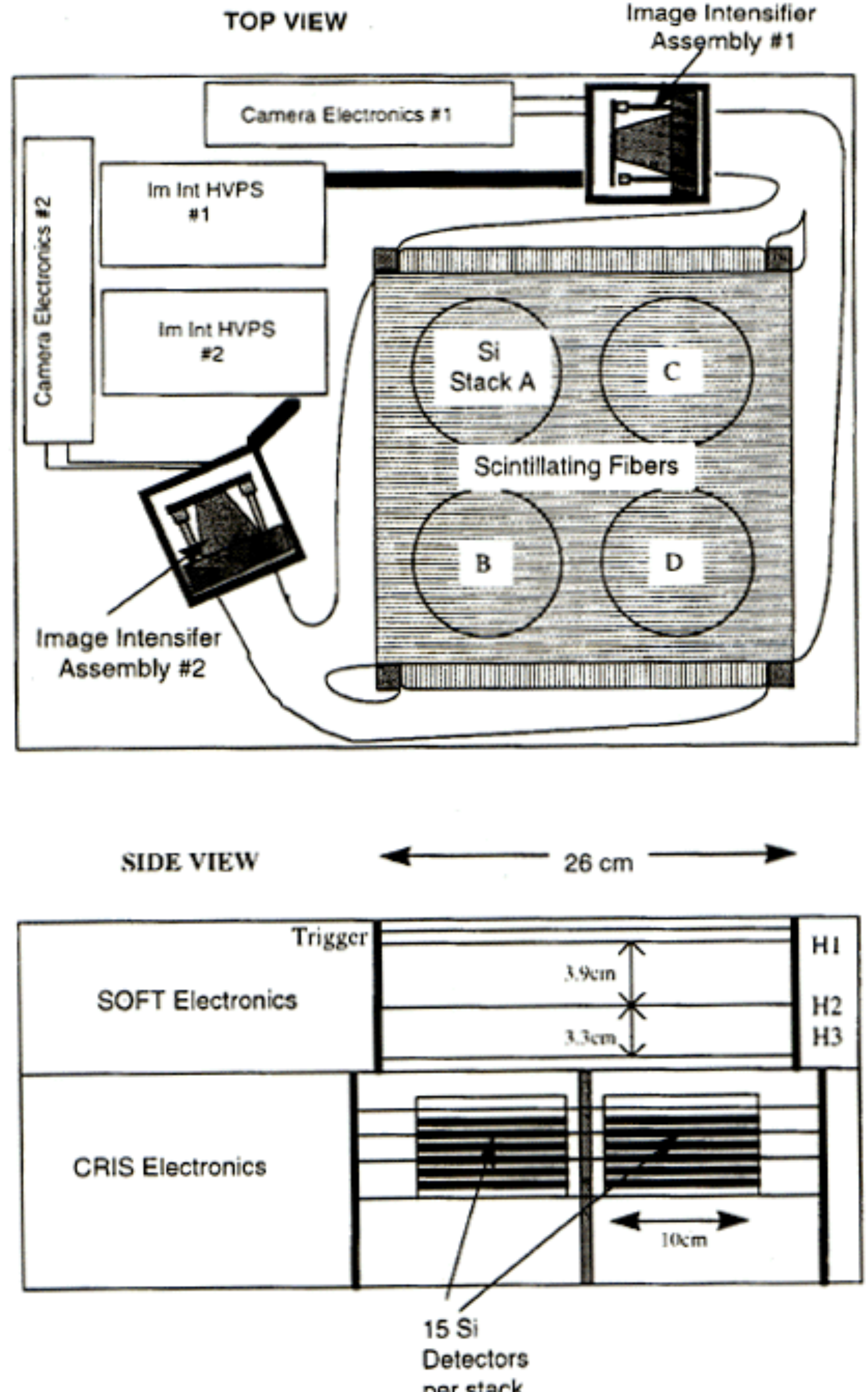
Advanced Composition Explorer (ACE)



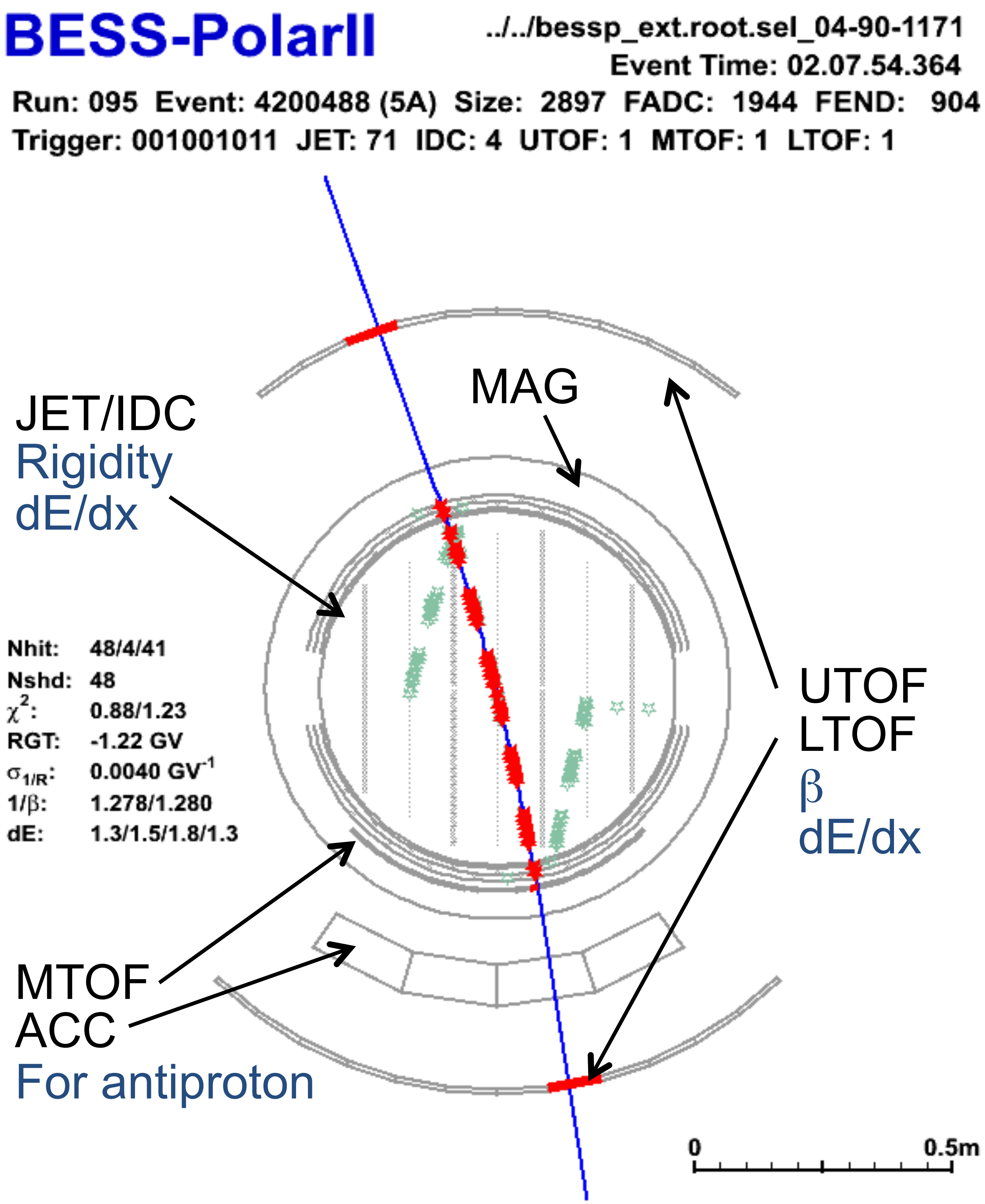
NASA / Goddard Space Flight Center; Start: 25.8.97,
9 wissensch. Instrumente (156 kg) ; 90% duty cycle
$1 \leq Z \leq 28$; 1 keV $\leq E \leq 600$ A·MeV

CRIS: The Cosmic Ray Isotope Spectrometer





BESS Instrumentation



Event display with reconstructed Antiproton track is shown.

Rigidity (MDR:240GV)

Solenoid: Uniform field (ϕ=1m, B=0.8T)
Thin material (2.4 g/cm^2)

Drift chamber: Redundant hits
(σ~150μm, 32~48+4hits)

Charge, Velocity

TOF, Chamber: dE/dx measurement
(Z = 1, 2, ...)

TOF: 1/β measurement (σ~1,2%)

$$m = ZeR\sqrt{1/\beta^2 - 1}$$

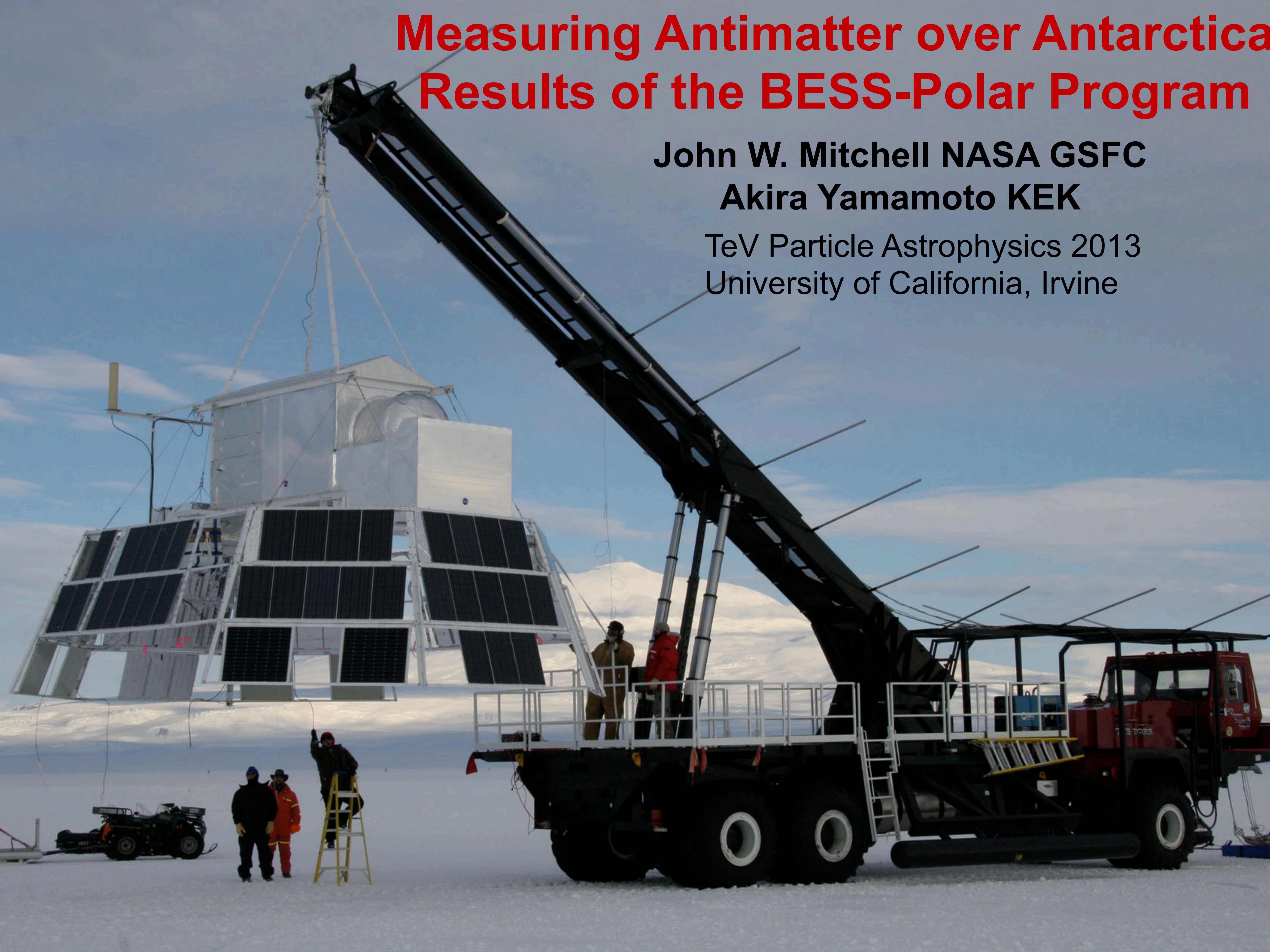
Measuring Antimatter over Antarctica
Results of the BESS-Polar Program

John W. Mitchell NASA GSFC

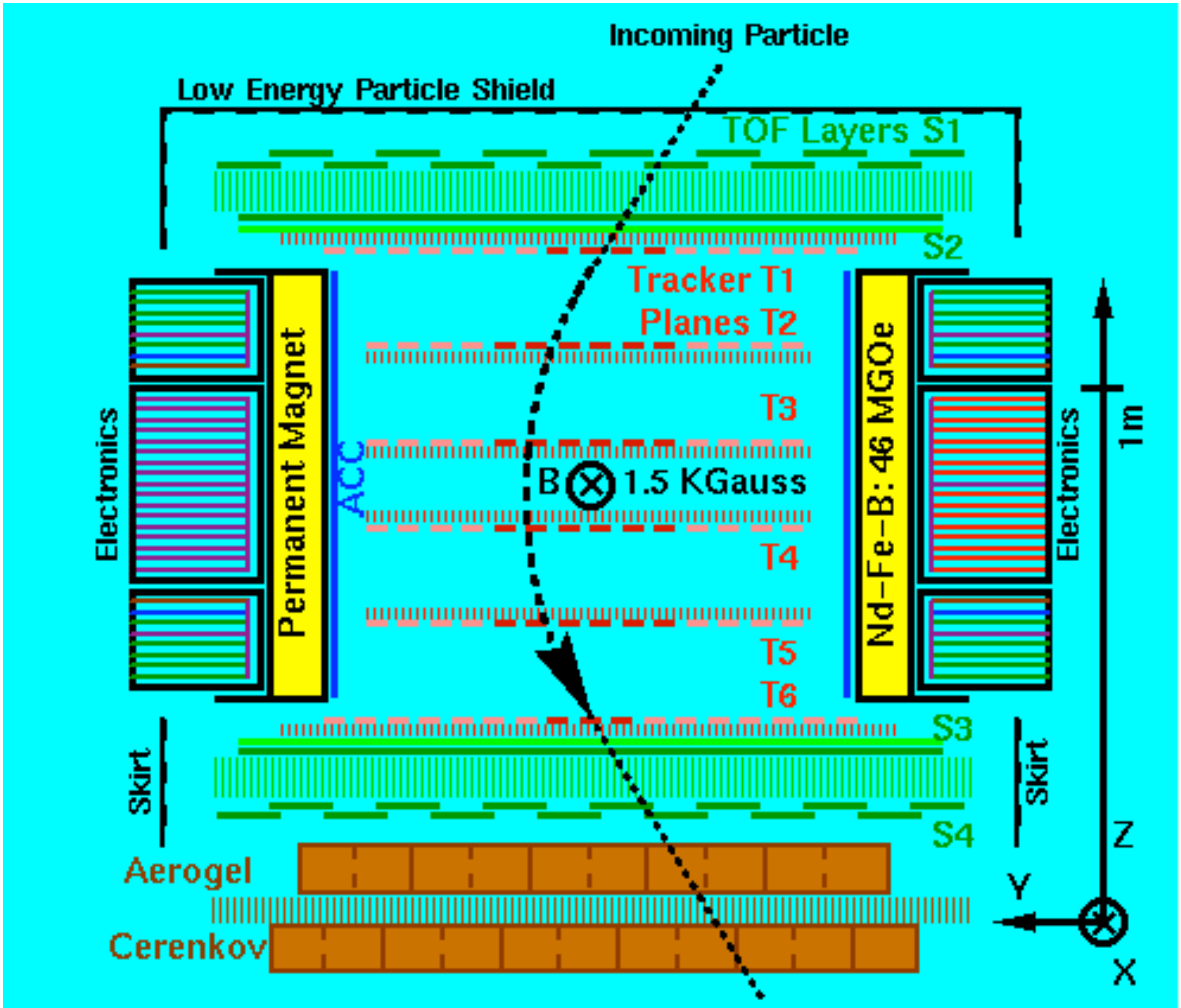
Akira Yamamoto KEK

TeV Particle Astrophysics 2013

University of California, Irvine

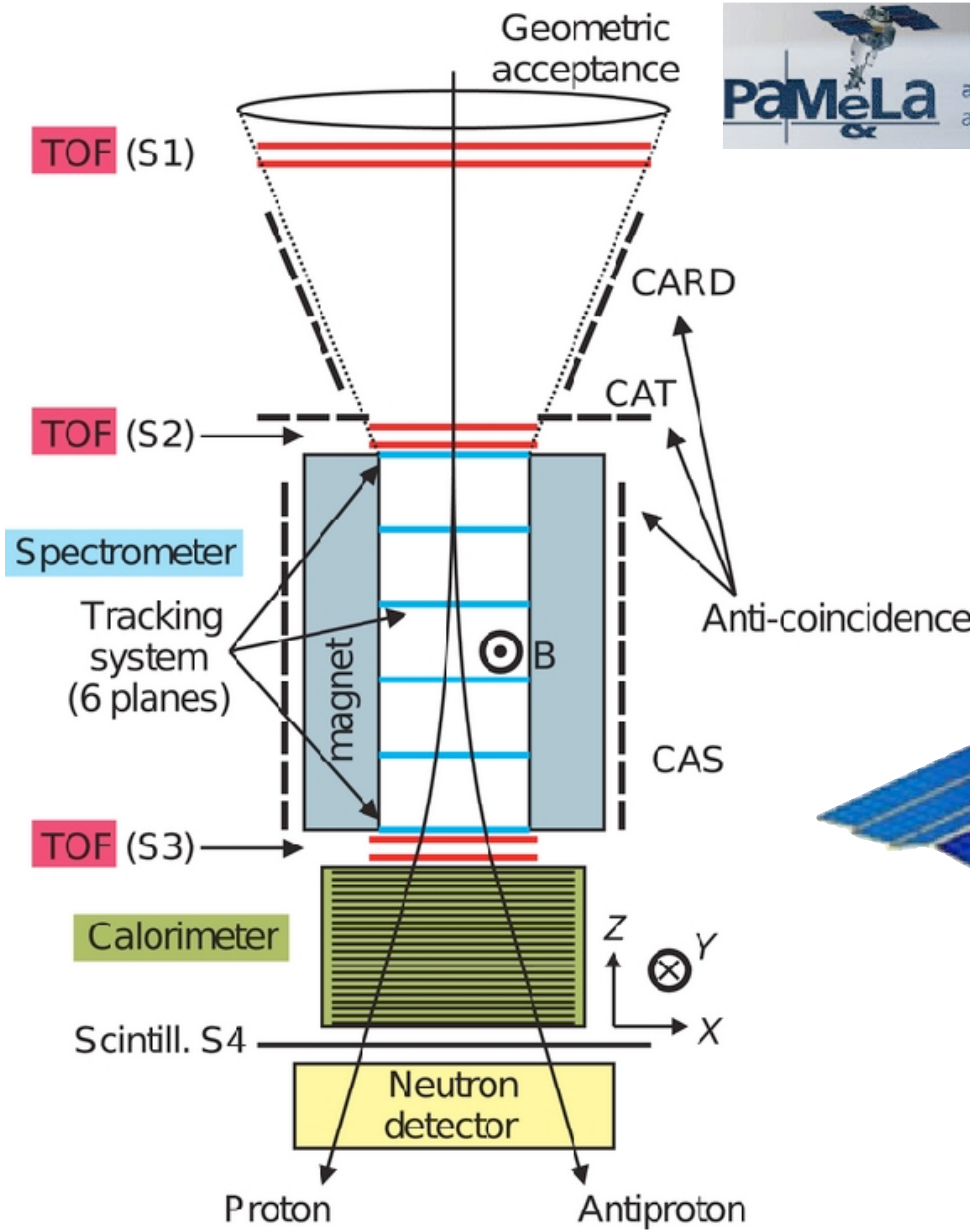


Alpha Magnetic Spectrometer - AMS

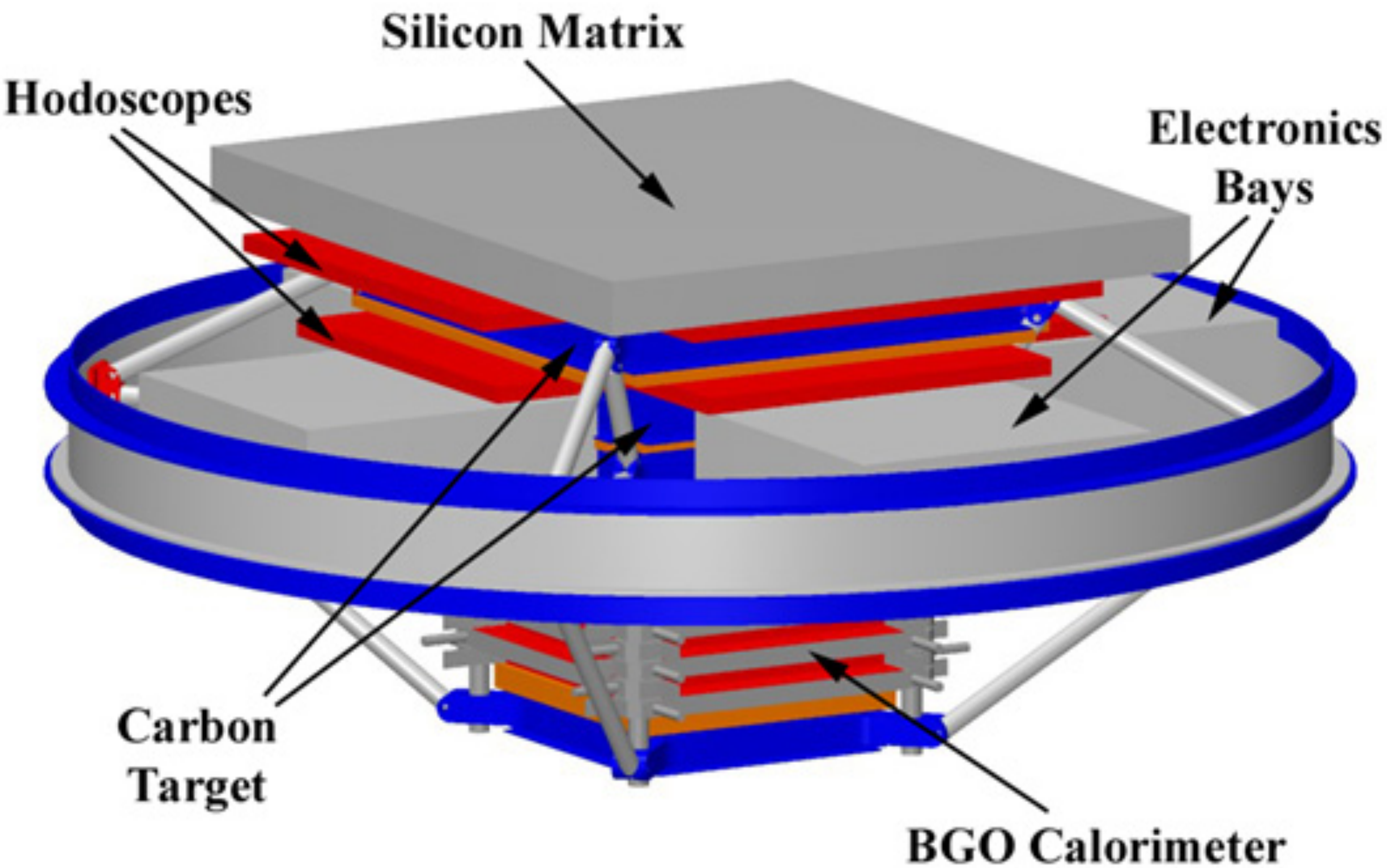


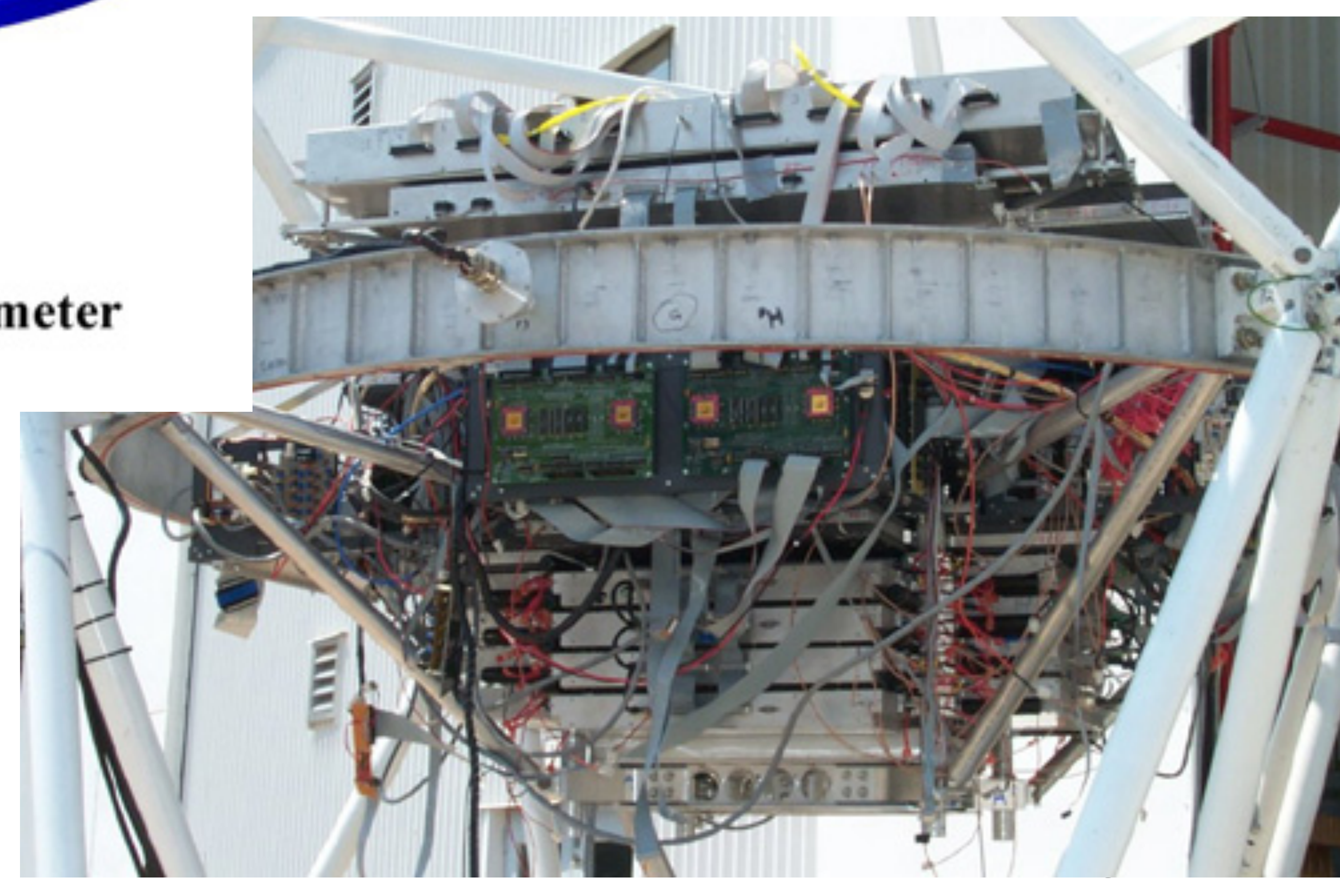
Alpha Magnetic Spectrometer - AMS

PaMeLa – a Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics

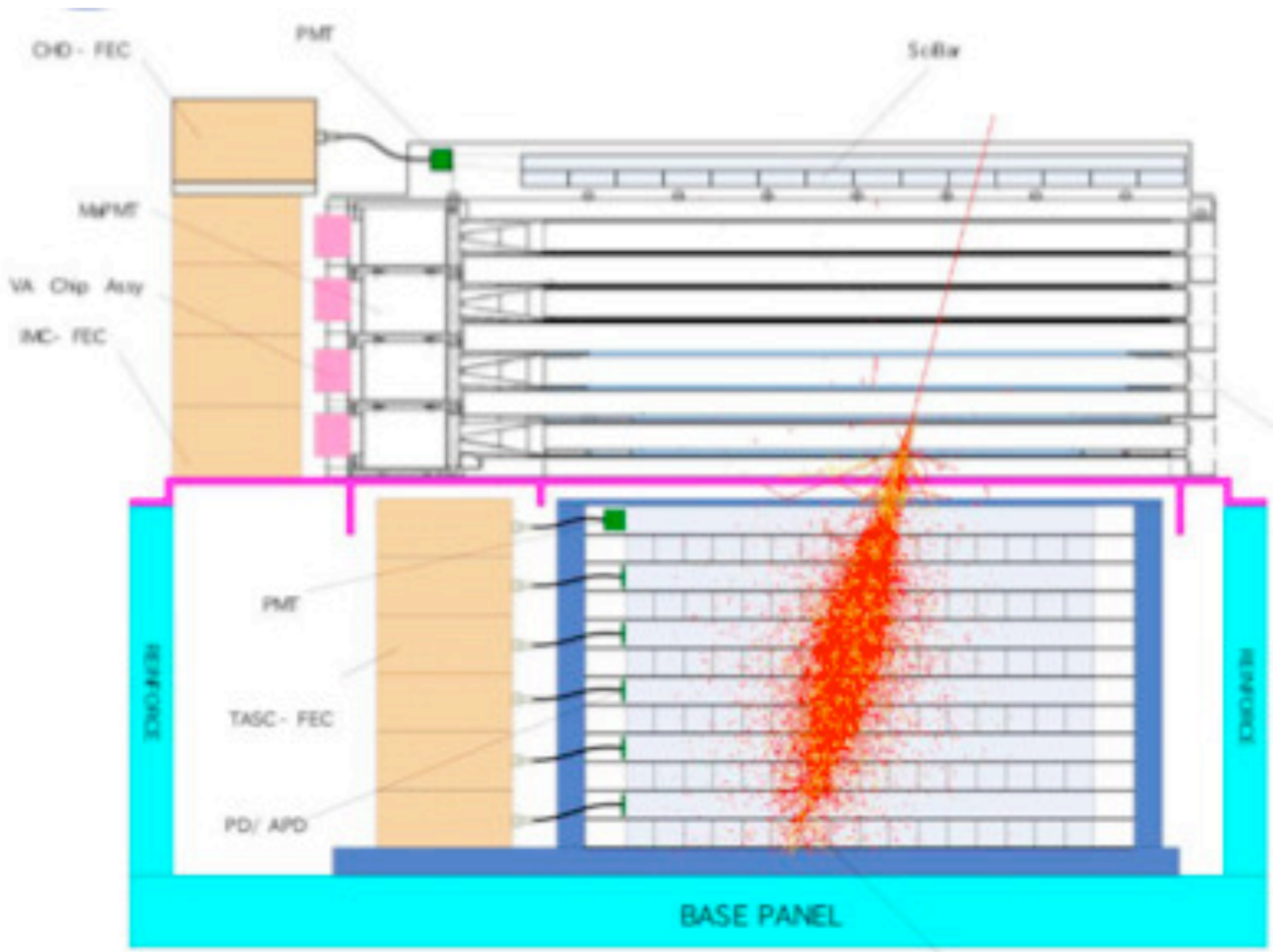



Advanced Thin Ionization Calorimeter


Silicon Matrix
Hodoscopes
Electronics
Bays
Carbon
Target
BGO Calorimeter

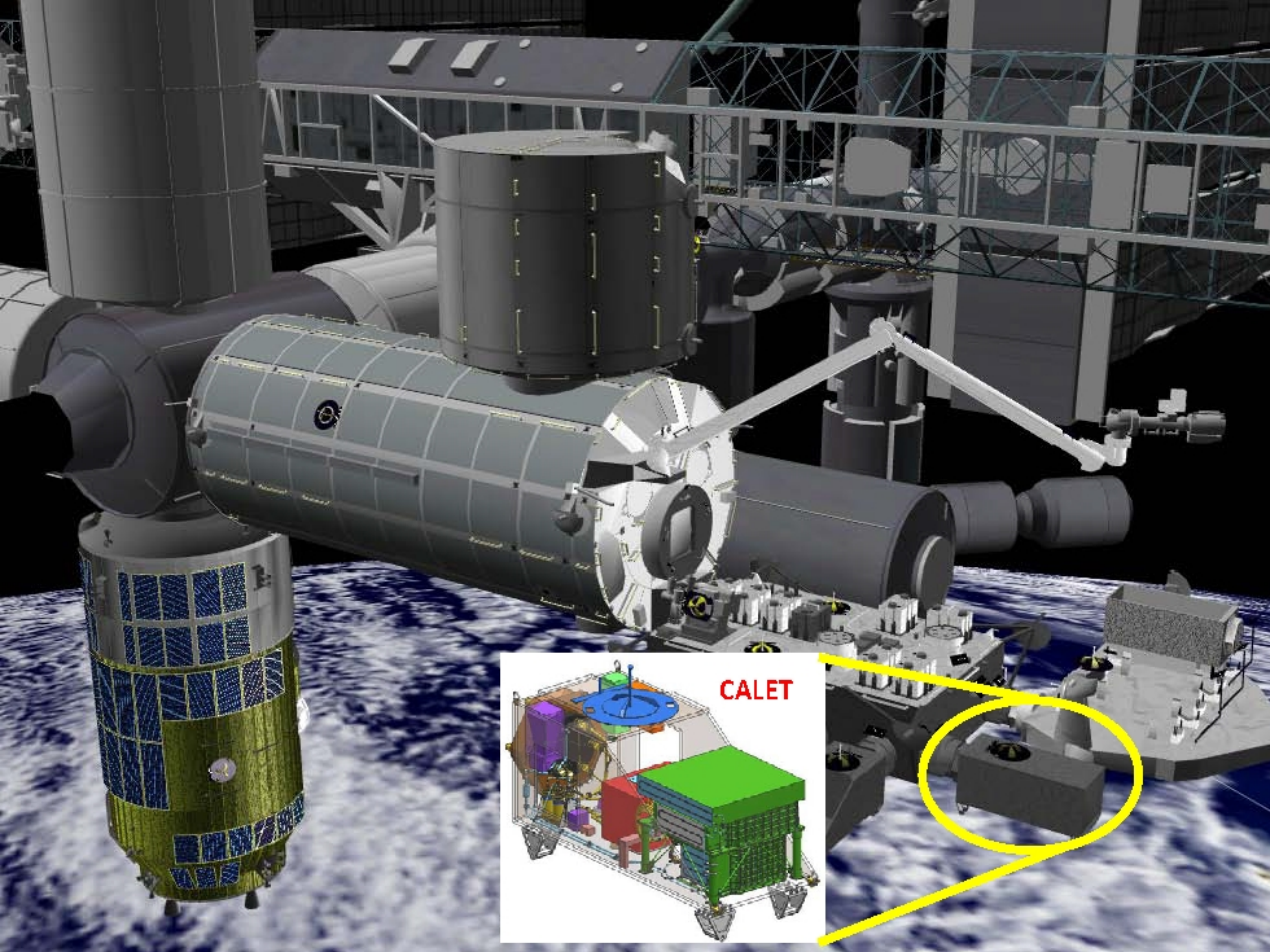


The CALorimetric Electron Telescope (CALET): High Energy Astroparticle Physics Observatory on the International Space Station



- **CHarge Detector (CHD)**
  (Charge Measurement in Z=1-40)
- **Imaging Calorimeter (IMC)**
  (Particle ID, Direction)
  Total Thickness of Tungsten (W): 3 X_0 , 0.11 λ_I
  Layer Number of Scifi Belts: 8 Layers × 2(X,Y)
- **Total Absorption Calorimeter (TASC)**
  (Energy Measurement, Particle ID)
  PWO 20mm x 20mm x 320mm
  Total Depth of PWO: 27 X_0 (24 cm) , 1.35 λ_I

	CHD (Charge Detector)	IMC (Imaging Calorimeter)	TASC (Total Absorption Calorimeter)
Function	**Charge Measurement (Z = 1 - 40)**	Arrival Direction, Particle ID	Energy Measurement, Particle ID
Sensor (+ Absorber)	**Plastic Scintillator : 2 layers Unit Size: 32mm x 10mm x 450mm**	SciFi : 16 layers Unit size: 1mm^2 x 448 mm Total thickness of Tungsten: 3 X_0	PWO log: 12 layers Unit size: 19mm x 20mm x 326mm Total Thickness of PWO: 27 X_0
Readout	**PMT+CSA**	64 -anode PMT+ ASIC	APD/PD+CSA PMT+CSA (for Trigger)


CALET

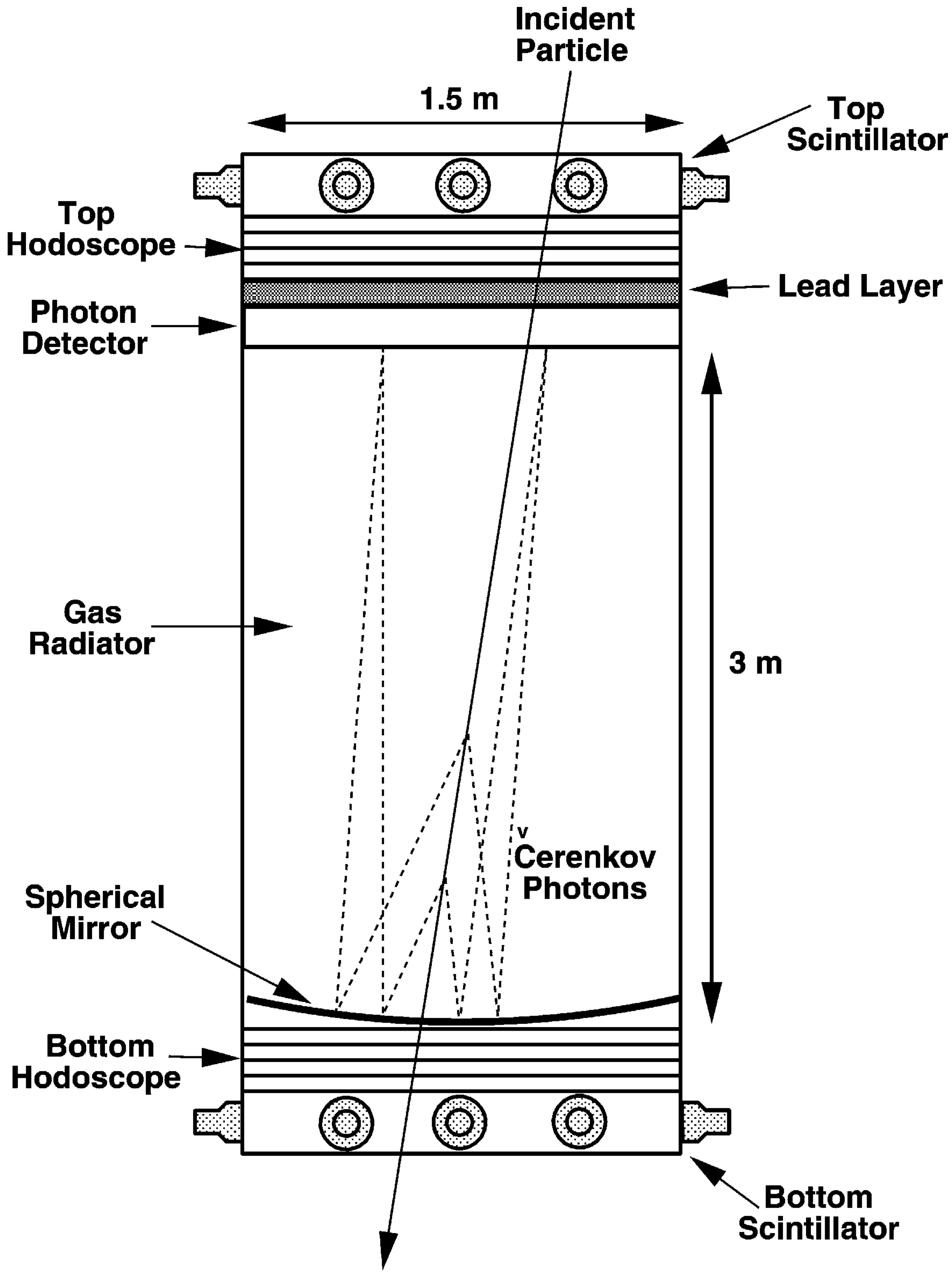


Fig. 1. Schematic cross-section of the instrument.

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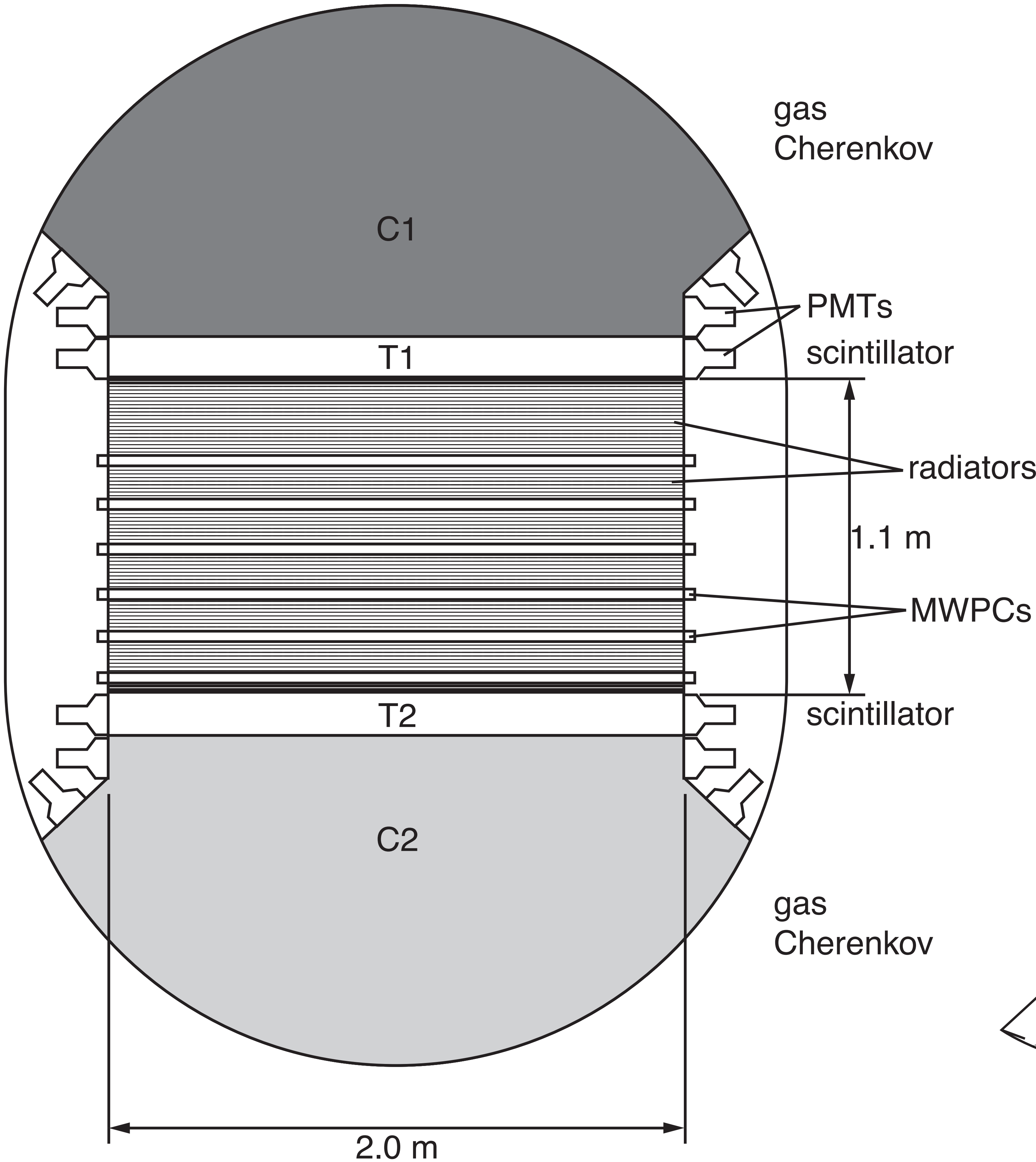
The energy spectrum of cosmic-ray protons and helium near 100 GeV

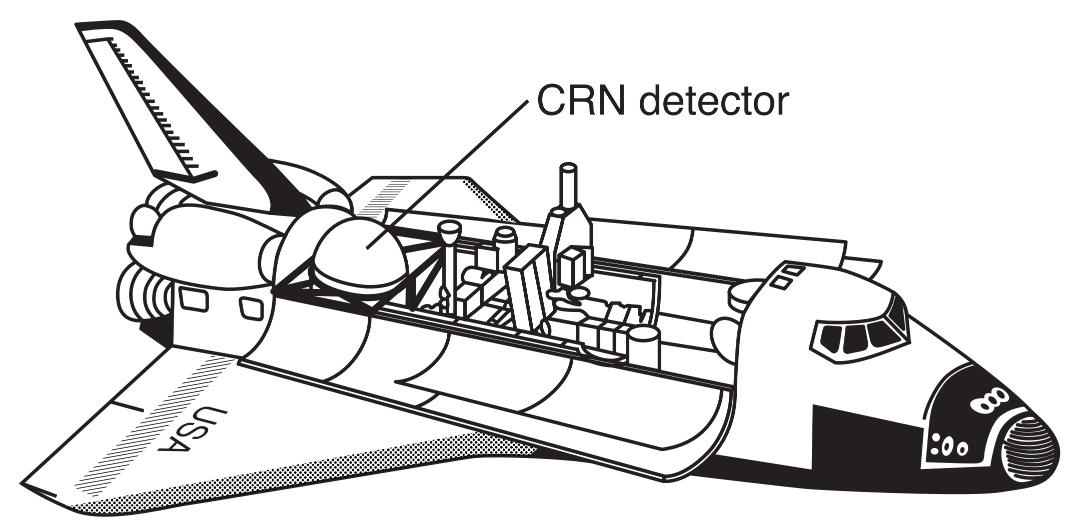
E. Diehl [1], D. Ellithorpe, D. Müller, S.P. Swordy *

Department of Physics, Enrico Fermi Institute, University of Chicago, 5640 Ellis Avenue, Chicago, IL 60637-1433, USA

Received 15 February 2002; accepted 2 May 2002

Cosmic Ray Nuclei instrument - CRN



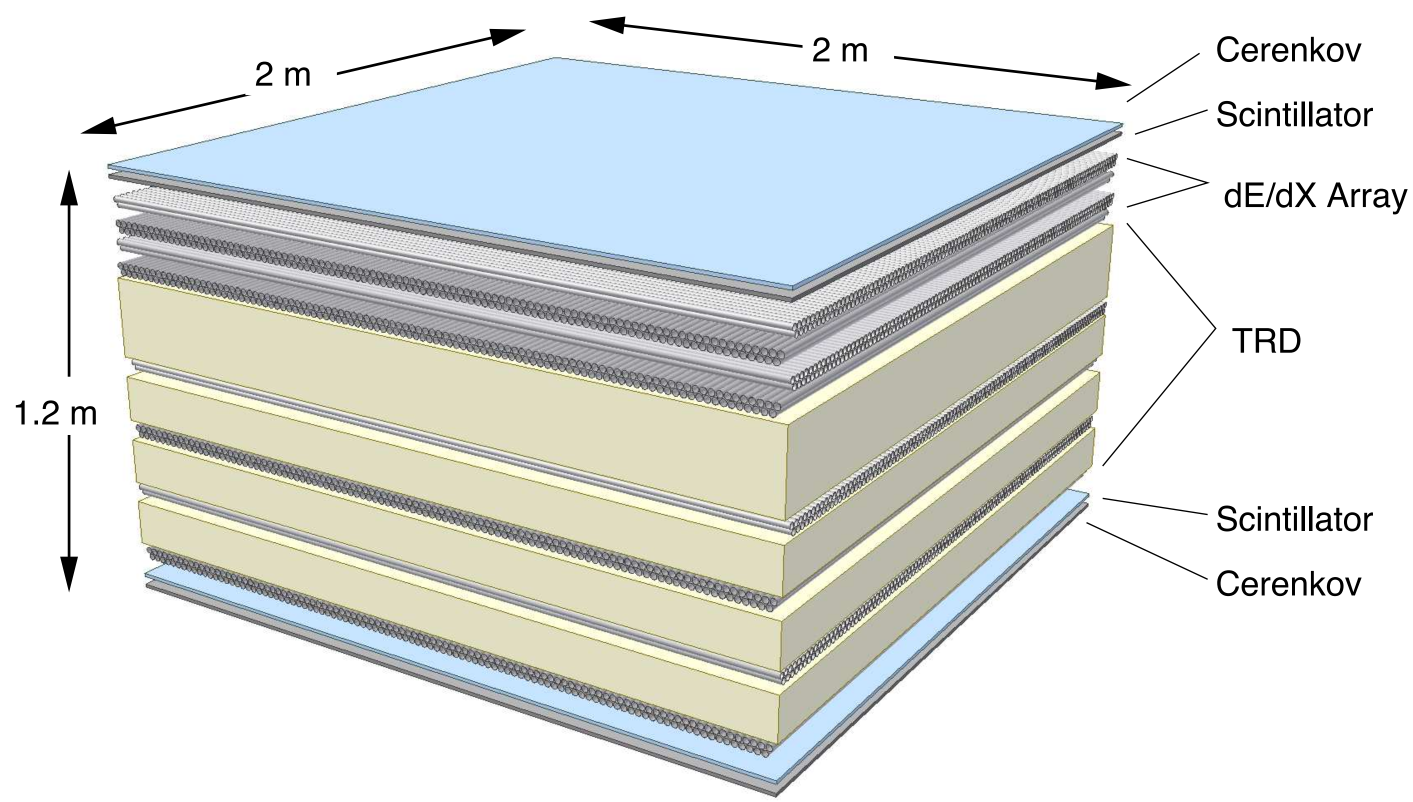


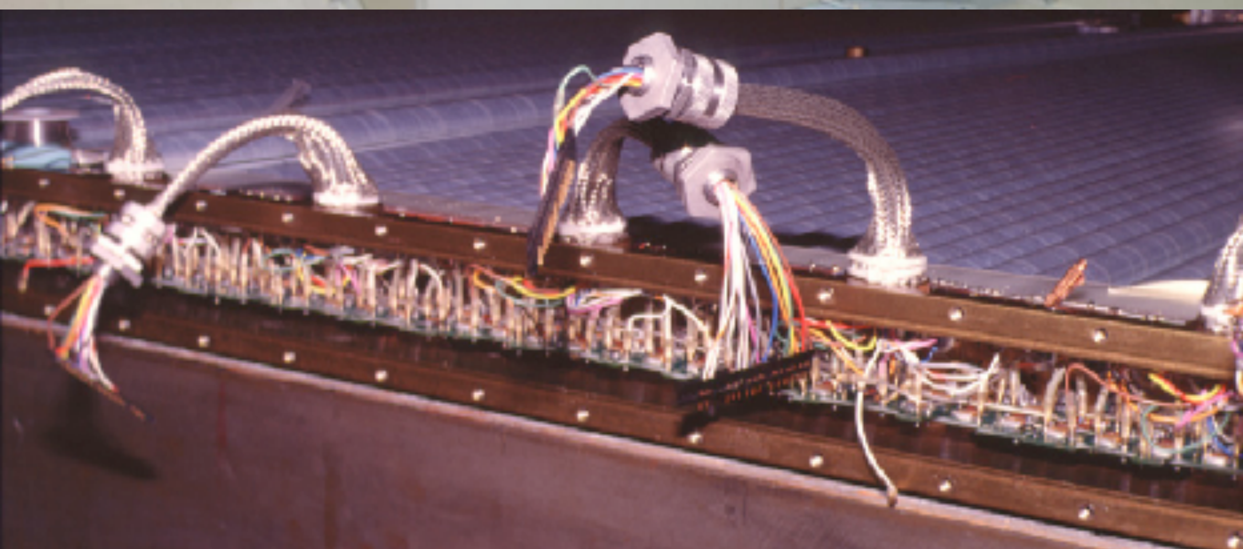
Challenger 1985

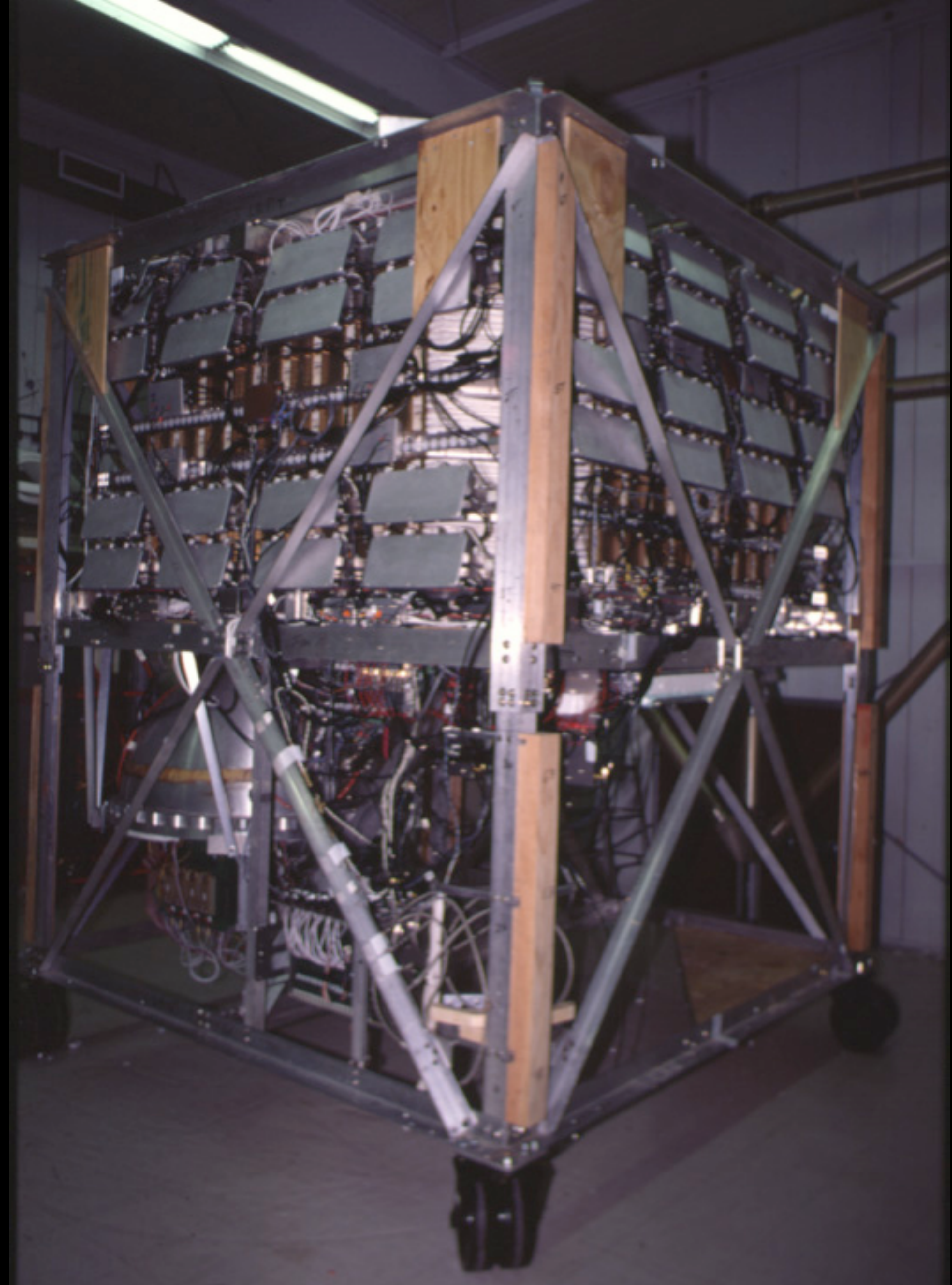
TRACER experiment

TRACER Overview

- Two pairs of Cerenkov and Scintillation Detectors
- 1600 Proportional Tubes (2cm $\times$ 2m) in 16 Layers
  - Upper 8 Layers: dE/dX in Gas (dE/dX array)
  - Lower 8 Layers: dE/dX+TR (TRD)





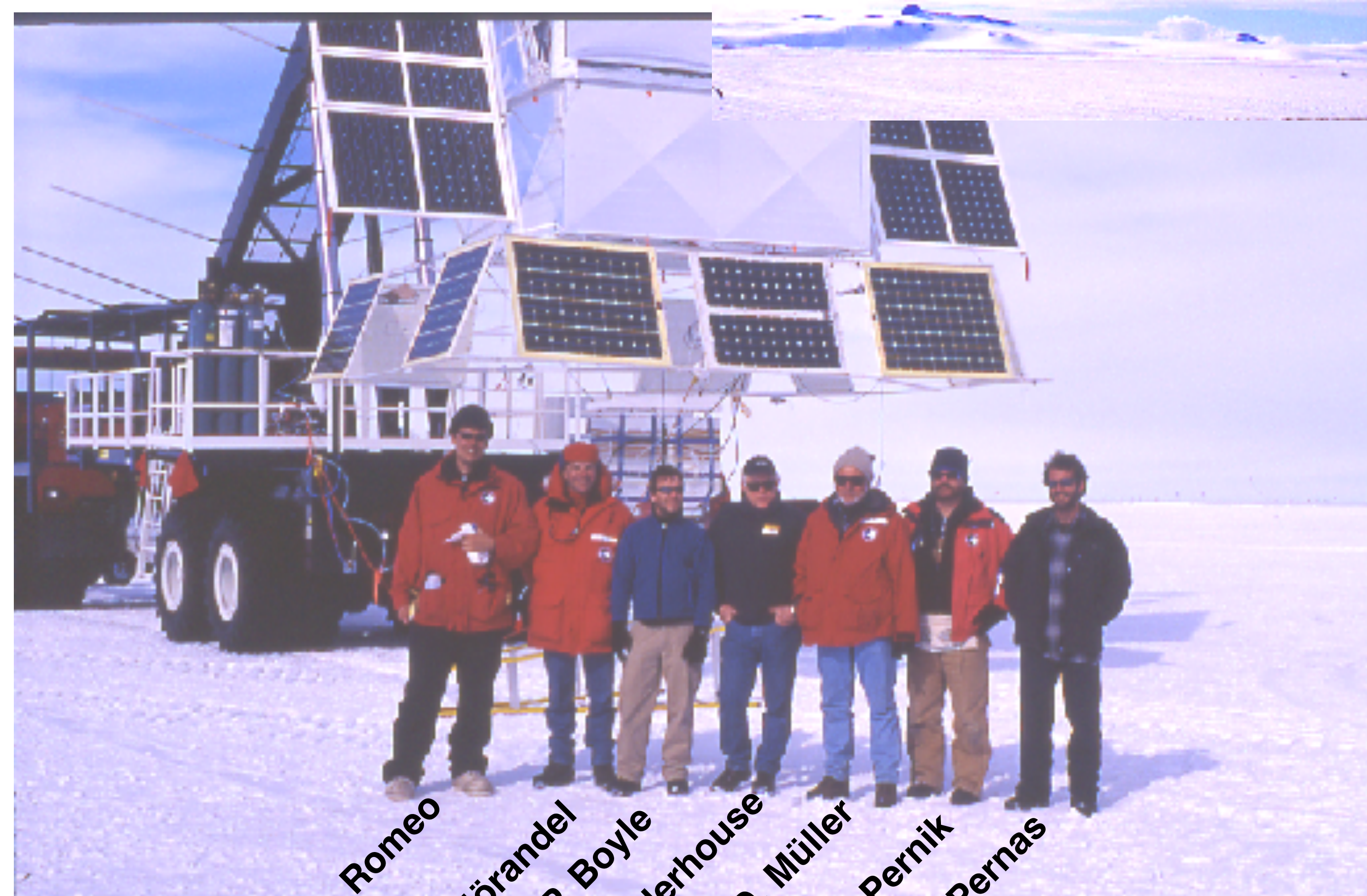


JRH 40220

TRACER Experiment - Mc Murdo, Antarctica
flight: 12. – 26. December 2003 ~ 40 km (3-5 g/cm^2)

balloon filled with 10^6 m^3 He
~130 m diameter
total mass ~5 t

TRACER Experiment



A. Romeo
J.R. Hörandel
P. Boyle
G. Kelderhouse
D. Müller
D. Pernik
M. Ave-Pernas

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