Accelerators and Detectors

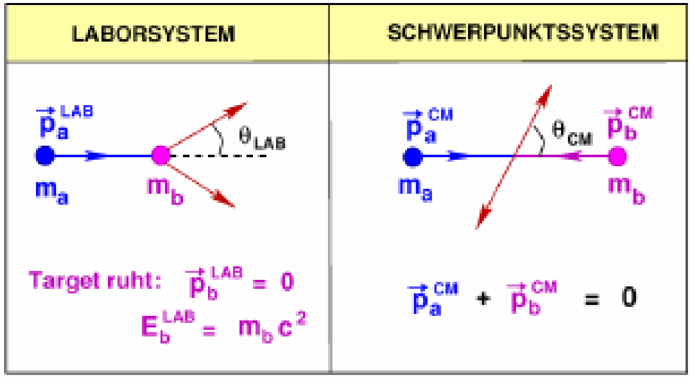
- **Accelerators**
  - Components
  - Examples

- **Detectors**
  - Principles of Measurement
  - Experiments: examples

Use of Accelerators as Tools for Particle Physics

- Conceptually
  - In scattering experiments as a microscope:
    - a ‘de Broglie’ wavelength is associated: $\lambda = h / p$ (momentum)
  - In collisions to create states of high energy density, from which new particle may be created: $E = mc^2$
- Experimentally
  - Accelerated beam impinges on target, creating
    - A physics state to be studied
    - Secondary particle, which may form a secondary high energy beam (electron, pion, neutrino,..)
      - ‘Fixed Target’ operation
    - Collisions of two beams, travelling in opposite direction:
      - ‘colliding beam’ operation

Fixed Target or Colliding Beams



- Two particle interaction a+b=c+d
  - $p = p_a + p_b$
  - $p^2 = M^2 c^4 = (E_a + E_b)^2 - (p_a + p_b)^2 c^2$ is an invariant
  - $s = (E_a^{CM} + E_b^{CM})^2$ (total energy in CM system)^2
  - for E_a, $E_b >> m_a c^2, m_b c^2$
  - Fixed Target: $s^2 \sim 2 E_a^{lab} m_b c^2$
  - Colliding Beams: $s = 4 E_a E_b = 4 E^2$ for $E_a = E_b$

Necessary Condition for Particle Accelerators

- Particle must be charged electrically
  - energy = charge • potential difference of accelerating field
  - Linear or circular path and focusing with magnetic fields

- Must have adequate life time
  - stable: protons, antiprotons, ions, electrons, positrons
  - almost stable: muons, Lorentz boost of life time

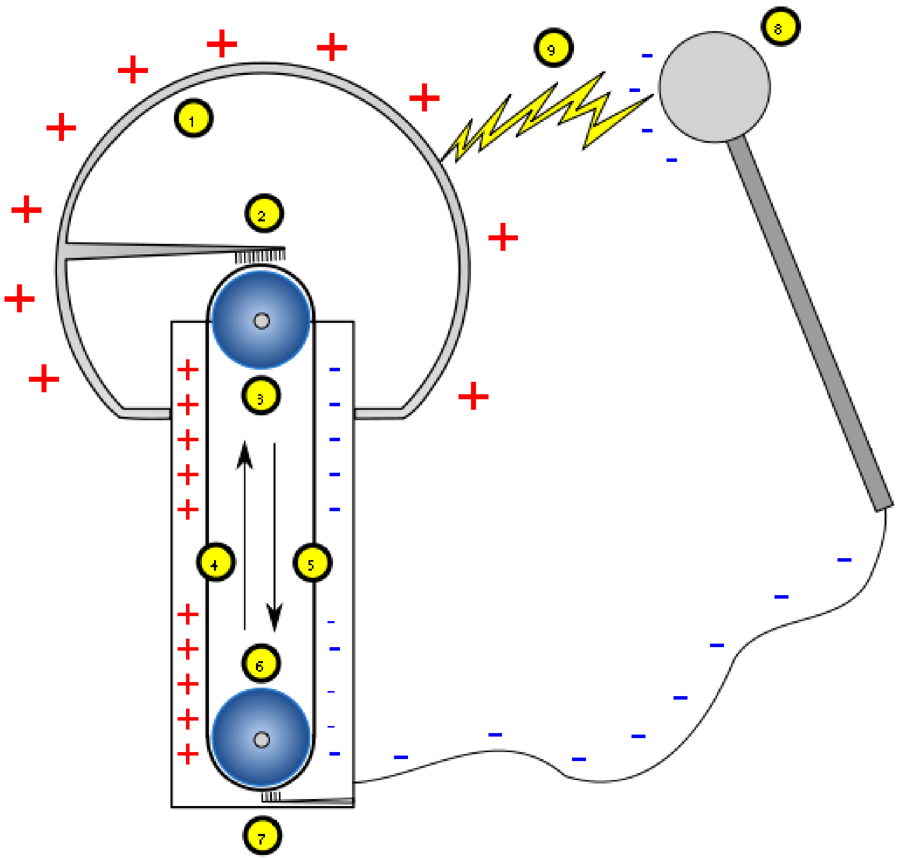
$\tau = \gamma \tau^0$ helps

Acceleration of Particles

- Acceleration with electric fields
  - DC potential: Van-der-Graaf Accelerator
    - o limited to ~ 20 MeV
  - for higher energies:
    - o high-frequency field, which accelerates particle synchronously

- For high energies: accelerations are circular
  - need magnetic field to keep particle on trajectory
    - o p (GeV/c) = 0.3 • B [T] • R [m]

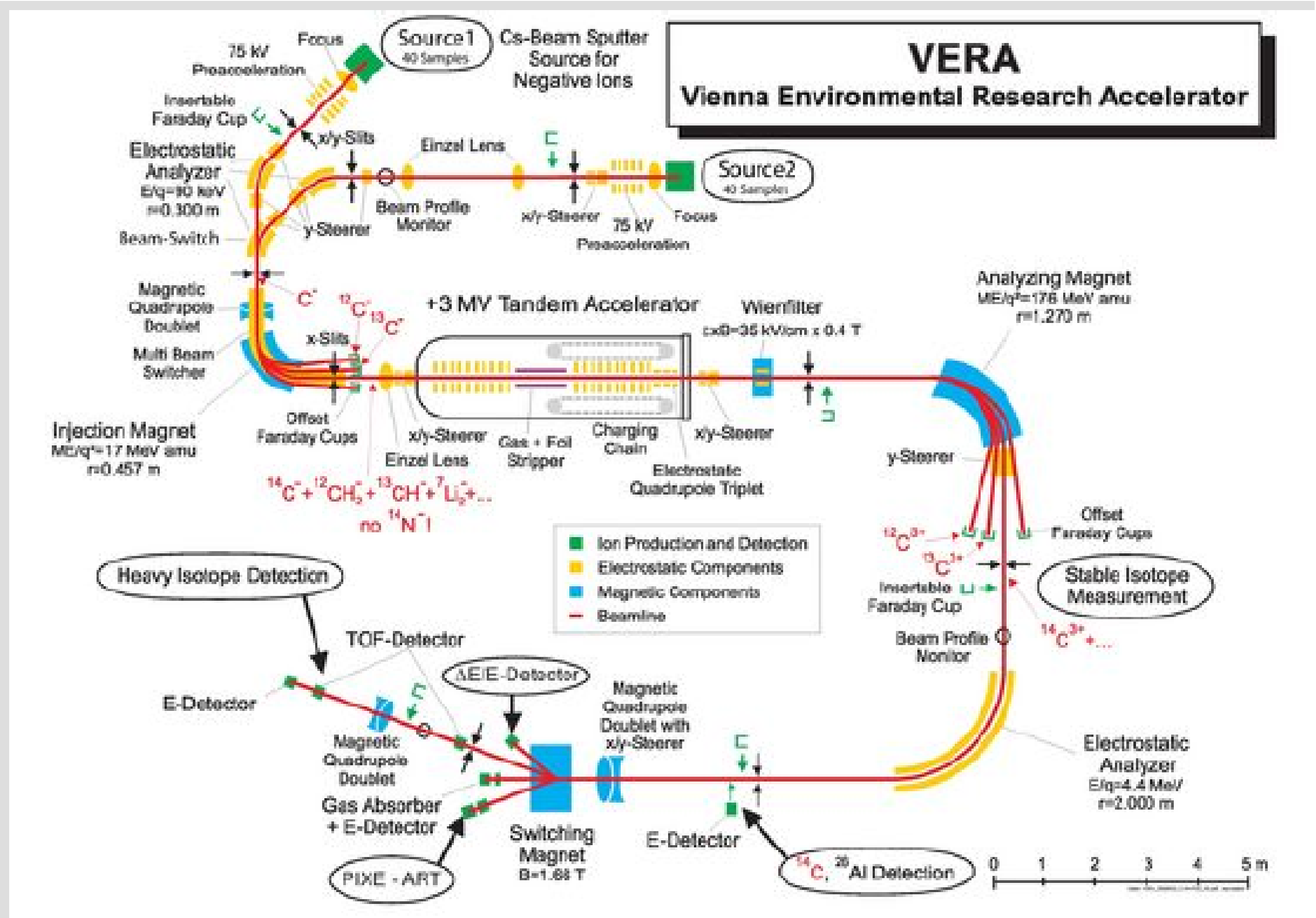
Van de Graaf High Voltage source



Insulating belt transports charge to upper sphere, creating high potential for acceleration

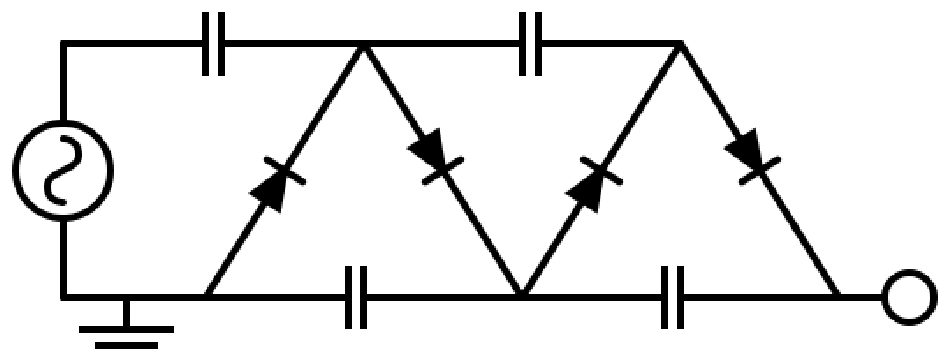
1) hollow metal sphere
2) upper electrode
3) upper roller (metal)
4) side of the belt with positive charges
5) opposite side of the belt with negative charges
6) lower roller (for example an acrylic glass)
7) lower electrode (ground)
8) spherical device with negative charges, used to discharge the main sphere
9) spark produced by the difference of potentials

Tandem Van de Graaf Accelerator in Vienna



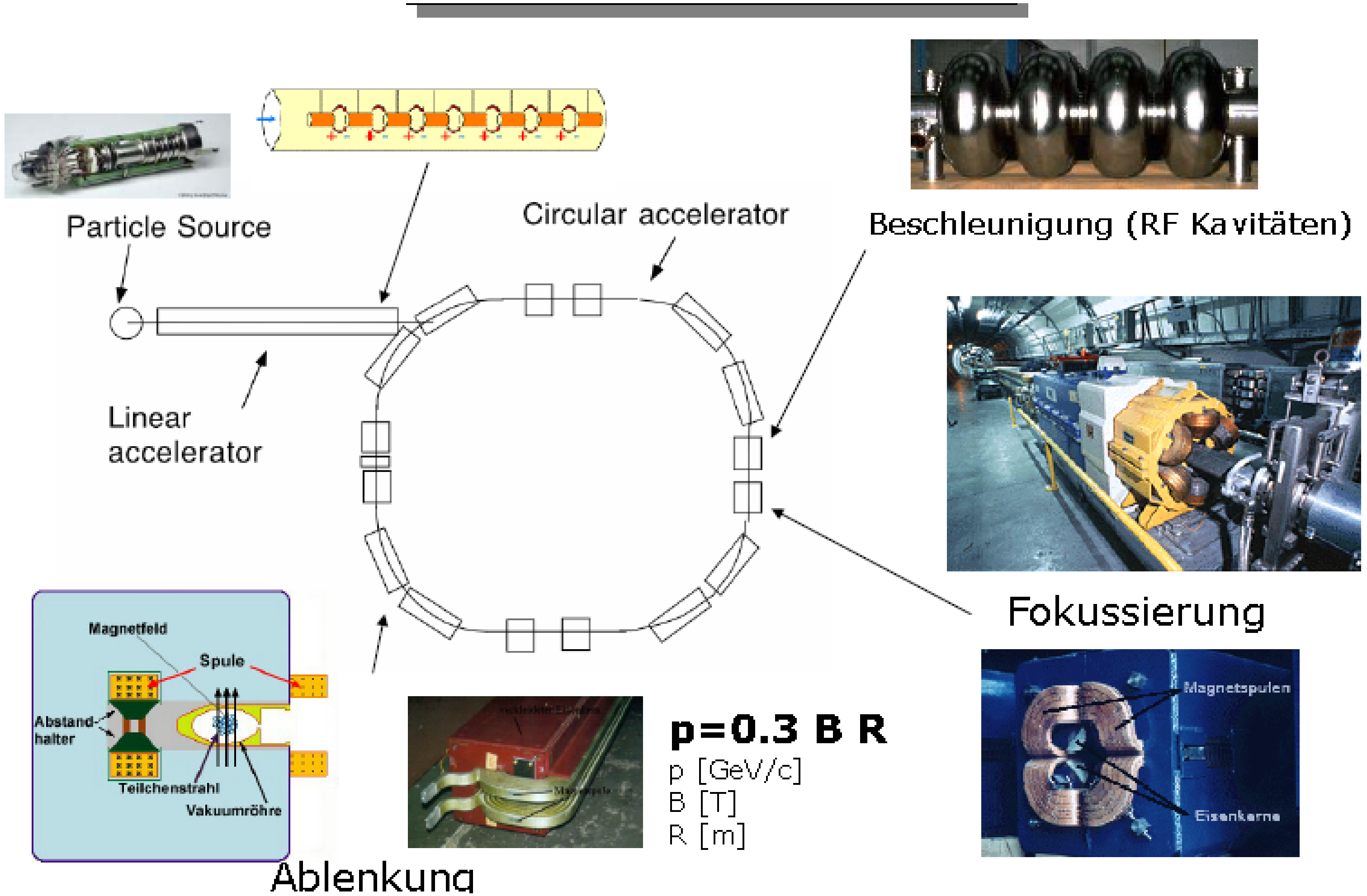
Cockroft Walton High Voltage generator

Voltage multiplier, converting AC current at low voltage to a higher DC level
Cockroft and walton used this scheme to Accelerate nuclei and performing the first Artificial transmutation of elements (Nobel Prize in 1951)



Now at the CERN Open Air Museum

Components of an Accelerator

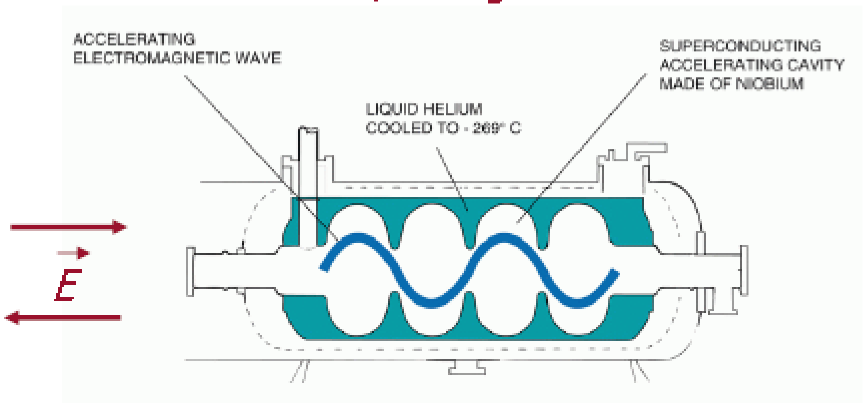


$$p = 0.3\ B\ R$$

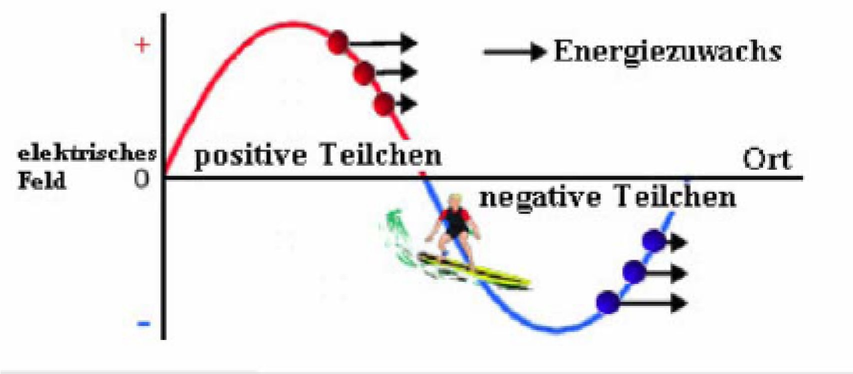
p [GeV/c]
B [T]
R [m]

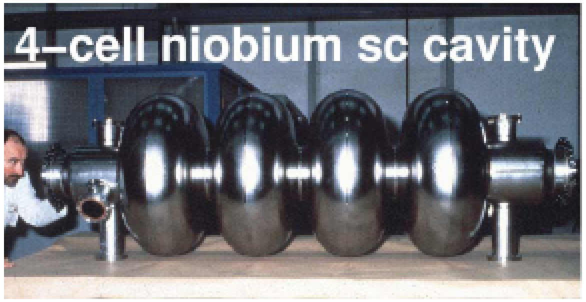
High-Frequency Acceleration

- Particle sees electric field in phase with passage through field
  - Erfolgt über stehende elektromagnetische Hochfrequenzfelder in Kavitäten
    - Teilchen sehen oszillierendes elektrisches Feld, in Phase mit Teilchendurchgang (als Teilchen-Pakete)
    - Bis zu 35 MV/m möglich



Supraleitende Kavitäten verbessern Leistung und verringern deutlich den Verbrauch elektrischer Energie





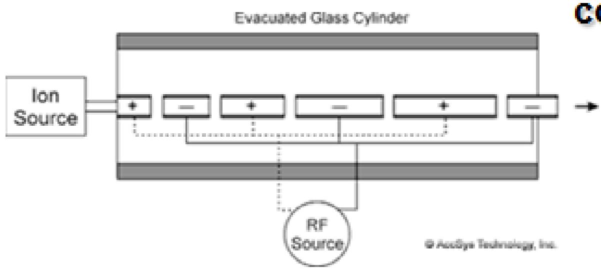
High Frequency Acceleration

Changing the Particle Energy
F. Sannibale

RF Accelerators: Wideroe and Alvarez Schemes

In 1925-28 Ising and Wideroe conceived the first linear accelerator (linac). The revolutionary device was based on the *drift tubes scheme*.

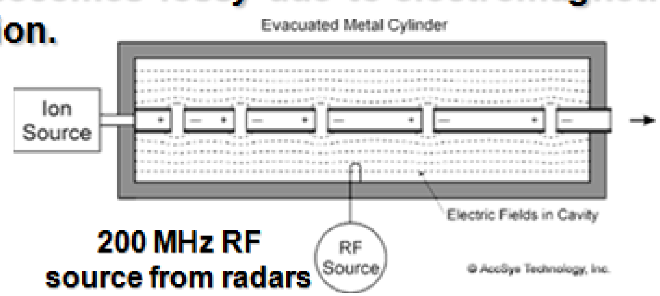
During the decelerating half period of the RF, the beam is shielded inside the conductive tubes.



Synchronicity condition: $L_i \cong \frac{1}{2} v_i T_{RF}$

At high frequency the Wideroe scheme becomes lossy due to electromagnetic radiation.

In 1946 Alvarez overcame to the inconvenient by including the Wideroe structure inside a large metallic tube forming an efficient cavity where the fields were confined.



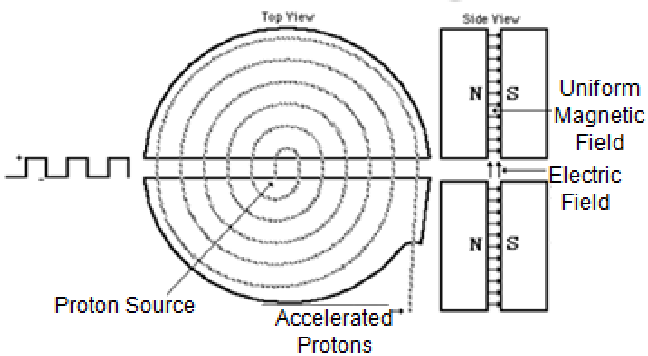
200 MHz RF source from radars

The Alvarez structures are still widely used as pre-accelerator for protons and ions. The particles at few hundred keV from a Cockcroft-Walton for example, are accelerated to few hundred MeV.

For higher energy: circular accelerators

Changing the Particle Energy
F. Sannibale

Cyclotron and Synchro-cyclotron



The first cyclotron
4.5" diameter (1929).

E. O. Lawrence
1939 Nobel Prize

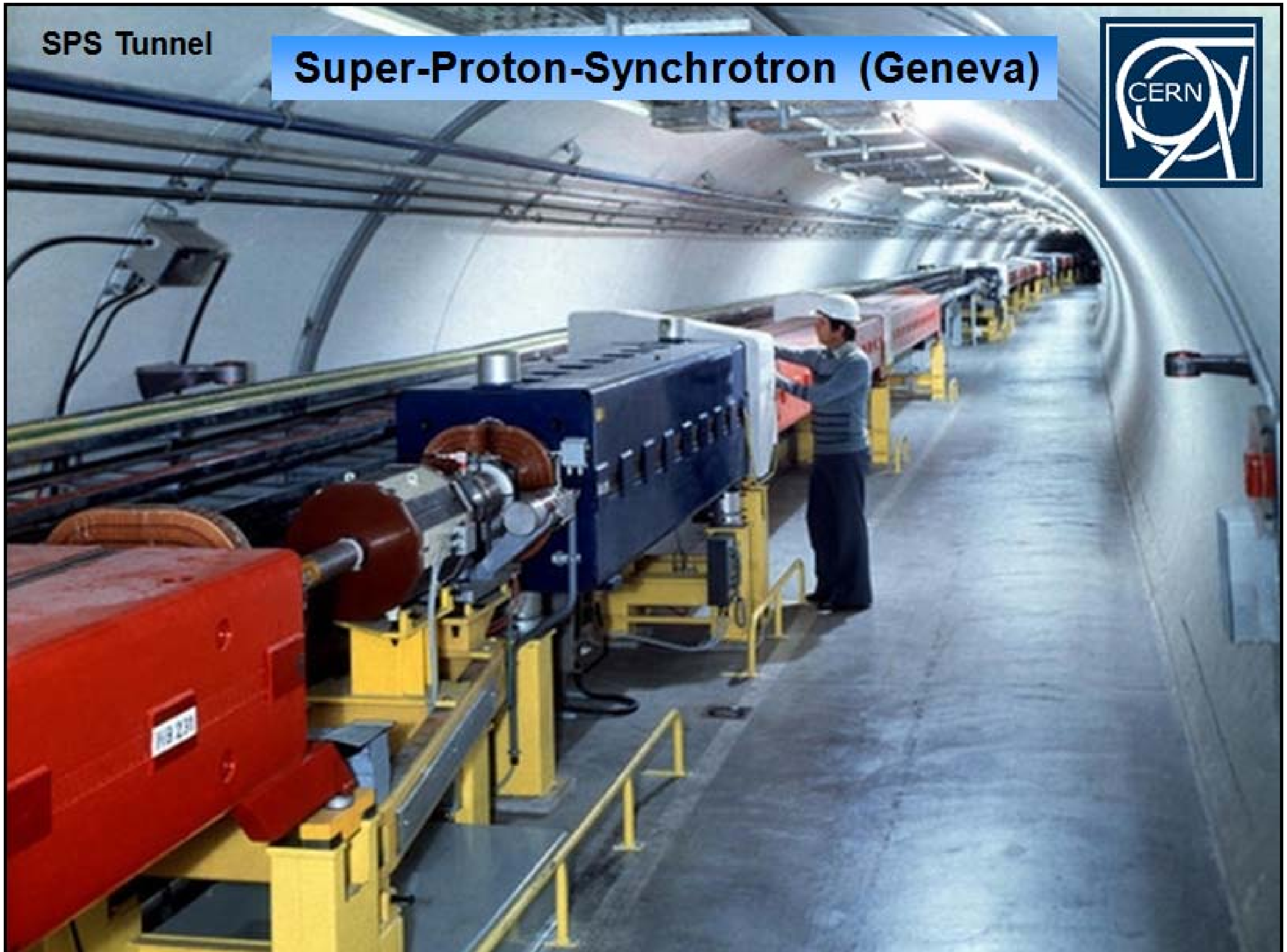
In an uniform magnetic field:

$$T_R = \frac{2\pi r}{v} = \frac{2\pi p}{veB} = \frac{2\pi mv}{veB} = \frac{2\pi m}{eB} \quad for \quad v << c$$

For non-relativistic particles the revolution period does not depend on energy

- **If the RF frequency is equal to the particles revolution frequency synchronicity is obtained and acceleration is achieved.**
- **The synchro-cyclotron is a variation that allows acceleration also of relativistic particles. The RF frequency is dynamically changed to match the changing revolution frequency of the particle**
- **In 1946 Lawrence built in Berkeley the 184" synchro-cyclotron with an orbit radius of 2.337 m and capable of 350 MeV protons. The largest cyclotron still in operation is in Gatchina and accelerates protons to up 1 GeV for nuclear physics experiments.**

Relativistic: Synchrotron (at CERN since 1959)



Synchrotron Radiation in Circular Electron/Positron Accelerators/Storage Rings

- Synchrotron radiation emitted by e^+/e^- on non-straight orbit (e.g. circular)

- Energy radiated per revolution

$$\Delta E = 4\pi\alpha\hbar C\beta^3\gamma^4 / 3R$$

R ... radius of curvature of trajetory

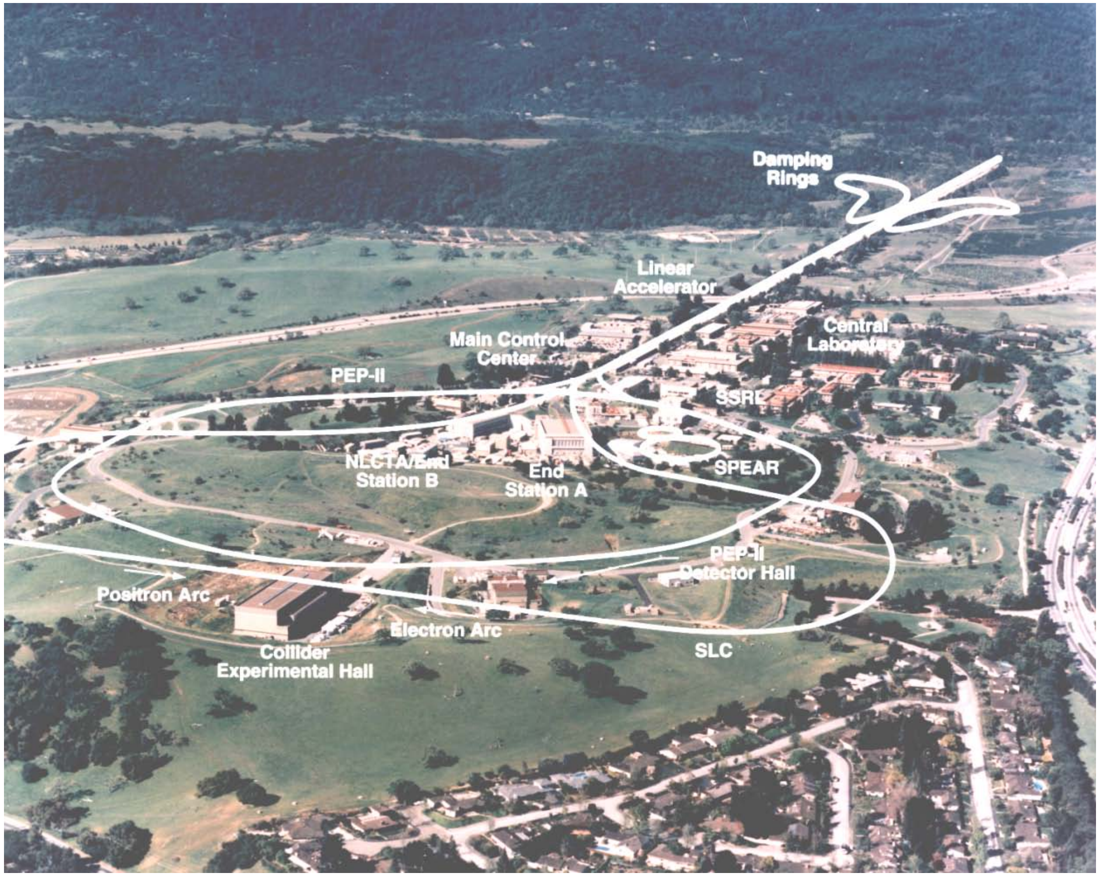
for $\beta \sim 1$

$$\Delta E[GeV] \approx 9\text{x}10^{-8} \quad E^4(GeV)/R(km)$$

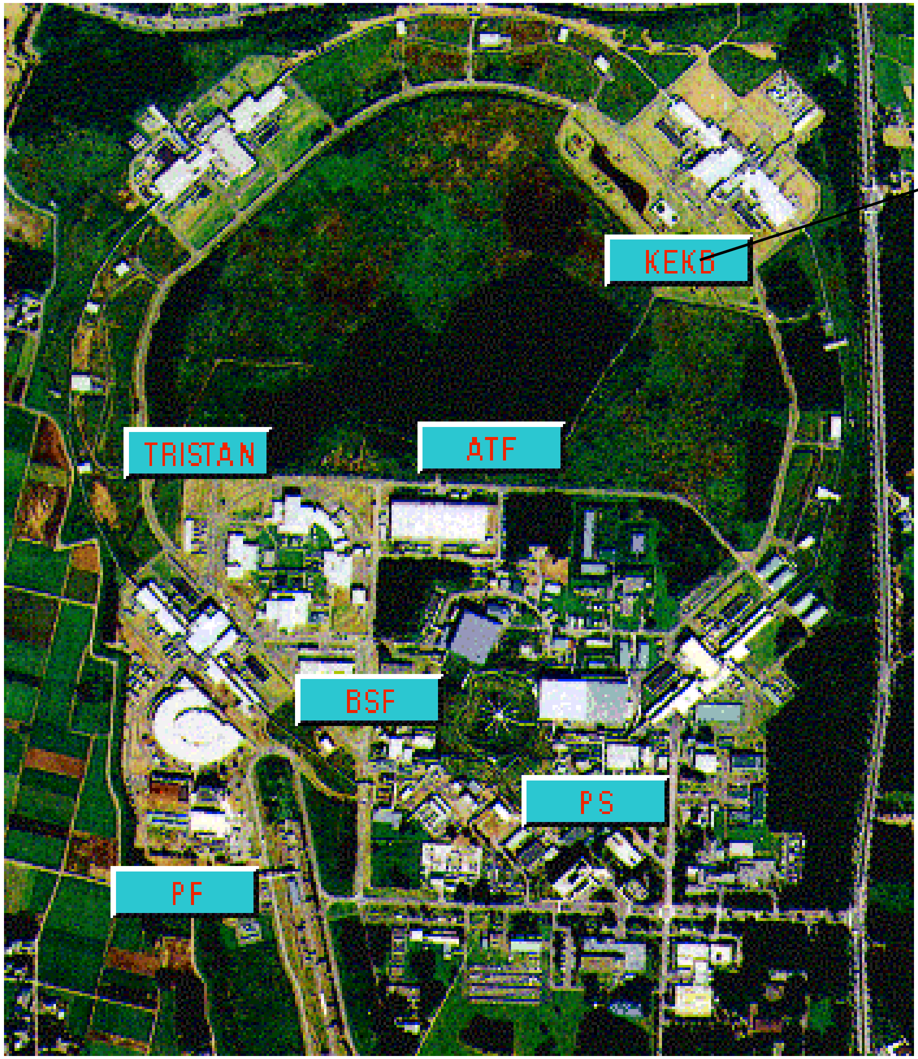
for LEP at *E* = 100 GeV $\Delta E \approx 25$ GeV

- LEP was the last high-energy circular e^+e^- collider

SLAC Accelerator Complex



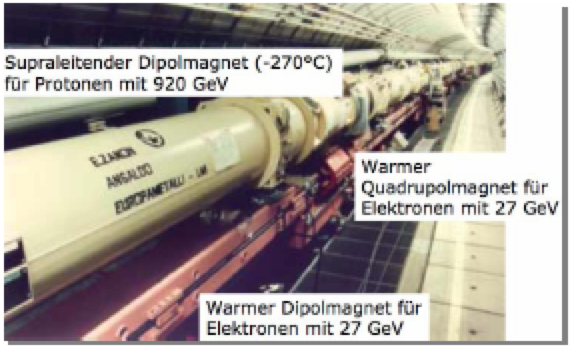
The KEK Accelerator Complex

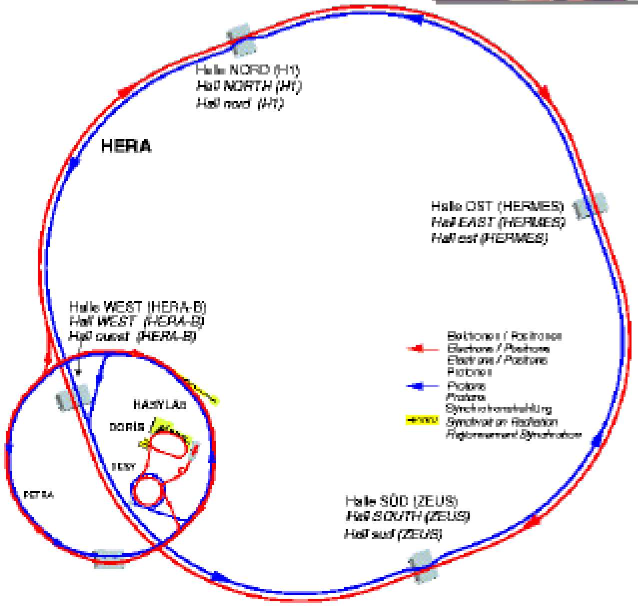


HEPHY is there

The FNAL Accelerator Complex

HERA





Betrieb :

1992 - Sommer 2007

Ort : DESY, Hamburg

Umfang = 6.3 km

Teilchen :

Elektronen (oder Positronen) - Protonen

Strahlenergie

e = 28 GeV , p = 820-920 GeV

Luminosität

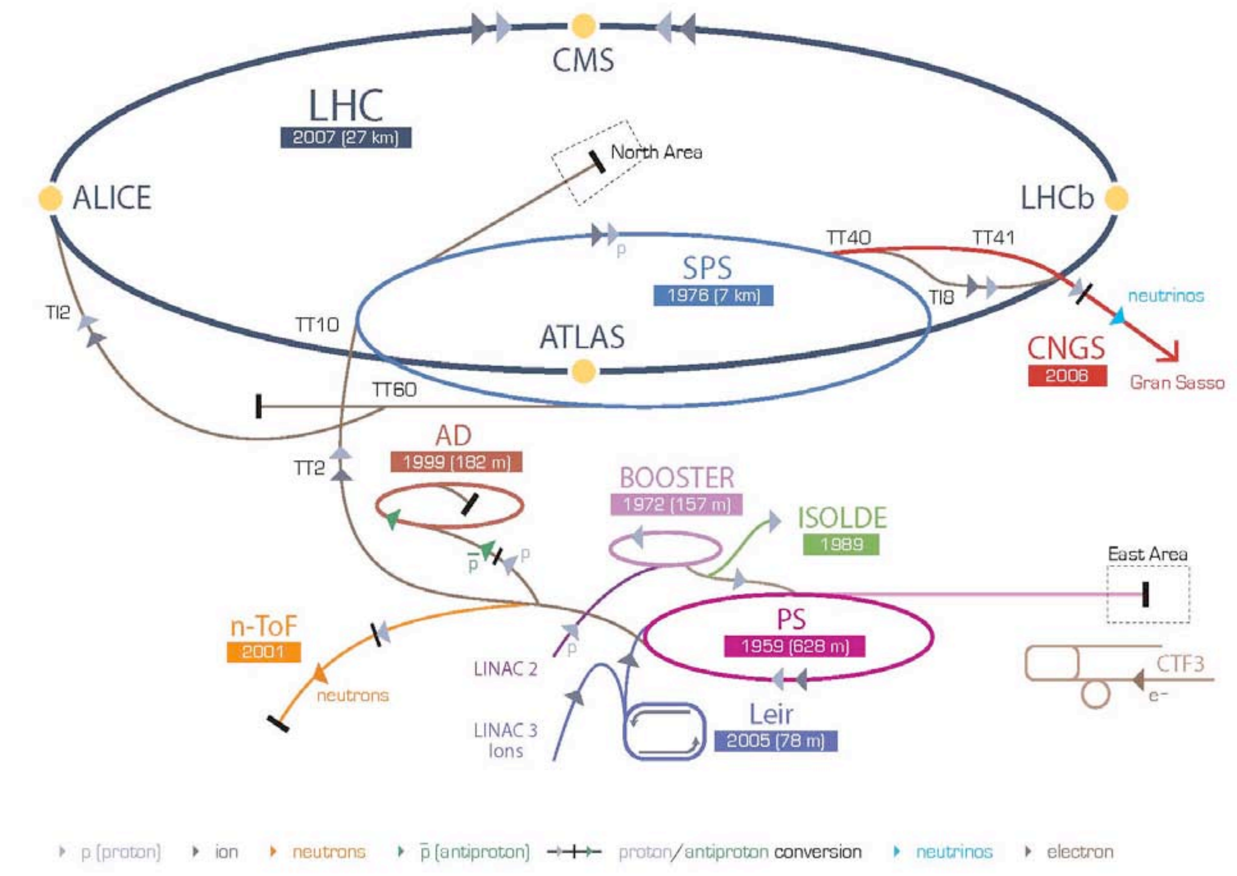
ca. 2×10^{31} cm^{-2} sec^{-1}

Experimente

H1, ZEUS ; HERMES, HERA-b

The CERN Accelerator Complex

The CERN Accelerator Complex

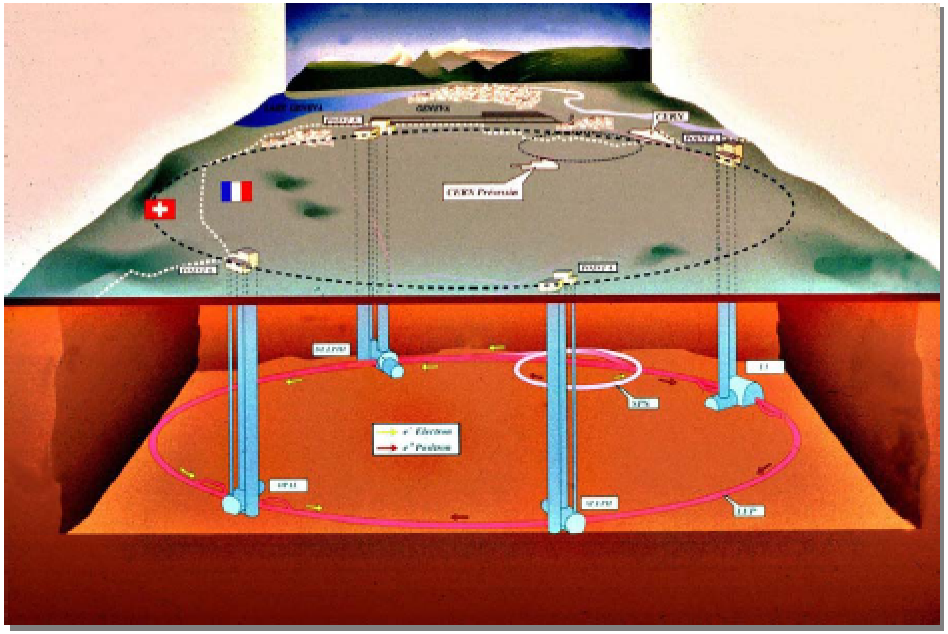


LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

LEP



In Betrieb :
1989 - November 2000

Ort : CERN, Genf

Umfang : 27 km

Teilchen :
Elektronen - Positronen

Strahlenergie :
45 GeV → 104.5 GeV

Luminosität :
10^{31} - 10^{32} cm^{-2} sec^{-1}
L_{int} » 1000 pb^{-1}

Experimente :
ALEPH, DELPHI, L3, OPAL

The LHC Technology Challenge: Protons at 7 TeV in LEP Tunnel

1232 superconducting Dipole Magnets, operated at 1.9 K

Cooled with superfluid Helium

Novel Design:

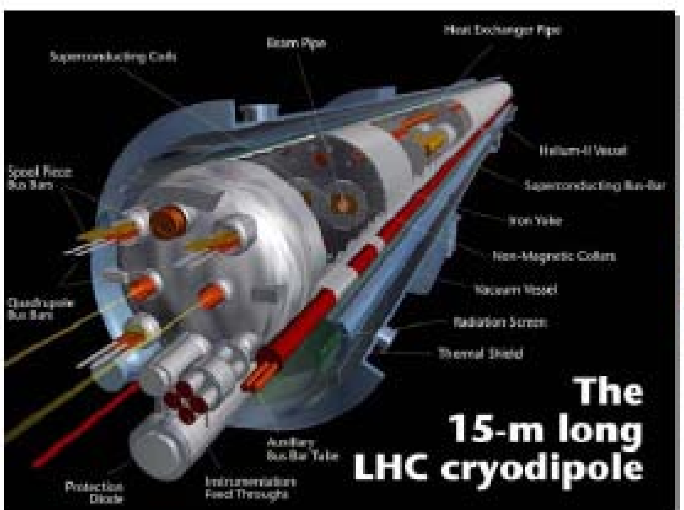
'Two-in-one' Magnet:

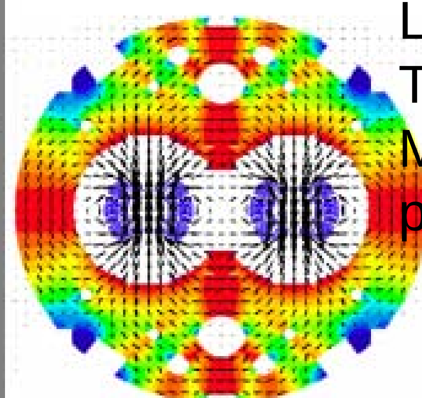
Each cryostat contains two B-fields, with opposite Direction for the two proton Beams

LHC is housed in the LEP Tunnel

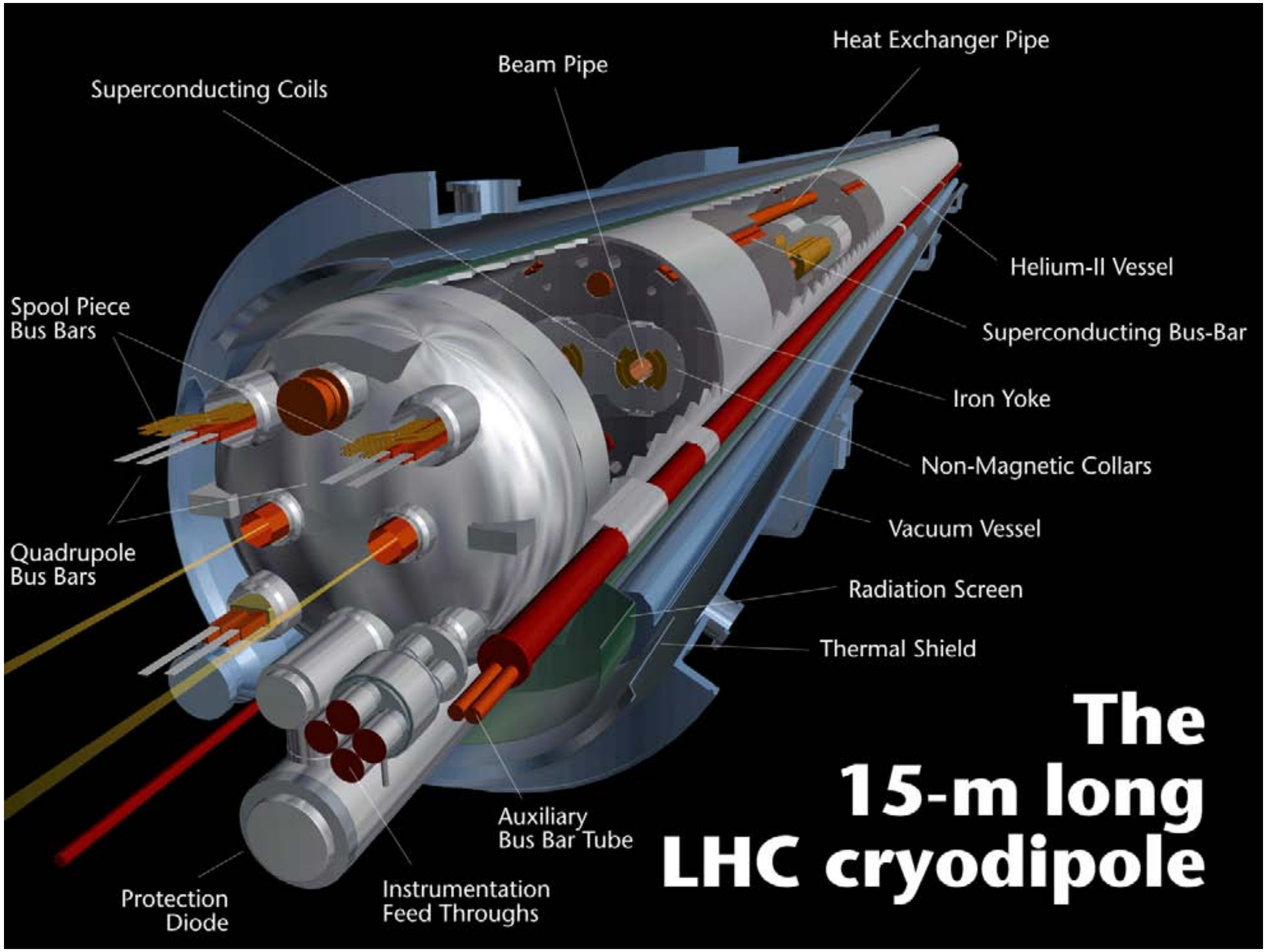
More than 10^{14} protons circulating

$\sqrt{s}$ = 14TeV



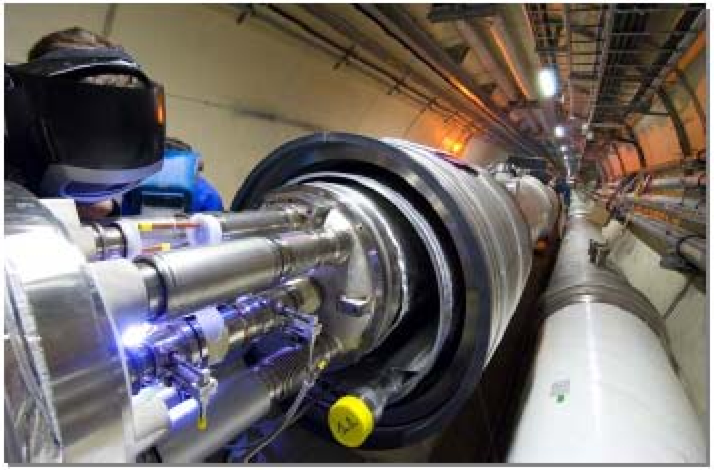


Details of a Cryodipole Magnet

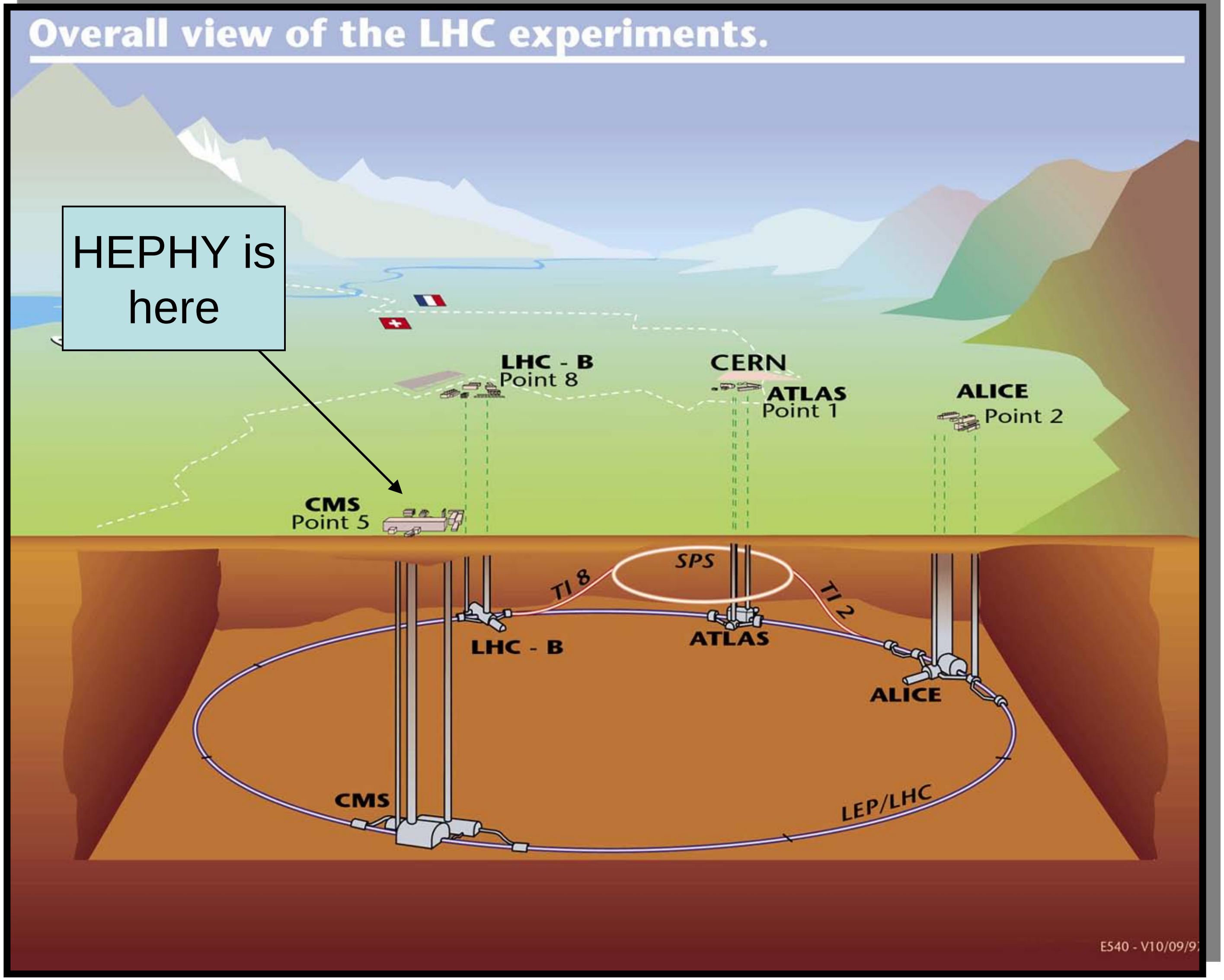


During the LHC Construction

Absenken des ersten LHC-Dipols
in den Tunnel : März 2005
März 2007: alle Dipolmagnete installiert



The four LHC Experiments



First beams 2nd half of Nov 2009 !

Particle Detectors

- Position measurement
  - Tracking; secondary vertices (particle lifetime)
  - Momentum measurement
- Identification of type of Particle

- Energy measurement of photons, electrons, hadrons
- Examples
  - The Antiproton Discovery
  - The W and Z- Boson discovery
  - CP Violation
  - CMS

Measurement tasks (1)

- In principle
  - Aim to measure all quantities: four-vector of all particles produced
  - Energy- momentum vector $(\frac{E}{c}, \vec{p})$
  - Scalar product of four-vector is invariant $\tilde{a} \cdot \tilde{a} = a_0^2 - |\vec{a}|^2$
- Invariant Mass of particle system is an invariant
  - Example: two-particle system : e.g. J/ψ -> $e^+ e^-$

$$
\begin{aligned}
c^2 M^2 &= (\tilde{p_1} + \tilde{p_2})^2 \\
&= \tilde{p_1}^2 + \tilde{p_2}^2 + 2 \cdot \tilde{p_1} \cdot \tilde{p_2} \\
&= c^2 m_1^2 + c^2 m_2^2 + 2(\frac{E_1 E_2}{2} - p_1 p_2 \cos\theta)
\end{aligned}
$$

- Need to measure: E, p or p, m or p and v….

Measurement tasks (2)

- Particles are characterized through
  - Charge Q
  - Mass m (specific to a given particle)
  - Spin
  - Magnetic moment
  - Lifetime (specific to a given particle)
  - Decay modes
- Momentum measurement through measurement of curvature of tracks in magnetic field
- Mass measurement with methods of ‘Particle Identification’
- Velocity measurement through direct or indirect methods
- Energy measurement through total absorption of the energy in ‘Calorimeters’

Energy Loss of Charged Particles: Ionisation, excitation

Bethe – Bloch: average energy loss:

$$-\frac{dE}{dx}\left[\frac{\mathrm{MeV.cm}^2}{\mathrm{g}}\right] = K\,Z^2\,\frac{z}{A}\cdot\frac{1}{\beta^2}\cdot\left[\frac{1}{2}\ln\frac{2mc^2\beta^2\gamma^2T_{max}}{I^2}-\beta^2-\frac{\delta}{2}\right]$$

$K = 4\,\pi\,N_A\,r^2\,mc^2 = 0.307$ MeV cm^2/mol

A … massnumber [g/mol] of the material

$T_{max} \approx 2mc^2\,ß^2\,\gamma^2$ max. kinetic energy, which can be transferred to electron

mc^2 ... Mass of electron * c^2

Z … charge of incident particle

z … atomic number of material traversed

δ … Density correction

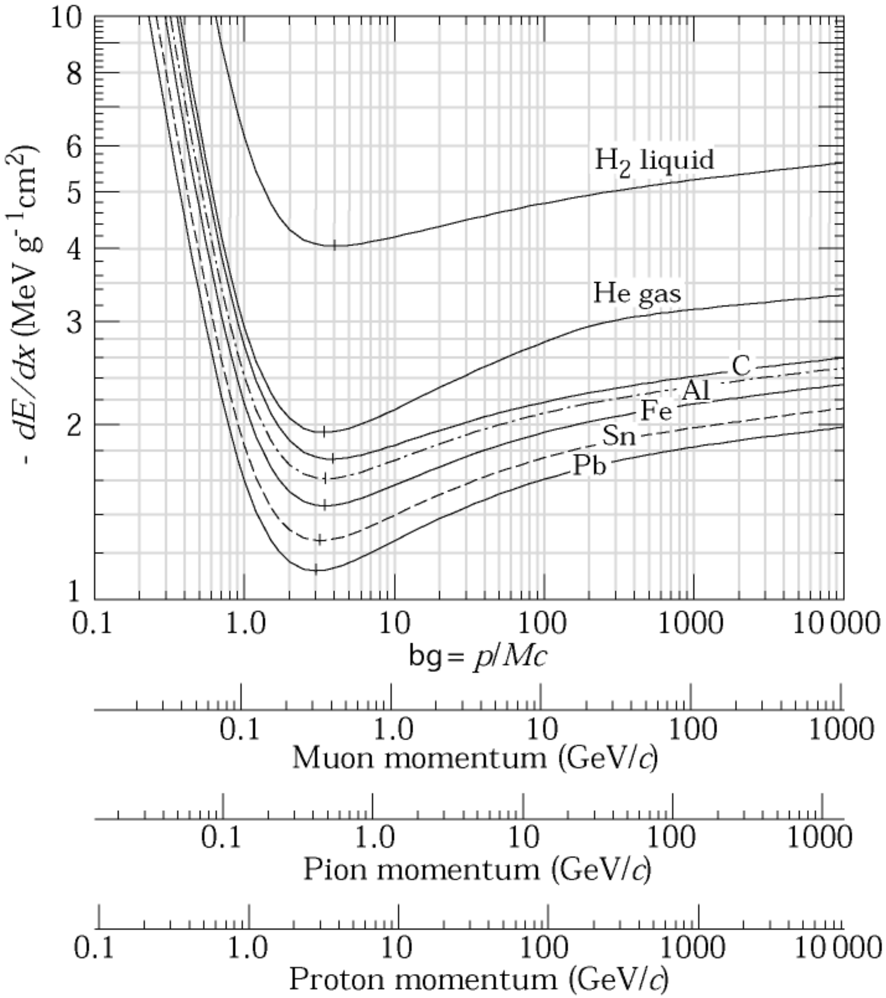
Average Energy Loss (Ionisation)

dE/dx has minimum for $\beta\gamma \approx 3$

For $Z \approx 0.5\,A$

dE/dx ≈ 1.4 MeV / g cm^{-2} for $\beta\gamma \approx 3$

$$\frac{dE}{dX}\frac{1}{\rho} \approx 1.4\,\text{MeV}$$



Energy Loss: Additional mechanisms

In addition to ionisation/excitation:

- Cherenkov radiation; transition radiation
  - minor (~ percent) compared to ionization losses;
    (to be discussed later)

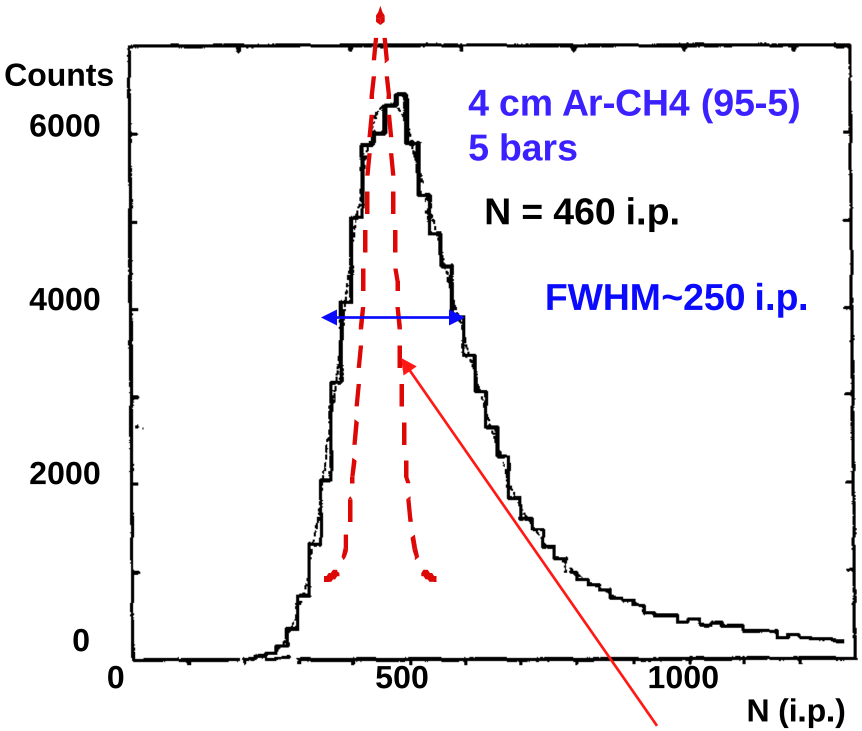
- Bremsstrahlungs loss ~ mass^{-2} of particle
  - significant for relativistic electrons and muons with $ßγ > 10^2$

- For hadrons (protons, pions…)
  - Energy loss via strong interactions

Ionisation: Fluctuations

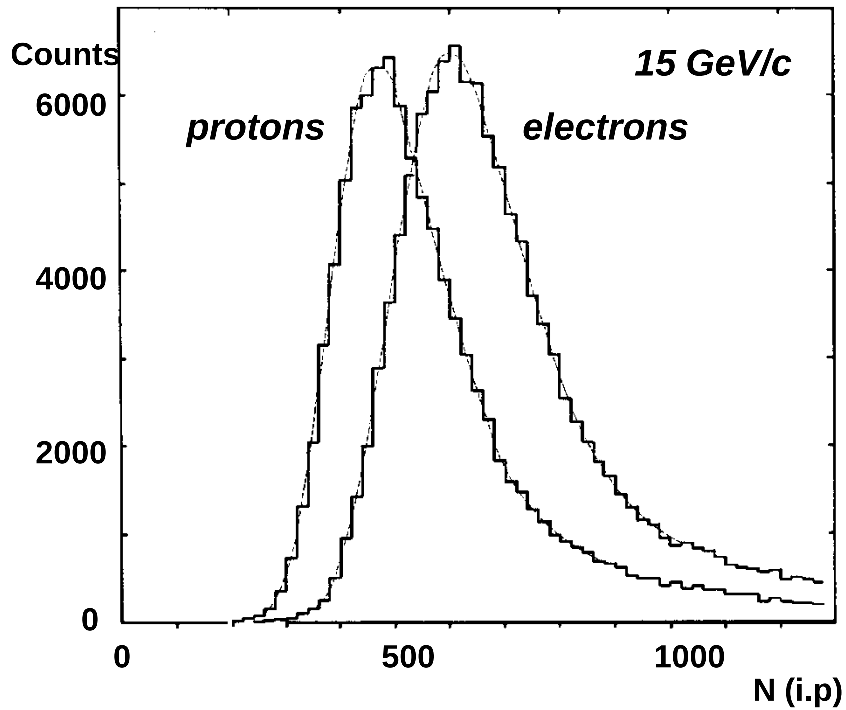
Due statistical nature of energy loss→energy loss distributions (under repeated measurements under identical conditions)

LANDAU DISTRIBUTION OF ENERGY LOSS:



For a Gaussian distribution: **σ_N ~ 21 i.p.**
FWHM ~ 50 i.p.

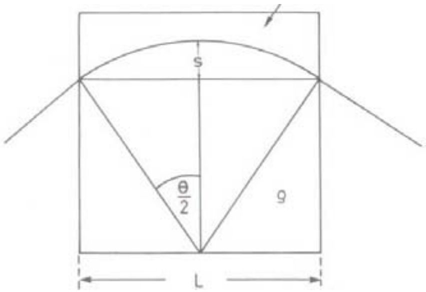
PARTICLE IDENTIFICATION
Requires statistical analysis of hundreds of samples



I. Lehraus et al, Phys. Scripta 23(1981)727

Momentum measurement in magnetic field

- Sagitta of track curvature



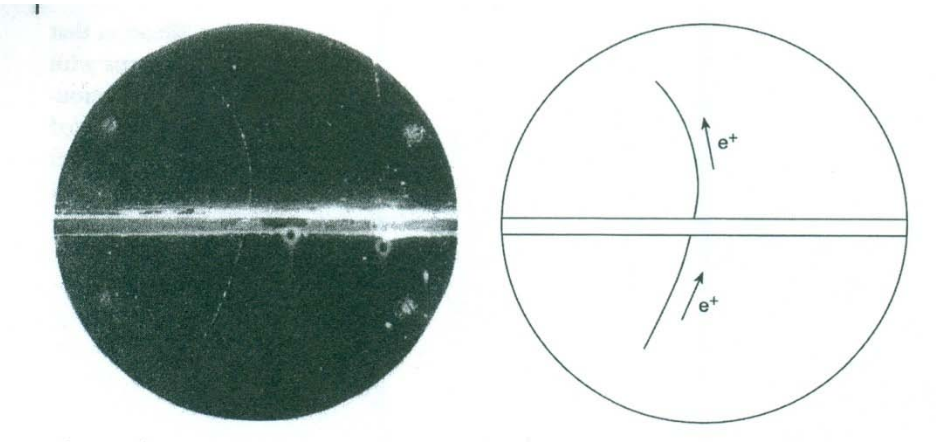
Lorentz force **F**= q[**E** + (**v** x **B**)]

where
F is the force (in newtons)
E is the electric field (in volts per metre)
B is the magnetic field (in teslas)
q is the electric charge of the particle (in coulombs)
v is the instantaneous velocity of the particle (in m/ s)

- Radius of curvature ρ as a function momentum and magnetic field
  - ρ[m] = 3.3 p [GeV/c] / q B [T]   q…charge; (units electron charge)
  - s[m] = 0.3 B [T] L^2 [m] / 8 p [GeV/c] for q=1
- Momentum accuracy with N measurements along the track of resolution σ_x

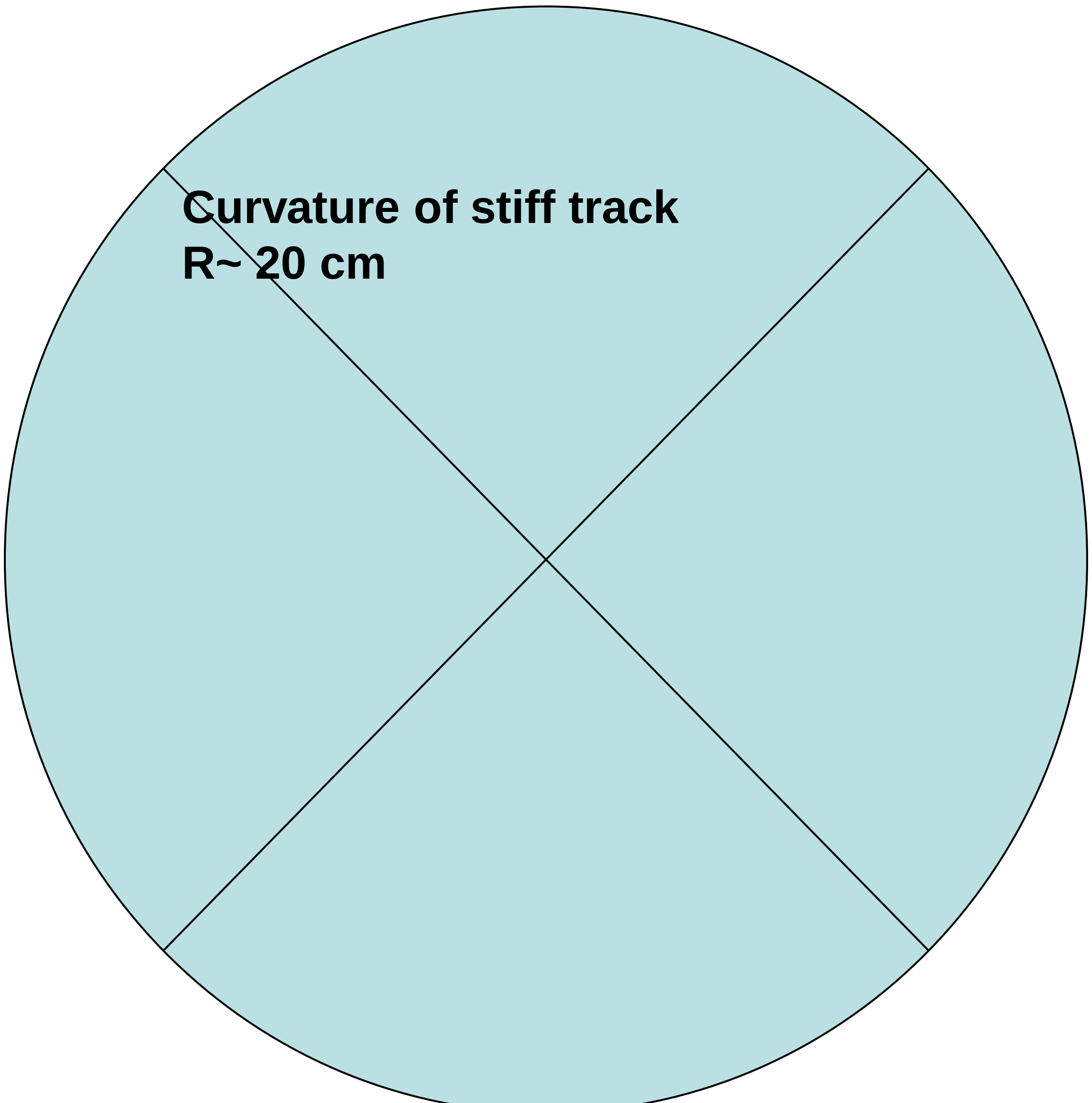
$$\frac{\delta p}{p} = \frac{\Delta s}{s} = \frac{\sigma_x[\mathrm{m}]}{\sqrt{N}} \cdot \frac{3.3 \cdot 8 \cdot p[\mathrm{GeV/c}]}{B[\mathrm{T}] \cdot L^2[\mathrm{m}^2]}$$

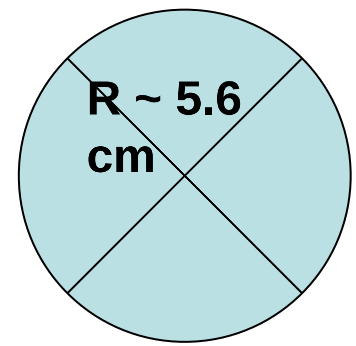
Discovery of positron



track in cloud chamber, placed in magnetic field
energy loss of particles in lead – plate ⇒ particle moves upwards ⇒ positively charged
Exercise: explain how Anderson estimated the mass of this particle
note: Pb-plate is 6 mm thick

Estimating the curvatures of the particle track of Anderson's positron candidate





Position Measurement of Charged Particles

- Energy loss of charges particles
  - Ionization, excitation
  - statistics of primary und secondary collisions
- Charge transport
  - transport of electrons and ions
  - diffusion and its consequence for track detectors
- Charge registration and measurement
  - ionizations chambers (gas, liquids, semiconductor)
  - charge amplification
- Tracking
  - intrinsic limitation to space resolution

Track Measurements in Gas and Semiconductors

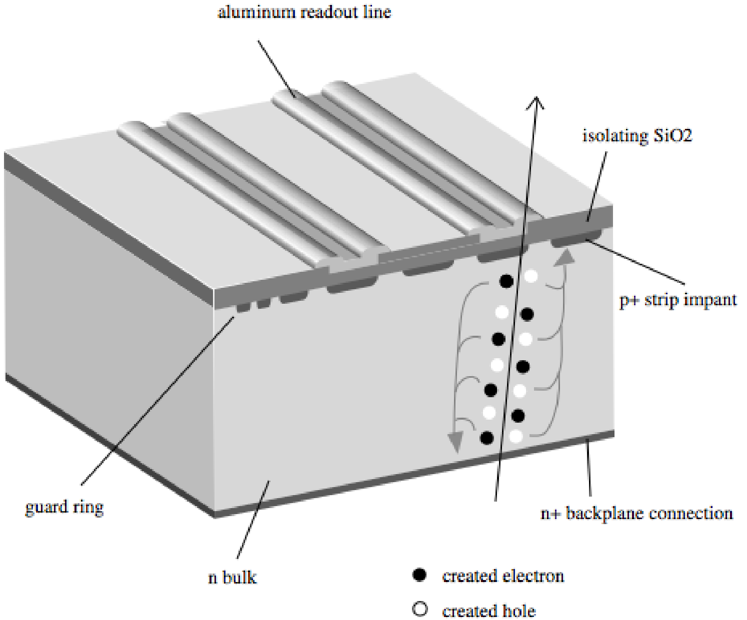
- Principle
  - charged particles ionize detector material
  - in applied, external electrical field transport of free charges towards electrodes
  - transport of charges induces charges at electrodes :
    - registered in semiconductor detectors (‘ion chamber’)
    - In gaseous detectors, charge is amplified around wire electrodes through internal amplification
  - signal distribution at electrodes permits position measurement of charged particle

Tracking in Gas and Semiconductors
(ionisation chambers and proportional chambers)

- Si-Detectors; Si-Pixels: ultimate resolution
- Wirechambers: start of a revolution
- Driftchambers: modern developments
- TPC
- from MWPCs to GEMs
- RPCs: what, how, why ?

Tracking with Semiconductor Detectors

- Principle: solid state – ionisation chamber



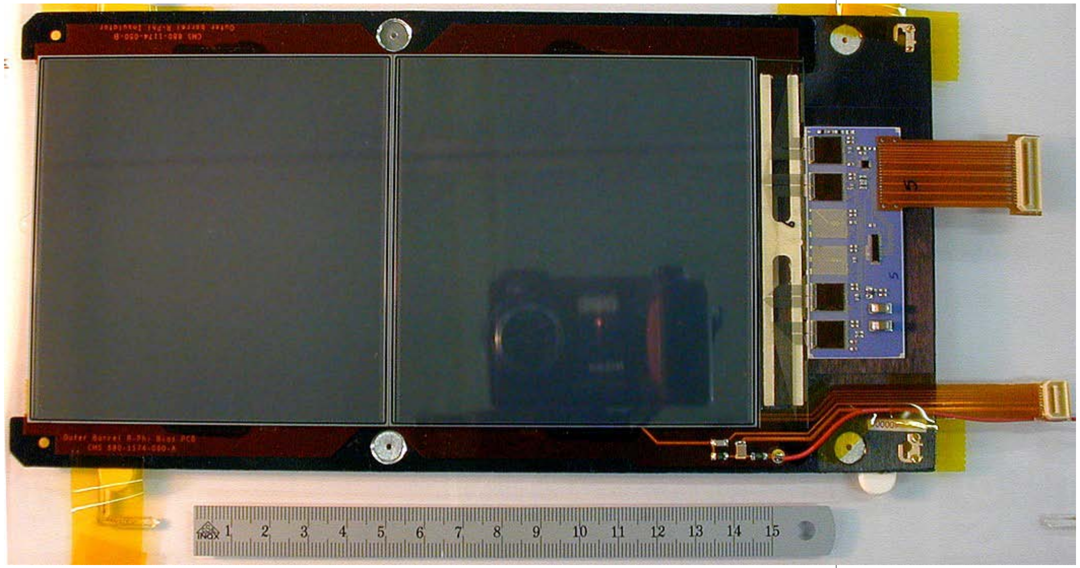
$$\frac{dE}{dx}(Si) \cong 4.3 MeV/cm$$

- Advantages
  - ~1000*dE/dx compared to gases/ unit distance (~1000 higher density)
  - w ~ 1/10 compared to gases: w (Si) = 3.6 eV
  - for min. ion.particles N (e-h) = 7200/100μm
  - due to much higher density, much better correlation of ionisation and particle track→ space resolution ~ 1μm

Picture of a CMS Si-Tracker Module

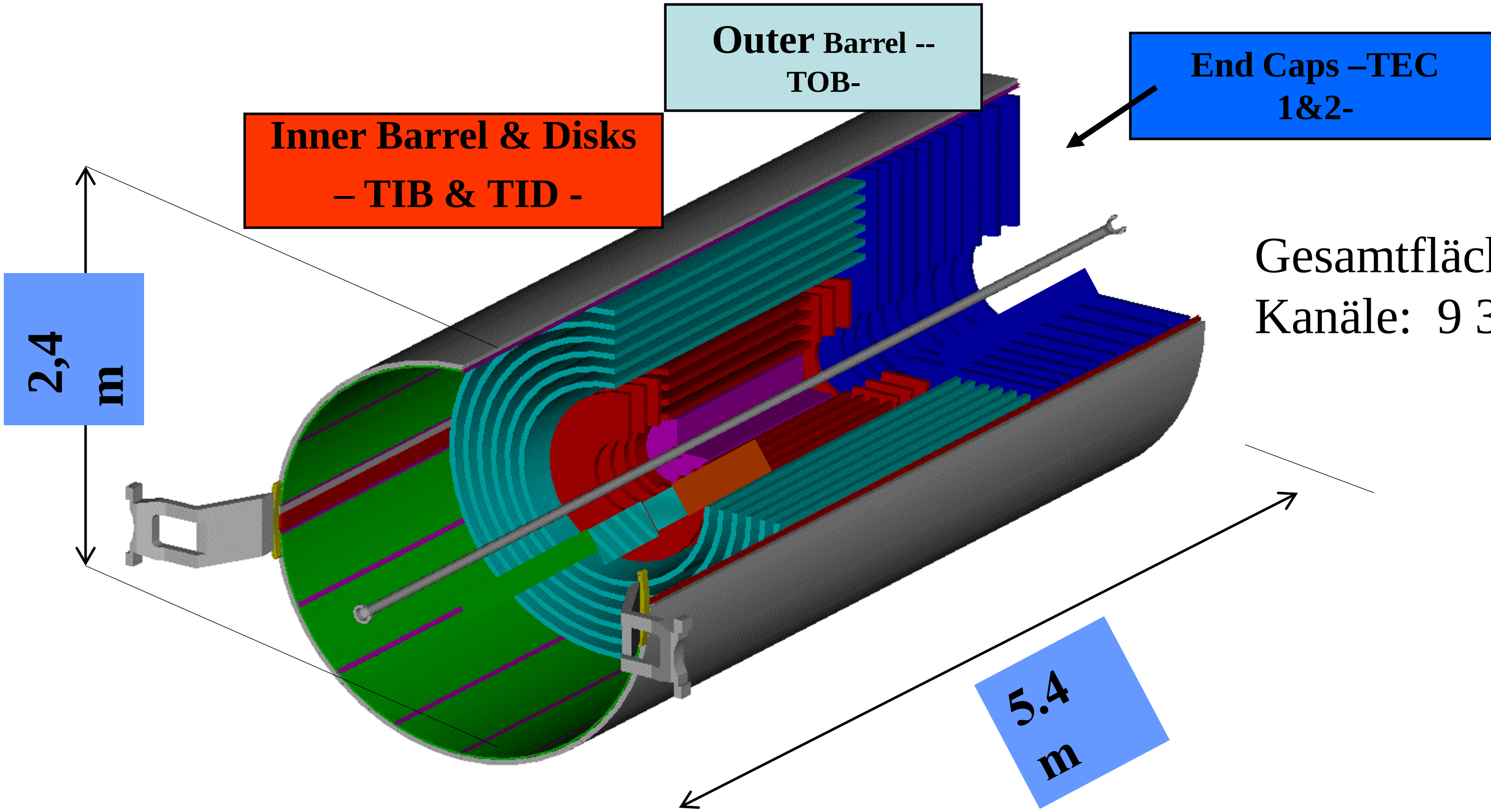
Outer Barrel module

Composed of two daisy-chained sensors, each made out of a 6-inch wafer



CMS Tracker Layout: the world's largest Silicon Tracker

Simplified drawing of the tracker layout, with external support tube and support brackets



Gesamtfläche: 200m²
Kanäle: 9 300 000

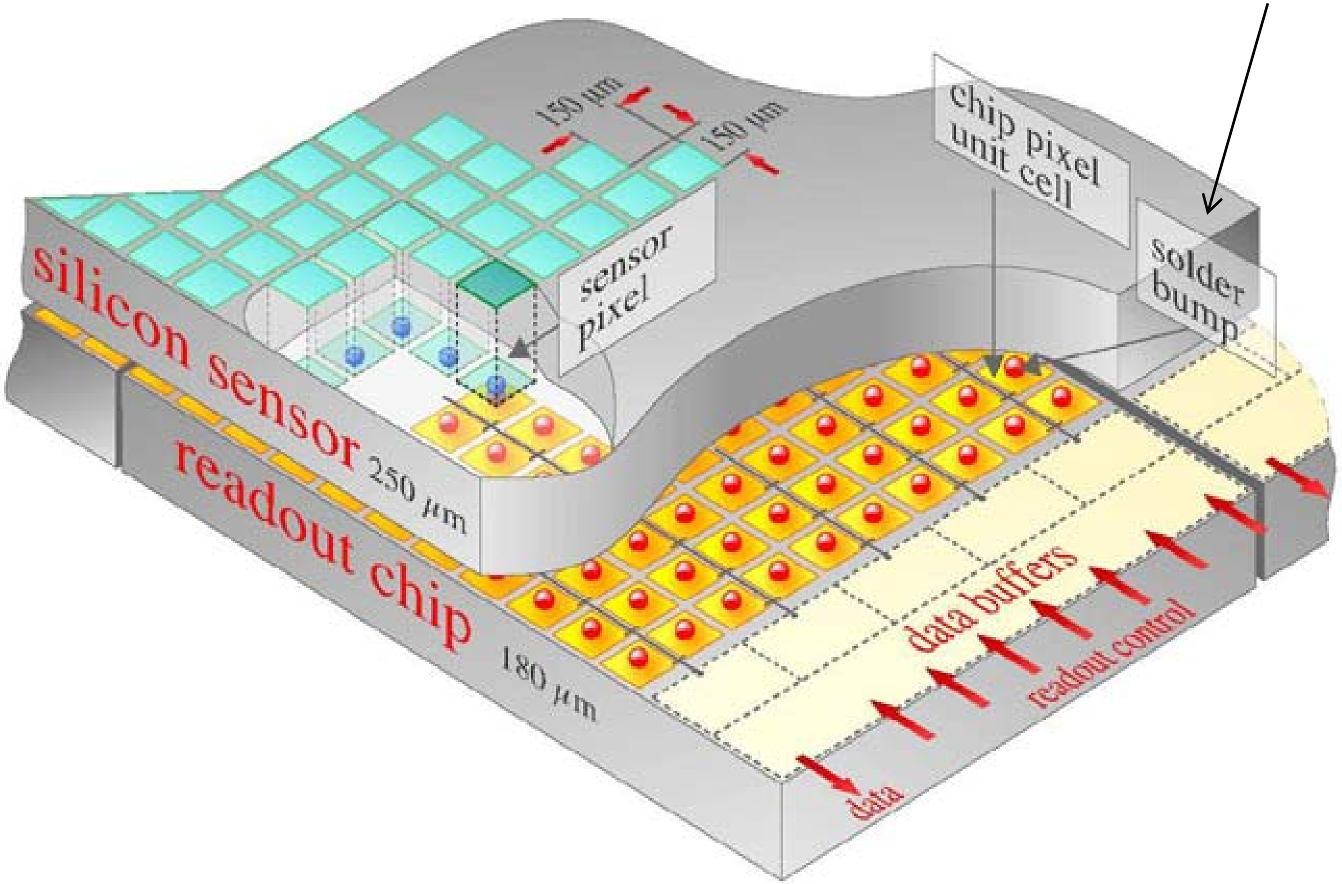
Pixel-Detectors

- Principle: Si-Detector with 2-dimensional ‘Checker board‘ of readout-electrodes
- Typical Size: $\approx$ 50 x 200 µm
- Applications: the very high spatial resolution permits reconstruction of the decay vertex of very short-lived particles (decay typically within a fraction of a millimeters (Charm, Beauty)
- Measurement of decay vertex: ‘Vertex-Detektoren’
- Difficulty: connectivity to readout electronics

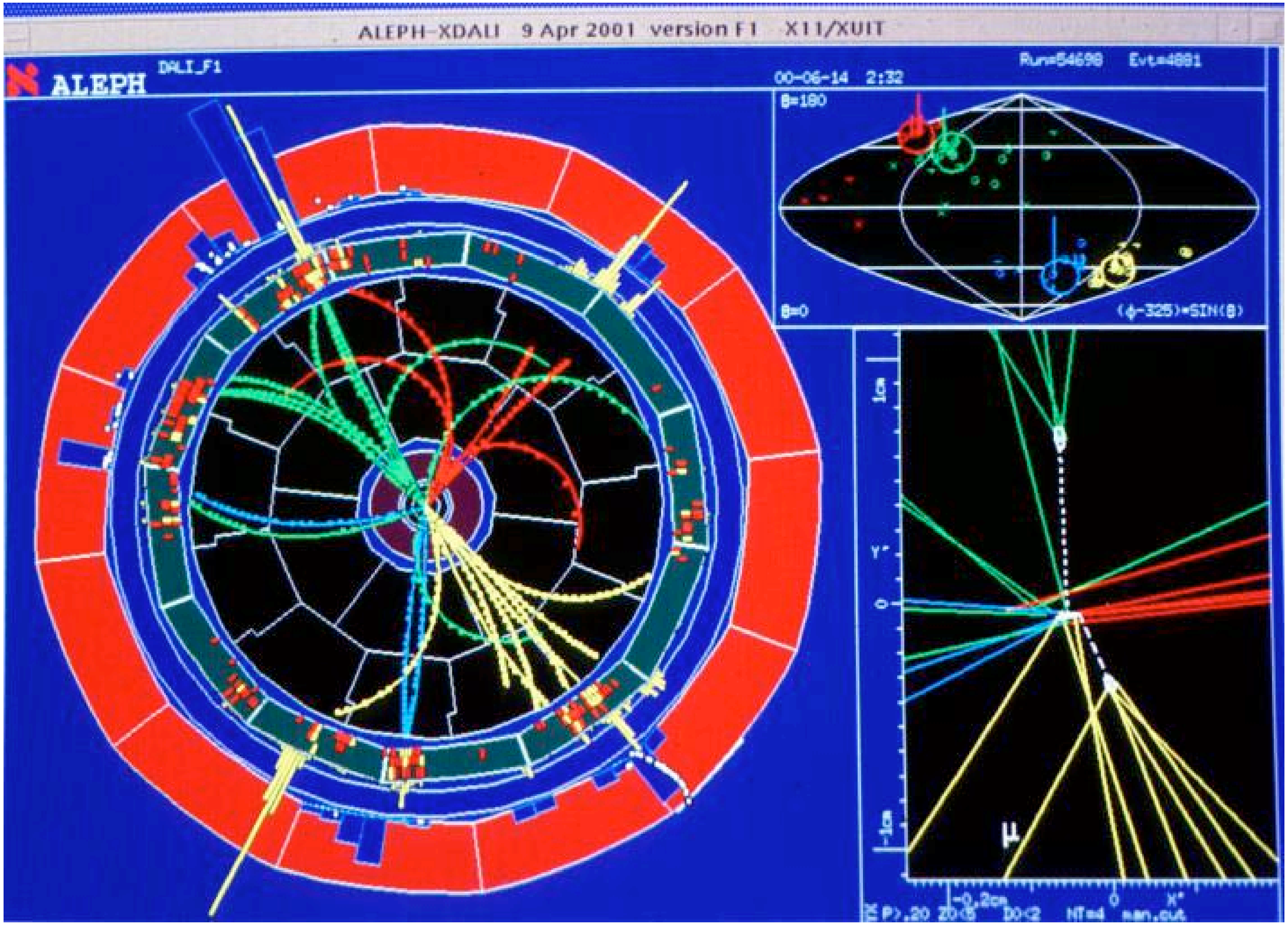
Schematic View: Pixel sensor coupled to readout chip with 'Solder Bumps'

Required development of miniaturized electronics (one preamplifier/pixel)

Required development of connection techniques pixel-preamp



ALEPH Higgs Candidate Event: Typical task of a vertex detector



Detectors with Internal Electron Multiplication

- Principle: at sufficiently high electrical fields (100kV/cm at STP): electrons moving in gas gain in between two ionization collisions more energy than ionization energy → Secondary Ionization

  (‘ Electron multiplication’)

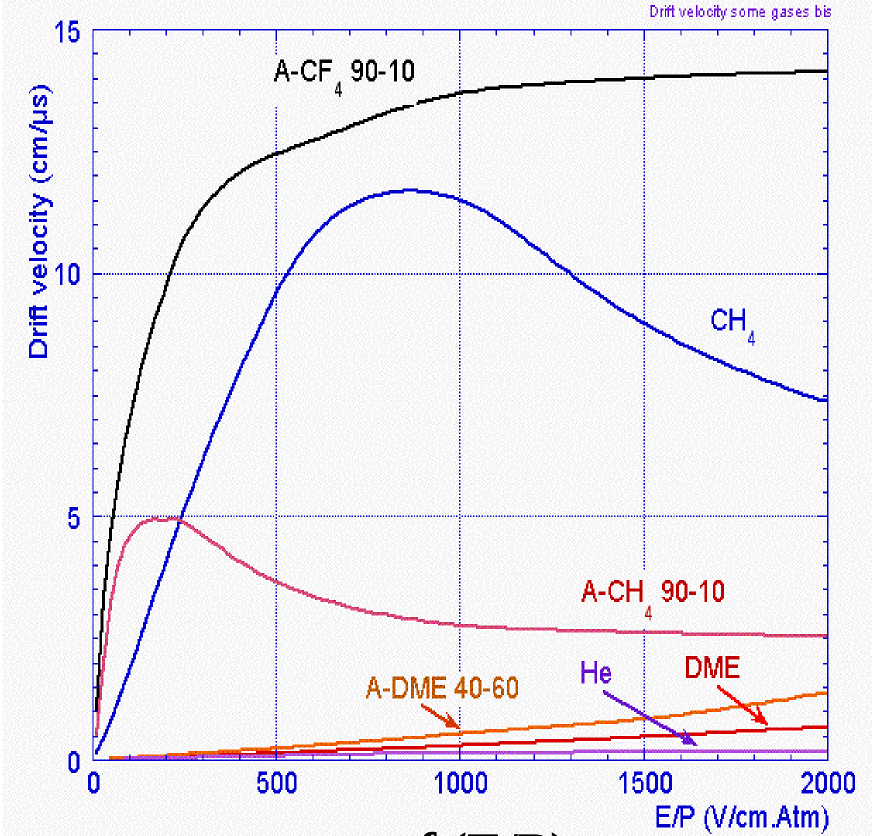
- Electron multiplication:
  - $dN(x) = N(x)\,\alpha\,dx$ α…’first Townsend Coefficient’
  - $N(x) = N_0 \exp(\alpha x)$ $\alpha = \alpha(\sigma(E))$ $N/N_0 = A$ (Amplification)
  - In addition: excitation of gas atome → emission of UV-photons → these may ionize in turn → ‘photoelectrons’
  - $NA\gamma$ photoelectrons → $NA^2\gamma$ electrons → $NA^2\gamma^2$ photoelectrons → $NA^3\gamma^2$ electrons
  - for finite gas amplification $\gamma < A^{-1}$

    γ … ‘second Townsend Coefficient’

Drift of Electrons in Gases

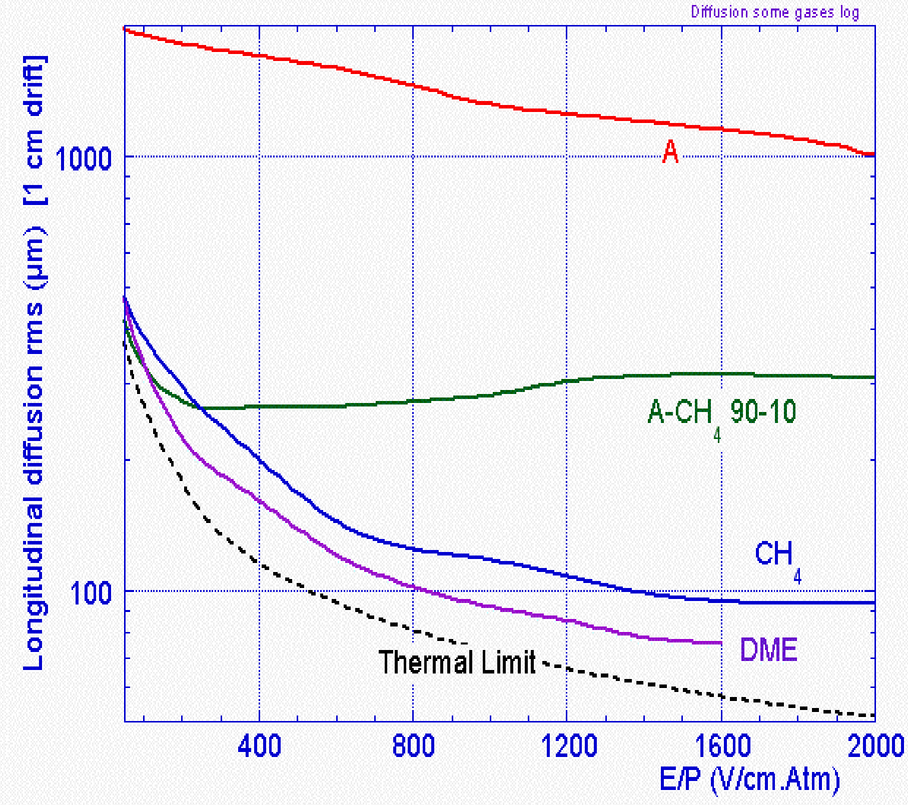
In external, applied electrical field: drift of free charges (electrons, ions)
Drift velocity and diffusion varies over wide range

DRIFT VELOCITY:

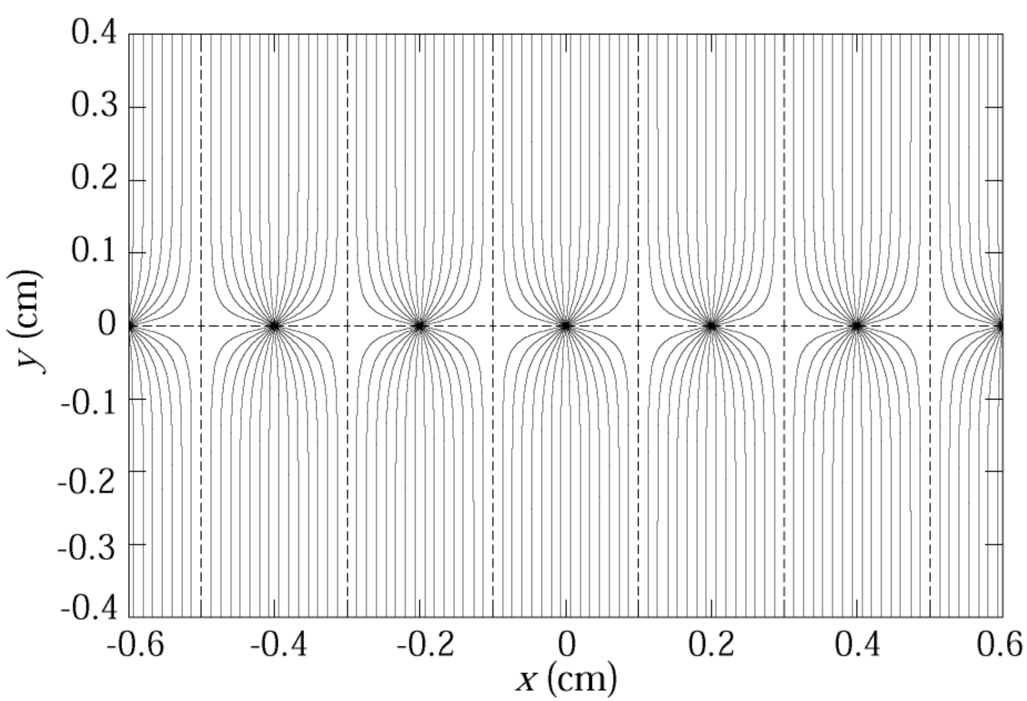


$v_D = f(E/P)$

DIFFUSION:



Multiwire Proportional Chambers (MWPC's)



Invented by G. Charpak (1968)

Revolutionized Particle Physics

Noble Prize in 1992

'Classic' geometry (cross section)

Typical dimensionen

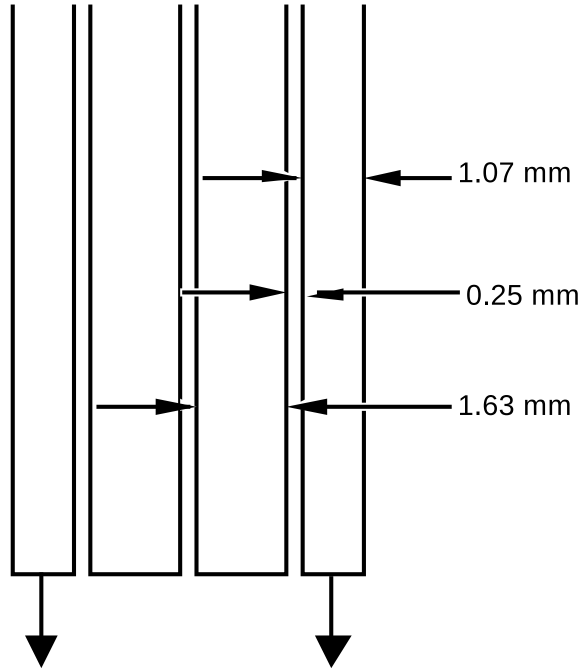
In high E- fields (≥ 100kV/cm) Ionization electrons accelerated to energies, sufficient for secondary ionization: $E \sim 1/r$; $E > E_c$ for $r \leq r_o$

- Typical counter gases: Ar (80-90%) / CO_2; Ar / CH_4; ...
- Role of 'Quench gas' CO_2, CH_4 : Absorption of excitation photons, produced during charge avalanche
- Typical values for one Electron-Ion pair w ≈ 30 eV
- Typical gas amplification G = G(E/P) from 1000 bis ~ 10^5
- Typical values for detected charge: few % of total charge

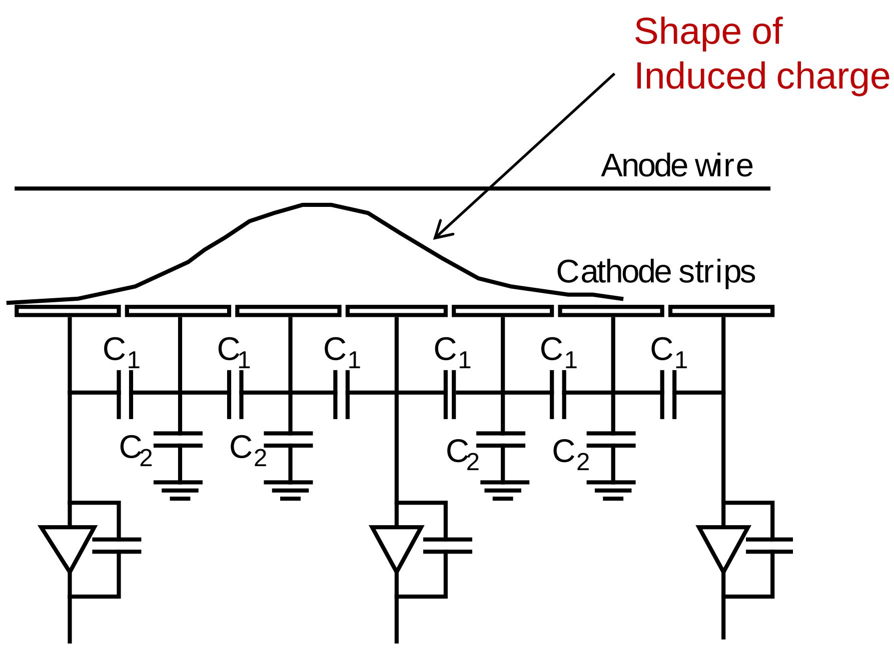
MWPC's: obtaining information on the 2nd coordinate

- Anode wire provides position information of one coordinate
- Cathode plane can be segmented in stripes perpendicular to anode wires: 2nd coordinate
- Cathode pale: segmented into 'checker board': unambiguous, 2-D readout

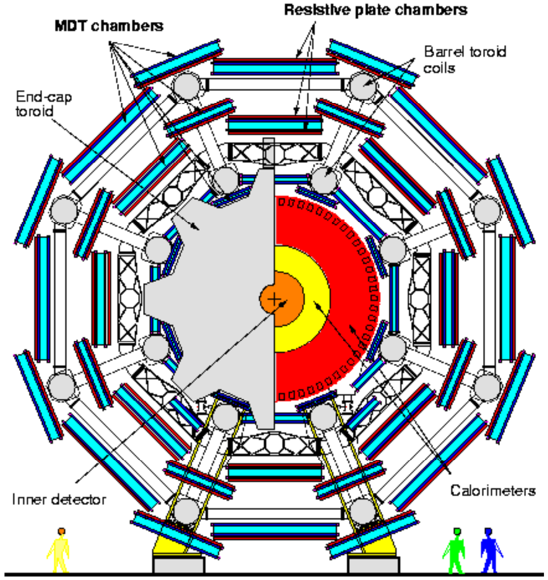
(a)

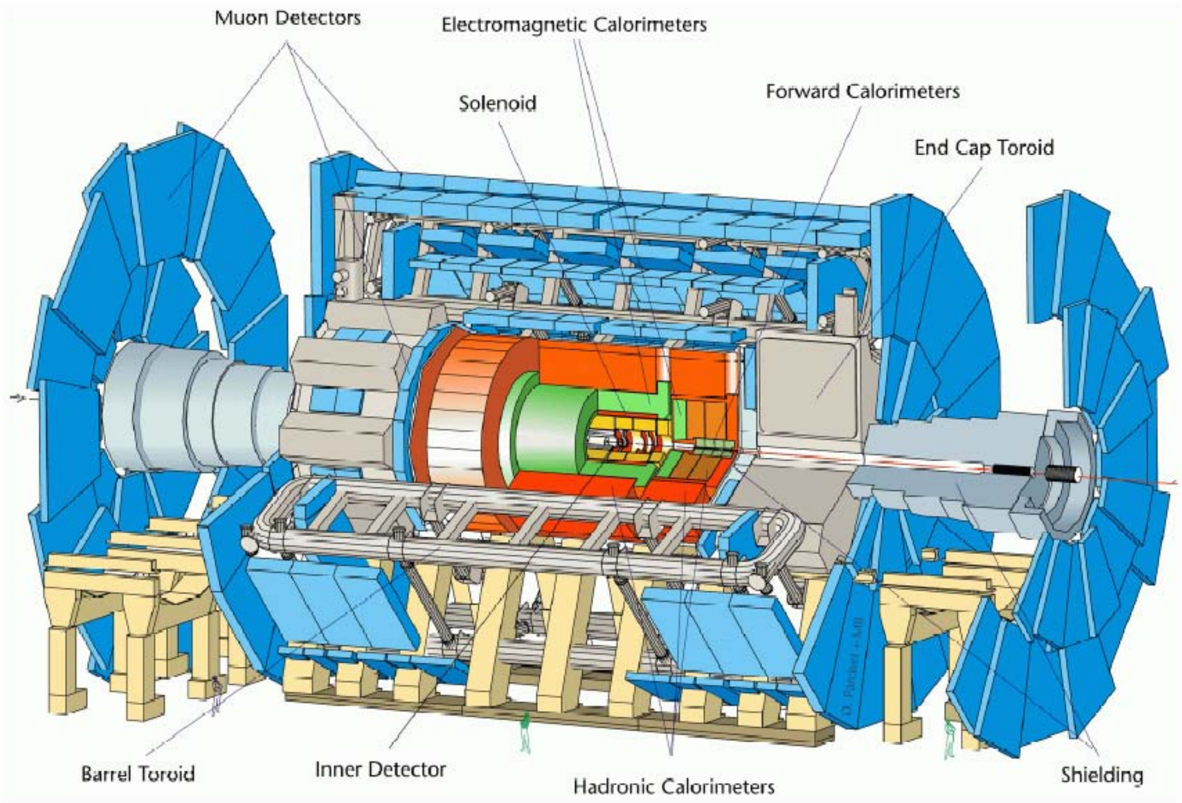


(b)



ATLAS Muon Spectrometer
blue outer detector planes are high-resolution wire chambers (~ 6000m^2)





Radius of outer Muon-Chambers: ~ 11 m

Total length: ~ 50 m

Time Projection Chamber (TPC): Principle & tasks

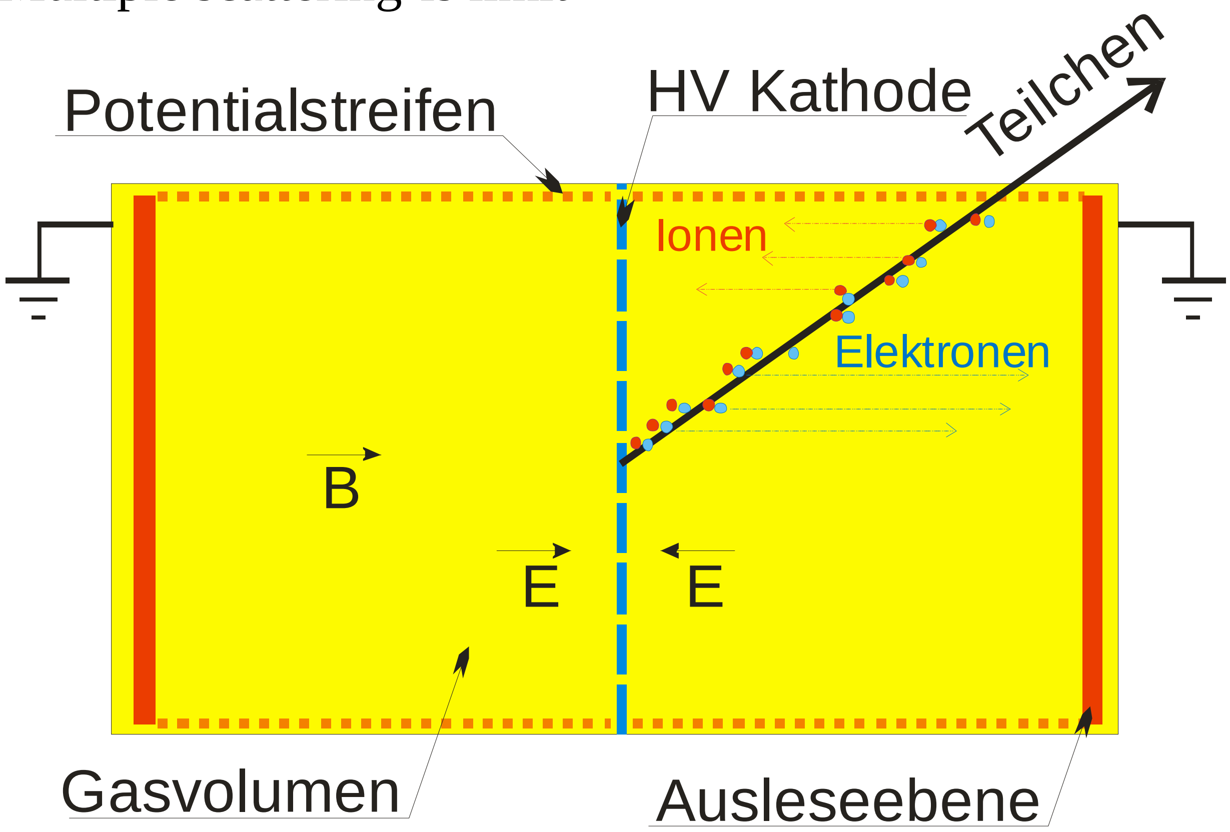
permits measurement of space points (x,y,z) along a particle trajectory

Momentum resolution σ(p)/p

- Space resolution + B-field
- Multiple scattering is limit

Energy resolution dE/dx

- Measure of primary ionization



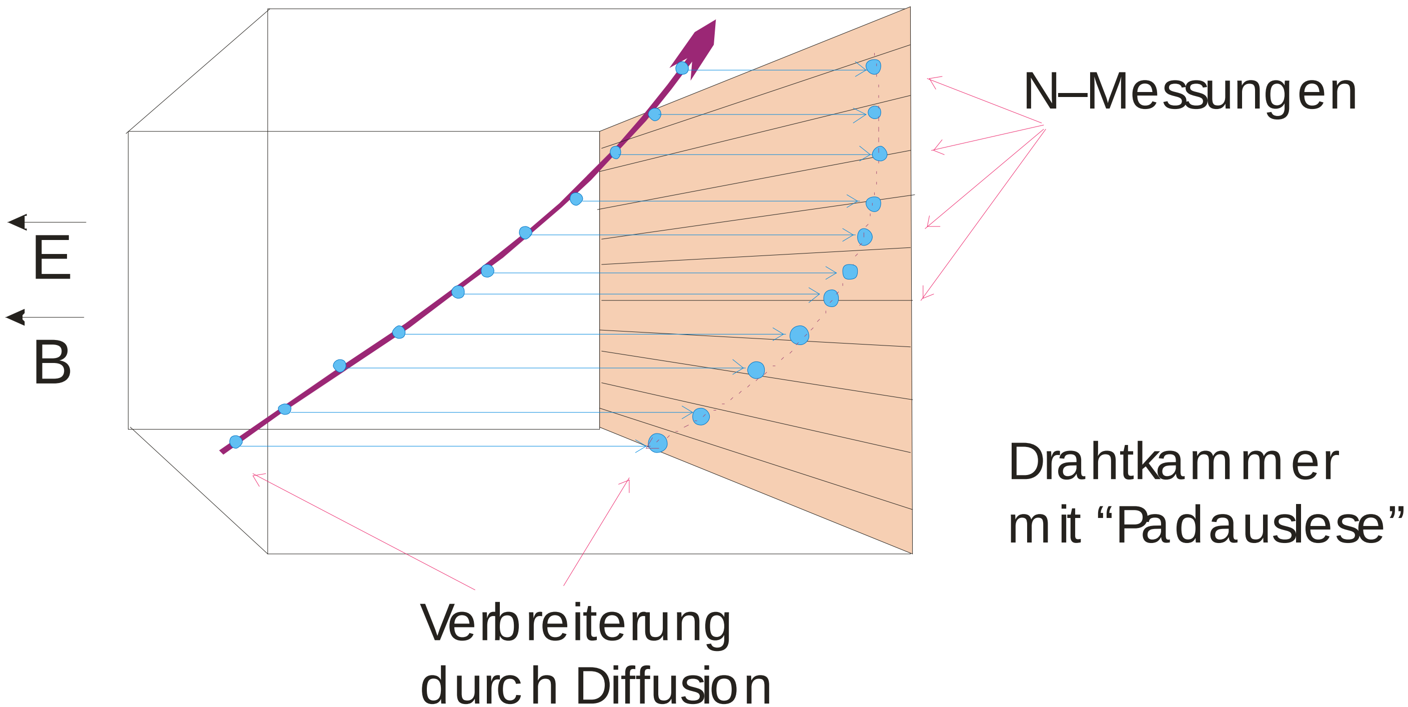
Principle of a TPC

Space resolution => momentum

- Number of "Pad-rows" and "Pad-size" (space points)
- Homogeneous, parallel E and B field
- Diffusion in Gases
  - Reduced through vxB
- Xo : choice of gas, materials

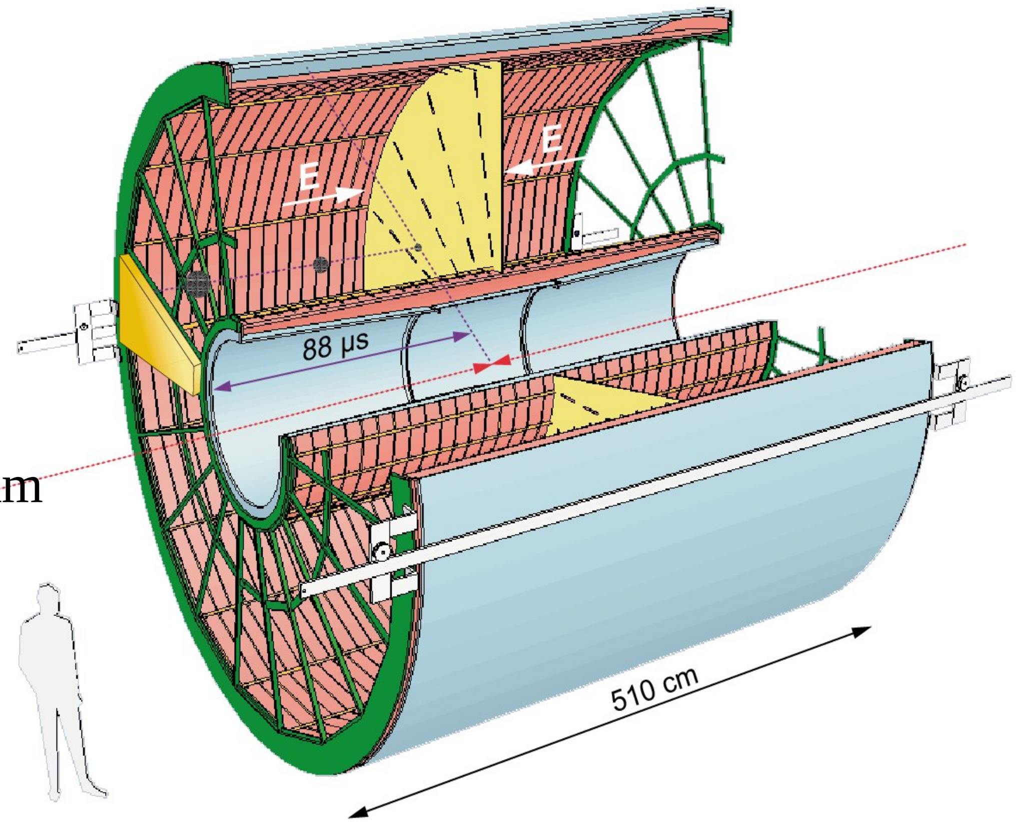
dE/dX resolution => particle identification

- Measure of primary charge
- homogeneous charge amplification of readout chambers
- Number of "Pad-rows"



ALICE TPC: Detector spezifications

- **Gas** Ne/ CO_2 90/10%
- **Gas Volume**: 100 m^3
- **Drift field** 400V/cm:
- **Gas amplification** $>10^4$
- **Wire chamber resolution** σ= 0.2mm
- **Diffusion** $\sigma_t = 200\mu m/\sqrt{cm}$
- **Pad size (inner)** 4x7.5mm
- **Pads (outer)** 6x15mm
- **Magnetic field** 0.5T



Summary: Tracking detectors

- Numerous detector geometries have been developed, optimized for a specific application
- Dominant role of detectors with ‘electronic’ signal processing
- Tendency (and necessity) to reach the limits of performance determined by the physics of the detector
- Increasingly applications outside particle and nuclear physics
- Major contributions to this development: progress in electronic signal processing (we are profiting from the industrial developments, e.g. in microelectronics and information technology,…)
- In modern detector-systems:
  - In large-volume gaseous detectors : several million signal channels;
  - In semiconductor detector systems: up to a few 10^8 **s**ignal-channels

PARTICLE IDENTIFICATION

WHAT IS PARTICLE IDENTIFICATION ?

Determination of the mass of ‘stable‘ hadrons: π, K, p
as function of $\gamma_L = (1-\beta^2)^{-1/2}$

- Time of flight (TOF)
- Multiple-Ionization (dE/dX) measurement
- Cherenkov detectors
- Transition radiation detectors

Measurement of characteristic particle lifetime

- (Charm, Beauty, τ-Lepton)
- Typical range: 10^{-8} bis 10^{-13}s

Kinematical methods

- Invariante mass of decay products
- Missing energy/momentum

Calorimetric shower distribution

- of electrons (photons) vs. hadrons

TIME of FLIGHT MEASUREMENT

COMBINED MEASUREMENT of MOMENTUM and VELOCITY

revolutionized ('Renaissance') through the development of high resolution RPCs ('Timing' RPCs)

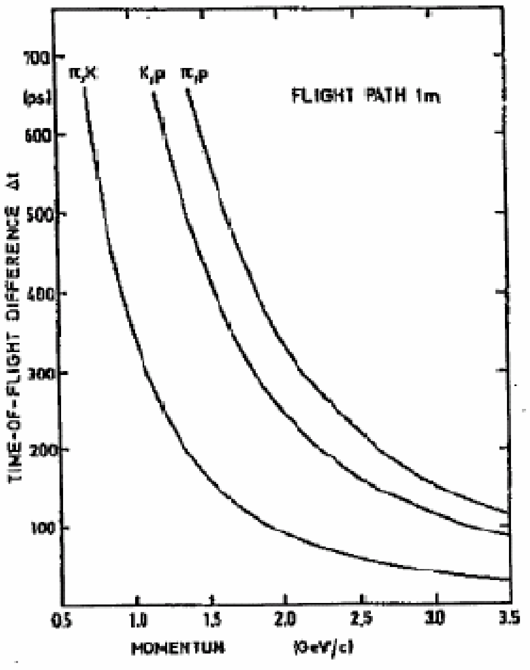


Abbildung 4.1: Differenz in der Flugzeit zwischen Paaren von Teilchen (πK, Kp, πp) als Funktion des Impulses

Required : σ(time) ~50 ps

In past : Scintillator,

Now…..Timing-RPCs

MULTIPLE ENERGY LOSS MEASUREMENTS

- Theory of ionization loss rather well understood;
  in modern treatments : full modeling of atomic levels of gases

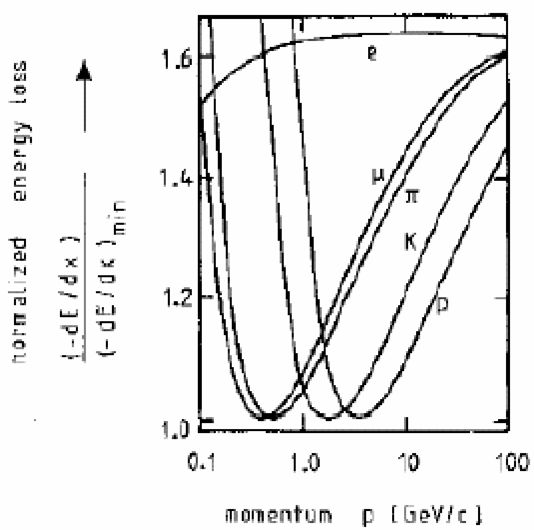
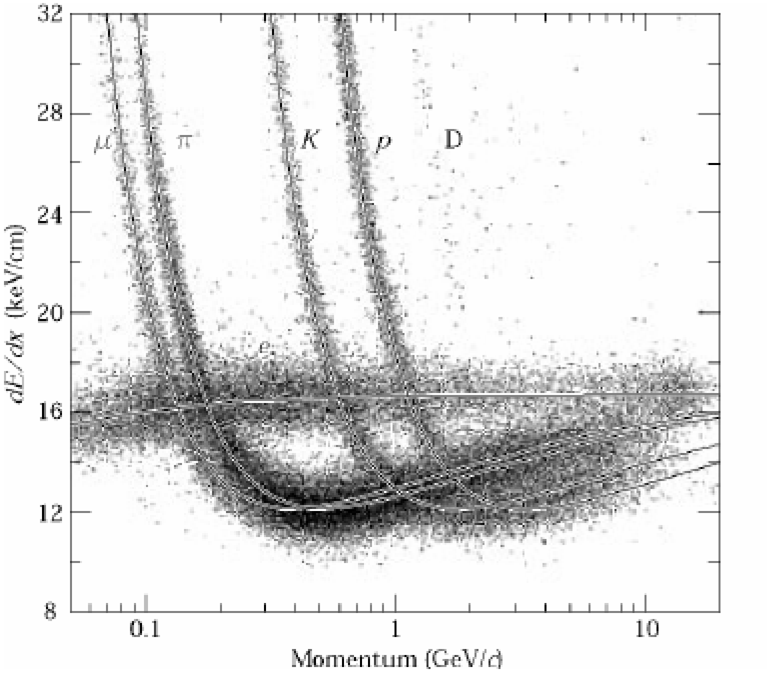
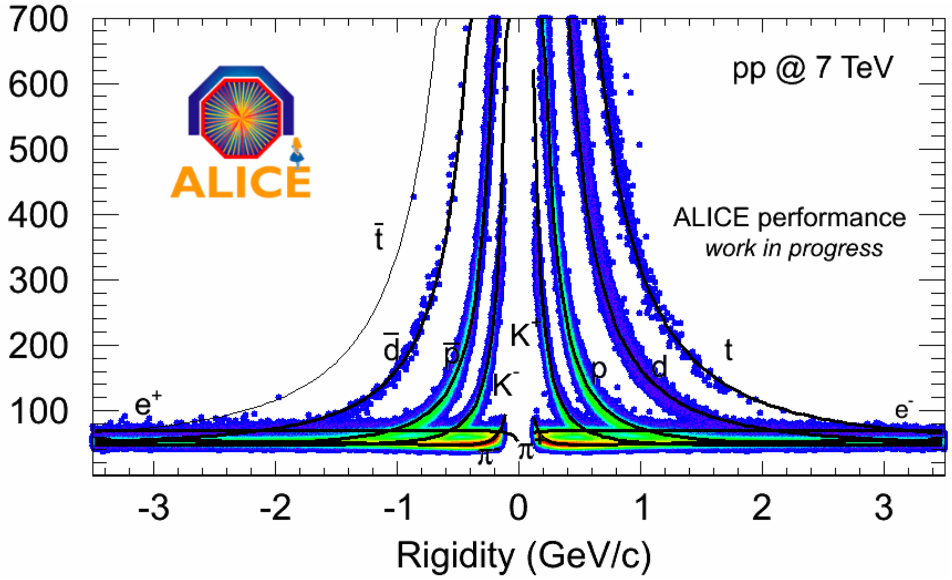


Fig. 6.29. Average energy loss of electrons, muons, pions, kaons and protons, normalized to minimum-ionizing value [1, 470].

in regime of relativistic rise (5 bis 50 GeV/c) differences in average dE/dx approx. 10%; significant identification requires dE/dX precision at few percent level→ multiple, Typically ~ 100 measurements

The Pioneer : PEP4 vs. state-of-the-art ALICE at LHC





TPC was operated at 8.5 atm gas pressure (80% Ar/20% CH_4)
Maximum number of measurements: 185 dE/dx measurements/track

TPC is operated at 1 atm. with a Neon/ CO_2 (90/10) mixture; typically up to 100 measurements

CHERENKOV DETECTORS FOR VELOCITY MEASUREMENT

CHERENKOV EFFECT:

- Electromagnetic interaction : incident, charged particle polarizes medium ⇒ time-dependent dipole moment, provided velocity of particle $\upsilon > c/n$; $n(.\lambda)$... Index of refraction
- Radiation emitted under angle $\cos\theta_{\mathbf{ch}} = 1/n\beta$

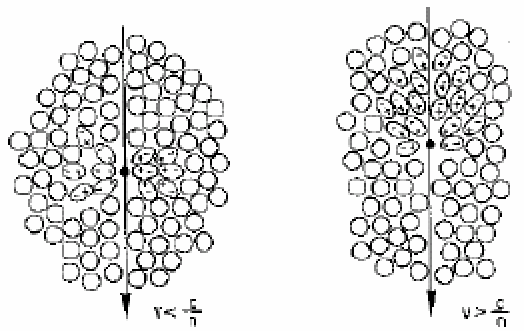


Fig. 6.7. Illustration of the Cherenkov effect [68].

CHERENKOV RADIATION

- CHERENKOV – ENERGY LOSS:
  is e.m effect → can be precisely evaluated

$dN(Photons)/dX = 2\pi \text{ x } Z^2 + (1-1/\beta^2 n^2) d\lambda / \lambda^2$; Z is charge of inc. part,

$dN/dx \sim 1/\lambda$

for n=const. : $dN/dx = 2\pi\alpha Z^2 \sin 2\theta_{CH} (1/\lambda_2 - 1/\lambda_1)$

- NUMERICALLY : $\lambda_1 = 400nm$; $\lambda_2 = 700nm$

$dN / dx \approx 4.9 \text{ x } 10^2 . \sin^2 \theta_c \ [cm^{-1}]$

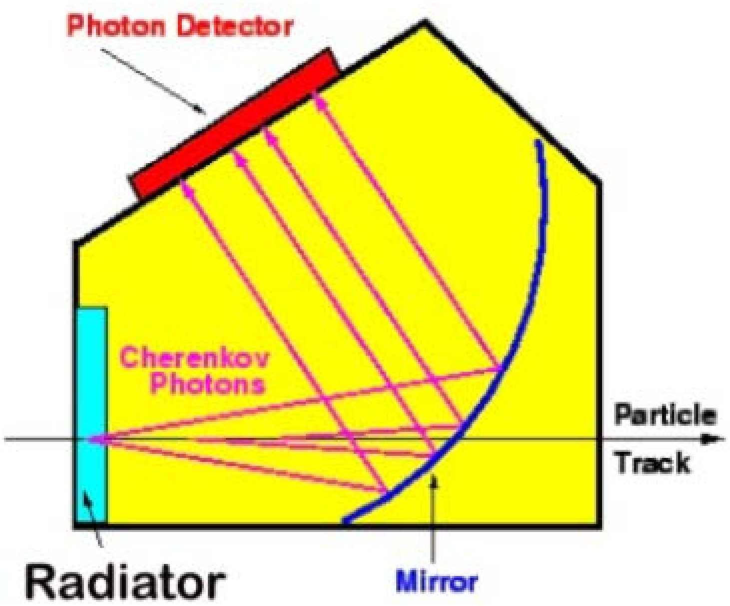
for n = 1.001 $\beta_{TH} = 0.999$ $\sin^2\theta_{CH} \sim 2 \text{ x } 10^{-3}$

$dN / dx = 2 \text{ x } 4, 9 \text{ x } 10^{-1} \sim 1 \ [cm^{-1}]$

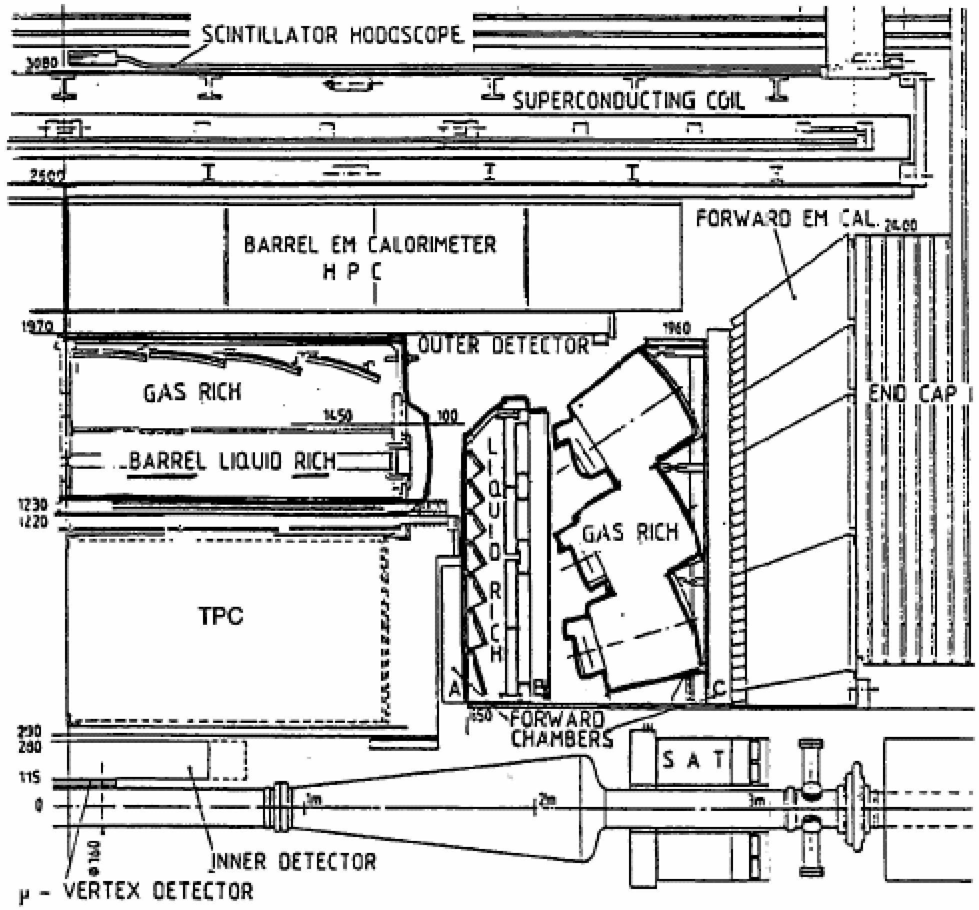
i.e.: approximately one photon per centimeter radiated...

FOCUSING CHERENKOV DETECTORS

- MODERN CHERENKOV DETECTORS MEASURE:
  Photons and their direction of emission
  ⇒ direct measurement of velocity
- PRINCIPLE : photons focused with spherical mirror with focal length f
  ⇒ Cherenkov cone focused into ring
- RADIUS of RING $R = f.\ tg\theta_{CH} = f\ (n/\gamma_{sch})\ [1-(\gamma_{sch}/\gamma)^2\ ]^{1/2}$



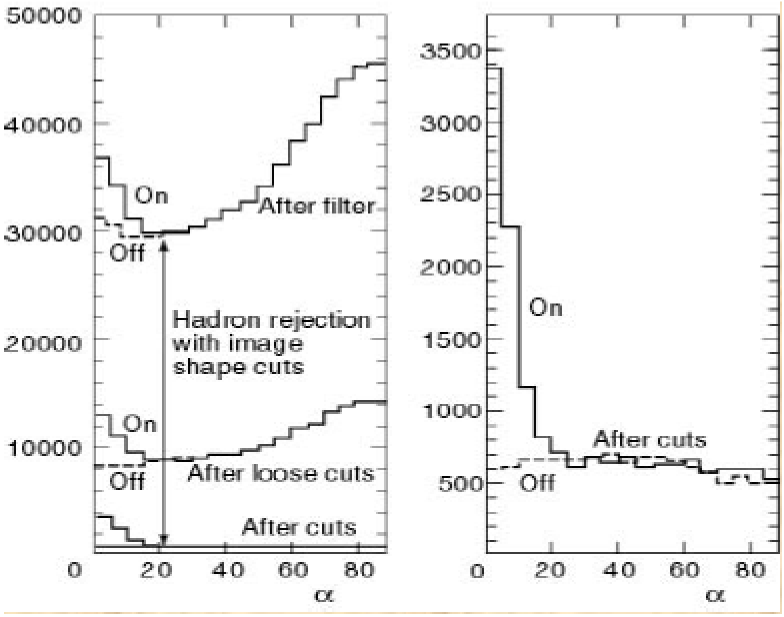
THE PIONIER : DELPHI



Cross section through Delphi Detector: at large angles (‘Barrel’) (moderate momenta) use of liquid radiator and gaseous radiator; similarly also at small angles (larger momenta)

FOCUSSING CHERENKOV:
THE ASTROPHYSICS FRONTIER

Whipple Observatory



Good (10^{-2}) hadron rejection based on analysis of Cherenkov-Light (EM showers are more collimated)

TRANSITION RADIATION (TR)

TR : electromagnetic effect for ultrarelativistic particles (γ>>1) traversing interface between two media with different dielectric constants (ε_1 , ε_2)

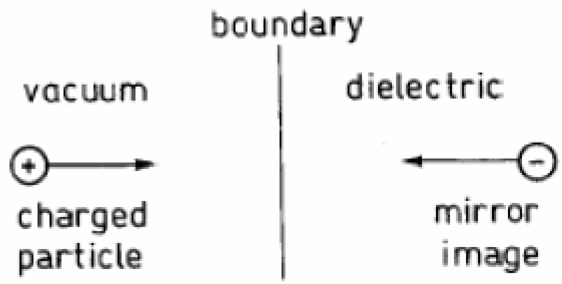


Illustration of the production of transition radiation at boundaries.

TR is em effect and therefore (in principle) precisely calculable
Vector of polarization ⇒ time dependent potential A (r,w) ⇒ radiation
Radiated energy/ interface E ∞ Lorentz factor γ; mostly in form of soft X-rays

One big problem : approx α (1/137) photons radiated /interface
For practical detector : need few hundred interfaces ('radiator')

PARTICLE IDENTIFICATION : SUMMARY

METHODS perfected with the aim to cover range of particle velocities with γ $1 \leq \gamma < 10{,}000$

Sometimes NATURE is kind to physicists and has provided a solution for (almost) all situations….

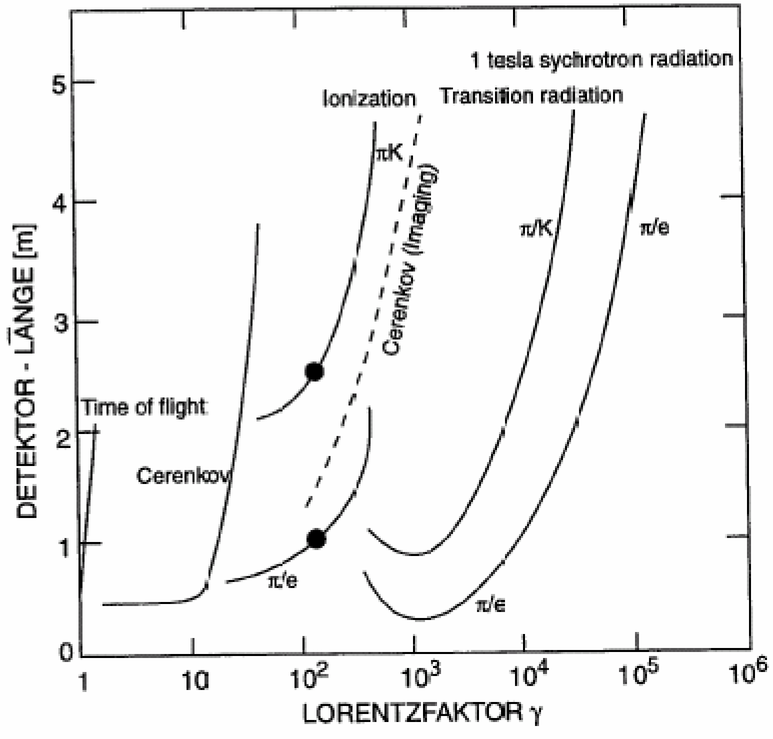


Abbildung 4.21 : Einstatz von verschiedenen Identifikationsmethoden als Funktion von γ. Der Detektorlänge L setzt eine Grenze für den Einsatzbereich

ENERGY MEASUREMENT WITH CALORIMETERS

PRINCIPLE OF CALORIMETER MEASUREMENT :

- Total absorption of particle in calorimeter material

INTERACTION (in general)

- Electromagnetic : electromagn. calorimeter
- Hadronic : hadronic calorimeter

ABSORPTION PROCESS

- Particle transfers energy in series of successive collisions;
- Formation of ‘Showers‘ of secondary-,tertiary-,... particles; process continues until energy of shower particles is below threshold for particle production .
- Ultimately : energy transferred into molecular vibrations ⇒ heat ⇒
- ‘Calorimeter’

ENERGY RANGE FOR CALORIMETRY

0.1 eV - 10 eV : ‘Low temperature’ – calorimeters for WIMPs, X-ray spectroscopy
⇒innovative developments

1 keV - 100 MeV: Applications in Nuclear Physics
100 MeV - few TeV: Applications for accelerator-based experiments
⇒development of the ‚classical‘ Calorimetry

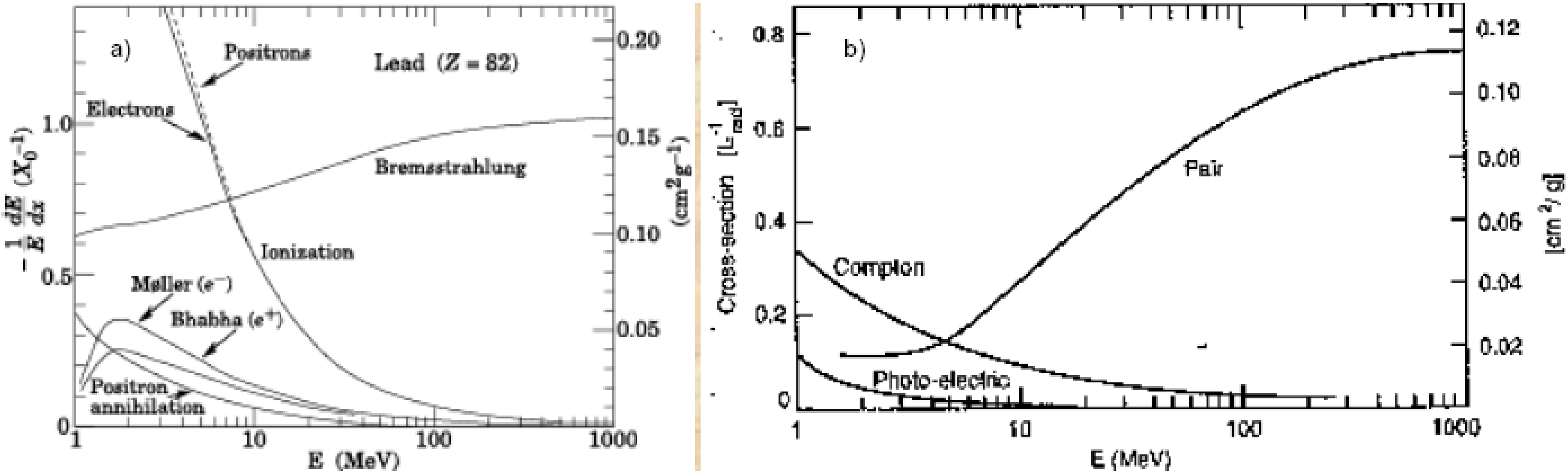
100 GeV->100 EeV: Astro-particle physics; UHE cosmic radiation
⇒Innovative developments

CHARACTERISTIC PROPERTIES OF CALORIMETERS

- Number of particles in cascade N ~ E
- Fluctuations (assuming uncorrelated production) ~ $1/\sqrt{N}$
- Energy resolution : $\Delta E/E \sim \Delta N/N \sim \sqrt{N}/N \sim 1/\sqrt{N} \sim 1/\sqrt{E}$

- Improves with increasing energy ! (in contrast to momentum measurement)
- Length of absorber L ~ Shower length ~ ln E
- Calorimetric measurement is charge independent
- Sole method to measure neutral particles
- Properties of absorption depend on particle type
- ⇒ Possibility to identify type of particle
  (Photons, electrons, charged / neutral hadrons, muons, neutrinos)
- Relatively fast detectors ⇒ 'Trigger' (Event – selection)
- With appropriate instrumentation ⇒ position measurement with mm – cm accuracy

ELECTROMAGNETIC CALORIMETERS
ENERGY LOSS : ELECTRONS; PHOTONS



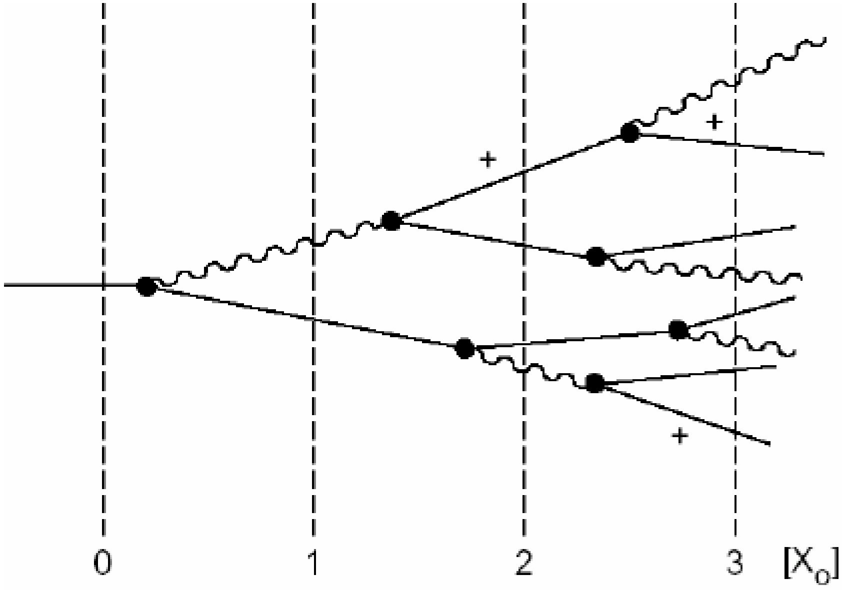
At high energies: 1/E dE/dx ~ const.

$dE/dx = - E / X_0$;

$E = E_0 \exp (- x / X_0)$; X_0 …characteristic length ‘ radiation length’

$$X_o\ (g/cm^2) \approx 716\ A / [Z\ (Z+1)\ln(287/Z^{1/2}] \approx 180\ A/Z^2$$

HEITLER – ROSSI MODEL : E.M. CALORIMETER

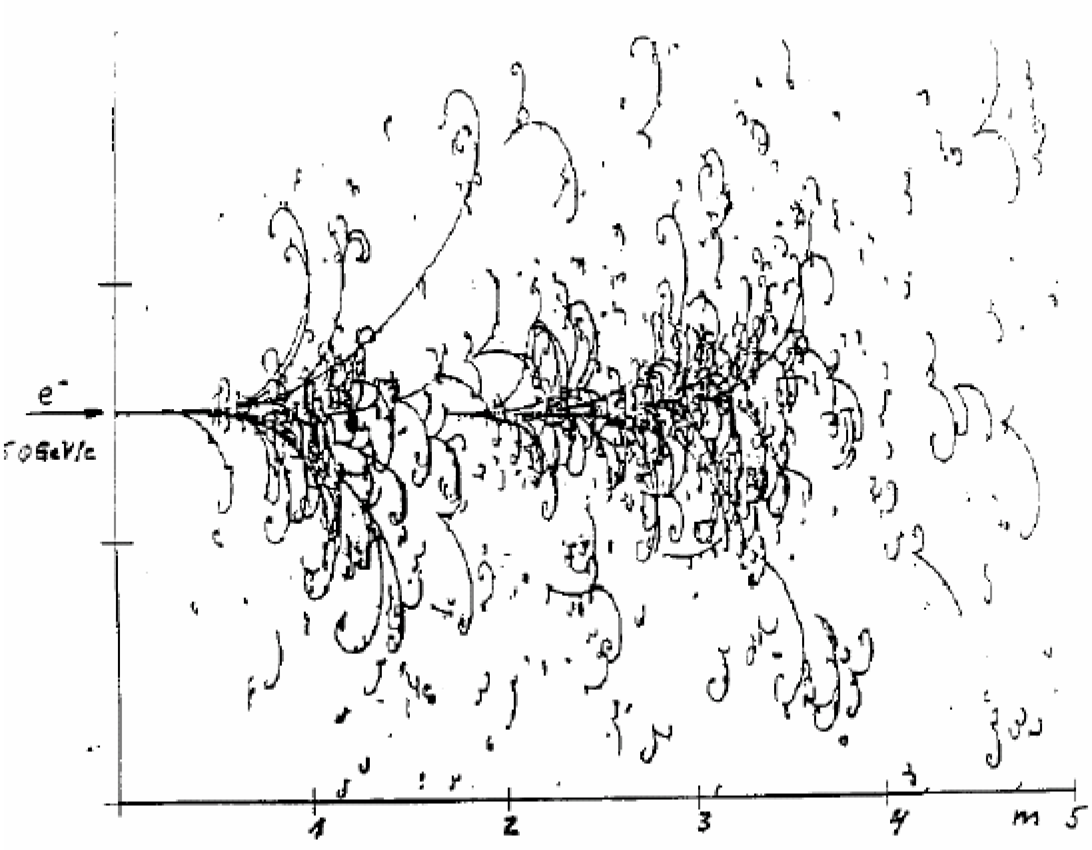


- Model: interaction after one free path (~ X_0)
- Number of particles after t X_0 : N (t) = 2^t, E (t) = $E_0/2^t$
- Shower formation until $E < E_c$: t_{max} = ln (E_0/ E) /ln2

  $N_{max} = E_0/E_c$
- Consequence : $N_{max} \sim E_0$

  Length for total absorption ~ t_{max} ~ ln E_0

BEAUTY IN THE EYE OF THE BEHOLDER



Photography of a 50 – GeV Electron – Shower
in L (70% Ne/30%H_2) – filled Bubble chamber (BEBC); B=3T

SIGNAL AND ENERGY RESOLUTION IN HOMOGENEOUS E.M. CALORIMETERS

- HOMOGENEOUS : Signal derived from complete Absorber volume (z.B. Scintillation light in crystal)
- SIGNAL : in 'Rossi'- model of e.m. shower evaluated by estimating track length of all the electrons and positrons in cascade; measured via ionization, dE/dx)
- SIGNAL ESTIMATE: Signal (electron, photon) ≈ ≈ Signal (muon with same energy loss in absorber)

⇒ estimate correct to better than ≤ 20 % !

- SIGNAL FLUCTUATIONS = > ENERGY RESOLUTION
- DEVIATION FROM SIMPLE 'LINEAR' MODEL; e.g. : fluctuations in number of low-energy particles ⇒ Saturation, Signal non-linearities,…
- ENERGY RESOLUTION : $\sigma/E \approx 0.01 / \sqrt{E}$; E in GeV

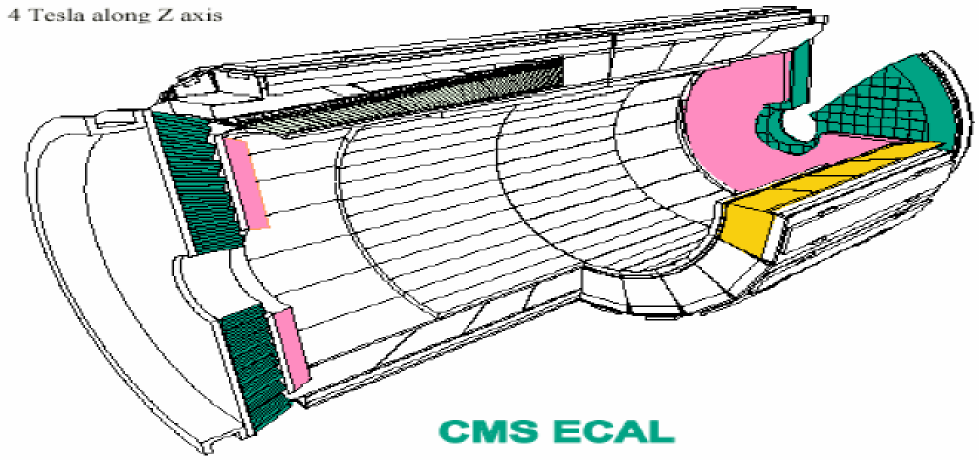
HETEROGENEOUS ('SAMPLING') CALORIMETERS

- HETEROGENEOUS C.: composed of alternating
  'passive' absorber plates (Fe, Pb,…) and
  'active' signal planes (Scintillator, MWPC,…
- ADVANTAGES : optimal choice of absorber (e.g : for e/π discrimination)
  optimal choice of signal readout system
- DISADVANTAGE : only fraction (~1-10%) of energy deposit measured $\Rightarrow$
  fluctuations in measured fraction of energy
  $\Rightarrow$ 'sampling fluctuations'
- 'SAMPLING' RESOLUION

$$\sigma(E) / E \approx 0.05\ [\Delta E\ (\mathrm{MeV}) / E\ (\mathrm{GeV})]^{1/2}$$

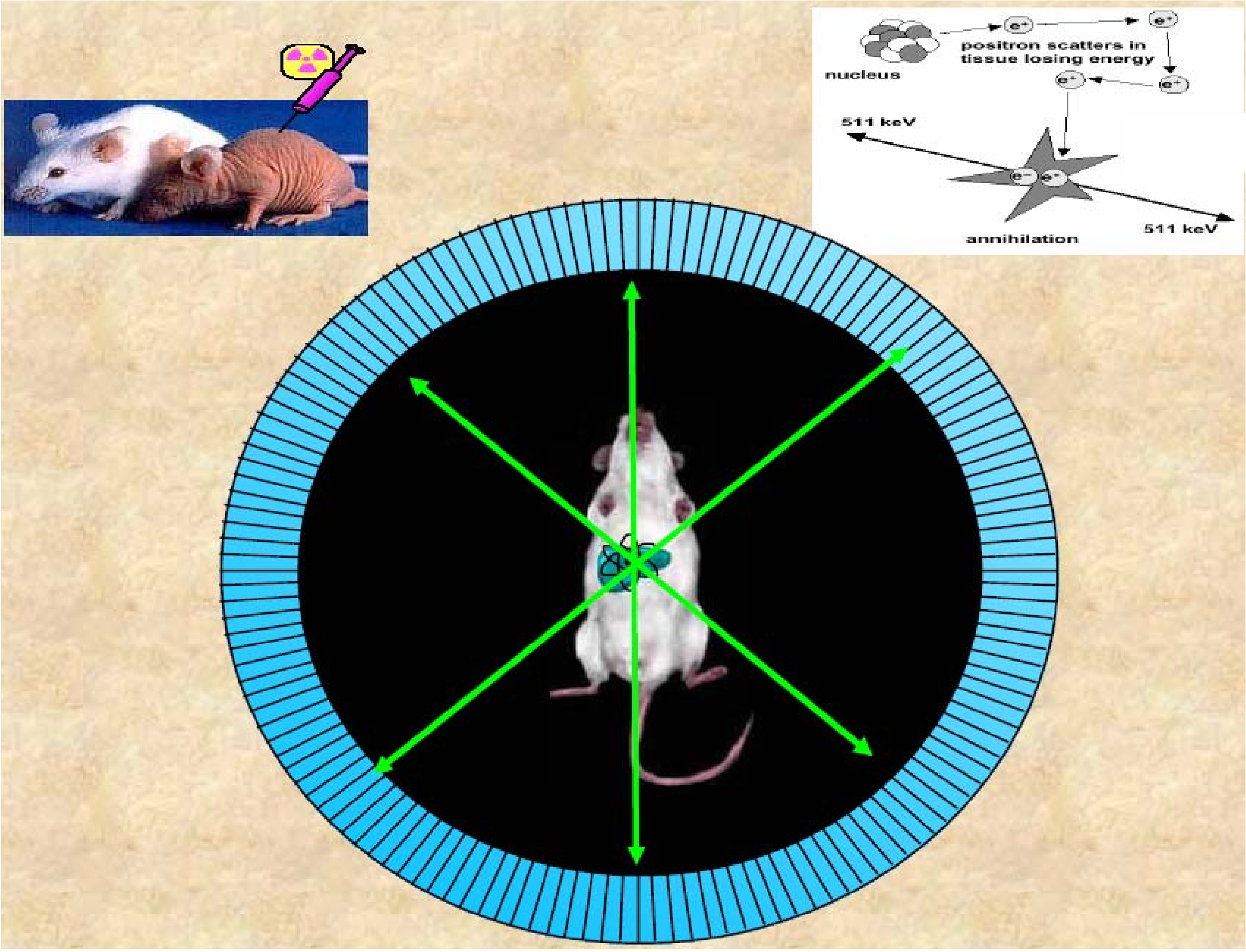
ΔE (MeV)….dE/dx (min.I.) in one cell
Cell = 1 Absorber plate + Signal plane

CMS Electromagnetic Calorimeter



Parameter	Barrel	Endcaps
η coverage	|η| < 1.48	1.48 <|η|< 3.0
r inner, r outer [mm]	1238, 1750	316, 1711
z inner, z outer [mm]	0, ±3045	±3170, ±3900
Δη x Δφ	0.0175 x 0.0175	0.021 x 0.021 to 0.050 x 0.050
Crystal dim.Front[mm3]	21.8 x 21.8 x 230	29.6 x 29.6 x 210
Depth in X0	25.8	23
Off-pointing	3 deg.	3 deg.
No. of crystals	61 200	15 632
Volume [m3]	8.14	2. 2
Crystal weight [t]	67.4	18. 2
Modularity	36 supermodules	4 Dees
crystals	1700 per SM (20 in φ, 85 in η]	3908 per Dee

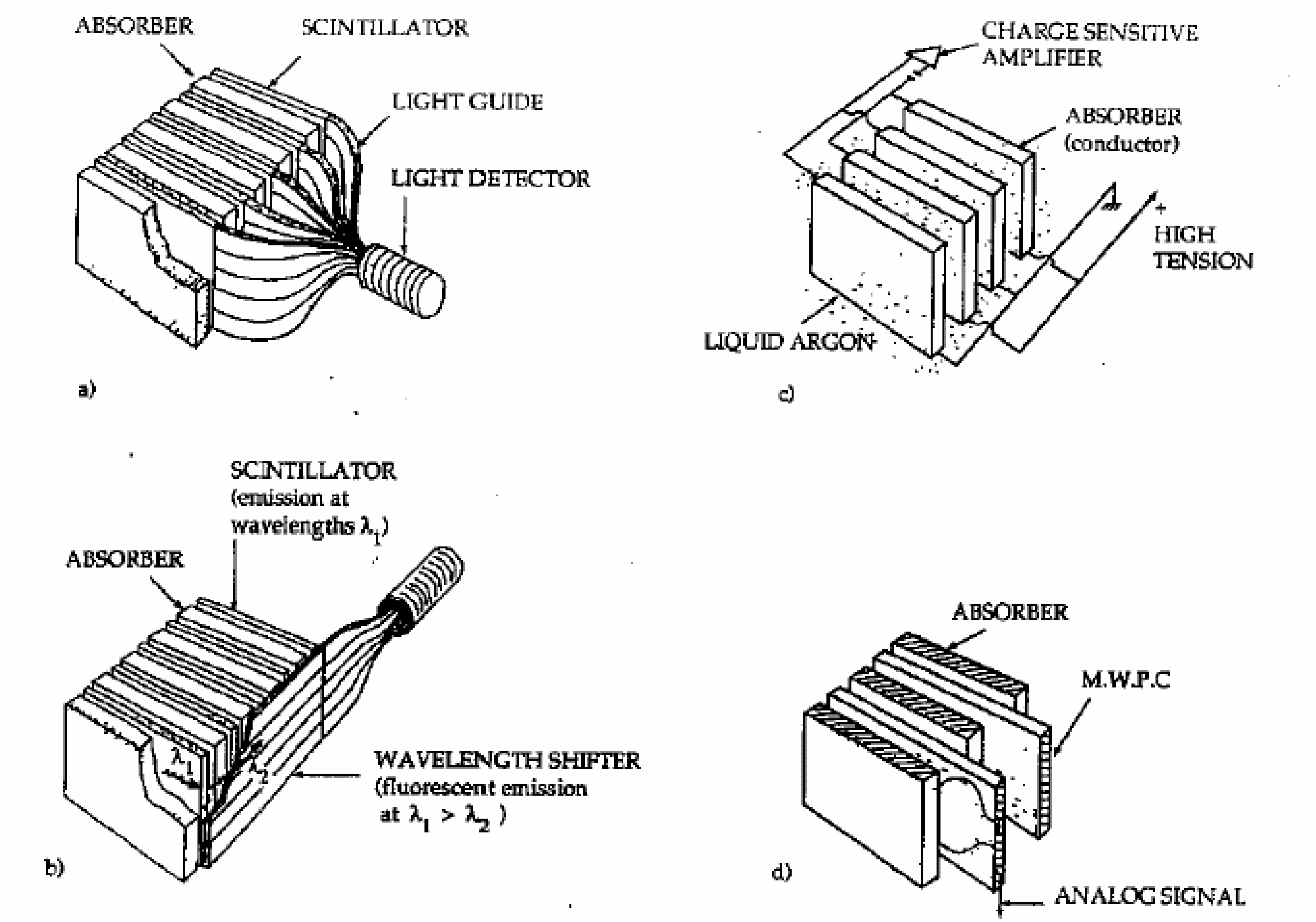
The PET principle



HADRONIC ENERGY MEASUREMENT

- CONCEPT : same as for e.m calorimetry, instead
  e.m interaction ⇒ strong interaction
- PRAXIS : Complex nuclear and particle physics determines in
  critical ways the quality of the measurement
- COLLISION with ABSORBER – Nuclei : typically
  ~ 50% of energy into ‘fast’ secondary
  hadrons ~ charged and neutral pions
  ⇒ these fast hadrons continue to propagate the
  hadronic cascade
  ⇒ NOTA BENE : neutral pions ⇒ photons ⇒
  e.m cascade
  ~ 50% of energy into low-energy
  nuclear processes : nuclear excitation,
  evaporation, spallation,..
  ⇒ 1 ≈ 20 MeV protons, neutrons, photons
  ⇒ BINDING ENERGY LOSSES means :
  non-measurable energy !
  INVISIBLE ENERGY

CATEGORIES of READOUT METHODS

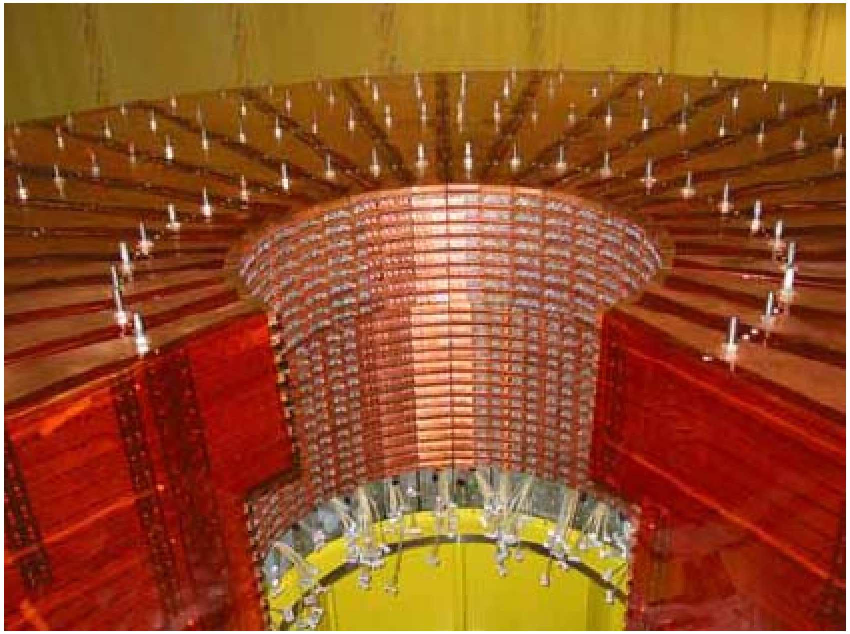


'MODERN' : - unconventional absorber geometries

- excellent control of instrumental errors, also for large systems

LAr hadronic end-cap calorimeters : during construction

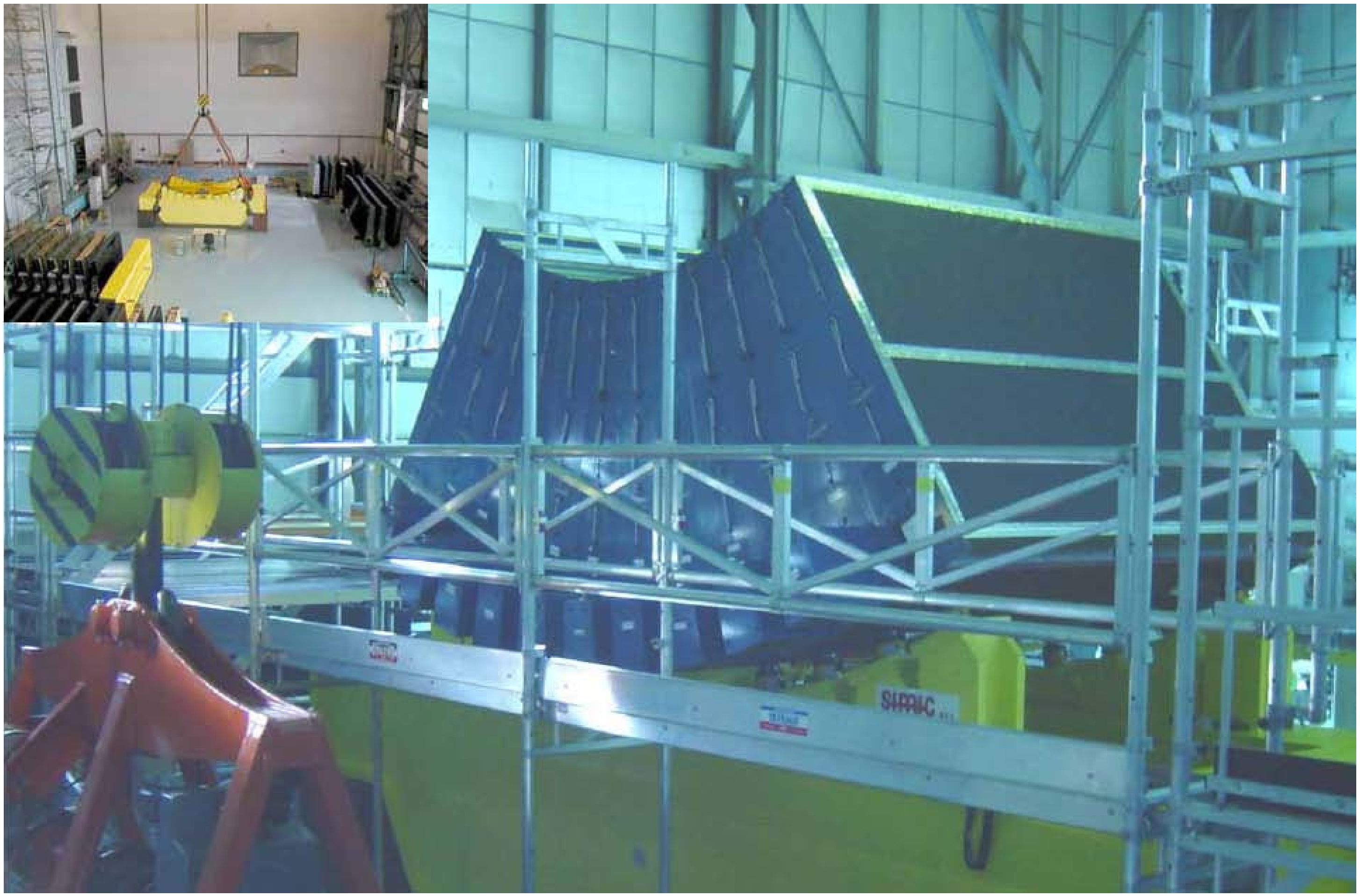
The LAr hadronic end-cap series production finished, all 134 modules (including spares) have been completed.



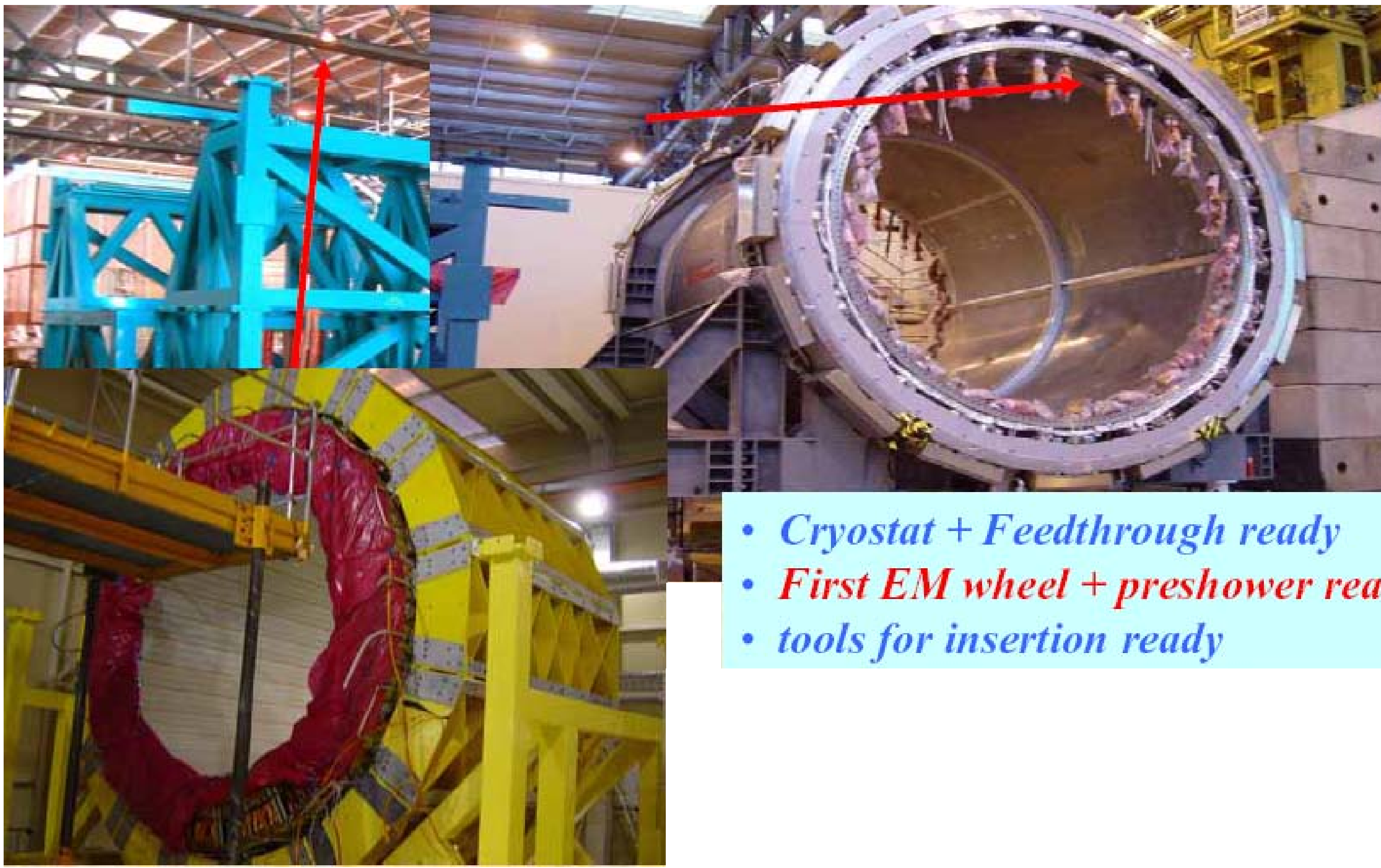
Assembly ongoing for the HEC wheel #3 out of four total

Two wheels are now complete and ready for insertion into the cryostat

Tile Calorimeter pre-assembly at CERN

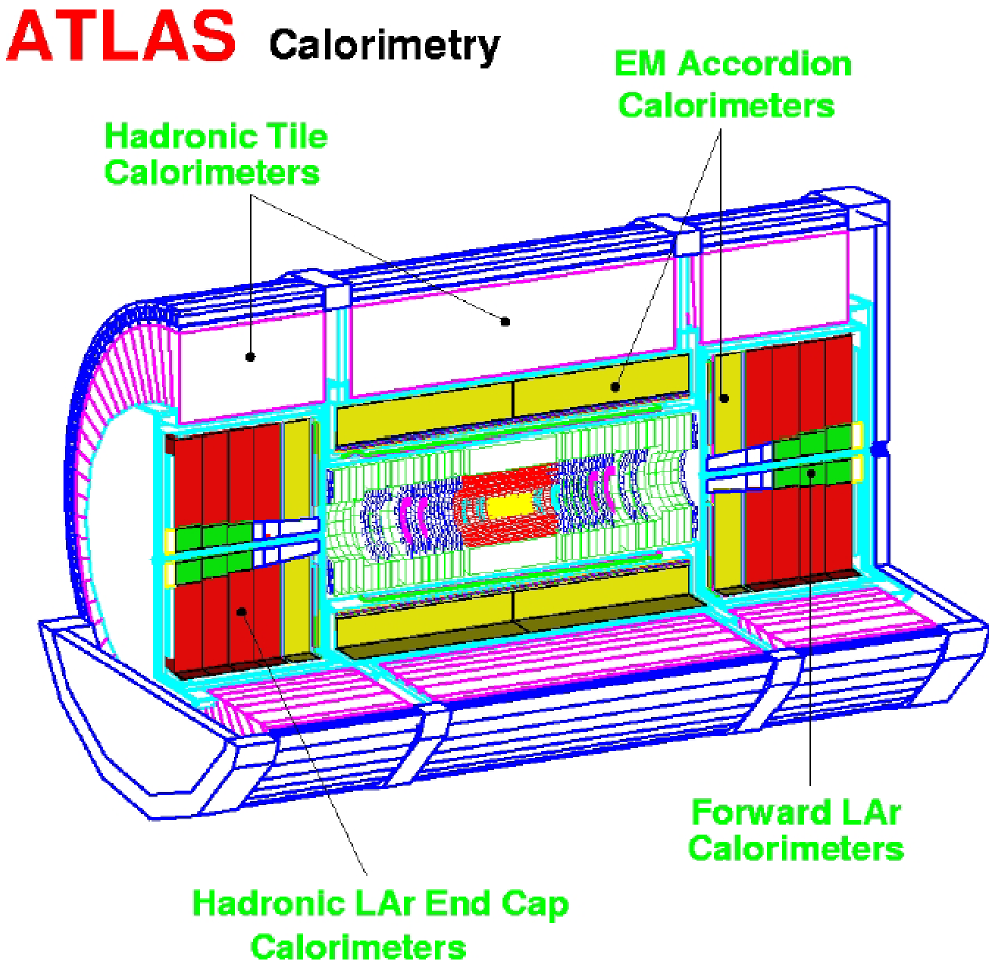


The first half EM Barrel Calorimeter Cylinder ready for insertion



- *Cryostat + Feedthrough ready*
- *First EM wheel + preshower ready*
- *tools for insertion ready*

EXAMPLE for CALORIMETER OPTIMIZATION



Liquid Argon:
High granularity
High radiation resistance;
Fe-Scintillator :
Smaller granularity
Smaller radiation resistance : acceptable, as radiation load behind e.m. cal. is smaller

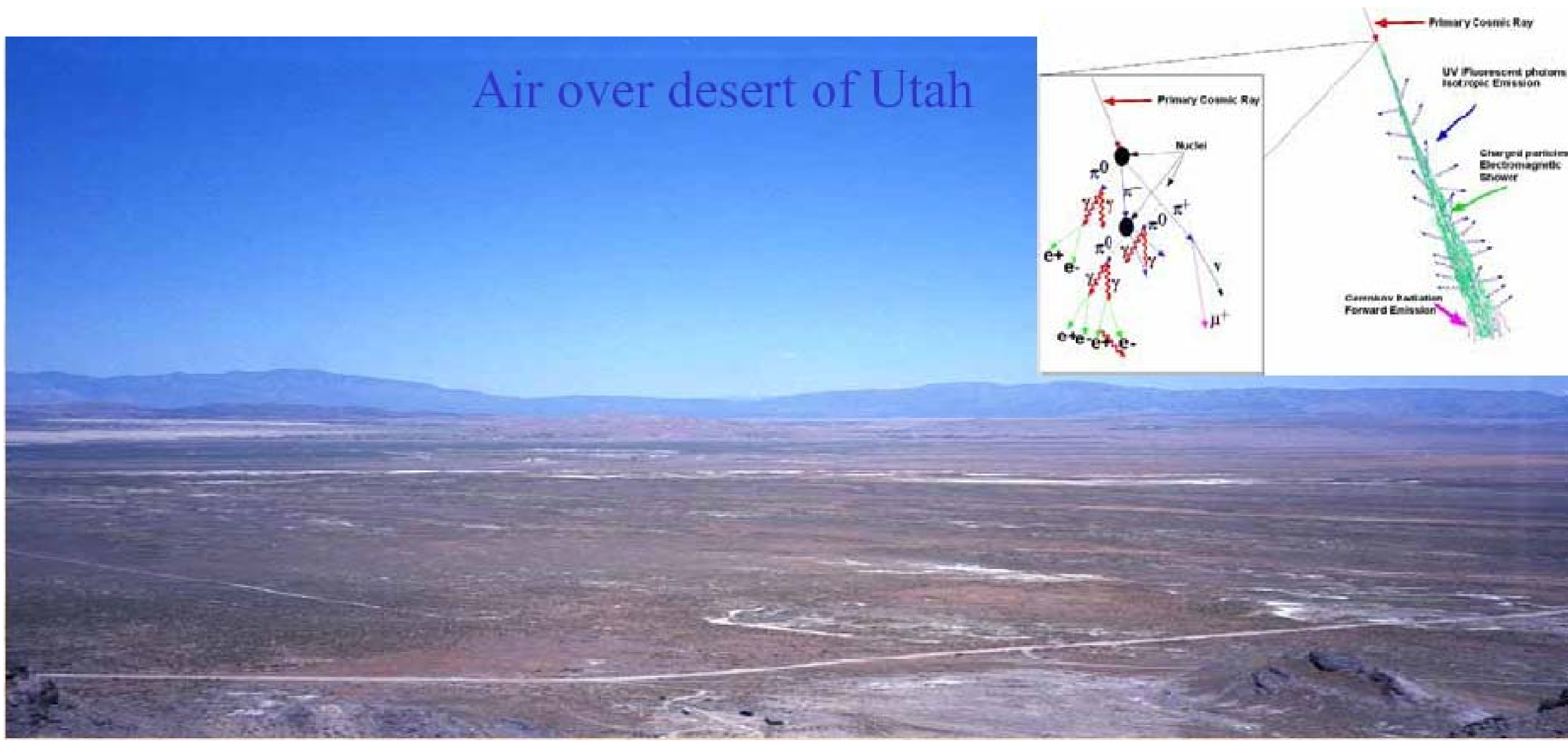
CITIUS, ALTIUS, FORTIUS

FOR ASTROPARTICLE STUDIES

- Atmosphere is calorimeter : ~ 28 X_0; 16,6 λ
  A wonderful gift of Nature
  Measurement of fluorescence light : Fly’s Eye, HiRes
  Measurement of Cherenkov light : Hegra, Magic, Hess,..
  Instruments on earth’s surface : CASA, AUGER,…
- Ocean (lake) water as calorimeter
  Measurement of Cherenkov light : Nestor, Antaras
- Ice (Antartic)
  Measurement of Cherenkov light : Armanda

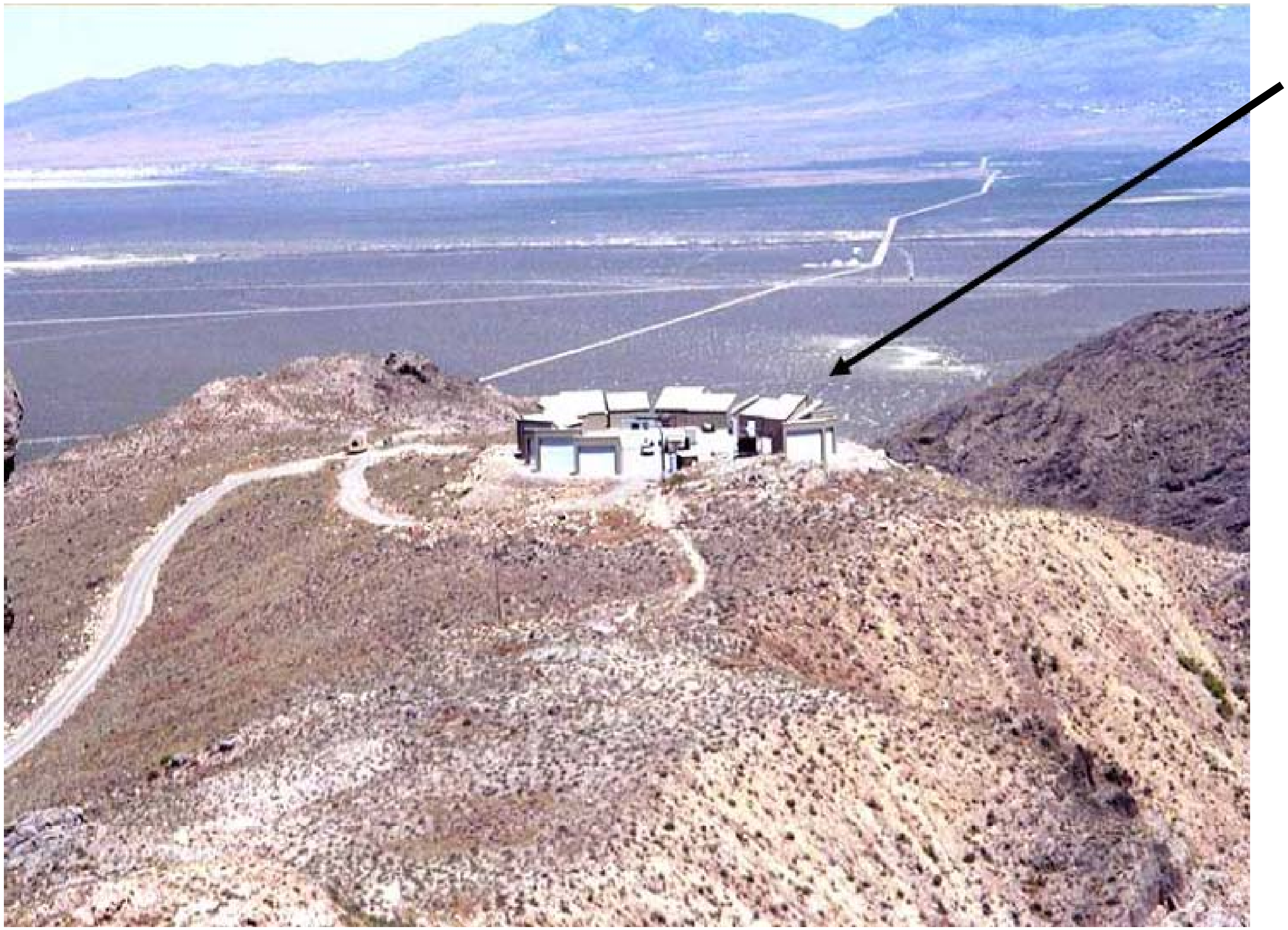
Atmosphere as the Active Volume of the Calorimeter

- Detector is sensitive to UV-light produced by air showers
- N_2 fluorescence dominates up to 20 km altitude
- Threshold energy for stereo observation is ~ $5x10^{17}$ eV
- Showers with energy over 1019 eV trigger detector from up to 50 km
- Aerosols in the air monitored by UV-laser shots (visible up to 50 km)



HIRES
the Air Shower Fluorescence Detector

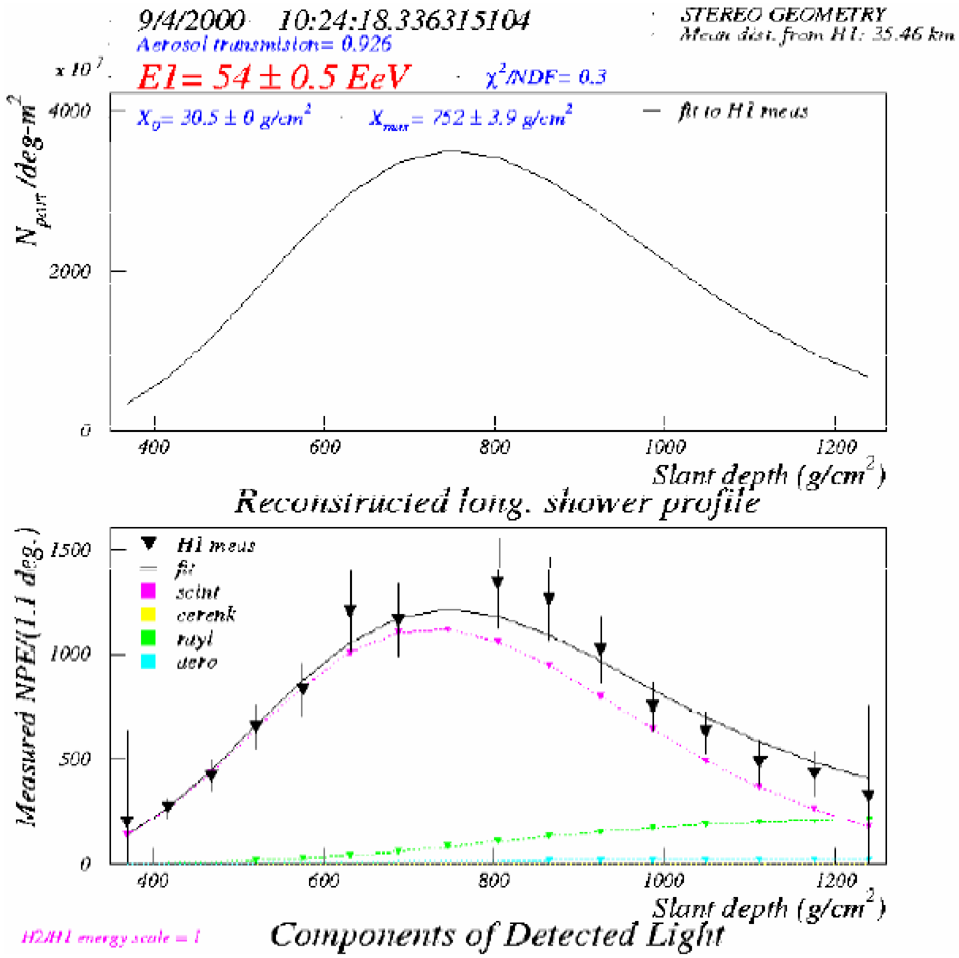
The Calorimeter With Air As Active Medium and Active Volume of More Than 10 Volume of More Than 10^{13} m^3



- View of HIRES 2 site
- 2 sites, 12.5 km apart
- Stereo observation of showers
- Dugway proving grounds, Utah, USA
- 120º W, 40º N
- Vertical atmospheric depth 856 g/cm^2

High Energy Shower (~5.3x10^19 eV)

- Results of the fit to the **HIRES 1** measurement
- **Upper part** : reconstructed number of charged particles in the shower versus depth of the shower
- **Lower part** : measured number of photoelectrons versus depth of the shower



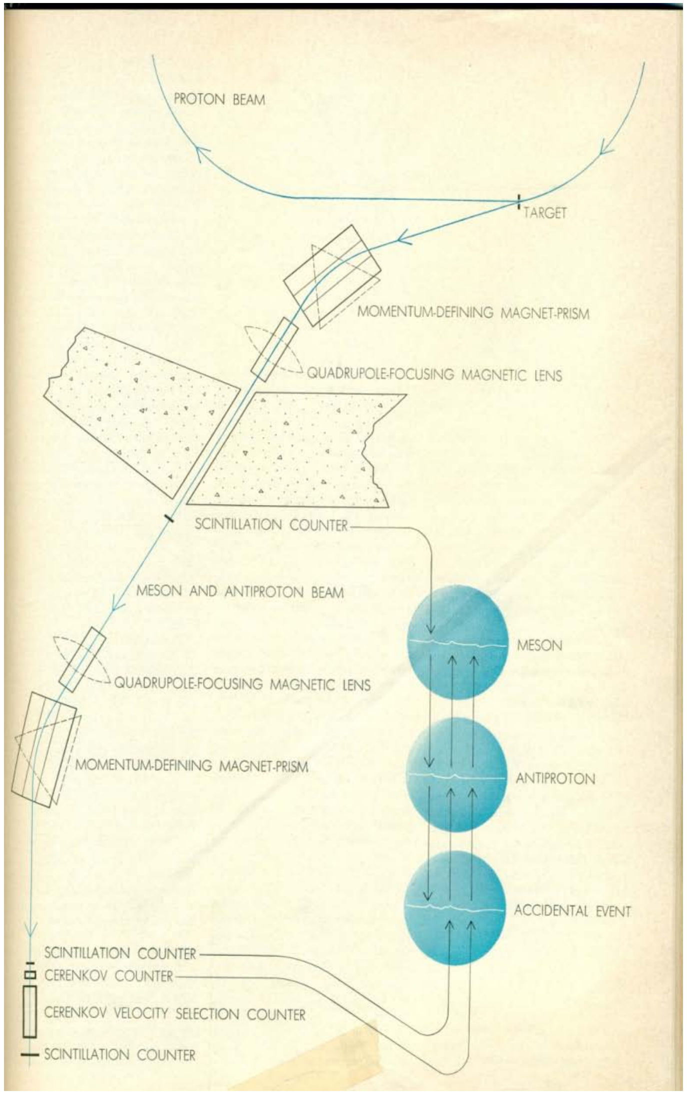
Particle Experiments: examples

- Discovery of Antiproton
  - Properties were known
  - Required energy for production: must be produced together with a proton (baryon number conservation)
  - $p + p \rightarrow p + p + p + \bar{p}$ (p + p → p + p + p + pbar)
- Before collision
  - $p^{\mu}_{TOT} = [\ (E+mc^2)/c,\ |p|,0,0\ ]$ E, p energy, momentum of incident proton
- After collision
  - $p^{\mu\prime}_{TOT}$ (CM) = (4mc, 0,0,0) need to consider incoming, struck protons and the p pbar system; value for threshold production (all particles at rest)
- Invariance of 4-vector
  - $[(E/c + mc)^2 - p^2 = (4mc)^2$ (remember: $E^2 - p^2c^2 = m^2c^4$)
  - $E = 7\ mc^2$ -> design energy of Bevalac

View of the Bevalac

E. McMillam and E. Lofgren on top of the shielding of the Bevalac

Antiproton Discovery



Sign of charge determined by magnetic deflection

Momentum measured by magetic deflection

Two scintillators, 14m seperated, measured velocity
To discriminate between slow antiprotons and
fast mesons;
This is not enough -> accidental coincidences can
‚mimick' antiproton

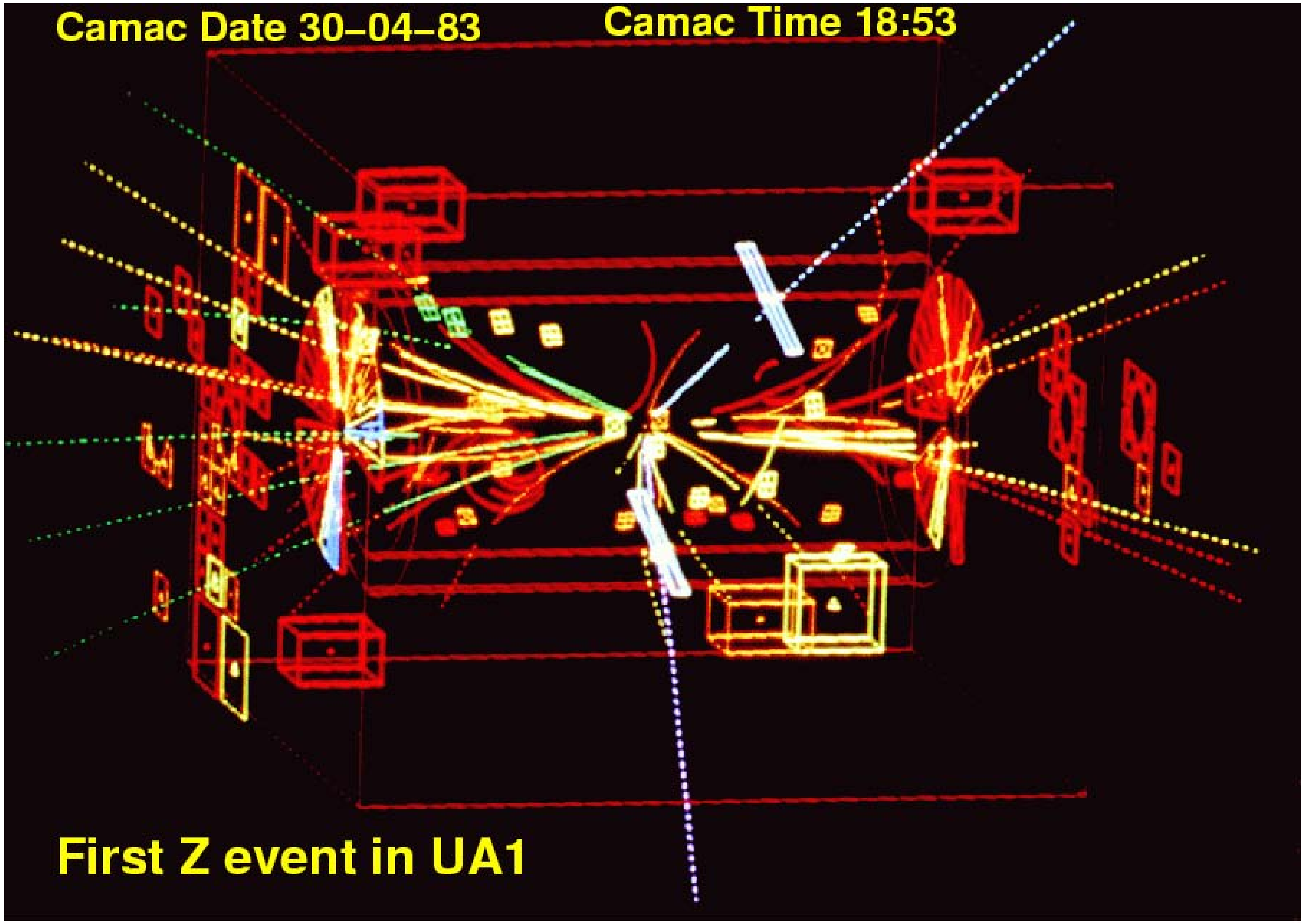
Velocity measured by ‚Cherenkov' technique
to discriminate between slow (antiproton) and
fast (mesons)
Two Cherenkov's were used to ‚see' fast mesons
or slow antiprotons

Discovered in 1956;
Nobel Prize to O. Chamberlain and e. Segre in 1959

Discovery of W -> e v

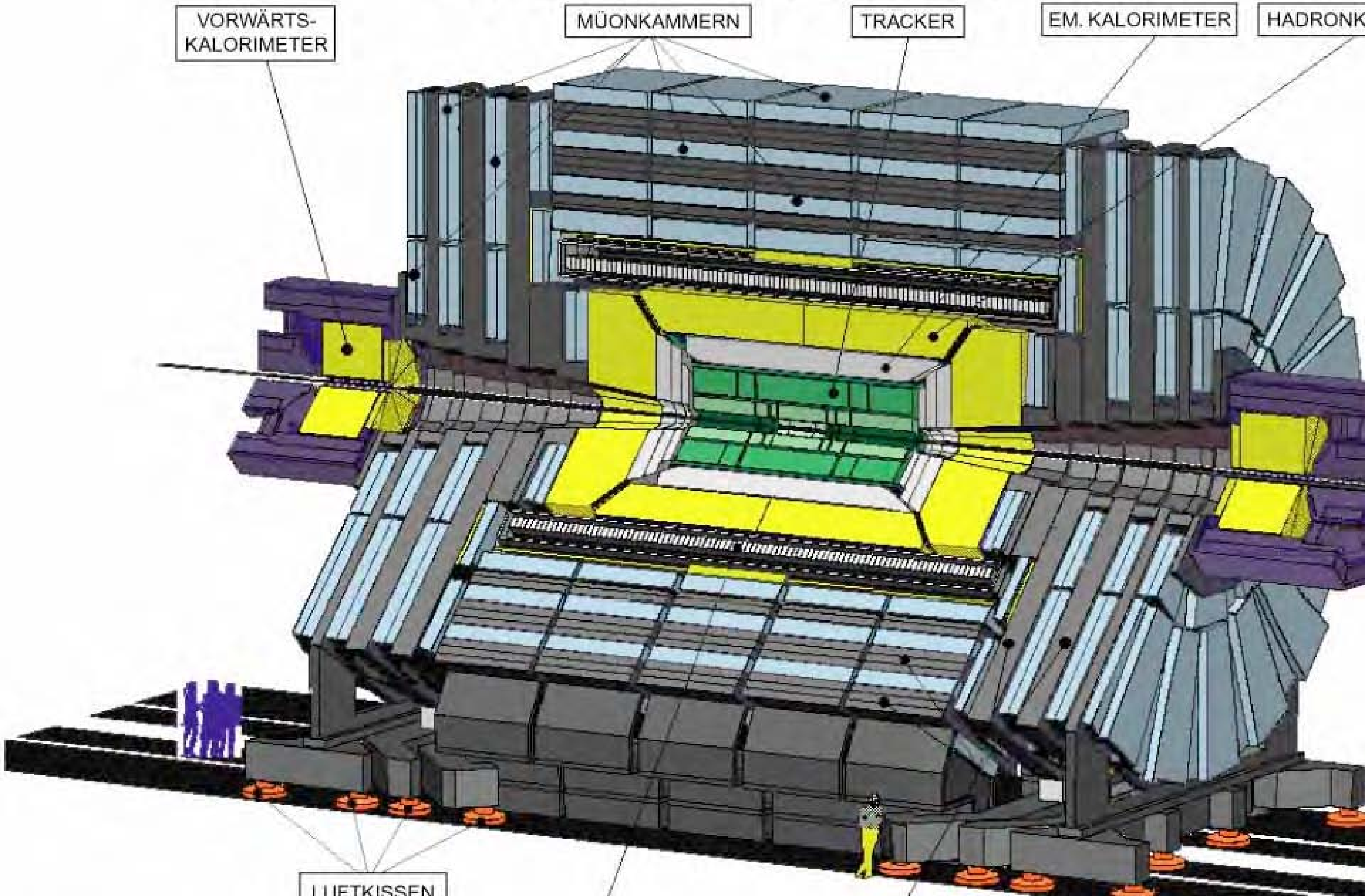
- W and Z produced in proton-antiproton collisions at the reconfigured CERN SPS → turned into collider be storing and colliding protons and antiprotons in the same beam-pipe
- Textbook example of the ‘Missing Energy’ detection methods of neutrinos
  - W -> e v is tow-body decay with well defined kinematics; W is produced with low momentum; e and v are almost back-to-back
  - Electron momentum is well measurable
  - Neutrino momentum revealed through apparent ’missing momentum or missing energy’
- Missing Energy Technique requires very good coverage
  - missing energy must not be ‘faked’ by particles traversing not-instrumented areas of the detector

The first Z event in UA1



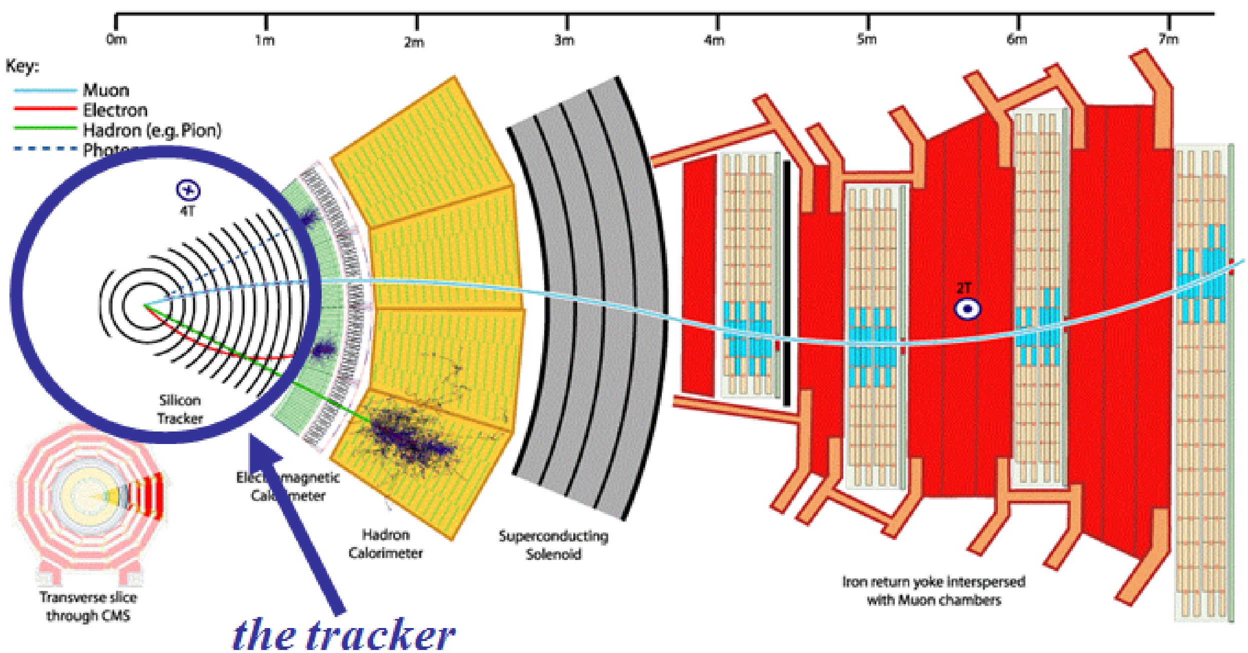
Z -> e^+ e^-

CMS
Compact Muon Solenoid



Cut through CMS Experiment

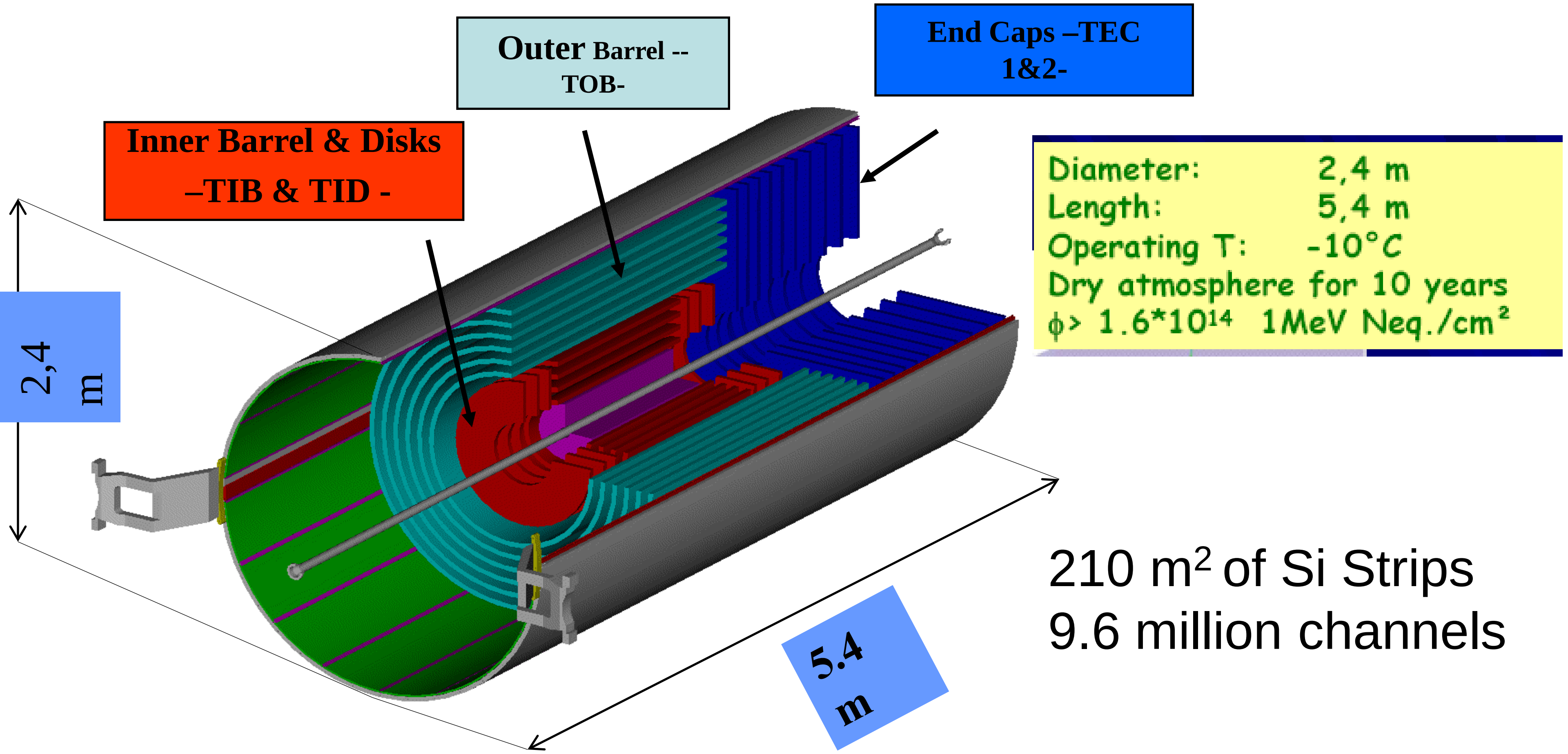
the task:
reconstructing particles and their movement in the detector



Tracks of particles in a typical collider experiment of the future (CMS @ LHC)

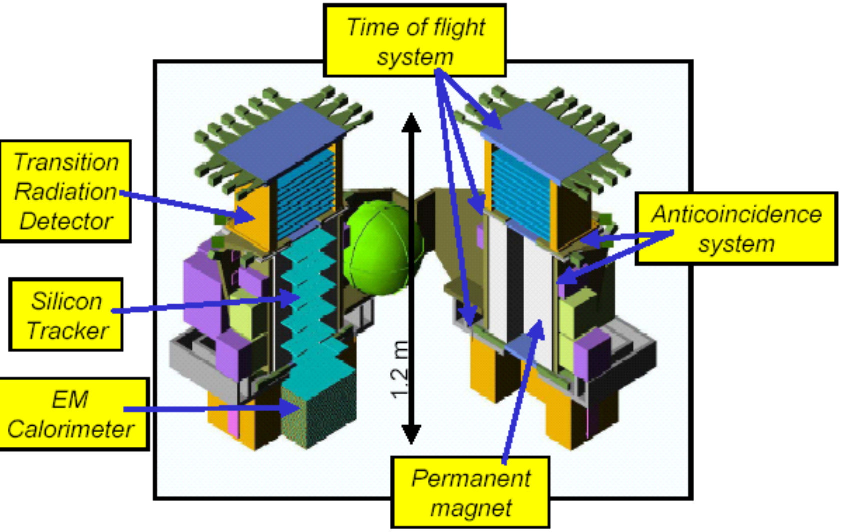
30

CMS Silicon Strip Tracker:
A Quantum Leap in Si Tracking: a major contribution of HEPHY

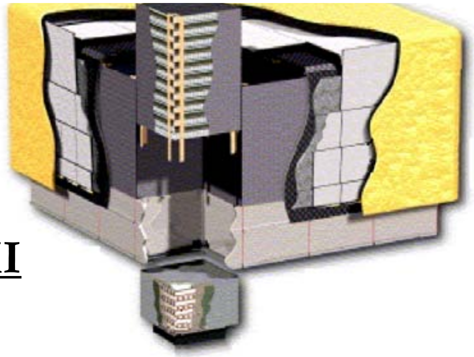


210 m² of Si Strips
9.6 million channels

Space Based Experimentation:

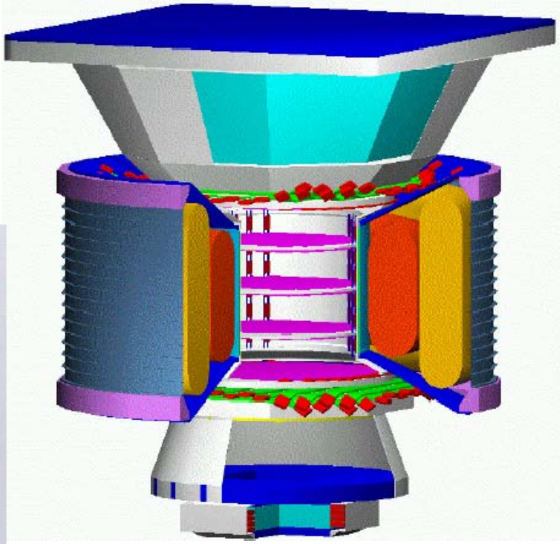


Pamela



FERMI

Euso



Ams-02

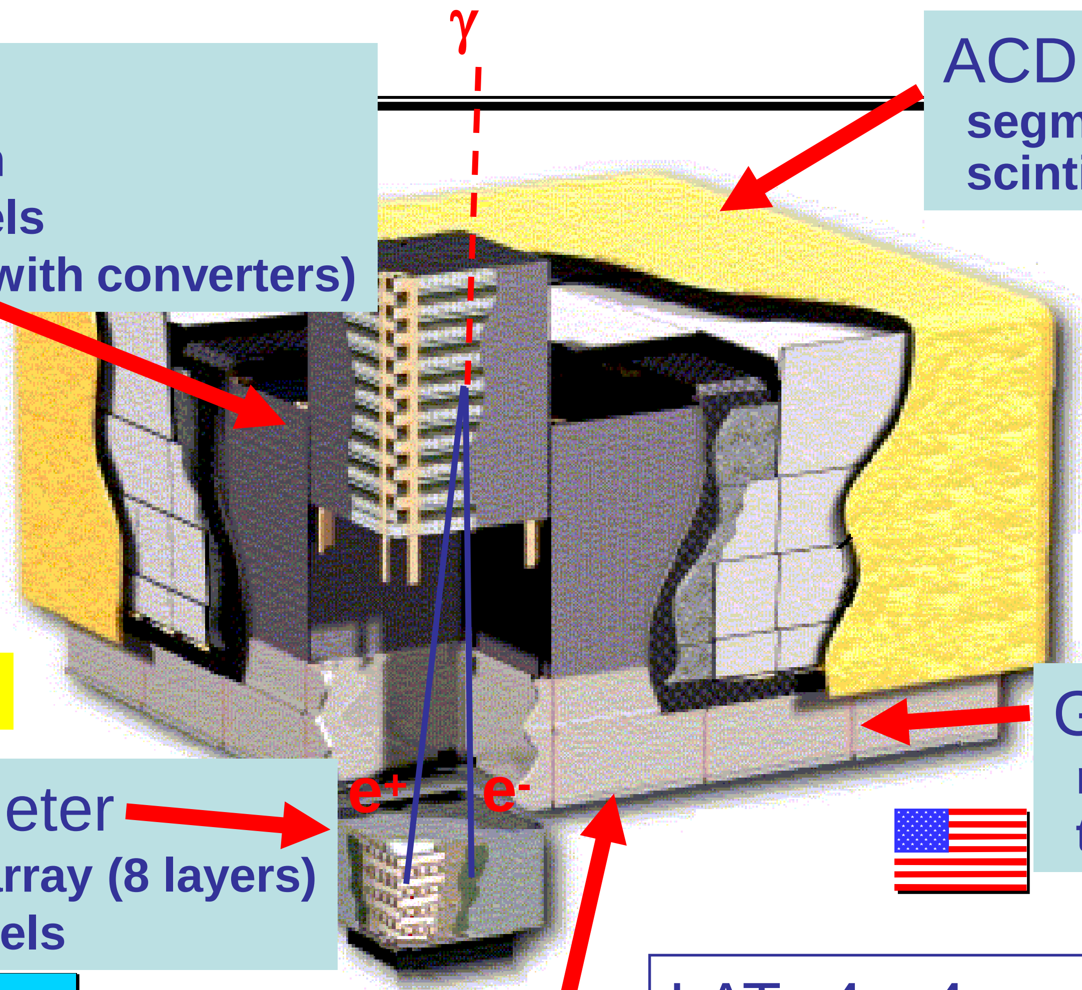
scheduled for the space station from next year onwards

Very active field with new detector and engineering challenges

AMS2 at CERN under preparation for employment at the ISS

Spectroscopy of Cosmic rays
Search fore anitparticles
Search for signals of Dark Matter
Scheduled to fly on the last Shuttle
In February 2011

FERMI Satellite Experiment



Si Tracker
pitch = 228 μm
8.8 10^5 channels
18 planes (16 with converters)

ACD
segmented scintillator tiles

H.F. Sandrozinski

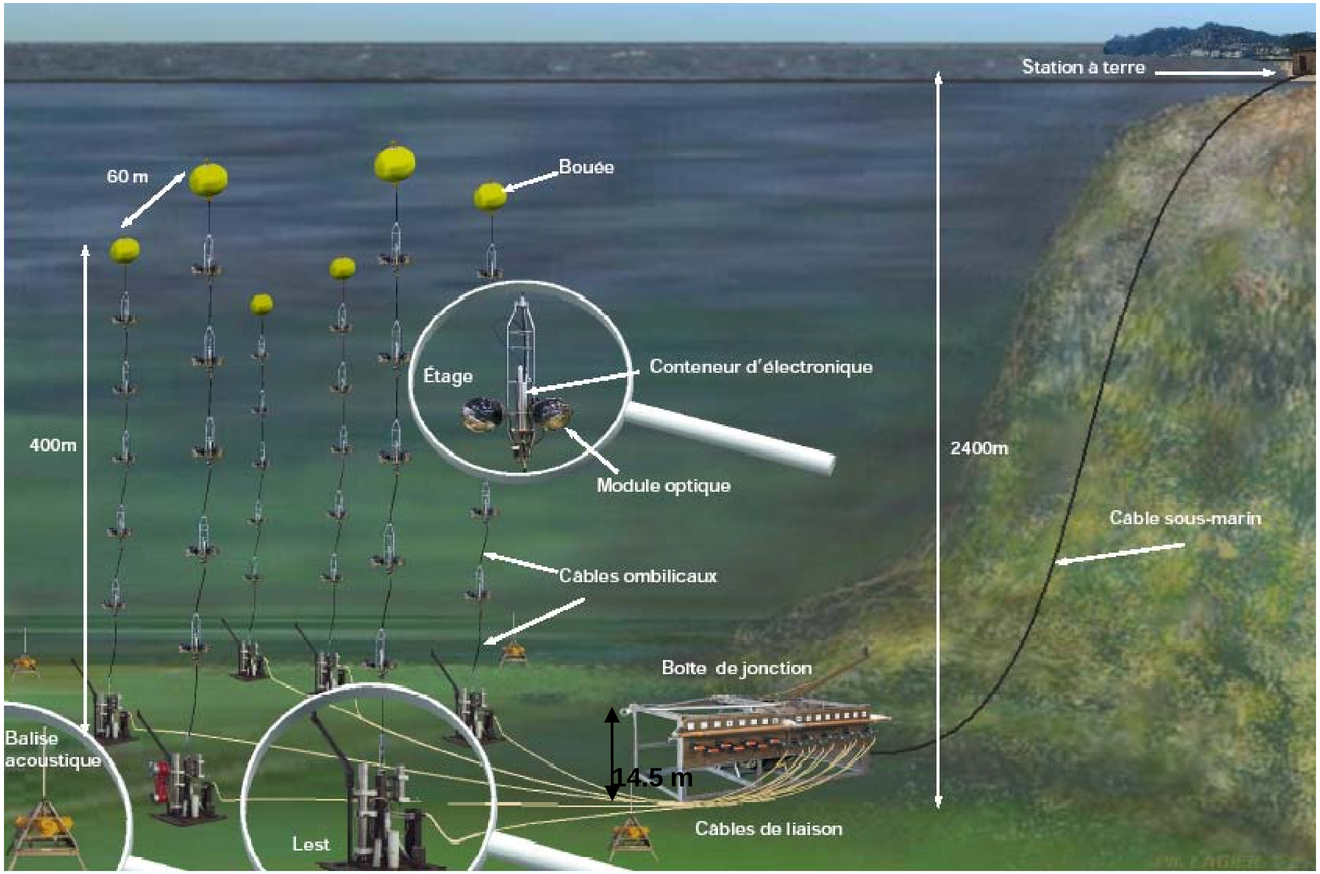
Grid
mechanical
thermal

CsI Calorimeter
hodoscopic array (8 layers)
6.1 10^4 channels

DAQ, FSW, ELEX

LAT: 4 x 4 modular array
3000 kg, 650 W
20 MeV – 300 GeV

ANTARES: towards neutrino astronomy

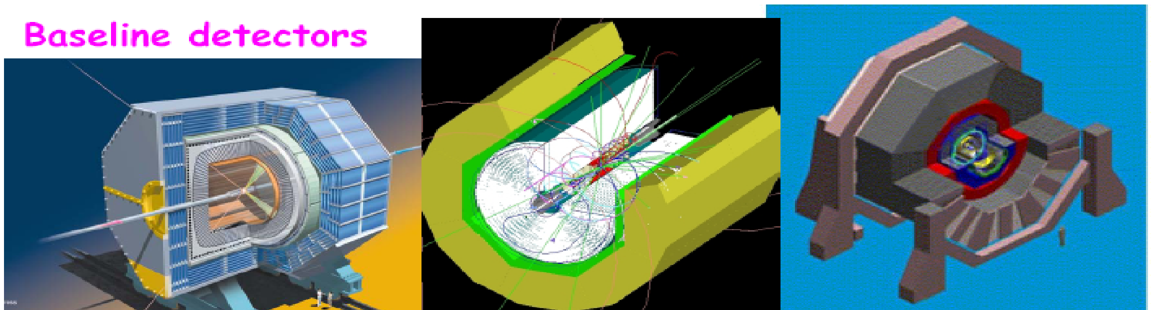


- 12 lines
- 25 storeys/line
- 3 PMTs /storey
- 900 PMTs

The 'ICECUBE' uses a similar concept burying PMs in the Antarctic Ice

Detector Concepts foe a High Energy electron – positron collider (ILC) the post-LHC era

Baseline detectors



GLC/US Large Det	TESLA TDR	Si D: US Silicon Det.
B=3 T, R_{coil}=3m/3.7m	4 T, 3.7m	5T, 2.5m
VTX: CCD	CCD, CMOS,others	CCD
IT: Si strips	Si strips	Si strips, Si drift
Gas:Jet Chamb. /TPC	Gas: TPC	
CAL:Tiles Pb-Scint	Si-W or Pb-Scint	Si-W
	Digital/steel	Digital

JE Augustin, Vienna Conference on Instrumentation 2004 12

Detector R&D directed towards novel solutions adapted to the low rate experimental environment.

Aiming for better momentum and energy resolution

a final word…

- Development, construction and operation of particle physics detectors has become a very professional and interdisciplinary activity
- The generation of experiments for LEP, HERA, LHC have triggered a worldwide R&D activity
- During the past 20 years R&D for detectors and experiments has shifted from the big Laboratories (BNL, CERN, DESY, FNAL) to the institutes and universities. E.g. HEPHY has become a major contributor to the construction of CMS
- For LHC approximately 85% of the contribution to the experiment were provided outside institutions and Universities
- New challenges and opportunities have come from collaborations on medical diagnostic instruments (PET, Radiation treatment optimization,..)
- These activities are intellectually and technically very stimulating: ideal opportunities for Project Work, Master and Ph.D. Theses
- In general: better detectors opens the road to new physics

The last word…
from one of the leading theoreticalphysicists

"New directions in science are launched by new tools much more often than by new concepts.

The effect of a concept-driven revolution is to explain old things in new ways.

The effect of a tool-driven revolution is to discover new things that have to be explained."

Freeman Dyson, Imagined Worlds