

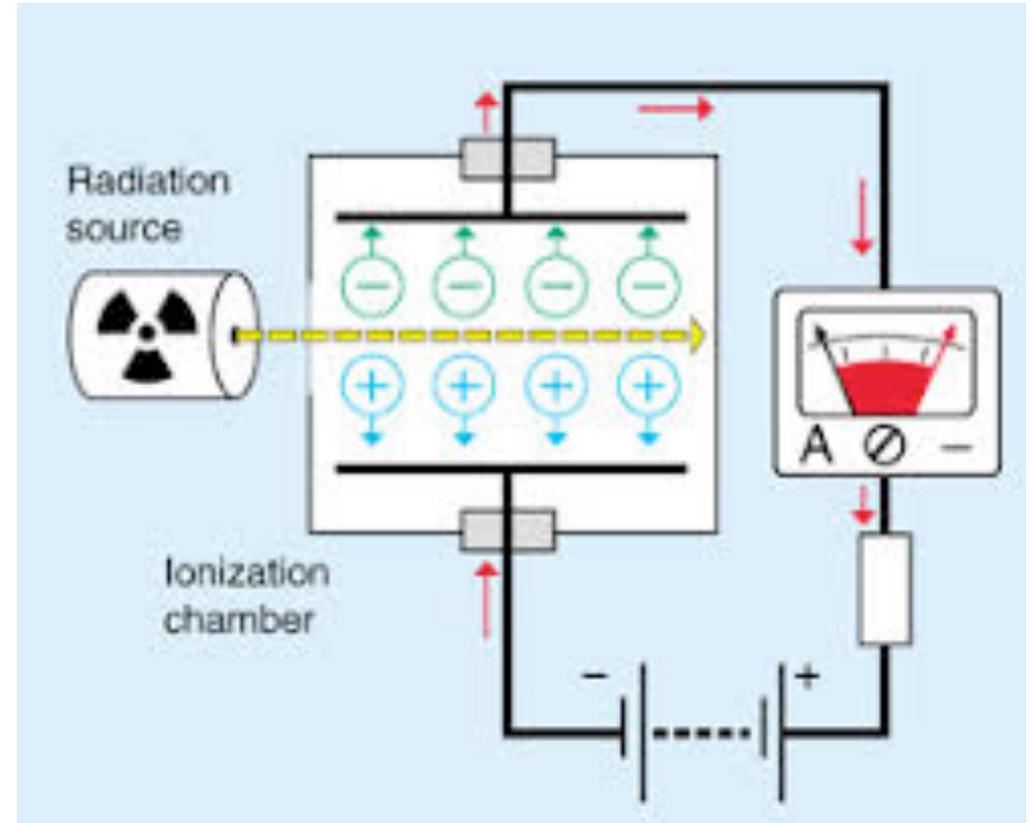
Ionization chamber

traversing particle liberates electrons (ionization)

electrons and (positive) ions drift in electric field

--> electric signal proportional to energy loss

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



energy in electric field reduced through free charge carriers

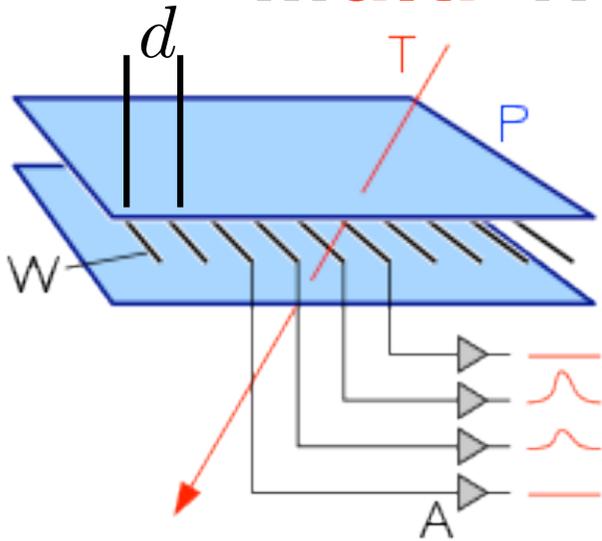
$$\frac{1}{2}CU^2 = \frac{1}{2}CU_0^2 - N \int_{x_0}^x qE dx$$

capacitor charged to U_0
 N charge carrier pairs

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

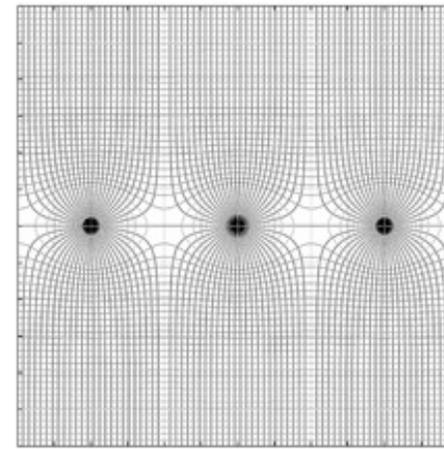
signal amplitude $\Delta U = -\frac{Nq}{Cd}(x - x_0)$ proportional to liberated charge and deposited energy

Multi-Wire Proportional Chamber



spatial resolution

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



electric field

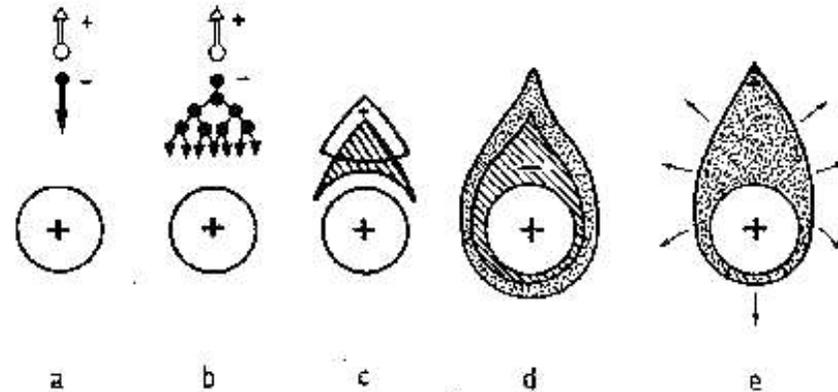
ionization liberates electrons
--> acceleration in electric field

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

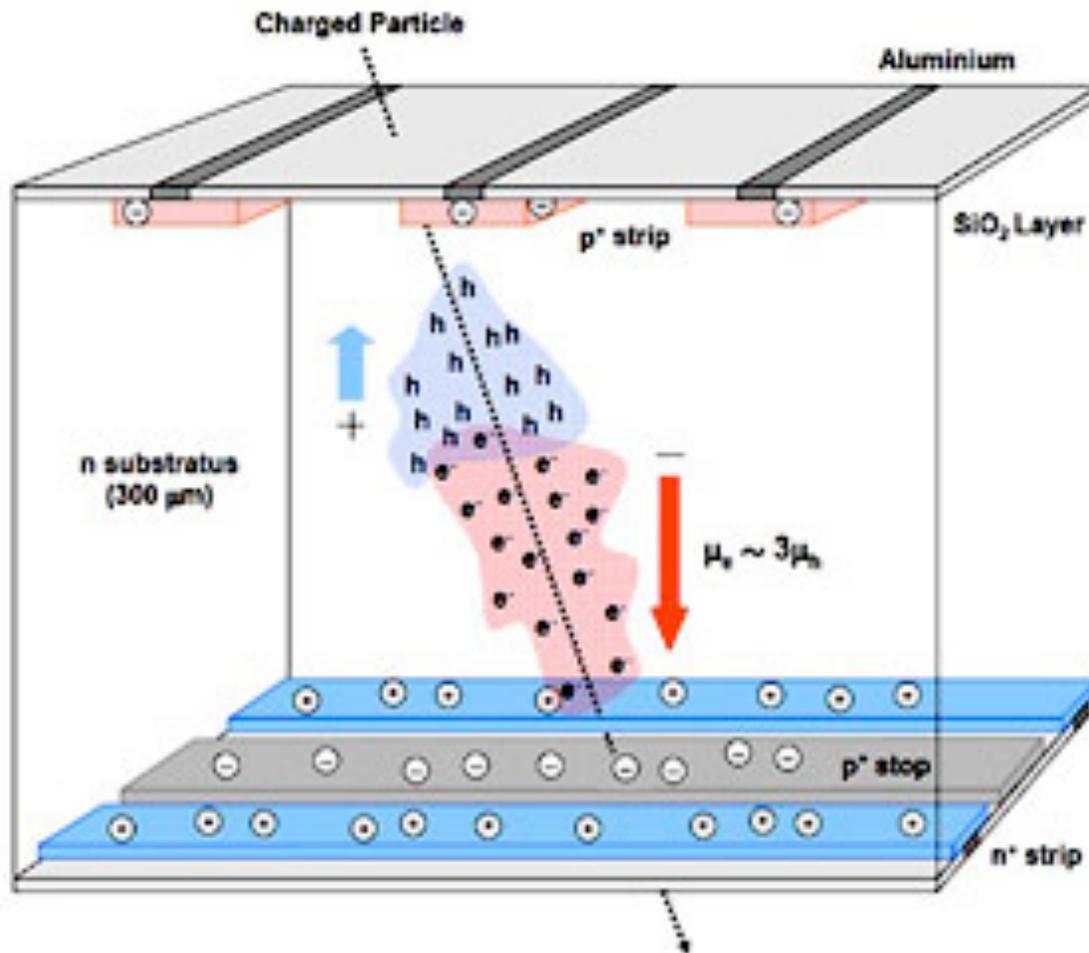


voltage signal $\Delta U = -\frac{eN}{C} A$

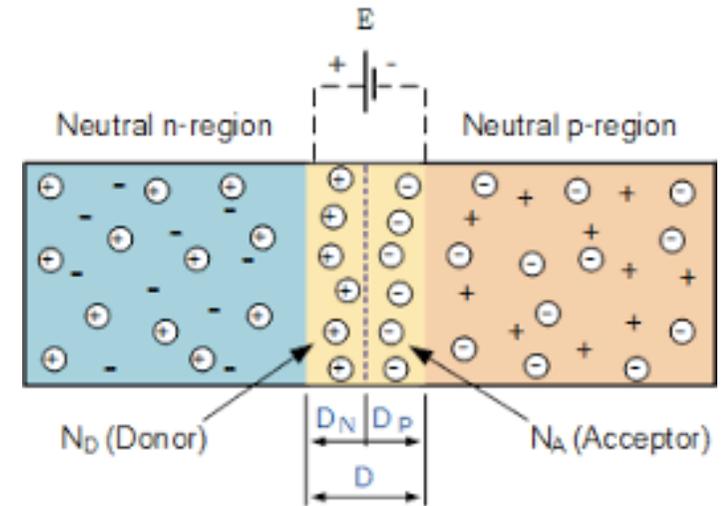
A gas amplification factor
N charge carrier pairs
C capacity

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/cm³

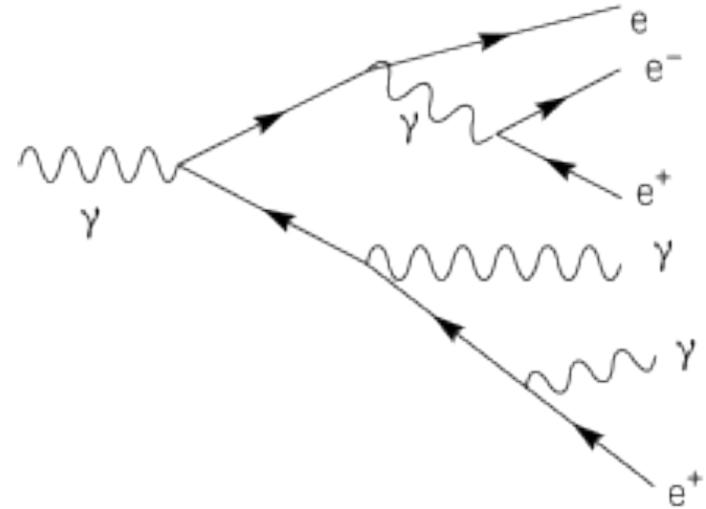
Energy measurement - calorimeter

electron-photon calorimeter

at high energies (>GeV):

electrons loose energy through Bremsstrahlung
photons loose energy through pair production

--> electromagnetic cascade

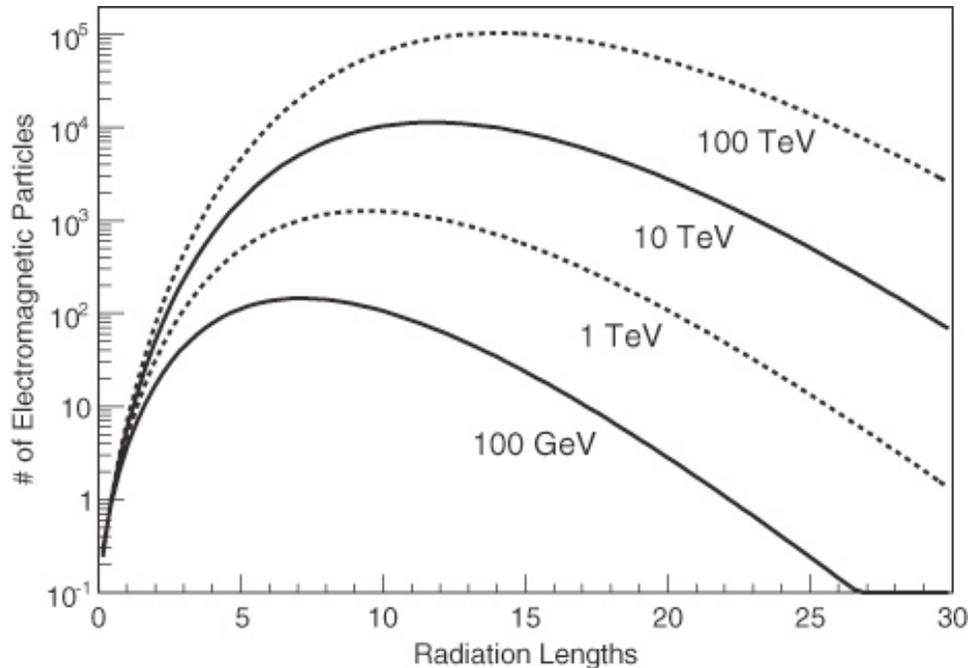


longitudinal shower development/energy loss

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

$$t = x/X_0$$

depth in material in units of the radiation length



depth of maximum depends on energy as

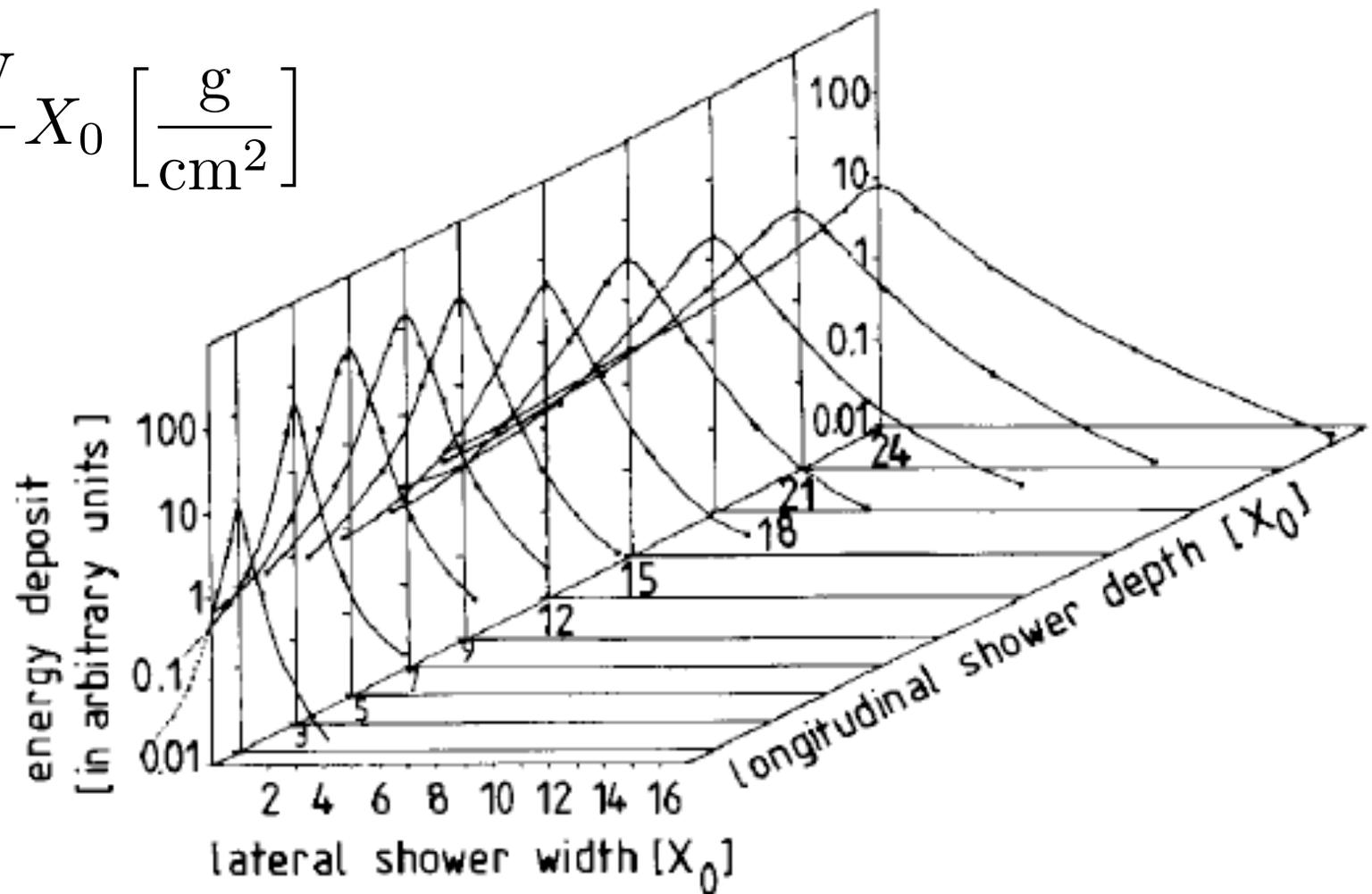
$$t_{max} \propto \ln \frac{E}{E_c}$$

Energy measurement - calorimeter

electromagnetic cascade

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

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



Electromagnetic calorimetry

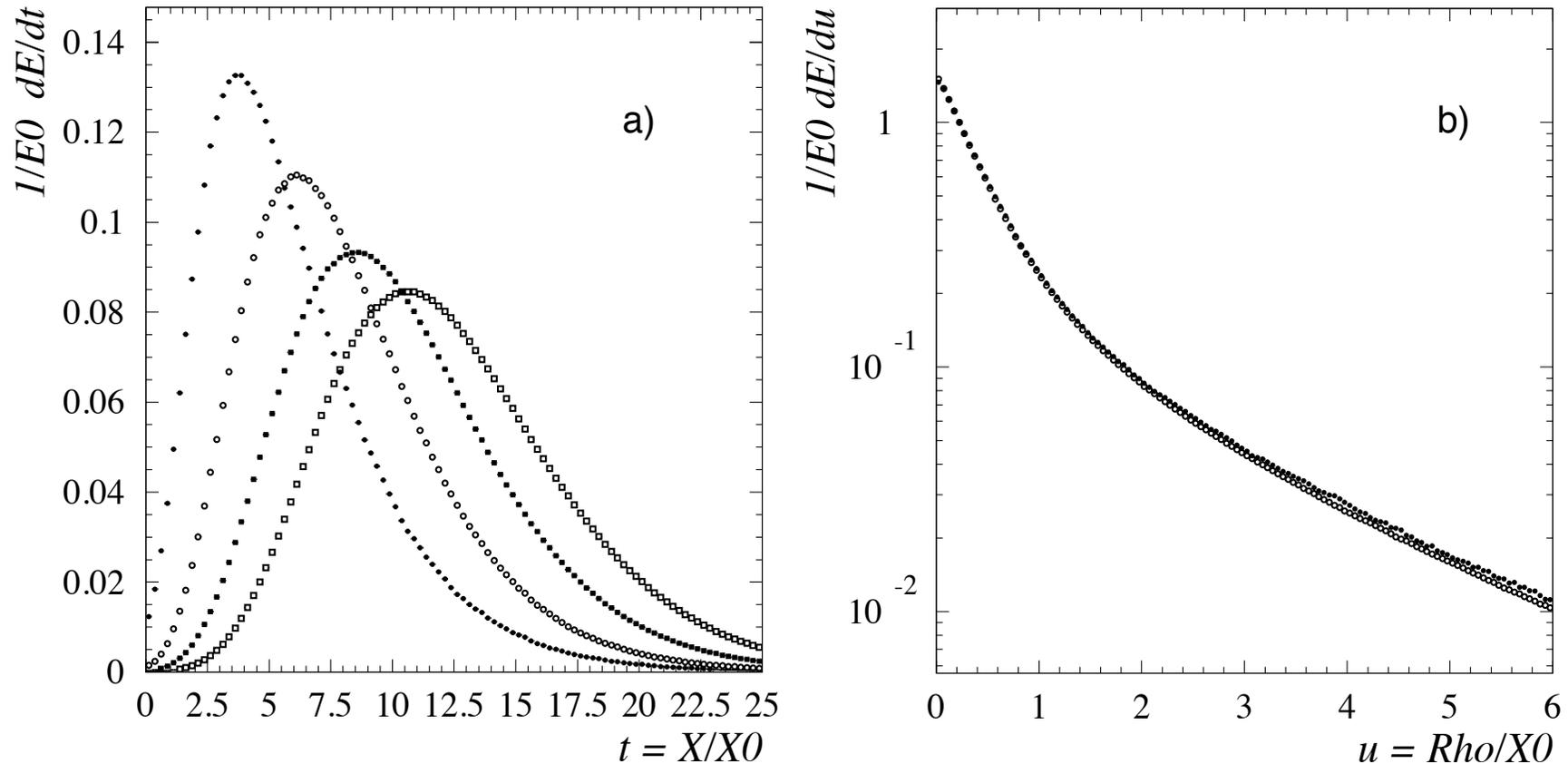


FIG. 2 (a): Simulated shower longitudinal profiles in PbWO_4 , as a function of the material thickness (expressed in radiation lengths), for incident electrons of energy (from left to right) 1 GeV, 10 GeV, 100 GeV, 1 TeV. (b): Simulated radial shower profiles in PbWO_4 , as a function of the radial distance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

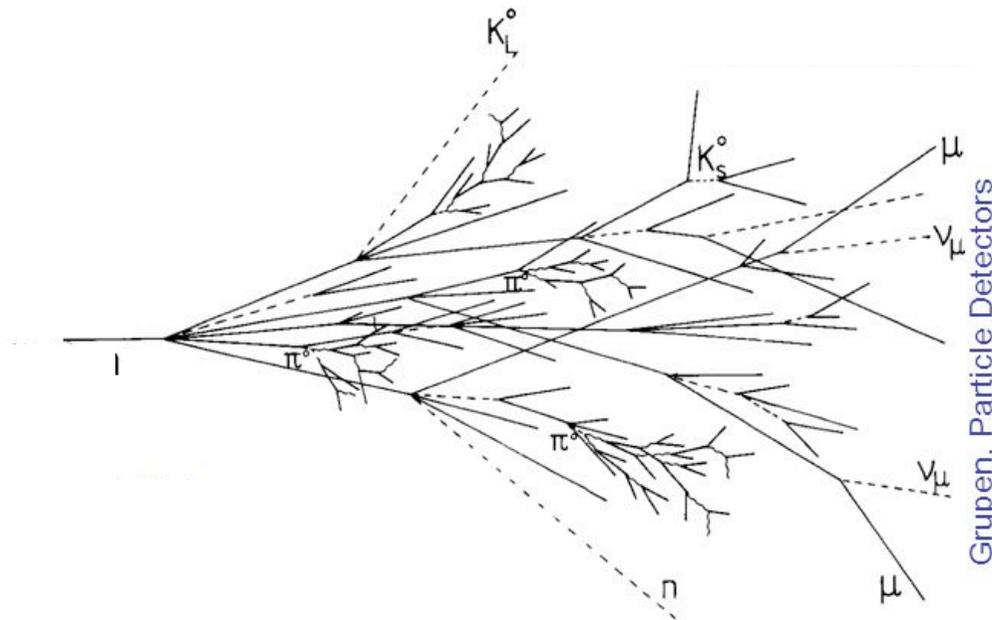
Energy measurement - calorimeter

hadron calorimeter

high-energy hadrons ($> \text{GeV}$) 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

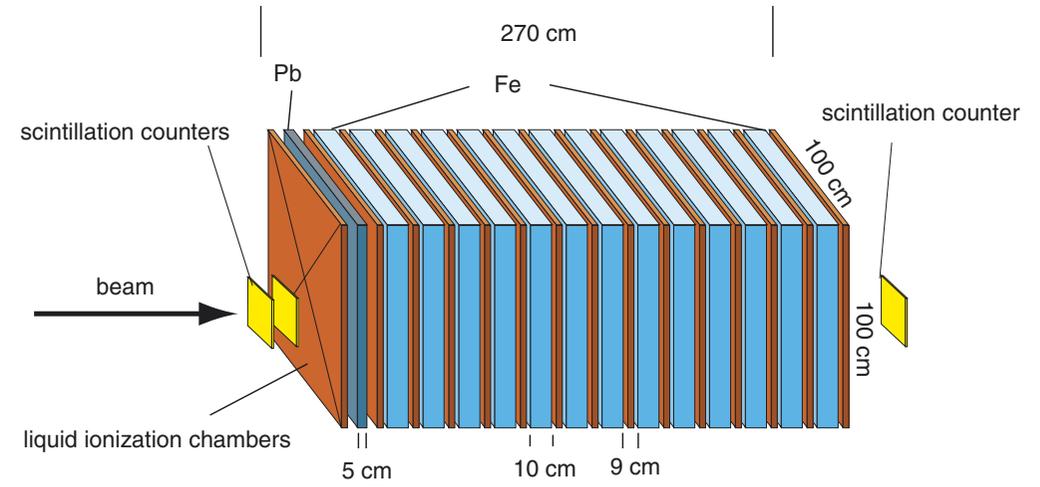


Fig. 2. Schematic view of the sampling calorimeter.

S. Plewnia et al. / Nuclear Instruments and Methods in Physics Research A 566 (2006) 422–432

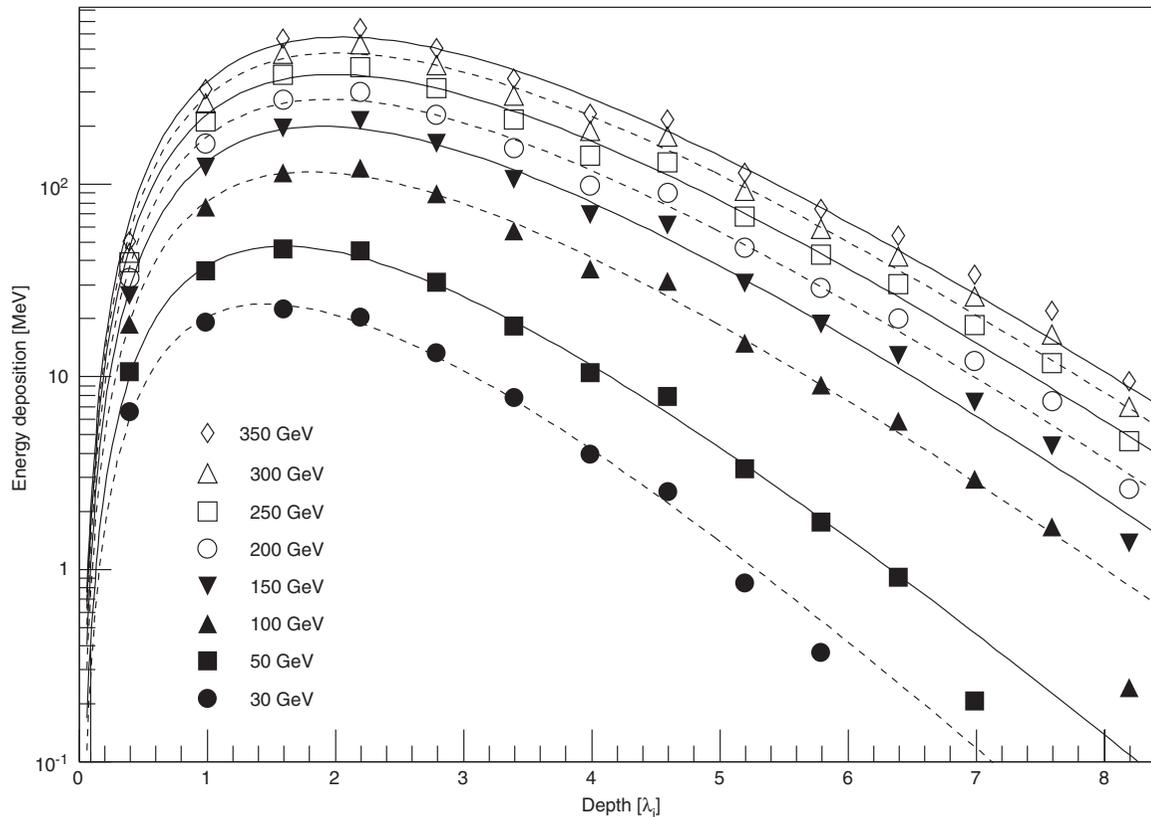


Fig. 13. Measured energy deposition as function of depth in the calorimeter for hadrons with energies from 30 to 350 GeV. The lines represent fits according to Eq. (7).

sampling calorimeter
alternating layers of absorber material and detectors

energy resolution

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

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

Energy measurement - calorimeter

hadron calorimeter

lateral shower development

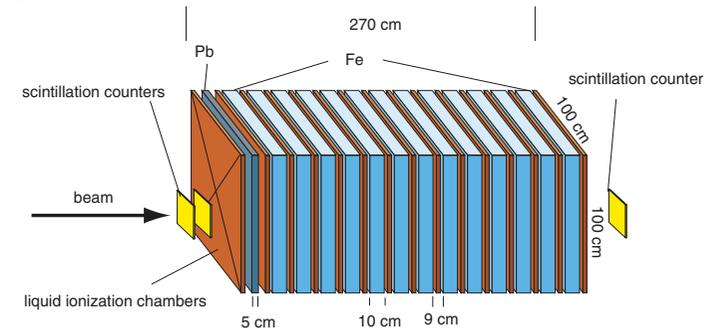
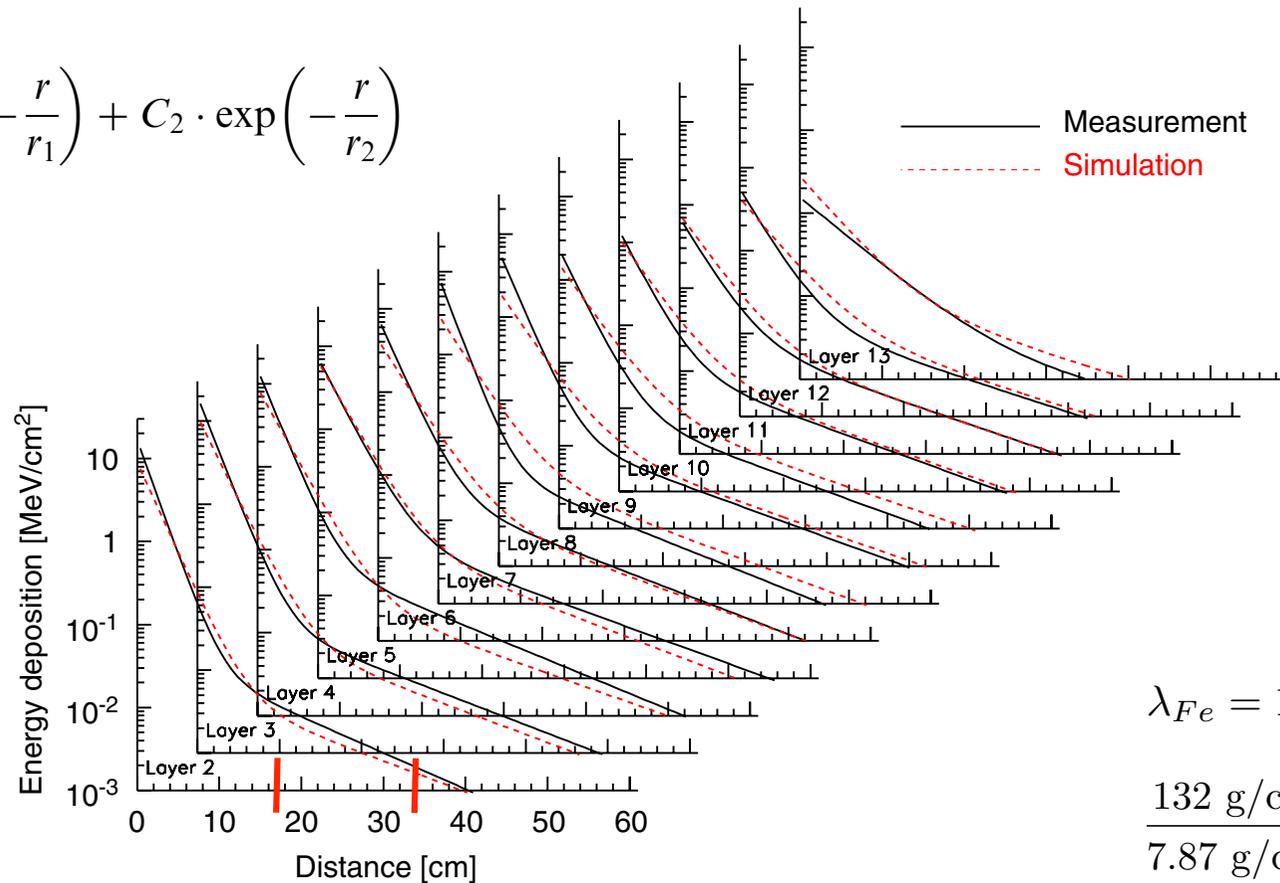


Fig. 2. Schematic view of the sampling calorimeter.

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



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

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

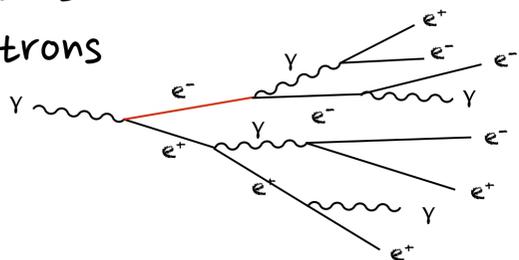
Fig. 9. Lateral distribution of the energy deposition in different layers of the calorimeter for 300 GeV hadrons. Measurements (solid lines) and simulations (dashed lines) are represented by parameterizations according to Eq. (5).

Particle identification - calorimeter

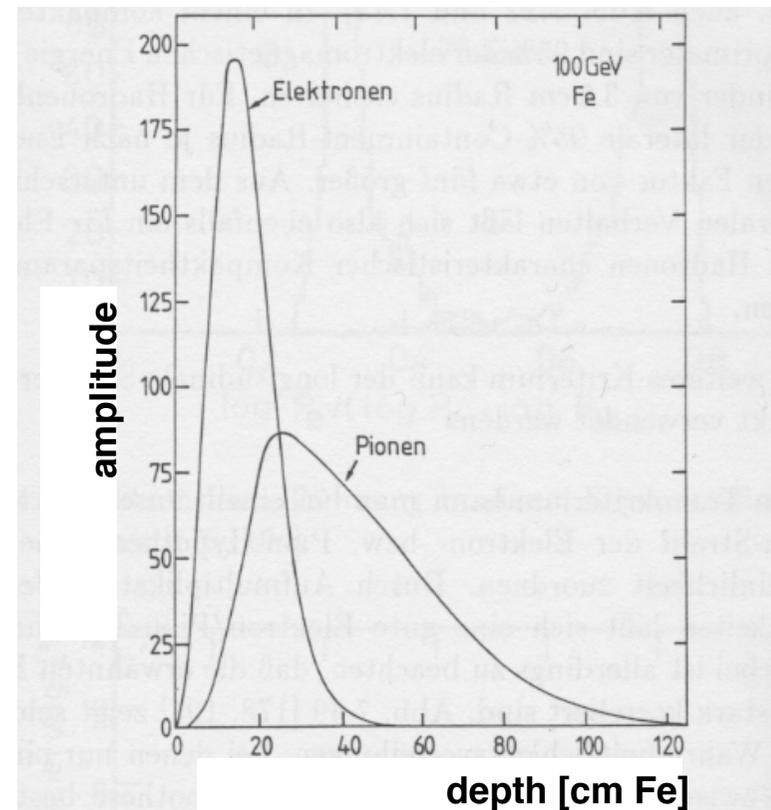
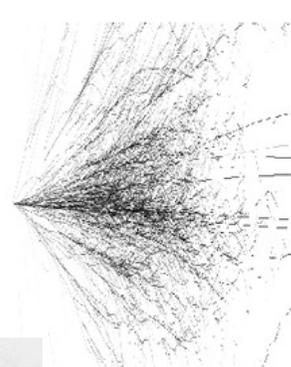
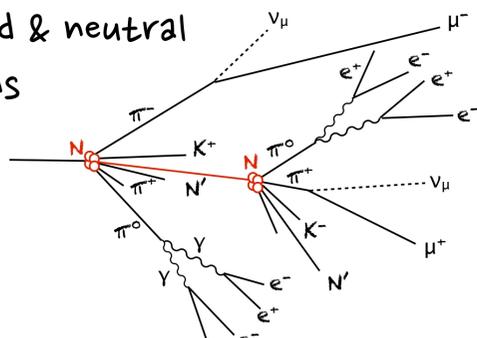
in calorimeters there are different shower responses for electrons and hadrons

Photons

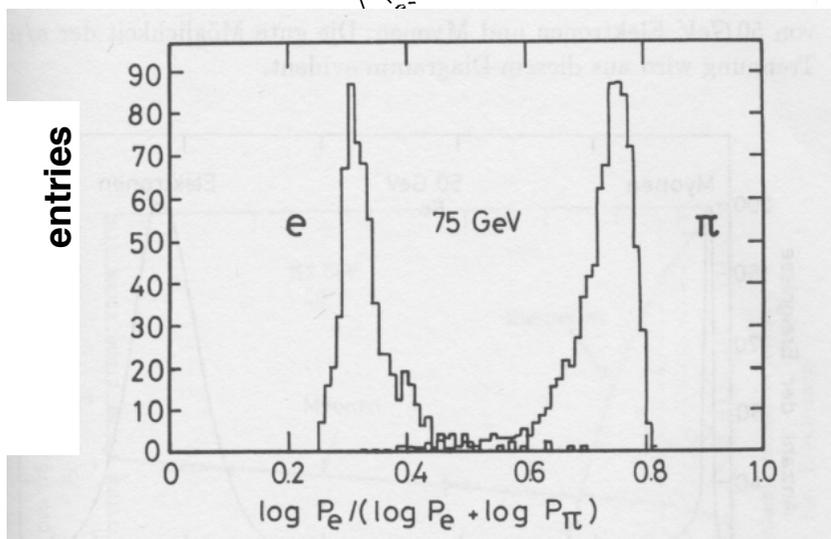
Electrons



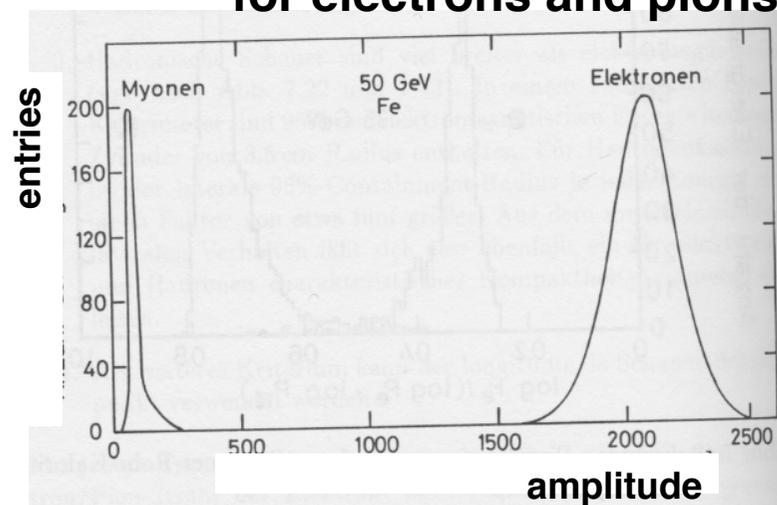
charged & neutral hadrons



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

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

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

**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

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

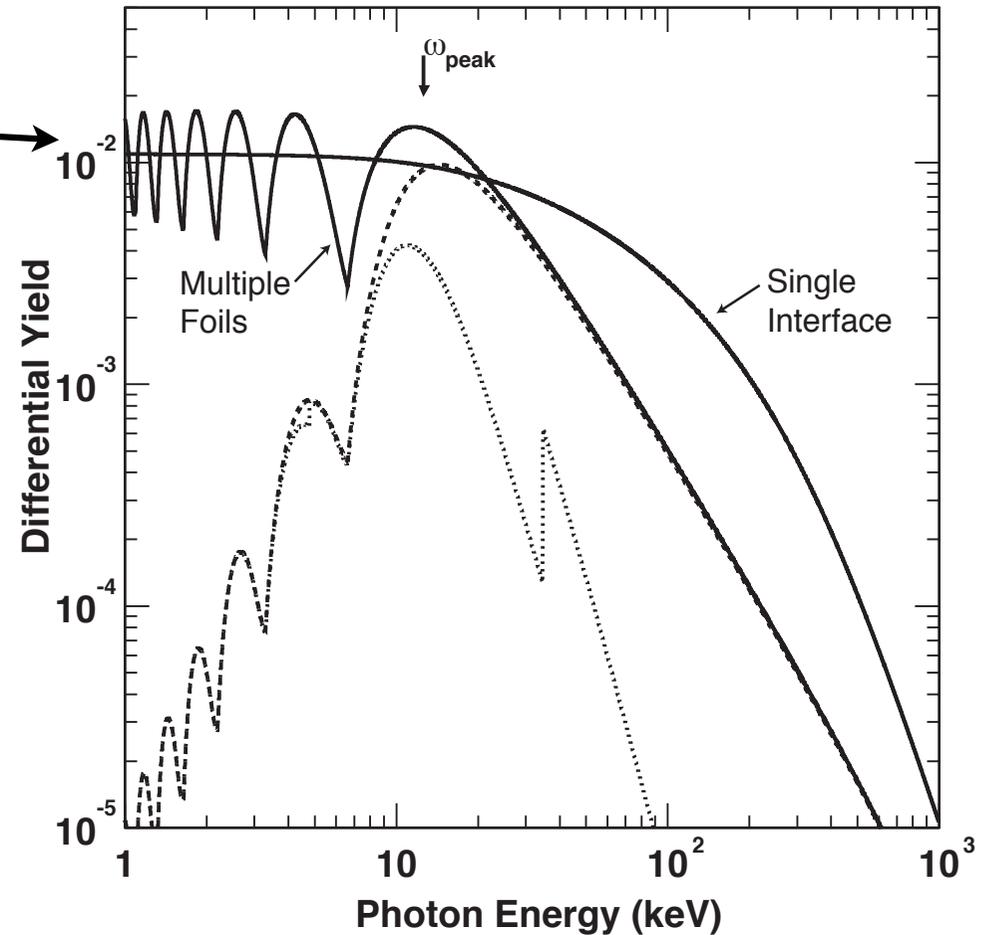
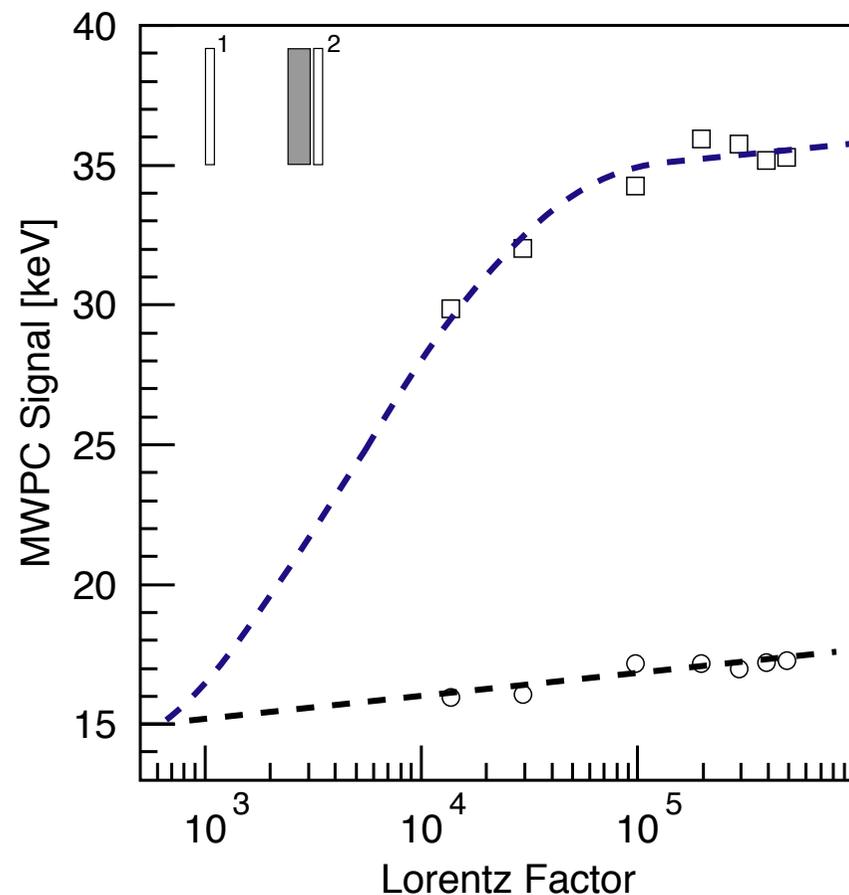


Fig. 1. Differential TR yield ($dW/d\omega$) versus Lorentz factor for several configurations. Shown are the single-interface (smooth line) and approximate multi-foil (oscillating line) energy spectra, as well as the multi-foil spectrum modified by self-absorption processes in the foil (dashed line). 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 $\gamma = 2 \times 10^4$, $l_1 = 35 \mu\text{m}$, $l_2 = 1000 \mu\text{m}$, $\omega_1 = 21.2 \text{ eV}$, and $\omega_2 = 0.75 \text{ eV}$.



Transition Radiation Detector

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

TRD test at CERN

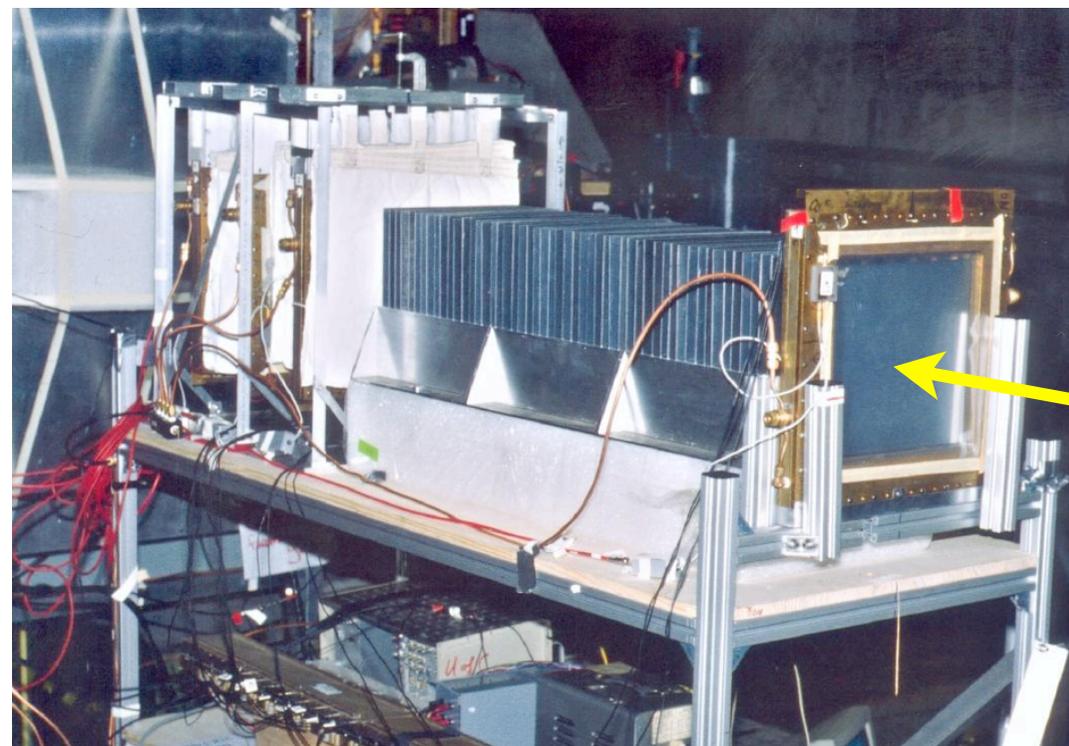
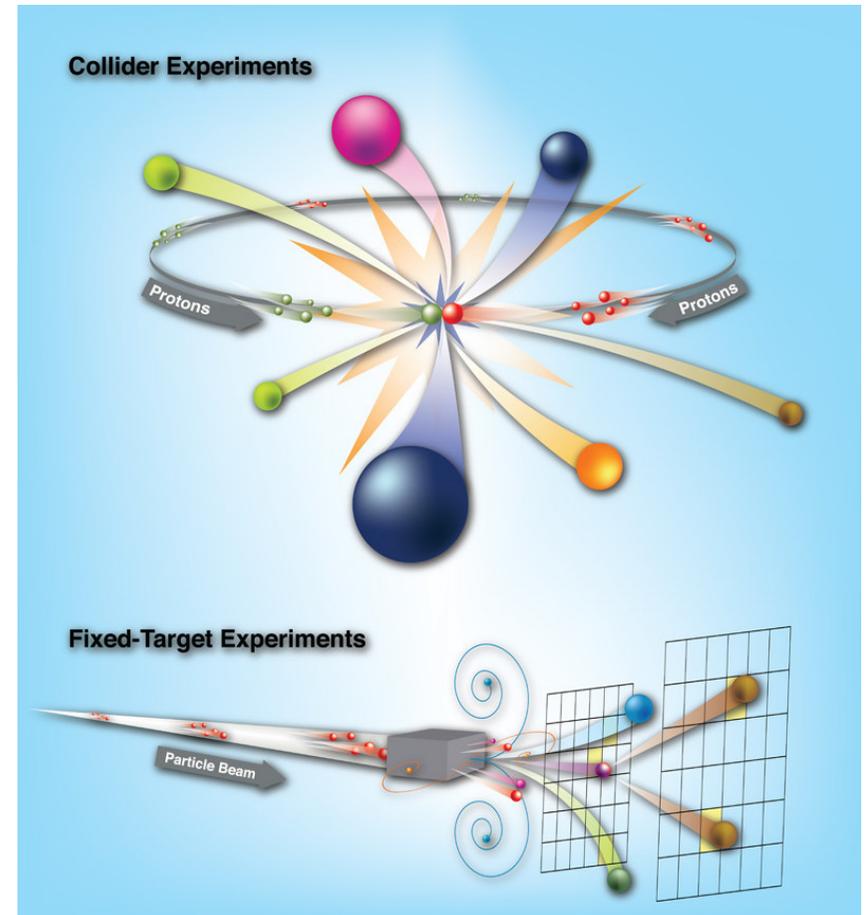
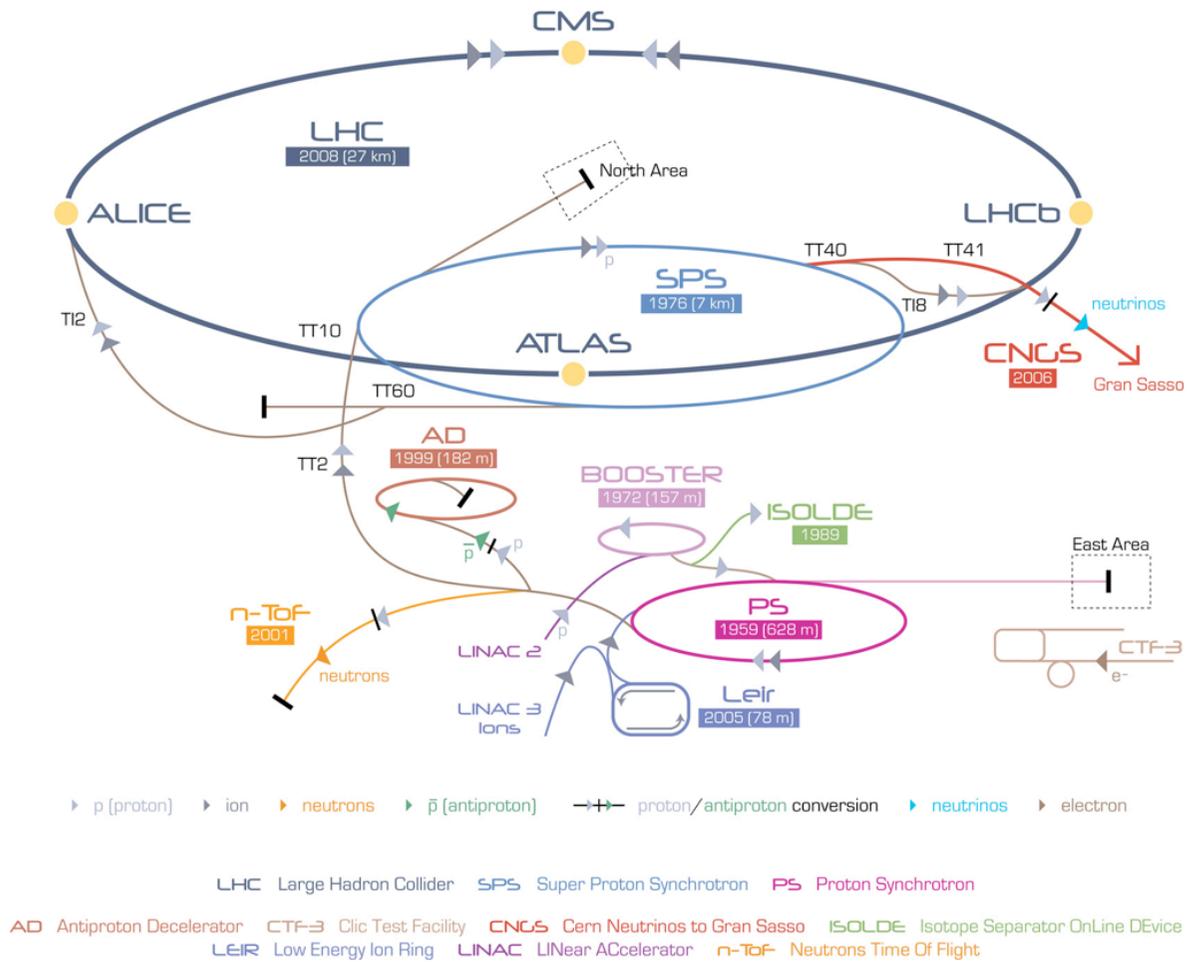
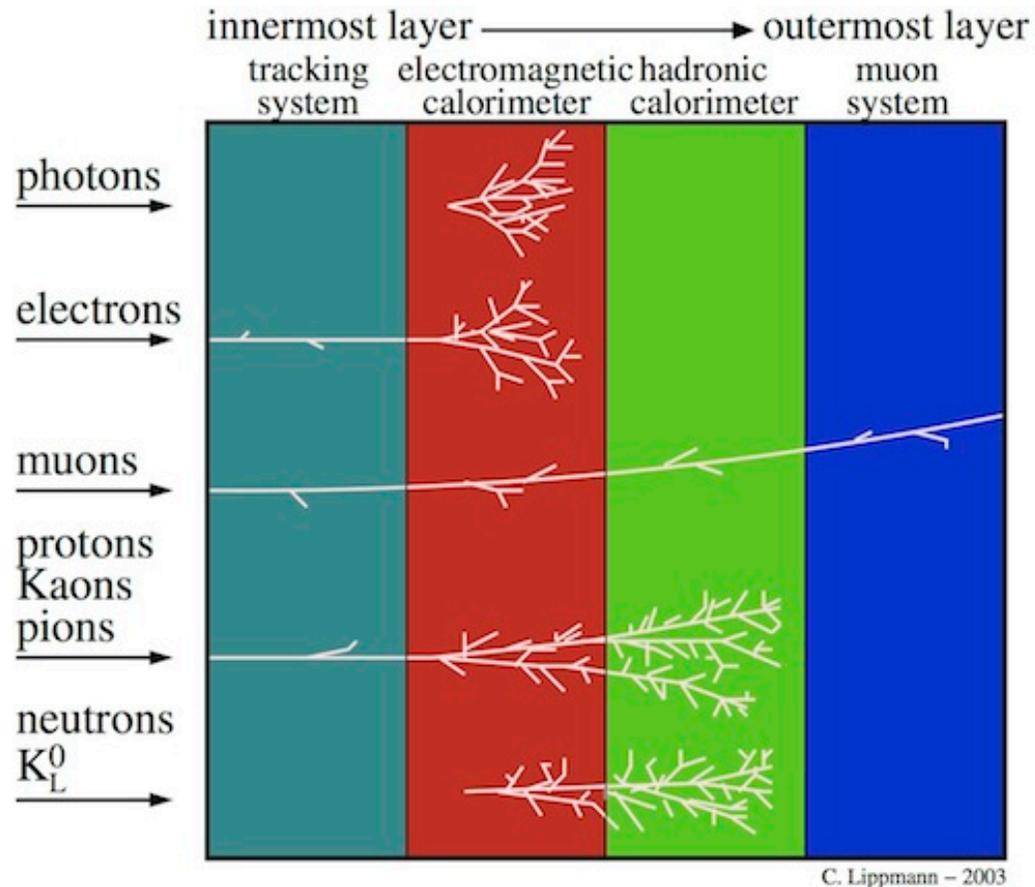


Fig. 8. Average detector signal versus Lorentz factor for a CRN-like radiator configuration. The open circles are data from MWPC 1, and the open squares are from MWPC 2, as shown in the inset schematic. The dashed lines serve to guide the eye.

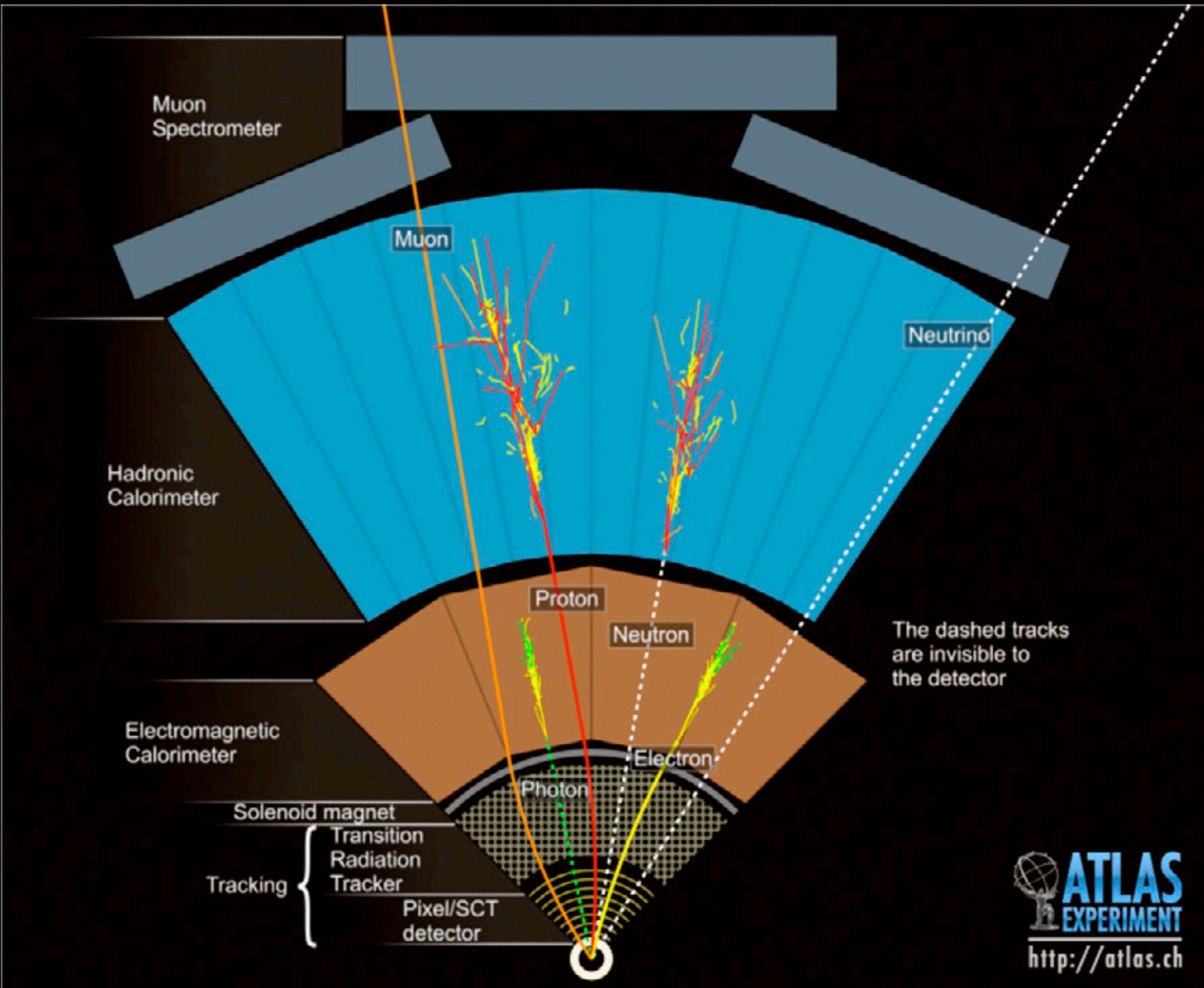
3) Observables and experiments

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.

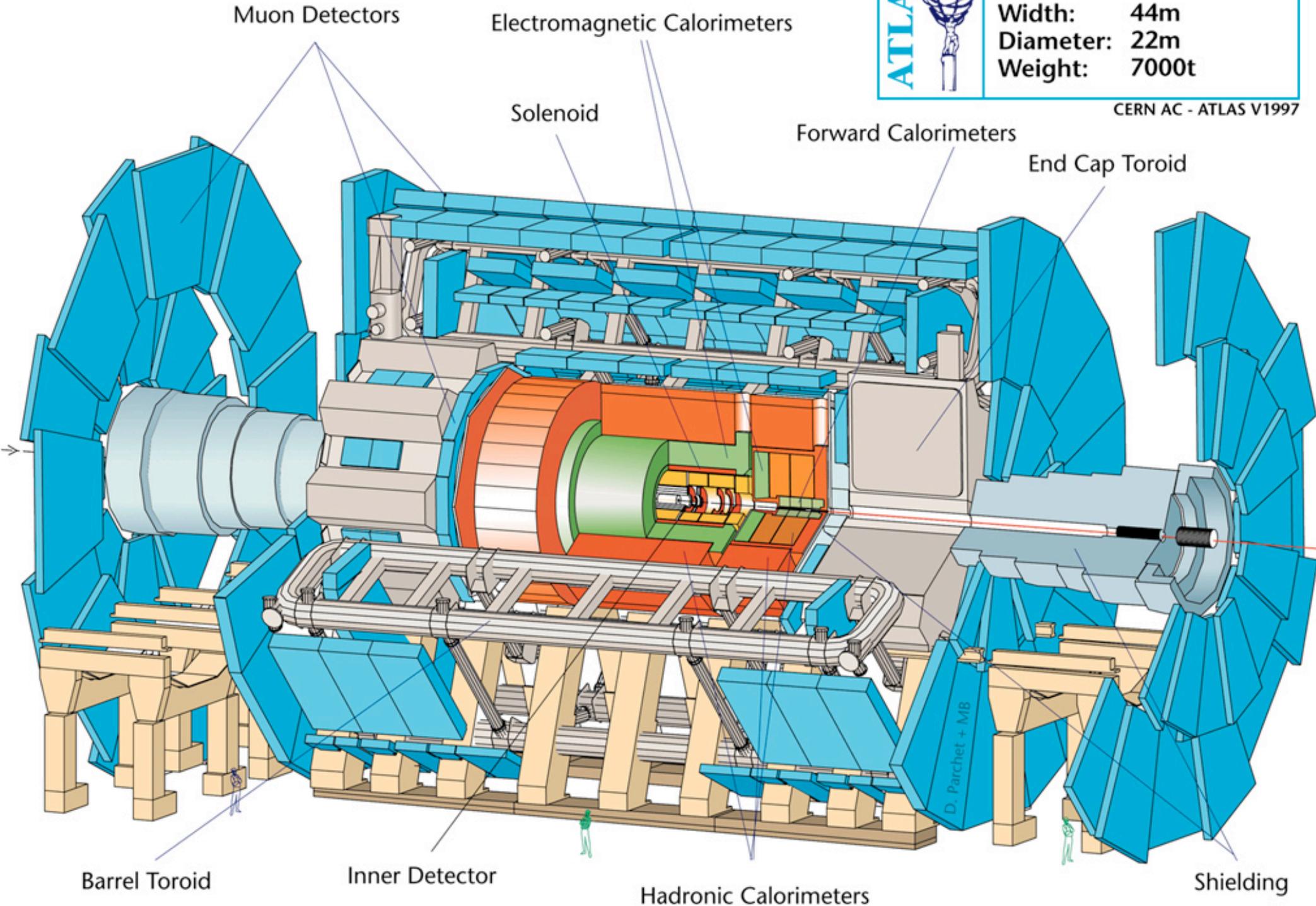


ATLAS 

Detector characteristics

Width:	44m
Diameter:	22m
Weight:	7000t

CERN AC - ATLAS V1997

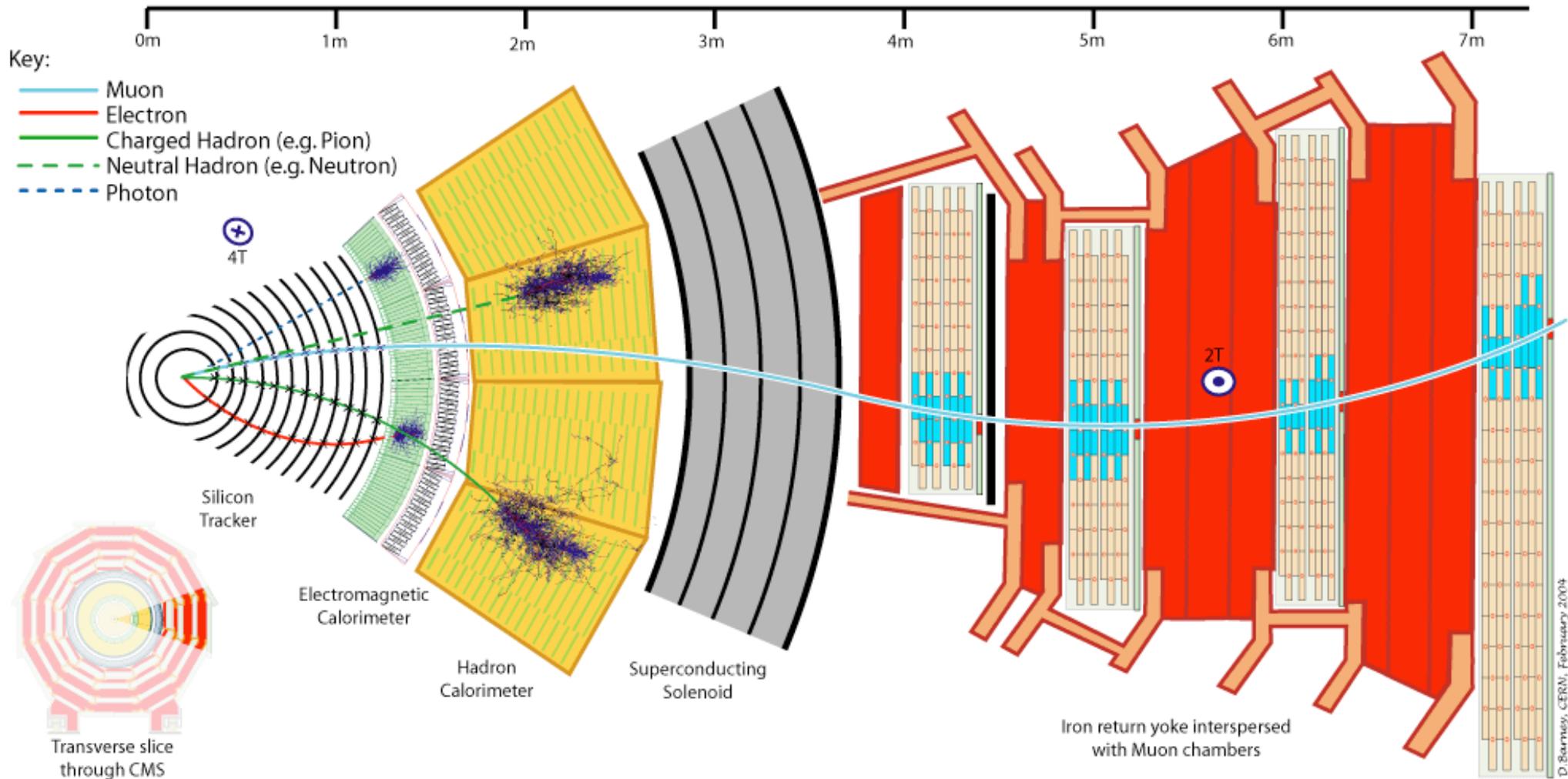


Barrel Toroid

Inner Detector

Hadronic Calorimeters

Shielding



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 ($100 \times 150 \mu\text{m}$) $\sim 16\text{m}^2 \sim 66\text{M}$ channels
Microstrips ($80 \times 180 \mu\text{m}$) $\sim 200\text{m}^2 \sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying $\sim 18,000\text{A}$

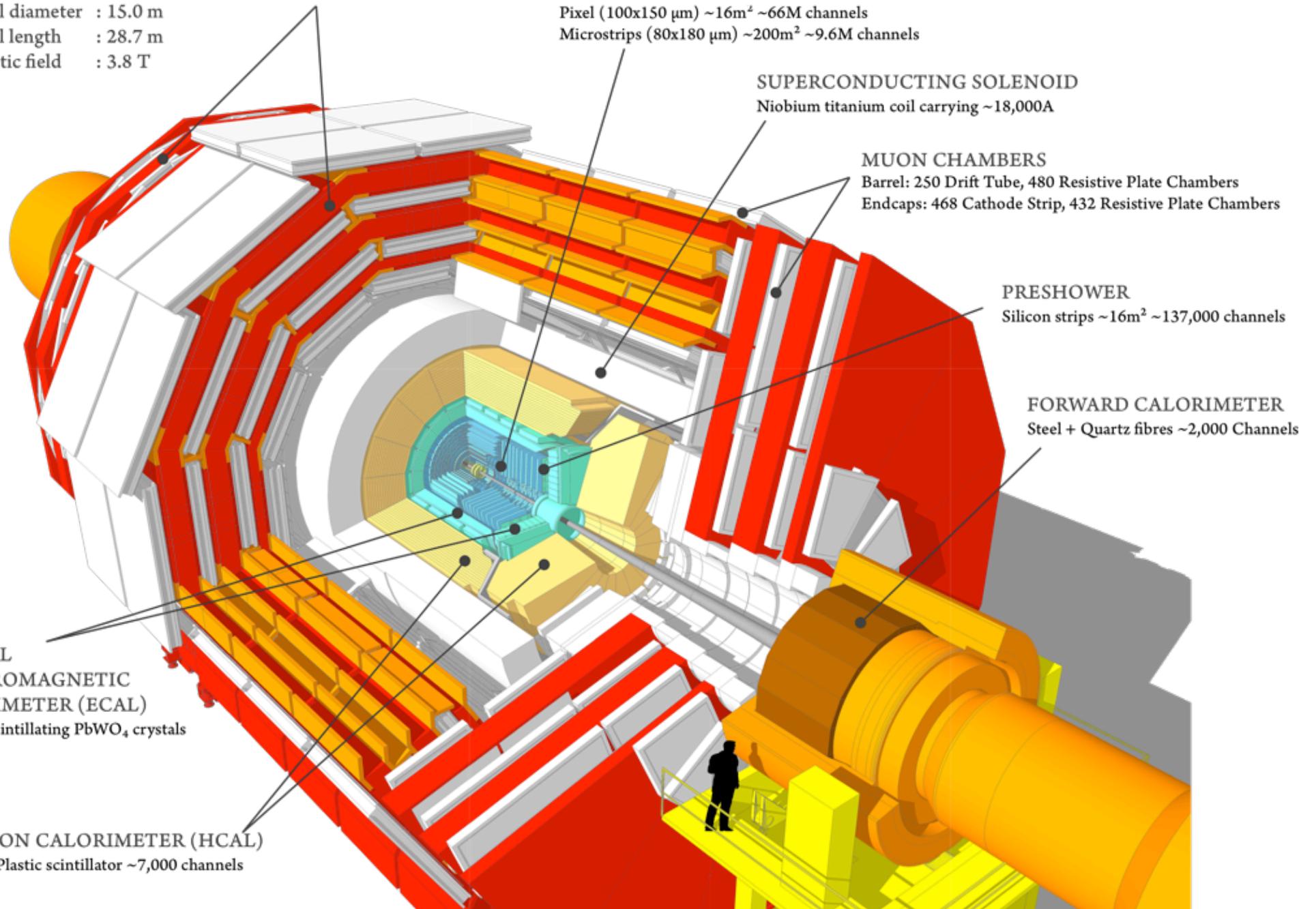
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
Silicon strips $\sim 16\text{m}^2 \sim 137,000$ channels

FORWARD CALORIMETER
Steel + Quartz fibres $\sim 2,000$ Channels

CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

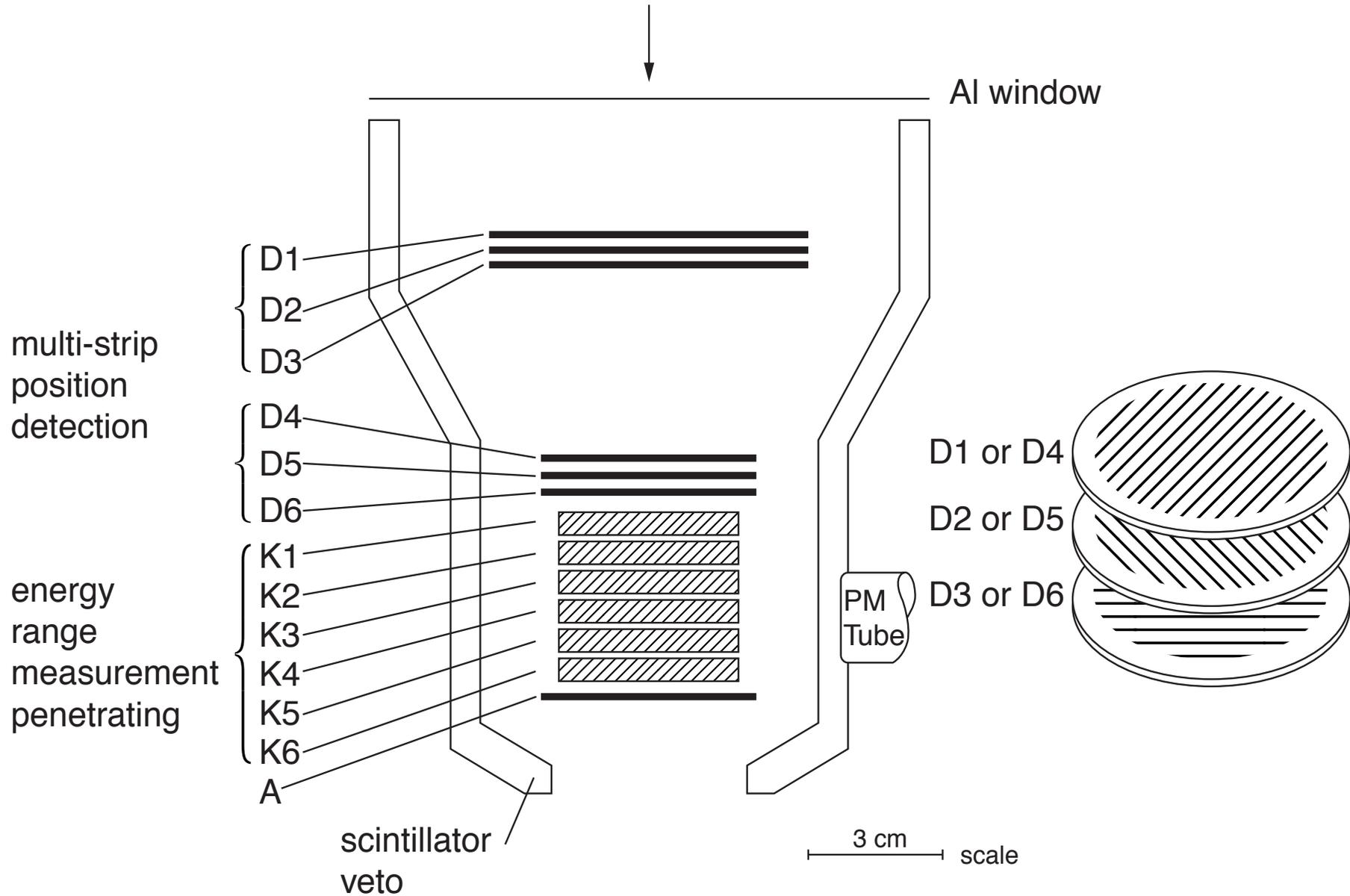
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator $\sim 7,000$ channels



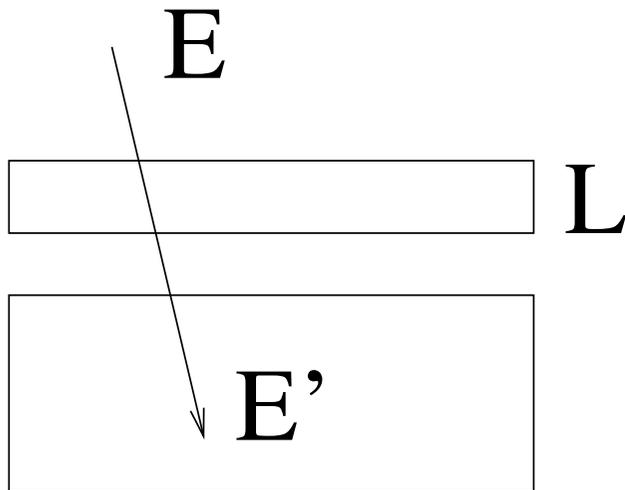
Detectors for direct measurements of Cosmic Rays above the atmosphere

• Silicon detector	$ Z , A, E$	isotopes
• Magnet spectrometer	$\pm Z, E$	anti-particles
• Calorimeter	$ Z , E$	elements
• Cherenkov detector	$ Z , E$	elements
• Transition radiation detector	$ Z , 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 thin
 layer can be expressed as

$$L = R_{Z,M}(E/M) - R_{Z,M}(E'/M)$$

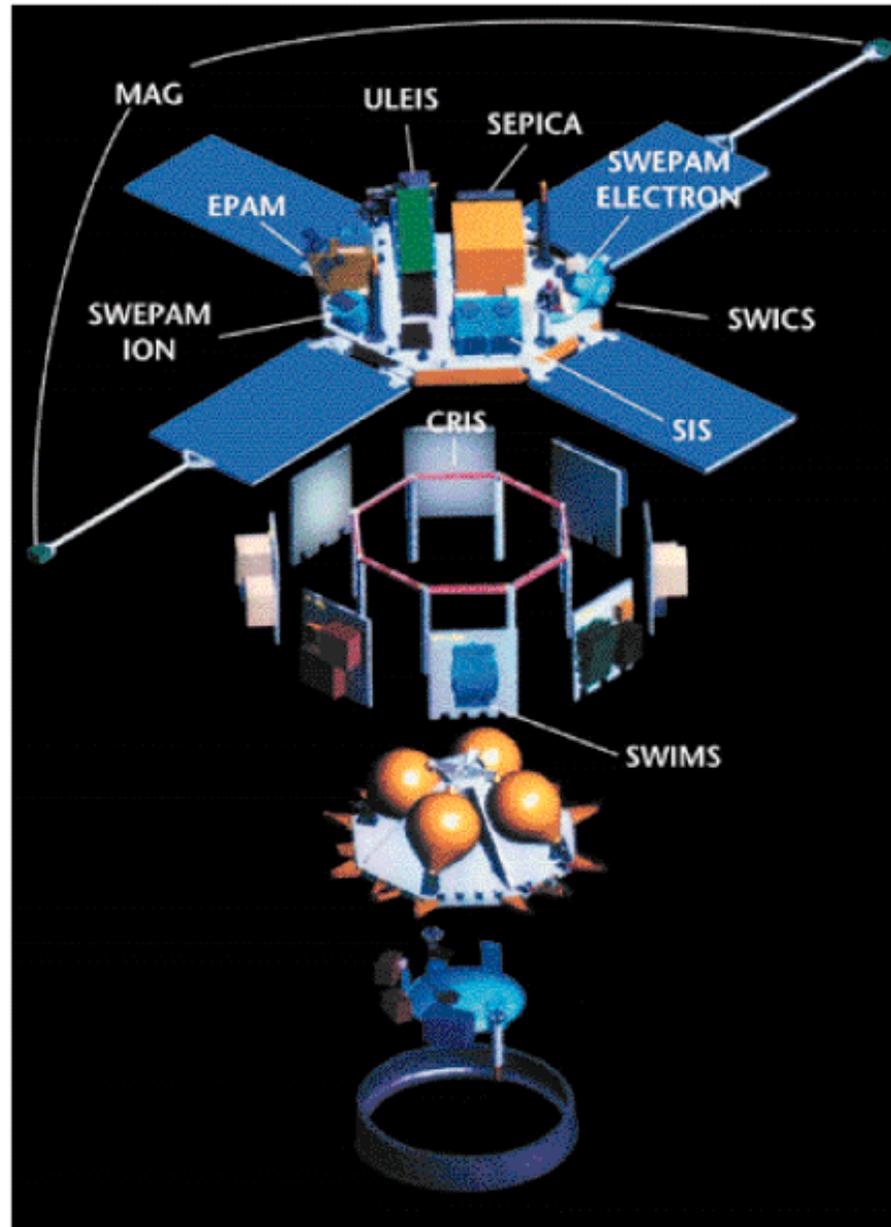
with such an set-up the charge Z and mass M of an incident particle is measured

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

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

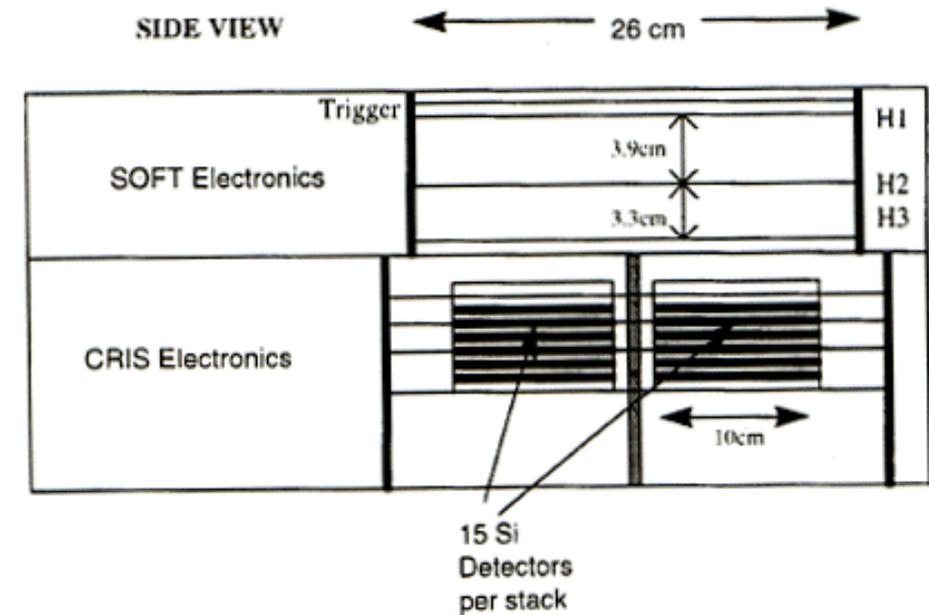
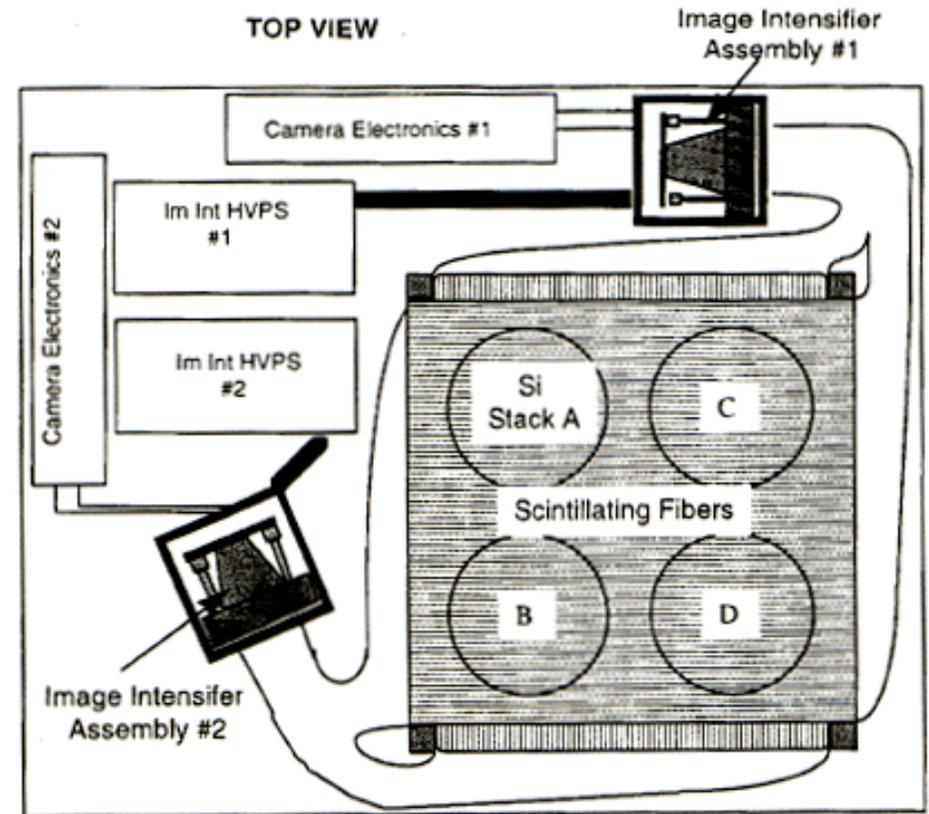
incident cosmic-ray nuclei are fully characterized (Z,A)

Advanced Composition Explorer (ACE)



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

CRIS: The Cosmic Ray Isotope Spectrometer



BESS Instrumentation

BESS-PolarII

../bessp_ext.root.sel_04-90-1171

Event Time: 02.07.54.364

Run: 095 Event: 4200488 (5A) Size: 2897 FADC: 1944 FEND: 904

Trigger: 001001011 JET: 71 IDC: 4 UTOF: 1 MTOF: 1 LTOF: 1

Event display with reconstructed Antiproton track is shown.

Rigidity (MDR:240GV)

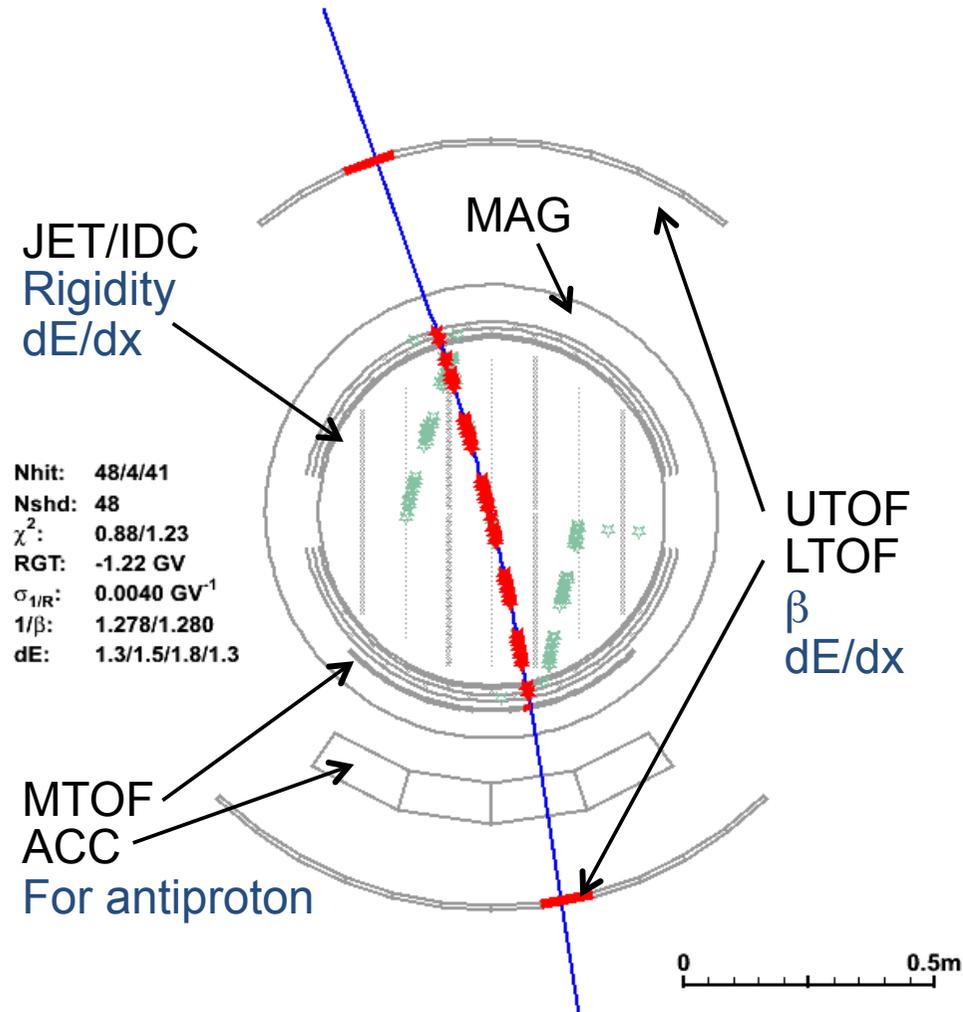
Solenoid: Uniform field ($\phi=1\text{m}$, $B=0.8\text{T}$)
Thin material (2.4 g/cm^2)

Drift chamber: Redundant hits
($\sigma\sim 150\mu\text{m}$, $32\sim 48+4\text{hits}$)

Charge, Velocity

TOF, Chamber: dE/dx measurement
($Z = 1, 2, \dots$)

TOF: $1/\beta$ measurement ($\sigma\sim 1,2\%$)

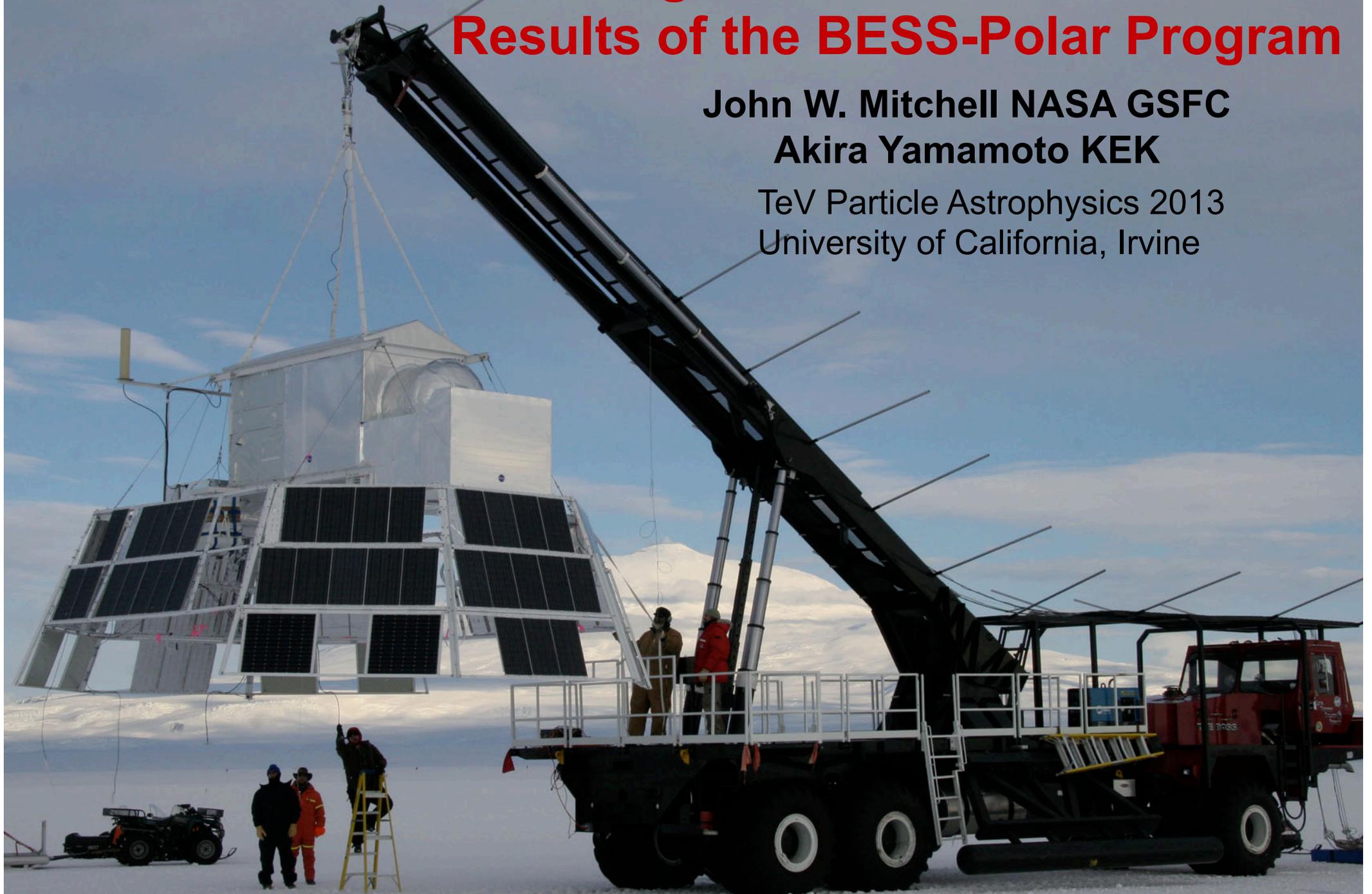


$$m = ZeR\sqrt{1/\beta^2 - 1}$$

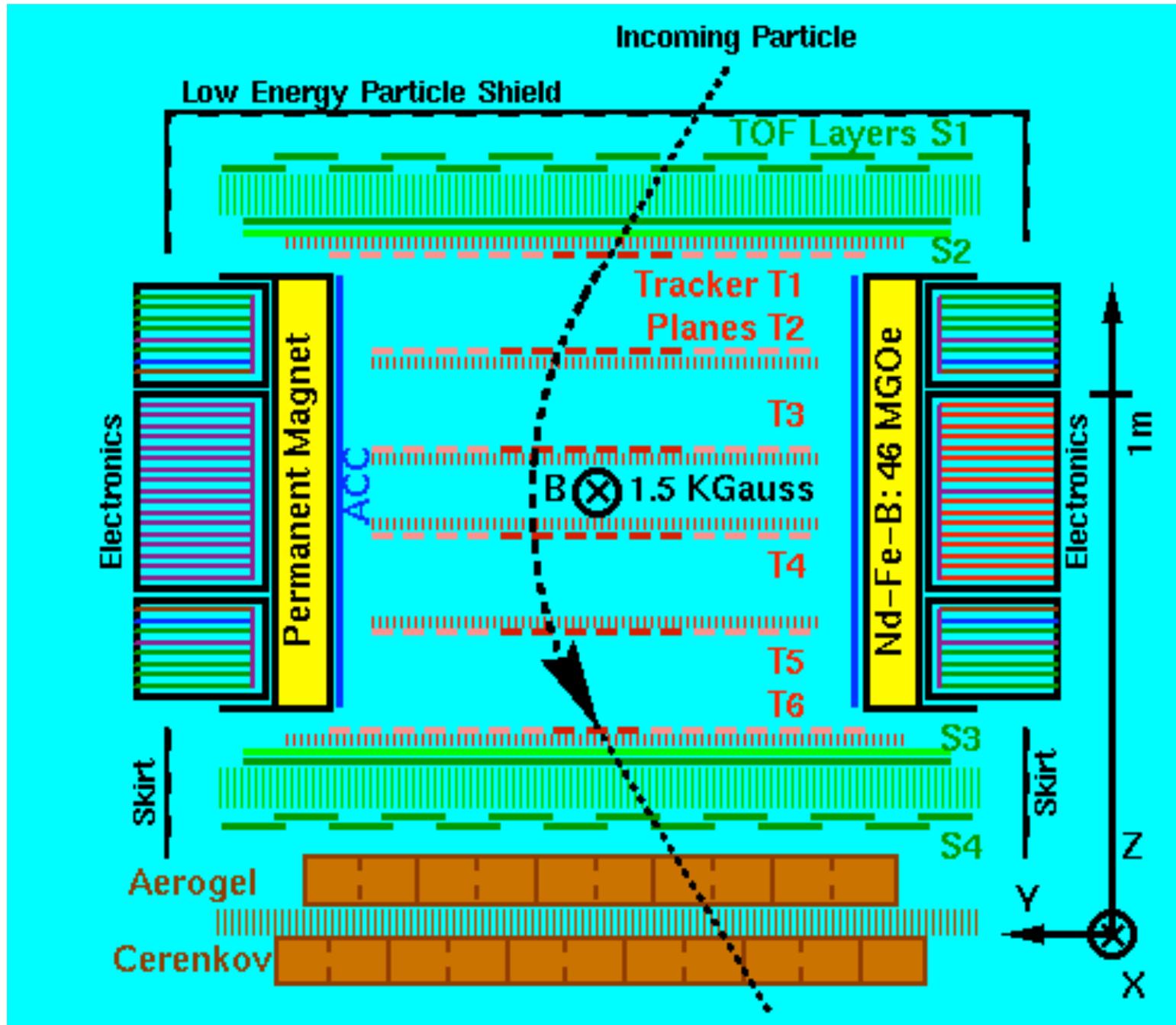
Measuring Antimatter over Antarctica Results of the BESS-Polar Program

John W. Mitchell NASA GSFC
Akira Yamamoto KEK

TeV Particle Astrophysics 2013
University of California, Irvine

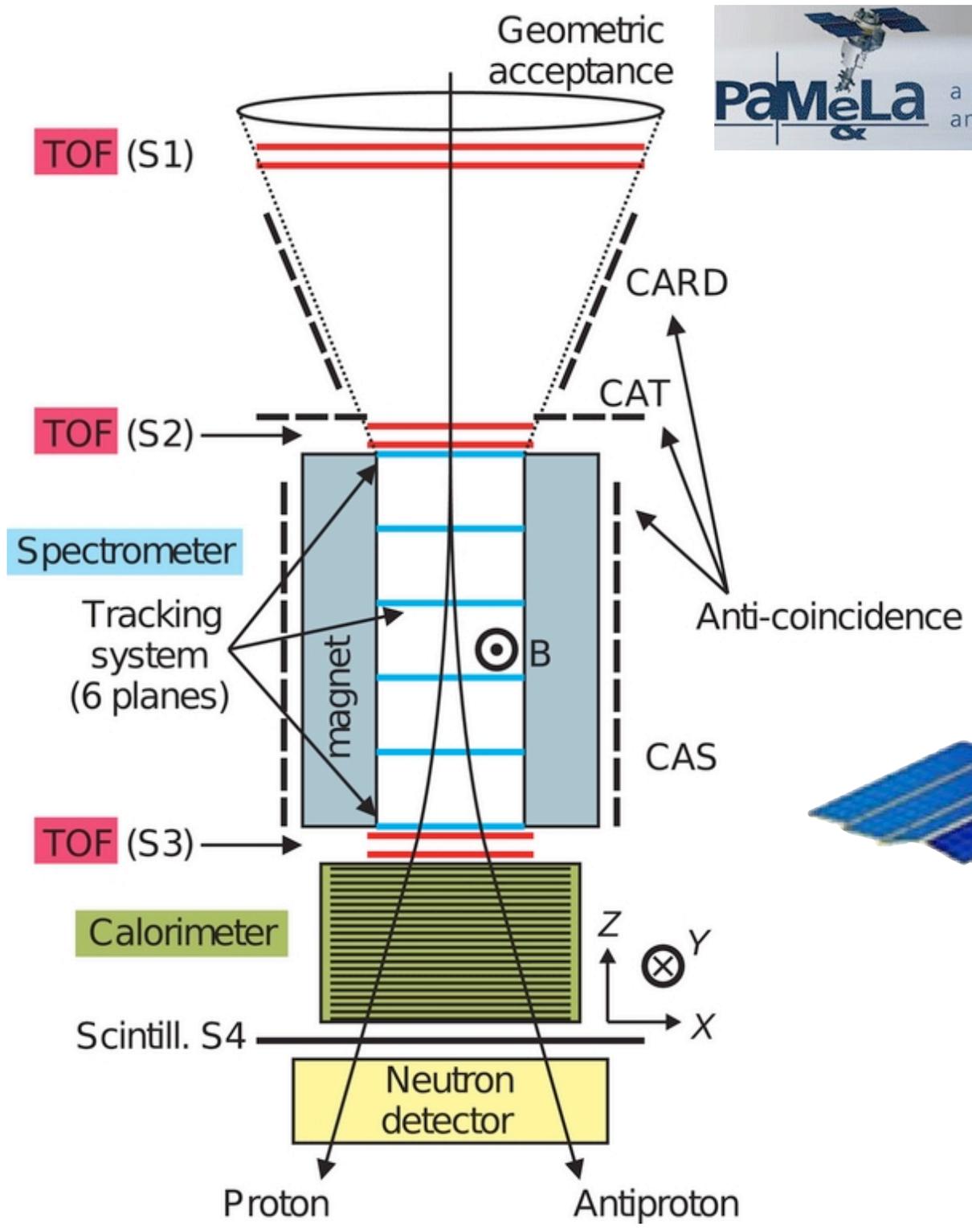


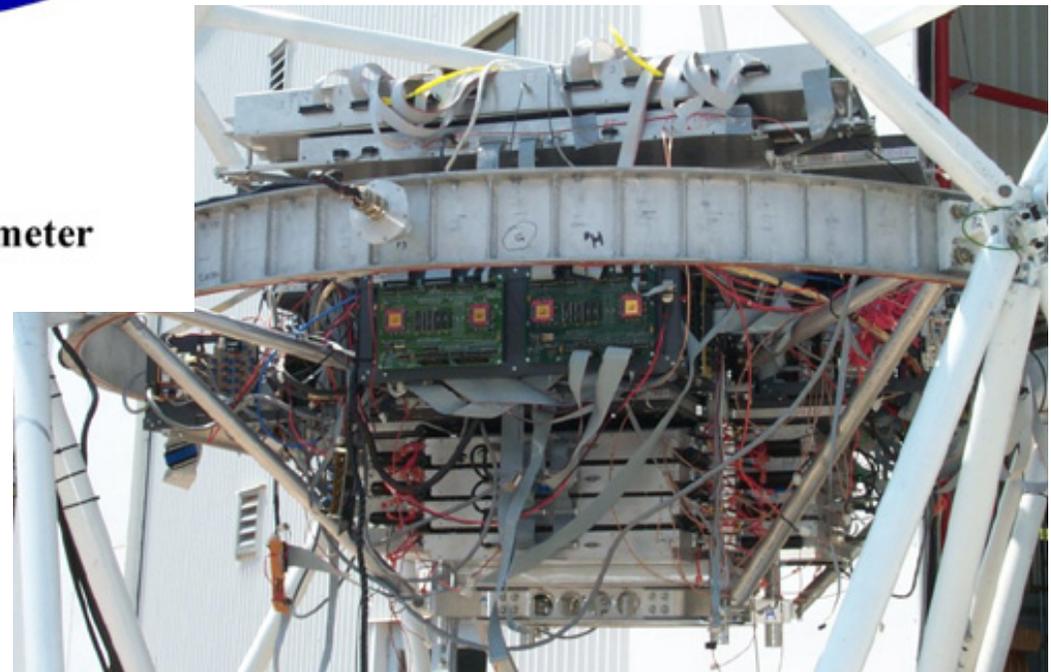
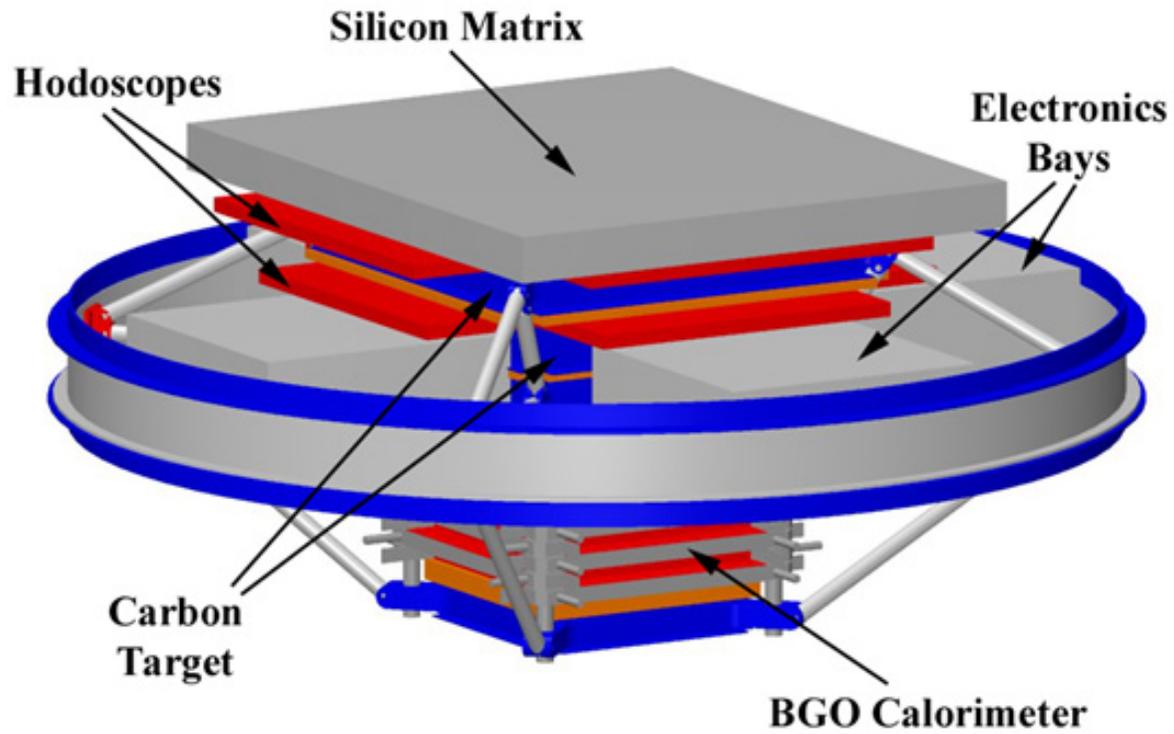
Alpha Magnetic Spectrometer - AMS



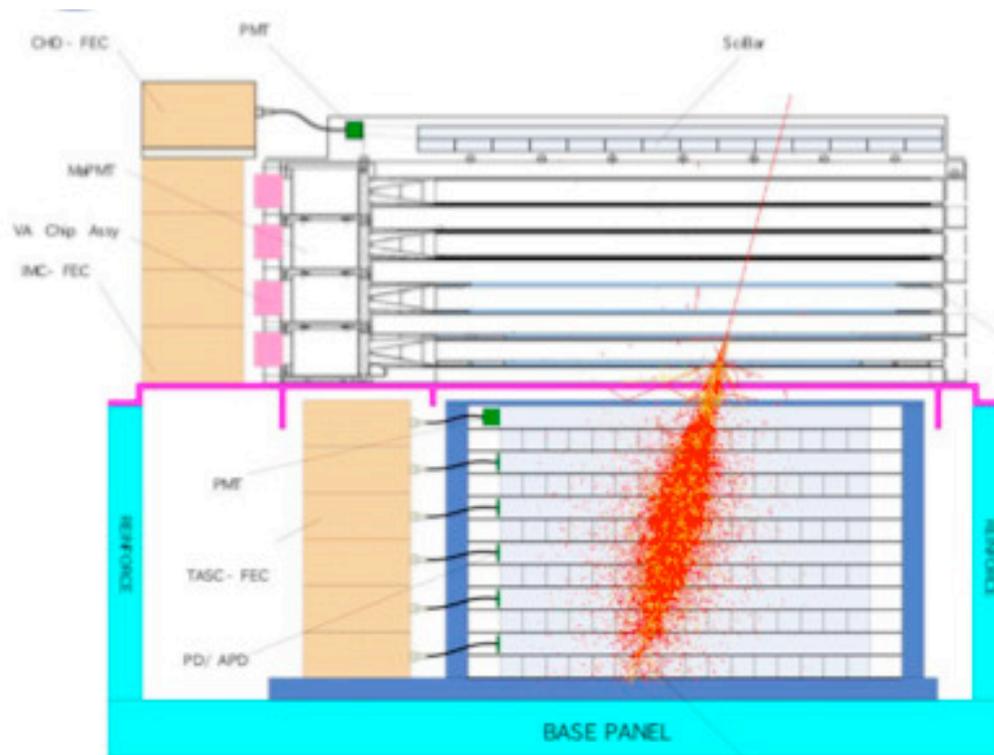
Alpha Magnetic Spectrometer - AMS





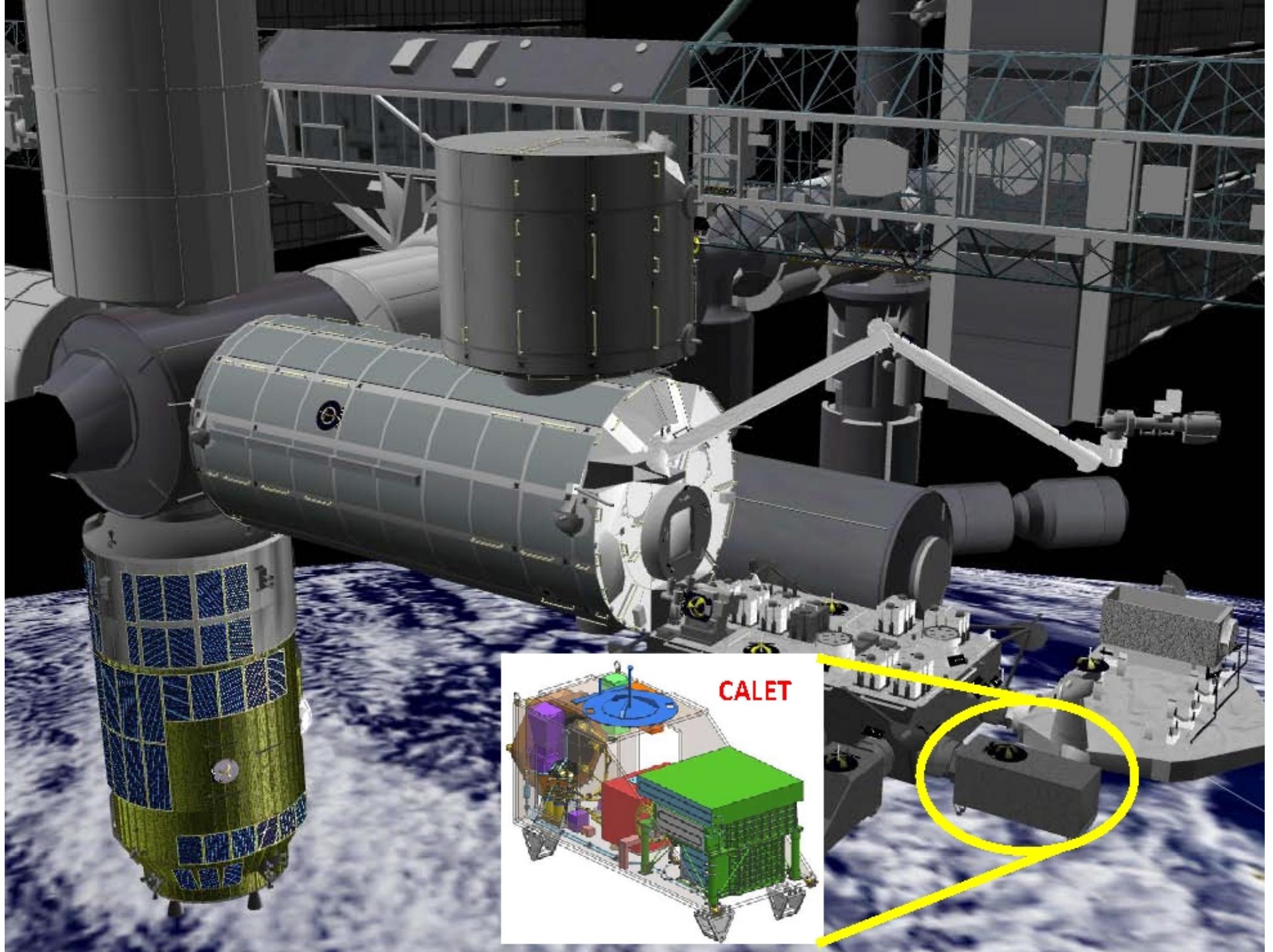


The CALorimetric Electron Telescope (CALET): High Energy Astroparticle Physics Observatory on the International Space Station



- **CHD Detector (CHD)**
(Charge Measurement in $Z=1-40$)
- **Imaging Calorimeter (IMC)**
(Particle ID, Direction)
Total Thickness of Tungsten (W): $3 X_0$, $0.11 \lambda_i$
Layer Number of SciFi Belts: 8 Layers $\times 2(X,Y)$
- **Total Absorption Calorimeter (TASC)**
(Energy Measurement, Particle ID)
PWO $20\text{mm} \times 20\text{mm} \times 320\text{mm}$
Total Depth of PWO: $27 X_0$ (24 cm), $1.35 \lambda_i$

	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: $32\text{mm} \times 10\text{mm} \times 450\text{mm}$	SciFi : 16 layers Unit size: $1\text{mm}^2 \times 448\text{mm}$ Total thickness of Tungsten: $3 X_0$	PWO log: 12 layers Unit size: $19\text{mm} \times 20\text{mm} \times 326\text{mm}$ Total Thickness of PWO: $27 X_0$
Readout	PMT+CSA	64 -anode PMT+ ASIC	APD/PD+CSA PMT+CSA (for Trigger)



CALET

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

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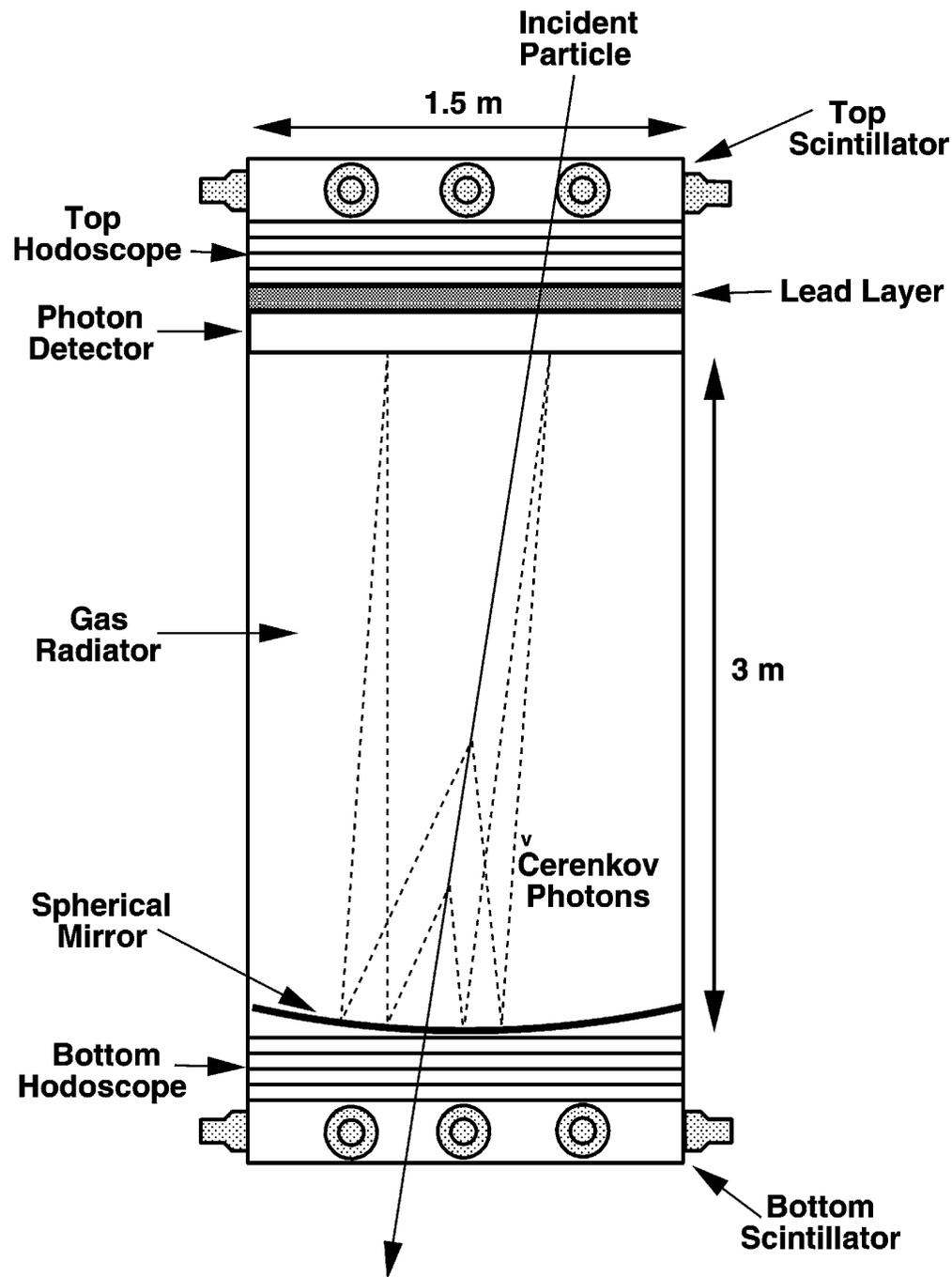
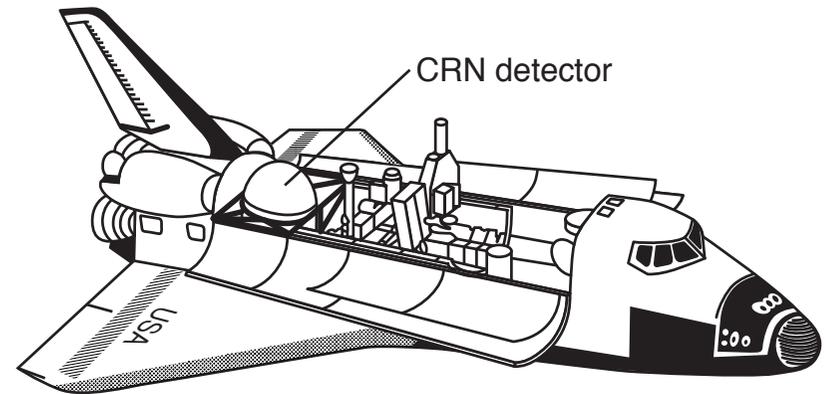
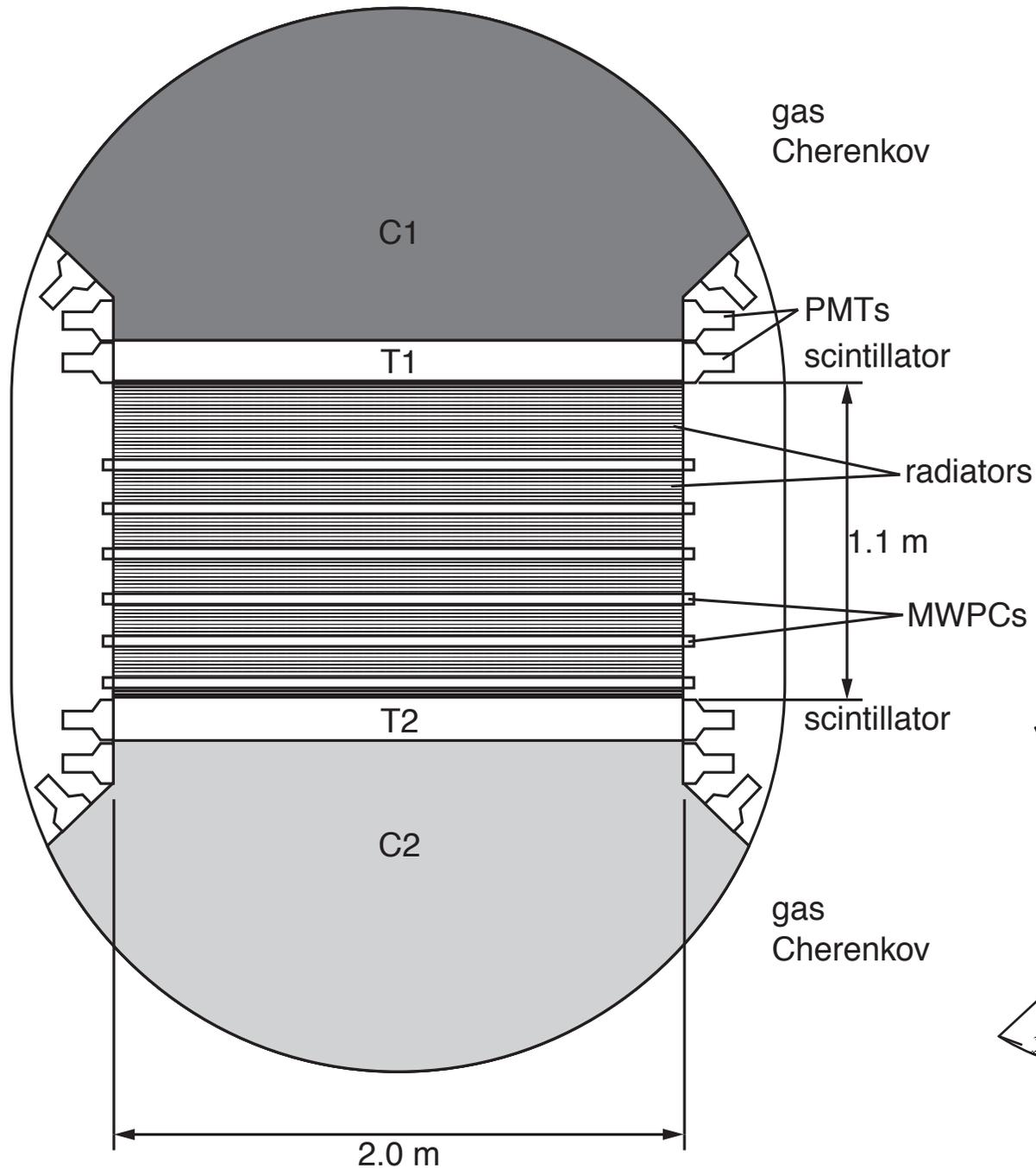


Fig. 1. Schematic cross-section of the instrument.

Cosmic Ray Nuclei instrument - CRN

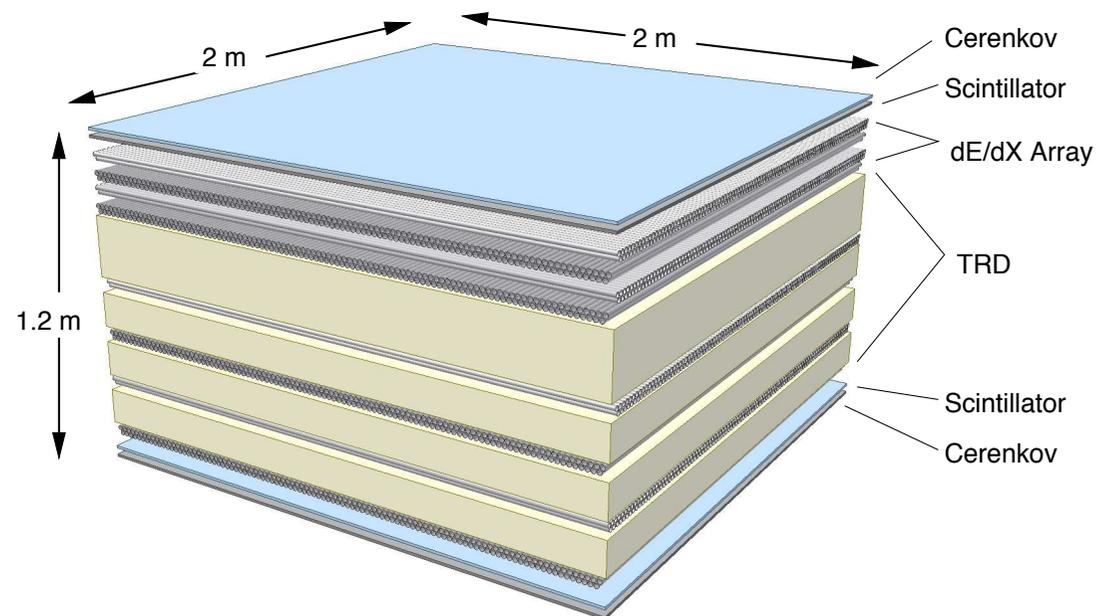


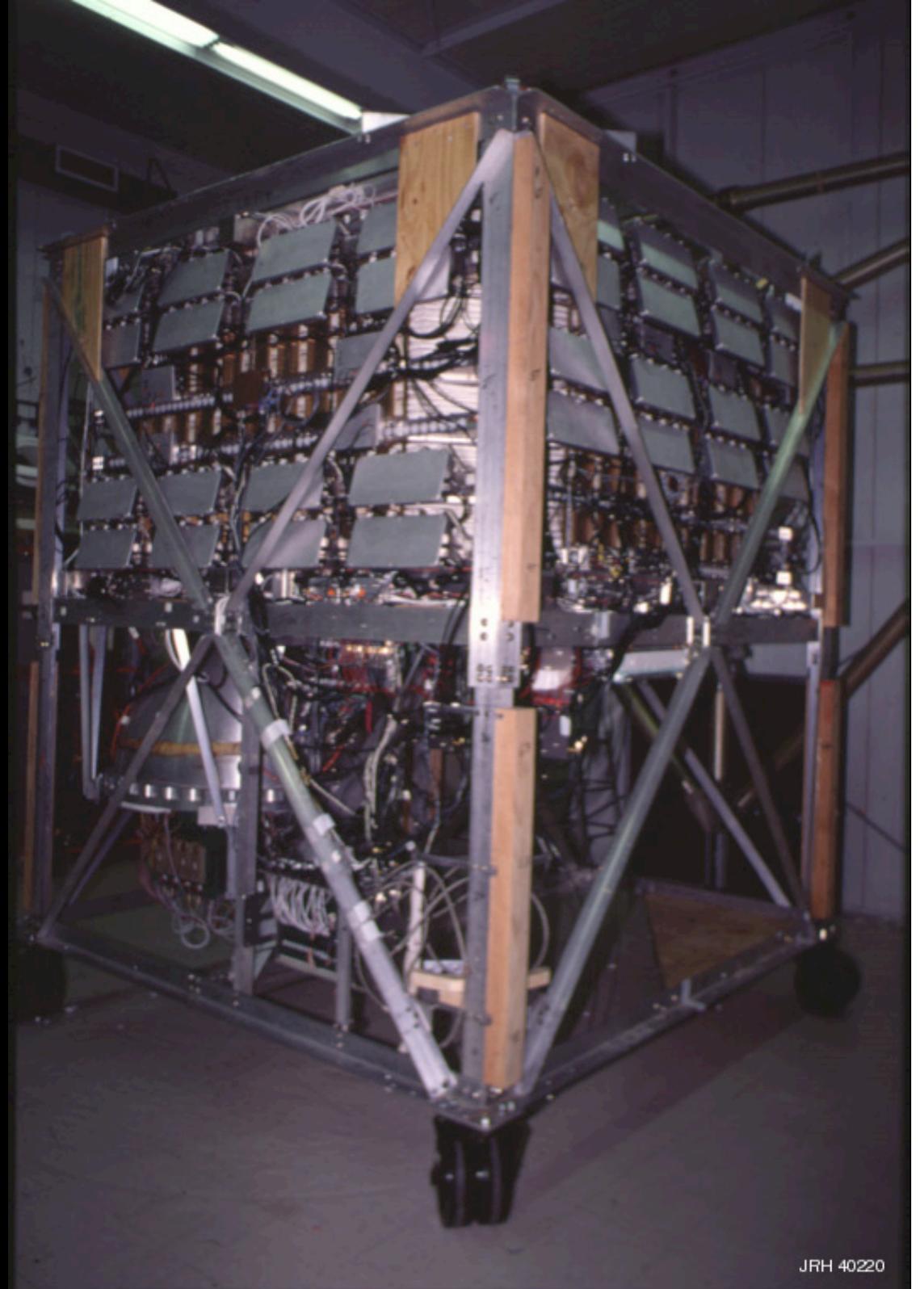
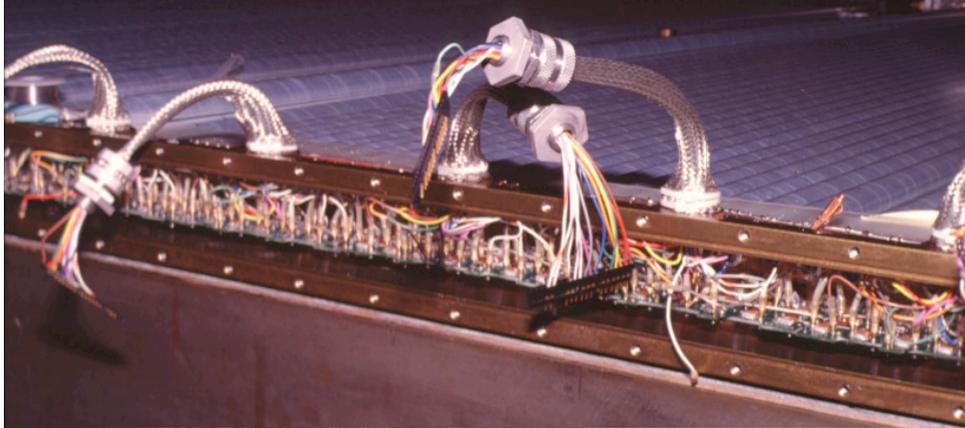
Challenger 1985

TRACER experiment

TRACER Overview

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

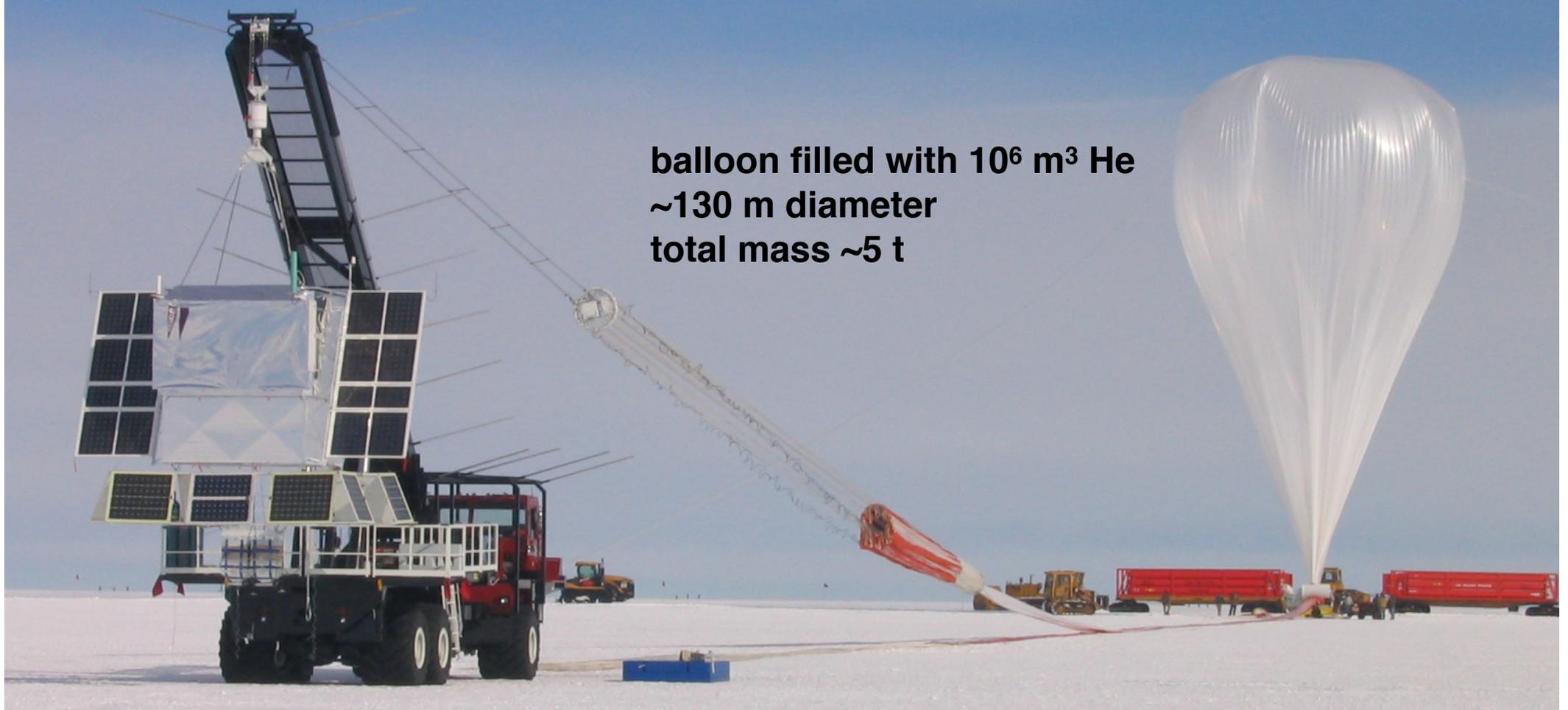




TRACER Experiment - Mc Murdo, Antarctica

flight: 12. – 26. December 2003

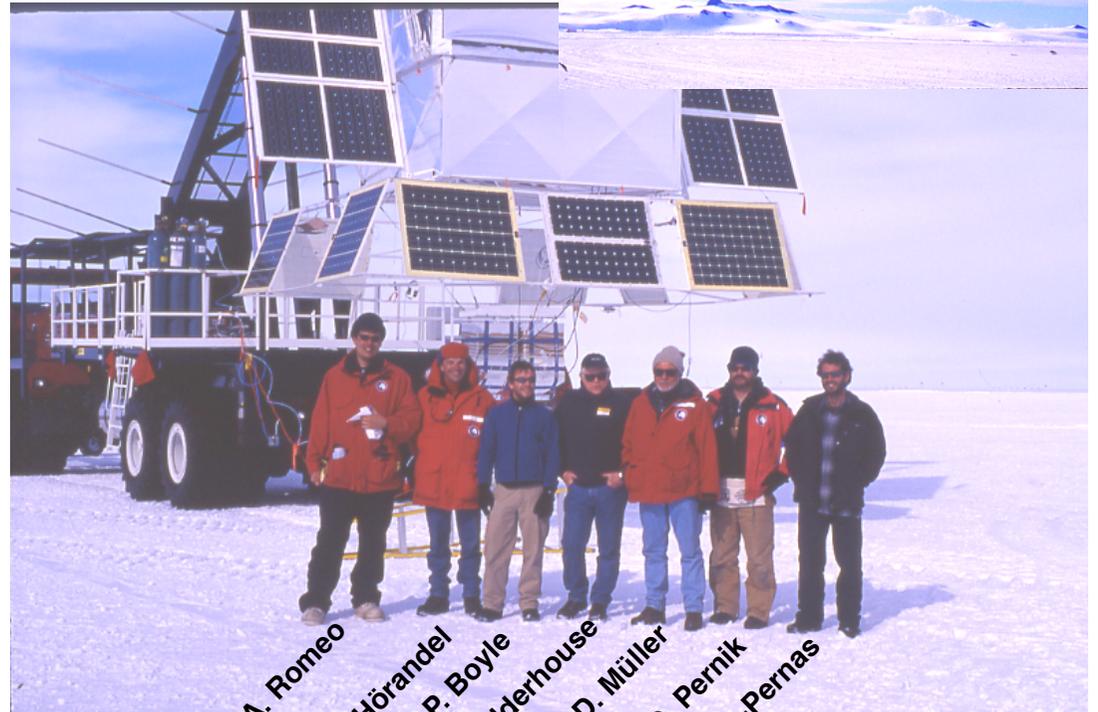
~ 40 km (3-5 g/cm²)



balloon filled with 10^6 m³ He
~130 m diameter
total mass ~5 t



TRACER Experiment



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

TRACER Experiment - Mc Murdo, Antarctica

flight: 12. – 26. December 2003

~ 40 km (3-5 g/cm²)

