experimental methods and detectors for present day particle physics

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Introduction

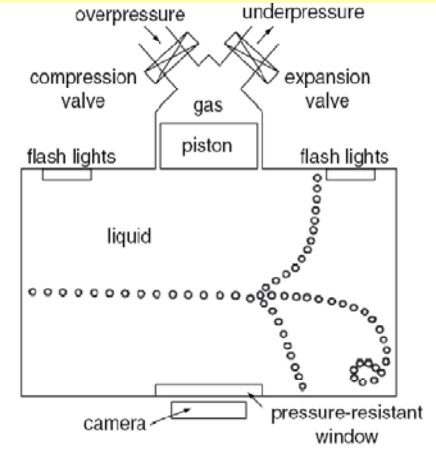
The development of particle detectors practically starts with the discovery of radioactivity by Henri Becquerel in the year 1896. He noticed that the radiation emanating from uranium salts could blacken photosensitive paper. Almost at the same time X rays, which originated from materials after the bombardment by energetic electrons, were discovered by Wilhelm Conrad R¨ontgen.

The scope of the detection techniques in particle detectors is very wide, depending on the aim of the measurement. Each physics phenomenon can be used as the basis for a particle detector. Elementary particles have to be identified with various techniques, and relevant quantities like time, energy, spatial coordinates have to be measured. Particle physics requires extremely high accuracies for these quantities using multi-purpose installations as well as dedicated experimental set-ups.

This days particle detectors deal with the particles in an extremely wide energy range - from very low energies (micro-electron volts) to the highest of energies observed in cosmic rays.

Historical remarks

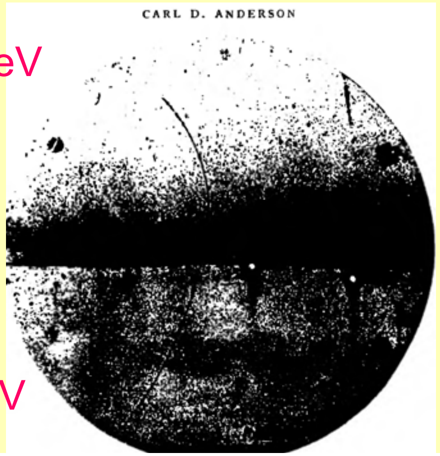
Cloud (Wilson) chamber ~ 1911



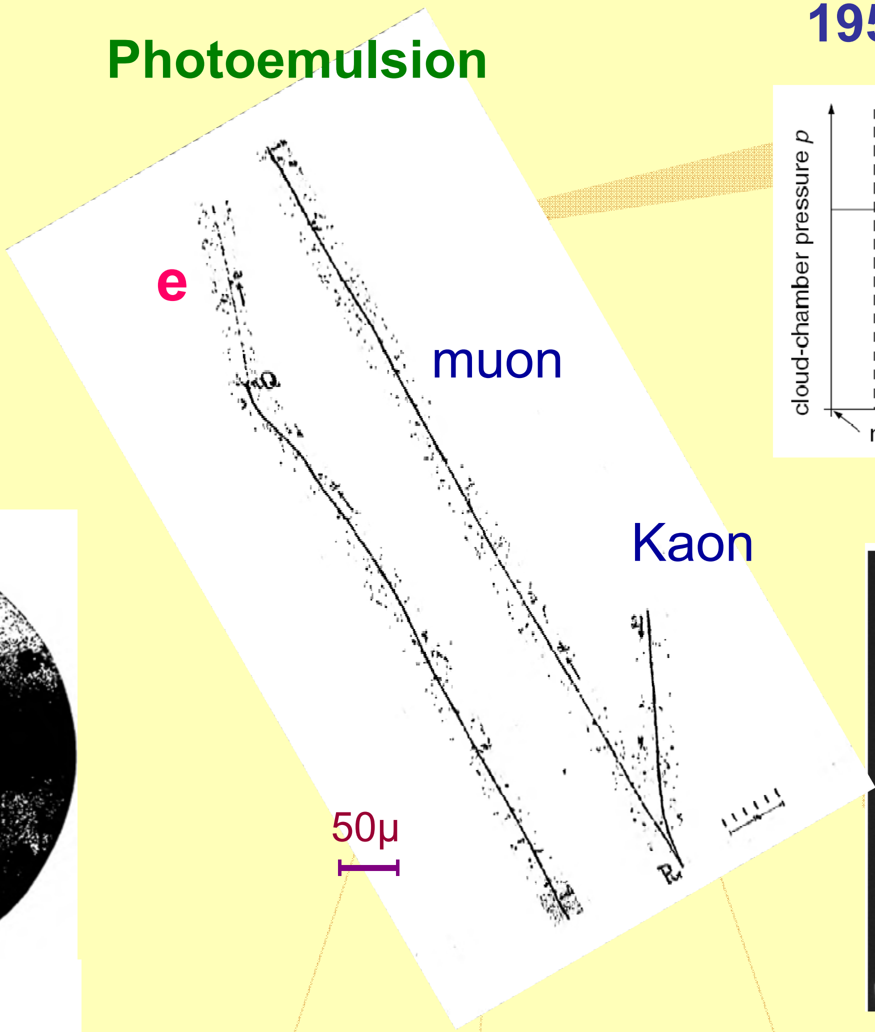
e^+, 63 MeV

Pb, 6 mm

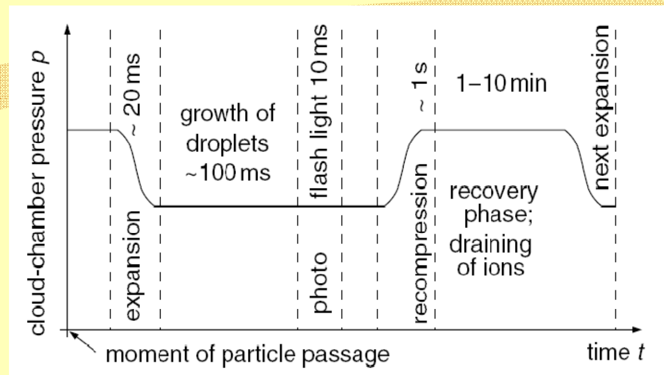
e^+, 23 MeV

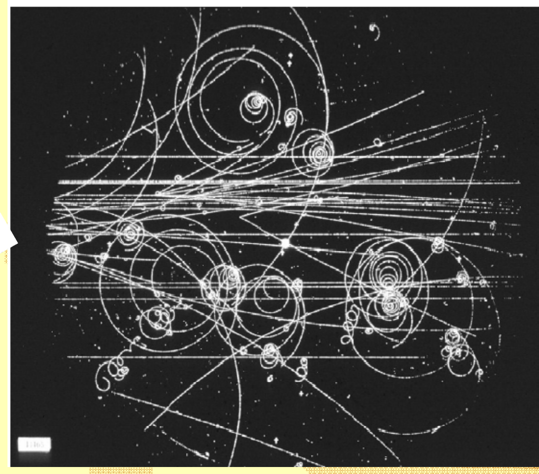


Photoemulsion



Bubble chamber ~ 1952,1953 (D.A.Glaser)





Typical resolutions and deadtimes of common detectors (PDG)

Detector Type	Accuracy (rms)	Resolution Time	Dead Time
Bubble chamber	10–150 μm	1 ms	50 ms[a]
Streamer chamber	300 μm	2μs	100 ms
Proportional chamber	50–300 μm[b,c,d]	2 ns	200 ns
Drift chamber	50–300 μm	2ns[e]	100 ns
Scintillator	—	100 ps/n[f]	10 ns
Emulsion	1 μm	—	—
Liquid Argon Drift	175–450 μm	200 ns	2 μs
Gas Micro Strip	30–40 μm	< 10 ns	—
Resistive Plate chamber	10 μm	1–2 ns	—
Silicon strip	pitch/(3 to 7)[g]	[h]	[h]
Silicon pixel	2 μm[i]	[h]	[h]

a Multiple pulsing time.
b 300 μm is for 1 mm pitch.
c Delay line cathode readout can give ±150 μm parallel to anode wire.
d wirespacing/√12.
e For two chambers.
f *n* = index of refraction.

g The highest resolution ("7") is obtained for small-pitch detectors (25 μm) with pulse-height-weighted center finding.
July 24, 2008 18:04
h Limited by the readout electronics [10]. (Time resolution of ≤ 25 ns is planned for the ATLAS SCT.)
i Analog readout of 34 μm pitch, monolithic pixel detectors

Main principles:

- ionisation - ~ 90%(?): charged – initial; neutral - secondary
- cherenkov
- transition radiation
- phonons (heat), Cooper pairs, etc.

What do we want to know about each particle?

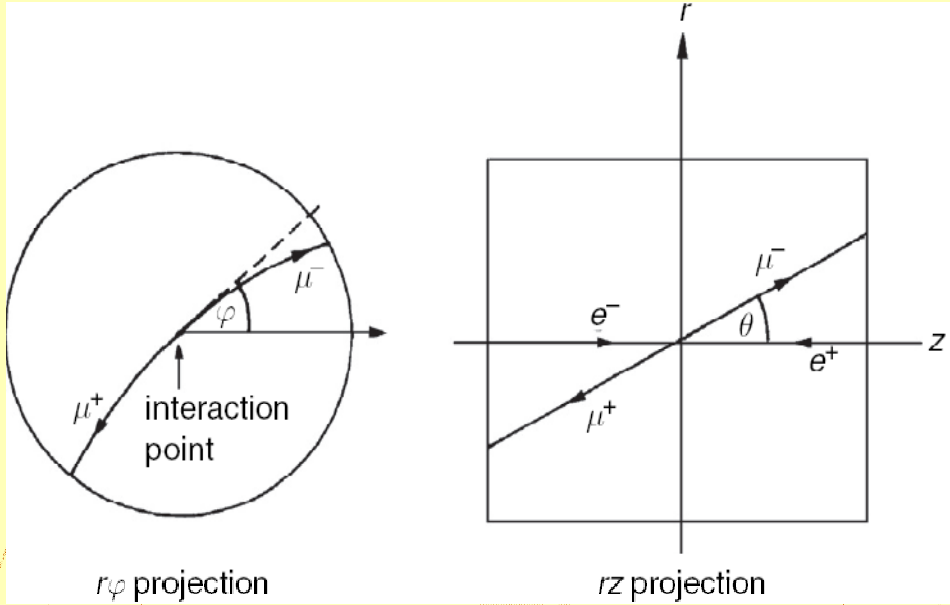
a point of origin (vertex)	**tracking**
momentum (absolute value and angles)	**tracking**
energy	**calorimetry**
the particle species	**particle identification**

charged particles momentum mesurement

main idea – curvature in the magnetic field

main device – drift chambers (however – CMS tracker is fully Si)

angles – usually as a component of the momentum measurements



chamber precision

$$\frac{\sigma(p)}{p_t} = \frac{\sigma_{r\varphi}[m]}{0.3B[T](L[m])^2}\sqrt{\frac{720}{N+4}} \cdot p_t[GeV/c]$$

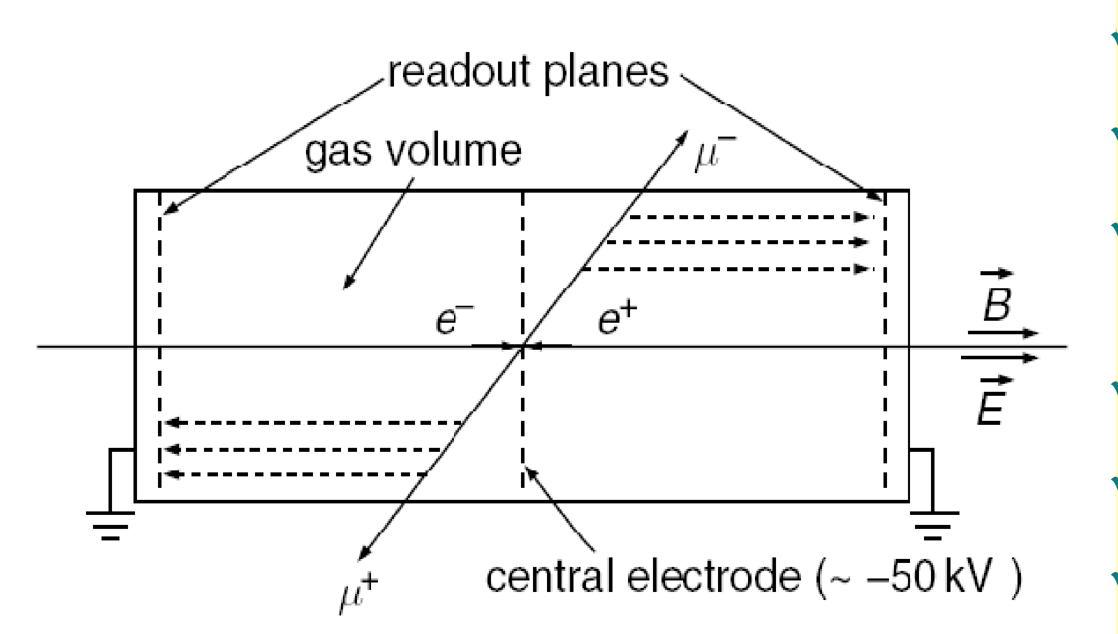
multiple scattering

$$\frac{\sigma(p)}{p_t} = 0.045 \cdot \frac{1}{\beta} \frac{1}{B[T]\sqrt{L[m]}X_0[m]}$$

Time progection chamber (TPC)

- The TPC is a gas-filled cylindrical chamber with one or two endplates
- Particle detector invented by D. R. Nygren in 1974

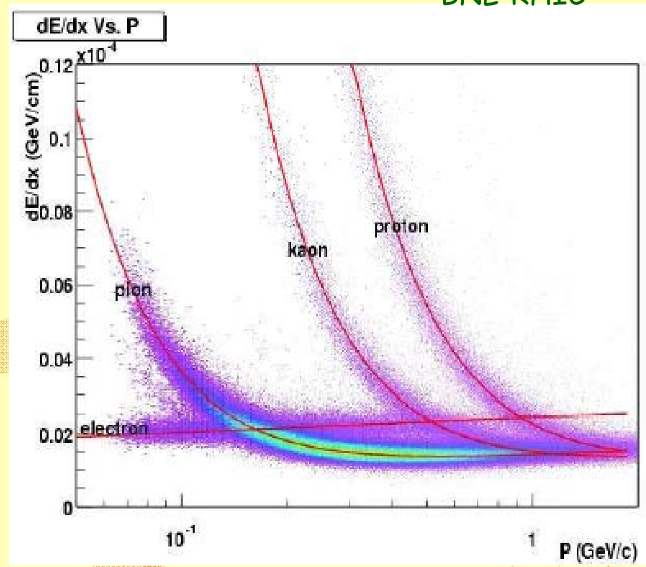
- **TPCs have been operated often as the main tracker in a wide range of physics experiments:**
  - **particle physics**
  - **heavy ion collision**
  - **underground experiments**



- **Ingredients:**
  - ✓**gas system**
  - ✓**field cage for the E field**
  - ✓**magnet for the B field**
  - ✓**amplification system at the anode**
  - ✓**gating grid to suppress the ion feedback**
  - ✓**laser calibration system**
  - ✓**readout electronics**
  - ✓**trigger**

Characteristics of a TPC

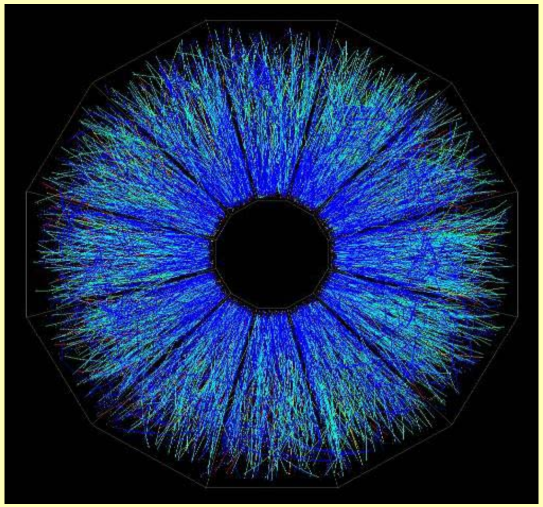
STAR ion TPC
BNL-RHIC

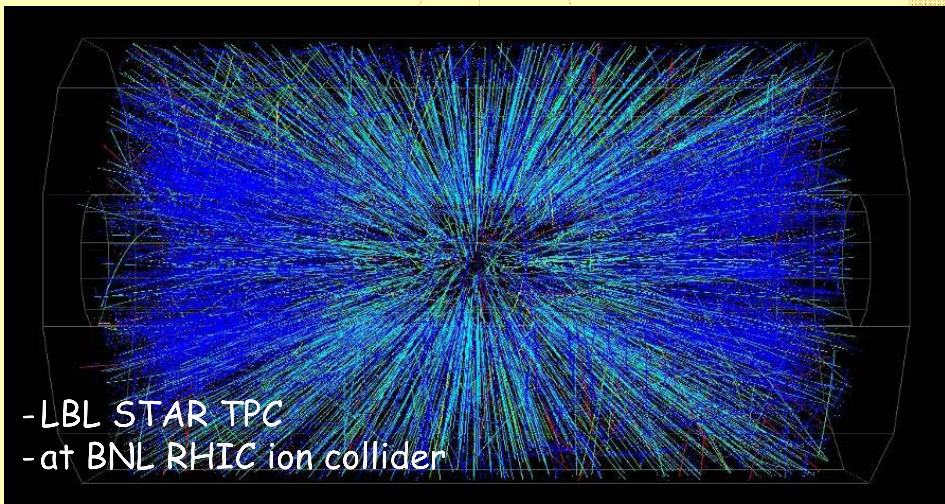


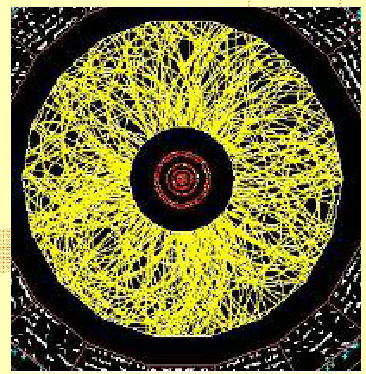
- Track point recorded in 3-D

  (2-D channels in x-y) x (1-D channel in z = v_{drift} x t_{drift})
- Low occupancy → large track densities possible
- Particle identification by dE/dx

  long ionization track, segmented in 100-200 measurements







ALICE simulation events

Vertex Detectors

- Resolution at IP for two layers with resolution σ

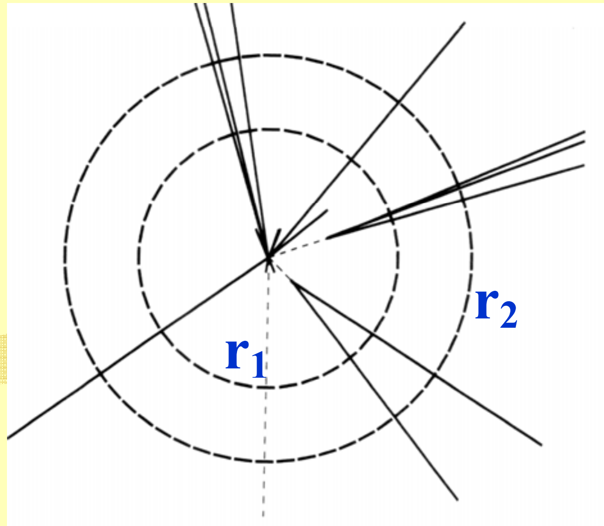
$$\sigma_v \approx \sigma_x \sqrt{1/(1-r_1/r_2)^2 + 1/(r_2/r_1 - 1)^2}$$

- → r_1/r_2 should be as small as possible
  - for σ=10 μm, r_1/r_2=0.5, σ_b = 20 μm
- multiple scattering → r_2 can't be large
  - Beampipe ϕ 5 cm, thickness 1 mm Be = 0.3% X_0
  - → 28 μm at IP for P = 1 GeV

Two conclusions

First layer as close as possible to Interaction Point

As thin as possible



Using silicon diode as s detector

1951: first observation of signals in reversely biased p-n junction from a's

Development for tracking stimulated by need to measure short-lived charm/beauty quarks and tau lepton in '70

1980, J.Kemmer: first proposed to use planar process developed in industry to produce strip silicon detectors

Fast, localized charge deposition → 3 micron intrinsic resolution

Planar process → dimensions precise to 1 micron, low cost

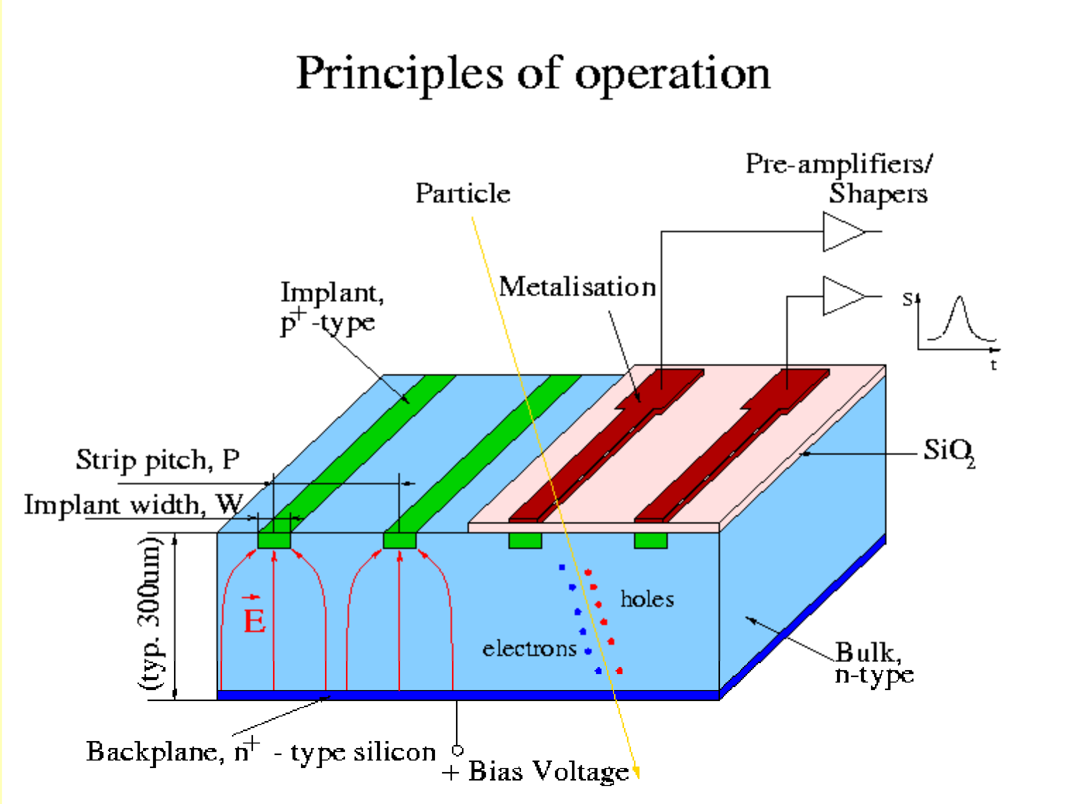
Strip Detectors

- Depleted p-n diodes
- Fast and efficient charge collection by drift in electric field
  - 4 fC in 300 micron of Si

  (100 e-h pair per 1 μm of Si)

- Each strip has capacitance to backplane and neighbours

- Noise is typically dominated by serial contributions → scales with detector capacitance



Strips vs Pixels

- Strip detectors
  - Large capacitance, 10 pF
  - Large signal, 24000 e
  - Large noise, 2000 e
- Well established area – dozens of small, large and huge trackers and vertex detectors in operation since ’90
- New development: strips in depth of sensor – 3D silicon strips

- Pixel detectors
  - Small capacitance
  - Extra low noise, 10-100 e
  - Could do with small signal
- Opens variety of interesting options

Motivation is to develop new pixel systems in the last years:

- ❖**Radiation hardness improvement**
- ❖**Decrease fabrication cost of pixel detector**
- ❖**Develop thinner pixel systems**
- ❖**New interconnect methods (3D, bonding and vias)**
- ❖**Easy fabrication of large area devices**

Linear Collider : Precise Thin Detectors

ILC physics demands excellent

Vertexing (b,c,t) and Tracking

Vertex detector characteristics

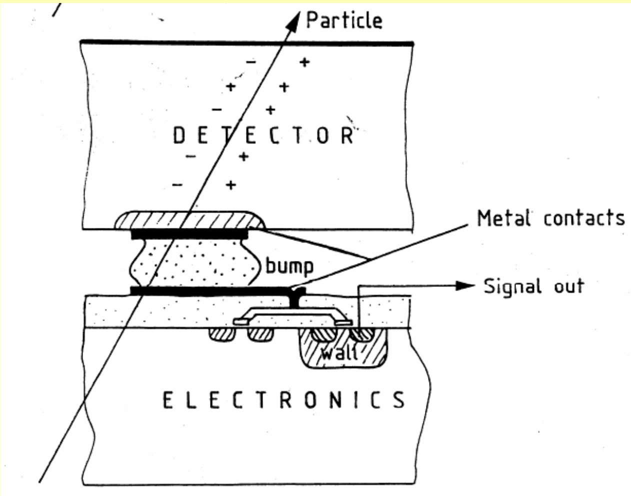
point resolution 3 μm

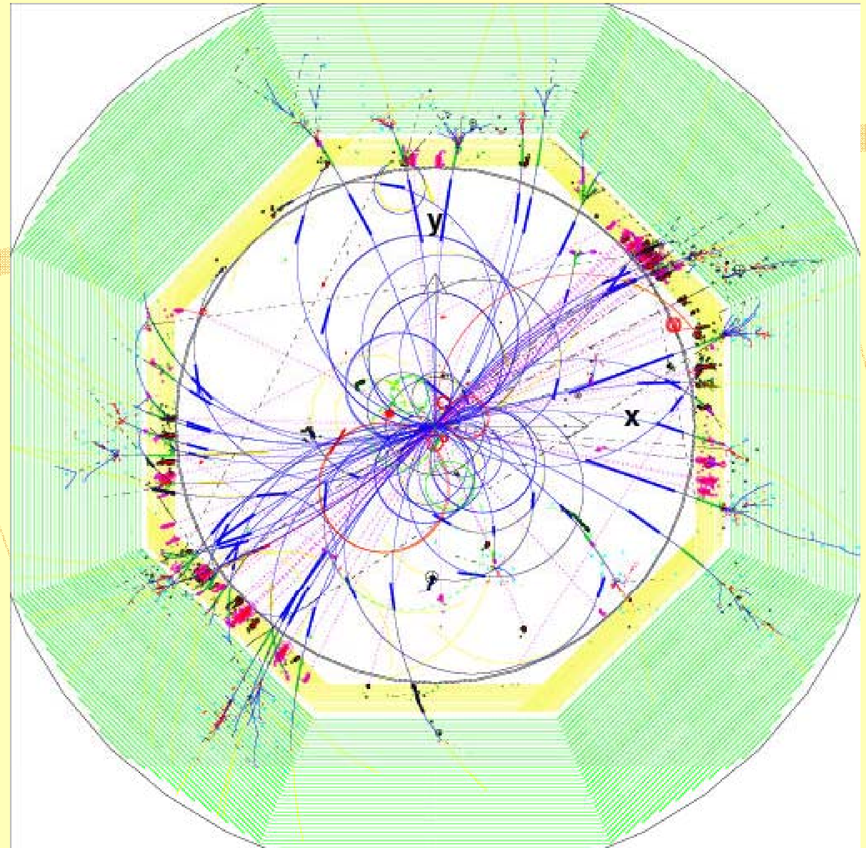
Thickness ~ 0.1 % X_0

5-6 layers

Inner radius ~ 1.5 cm

Hybrid pixel detector





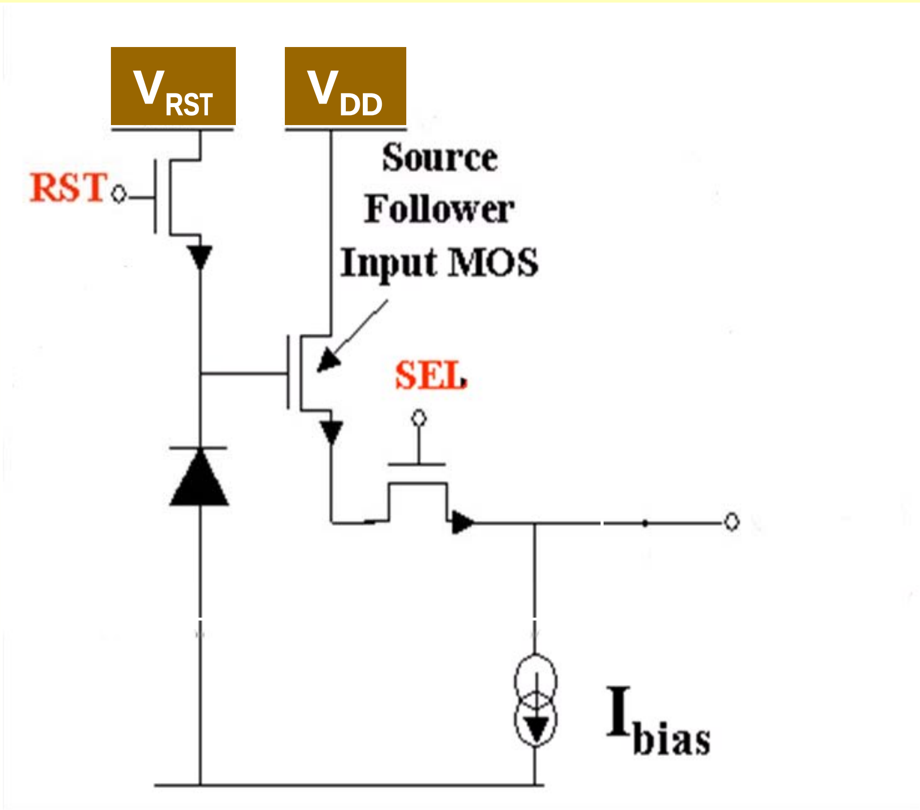
δ **(IP) < 5 μm ⊕ 10 μm/(p sin$^{3/2}$ θ)**

(best SLD 8 μm ⊕ 33 μm/(p sin$^{3/2}$ θ))

Active Pixel Sensors – Principle of Operation

Simplest design of APS: 3MOS pixel

- Photo diode
- Reset MOS (switch)
- Select MOS (switch)
- Source follower MOS



Functional description

- **Photo diode: n-well in the p-type epilayer of the silicon**
- **Charge collection:**
  - **e-h pairs from ionising radiation**
  - **Diffusion of charge in epi-layer**
  - **Collected by the diode by the built-in field in the pn-junction**
- **In-pixel circuitry built in p-well.**
- **Collected charge changes the potential on the source follower gate $V_G = Q_{PD}/C_{PD}$**
- **Gate voltage changes the transconductance**
- **Pixel selected by the select MOS**
- **Output voltage = V_{DD}-g_{ds}*I_{Bias}**

Active Pixel Sensor - Cartoon

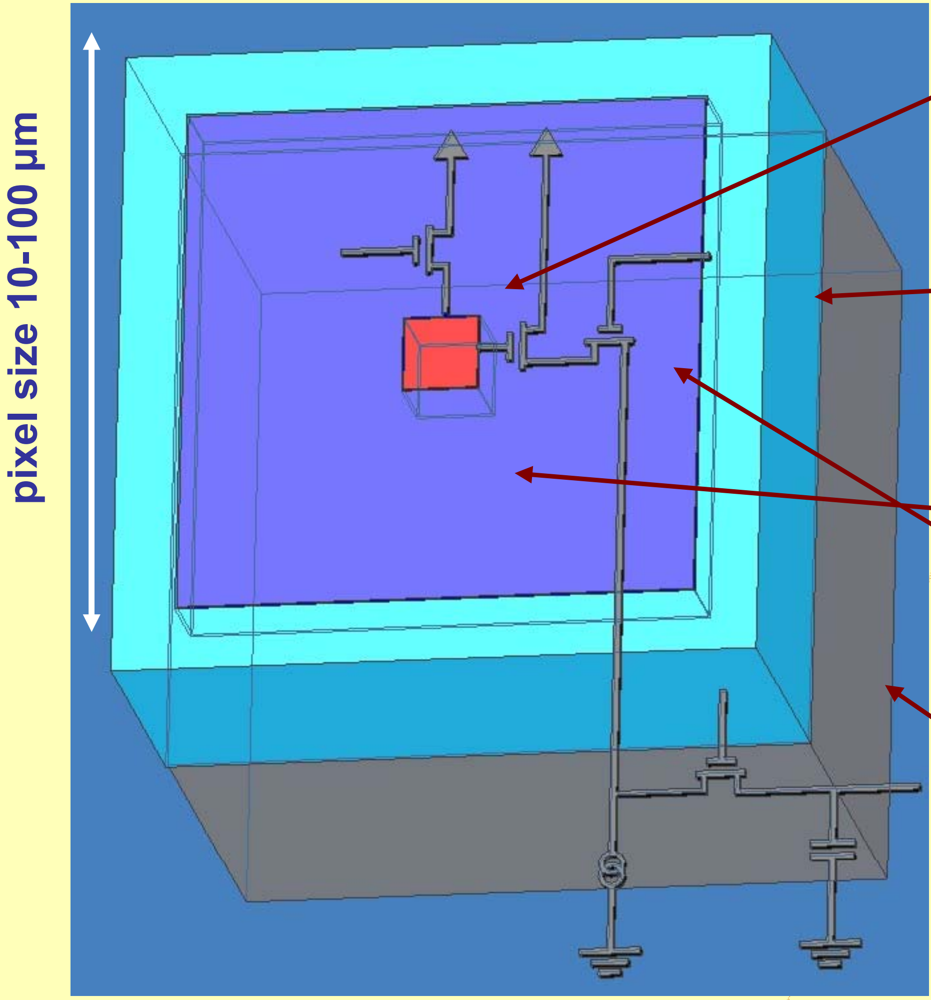


Photo diode (n-well)

- pn-junction with p-epi
- 1-several diodes of varying sizes in different designs.

Epi-layer (5-25 µm)

- Active volume of the device
- Expected MIP: 400-2000 e^-

p-well

- For in-pixel circuitry

In-pixel circuitry

- NMOS transistors

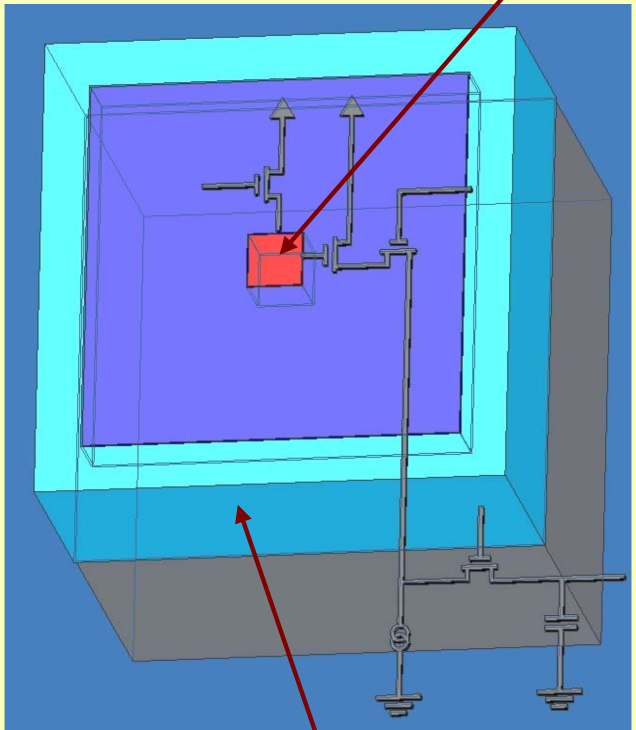
Silicon bulk (10-700 µm)

- Can be thinned as much as mechanical stability allows

* Typical values found in different designs

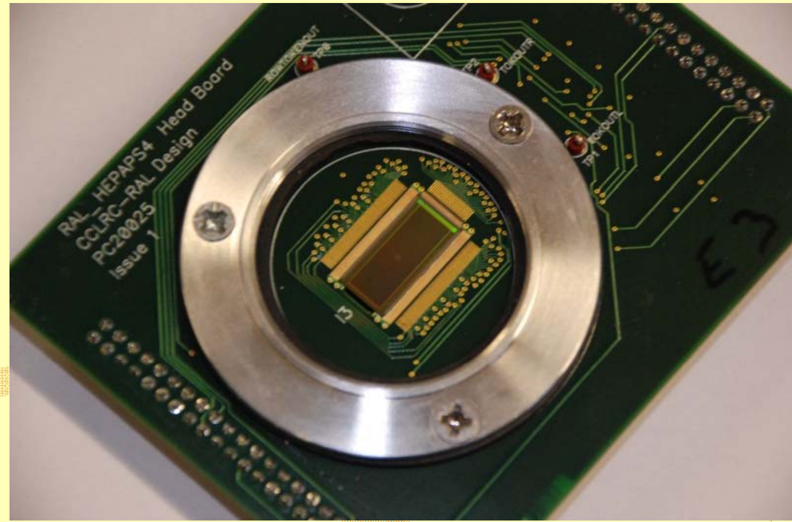
The HEPAPS4 – large area sensor for HEP applications

Photo diode (n-well)
pn-junction with p-epi



Epi-layer (5-25 μm)

- **Active volume of the device**



- Fourth in series designed at RAL
- Selected most promising design in HEPAPS2
- Basic parameters
  - 15x15 μm^2 pixel size
  - 384x1024 pixels
  - 20 μm epi-layer
  - 1 MIP = 1600 e^- spread over several pixels
- Signal – 10-15 μV/e; Noise – 40-45 e

Since the momenta of the neutral particle can not be measured directly, we have to determine its total energy and angular coordinates.

The most widely used method of the energy measurement is a calorimetric one that means the absorption of the incident particle and the detection of the responce.

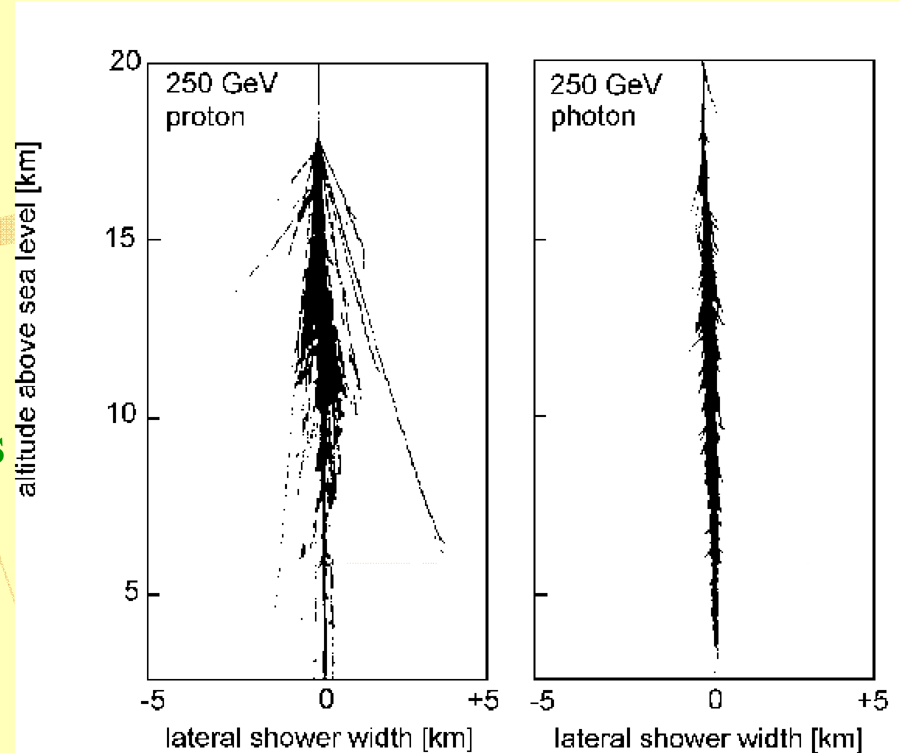
The main tasks of the calorimeters

- detection of gamma-quanta and other neutral particles with high efficiency
- Photon, electron and hadron energy measurements
- photon coordinates determination
- electron/hadron separation
- neutral trigger and total energy trigger signal generation

Main calorimeter principles

Calorimetric methods imply total absorption of the particle energy in a bulk of material followed by the measurement of the deposited energy. Let us take as an example a 10 GeV muon. Passing through material this particle loses its energy mainly by the ionization of atoms while other contributions are negligible. To absorb all the energy of the muon one needs about 9 m of iron or about 8 m of lead. It is quite a big bulk of material!

On the other hand, high energy photons, electrons and hadrons can interact with media producing secondary particles which leads to a shower development. Then the particle energy is deposited in the material much more efficiently. Thus calorimeters are most widely used in high energy physics to detect the electromagnetic and hadronic showers. Accordingly, such detector systems are referred to as "electromagnetic" and "hadron" calorimeters.



To absorb 95% of the initial energy of the 10 GeV photon only about 25 cm of Pb is needed.

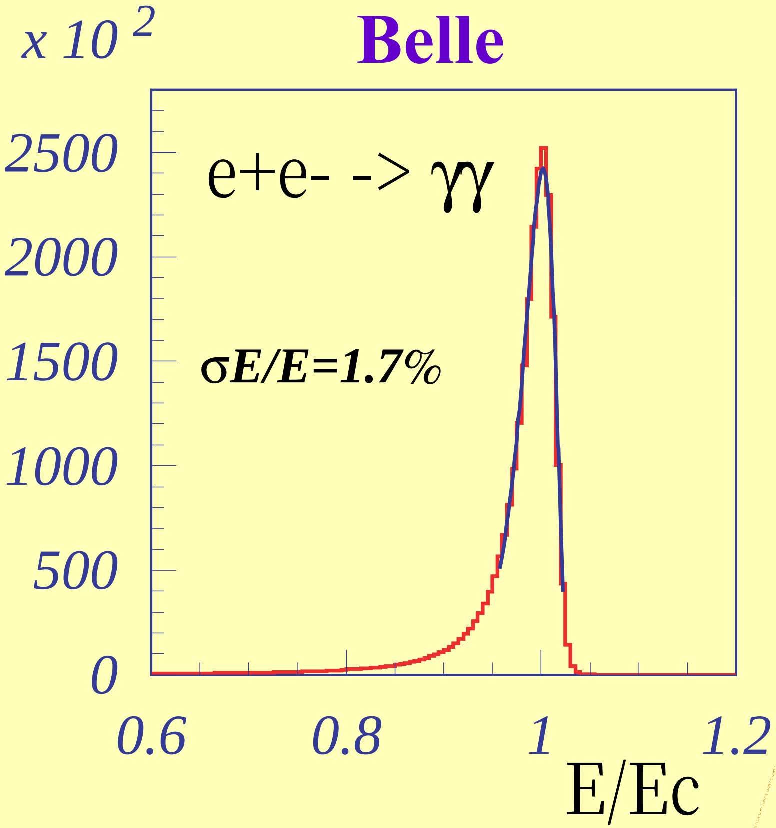
Homogenious calorimeters - all (almost) material are sensitive.

As a read out signal:

Scintillation light (crystals, liquid noble gases);

Cherenkov light (lead glass calorimeters);

Ionization (Lxe, LKr calorimeters)



Energy resolution vs energy is approximated as:

$$\frac{\sigma_E}{E} = \frac{\sigma_1}{\sqrt[4]{E}} \oplus \frac{\sigma_2}{\sqrt{E}} \oplus \frac{\sigma_3}{E} \oplus \sigma_0$$

σ_1 - rear leakage

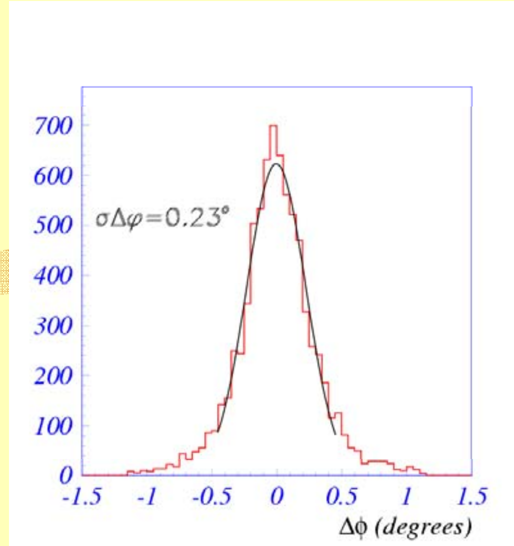
σ_2 - side leakage, back leakage photoelectron statistics

σ_3 - electronics noise, dark current noise pile-up noise

σ_0 - nonuniformity, calibration, rear leakage

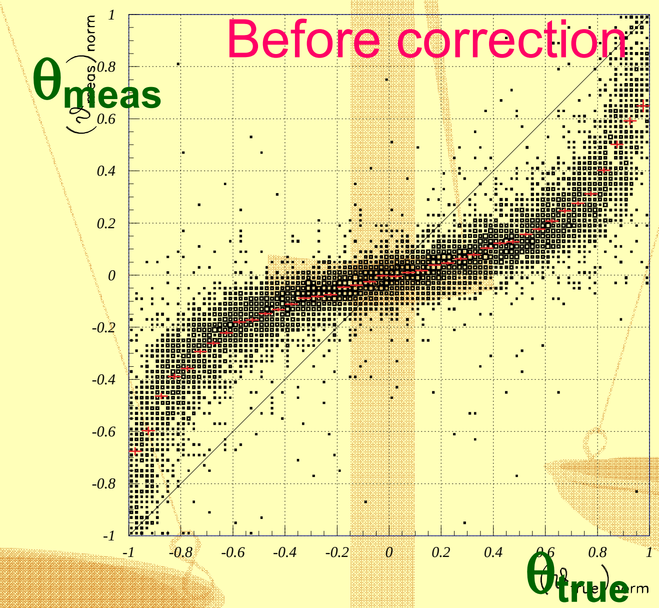
Calorimeter angular resolution

Photon angles (or coordinates) in the crystal calorimeters are measured usually as corrected center of gravity of the energy deposition:



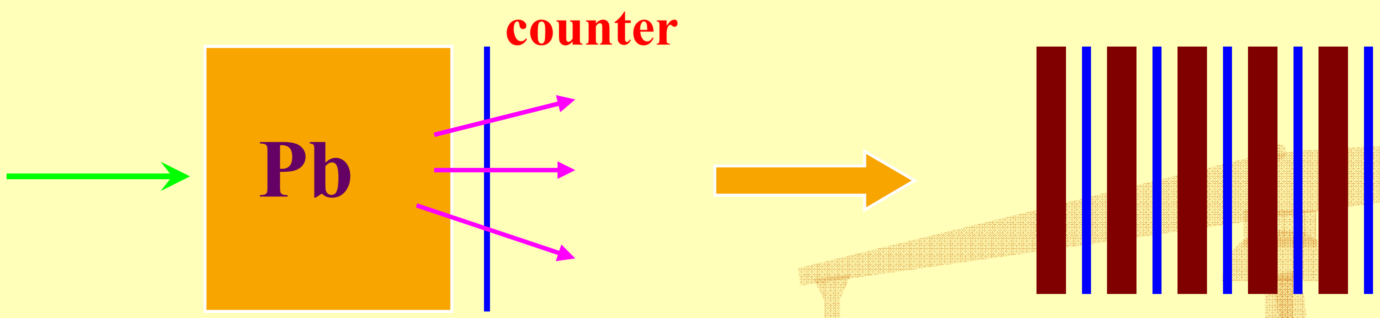
$$\theta_\gamma = \frac{\sum \theta_i E_i}{\sum E_i} F_\theta(\varphi, \theta, E) \qquad \varphi_\gamma = \frac{\sum \varphi_i E_i}{\sum E_i} F_\varphi(\varphi, \theta, E)$$

Correction functions (F) can be usually written as a function of one of the angles and energy.



However, ionization calorimeters with liquid noble gases provides 10 times better coordinate resolution!

Sampling calorimeters



There is a simpler and more economical way to measure the photon energy if the ultimate energy resolution is not crucial. Let us place a thin flat counter behind a thick layer of an absorber corresponding to the depth of the shower maximum. In this naive model the number of electrons crossing the counter is just 2/3 of $N_{max} = E_\gamma/E_{cr}$, because N_{max} is equally shared between electrons, positrons and photons. The amplitude of the counter signal is normally proportional to the number of charged particles. For a lead absorber E_{cr} = 7.4 MeV and E_γ = 1 GeV, Ne ~ 90. The relative fluctuation of this value is $\sigma(N_e)/N_e = 1/ N_e \sim 10\%$, that provides not so bad an energy resolution!

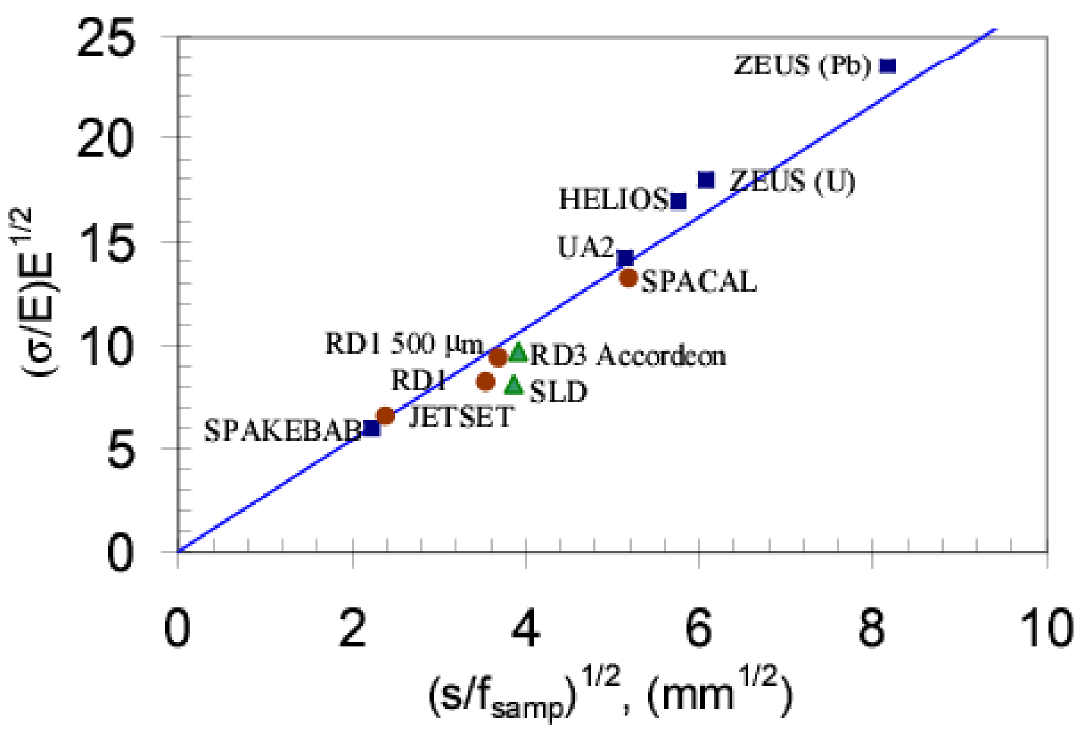
The same idea work for hadrons!

Sampling em calorimeters

Signal ~ N_{tot} = T/d,

T – total track length,

d – one layer thickness



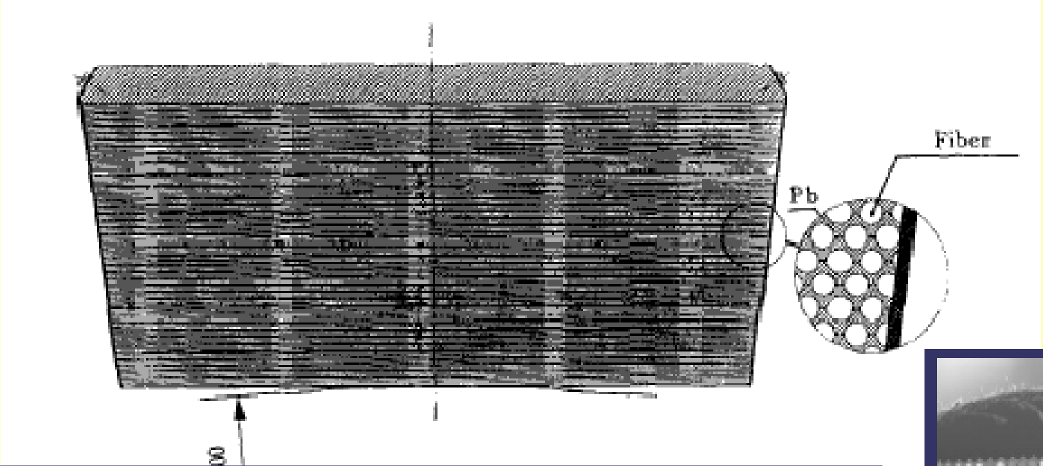
$$T_m = F(\varepsilon_{th}/E_{cr})\frac{E_0}{E_{cr}}X_0$$

$$\frac{\sigma_{samp}}{E} = \frac{2.7\%}{\sqrt{E(GeV)}}\sqrt{\frac{s}{f}}$$

s– thickness of sensitive layer

f – sampling fraction

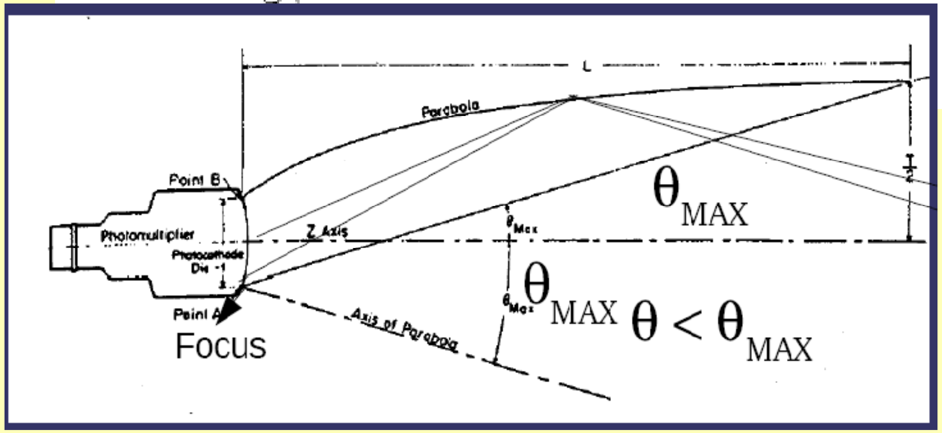
KLOE electromagnetic calorimeter

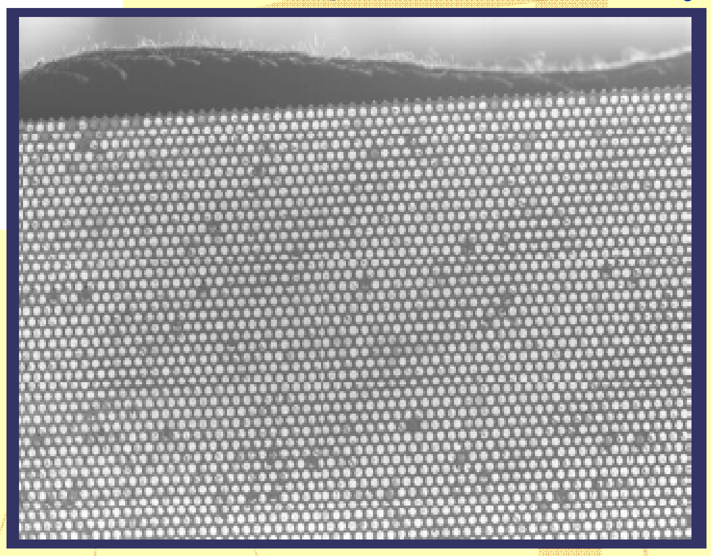


Spaghetti calorimeter

1 mm fiber in Pb,

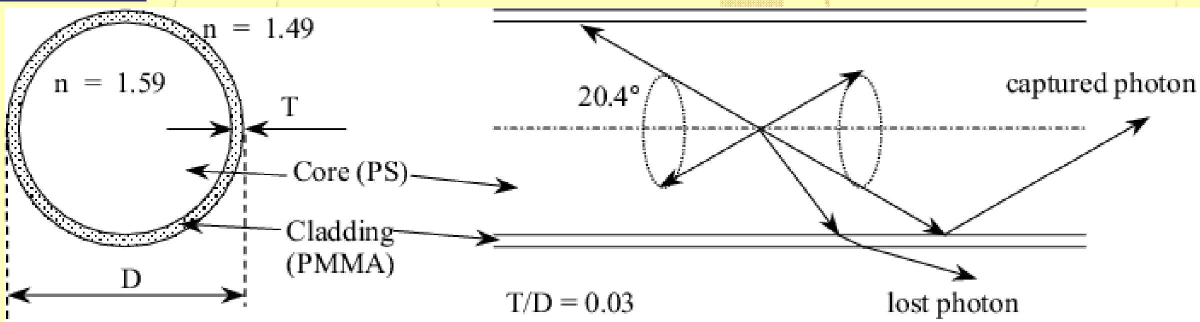
$\rho = 5\ g/cm^2$, $X_0 = 1.6$ cm

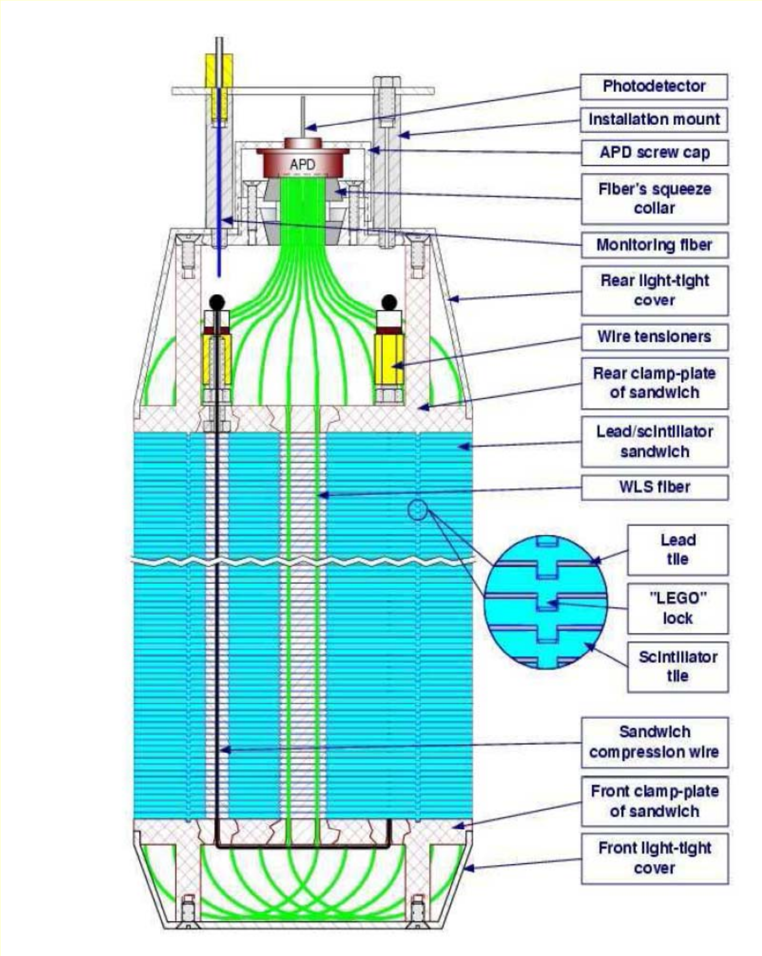


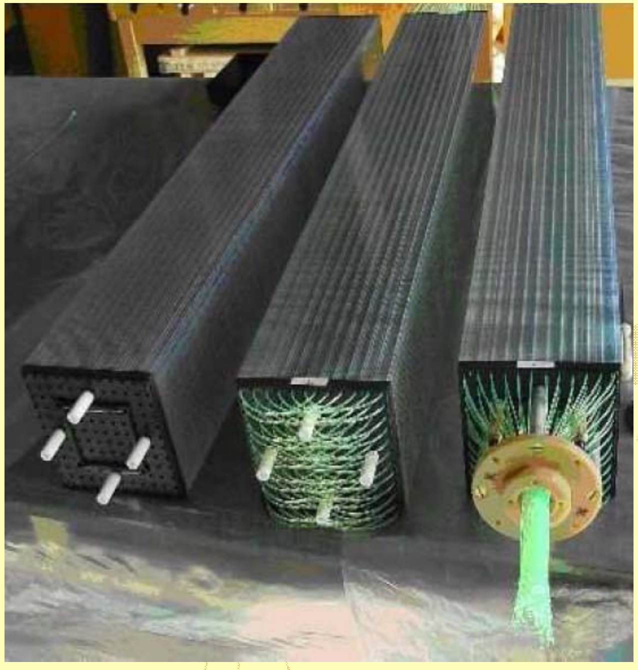


$\sigma_E/E = 5.7\%/\sqrt{E(GeV)}$;

$\sigma_t = 50ps/\sqrt{E(GeV)}$.



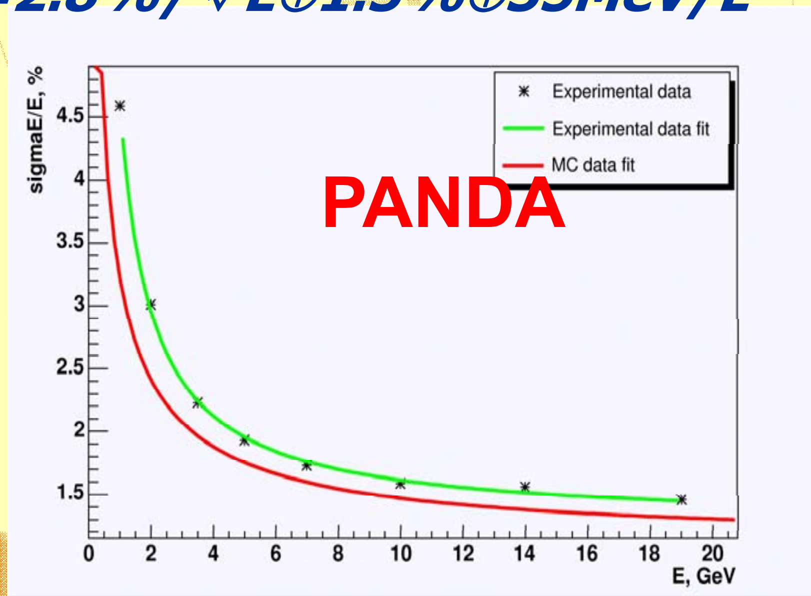




300 x Pb:Sc = 0.275 : 1.5 mm

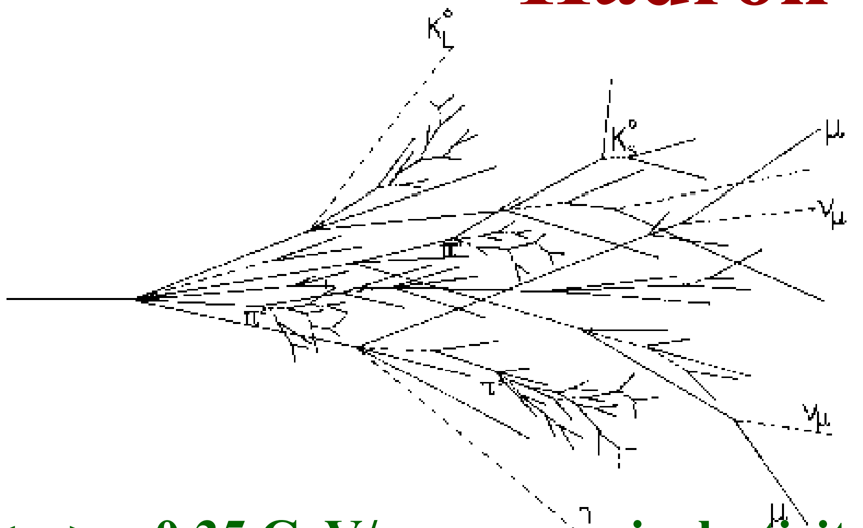
$\sigma_E/E = 2.8\%/\sqrt{E} \oplus 1.3\% \oplus 35MeV/E$

Layers	300, 360
Fibers	72 x 1.5m = 108m
Effective X_0	34.9 mm
Moliere radius	59.8 mm
Active depth	555mm (15.9 X_0)
Weight	21 kg/module



NIM A584(2008)291, G.S.Atoian et al.

Hadron calorimeters



$\langle p_T \rangle \approx 0.35$ GeV/c, average inelasticity ~ 50%

Typical energy resolution – $\sigma_E/E \sim (50\text{-}70)\%/\sqrt{E(\text{GeV})}$

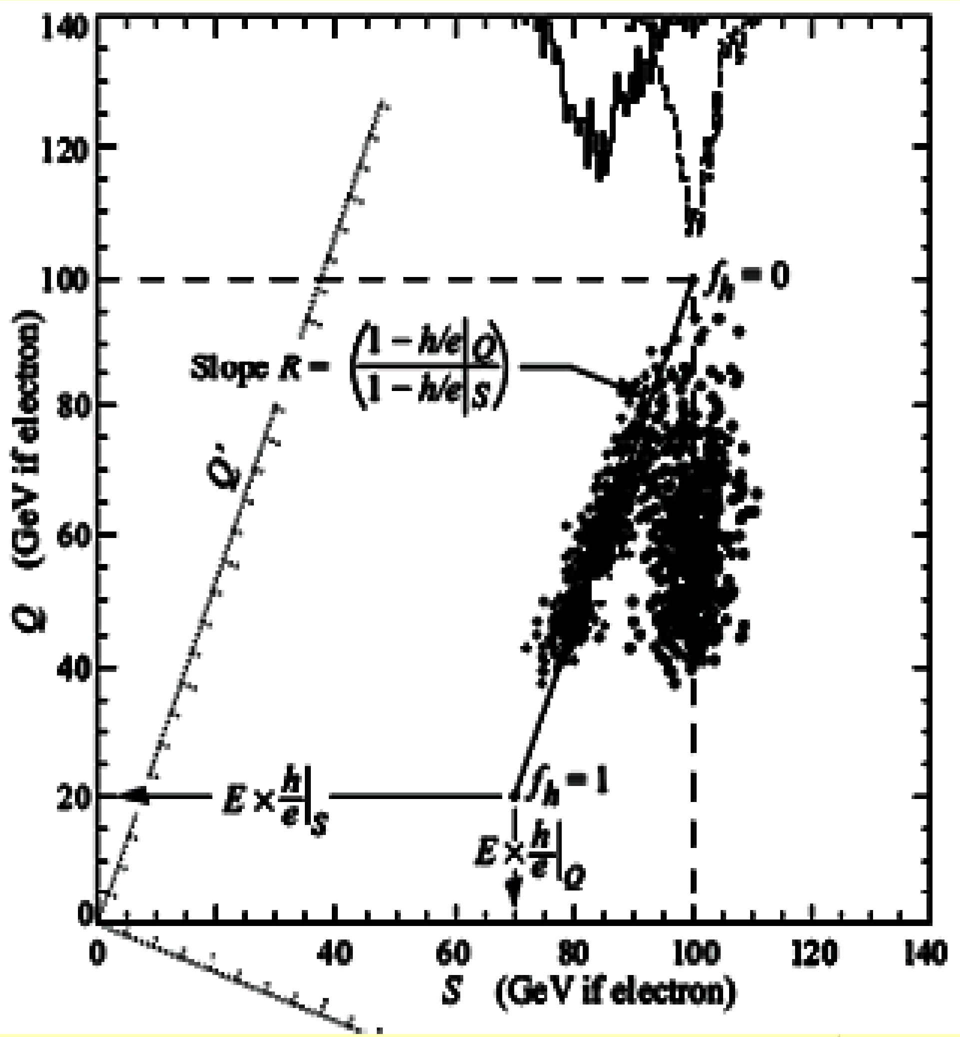
$E_{sh} = E_0 (f_{EM} + f_{ion} + f_{inv})$, where

f_{EM} - energy of e-m showers initiated by secondary neutral pions;

f_{ion} – ionization losses of charged particles;

f_{inv} – invisible energy (binding energy, slow recoiles and neutrino)

Dual readout calorimeters



How alternative measurement of em component can improve the resolution?

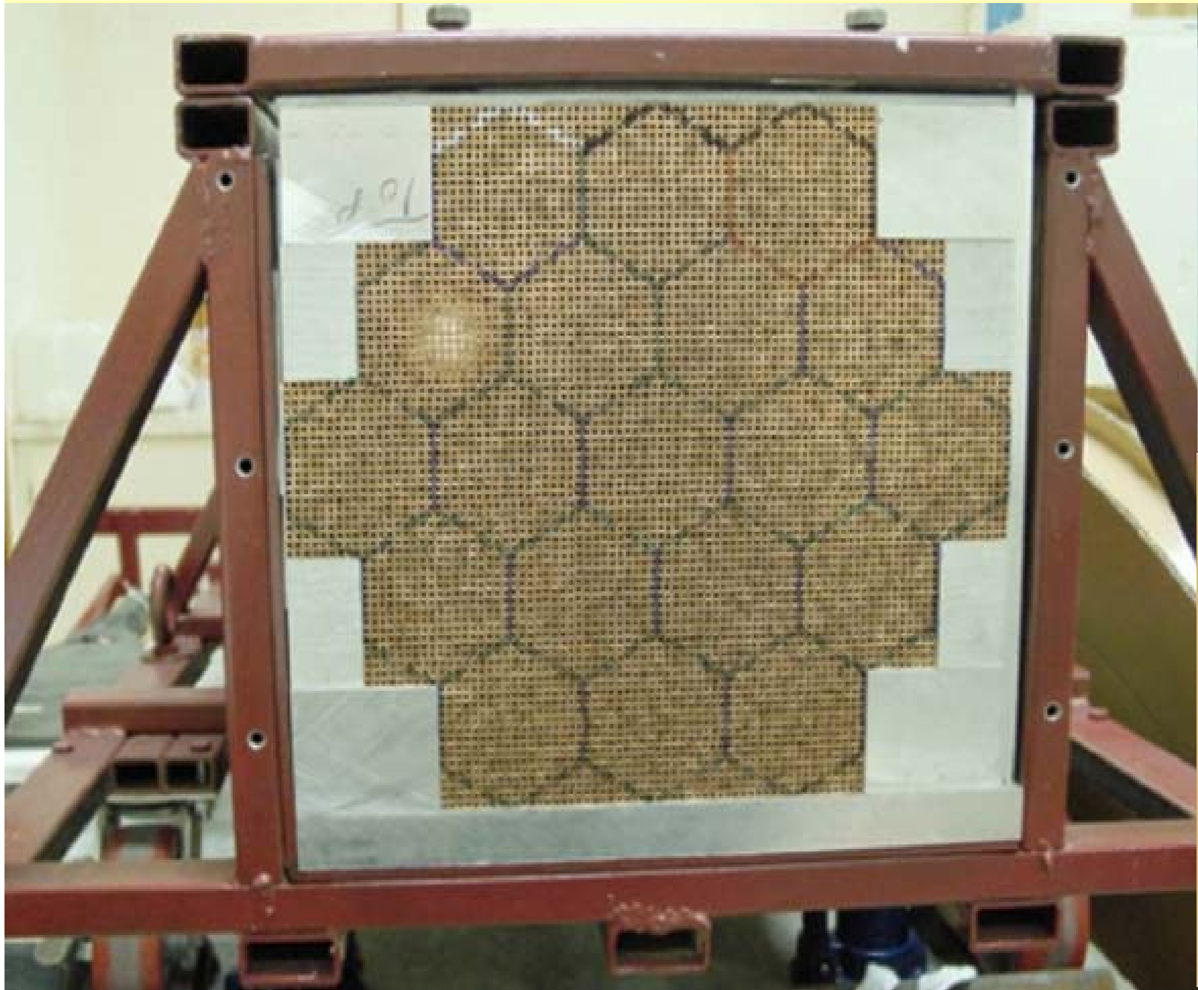
Q = quartz sensitive to em
S = scintillating light

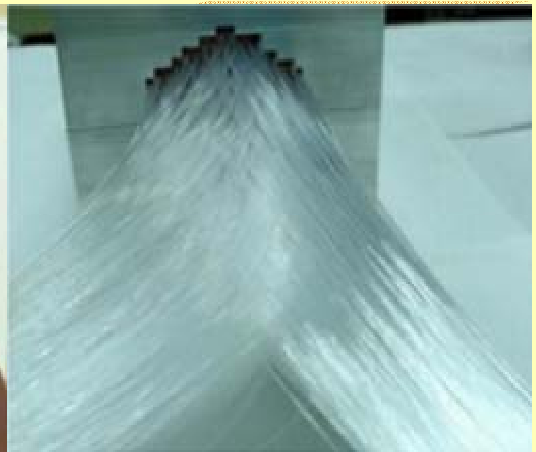
$R=(1\text{-}h/e)_Q / (1\text{-}h/e)_S$

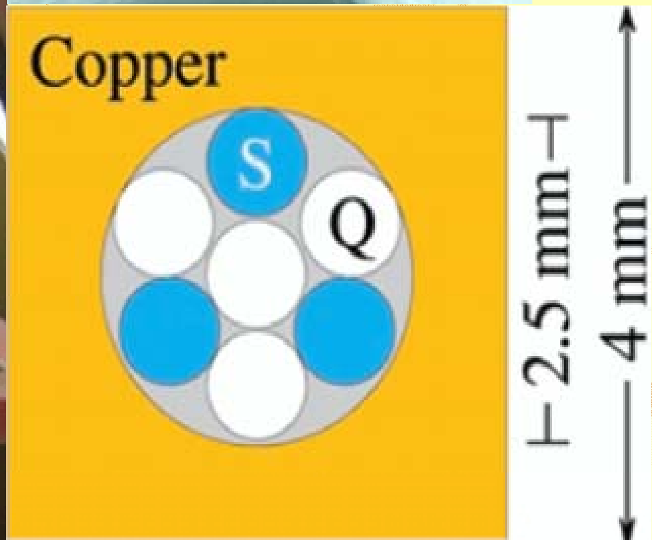
$E_{corr} = (RS\text{-}Q)/(R\text{-}1)$

- Depth 200 cm (10.0 λ_{int})
- Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
- Mass instrumented volume 1030 kg
- Number of fibers 35910, diameter 0.8 mm, total length ≈ 90 km
- Hexagonal towers (19), each read out by 2 PMTs

DREAM prototype test-beam

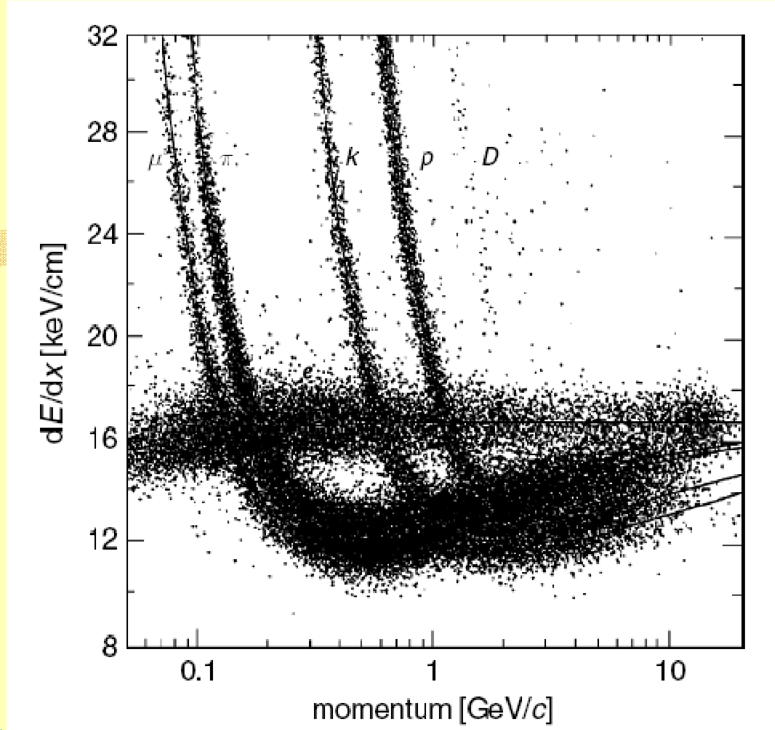






Particle identification

- **electrons vs muons, hadrons – showers in the EM cal.**
- **muons vs hadrons – ionisation range**
- **common for the charged particles:**
  - ionization
  - particle velocity – ionization
  - cherenkov radiation
  - transition radiation



ALEPH TPC – 0.6 truncated mean method

Time-of-flight: New ingredients:
Faster photon detectors (working PMT)
Use of Cherenkov light instead of scintillation photons
Faster electronics

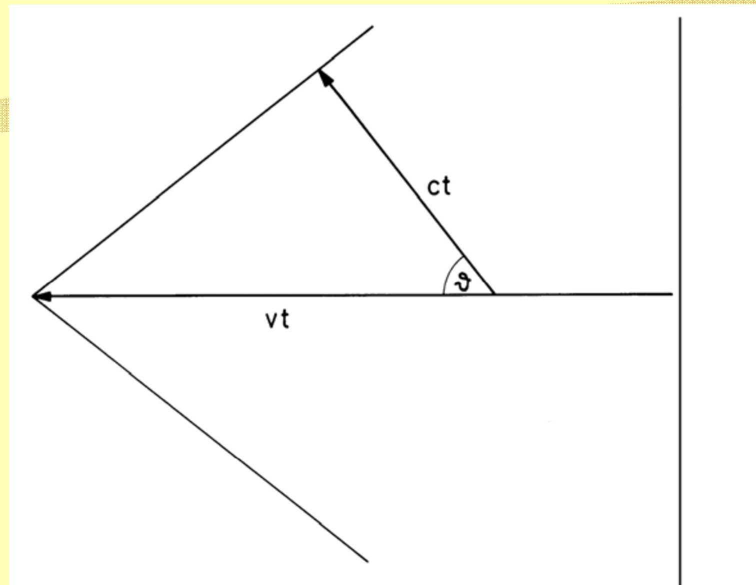
Recent results:
→resolution ~5ps measured
K. Inami NIMA 560 (2006) 303

neutral particles identification – specific for each exp.

Cherenkov radiation

A charged track with velocity v=βc exceeding the speed of light c/n in a medium with refractive index n emits polarized light at a characteristic (Čerenkov) angle,

$\cos\theta = c/nv = 1/\beta n$



Two cases:

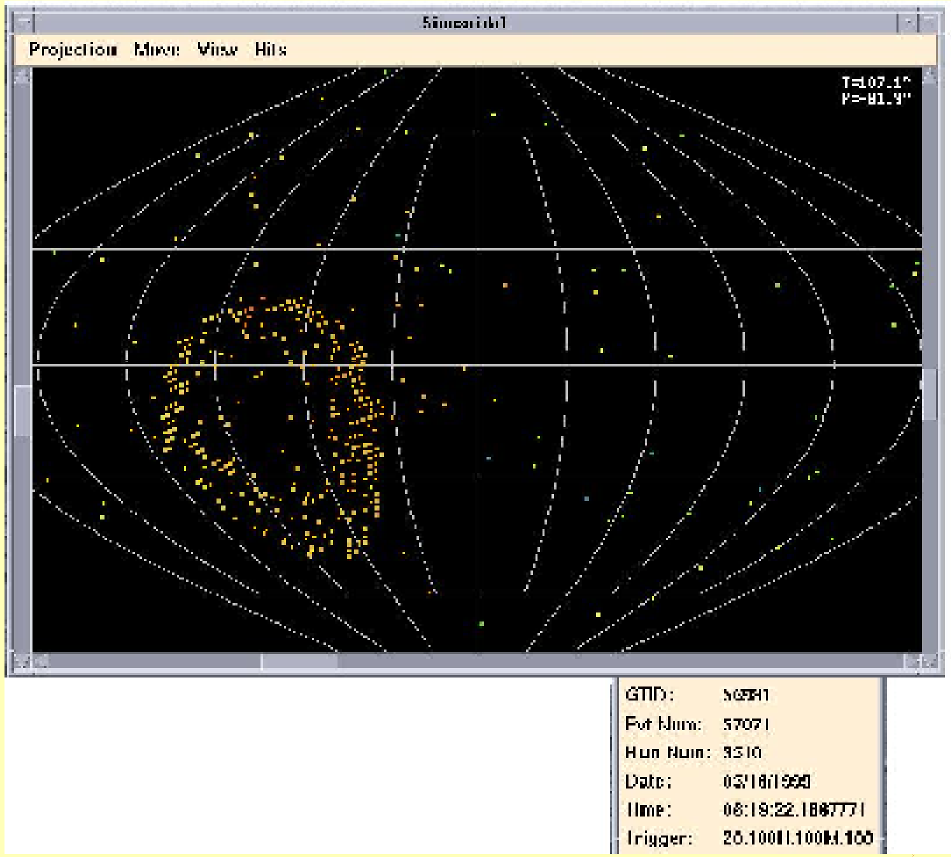
→ **b < βt** = 1/n: below threshold no Cherenkov light is emitted.

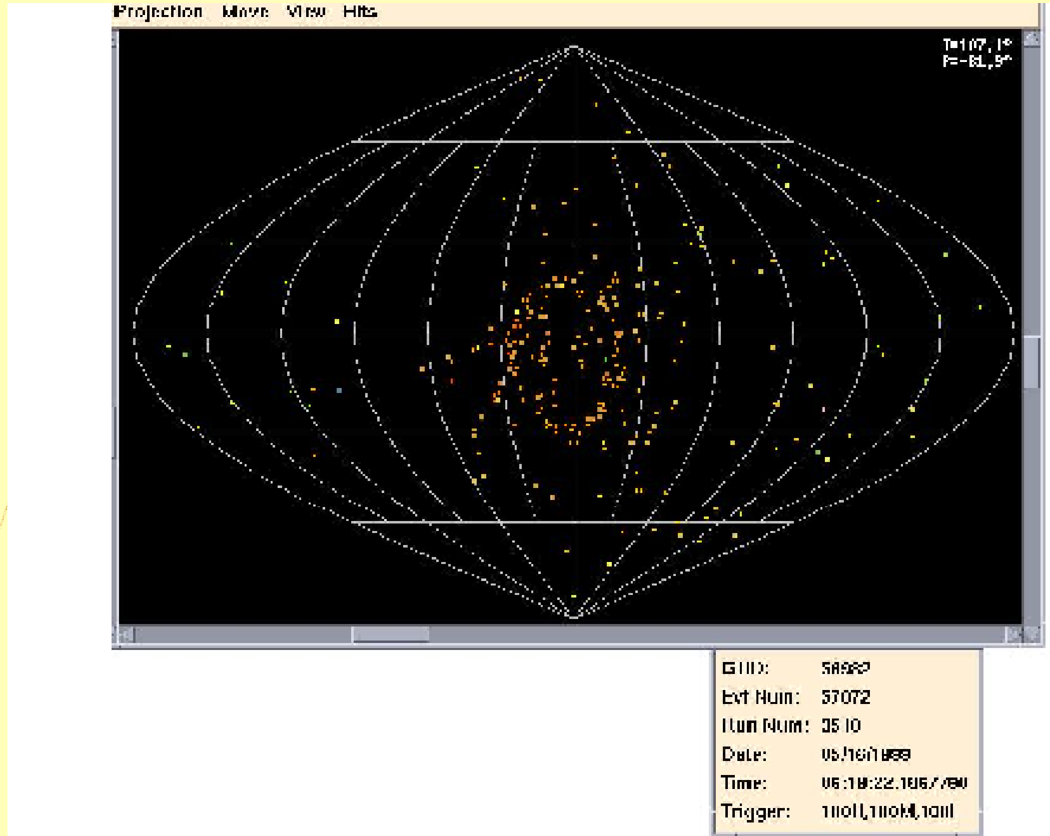
→ **b > βt** : the number of Cherenkov photons emitted over unit photon energy E=h**n** in a radiator of length ***L***:

$$\frac{dN}{dE} = \frac{\alpha}{\hbar c} L \sin^2\theta = 370(cm)^{-1}(eV)^{-1} L \sin^2\theta$$

→Few detected photons

Examples of Cherenkov rings – SNO experiment – 1000 ton heavy water viewed by 10000 PMT





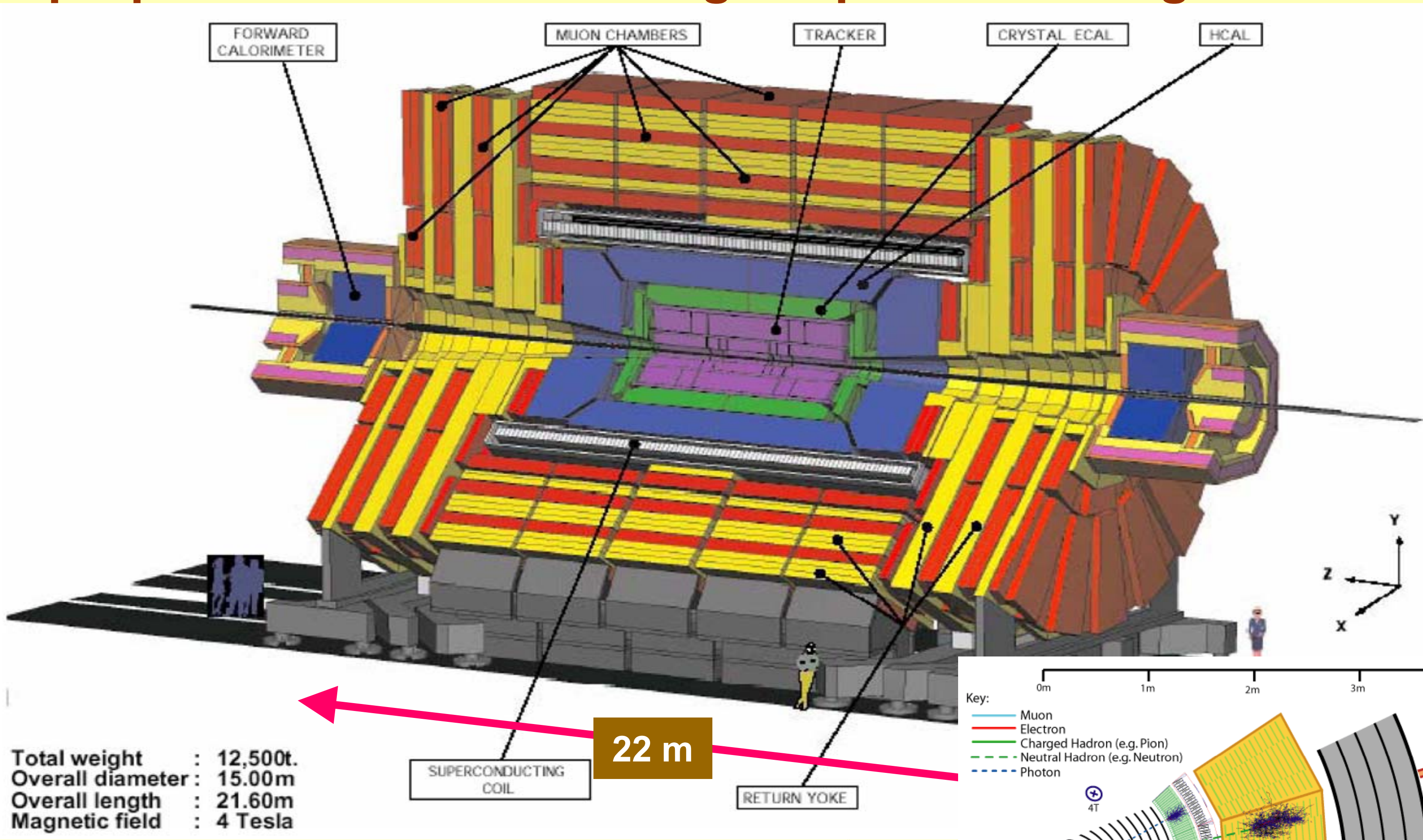
$\nu_\mu + N \rightarrow \mu^- + X$

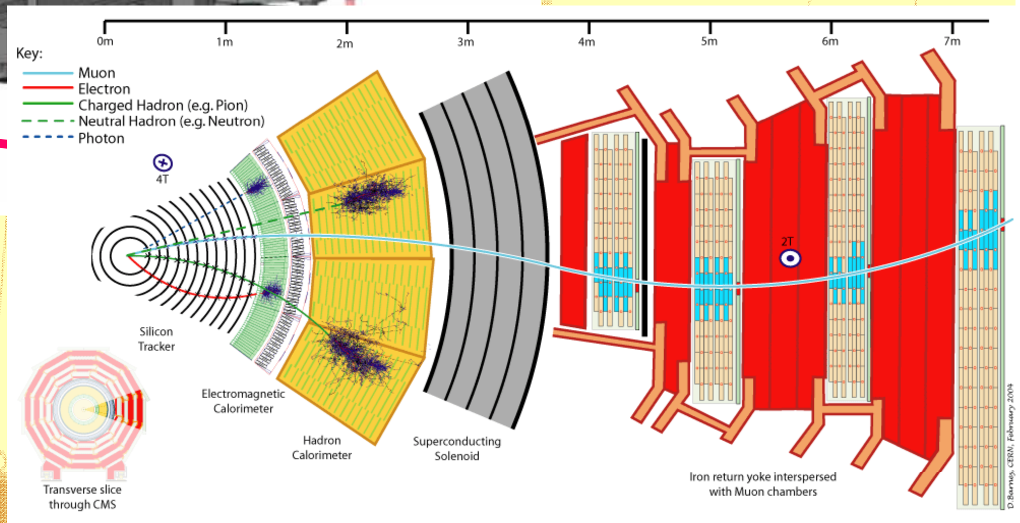
SNO experiment

0.9 μs later

$\mu \rightarrow e + \nu_\mu + \nu_e$

The Compact Muon Solenoid detector (CMS) is a general purpose detector with a large superconducting solenoid





Cryogenic detectors

The main idea to use the quantum transition requiring lower energy than that for ionization.

1. Phonons - 10^{-5} eV

2. Cooper pairs – $4{\cdot}10^{-5}$ - $3\cdot10^{-3}$ eV

+ Low temperature → low noise

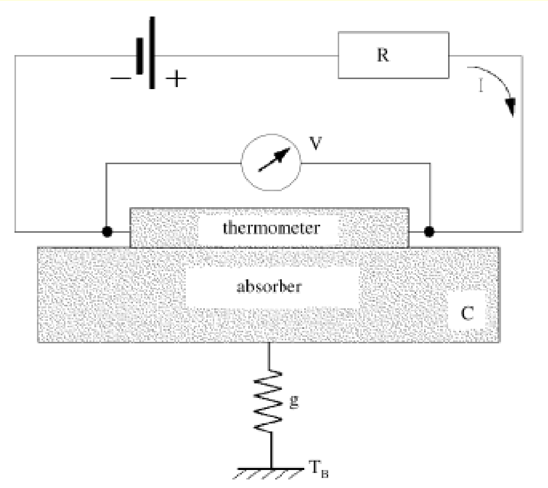
These detectors are developed for already more than 20 years. Now variety of detectors exist – from 1 g (microcalorimeters) to 10th of kilograms (macrocalorimeters) of working wolume.

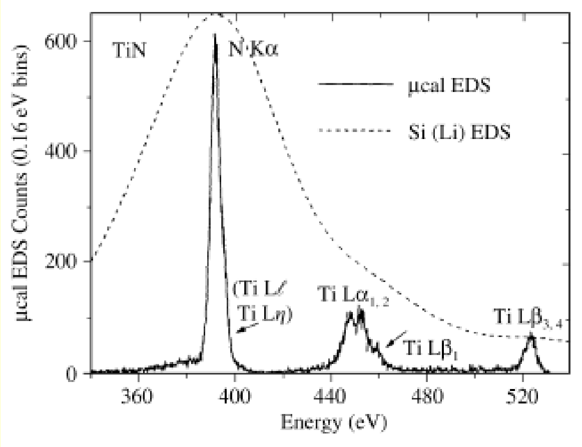
compare:

scintillator – 100 eV/ph

germanium – 3 eV/ e-h pair

$$\Delta T = E/C$$





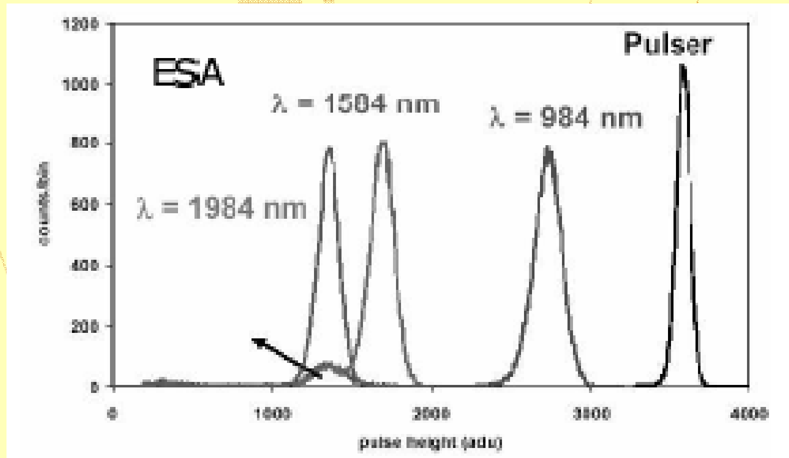


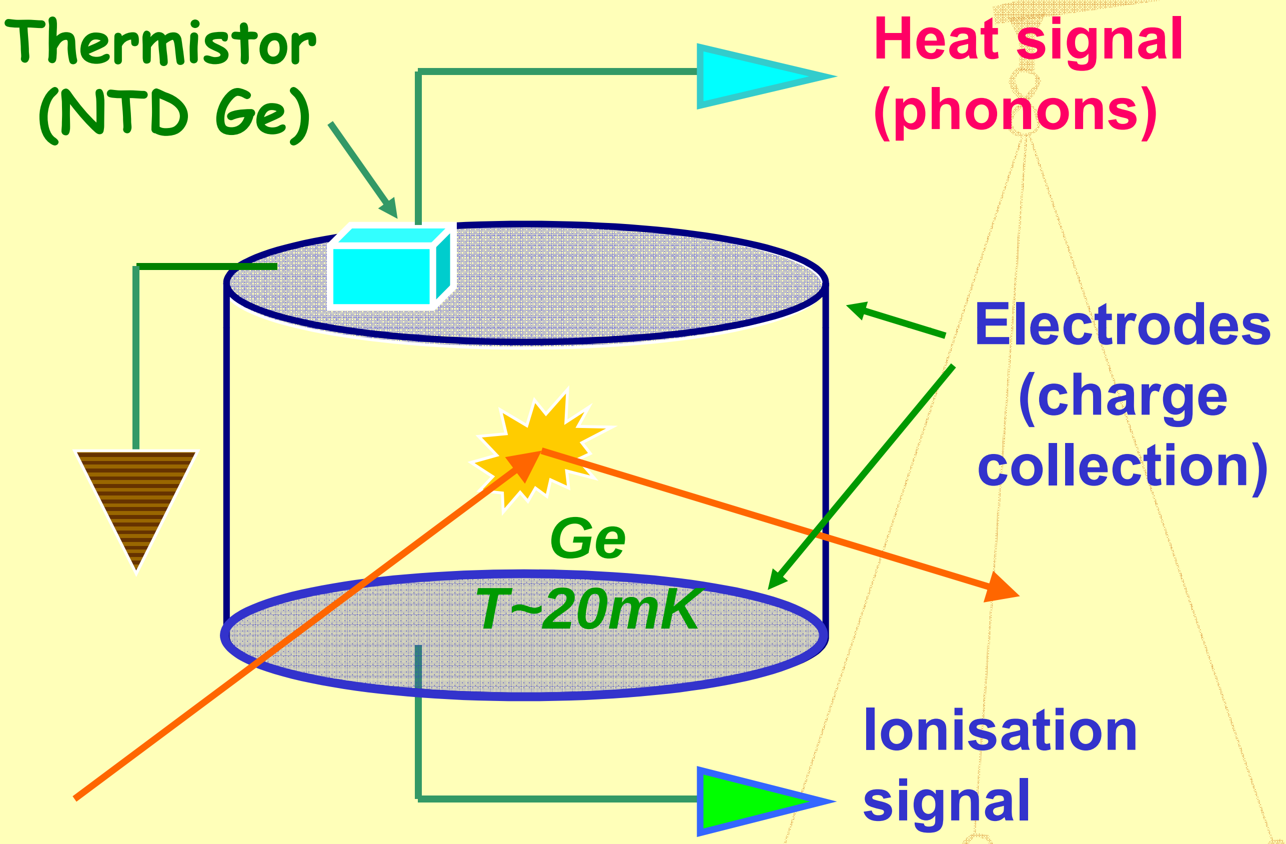
Table 1. Direct dark matter search experiments

Experiment	Detector	Status	Location	Collaboration
DAMA/LIBRA	NaI	running	Gran Sasso	Italy, China
ANAIS	NaI	constructing	Canfranc	Spain
KIMS	CsI	R & D	Korea	Korea
HDMS	Ge	running	Gran Sasso	Germany, Russia
Dama-LXe	LXe	running	Gran Sasso	Italy, China
Zeplin II	LXe	running	Boulby	PT, UK, RU, US
Zeplin III	LXe	installing	Boulby	PT, UK, RU, US
XENON 10	LXe	commiss	Gran Sasso	DE, IT, PT, US
LUX				US
XMASS	LXe		Kamioka	Japan
WARP	LAr	running	Gran Sasso	Italy, US
ArDM	LAr	R & D	Canfranc	CH, ES, PO
DEAP	LAr	R & D	SNOLAB	Canada, US
CLEAN	LNe	R & D	SNOLAB?	US, Canada
Rosebud	Bolom. / Scint.	R & D	Canfranc	Spain, France
EDELWEISS	Bolometer	running	Frejus	F, GE, RU
CRESST	Bolometer	running	Gran Sasso	DE, UK, IT, RO
CDMS	Bolometer	running	Soudan	US
SIMPLE	Superheated liquid	running	Rustrel	PT, F, US
PICASSO	Superheated liquid	running + R & D	SNOLAB	CA, US, CZ
COUPP	Superheated liquid	R & D	Fermilab	US
Drift	Xe gas	R & D	Boulty	UK, US
MIMAC	^{3}He gas	R & D		France

Эксперимент CDMS

Cryogenic Dark Matter Search (USA)

Detection with low-temperature bolometers



At the low temperature, the specific heat capacity becomes very small. According to the Debye model:

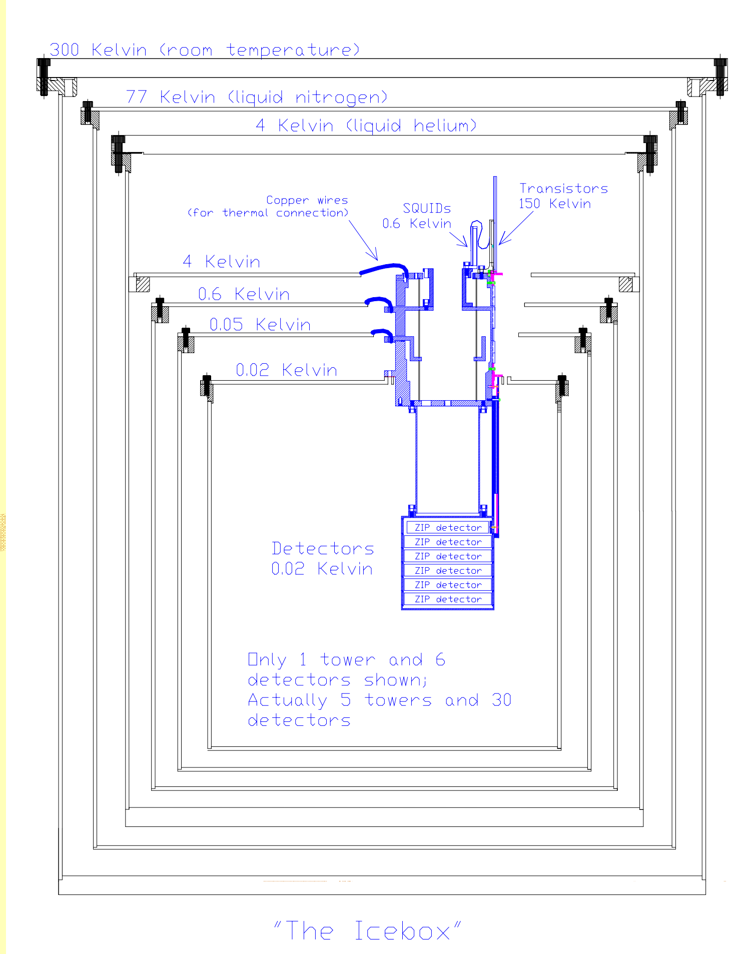
$$C = \lambda_D \left(\frac{T}{\Theta_D} \right)^3,$$

λ_D=1944 J/mol/K,
T –temperature (K),
Θ_D–Debye temperature.

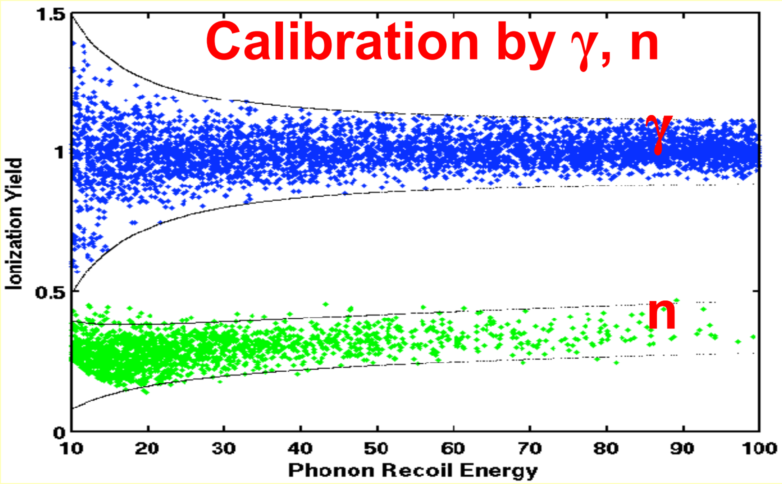
For Ge, Θ_D = 374K.
At T ~ 20 мК
C_{Ge} ~ 1 keV/mol/μK.

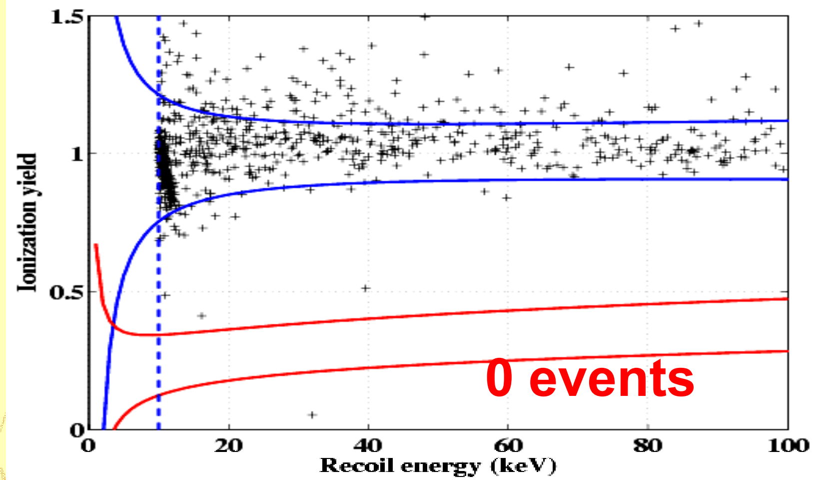
Эксперимент CDMS

The detectors are assembled into "towers". One tower has 7 detectors. The towers are inserted into the "icebox", which is really much colder than ice! In fact, the detectors work best at only 0.05 degrees Celsius above absolute zero, the temperature where all random thermal motion stops.

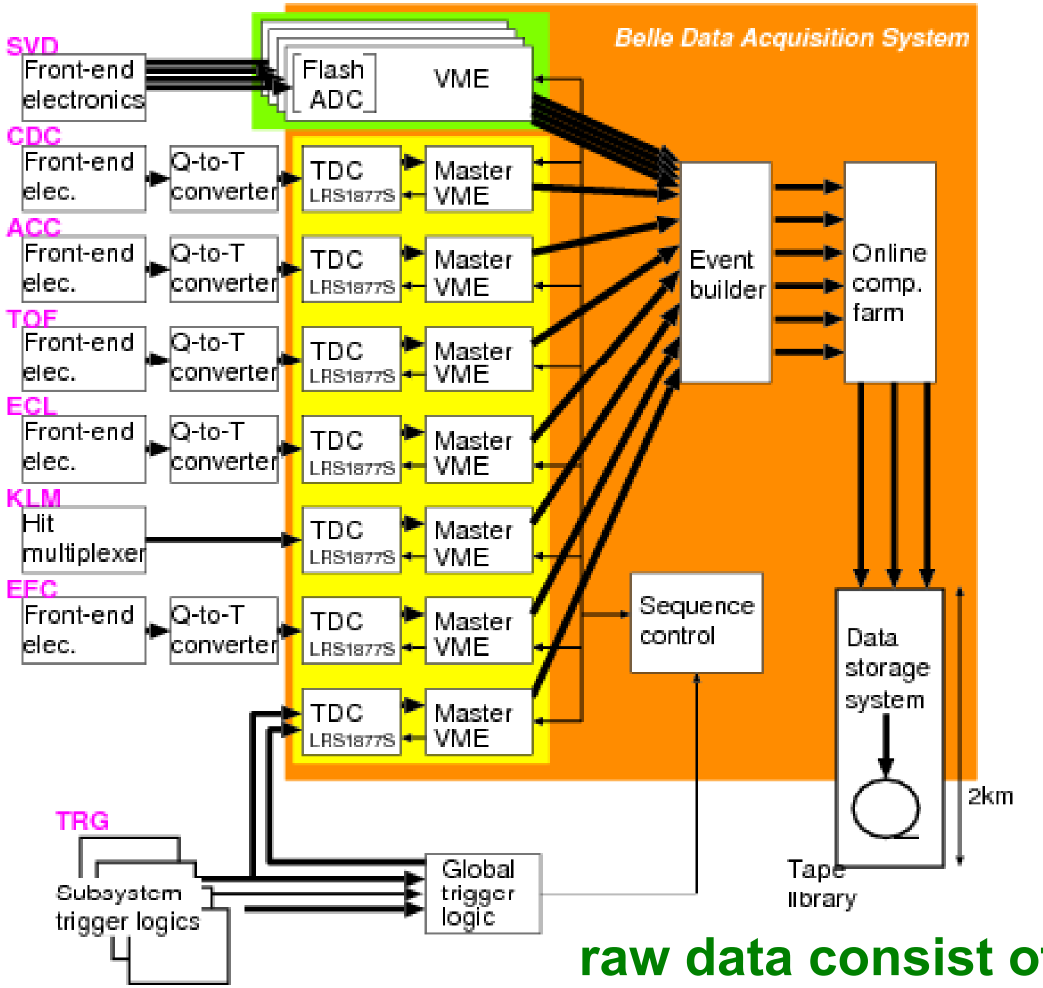


4.75 kg Ge,
1.1 kg Si





electical signals to particle parameters



trigger provides signal to start the data acquisition:

background suppression down to the acceptable level while to keep signal efficiency close to 100%.

Modern option – pipe line readout

raw data consist of the "events" which contain:

N_i – number of hit channel; i = 1, …. M, where M – number of hits in the event;

A_i – amplitude (charge) of the signal of this cjannel;

t_i – time of signal occurrence.

Data processing

$E_i = \alpha_i \cdot (A_i - P_i)$

$T_i = \beta_i \cdot (t_i - t_{i0})$

α_i, β_i - calibration coefficients

P_i, t_{i0} - pedestals

$$"point"_i, \quad \vec{r}_i = \mathbf{R}(N_i, T_i)$$

$$"track"_j = \mathbf{T}(\vec{r}_1, \ldots, \vec{r}_{Mj})$$

$$"cluster"_k = \mathbf{CL}(E_1, \ldots, E_{Mk})$$

"photon" = "cluster" but not "track"

$V_k = V(\text{"track}_1\text{"}, \ldots \text{"track}_{Lk}\text{"})$

$(\theta_k, \varphi_k) = \mathbf{F}(\text{"track"}_k)$

$Eph_k = (E_1 + E_2 + \ldots + E_{ck}) \cdot f(E_t, \theta, \varphi)$

$Lk = ID(\text{track, cluster, id-spec})$

minimal kit for further analysis

How to learn the calibration coefficients?

Calorimeter (for example):

Cosmic rays give C_i without beam (initial input)

Ci absolute calibration; Bhabha, $e^+e^- \to \gamma\gamma$.

by minimizing

$$\chi^2 = \sum_j \frac{(Esum_j - Eexp_j)^2}{\sigma^2}$$

Results evaluation

$$\sigma(E) = \frac{N_{events}(E)}{L\varepsilon}$$

ε - efficiency of the detector;

L – luminosity of the accelerator

$$\sigma(E) = \frac{N_{events}(E) - N_{bkg}(E)}{L\varepsilon^{MC}(1+\delta_{\exp})(1+\delta_{trig})(1+\delta_{E}(\sigma))(1+\delta_{rad}(\sigma))}$$

ε^{MC} – efficiency, obtained by the MC simulation;

δ_{exp} – correction found from the experimental data;

δ_{trig} – correction for trigger inefficiency;

δ_{E} – correction for the energy spread or energy resolution;

δ_{rad} – radiative corrections

Finally:

$\sigma = \sigma^{exp} \pm \delta^{stat} \pm \delta^{syst.} \pm [\delta^{mod}]$

Conclusion

Measure what is measurable, and make measurable what is not so.

Galileo Galilei

The scope of detection techniques is very wide and diverse. Depending on the aim of the measurement, different physics effects are used. Basically, each physics phenomenon can be the basis for a particle detector. If complex experimental problems are to be solved, it is desirable to develop a multipurpose detector which allows one to unify a large variety of different measurement techniques. This would include a high (possibly 100%) efficiency, excellent time, spatial and energy resolution with particle identification. For certain energies these requirements can be fulfilled, e.g. with suitably instrumented calorimeters. Calorimetric detectors for the multi-GeV and for the eV range, however, have to be basically different.

The discovery of new physics phenomena allows one to develop new detector concepts and to investigate difficult physics problems. For example, superconductivity provides a means to measure extremely small energy depositions with high resolution. The improvement of such measurement techniques, e.g. for the discovery and detection of Weakly Interacting Massive Particles (WIMPs), predicted by supersymmetry or cosmological neutrinos, would be of large astrophysical and cosmological interest.