Particle Physics Experiments

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

HEP Detectors and their Technologies

Silvia Schuh
CERN

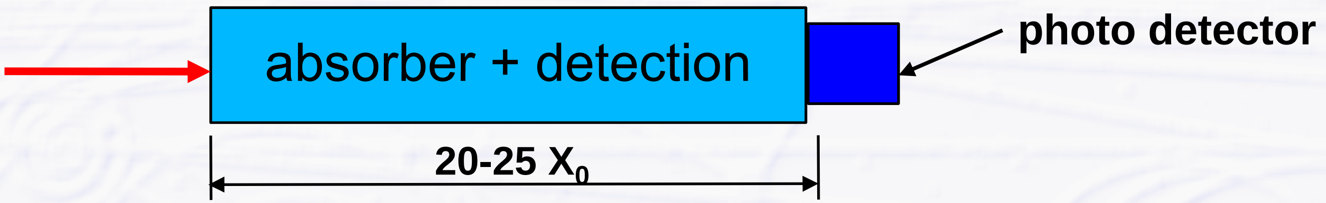
Overview

- Introduction and Concepts
- Properties of Particles
  - Which are measurable? How?
- Particle Interactions
- Particle Detectors in HEP
  - Tracking Detectors
  - Energy Measurement
  - Particle Identification
  - LHC Particle Detectors
  - Infrastructure

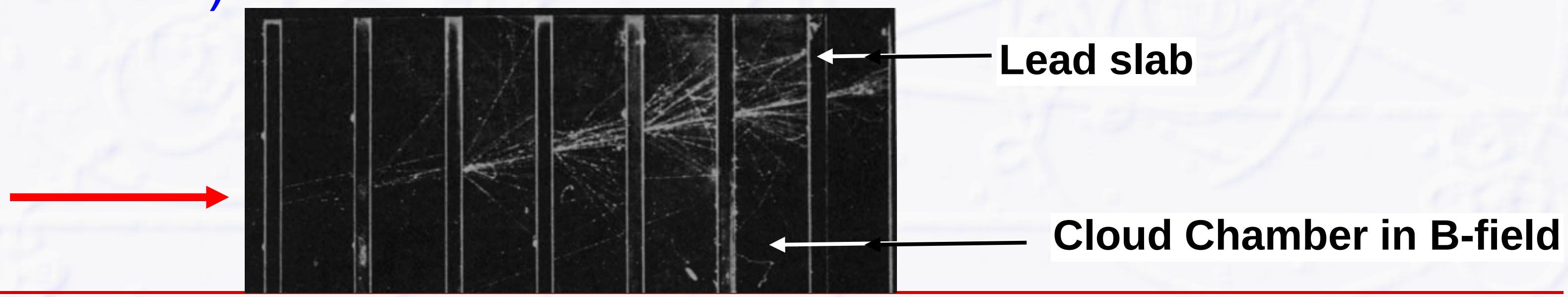
} **Day 3**

Calorimeters - conceptual design

- Homogeneous calorimeters
  - absorber material = detector
    - (Typically) em shower created in optically transparent absorber, photons created in the shower are collected and detected with some photo detector

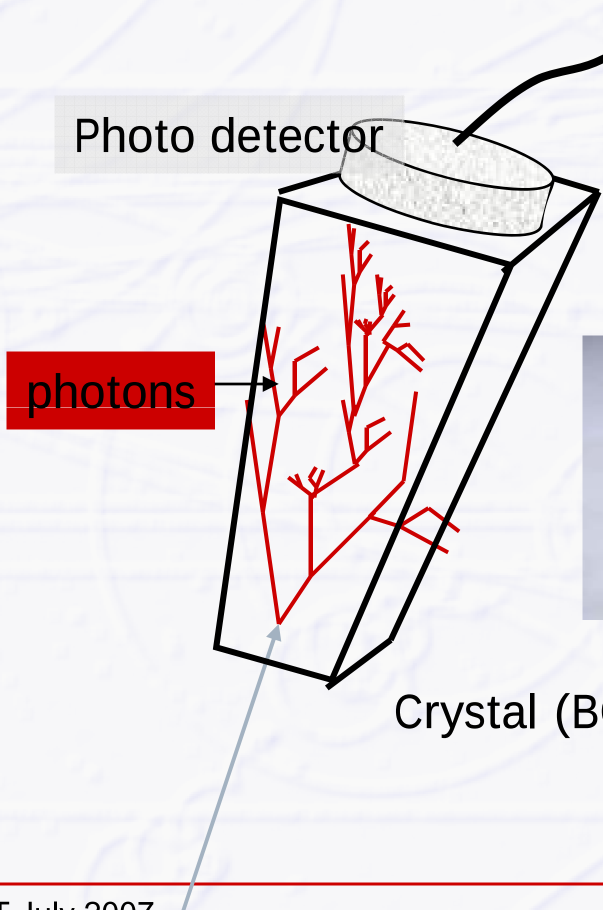


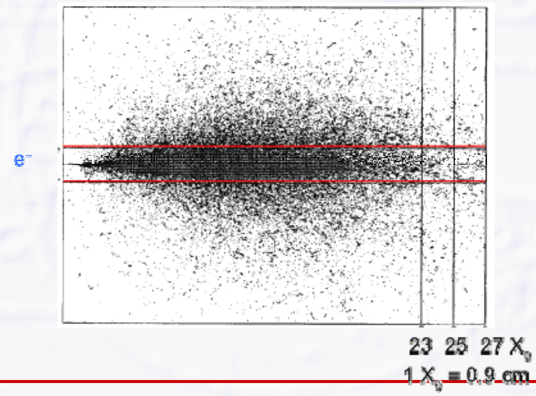
- Sampling calorimeters
  - passive absorber material (iron, copper, lead, tungsten, uranium) interleaved with active detector material



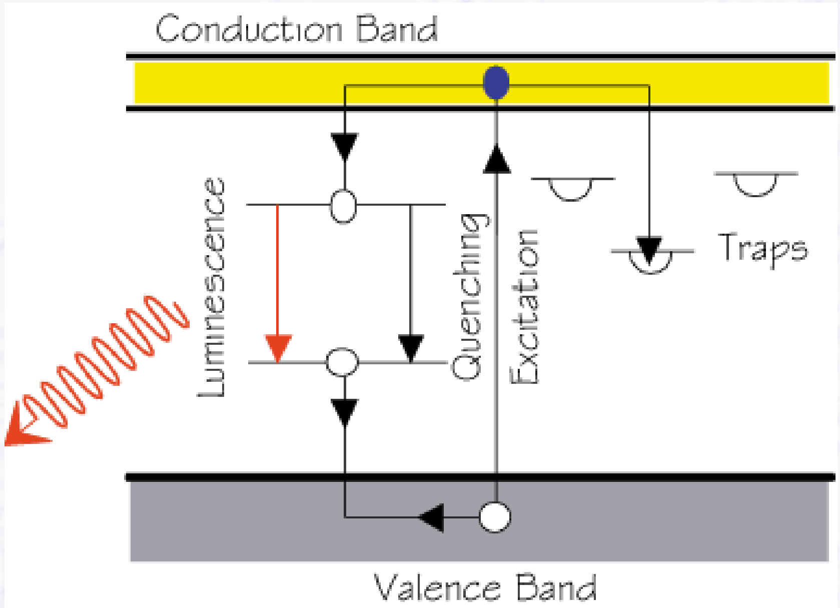
Homogeneous calorimeters

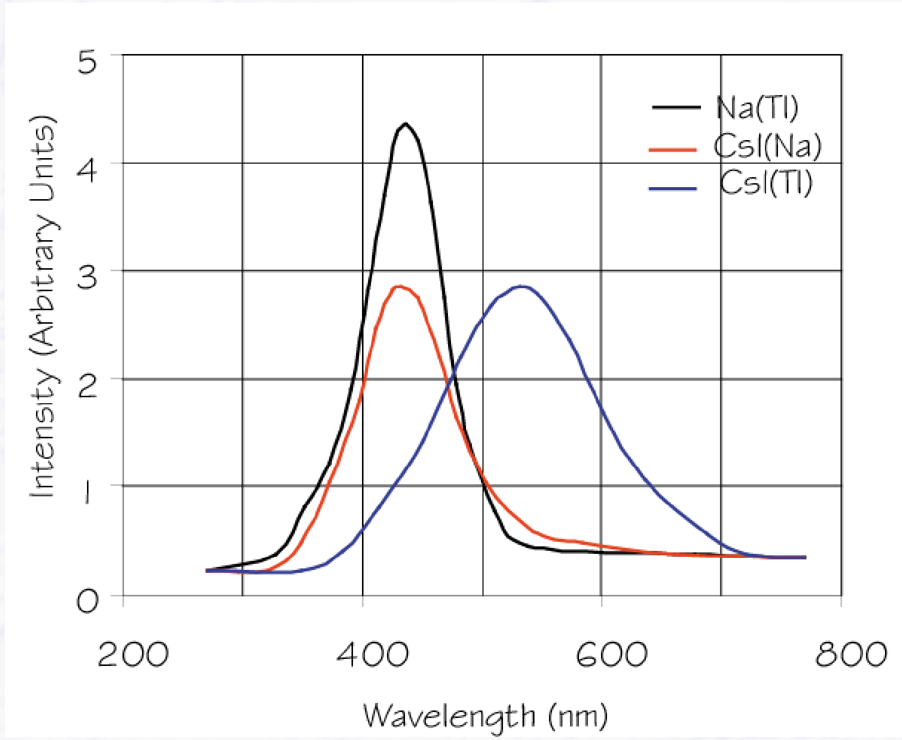
- crystal calorimeters

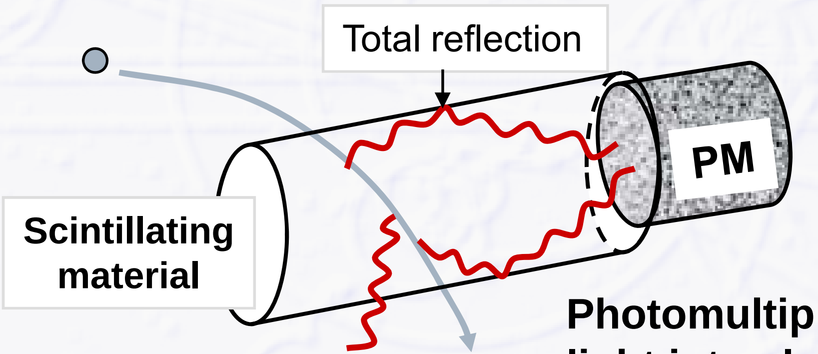




Szintillator: working principle







Photomultiplier: converts light into electronic signal

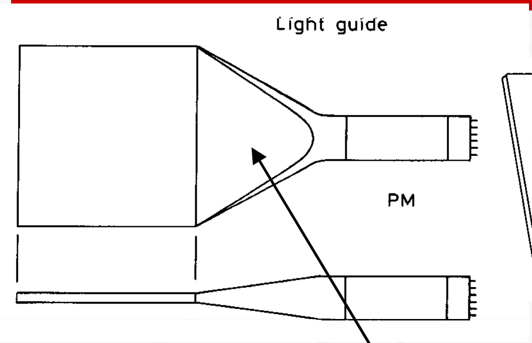
Most common inorganic scintillator is sodium iodide activated with trace of thallium [NaI(Tl)].

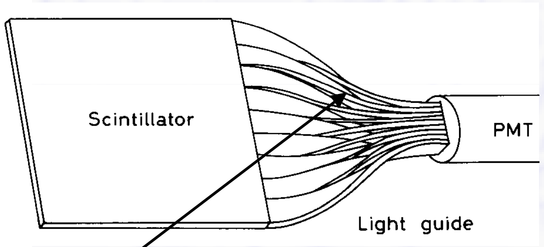
Scintillator materials

Scintillator composition	Density (g/cm^3)	Index of refraction	Wavelength of max.Em. (nm)	Decay time Constant (µs)	Scinti Pulse height[1)]	Notes
NaI(Tl)	3.67	1.9	410	0.25	100	hygro
CsI	4.51	1.8	310	0.01	6	Water soluble
CsI(Tl)	4.51	1.8	565	1.0	45	Water soluble
CaF_2(Eu)	3.19	1.4	435	0.9	50	
BaF_2	4.88	1.5	190/220 310	0,0006 0.63	5 15	
BGO	7.13	2.2	480	0.30	10	
$CdW0_4$	7.90	2.3	540	5.0	40	
$PbWO_4$	8.28	2.1	440	0.020	0.1	
CeF_3	6.16	1.7	300 340	0.005 0.020	5	
GSO	6.71	1.9	430	0.060	40	
LSO	7	1.8	420	0.040	75	
YAP	5.50	1.9	370	0.030	70	

from C. D'Ambrosio, Academic Training, 2005

Photomultiplier

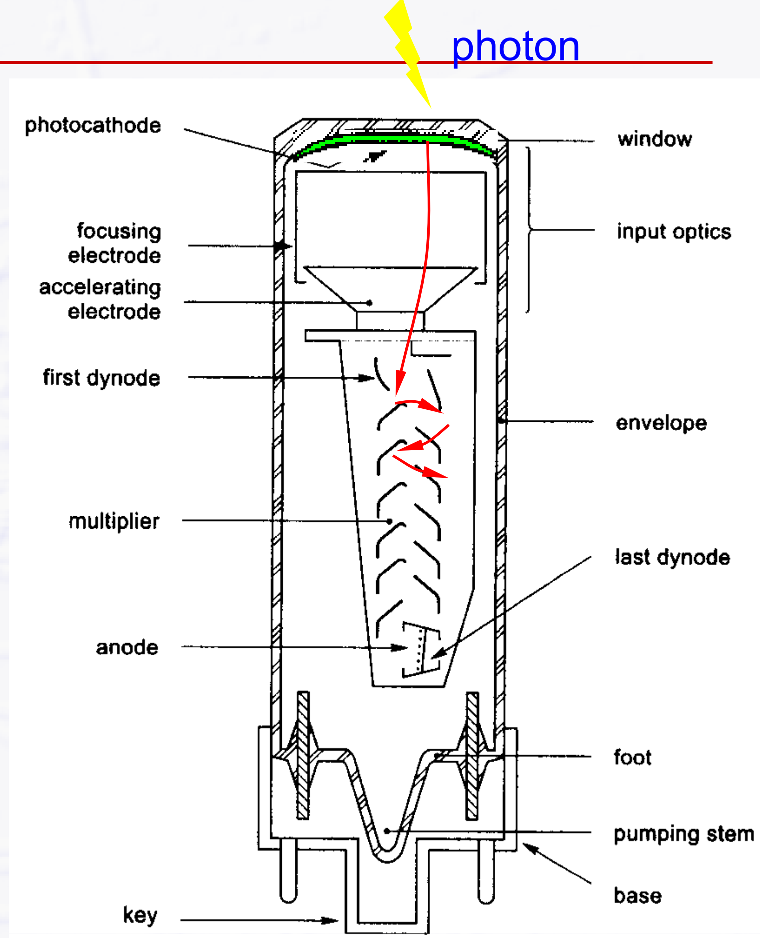




adiabatic

"fish tail"

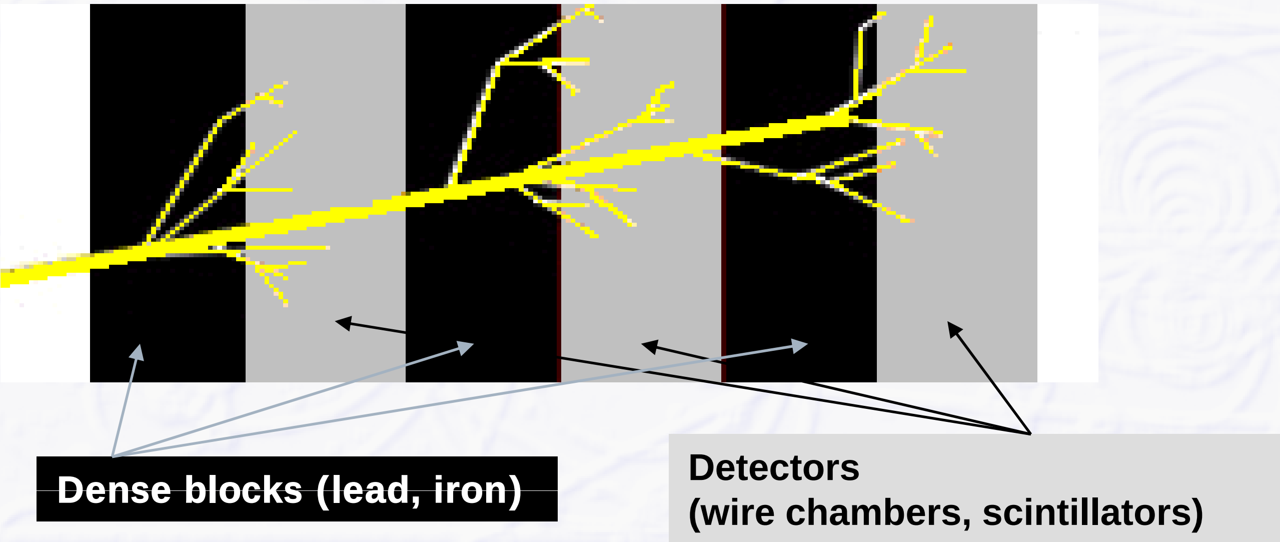
Light guides: transfer via total internal reflection



Photon in window → atomic excitation → γ radiation → Photoeffekt at Photocathode → primary electron → Multiplication on dynodes G~4, M~10^6

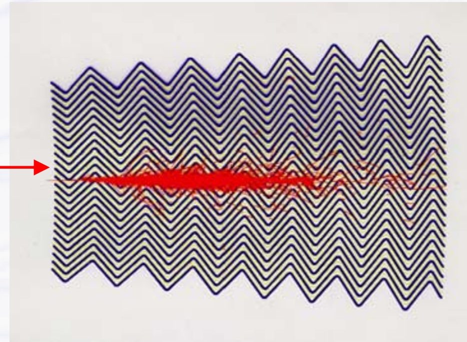
Sampling Calorimeters

- Sandwich structure
  - Lead/iron + gas/scintillator/LAr/LKr
  - Total signal registered $\propto E_0$
  - BUT: must calibrate with beams of known energy!
- Use as em + hadronic calorimeter

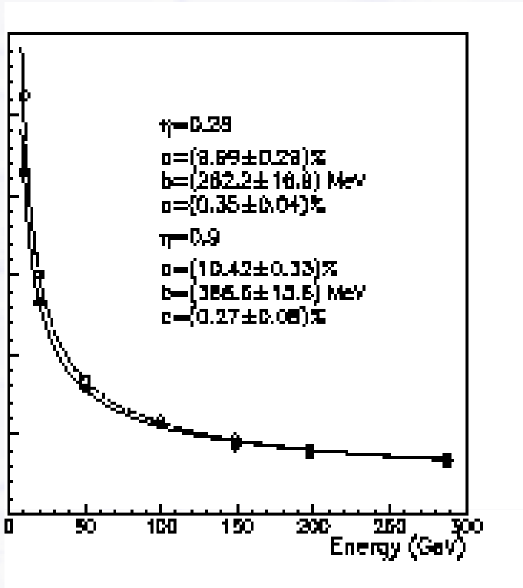


LHC sampling calorimeters

- ATLAS: LAr “acordeon” lead absorbers
  - LAr ionized by charged shower particles
  - Charge collected on pads
    - ionization chamber
    - pads formed as needed ✸ high granularity
  - Accordion: avoid dead zones



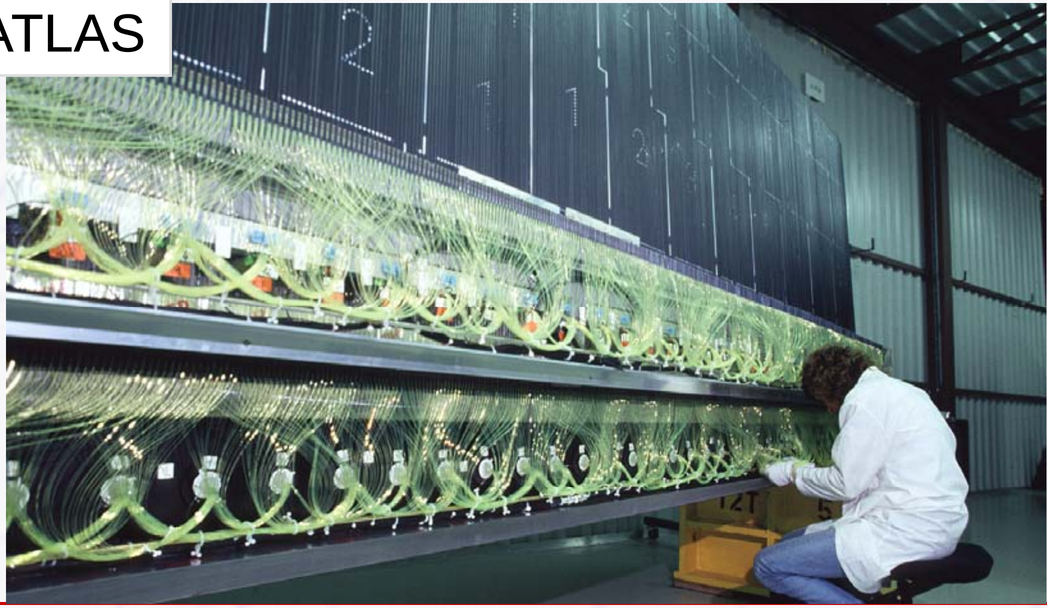
$$\frac{\sigma(E)}{E} = \frac{9.24\%}{\sqrt{E}} \oplus \frac{280 MeV}{E} \oplus 0.35\%$$

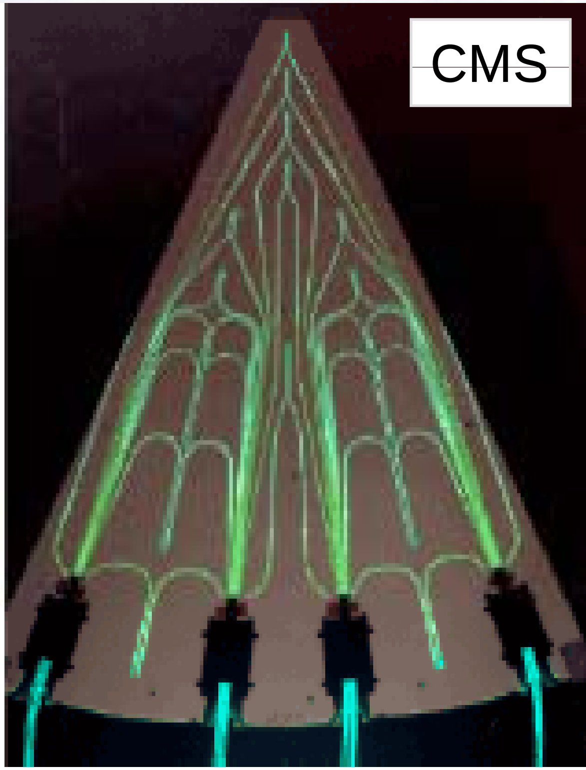


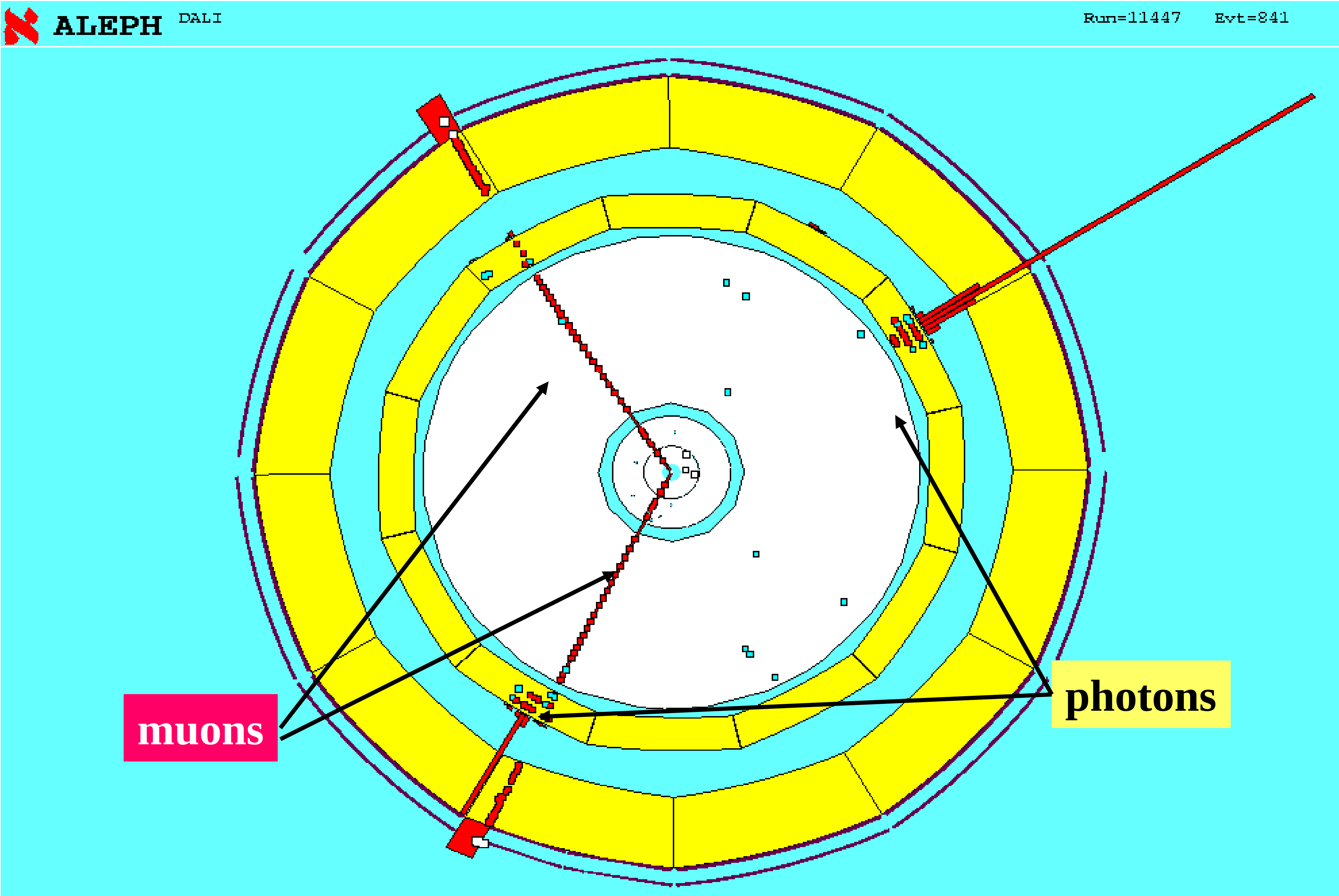

ATLAS LAr calorimeter

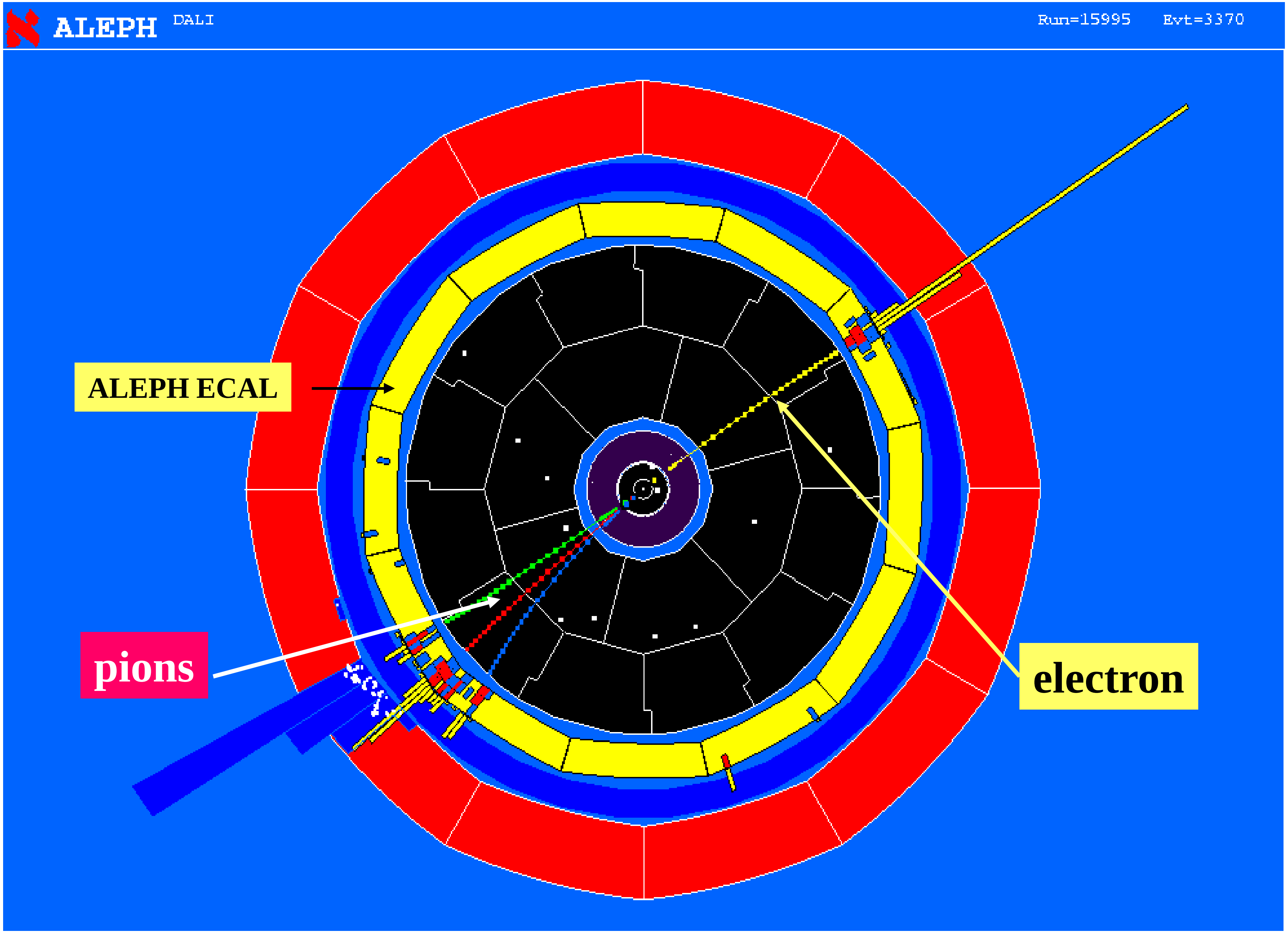
LHC Hadronic Calorimeter

- Energy resolution much worse than for em calorimeters
  - larger fluctuations in hadronic shower
  - usually only a few nuclear interactions length deep (5 – 6 ●$_l$)
- Typically scintillators as detector material
  - need many optical fibers to transport light from scintillators to photo detectors

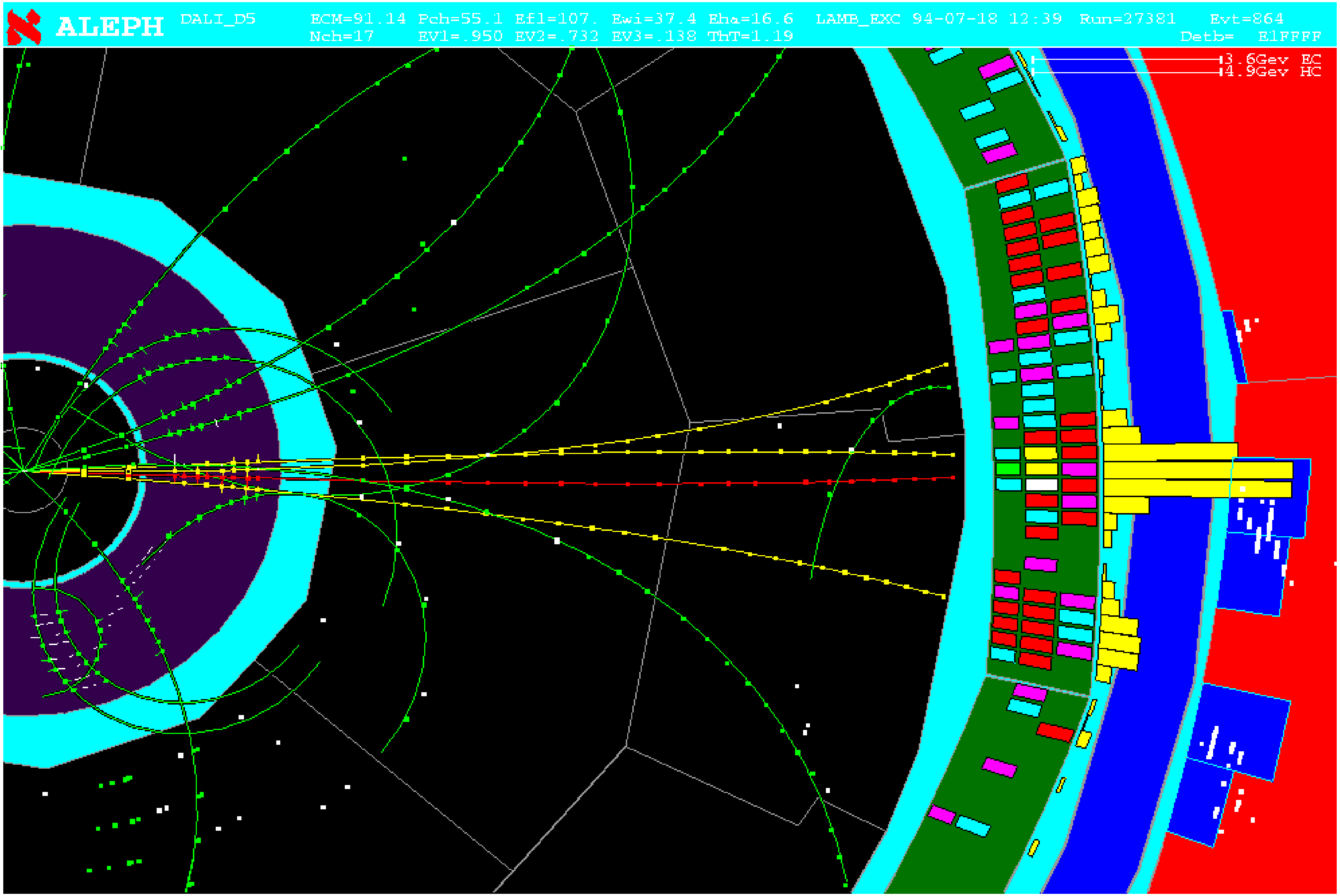





ALEPH
DALI
Run=11447
Evt=841
muons
photons



ALEPH
DALI
Run=15995
Evt=3370
ALEPH ECAL
pions
electron

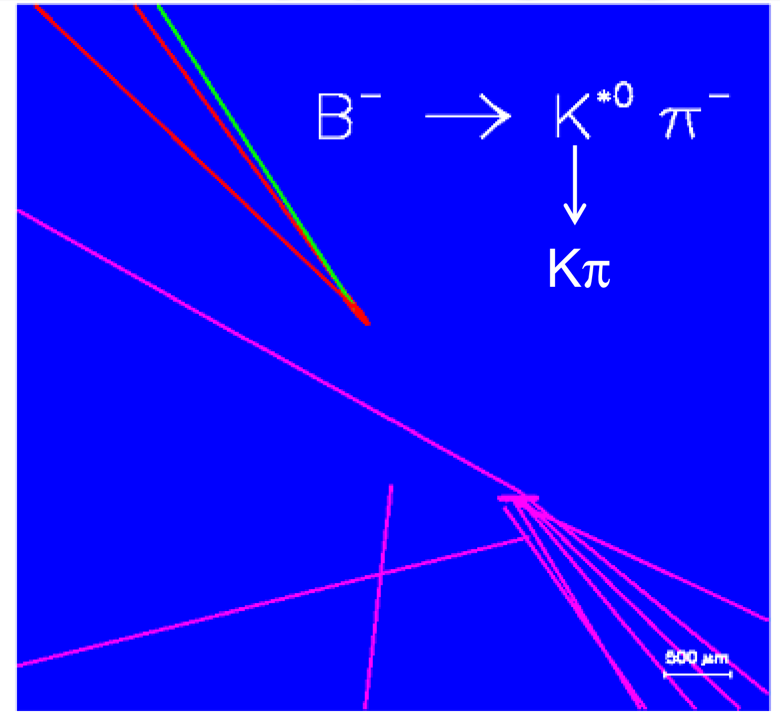

ALEPH
DALI_D5
ECM=91.14 Pch=55.1 Efl=107. Ewi=37.4 Eha=16.6
LAMB_EXC 94-07-18 12:39 Run=27381 Evt=864
Nch=17 EV1=.950 EV2=.732 EV3=.138 ThT=1.19
Detb= E1FFFF
3.6Gev EC
4.9Gev HC

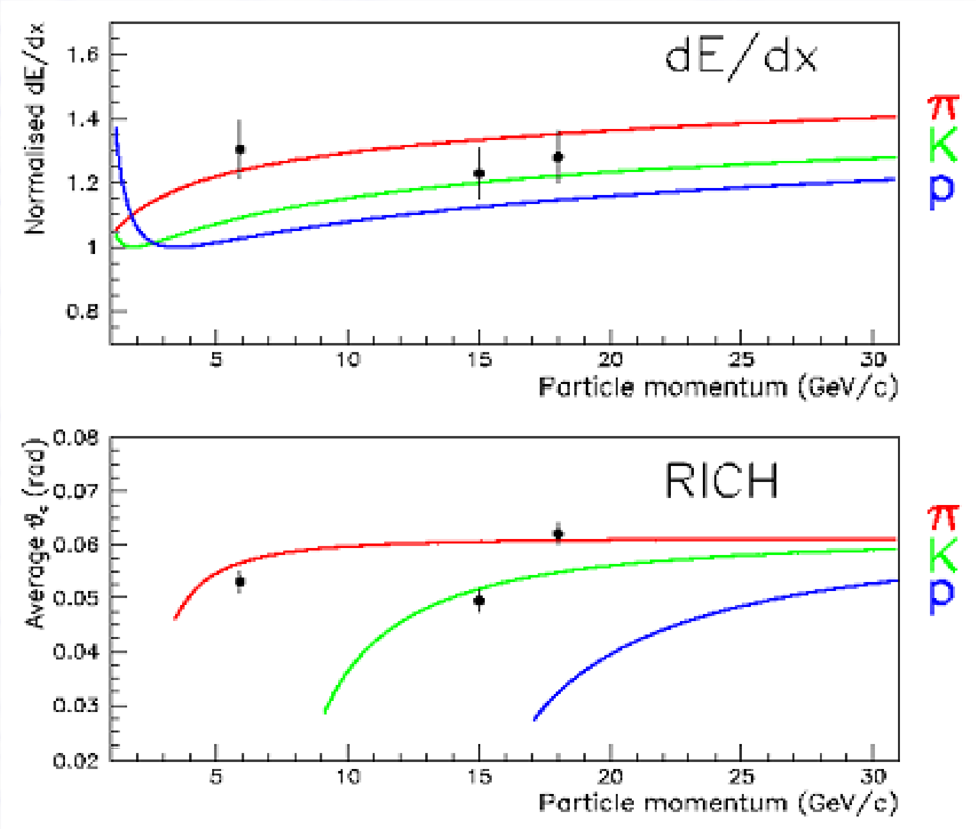
Particle Identification

- via different interaction with matter
- by measuring (invariant) mass of decay products
- by measuring velocity & independently (!) momentum
  - dE/dx (characteristic energy loss per distance)
  - Time Of Flight TOF
  - Cherenkov Radiation (RICH)
  - Transition Radiation

Why PID?

- 'Charmless' B-decay
  - 1 K + 2π in final state
  - Who is who?





Specific energy loss

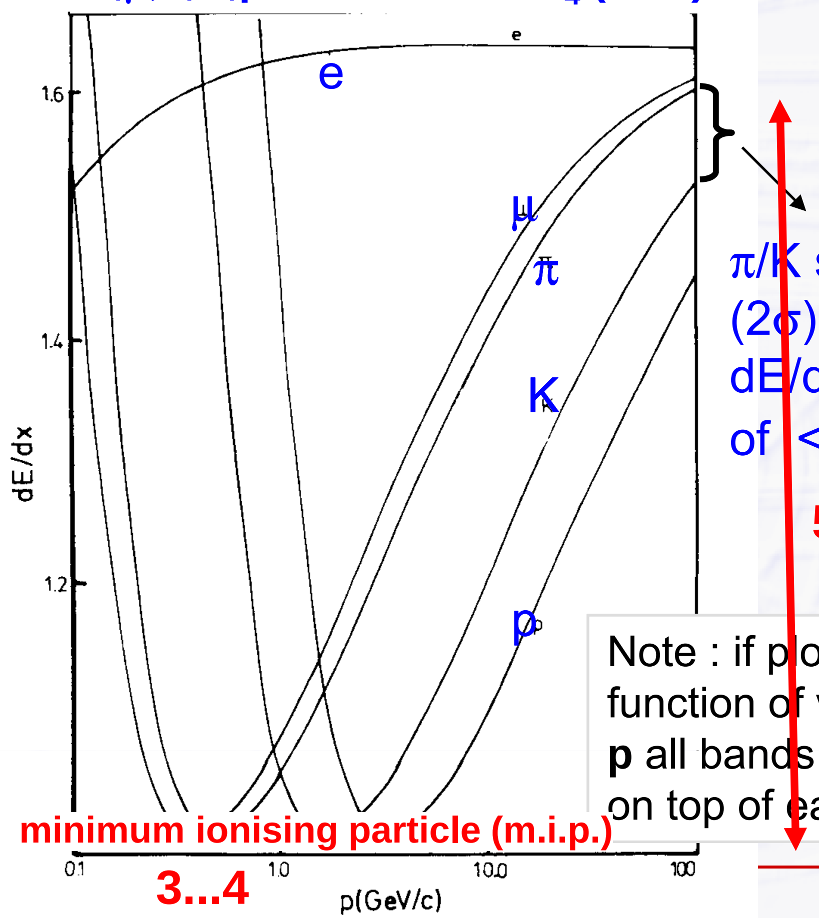
- Mean energy loss (via ionization) as function of β=v/c
  Bethe-Bloch formula

$$p = m_0 \beta \gamma c$$

$$\frac{dE}{dx} \propto \frac{1}{\beta^2} \ln\left(\beta^2 \gamma^2\right)$$

- Measure simultaneously p & dE/dx ⇒ mass ⇒ PID!
  - ⟨E_{lost}⟩ amount of ionization, ∝ signal charge on wires
  - dE/dx precision
    - Gas w/ high specific ionization
    - Divide detector length L in N gaps of thickness T
    - Sample dE/dx N times

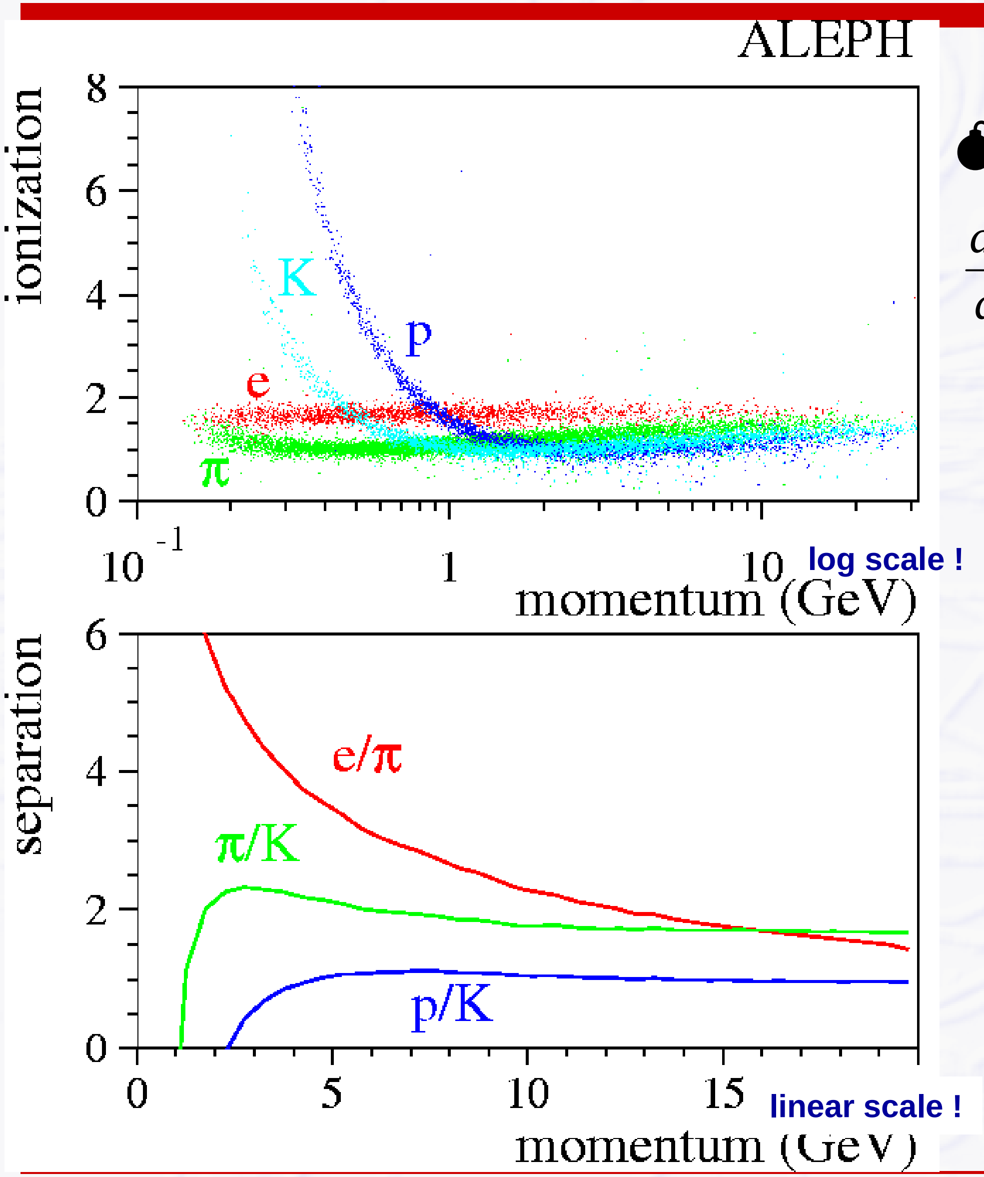
Average energy loss for e,μ,π,K,p in 80/20 Ar/CH_4 (NTP)



π/K separation (2σ) requires a dE/dx resolution of < 5%

Note : if plotted as function of **v** and **not p** all bands would lie on top of each other!

dE/dx measurement



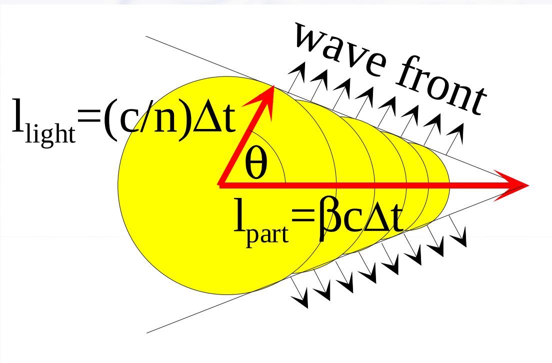
- Bethe Bloch Formula (full)

$$\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} - \beta^2 - \frac{\delta}{2} \right]$$

  - Energy loss depends on particle v, ~indep on particle mass
  - Energy loss as a function of momentum (p=mcβγ) does depend on particle mass
  - below a given momentum, cannot distinguish certain particle pairs with dE/dx - as they are both in the $1/\beta^2$ part of the Bethe Bloch Formula (see plot p 17)

Cherenkov radiation

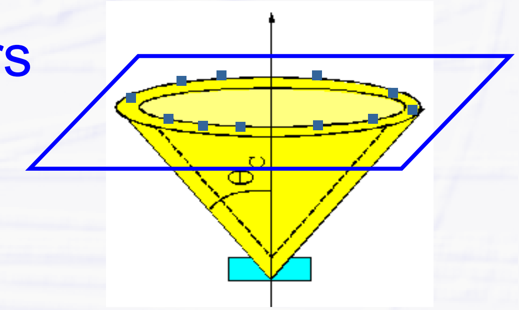
- Ionization is one way of energy loss
  - emission of photons another...
- Cherenkov radiation: emitted when charged particle passes dielectric medium with velocity $\beta \geq \beta_{thr}=1/n$
  - $N_\gamma(\beta)$: threshold detector
  - $\theta(\beta)$: differential & Ring Imaging Cherenkov counter



$$\cos\theta_C = \frac{1}{n\beta} \quad \text{with} \quad n = n(\lambda) \geq 1$$

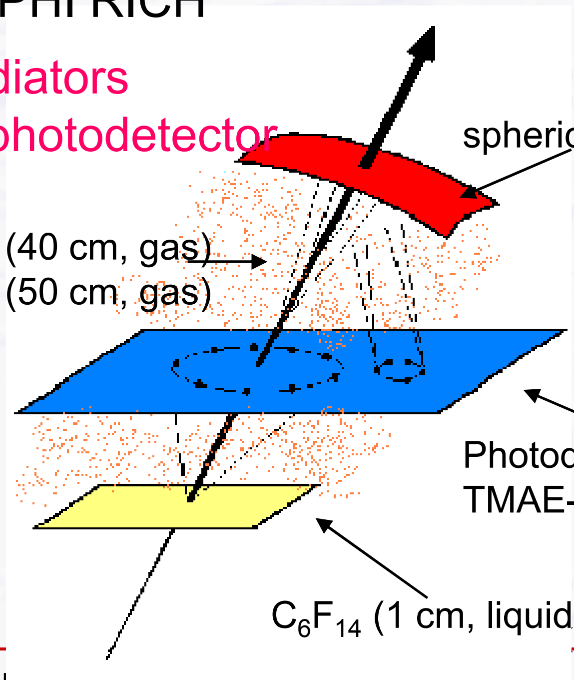
RICH Detectors

- RICH detectors determine θ_C by intersecting Cherenkov cone with photosensitive plane
  - Requires large-area photosensitive detectors
    - Wire chambers with photosensitive gas
    - PMT arrays



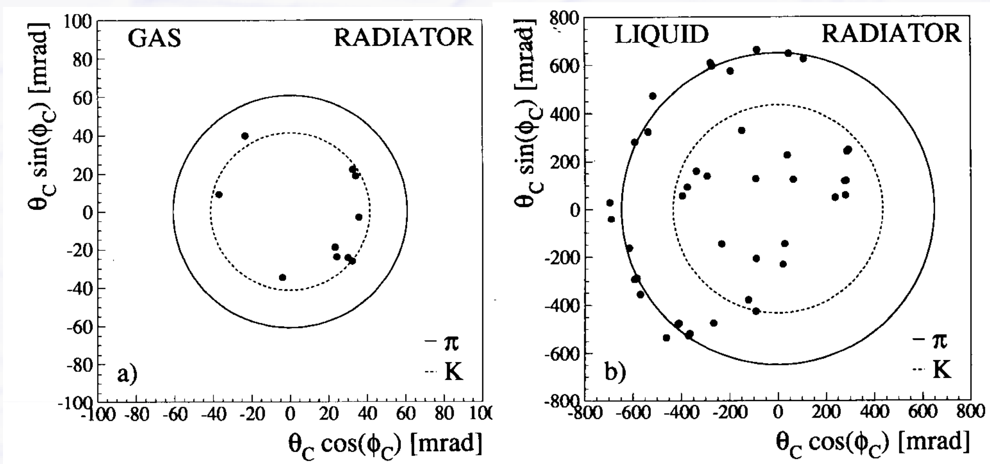
DELPHI RICH

2 radiators
+ 1 photodetector



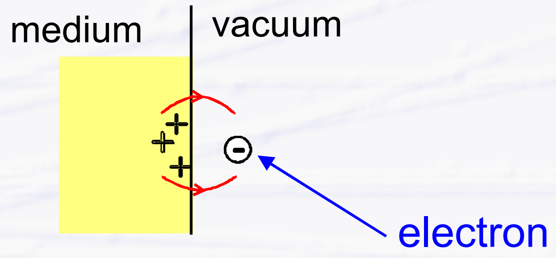
1996) 240)

π/K/p separation 0.7-45 GeV/c



Transition Radiation

- Charged particle traverses boundary of two media with different refractive index, emits photons (Ginzburg/Franck 1946)



- (very) simple picture
  - charged particle is polarizing medium
  - polarized medium is left behind when particle
  - leaves media and enters unpolarized vacuum
  - formation of electrical dipol with (transition) radiation (X-ray)
- only very high energetic particles radiate significant energy, $\beta > 1000$
  - only electrons
  - BUT probability to emit photons still small
  - $N_\gamma \propto 1/137 \rightarrow$ many boundaries!

ATLAS Transition Radiation Tracker

- Combines straw tracker (small ∅ drift tube) with transition radiation detection

TRACKING of charged particles

2 keV

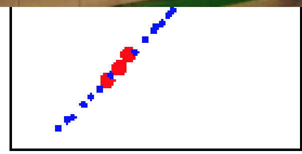
PARTICLE

Inc

Ra

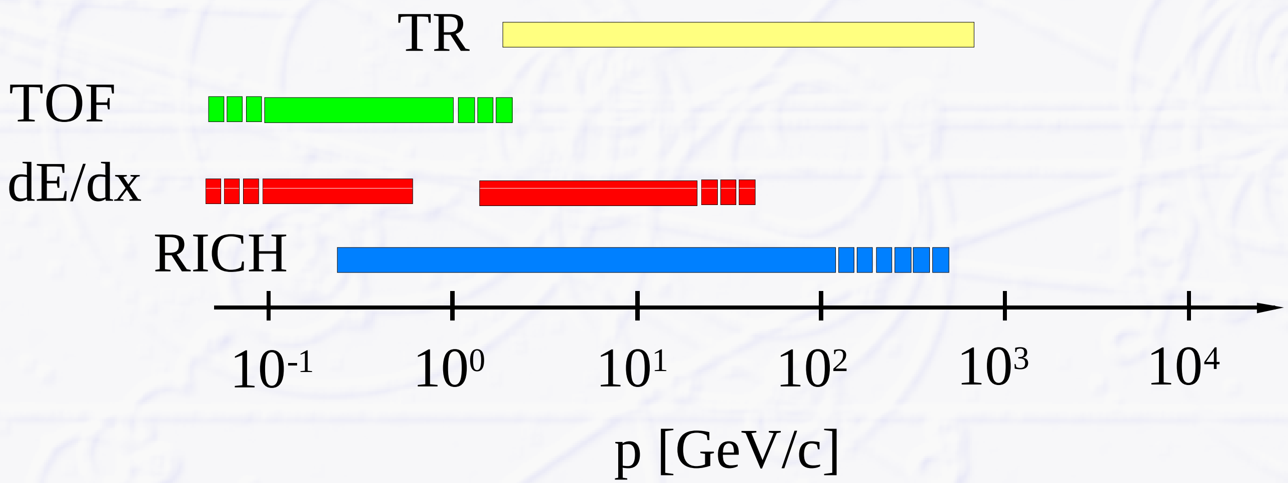
thin plastic foils + air

Straw Tube detecting element. 4 mm diameter with 50 μm wire.



PID Summary

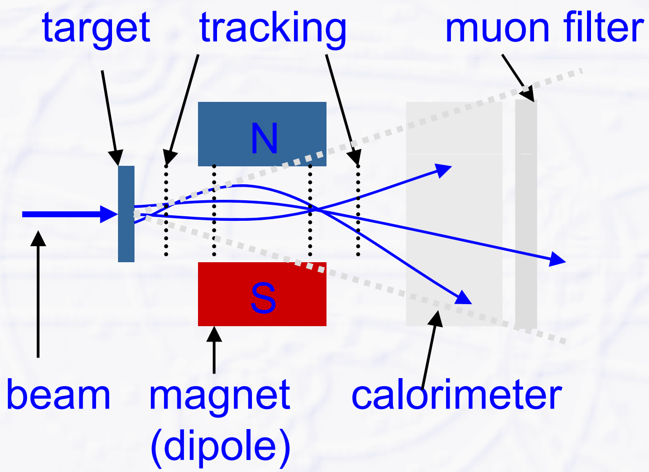
- A number of powerful methods are available to identify particles over a large momentum range.
- Depending on the available space and the environment, the identification power can vary significantly.



Detector Systems

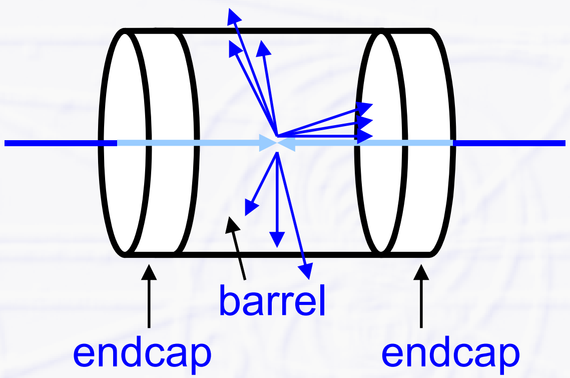
- Remember: we want to have info on...
  - number of particles, event topology
  - momentum / energy / particle identity
  - ⇒ integrate detectors to detector systems

Fixed target geometry
"Magnet spectrometer"



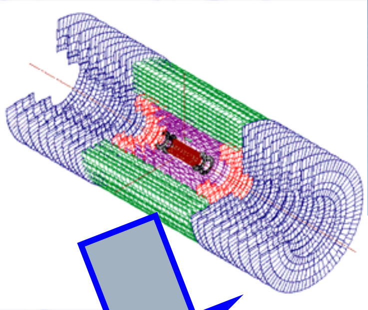
- Limited solid angle dΩ coverage
- rel. easy access (cables, maintenance)

Collider Geometry
"4π Multi purpose detector"

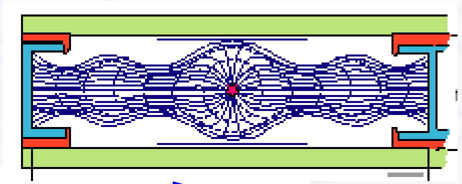


- "full" dΩ coverage
- very restricted access

Detector Systems: CMS



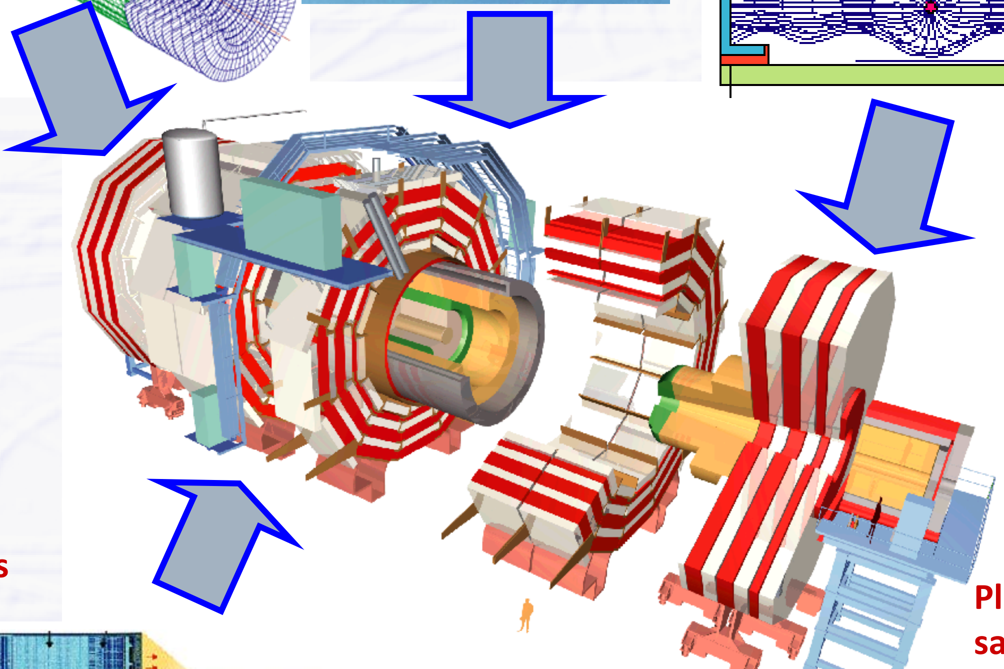
Scintillating PbWO4 crystals



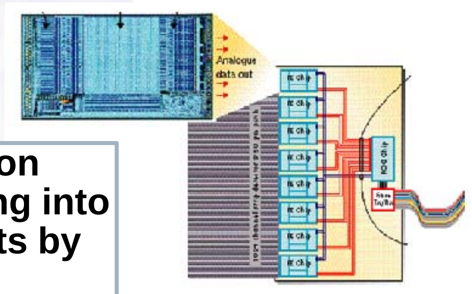
Drift Tube Chambers

Resistive Plate Chambers

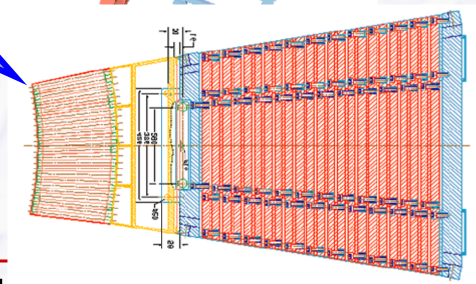
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla



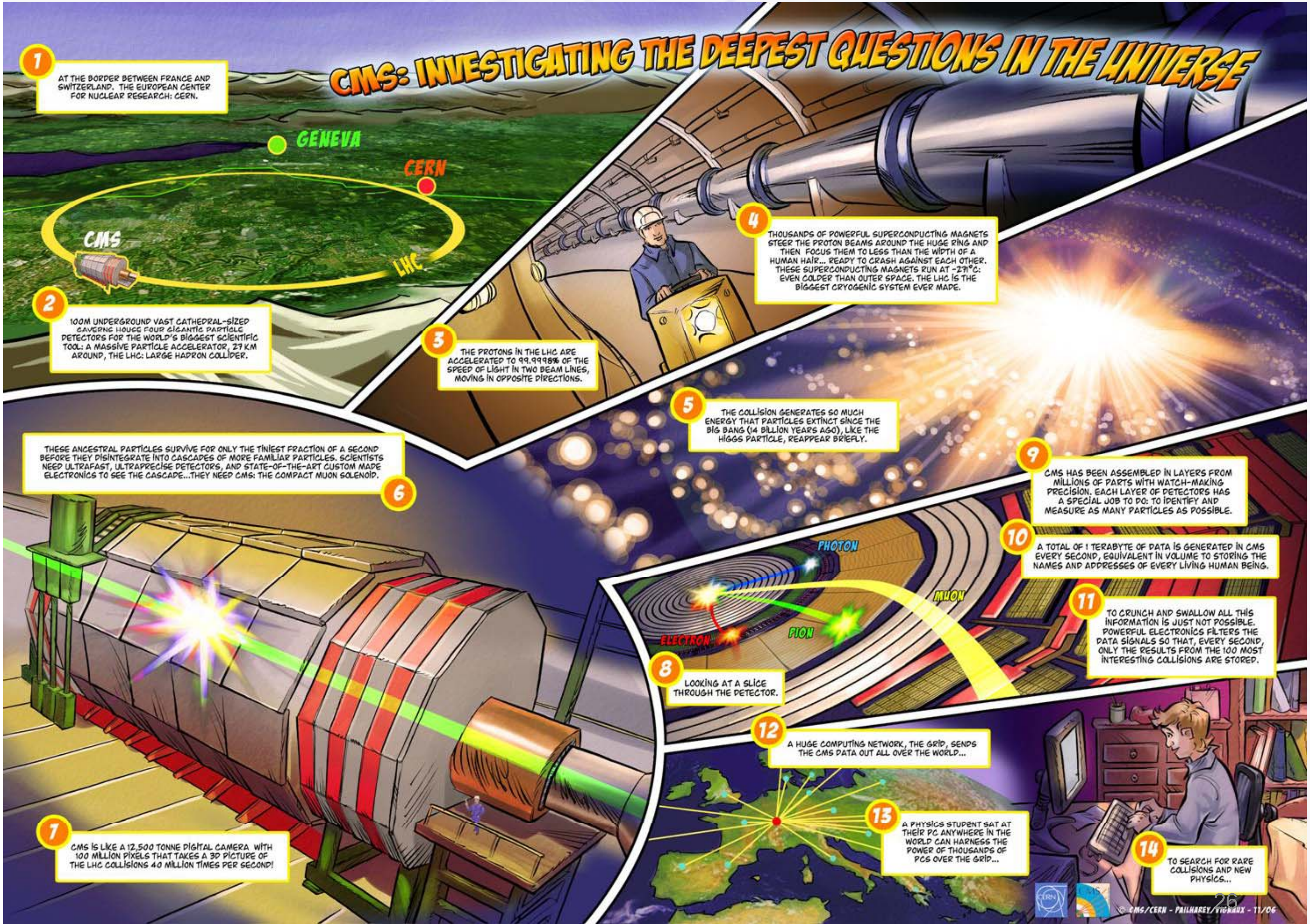
Silicon Microstrips
Pixels



Plastic scintillator/brass sandwich



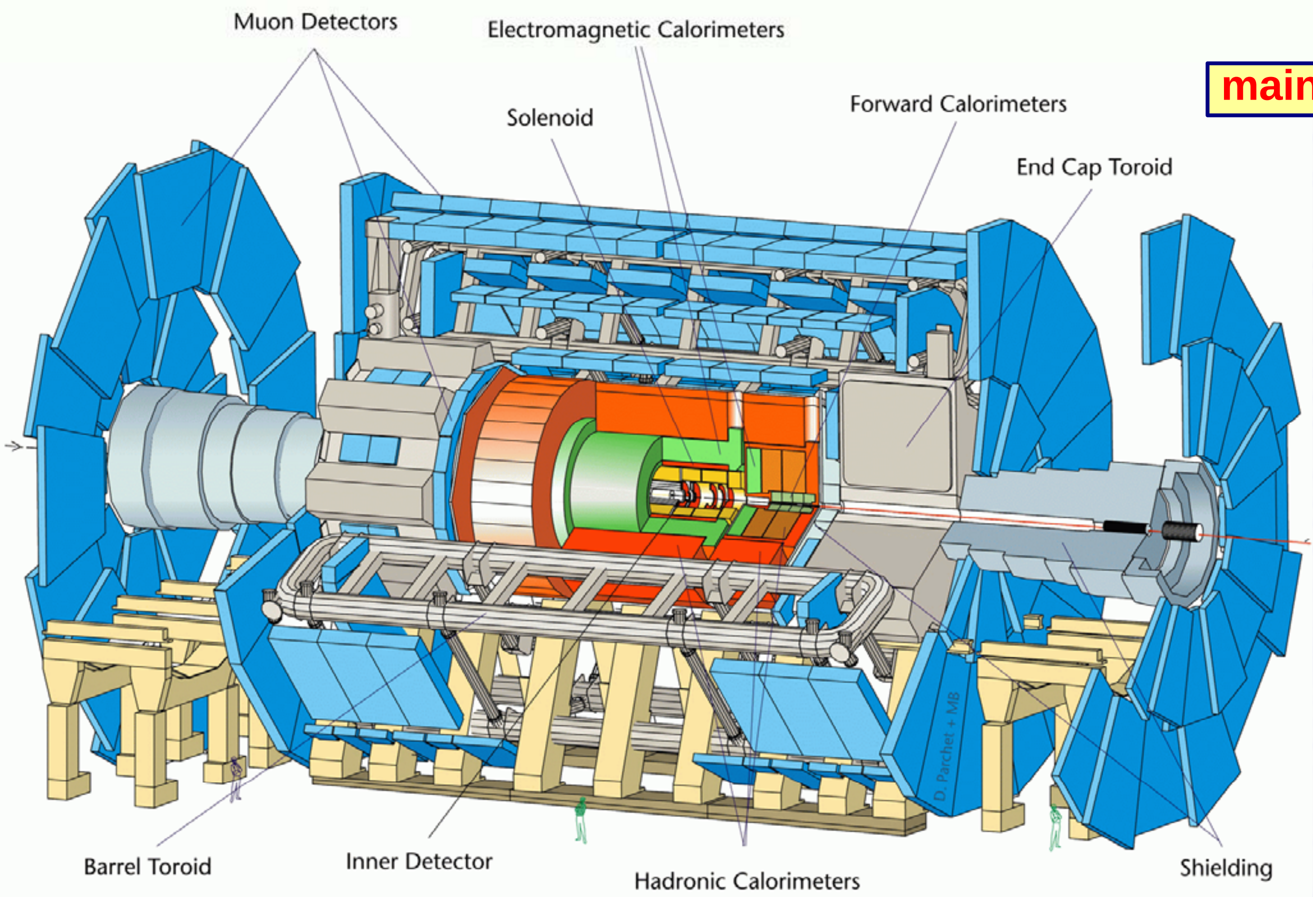
main assembly on surface, then lowering into cavern in 5 big parts by ~3000t crane


CMS: INVESTIGATING THE DEEPEST QUESTIONS IN THE UNIVERSE
1
AT THE BORDER BETWEEN FRANCE AND SWITZERLAND. THE EUROPEAN CENTER FOR NUCLEAR RESEARCH: CERN.
GENEVA
CERN
CMS
LHC
2
100M UNDERGROUND VAST CATHEDRAL-SIZED CAVERNS HOUSE FOUR GIGANTIC PARTICLE DETECTORS FOR THE WORLD'S BIGGEST SCIENTIFIC TOOL: A MASSIVE PARTICLE ACCELERATOR, 27 KM AROUND, THE LHC: LARGE HADRON COLLIDER.
3
THE PROTONS IN THE LHC ARE ACCELERATED TO 99.9998% OF THE SPEED OF LIGHT IN TWO BEAM LINES, MOVING IN OPPOSITE DIRECTIONS.
4
THOUSANDS OF POWERFUL SUPERCONDUCTING MAGNETS STEER THE PROTON BEAMS AROUND THE HUGE RING AND THEN FOCUS THEM TO LESS THAN THE WIDTH OF A HUMAN HAIR... READY TO CRASH AGAINST EACH OTHER. THESE SUPERCONDUCTING MAGNETS RUN AT -271°C: EVEN COLDER THAN OUTER SPACE. THE LHC IS THE BIGGEST CRYOGENIC SYSTEM EVER MADE.
5
THE COLLISION GENERATES SO MUCH ENERGY THAT PARTICLES EXTINCT SINCE THE BIG BANG (14 BILLION YEARS AGO), LIKE THE HIGGS PARTICLE, REAPPEAR BRIEFLY.
6
THESE ANCESTRAL PARTICLES SURVIVE FOR ONLY THE TINIEST FRACTION OF A SECOND BEFORE THEY DISINTEGRATE INTO CASCADES OF MORE FAMILIAR PARTICLES. SCIENTISTS NEED ULTRAFAST, ULTRAPRECISE DETECTORS, AND STATE-OF-THE-ART CUSTOM MADE ELECTRONICS TO SEE THE CASCADE...THEY NEED CMS: THE COMPACT MUON SOLENOID.
7
CMS IS LIKE A 12,500 TONNE DIGITAL CAMERA WITH 100 MILLION PIXELS THAT TAKES A 3D PICTURE OF THE LHC COLLISIONS 40 MILLION TIMES PER SECOND!
8
LOOKING AT A SLICE THROUGH THE DETECTOR.
PHOTON
MUON
ELECTRON
PION
9
CMS HAS BEEN ASSEMBLED IN LAYERS FROM MILLIONS OF PARTS WITH WATCH-MAKING PRECISION. EACH LAYER OF DETECTORS HAS A SPECIAL JOB TO DO: TO IDENTIFY AND MEASURE AS MANY PARTICLES AS POSSIBLE.
10
A TOTAL OF 1 TERABYTE OF DATA IS GENERATED IN CMS EVERY SECOND, EQUIVALENT IN VOLUME TO STORING THE NAMES AND ADDRESSES OF EVERY LIVING HUMAN BEING.
11
TO CRUNCH AND SWALLOW ALL THIS INFORMATION IS JUST NOT POSSIBLE. POWERFUL ELECTRONICS FILTERS THE DATA SIGNALS SO THAT, EVERY SECOND, ONLY THE RESULTS FROM THE 100 MOST INTERESTING COLLISIONS ARE STORED.
12
A HUGE COMPUTING NETWORK, THE GRID, SENDS THE CMS DATA OUT ALL OVER THE WORLD...
13
A PHYSICS STUDENT SAT AT THEIR PC ANYWHERE IN THE WORLD CAN HARNESS THE POWER OF THOUSANDS OF PCS OVER THE GRID...
14
TO SEARCH FOR RARE COLLISIONS AND NEW PHYSICS...
© CMS/CERN - PAILHAREY/VIGNAUX - 11/06

ATLAS *(A Toroidal LHC ApparatuS)*

~7'000 t

main assembly in cavern

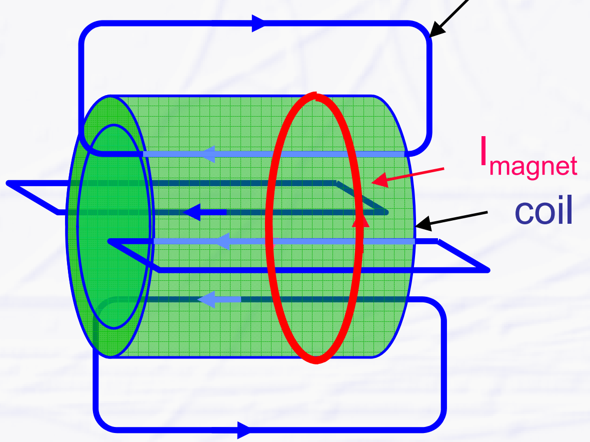


22 m

44 m

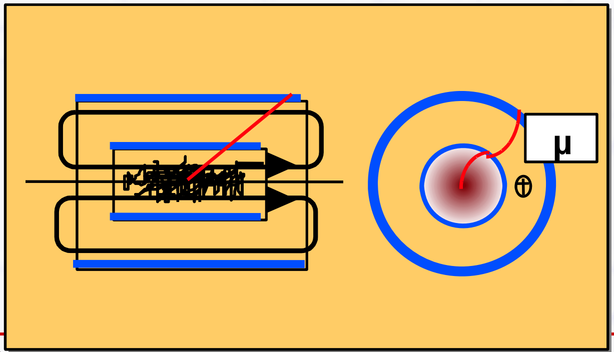
Magnet Configurations of LHC Experiments

Solenoid

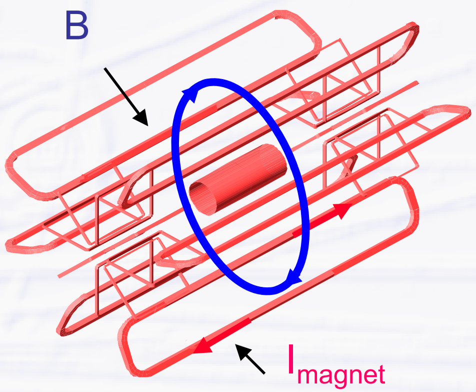


+ strong homogeneous field in coil
- big iron return-yoke necessary
- limited size (cost)
- coil thickness (scattering)

CMS, ALICE, LEP detectors

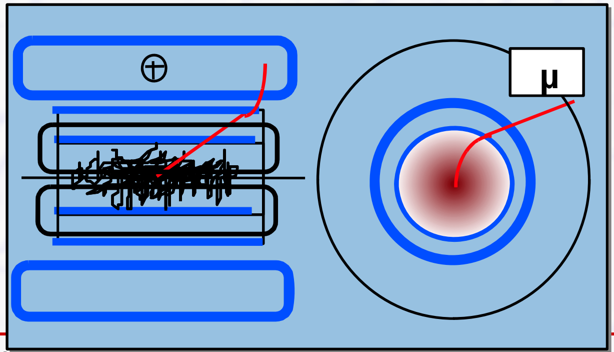


(air-core) Toroid

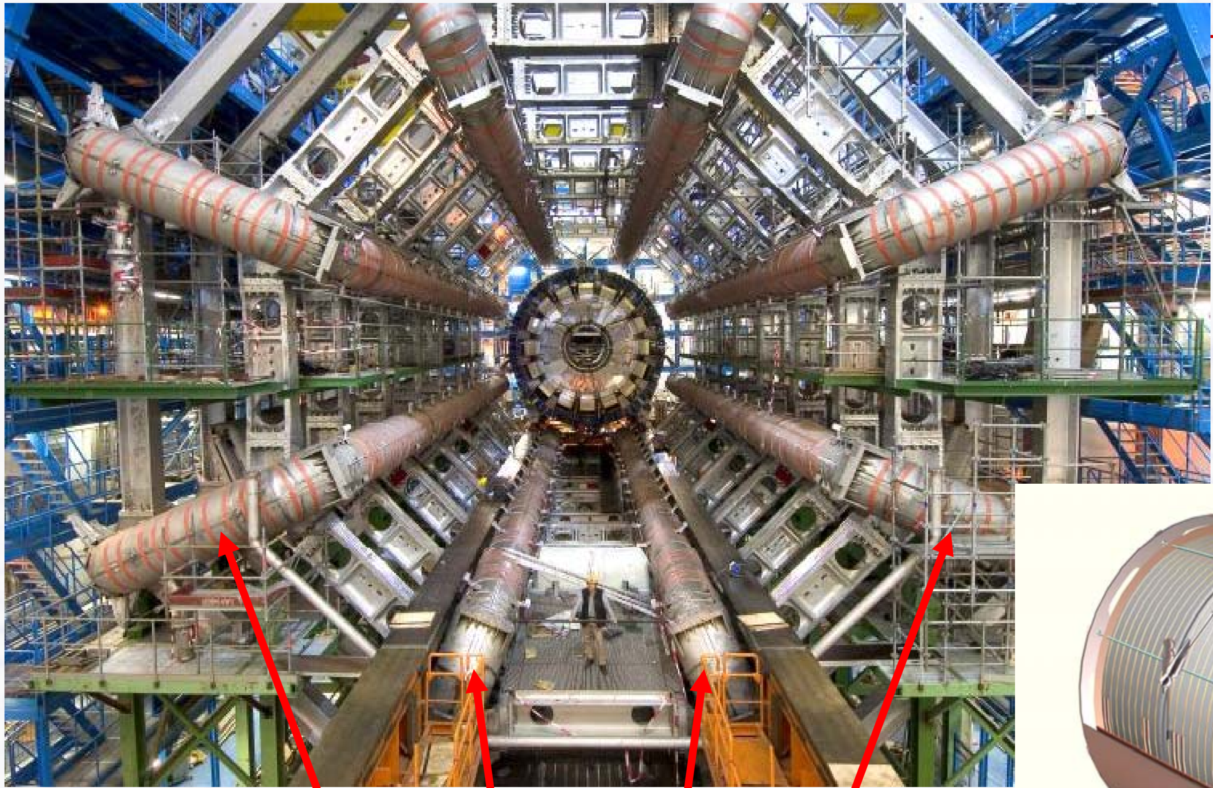


+ big Volume
+ „air core“, no iron, little material
- additional solenoid for ID necessary
-- inhomogeneous field
- complex structure

ATLAS



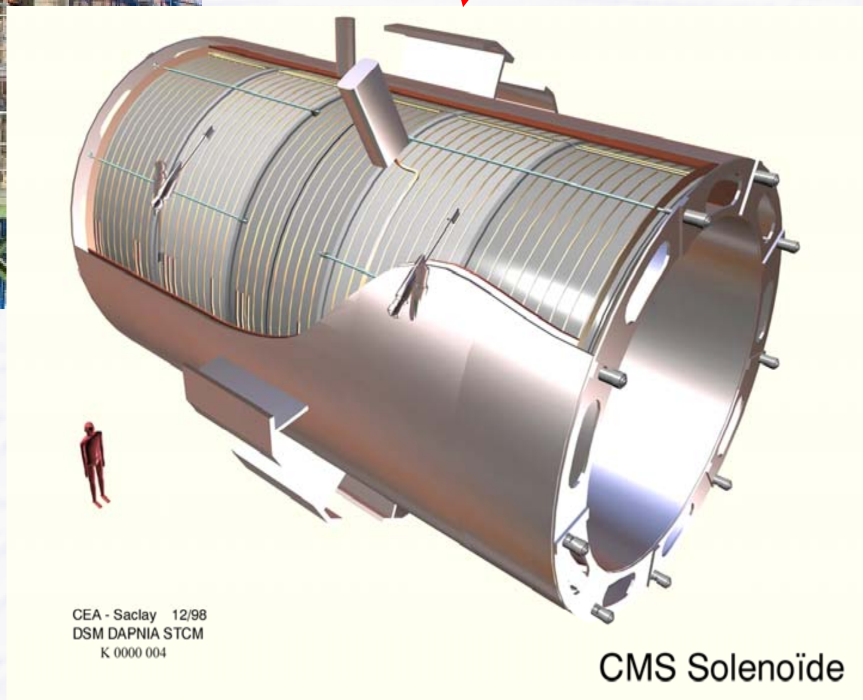
ATLAS & CMS Magnet Coils



ATLAS Toroid Coils

Fall 2005

CMS Solenoid (5 segments)

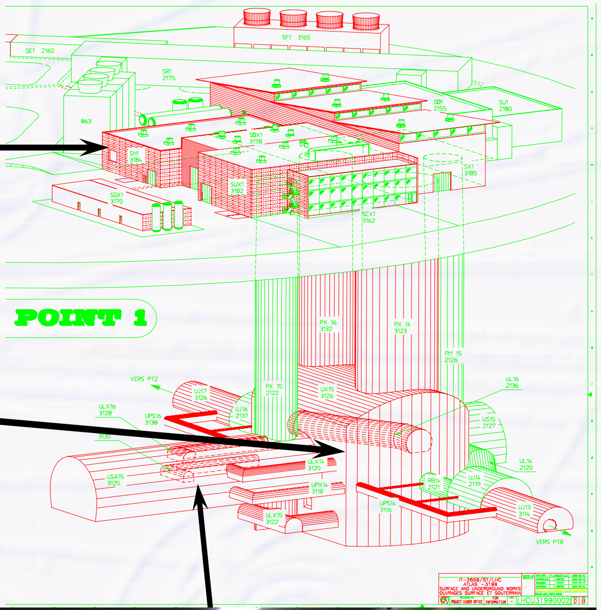


Infrastructure

- experiments are not only detectors
- you need
  - possibilities to control the detectors
  - possibilities to take the data out and record it
  - possibilities to analyze the recorded data
  - …

ATLAS: Infrastructure installation

Cryogenic plant complete & commissioned



Caverns delivered & basic infrastructure installed in 2003

ATLAS Trigger, DAQ & Control

- The characteristic patterns are examined
- only one out of 5 000 000 is kept
- the rest are discarded

CMS Trigger & DAQ

Every 25 ns

40 MHz
COLLISION RATE

100 kHz
LEVEL-1 TRIGGER

DAQ accepts Level-1 rate of 75/100kHz

1 Terabit/s
(50000 DATA CHANNELS)

Level-1 rate of 2kHz

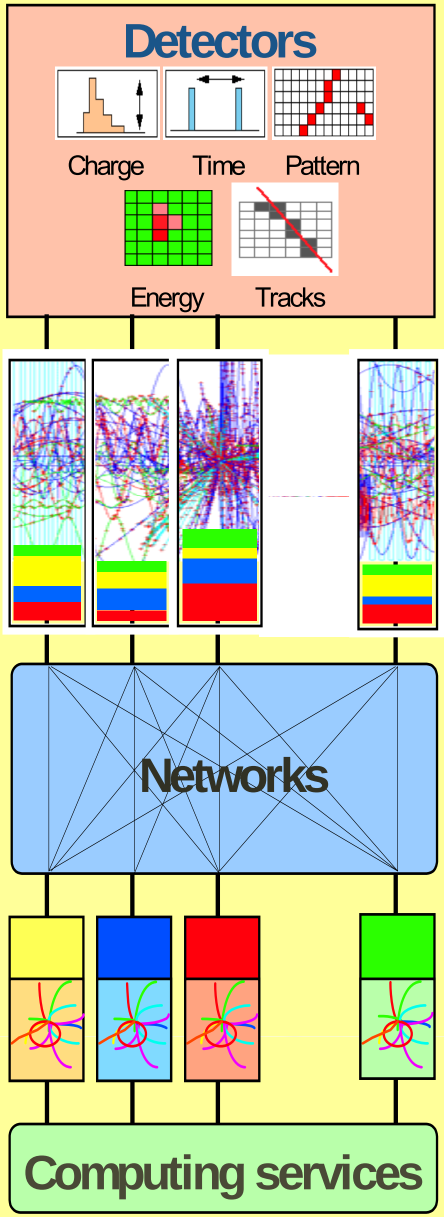
500 Gigabit/s

HLT (High Level Trigger) developed for ~100-200Hz

- Filtering level 1000

~2000 CPUs

Gigabit/s SERVICE LAN



16 Million channels
3 Gigacell buffers

1 Megabyte EVENT DATA

120 GB/s

200 Gigabyte BUFFERS
500 Readout memories

EVENT BUILDER. A large switching network (512+512 ports) with a total throughput of approximately 500 Gbit/s forms the interconnection between the sources (Readout Dual Port Memory) and the destinations (switch to Farm Interface). The Event Manager collects the status and request of event filters and distributes event building commands (read/clear) to RDPMs

~2+4 GB/s

5 TeraIPS

EVENT FILTER. It consists of a set of high performance commercial processors organized into many farms convenient for on-line and off-line applications. The farm architecture is such that a single CPU processes one event

~ 300 MB/s

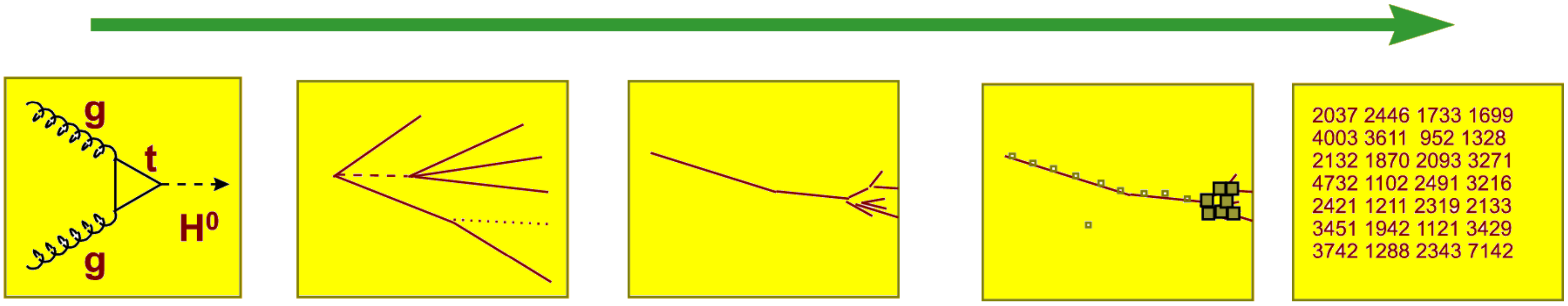
Petabyte ARCHIVE

Trigger & DAQ

large effort in the last years to validate the DAQ architecture using prototype modules and emulators

DAQ system installation at experiment points

From Physics to Raw Data



Basic physics

Fragmentation, Decay

Interaction with detector material
Multiple scattering, interactions

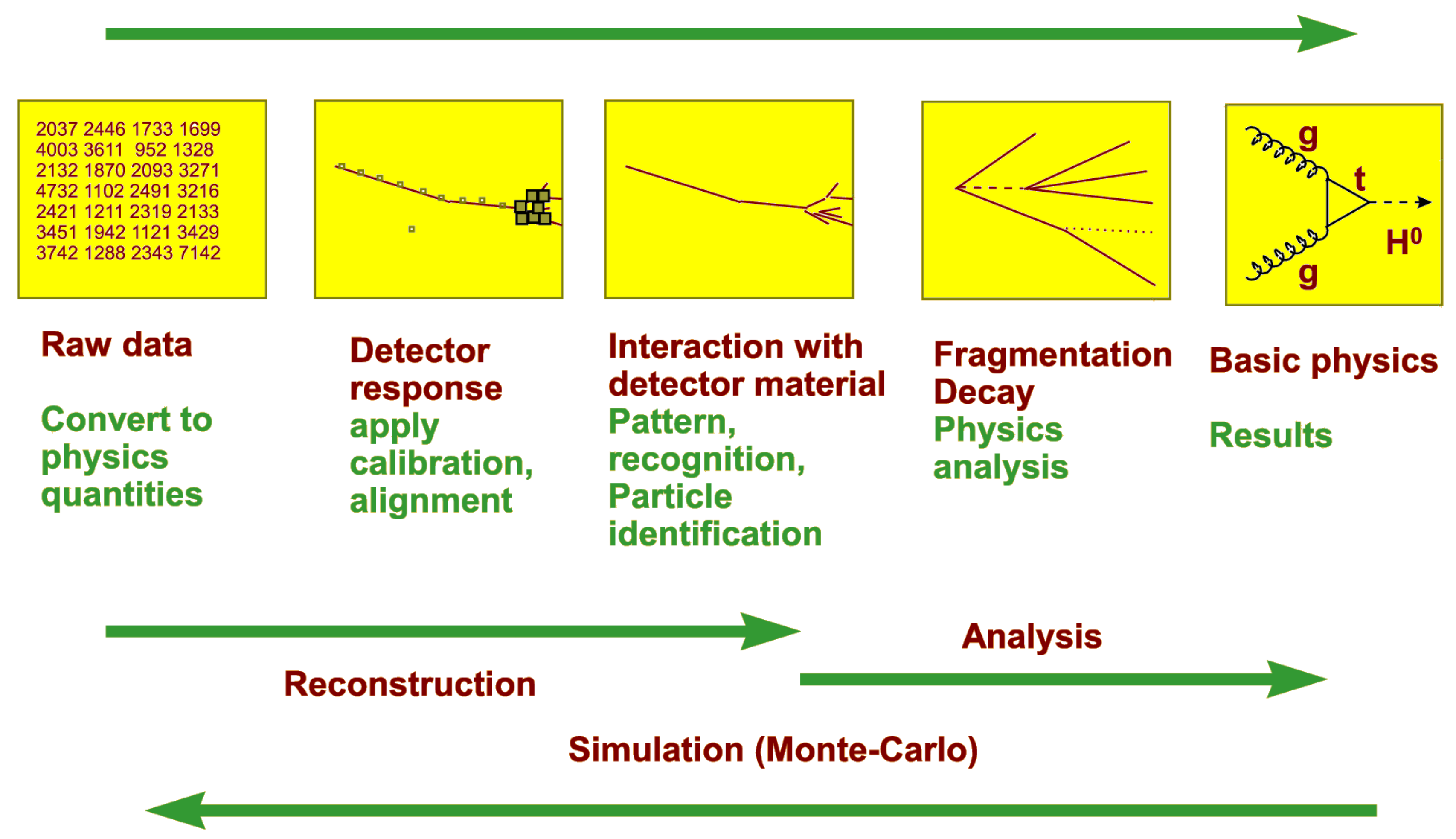
Detector response
Noise, pile-up, cross-talk, inefficiency, ambiguity, resolution, response function, alignment

Raw data

Read-out addresses, ADC, TDC values, Bit patterns

- Really recorded raw data for ATLAS/CMS ~400 MB/s
  - mainly electronics numbers
    - e.g. number of detector element where ADC (Analog-to-Digital converter) saw signal with x counts...

From Physics to Raw Data



- We need to go from raw data back to physics
  - reconstruction + analysis of the event(s)

That was all :)) Questions?

These lectures in DETECTORS are based upon (and from time to time directly lifted from):

John D. Jackson	*Classical Electrodynamics*
Dan Green	*The Physics of Particle Detectors*
Fabio Sauli	*Principles of Operation of Multiwire Proportional and Drift Chambers*
Richard Wigmans	*Calorimetry*
Christian Joram	*Particle Detectors* CERN Summer Student lectures 2003
C. Joram et al.	*Particle detectors : principles and techniques* Academic Training Lectures , CERN 2005
H.P. Wellisch	*Physics of shower simulation at LHC.* Academic Training Lectures, CERN 2004
R. Gilmore and G. P. Heath	Particle Interactions University of Bristol http://wwwteach.phy.bris.ac.uk/Level3/phys30800/CourseMaterials/ http://wwwteach.phy.bris.ac.uk/Level3/phys30800/CourseMaterials/p308_slides_part2.ppt
Sascha Schmeling	HST Program CERN 2003-2006
Michael Hauschild	Detectors: Doktoranden Herbstschule Maria Laach
Frank Hartmann	Detectoren: German HST CERN 2007

A good many plots and pictures from

http://pdg.web.cern.ch/pdg/

http://www.britannica.com/

Other references are given whenever appropriate.

Help from collaborators is gratefully acknowledged.

Disclaimer

The data presented is believed to be correct, but is not guaranteed to be so.

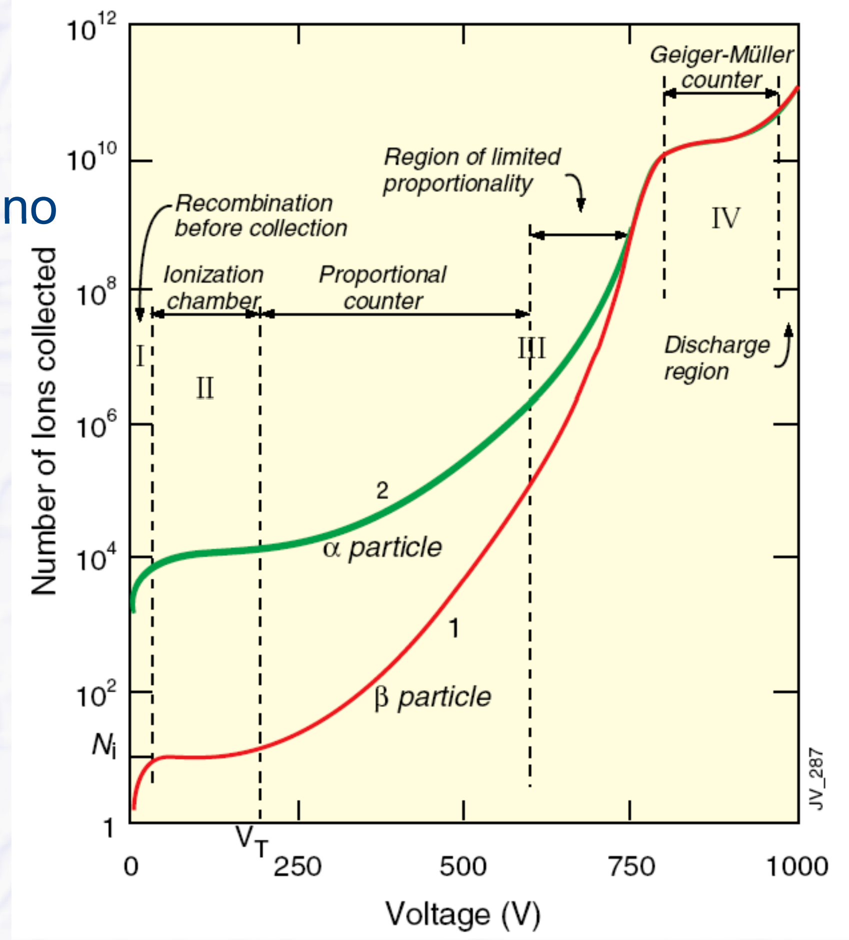
ATLAS/CMS in detail

	ATLAS	CMS
Tracker or Inner Detector	Silicon pixels, Silicon strips, Transition Radiation Tracker, 2 T magnetic field (small solenoid)	Silicon pixels, Silicon strips, 4 T magnetic field (large solenoid)
Electromagnetic calorimeter	Lead plates as absorbers with liquid argon as the active medium	Lead tungstate ($PbWO_4$) crystals both absorb and respond by scintillation
Hadronic calorimeter	Iron absorber with plastic scintillating tiles as detectors in central region, copper and tungsten absorber with liquid argon in forward regions.	Stainless steel and copper absorber with plastic scintillating tiles as detectors
Muon detector	Large air-core toroid magnets with muon chamber form outer shell of the whole ATLAS	Muons measured already in the central field, further muon chambers inserted in the magnet return yoke

Wire Chambers – Operation Modes

High Voltage

- No collection (I)
  - ions recombine before collected
- Ionization Mode (II)
  - ionization charge fully collected, no charge multiplication, G~1
- Proportional Mode (IIIa)
  - gas multiplication, signal on wire proportional to original ionization
  - G~10^4
- Limited Proportional Mode (IIIb)
  - secondary avalances created by photoemission from primary avalances, signal no longer proportional to ionization,G~10^{10}
- Geiger Mode (IV)
  - massive photoemission + discharge, stopped by HV breakdown



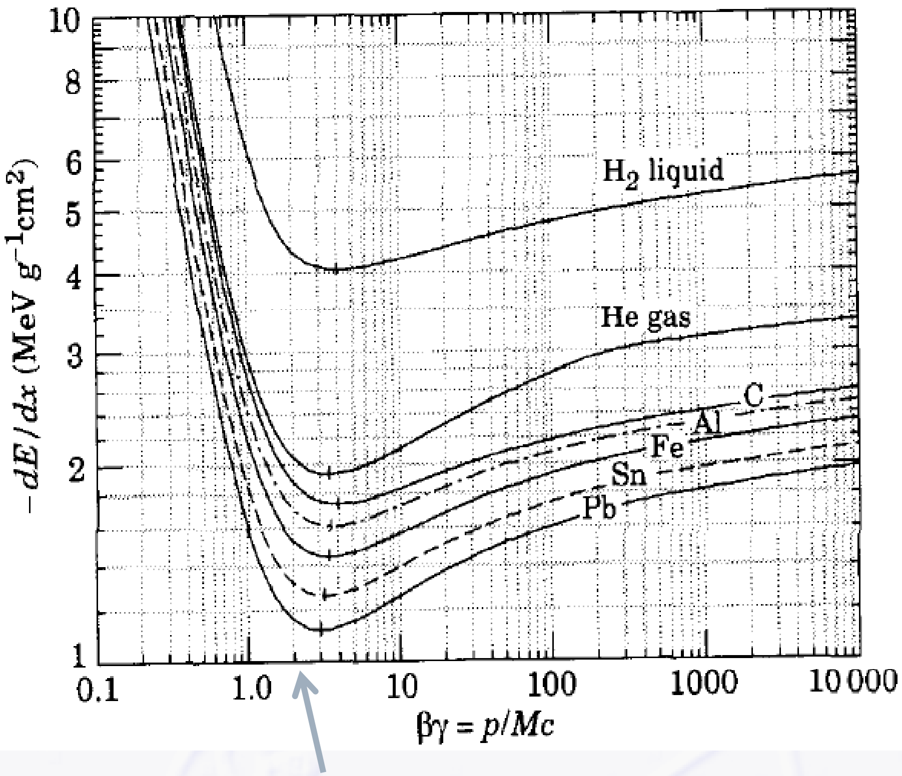
Ionisation: Bethe-Bloch-Formel

Colombwechselwirkung

Energieverlust der Teilchen pro Wegstrecke

➔ Ionisation (Ionen, Elektron-Lochpaare können nachgewiesen werden)

$$-\left(\frac{dE}{dx}\right)_{coll} = 2\pi N_A r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2} \cdot \left[\ln\left(\frac{2m_e c^2 \gamma^2 \beta^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right]$$



z … Ladung des einfallenden Teilchens

Z, A … Ordnungszahl und Massenzahl des Targets

ρ … Targetdichte,

N_A … Avogadrozahl

I … mittleres Ionisationspotential (Materialkonstante des Targets)

W_{max} ... max. Energieübertrag in einer Einzelkollision

δ … Dichtekorrektur (Polarisationseffekt, δ ≈ 2.lnγ + K)

C … Schalenkorrektur (wichtig für kleine Projektilgeschwindigkeiten)

β: Geschwindigkeit/c

$$\beta = \frac{v}{c}, \quad \gamma = \frac{1}{\sqrt{1-\beta^2}},$$

$$r_e = \frac{1}{4\pi\varepsilon_0} \cdot \frac{e^2}{m_e c^2} \text{ ... klassischer } e^- - \text{Radius}$$

Minimal ionisierendes Teilchen MIP