Particle Detectors

Summer Student Lectures 2009

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- **History of Instrumentation ↔ History of Particle Physics**
- **The ‘Real’ World of Particles**
- **Interaction of Particles with Matter**
- **Tracking with Gas and Solid State Detectors**
- **Calorimetry, Particle ID, (Detector Systems)**

Detectors based on Ionization

Gas detectors:

- Wire Chambers
- Drift Chambers
- Time Projection Chambers
- Transport of Electrons and Ions in Gases

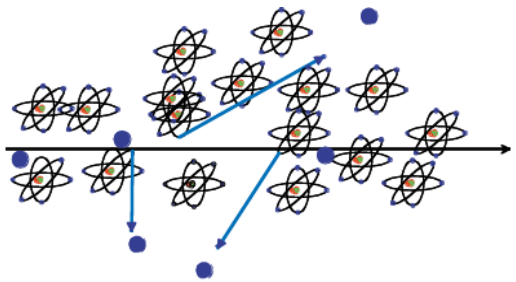
→ Solid State Detectors

- Transport of Electrons and Holes in Solids
- Si- Detectors
- Diamond Detectors

Solid State Detectors

Gas Detectors

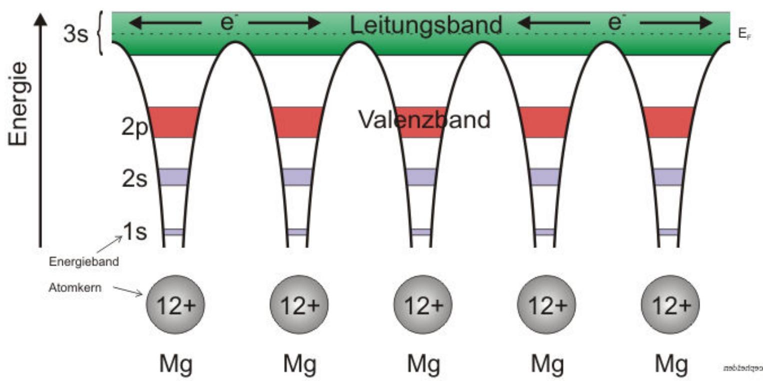
In gaseous detectors, a charged particle is liberating electrons from the atoms, which are freely bouncing between the gas atoms.



An applied electric field makes the electrons and ions move, which induces signals on the metal readout electrodes.

For individual gas atoms, the electron energy levels are discrete.

Solid State Detectors

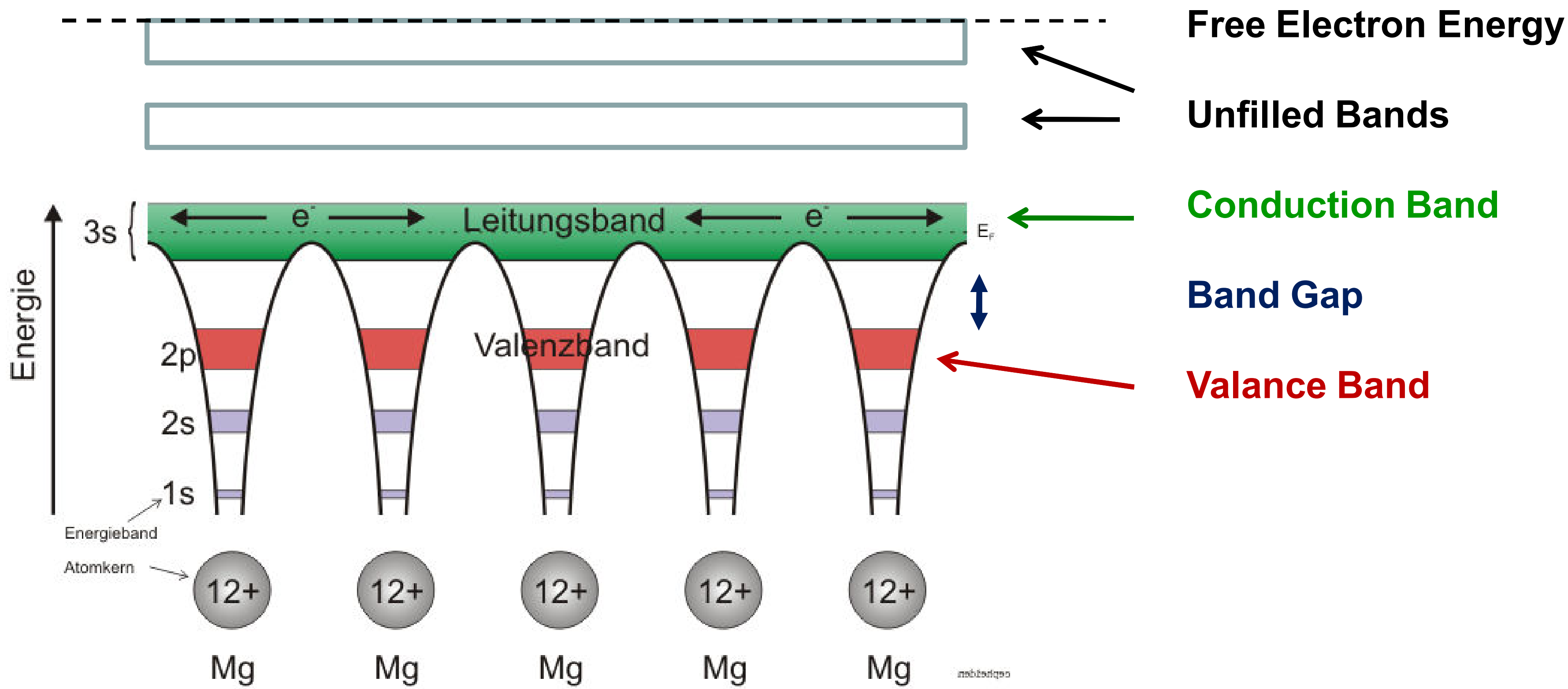


In solids (crystals), the electron energy levels are in 'bands'.

Inner shell electrons, in the lower energy bands, are closely bound to the individual atoms and always stay with 'their' atoms.

In a crystal there are however energy bands that are still bound states of the crystal, but they belong to the entire crystal. Electrons in these bands and the holes in the lower band can freely move around the crystal, if an electric field is applied.

Solid State Detectors



Conductor, Insulator, Semiconductor

In case the conduction band is filled the crystal is a conductor.

In case the conduction band is empty and 'far away' from the valence band, the crystal is an insulator.

In case the conduction band is empty but the distance to the valence band is small, the crystal is a semiconductor.

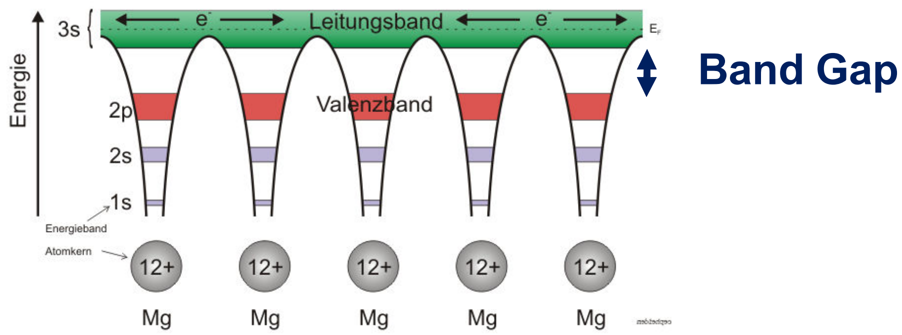
Solid State Detectors

Band Gap, e-h pair Energy

The energy gap between the last filled band – the valence band – and the conduction band is called band gap E_g.

The band gap of Diamond/Silicon/Germanium is 5.5, 1.12, 0.66 eV.

The average energy to produce an electron/hole pair for Diamond/Silicon/Germanium is 13, 3.6, 2.9eV.



Temperature, Charged Particle Detection

In case an electron in the valence band gains energy by some process, it can be excited into the conduction band and a hole in the valence band is left behind.

Such a process can be the passage of a charged particle, but also thermal excitation → probability is proportional Exp($-E_g/kT$).

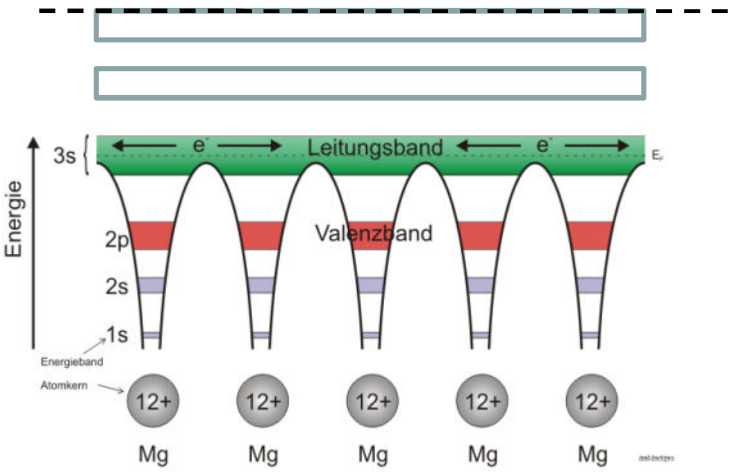
The number of electrons in the conduction band is therefore increasing with temperature i.e. the conductivity of a semiconductor increases with temperature.

Solid State Detectors

Electron, Hole Movement:

It is possible to treat electrons in the conduction band and holes in the valence band similar to free particles, but with an effective mass different from elementary electrons not embedded in the lattice.

This mass is furthermore dependent on other parameters such as the direction of movement with respect to the crystal axis. All this follows from the QM treatment of the crystal (solid state physics).



Cooling:

If we want to use a semiconductor as a detector for charged particles, the number of charge carriers in the conduction band due to thermal excitation must be smaller than the number of charge carriers in the conduction band produced by the passage of a charged particle.

Diamond (E_g=5.5eV) can be used for particle detection at room temperature,
Silicon (E_g=1.12 eV) and Germanium (E_g=0.66eV) must be cooled, or the free charge carriers must be eliminated by other tricks → doping → see later.

Solid State Detectors

Primary 'ionization':

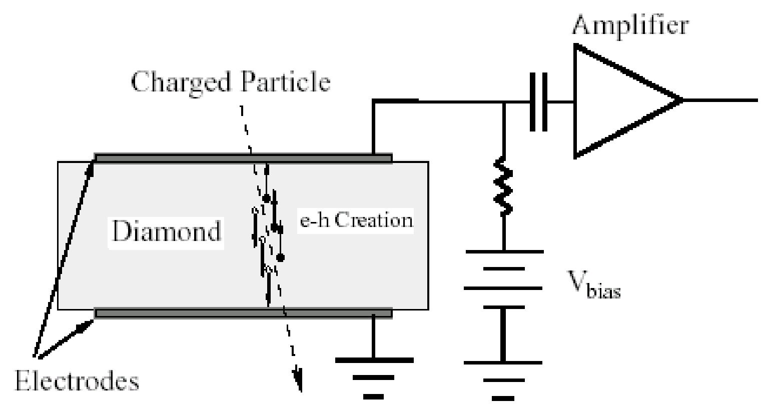
The average energy to produce an electron/hole pair is: Diamond (13eV), Silicon (3.6eV), Germanium (2.9eV)

Comparing to gas detectors, the density of a solid is about a factor 1000 larger than that of a gas and the energy to produce and electron/hole pair e.g. for Si is a factor 7 smaller than the energy to produce an electron-ion pair in Argon.

Solid State vs. Gas Detector:

The number of primary charges in a Si detector is therefore about 10^4 times larger than the one in gas → while gas detectors need internal charge amplification, solid state detectors don't need internal amplification.

While in gaseous detectors, the velocity of electrons and ions differs by a factor 1000, the velocity of electrons and holes in many semiconductor detectors is quite similar → very short signals.



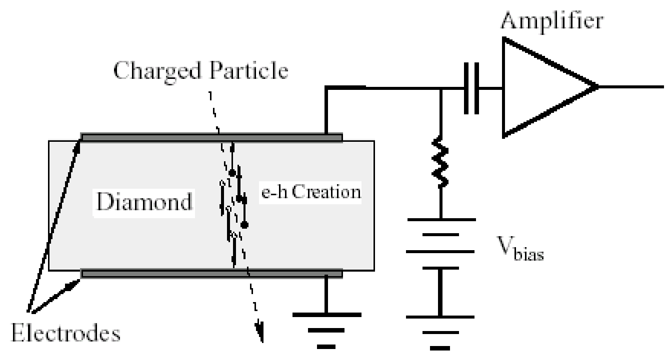
Diamond → A solid state ionization chamber

Why do solid state detectors exist only since around 1980 while gas detectors are used since 1906 ?

Diamond Detector

Typical thickness – a few 100μm.

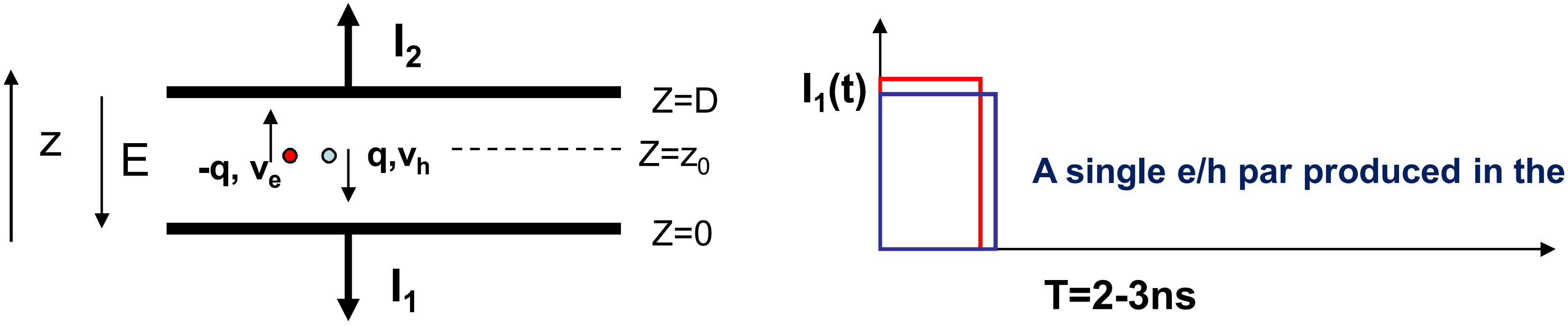
<1000 charge carriers/cm³ at room temperature due to large band gap.



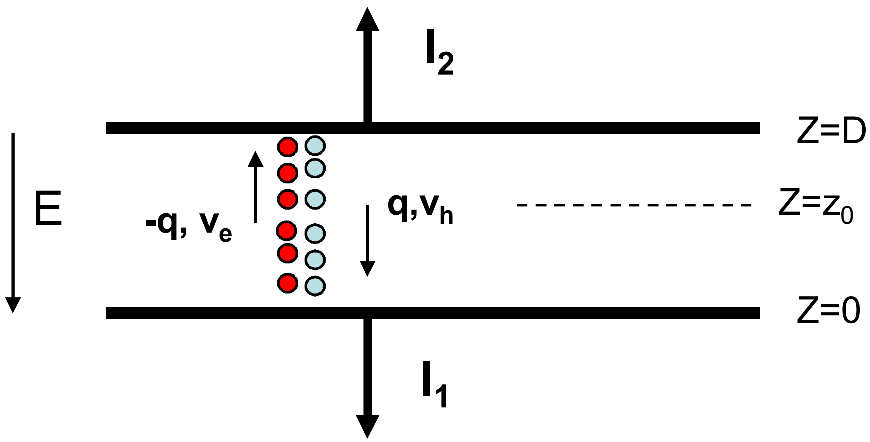
Velocity:

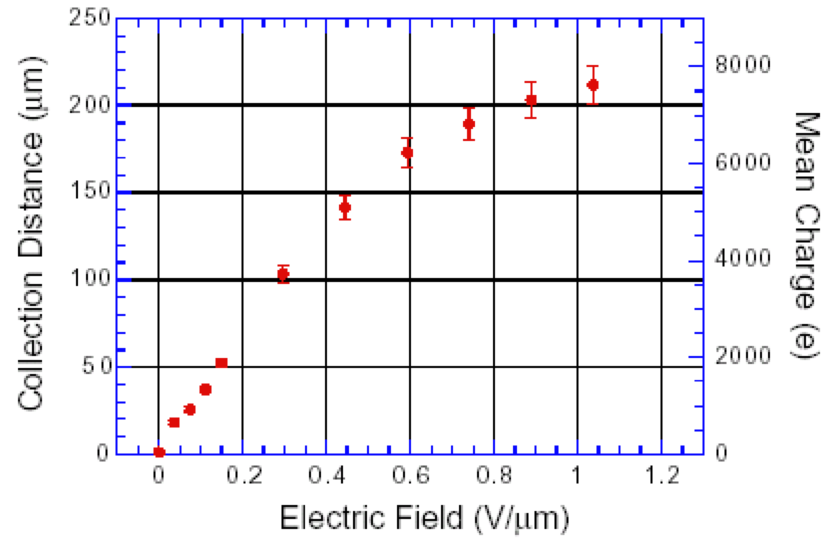
μ_e=1800 cm²/Vs, μ_h=1600 cm²/Vs

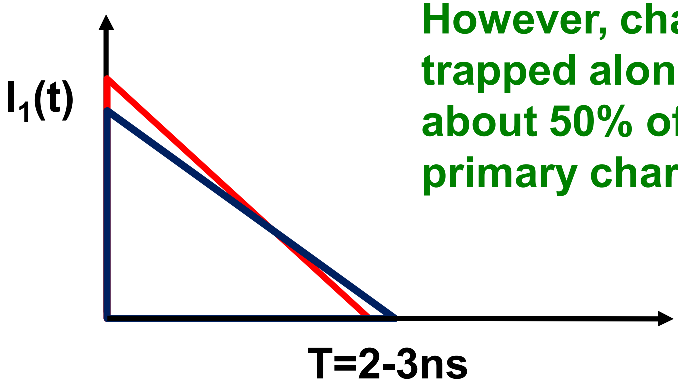
Velocity = μE, 10kV/cm → v=180 μm/ns → Very fast signals of only a few ns length !



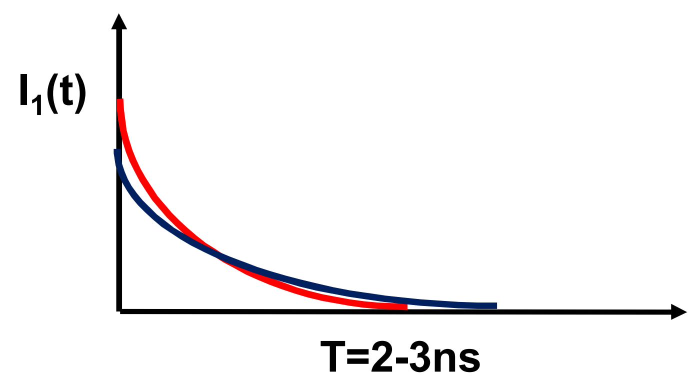
Diamond Detector







However, charges are trapped along the track, only about 50% of *produced* primary charge is *induced* →



Silicon Detector

Velocity:

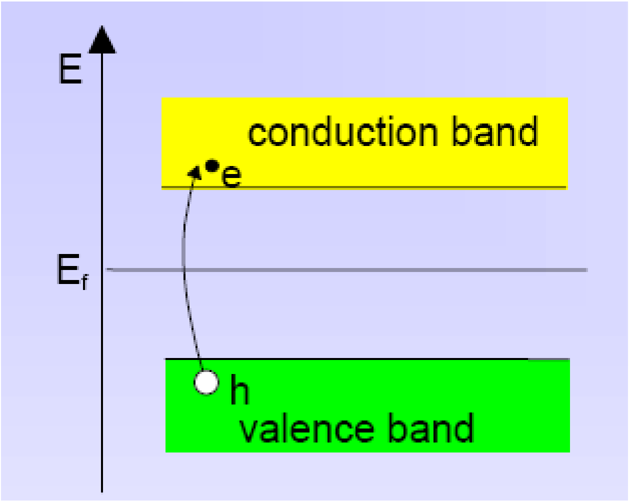
μ_e=1450 cm²/Vs, μ_h=505 cm²/Vs, 3.63eV per e-h pair.

~11000 e/h pairs in 100µm of silicon.

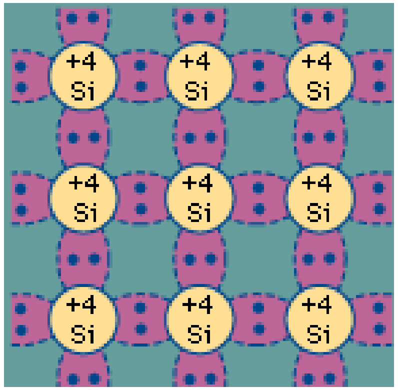
However: Free charge carriers in Si:

T=300 K: e,h = 1.45 x 10^{10} / cm^3 but only 33000 e/h pairs in 300µm produced by a high energy particle.

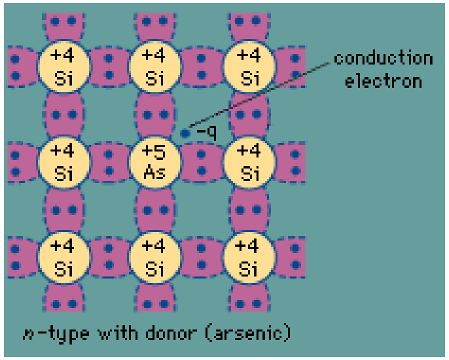
Why can we use Si as a solid state detector ???

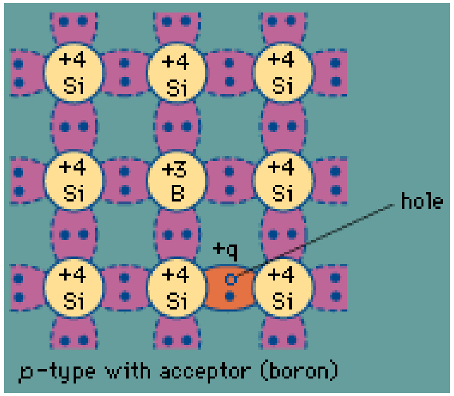


Doping of Silicon



doping



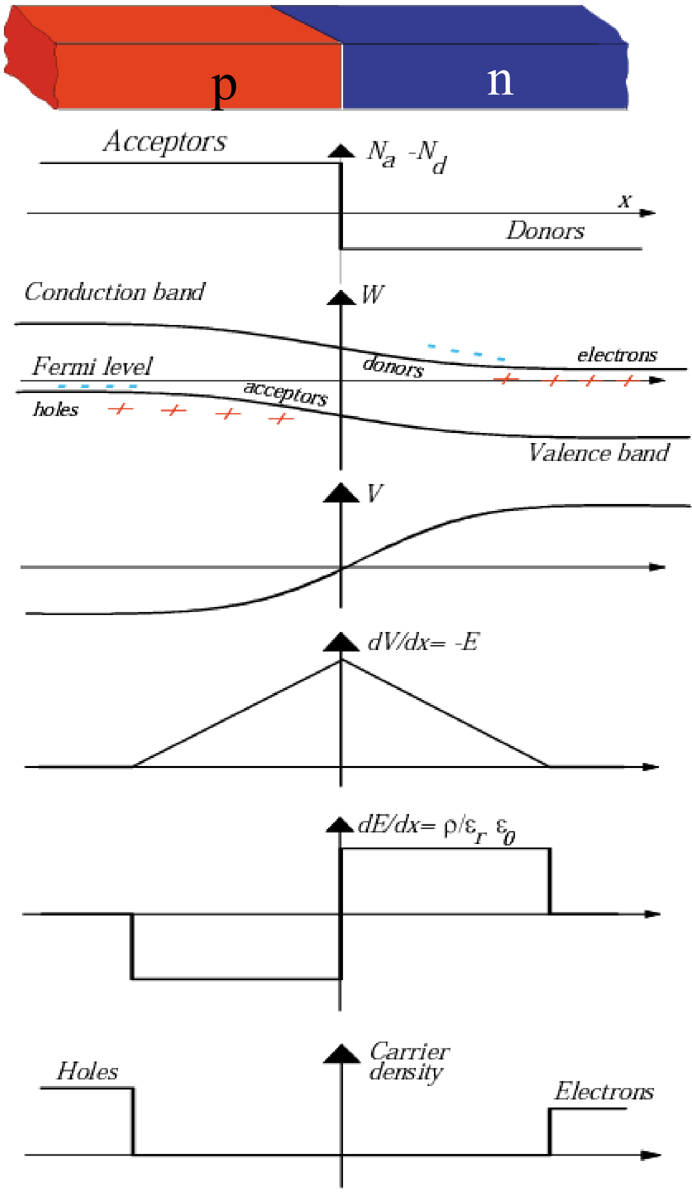


In a silicon crystal at a given temperature the number of electrons in the conduction band is equal to the number of holes in the valence band.

Doping Silicon with Arsen (+5) it becomes and n-type conductor (more electrons than holes).

Doping Silicon with Boron (+3) it becomes a p-type conductor (more holes than electrons).

Bringing p and n in contact makes a diode.



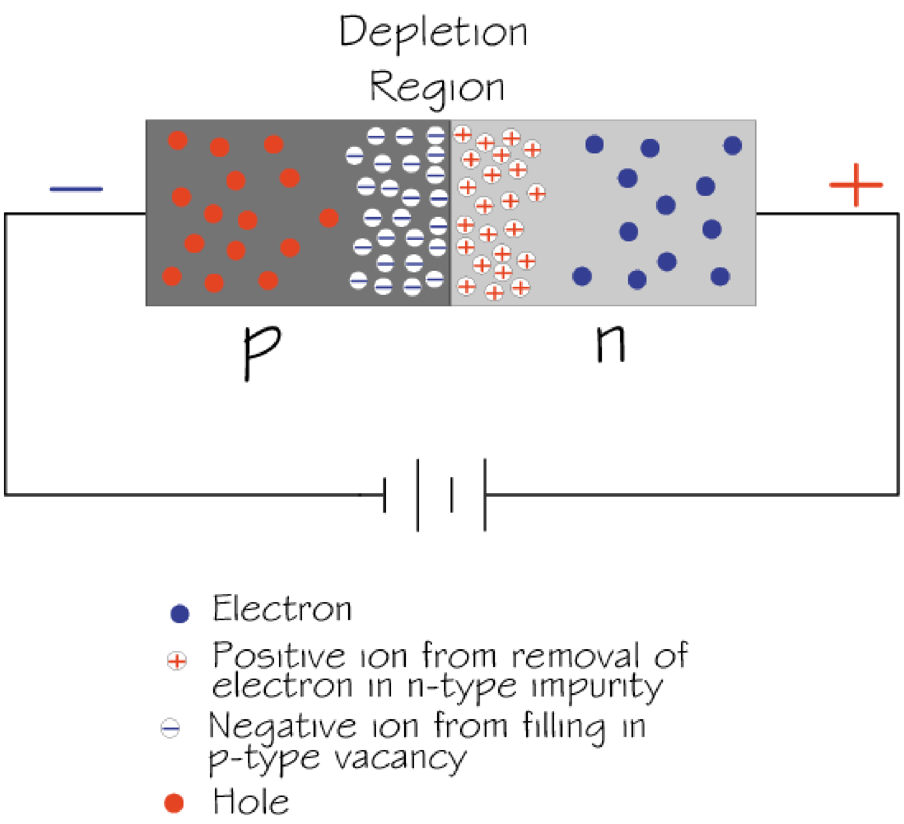
Si-Diode used as a Particle Detector !

At the p-n junction the charges are depleted and a zone free of charge carriers is established.

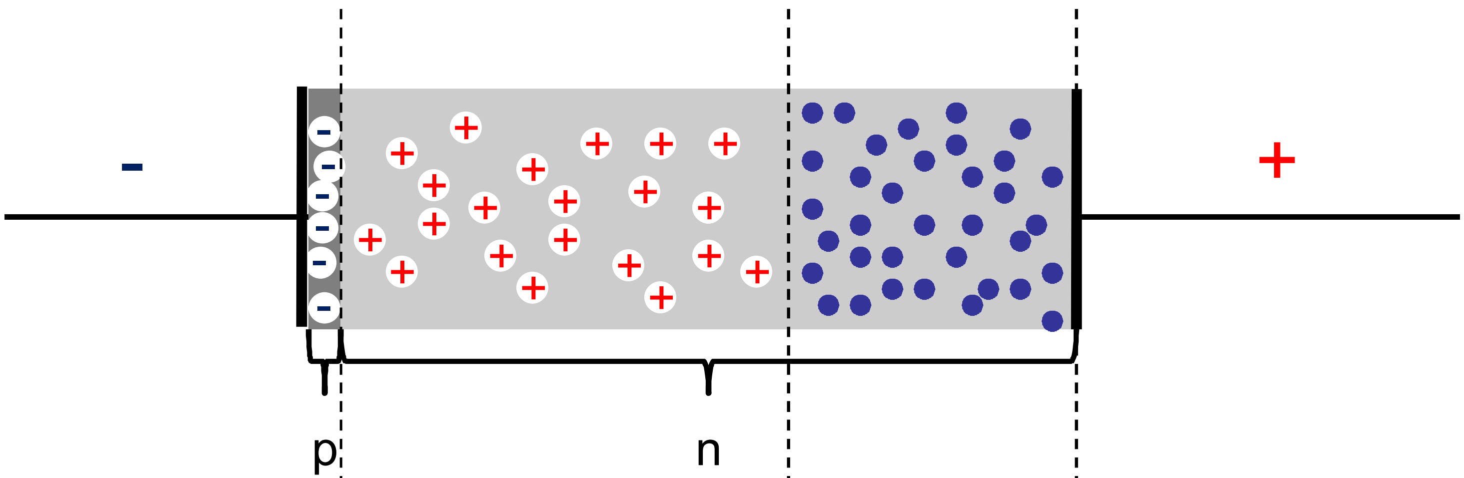
By applying a voltage, the depletion zone can be extended to the entire diode → highly insulating layer.

An ionizing particle produces free charge carriers in the diode, which drift in the electric field and induce an electrical signal on the metal electrodes.

As silicon is the most commonly used material in the electronics industry, it has one big advantage with respect to other materials, namely highly developed technology.

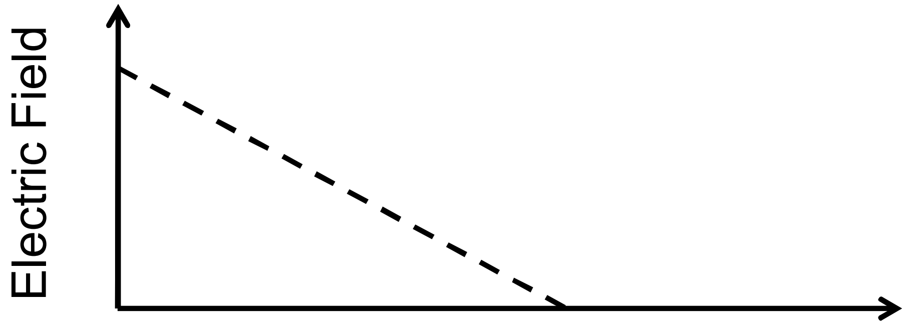


Under-Depleted Silicon Detector

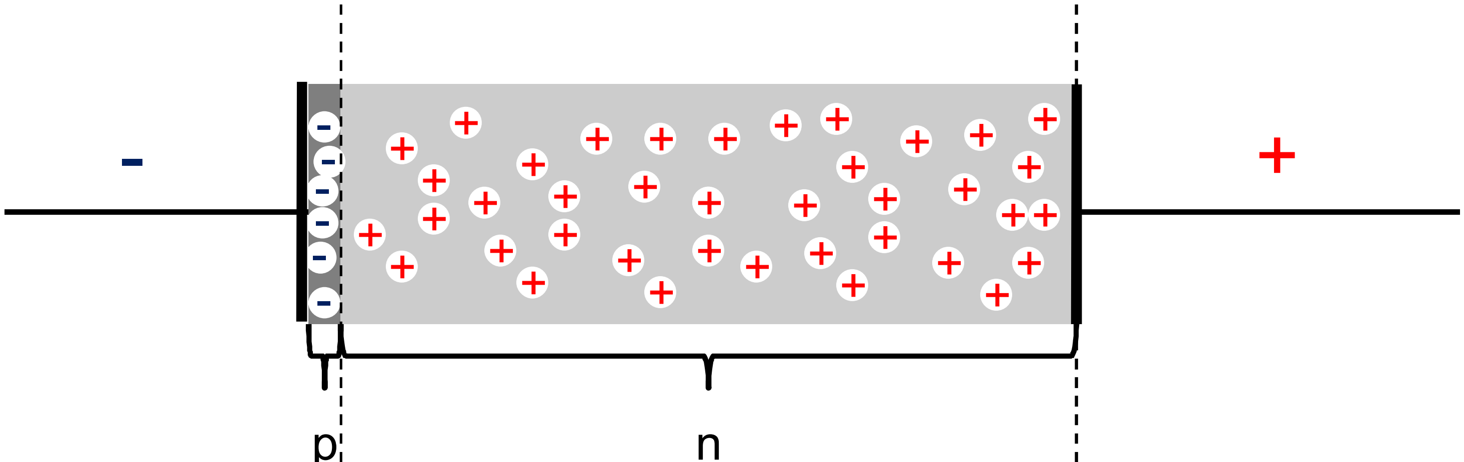


Zone without free charge carriers positively charged. Sensitive Detector Volume.

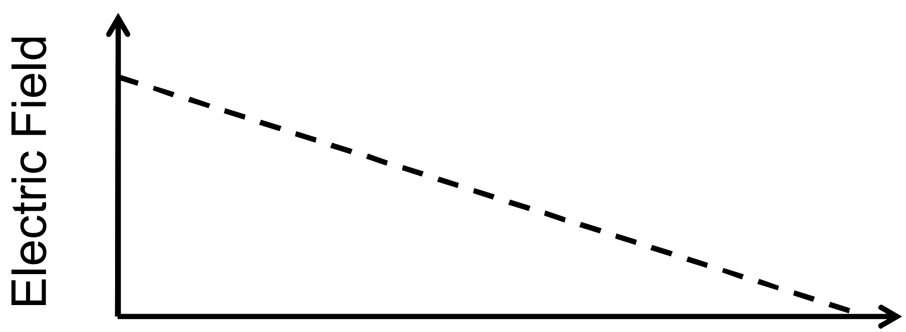
Zone with free electrons. Conductive. Insensitive to particles.



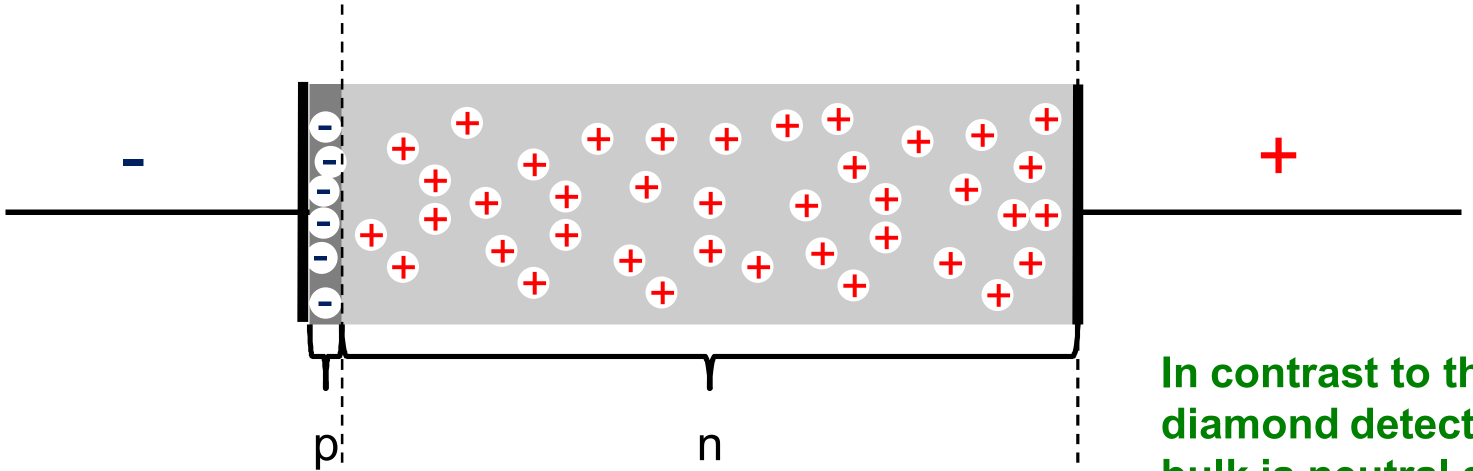
Fully-Depleted Silicon Detector



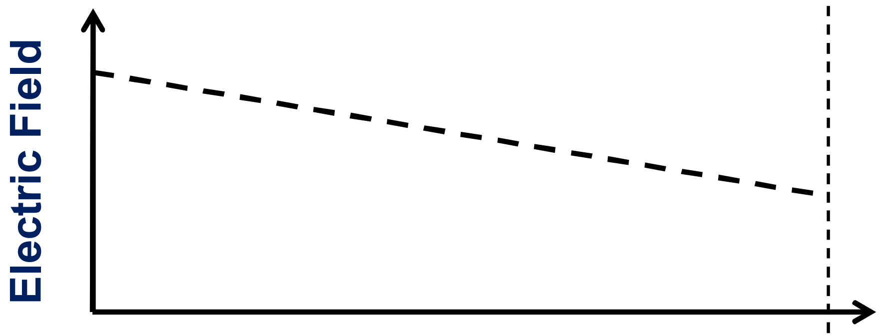
Zone without free charge carriers positively charged.
Sensitive Detector Volume.



Over-Depleted Silicon Detector



Zone without free charge carriers positively charged. Sensitive Detector Volume.

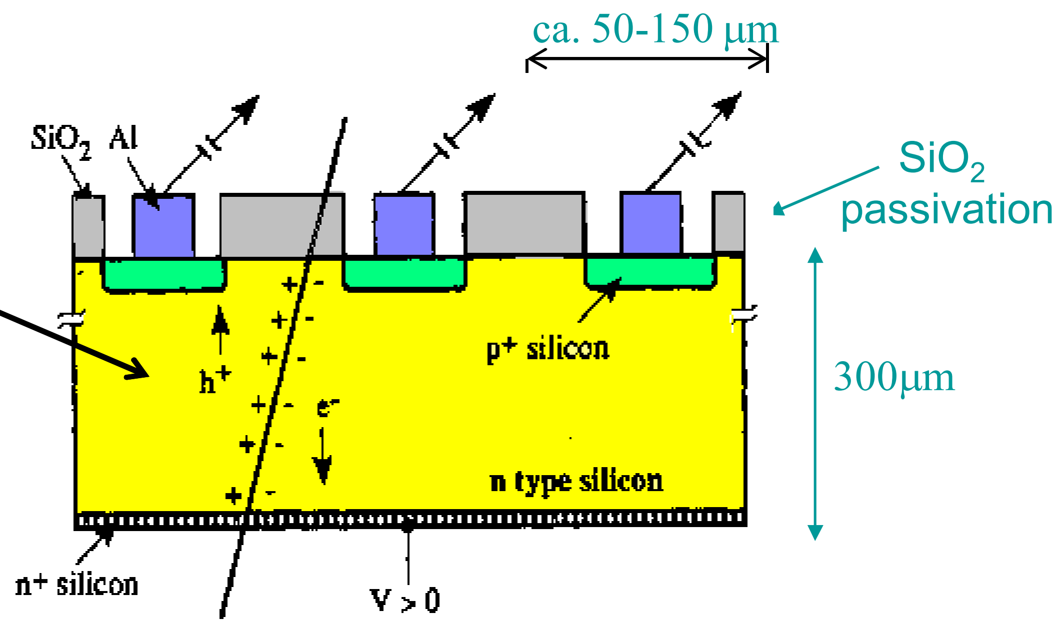


In contrast to the (un-doped) diamond detector where the bulk is neutral and the electric field is therefore constant, the sensitive volume of a doped silicon detector is charged (space charge region) and the field is therefore changing along the detector.

→ Velocity of electrons and holes is not constant along the detector.

Silicon Detector

Fully depleted zone



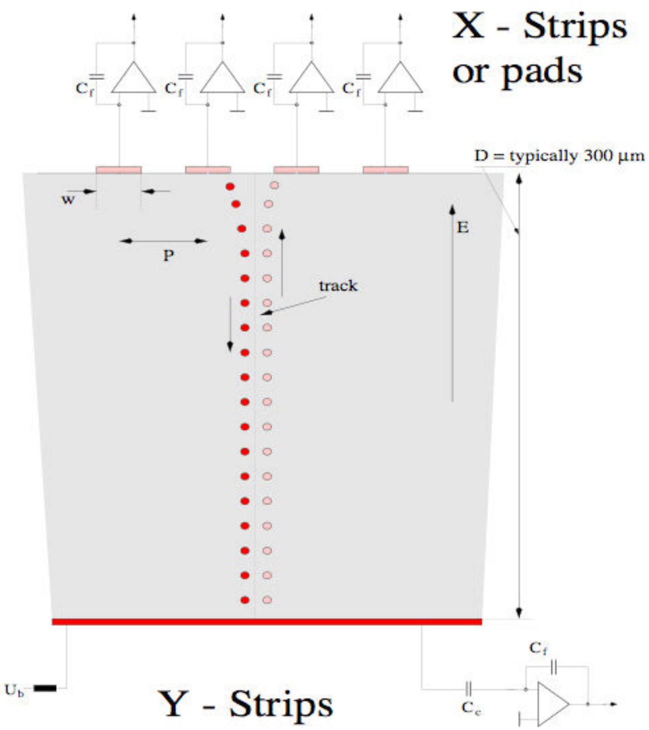
N (e-h) = 11 000/100µm

Position Resolution down to ~ 5µm !

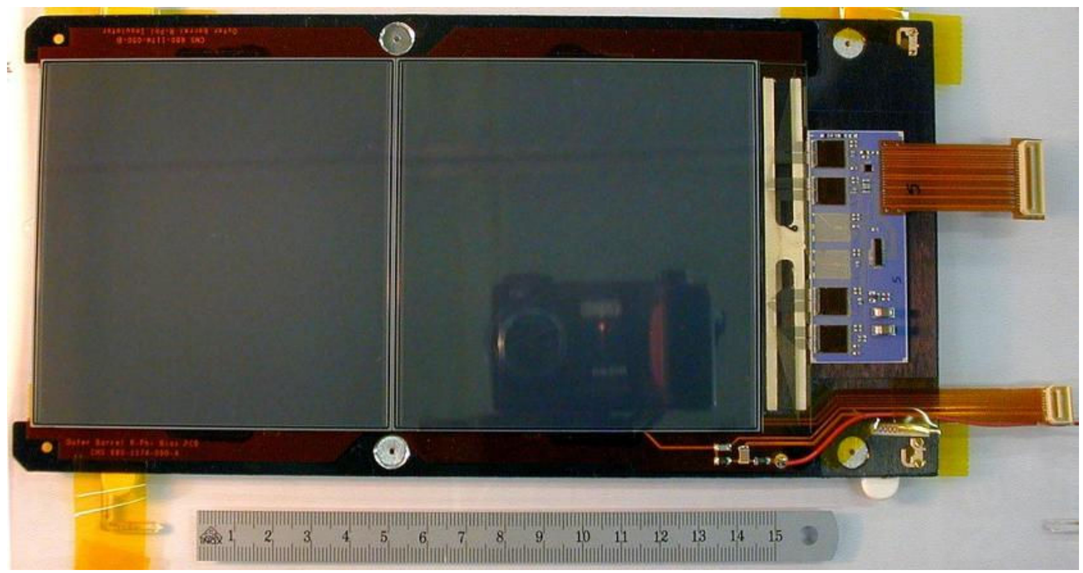
Silicon Detector

Every electrode is connected to an amplifier →
Highly integrated readout electronics.

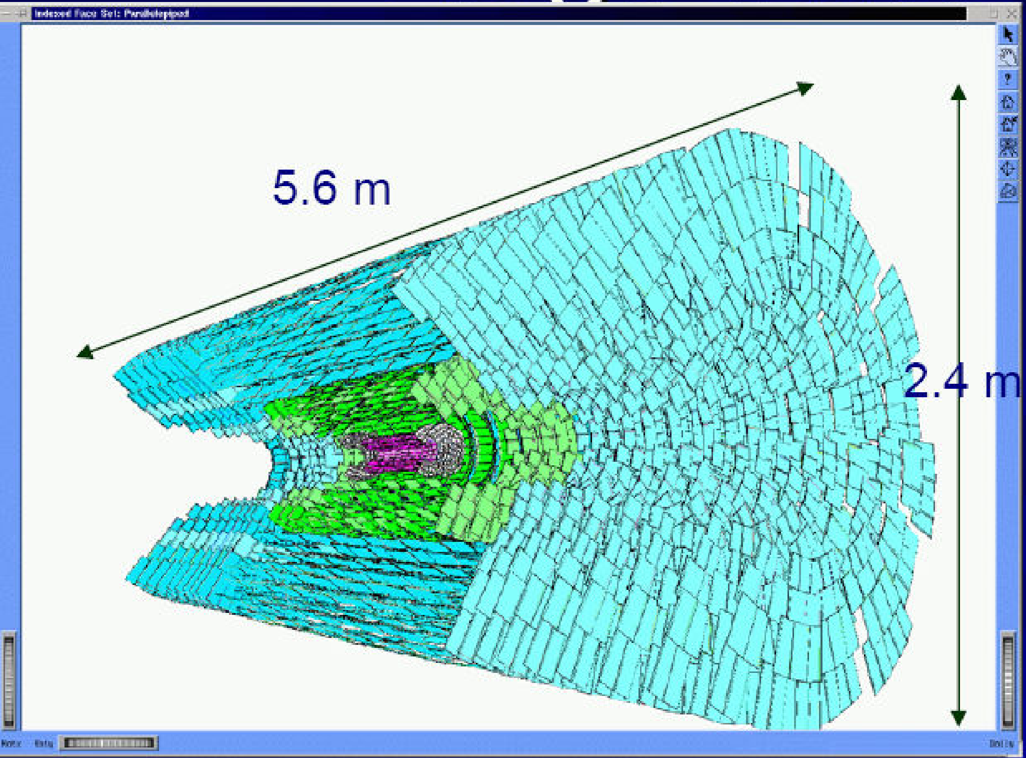
Two dimensional readout is possible.

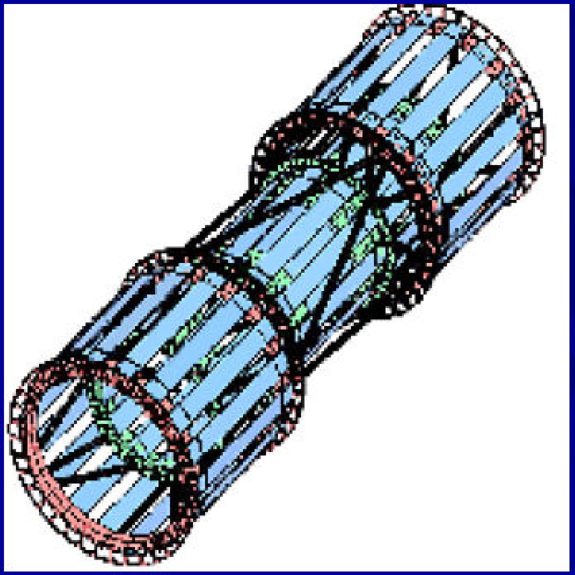


CMS Outer Barrel Module



Large Silicon Systems





CMS tracker (~2007)

12000 modules

~ 445 m^2 silicon area

~ 24,328 silicon wafers

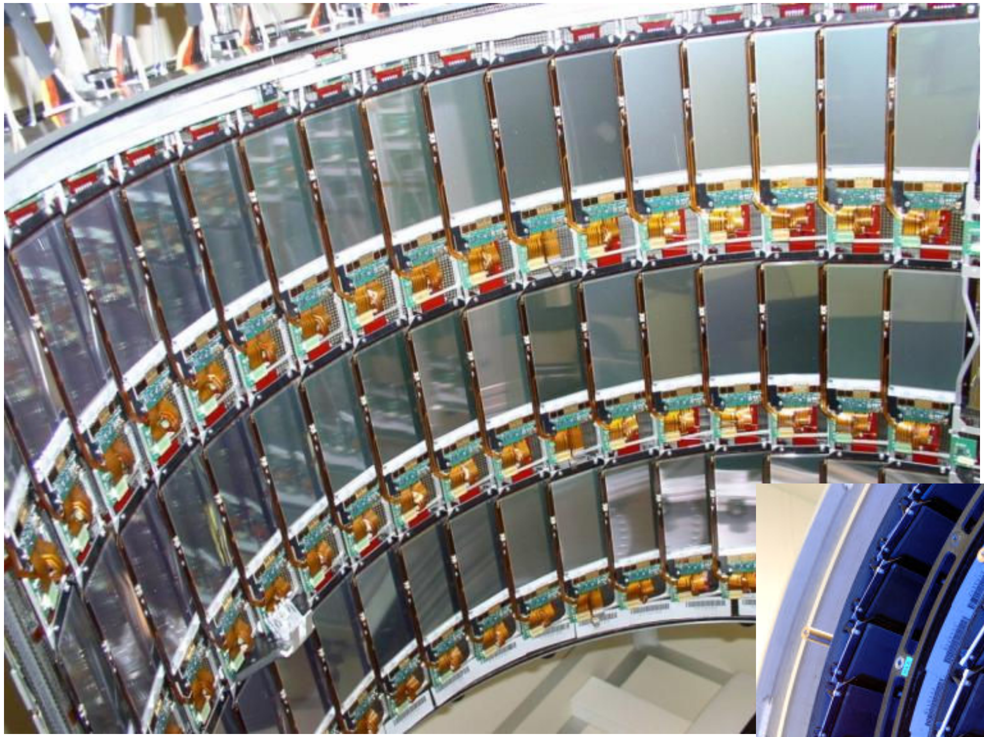
~ 60 M readout channels

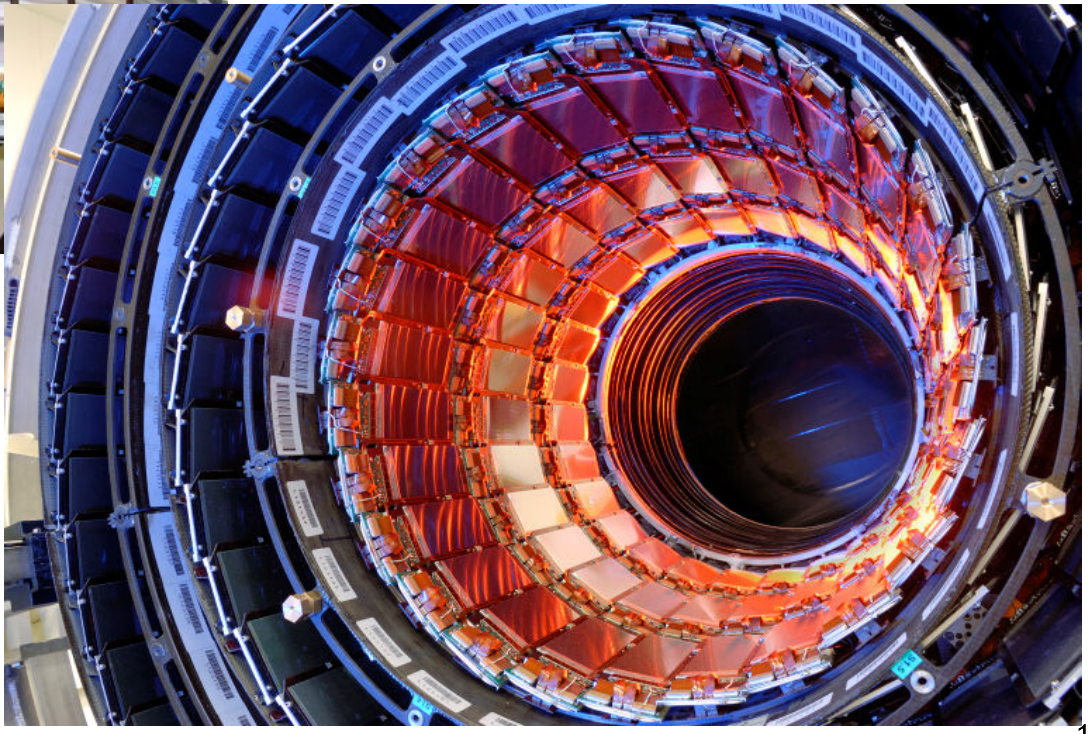
CDF SVX IIa (2001-)

~ 11m^2 silicon area

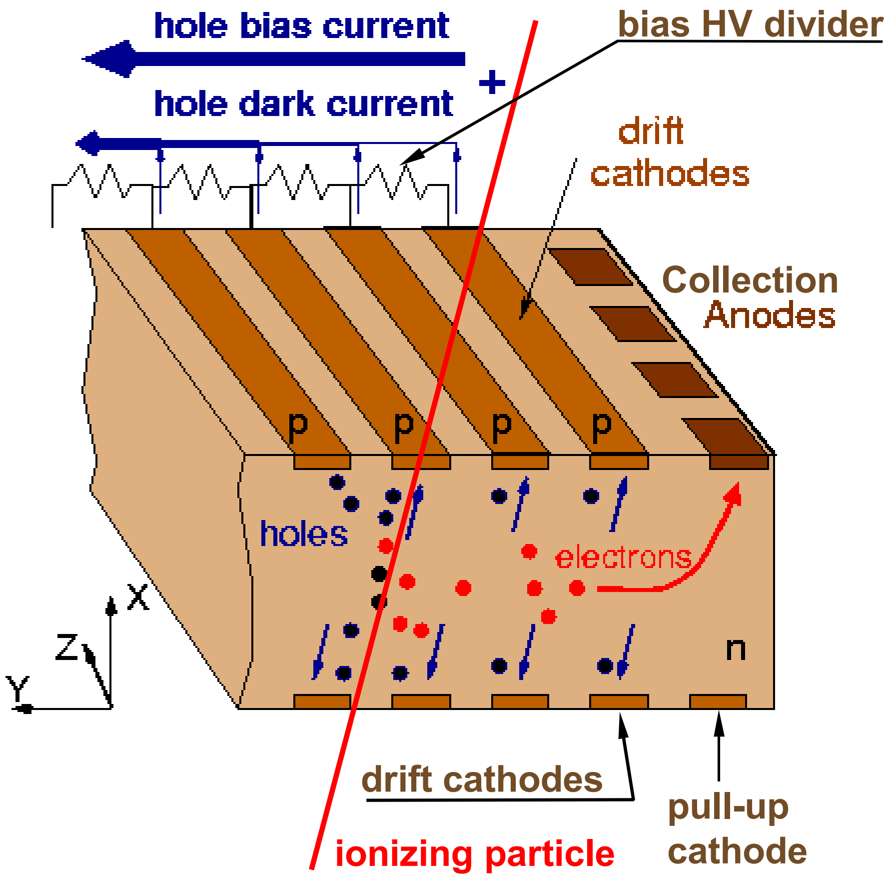
~ 750 000 readout channels

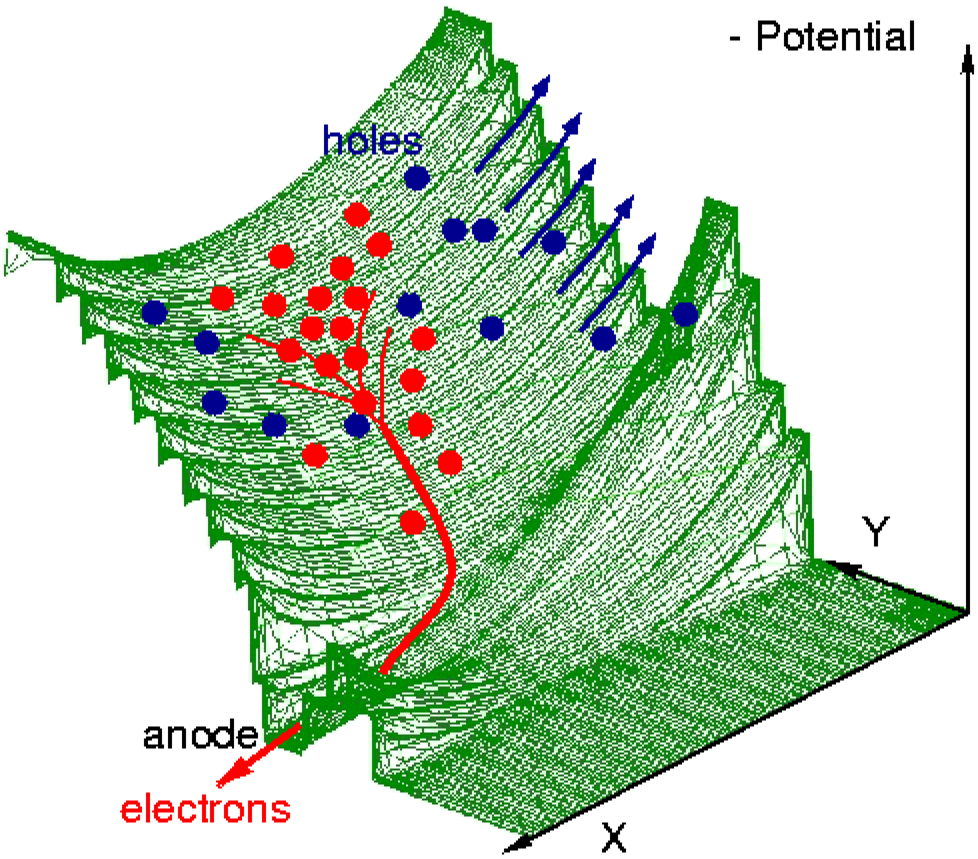
CMS Tracker



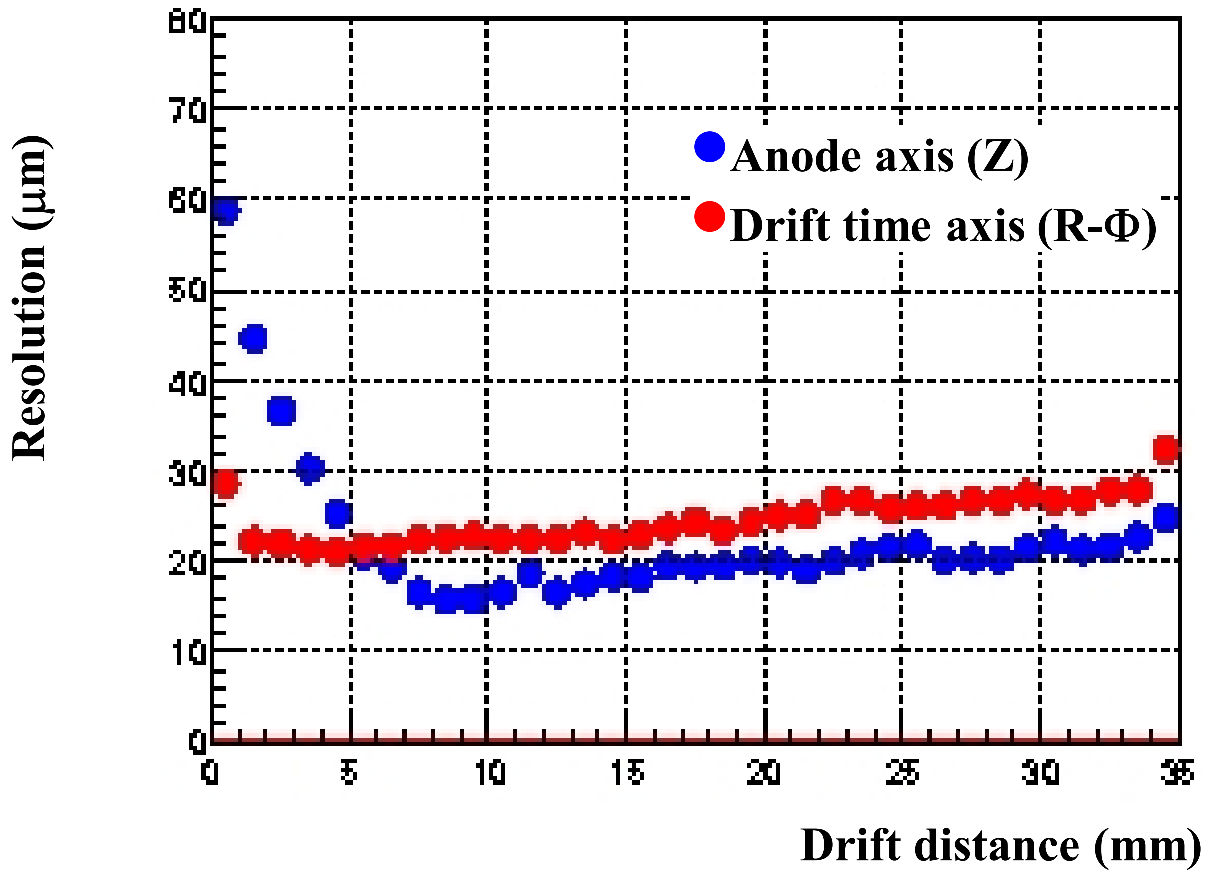


Silicon Drift Detector (like gas TPC !)





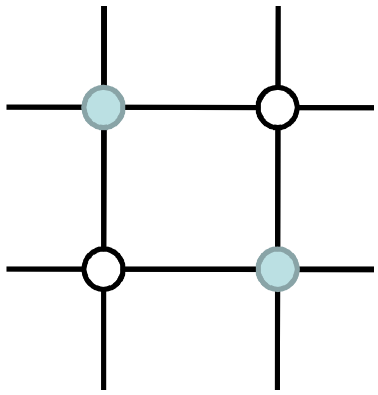
Silicon Drift Detector (like gas TPC !)



Pixel-Detectors

Problem:

2-dimensional readout of strip detectors results in 'Ghost Tracks' at high particle multiplicities i.e. many particles at the same time.



Solution:

Si detectors with 2 dimensional 'chessboard' readout. Typical size 50 x 200 μm.

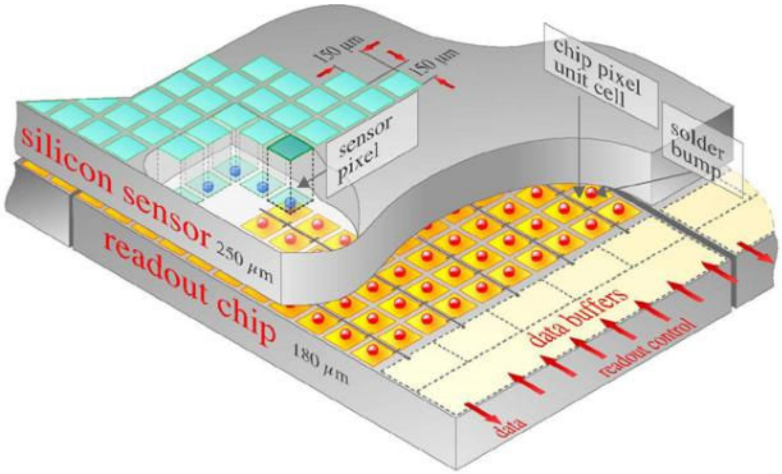
Problem:

Coupling of readout electronics to the detector

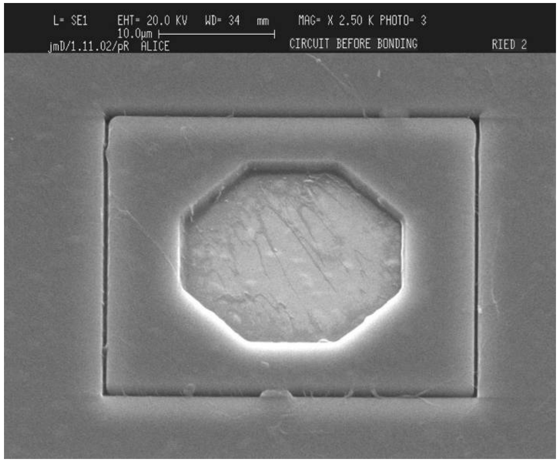
Solution:

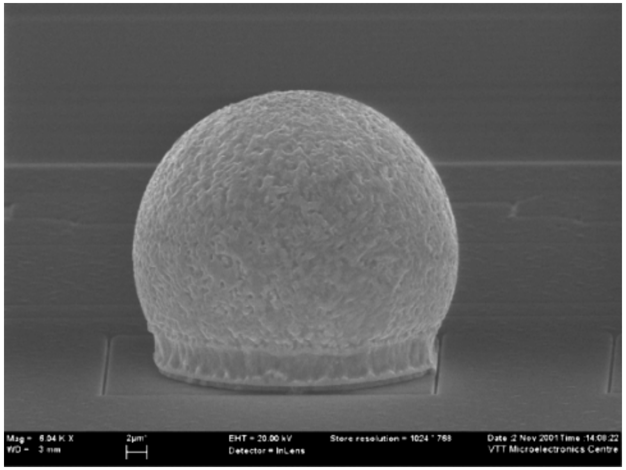
Bump bonding

Bump Bonding of each Pixel Sensor to the Readout Electronics



ATLAS: 1.4x10^8 pixels



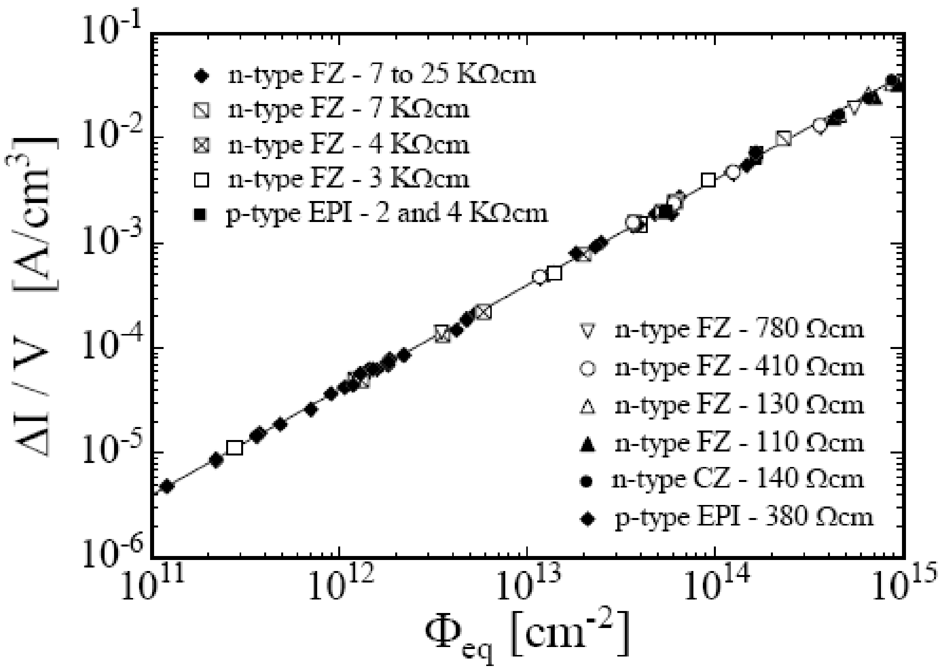


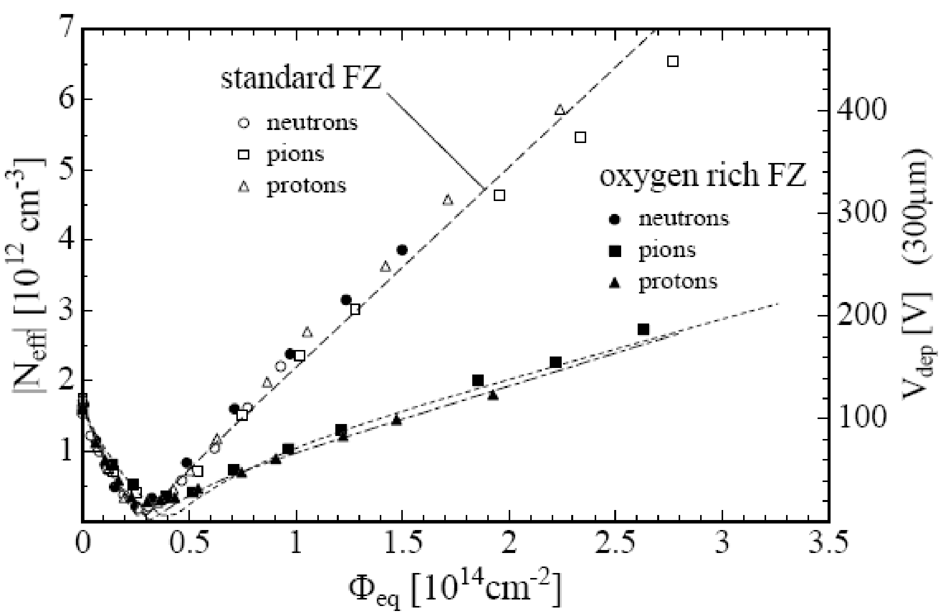
Radiation Effects 'Aging'

Increase in leakage current

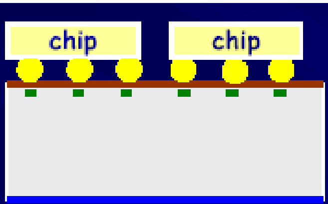
Increase in depletion voltage

Decrease in charge collection efficiency due to under-depletion and charge trapping.

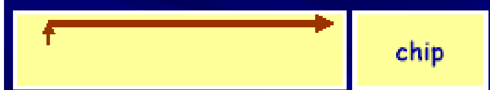




Obvious Goal: Monolithic Solid State Detectors
→Sensor and Readout Electronics as integral unit



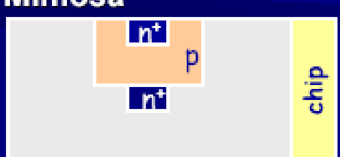
Hybrid Active Pixel: Chip bump bonded to sensor
RD: make it thinner (LHC sensors 2% X_0/layer), improve space point resolution with interleaved pixels



CCD: charge collected in thin layer and transferred through silicon
RD: readout speed, radiation hardness, material support

Poster by Deptuch on Mimosa

CMOS sensors (MAPS, FAPS): standard CMOS wafer integrates all functions.
RD: fast readout, non-standard technologies



DEPFET, CMOS on SOI (talk by Kucewiz) :
Fully depleted sensor with integrated preamp
RD:pixel size, power, thinning, speed

Large variety of monolithic pixel Detectors are explored, Currently mostly adapted to low collision rates of Linear Colliders.

Summary on Solid State Detectors

Solid state detectors provide very high precision tracking in particle physics experiments (down to 5um) for vertex measurement but also for momentum spectroscopy over large areas (CMS).

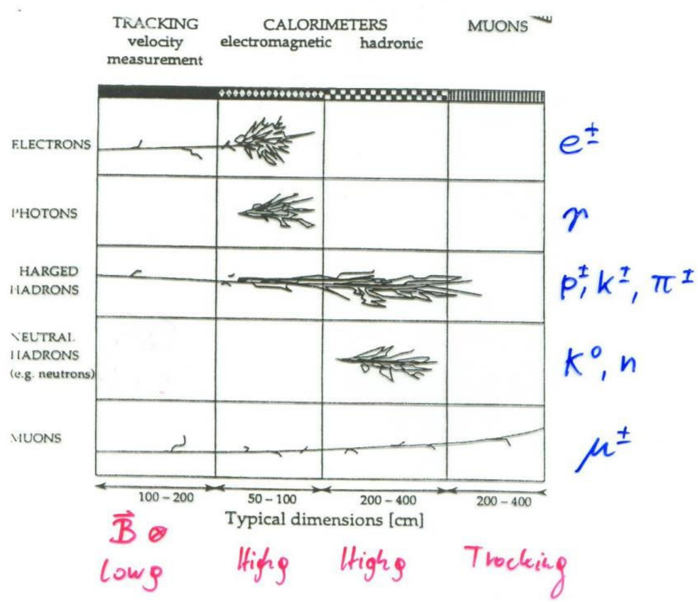
Technology is improving rapidly due to rapid Silicon development for electronics industry.

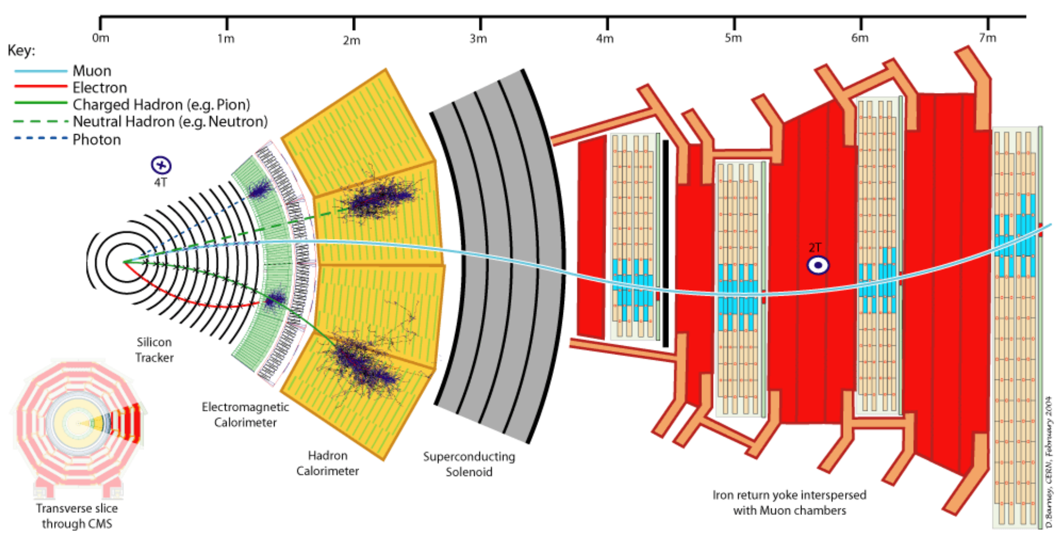
Typical numbers where detectors start to strongly degrade are 10^{14}-10^{15} hadron/cm^2.

Diamond, engineered Silicon and novel geometries provide higher radiation resistance.

Clearly, monolithic solid state detectors are the ultimate goal. Current developments along these lines are useful for low rate applications.

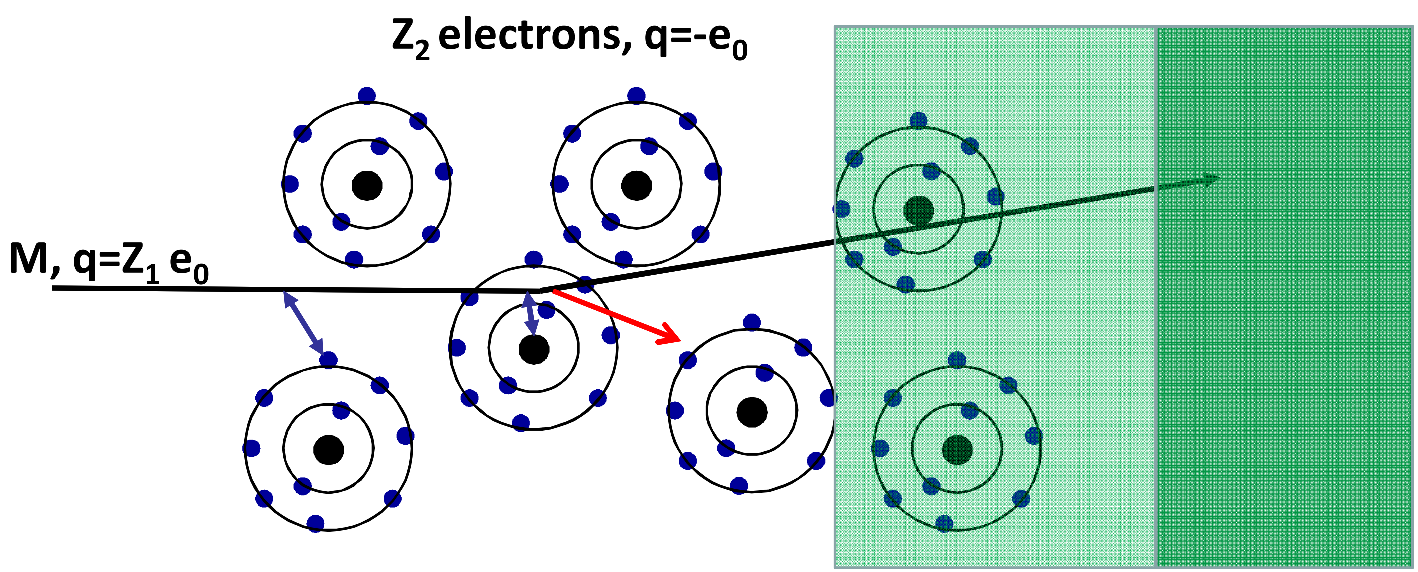
Calorimetry and Particle Identification





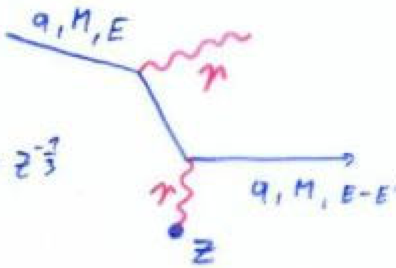
Bremsstrahlung

A charged particle of mass M and charge $q=Z_1e$ is deflected by a nucleus of charge Ze (which is partially 'shielded' by the electrons). During this deflection the charge is 'accelerated' and it therefore radiates → Bremsstrahlung.



Bremsstrahlung, QM

2b Bremsstrahlung QM



$q = Z_1 e, \quad E + Mc^2 \gg 137\, Mc^2 Z^{-\frac{1}{3}}$

→ highly Relativistic:

$$\frac{d\sigma(E,E')}{dE'} = 4\alpha Z^2 Z_1^4 \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{Mc^2}\right)^2 \frac{1}{E'} F(E,E')$$

$$F(E,E') = \left[1 + \left(1 - \frac{E'}{E+Mc^2}\right)^2 - \frac{2}{3}\left(1 - \frac{E'}{E+Mc^2}\right)\right] \ln 183 Z^{-\frac{1}{3}} + \frac{1}{9}\left(1 - \frac{E'}{E+Mc^2}\right)$$

$$\frac{dE}{dx} = -\frac{N_A \rho}{A}\int_0^E E' \frac{d\sigma}{dE'} dE' \approx 4\alpha Z^2 Z_1^4 \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{Mc^2}\right)^2 E \left[\ln 183 Z^{-\frac{1}{3}} + \frac{1}{18}\right]$$

$$\frac{dE}{dx} = -\frac{N_A \rho}{A} 4\alpha Z^2 Z_1^4 \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{Mc^2}\right)^2 E \ln\left(183 Z^{-\frac{1}{3}}\right)$$

$$E(x) = E_0 e^{-\frac{x}{X_0}} \qquad X_0 = \frac{A}{4\alpha N_A \rho Z^2 \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{Mc^2}\right)^2 \ln 183 Z^{-\frac{1}{3}}}$$

X_0 ... Radiation length

Proportional to Z^2/A of the Material.

Proportional to Z_1^4 of the incoming particle.

Proportional to ρ of the material.

Proportional $1/M^2$ of the incoming particle.

Proportional to the Energy of the Incoming particle →

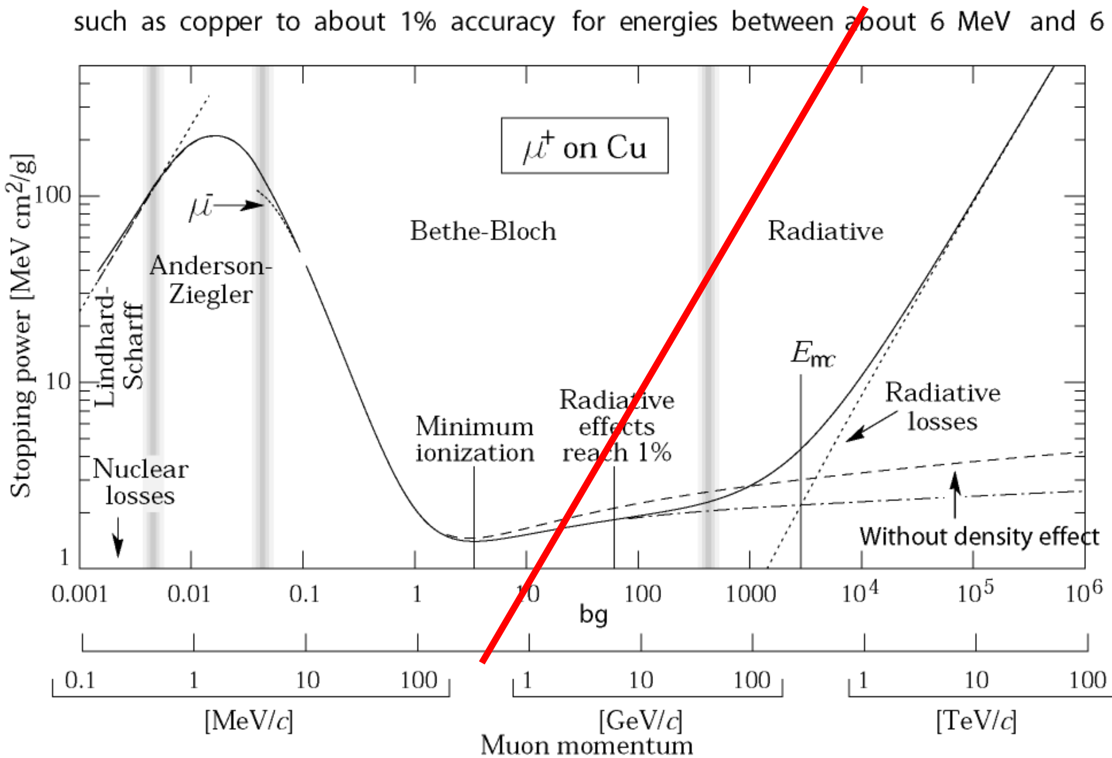
$E(x)=\mathrm{Exp}(-x/X_0)$ – 'Radiation Length'

$X_0 \propto M^2 A / (\rho Z_1^4 Z^2)$

X_0: Distance where the Energy E_0 of the incoming particle decreases $E_0 \mathrm{Exp}(-1)=0.37 E_0$.

Critical Energy

such as copper to about 1% accuracy for energies between about 6 MeV and 6 GeV



Electron Momentum 5 50 500 MeV/c

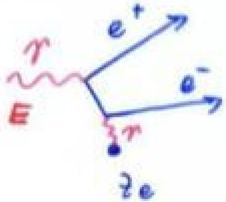
For the muon, the second lightest particle after the electron, the critical energy is at 400GeV.

The EM Bremsstrahlung is therefore only relevant for electrons at energies of past and present detectors.

Critical Energy: If dE/dx (Ionization) = dE/dx (Bremsstrahlung)

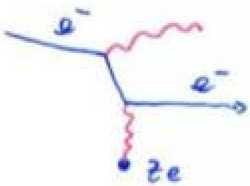
Myon in Copper: p ≈ 400GeV
Electron in Copper: p ≈ 20MeV

Pair Production, QM



$\gamma + \text{Nucl.} \rightarrow e^+ + e^- + \text{Nucl}$

The Diagram is very similar to Bremsstrahlung



$e^- + \text{Nucl} \rightarrow \gamma + e^- + \text{Nucl}$

"Crossing Symmetry: bring particle to the other side and make it the antiparticle" → 'same' crossection ...

$$\frac{d\sigma(E,E')}{dE'} = 4\alpha Z^2 r_e^2 \frac{1}{E} \cdot G(E,E') \qquad E \gg 137 m_e c^2 Z^{-\frac{1}{3}}$$

$$G(E,E') = \left[\left(\frac{E'+m_ec^2}{E}\right)^2 + \left(1-\frac{E'+m_ec^2}{E}\right)^2 + \frac{2}{3}\frac{E'+m_ec^2}{E}\left(1-\frac{E'+m_ec^2}{E}\right)\ln Z^{-\frac{1}{3}} - \frac{1}{9}\frac{E'+m_ec^2}{E}\left(1-\frac{E'+m_ec^2}{E}\right)\right]$$

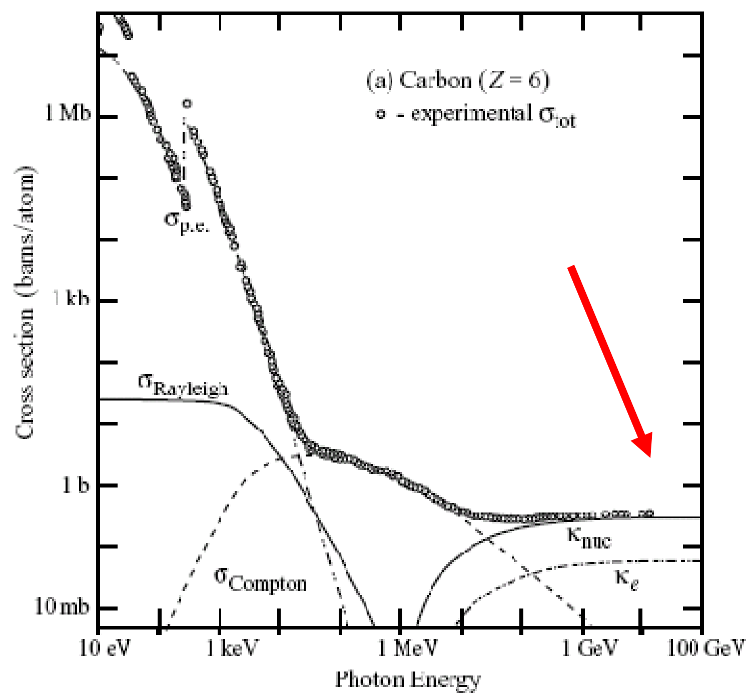
$$\sigma = \int_0^{E-2m_ec^2} \frac{d\sigma}{dE'} dE' = 4\alpha Z^2 r_e^2 \cdot \frac{7}{9} \ln 183 Z^{-\frac{1}{3}}$$

$$P(x) = \frac{1}{\lambda} e^{-\frac{x}{\lambda}} \qquad \lambda = \frac{A}{\rho N_A \sigma} = \frac{9}{7} X_0$$

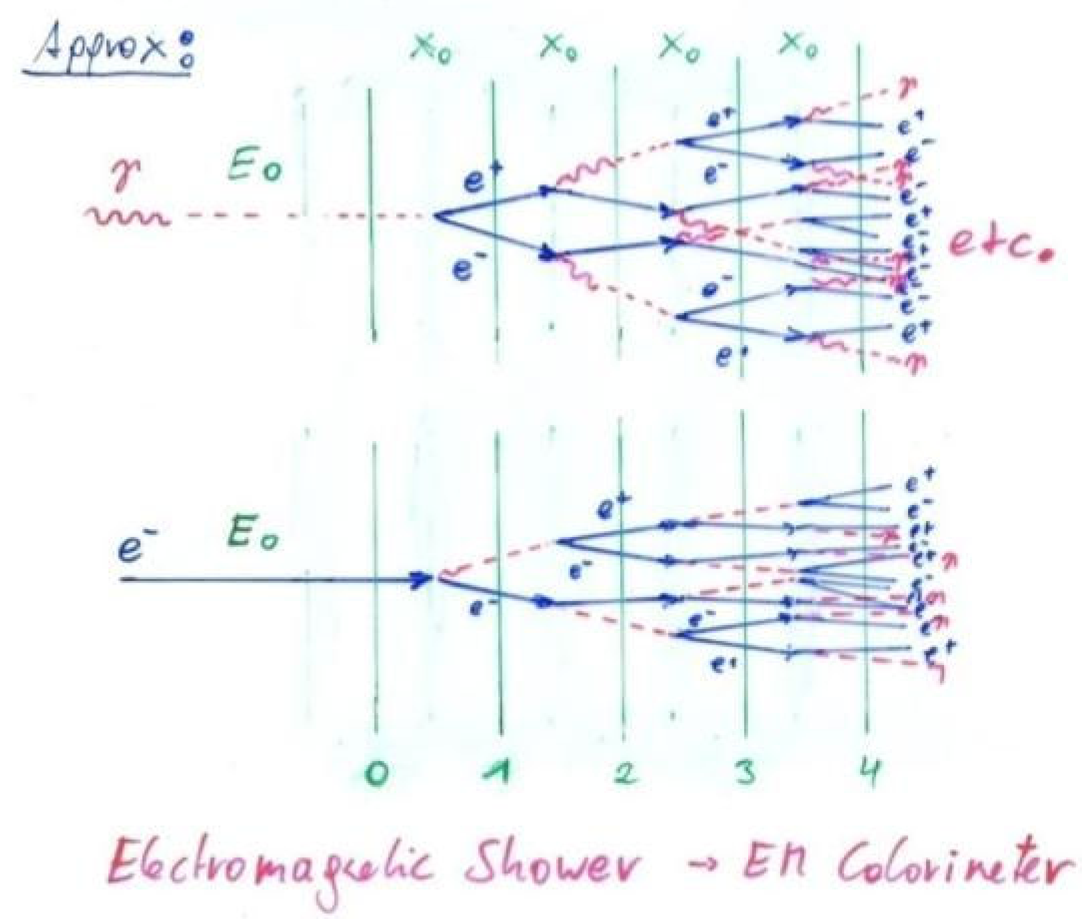
↳ Probability that Photon converts to $e^+ e^-$ after a distance x.

For $E\gamma \gg m_ec^2 = 0.5\,\text{MeV}$: $\lambda = 9/7 X_0$

Average distance a high energy photon has to travel before it converts into an $e^+ e^-$ pair is equal to 9/7 of the distance that a high energy electron has to travel before reducing it's energy from E_0 to E_0*Exp(-1) by photon radiation.



Bremsstrahlung + Pair Production → EM Shower



Electro-Magnetic Shower of High Energy Electrons and Photons

$N(n) = 2^n$ ..... Number of particles ($e^\pm, \gamma$) after $n X_0$

$E(n) = \frac{E_0}{2^n}$ .... Average Energy of particles after $n X_0$

Shower stops if $E(n) = E_{critical}$

$\rightarrow n_{max} = \frac{1}{\ln 2} \ln \frac{E_0}{E_c}$ $\rightarrow$ Shower length rises with $\ln E_0$

Number of $e^\pm$ track segments (of length X_0) after $n X_0$:

$$N_{tr}(n) = 2^n$$

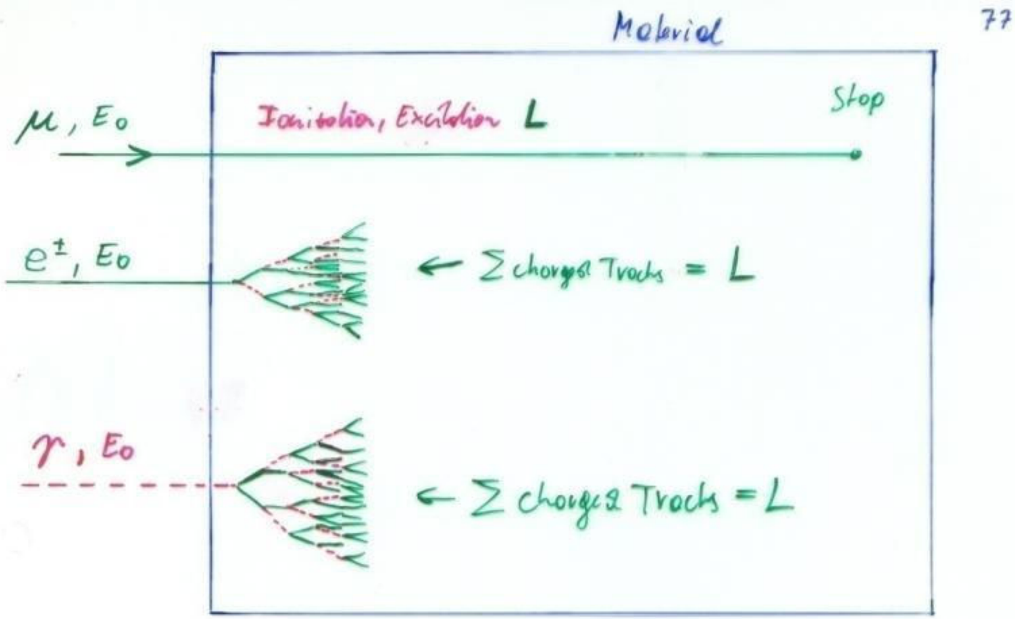
Total $e^\pm$ track length (after $n_{max} X_0$)

$$L = \sum_{n=0}^{n_{max}} 2^n X_0 = \left(2 \frac{E_0}{E_c} - 1\right) X_0 \sim 2 \frac{E_0}{E_c} X_0 = c_1 \cdot E_0$$

Total (charged) track length is proportional to the Energy of the Particle.

$\rightarrow$ Calorimeter Principle

Calorimetry: Energy Measurement by total Absorption of Particles



The $e^\pm$ in the Calorimeter ionize and excite the Material

Ionization: e^-, I^+ pairs in the Material

Excitation: Photons in the Material

Measuring the total Number of e^-, I^+ pairs or the total Number of Photons gives the particle Energy.

If N is the total Number of e^-, I^+ pairs or photons, or $N = c_1 E_0$:

$\Delta N = \sqrt{N}$ (Poisson Statistics)

$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = \frac{1}{\sqrt{N}} = \frac{a}{\sqrt{E}} \rightarrow \text{Resolution}$$

Only Electrons and High Energy Photons show EM cascades at current GeV-TeV level Energies.

Strongly interacting particles like Pions, Kaons, produce hadonic showers in a similar fashion to the EM cascade →Hadronic calorimetry

Momentum Spectrometer: Δp/p α p

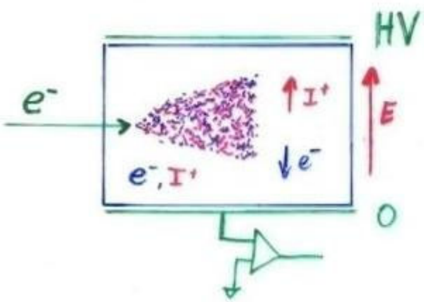
Calorimeter: Δ E/E α 1/ √ E

Energy measurement improves with higher particle energies – LHC !

Calorimetry: Energy Measurement by total Absorption of Particles

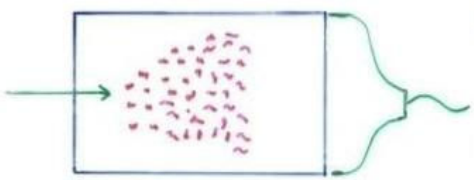
The Measurement is destructive. The particle can not be subject to further study.

Energy Measurement by



Collecting the produced Charge

Liquid Nobel Gases (Nobel Liquids)



Measuring the Photons produced by the collision of the $e^\pm$ with Atom Electrons of the Material.

Scintillating Crystals, Plastic Scintillators

Total Amount of e^-, I^+ pairs or Photons is proportional to the total track length is proportional to the particle Energy.

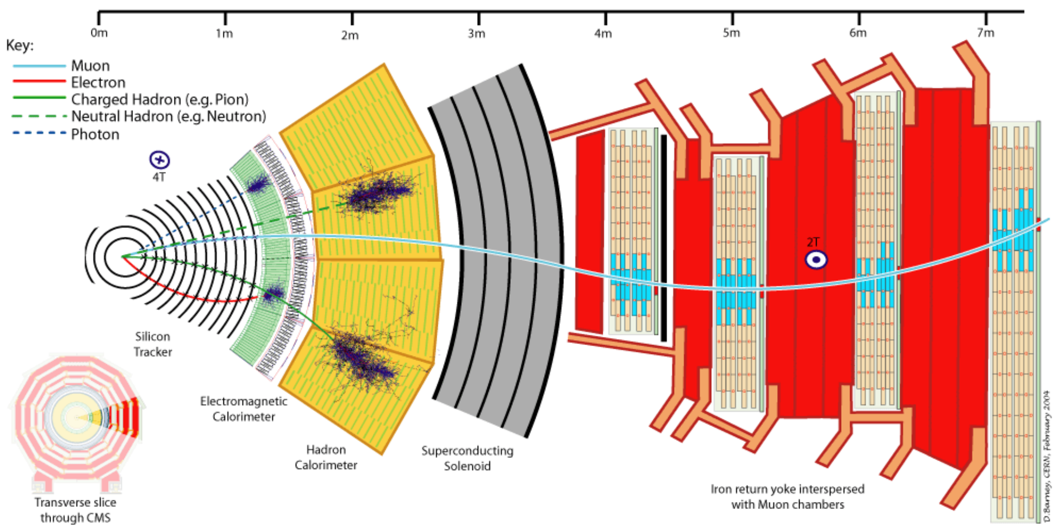
Calorimetry

Calorimeters are blocks of instrumented material in which particles to be measured are fully absorbed and their energy transformed into a measurable quantity.

The interaction of the incident particle with the detector (through electro-magnetic or strong processes) produces a shower of secondary particles with progressively degraded energy.

The energy deposited by the charged particles of the shower in the active part of the calorimeter, which can be detected in the form of charge or light, serves as a measurement of the energy of the incident particle.

C.W. Fabjan and F. Gianotti, Rev. Mod. Phys., Vol. 75, N0. 4, October 2003



Calorimetry

Calorimeters can be classified into:

Electromagnetic Calorimeters,
to measure electrons and photons through their EM interactions.

Hadron Calorimeters,
Used to measure hadrons through their strong and EM interactions.

The construction can be classified into:

Homogeneous Calorimeters,
that are built of only one type of material that performs both tasks, energy degradation and signal generation.

Sampling Calorimeters,
that consist of alternating layers of an absorber, a dense material used to degrade the energy of the incident particle, and an active medium that provides the detectable signal.

C.W. Fabjan and F. Gianotti, Rev. Mod. Phys., Vol. 75, N0. 4, October 2003

Calorimetry

Calorimeters are attractive in our field for various reasons:

In contrast with magnet spectrometers, in which the momentum resolution deteriorates linearly with the particle momentum, on most cases the calorimeter energy resolution improves as 1/Sqrt(E), where E is the energy of the incident particle. Therefore calorimeters are very well suited for high-energy physics experiments.

In contrast to magnet spectrometers, calorimeters are sensitive to all types of particles, charged and neutral. They can even provide indirect detection of neutrinos and their energy through a measurement of the event missing energy.

Calorimeters are commonly used for trigger purposes since they can provide since they can provide fast signals that are easy to process and interpret.

They are space and therefore cost effective. Because the shower length increases only logarithmically with energy, the detector thickness needs to increase only logarithmically with the energy of the particles. In contrast for a fixed momentum resolution, the bending power BL^2 of a magnetic spectrometer must increase linearly with the particle momentum.

C.W. Fabjan and F. Gianotti, Rev. Mod. Phys., Vol. 75, N0. 4, October 2003

EM Calorimetry

Approximate longitudinal shower development

$N(n) = 2^n$ ..... Number of particles $(e^\pm, \gamma)$ after $n X_0$

$E(n) = \frac{E_0}{2^n}$ .... Average Energy of particles after $n X_0$

Shower stops if $E(n) = E_{critical}$

$\Rightarrow n_{max} = \frac{1}{\ln 2} \ln \frac{E_0}{E_c}$ $\rightarrow$ Shower length rises with $\ln E_0$

Radiation Length X_0 and Moliere Radius are two key parameters for choice of calorimeter materials

Approximate transverse shower development

The transverse Shower Dimension is mainly related to the Multiple scattering of the low Energy Electrons.

$$\Theta_0 \sim \frac{21\,[\mathrm{MeV}]}{\beta\, p\,[\frac{\mathrm{MeV}}{c}]}\, z_1 \cdot \sqrt{\frac{x}{X_0}}$$

Electrons E_c , $E \sim p \cdot c$

$$\Theta_0 \sim \frac{21\,[\mathrm{MeV}]}{\beta\, E_c\,[\mathrm{MeV}]} \cdot z_1 \cdot \sqrt{\frac{x}{X_0}} \qquad z_1 = 1,\ \beta \sim 1$$

$$E_c \sim \frac{610}{Z+1.24}\ \mathrm{MeV} \sim \frac{610}{Z}\ \mathrm{MeV}$$

$$\Theta_0 = 0.0344 \cdot Z \cdot \sqrt{\frac{x}{X_0}}$$

Moliere Radius ρ_m = Lateral Shower Radius after $1 X_0$:

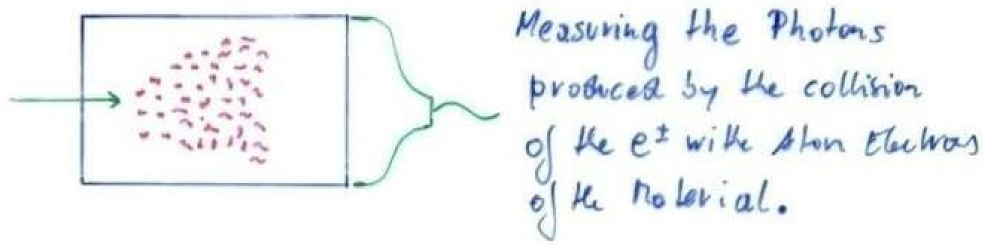
$$\rho_m \approx 0.0344 \cdot Z \cdot X_0$$

95% of Energy are in a Cylinder of $2\rho_m$ Radius.

Crystals for Homogeneous EM Calorimetry

In crystals the light emission is related to the crystal structure of the material. Incident charged particles create electron-hole pairs and photons are emitted when electrons return to the valence band.

The incident electron or photon is completely absorbed and the produced amount of light, which is reflected through the transparent crystal, is measured by photomultipliers or solid state photon detectors.



Crystals for Homogeneous EM Calorimetry

	NaI(Tl)	CsI(Tl)	CsI	BGO	$PbWO_4$
Density (g/cm^3)	3.67	4.53	4.53	7.13	8.28
X_0 (cm)	2.59	1.85	1.85	1.12	0.89
R_M (cm)	4.5	3.8	3.8	2.4	2.2
Decay time (ns)	250	1000	10	300	5
slow component			36		15
Emission peak (nm)	410	565	305	410	440
slow component			480		
Light yield γ/MeV	4×10^4	5×10^4	4×10^4	8×10^3	1.5×10^2
Photoelectron yield (relative to NaI)	1	0.4	0.1	0.15	0.01
Rad. hardness (Gy)	1	10	10^3	1	10^5

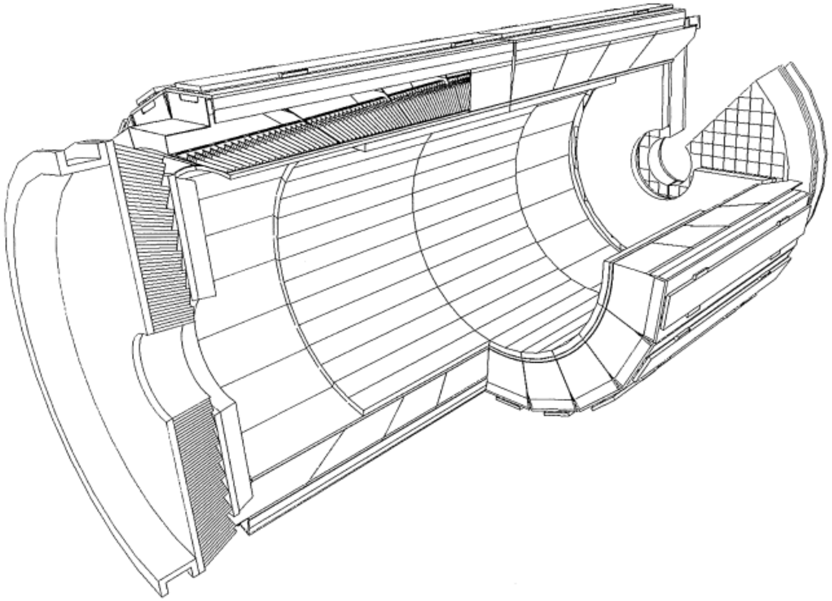
Barbar@PEPII, 10ms interaction rate, good light yield, good S/N

KTeV@Tevatron, High rate, Good resolution

L3@LEP, 25us bunch crossing, Low radiation dose

CMS@LHC, 25ns bunch crossing, high radiation dose

Crystals for Homogeneous EM Calorimetry



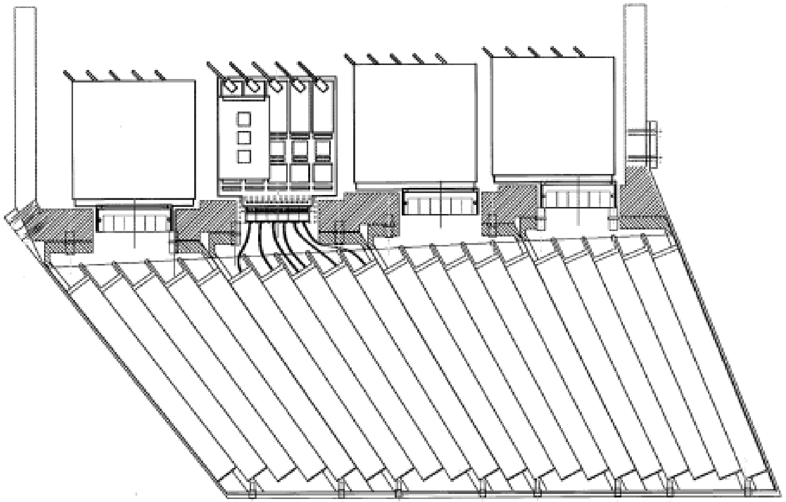
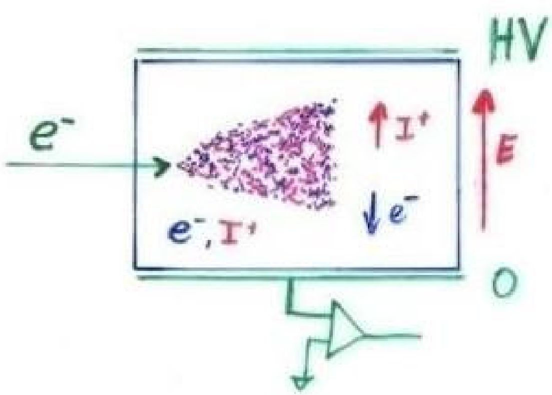


Fig. 2. Longitudinal drawing of module 2, showing the structure and the front-end electronics layout.

Noble Liquids for Homogeneous EM Calorimetry

	Ar	Kr	Xe
Z	18	36	58
A	40	84	131
X_0 (cm)	14	4.7	2.8
R_M (cm)	7.2	4.7	4.2
Density (g/cm^3)	1.4	2.5	3.0
Ionization energy (eV/pair)	23.3	20.5	15.6
Critical energy ϵ (MeV)	41.7	21.5	14.5
Drift velocity at saturation (mm/μs)	10	5	3

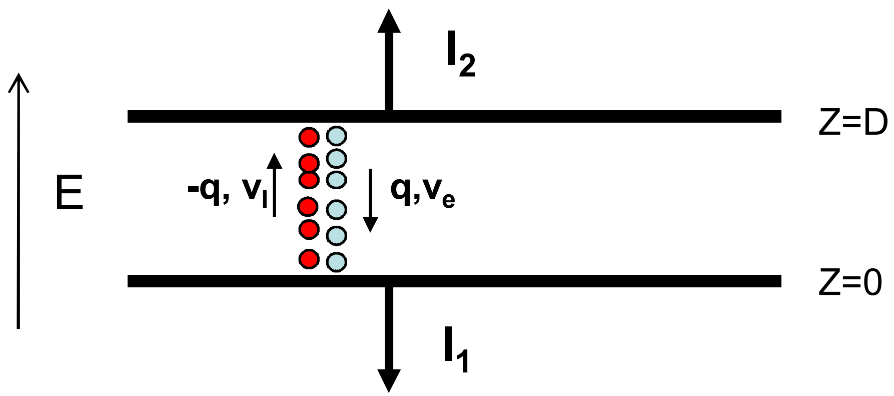


When a charge particle traverses these materials, about half the lost energy is converted into ionization and half into scintillation.

The best energy resolution would obviously be obtained by collecting both the charge and light signal. This is however rarely done because of the technical difficulties to extract light and charge in the same instrument.

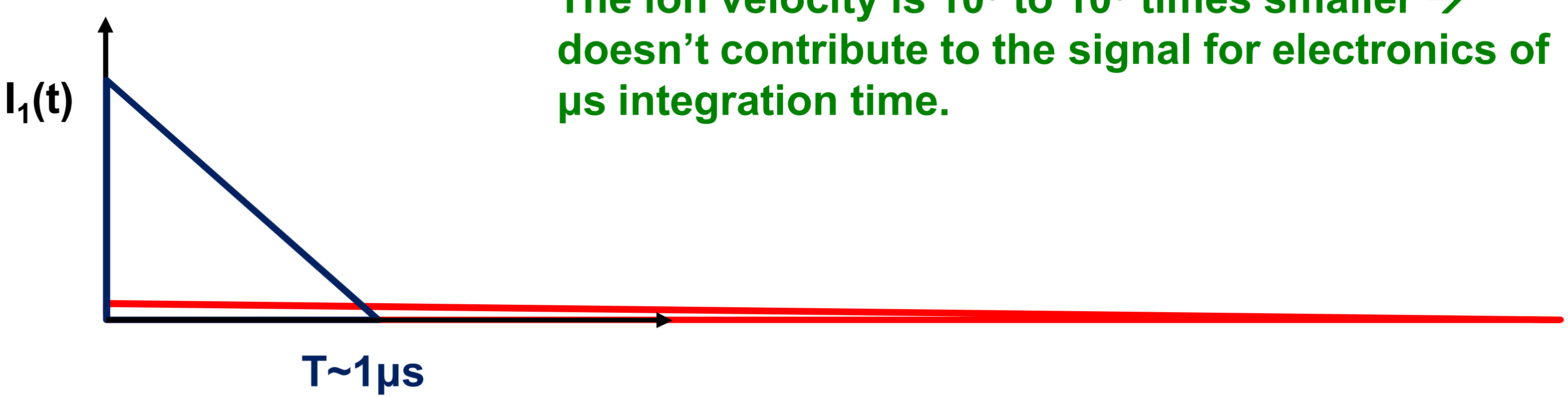
Krypton is preferred in homogeneous detectors due to small radiation length and therefore compact detectors. Liquid Argon is frequently used due to low cost and high purity in sampling calorimeters (see later).

Noble Liquids for Homogeneous EM Calorimetry



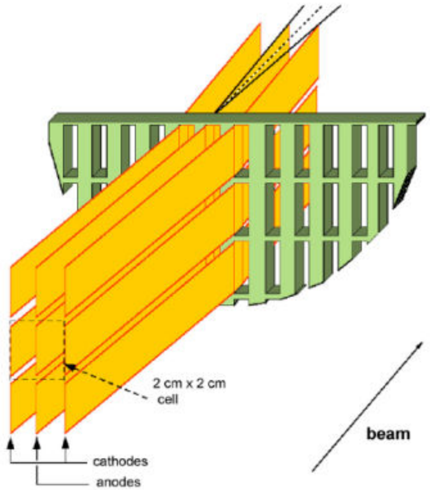
E.g. Liquid Argon, 5mm/ μs at 1kV/cm, 5mm gap → 1 μs for all electrons to reach the electrode.

The ion velocity is 10^3 to 10^5 times smaller → doesn’t contribute to the signal for electronics of μs integration time.



Homogeneous EM Calorimeters, Examples

NA48 Liquid Krypton
2cmx2cm cells
X_0 = 4.7cm
125cm length (27X_0)
ρ = 5.5cm



KTeV CsI
5cmx5cm and
X_0 = 1.85cm
2.5cmx2.5cm crystals
50cm length (27X_0)
ρ = 3.5cm

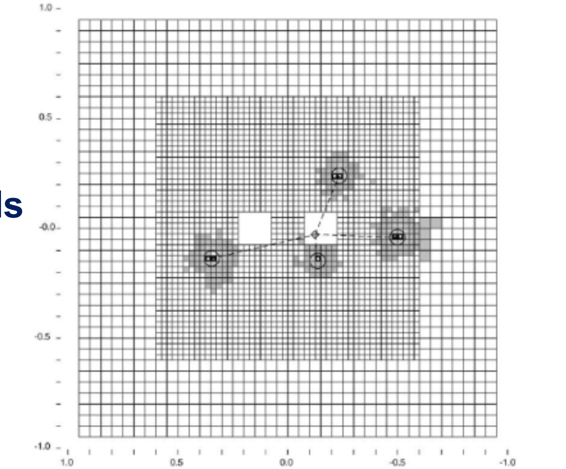
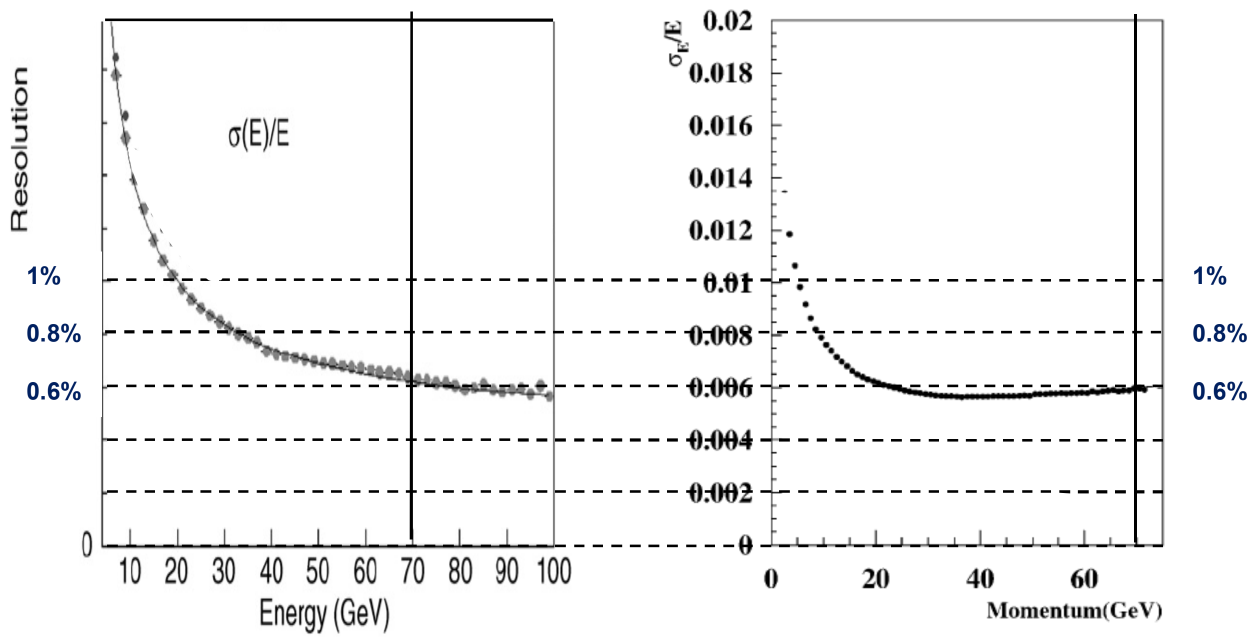
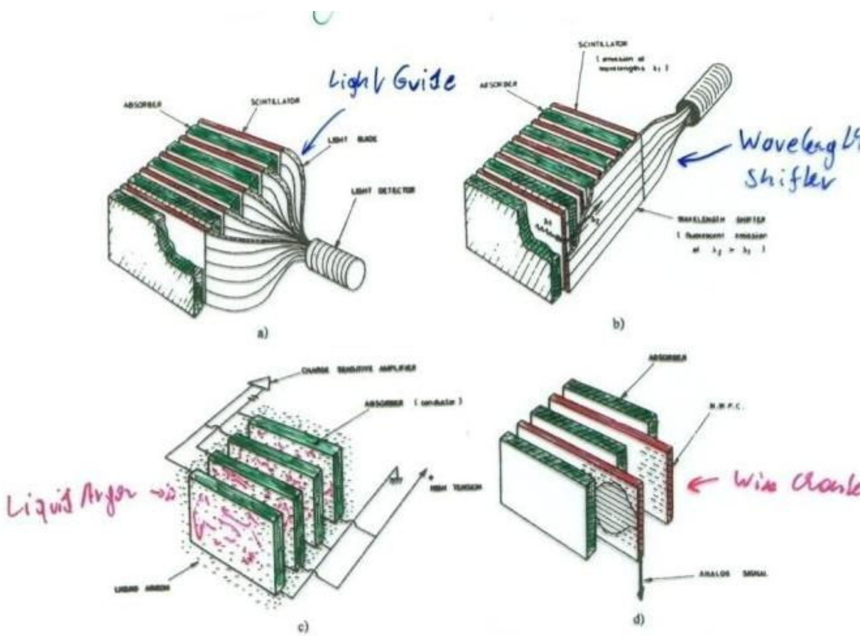


Fig. 1. Schematic of the KTeV CsI Calorimeter showing the cluster energy profiles due to four photons.

NA48 Experiment at CERN and KTeV Experiment at Fermilab, both built for measurement of direct CP violation. Homogenous calorimeters with Liquid Krypton (NA48) and CsI (KTeV). Excellent and very similar resolution.



Sampling Calorimeters



Alternation of "passive" absorber plates and "active" readout sections

Advantage:
- optimum choice of Absorber Material
- optimum choice of Signal Readout
- Compact and cheap Construction

"passive": Pb, Fe ....

"active": Scintillator (Signal -> Photons)

Noble Liquid, e.g. Ar (Signal -> e^-, I^+)

Wire Chambers (Signal -> e^-, I^+)

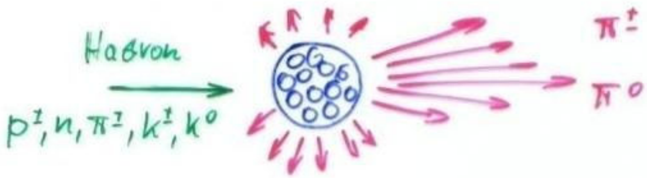
Energy resolution of sampling calorimeters is in general worse than that of homogeneous calorimeters, owing to the sampling fluctuations – the fluctuation of ratio of energy deposited in the active and passive material.

The resolution is typically in the range 5-20%/Sqrt[E(GeV)] for EM calorimeters. On the other hand they are relatively easy to segment longitudinally and laterally and therefore they usually offer better space resolution and particle identification than homogeneous calorimeters.

The active medium can be scintillators (organic), solid state detectors, gas detectors or liquids.

Sampling Fraction = Energy deposited in Active/Energy deposited in passive material.

Hadronic Calorimetry



Strong Interaction

Approximate Energy Distribution

~50%	~20%	~30%
π^+, π^- $\pi^0 \to \gamma\gamma$	Nuclear Excitation	Slow Nucleons
	5–30 MeV	
	p, n, γ	

π^+, π^- → π^+, π^- ; π^+, π^-, π^0 → $\gamma\gamma$

Hadron kaskade

$\pi^0 \to \gamma\gamma$ → Electromagnetic Component

In Hadronic Cascades the Longitudinal Shower is given by the Absorbtion Length λ_a $I \sim e^{-\frac{x}{\lambda_a}}$

In typical Detector Materials λ_a is much larger than X_0

$$\lambda \sim \frac{1}{\rho} \cdot 35\, A^{\frac{1}{3}}$$

	ρ	X_0	λ
Fe	7.87	1.76 cm	~17 cm
Pb	11.35	0.56 cm	~17 cm

Energy Resolution:

- A large Fraction of the Energy 'disappears' into
  - Binding Energy of emitted Nucleons
  - $\pi \to \mu + \nu$ which are not absorbed
- π^0's Decaying into $\gamma\gamma$ start an EM Cascade ($\tau \sim 10^{-16}$ s)

– Energy Resolution is worse than for EM Calorimeters

W. Riegler/CERN

Hadron Calorimeters are Large because ● is large

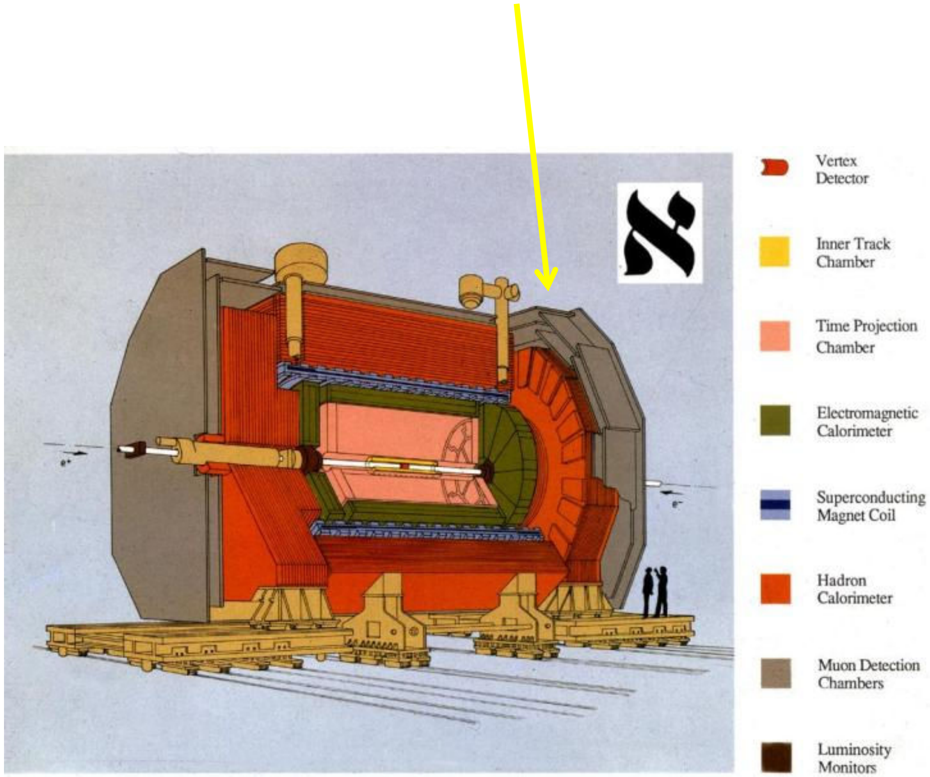
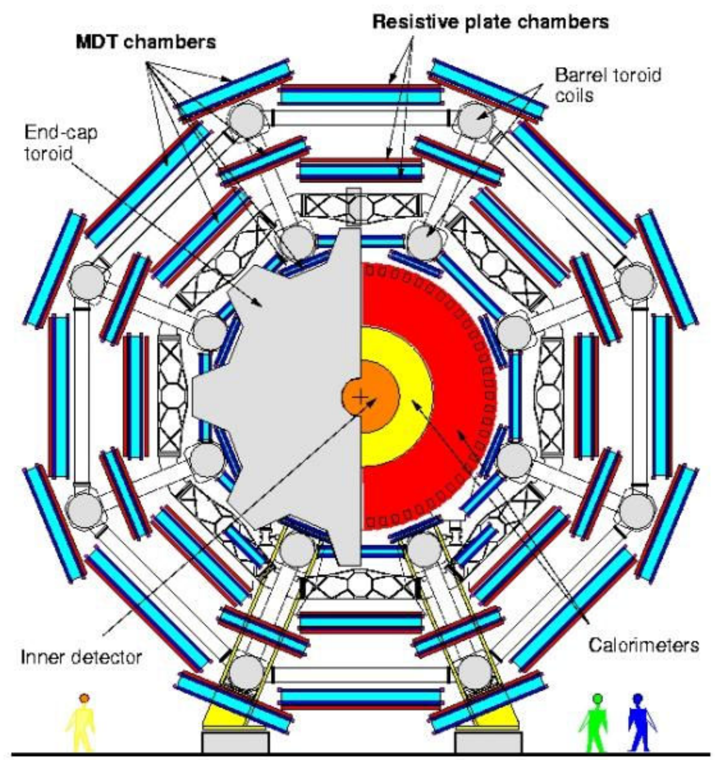


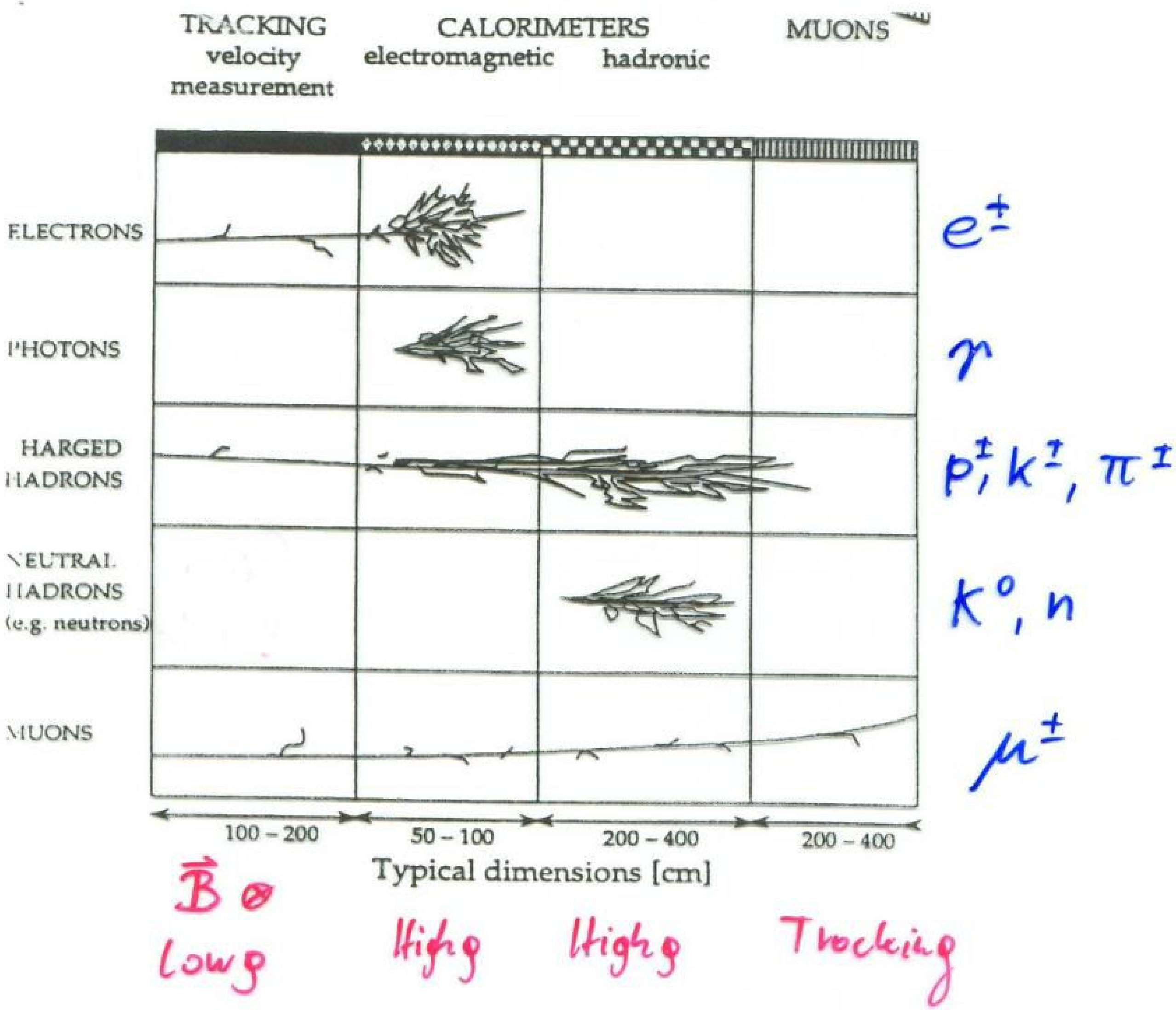
Fig. 1 - The ALEPH Detector

Hadron Calorimeters are large and heavy because the hadronic interaction length ●, the 'strong interaction equivalent' to the EM radiation length X_0, is large (5-10 times larger than X_0)



Because part of the energy is 'invisible' (nuclear excitation, slow nucleons), the resolution of hadron calorimeters is typically worse than in EM calorimeters 20-100%/Sqrt[E(GeV)] .

Particle Identification

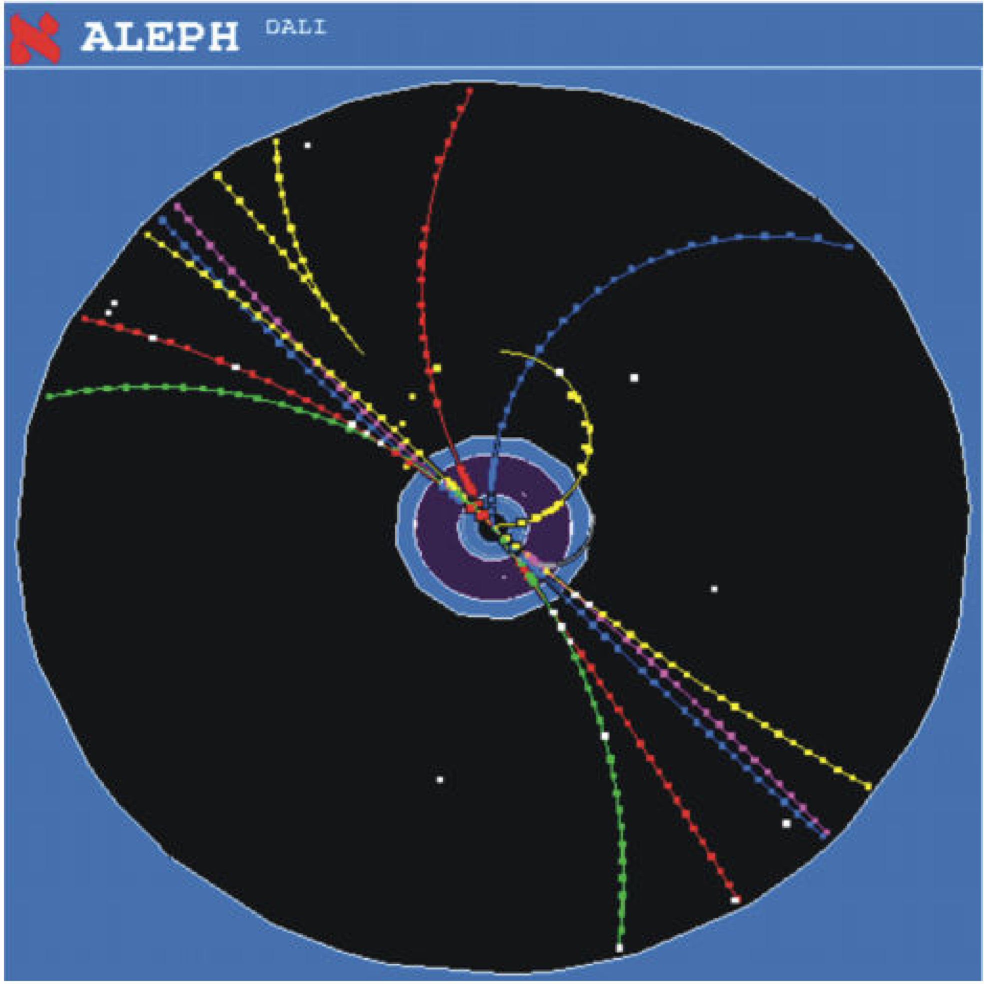


Particle Identification

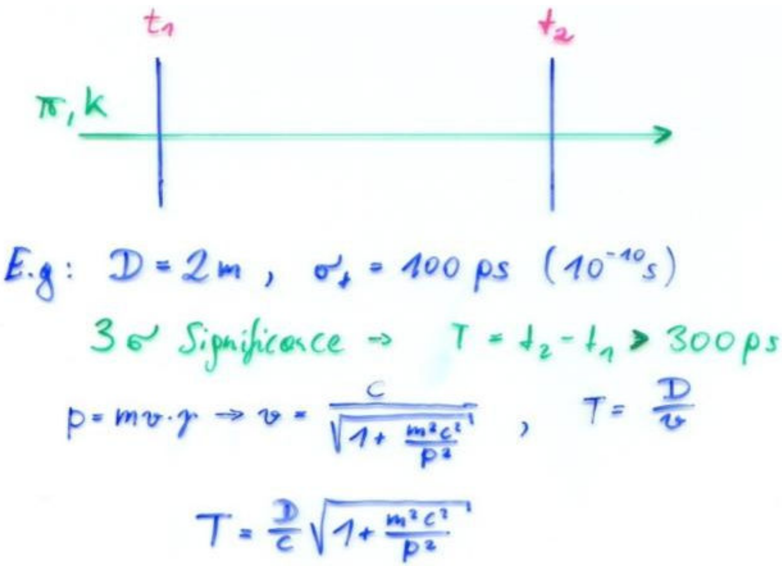
The momentum of a charged particle is determined by the bending radius in the magnetic field.

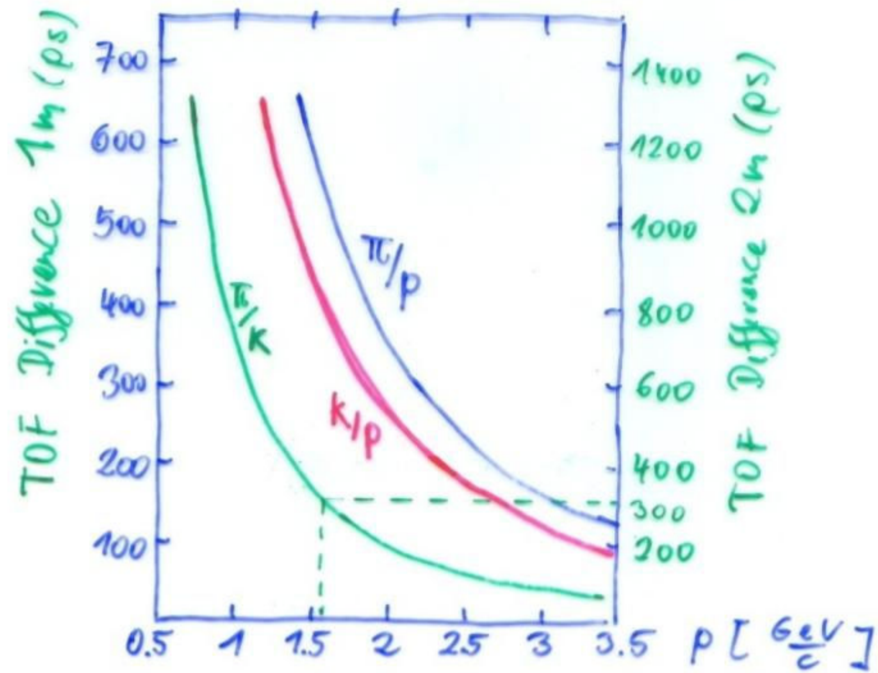
$$p = \frac{m_0 v}{\sqrt{1 - \frac{v^2}{c^2}}}$$

If we measure the velocity in addition to the momentum we find the mass i.e. the particle type !



Time of Flight (TOF)

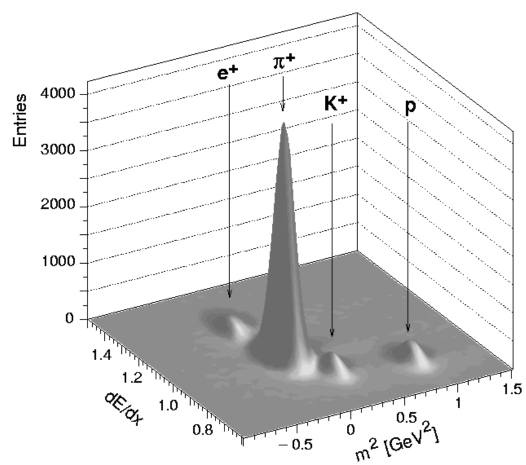


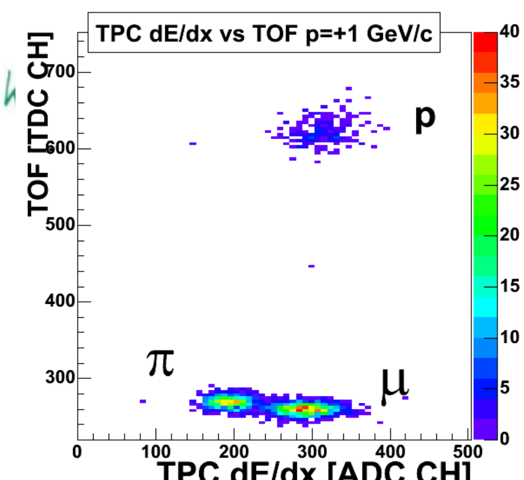


Detectors with the best possible time resolution are needed. With Scintillators or Resistive Plate Chambers, <50ps can be achieved !

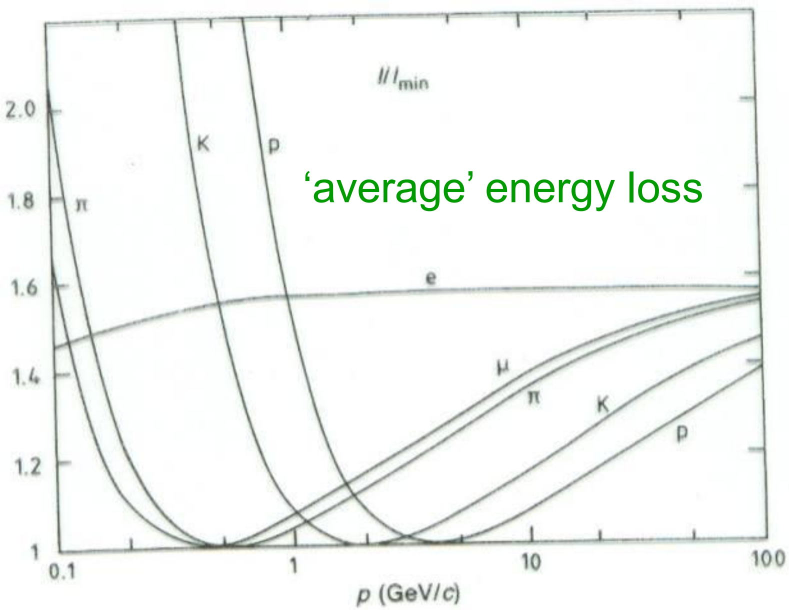
Kaon, Pion, Proton separation up to a few GeV/c.

NA49 combined particle ID: TOF + dE/dx (TPC)

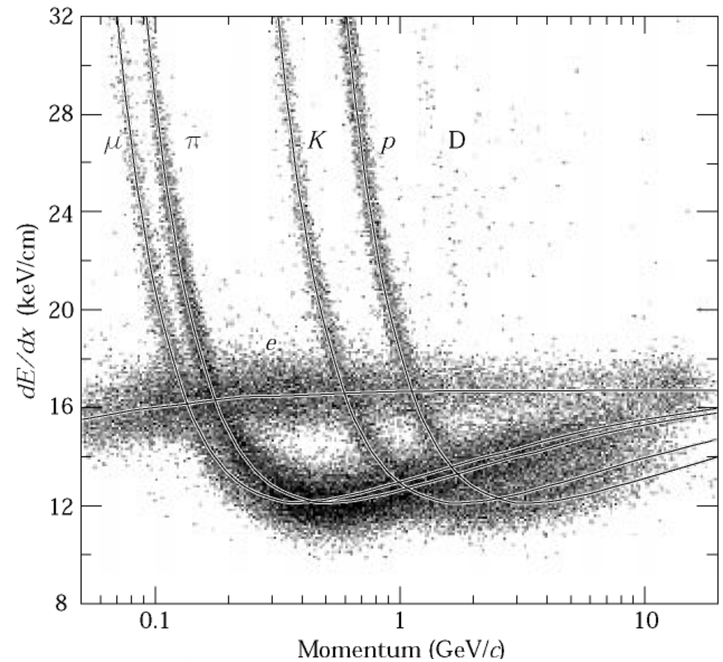




dE/dx Measurements

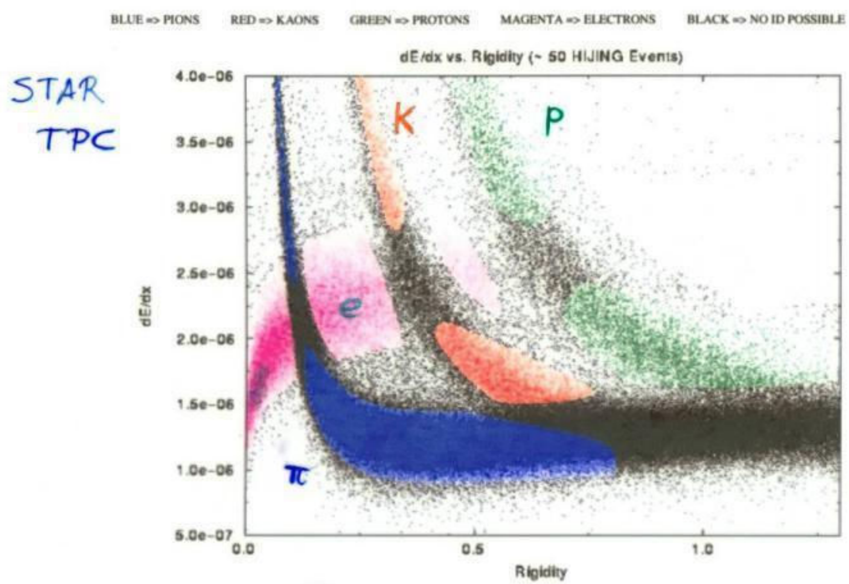


Measured energy loss



The energy loss of a particle depends on the particle velocity only (Bethe Bloch Formula)

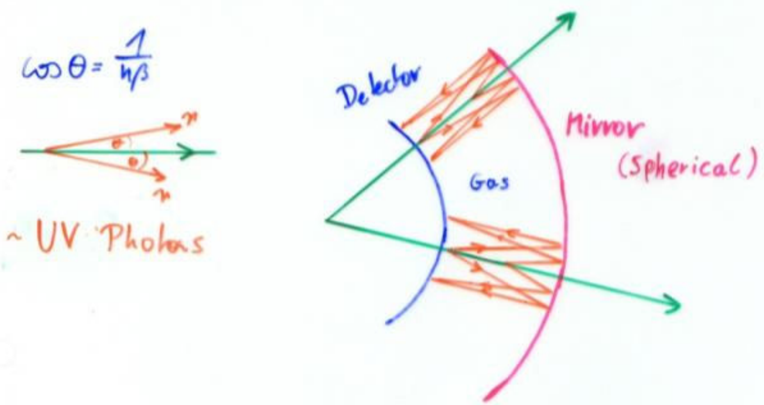
→ In certain momentum ranges up to tens of GeV, particles can be identified by measuring the energy loss.

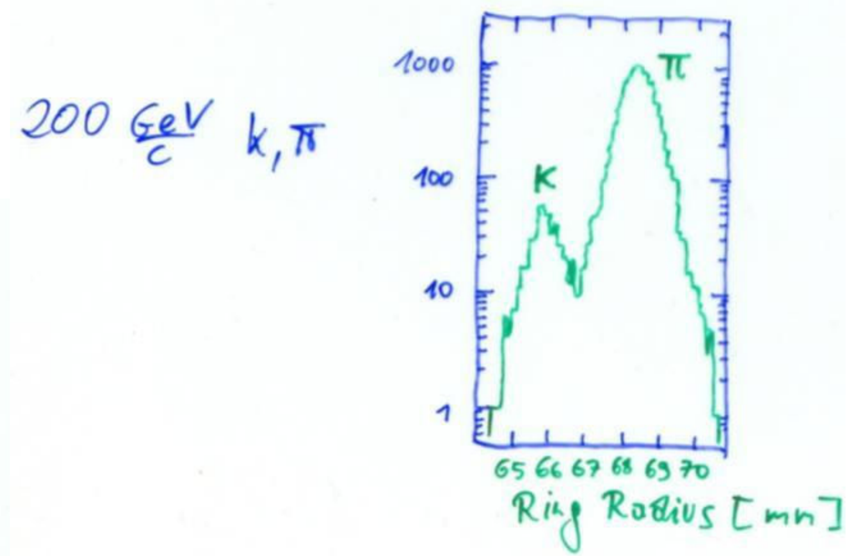


Ring Imaging Cherenkov Detector

If the velocity of a charged particle is larger than the velocity of light in the medium $v > \frac{c}{n}$ (n… Refractive Index of material) it emits 'Cerenkov' radiation at a characteristic angle of $\cos\theta_c = \frac{1}{n\beta}$ $\left(\beta = \frac{v}{c}\right)$

Measuring the Cerenkov angle i.e. the ring radius when using a spherical mirror determines the particle velocity.

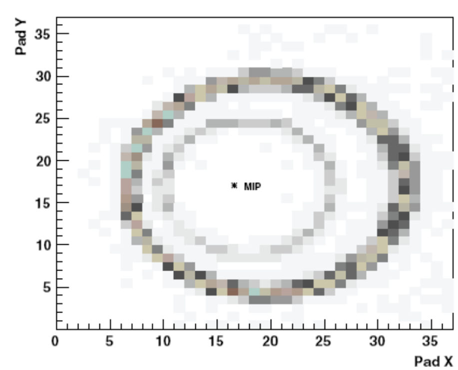


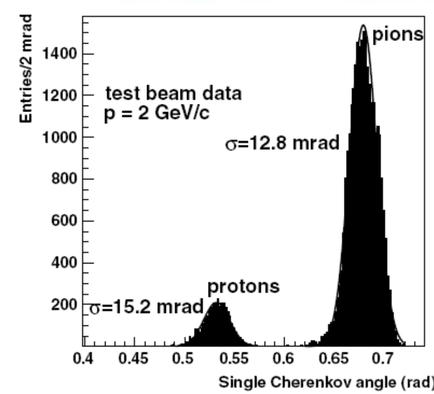


Resolution $\frac{\Delta\gamma}{\gamma} = \gamma^2\beta^3 n\,\Delta\theta \frac{1}{\sqrt{N_0 L}}$ $\left(\gamma = \frac{1}{\sqrt{1-\beta^2}}\right)$

Angle Measurement accuracy

Photon Statistics





Transition Radiation

Radiation (~ keV) emitted by ultra-relativistic Particles when they traverse the boarder of 2 materials of different Dielectric Permittivity ($\varepsilon_1, \varepsilon_2$)

Vacuum ε_0 | ε_2 Medium

q (charge) | $-q$ (mirror Charge)

Classical Picture

$q = Z_1 e$

$$I = \frac{1}{3} \alpha Z_1^2 (\hbar\omega_p) \gamma$$ ... Radiated Energy per Transition

$\hbar\omega_p$ .... plasma Frequency of the Medium

.... ~ 20 eV for Styrene

About half the Energy is radiated between

$$0.1\, \hbar\omega_p \gamma < \hbar\omega < \hbar\omega_p \gamma$$

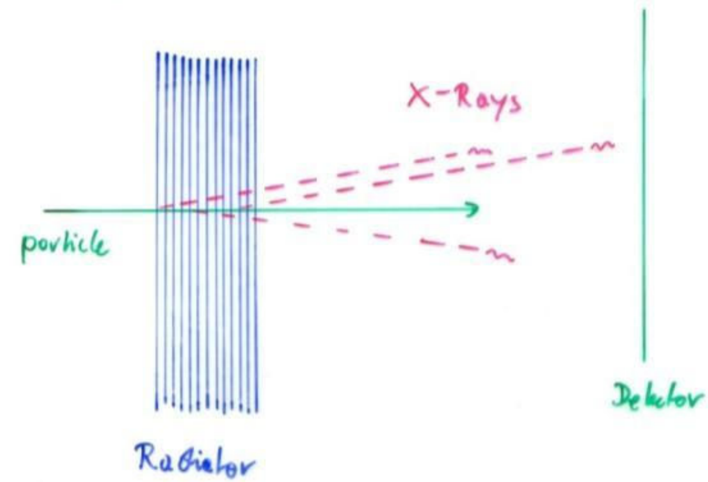
E.g. $\gamma = 1000$ 2-20 keV X-Rays

$$N_\gamma \sim \frac{2}{3} \alpha Z_1^2 \sim 5 \cdot 10^{-3} \cdot Z_1^2$$

γ - Dependence from hardening rather than N_γ

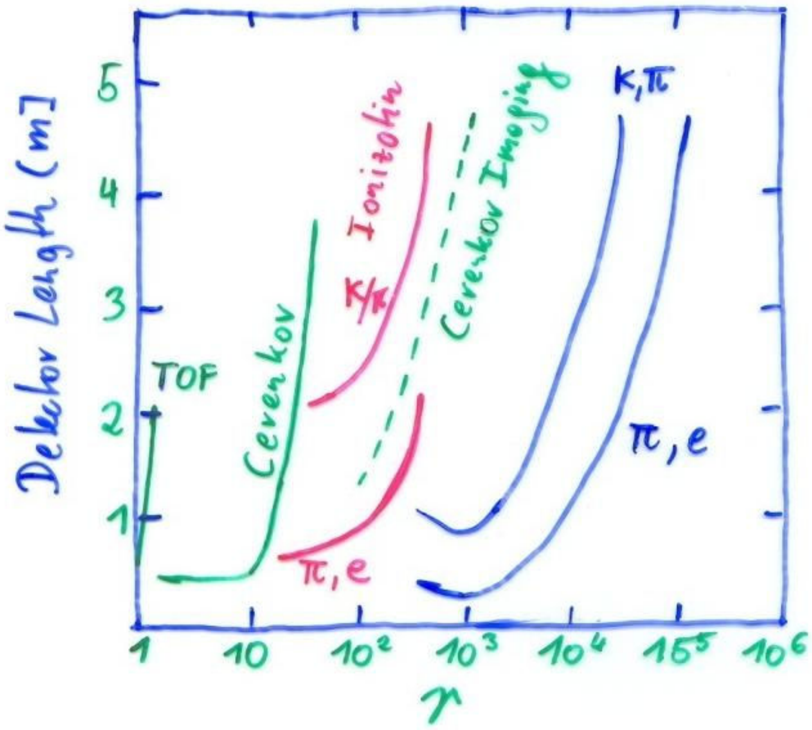
Emission Angle ~ $\frac{1}{\gamma}$

The Number of Photons can be increased by placing many foils of Material.



Particle Identification

TOF, dE/dx, Cerenkov, Transition radiation (Calorimetry)



1) • For low Energies the Time of Flight (TOF) measures the velocity $p, v \rightarrow m$

2) • For larger Energies the Cerenkov Threshold $v > \frac{c}{n}$ discriminates between Particles

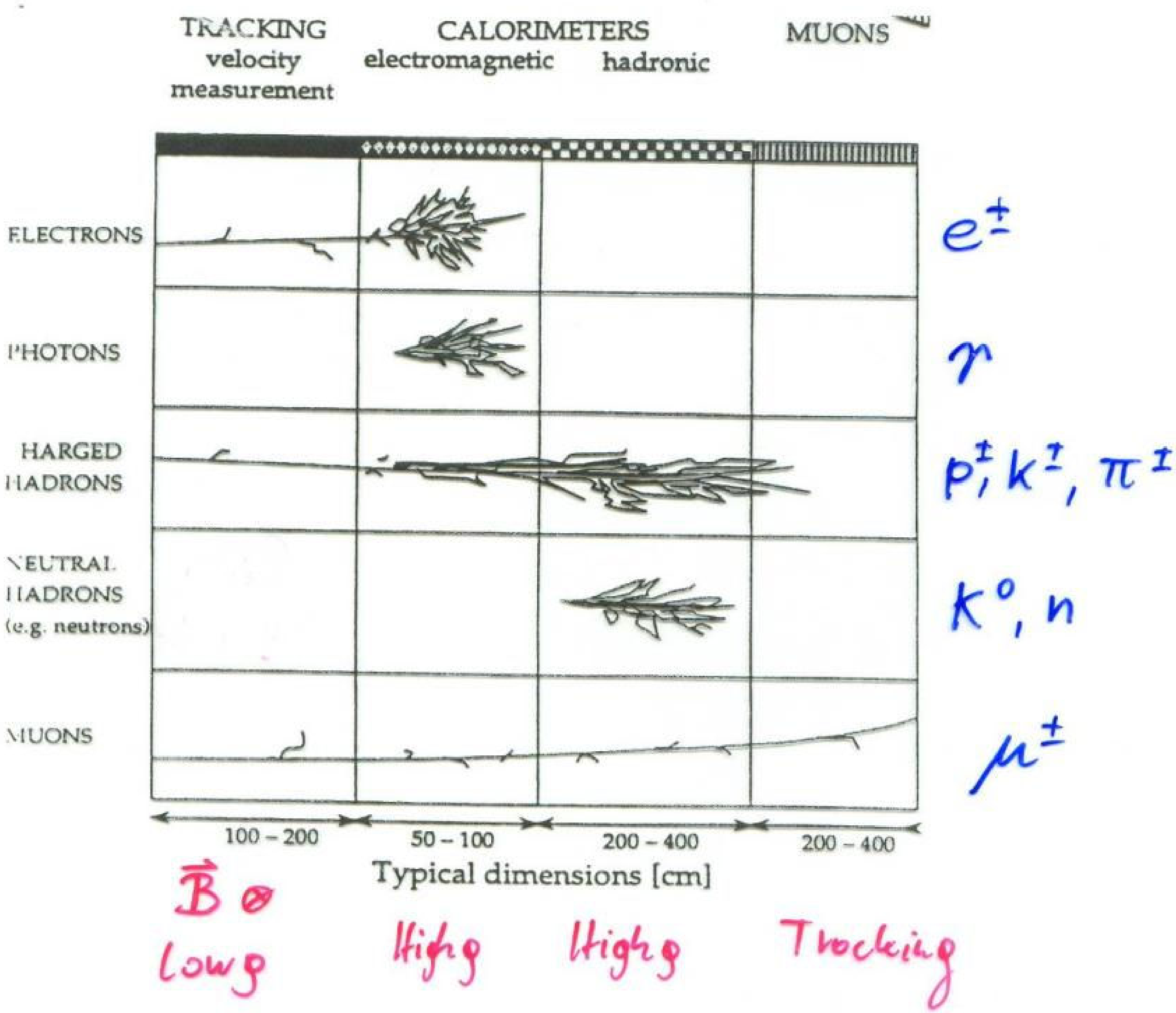
3) • For $\gamma \sim 100$ the multiple $\frac{dE}{dx}$ measurements provide Identification

4) • Cerenkov Angle Measurements $\cos\theta = \frac{1}{n\beta}$ provide Particle ID

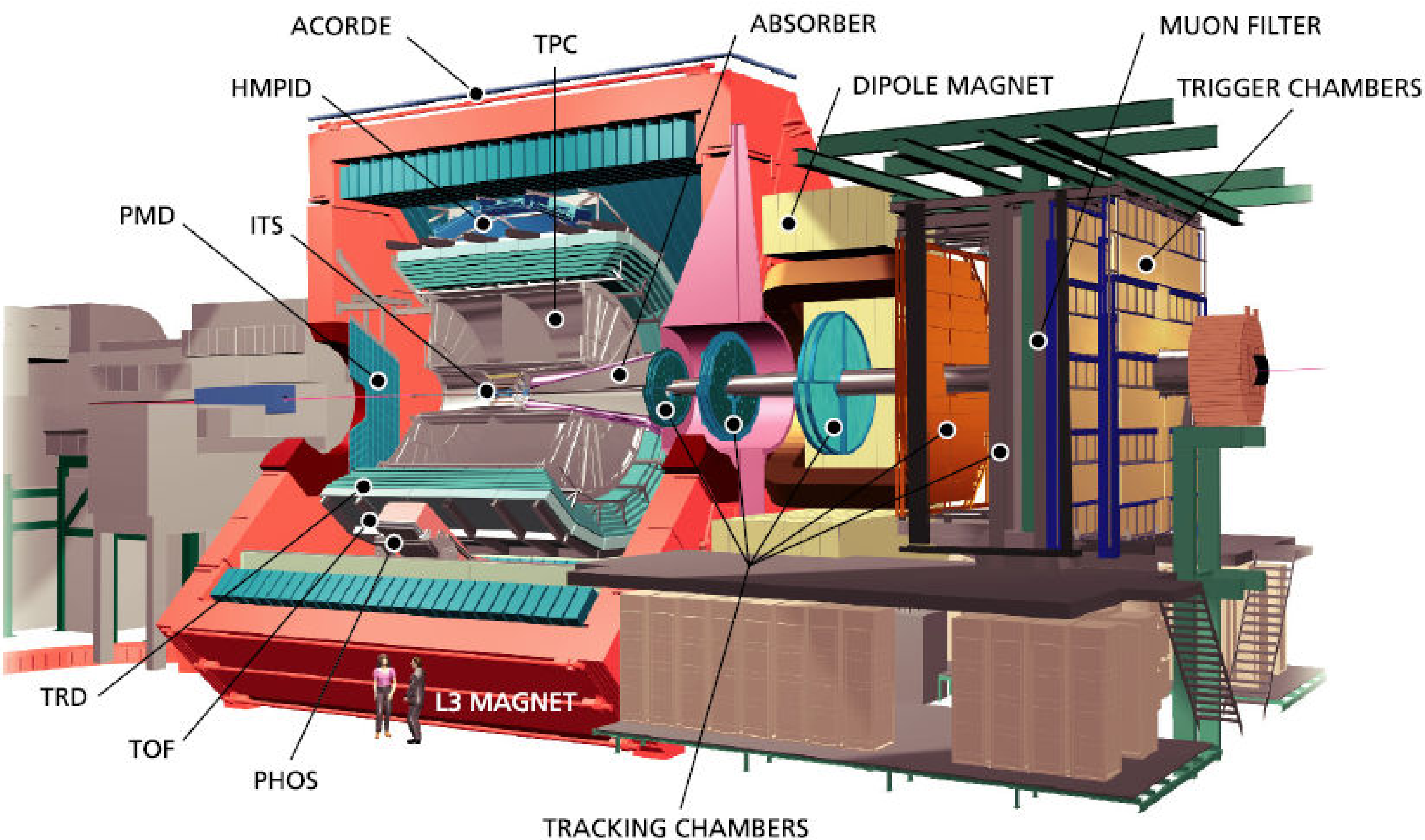
5) • At very high γ the Transition Radiation allows Identification

Nature provides us with a technique for every momentum rage (gamma rage) !

Particle Identification

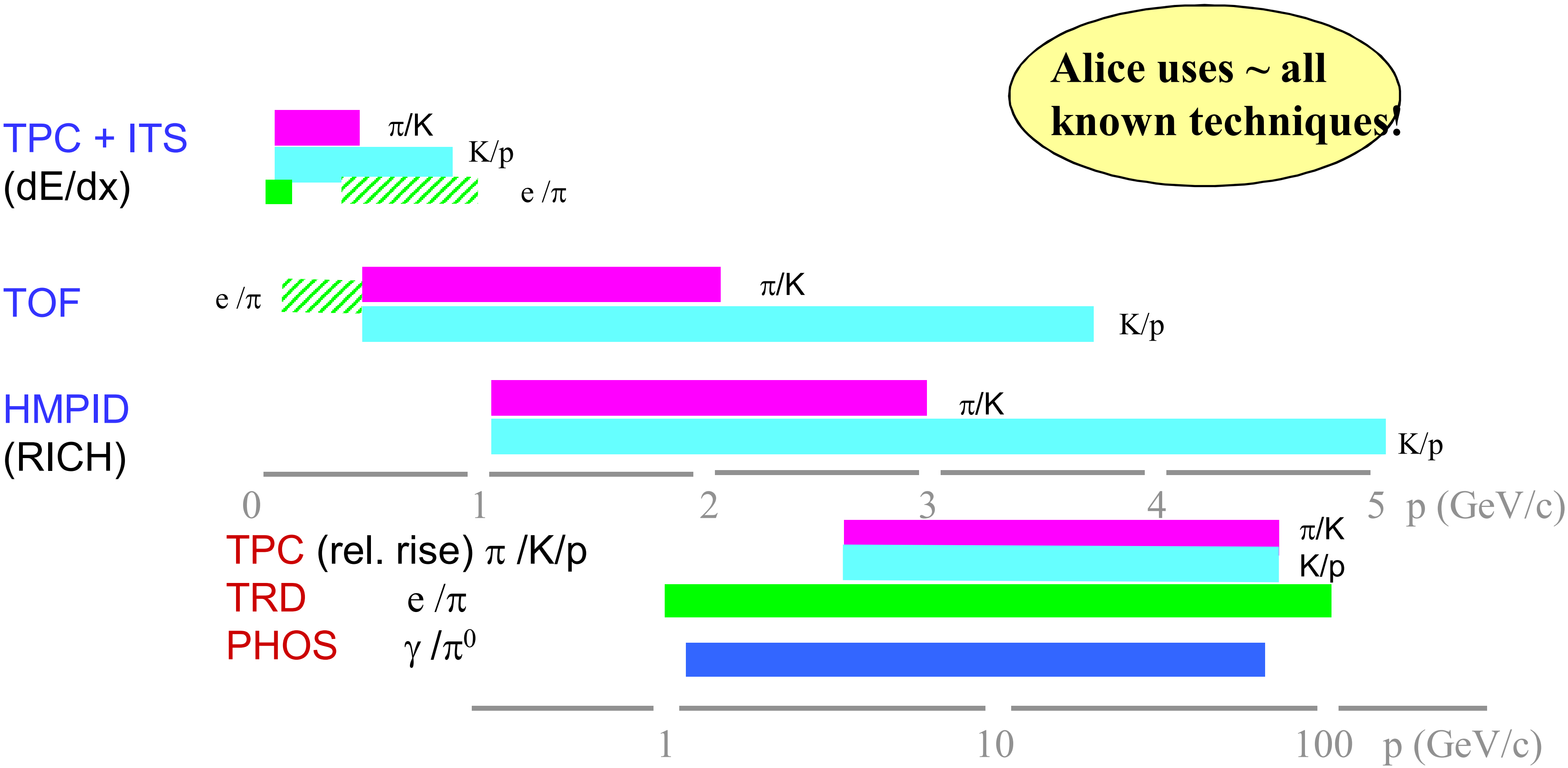


ALICE



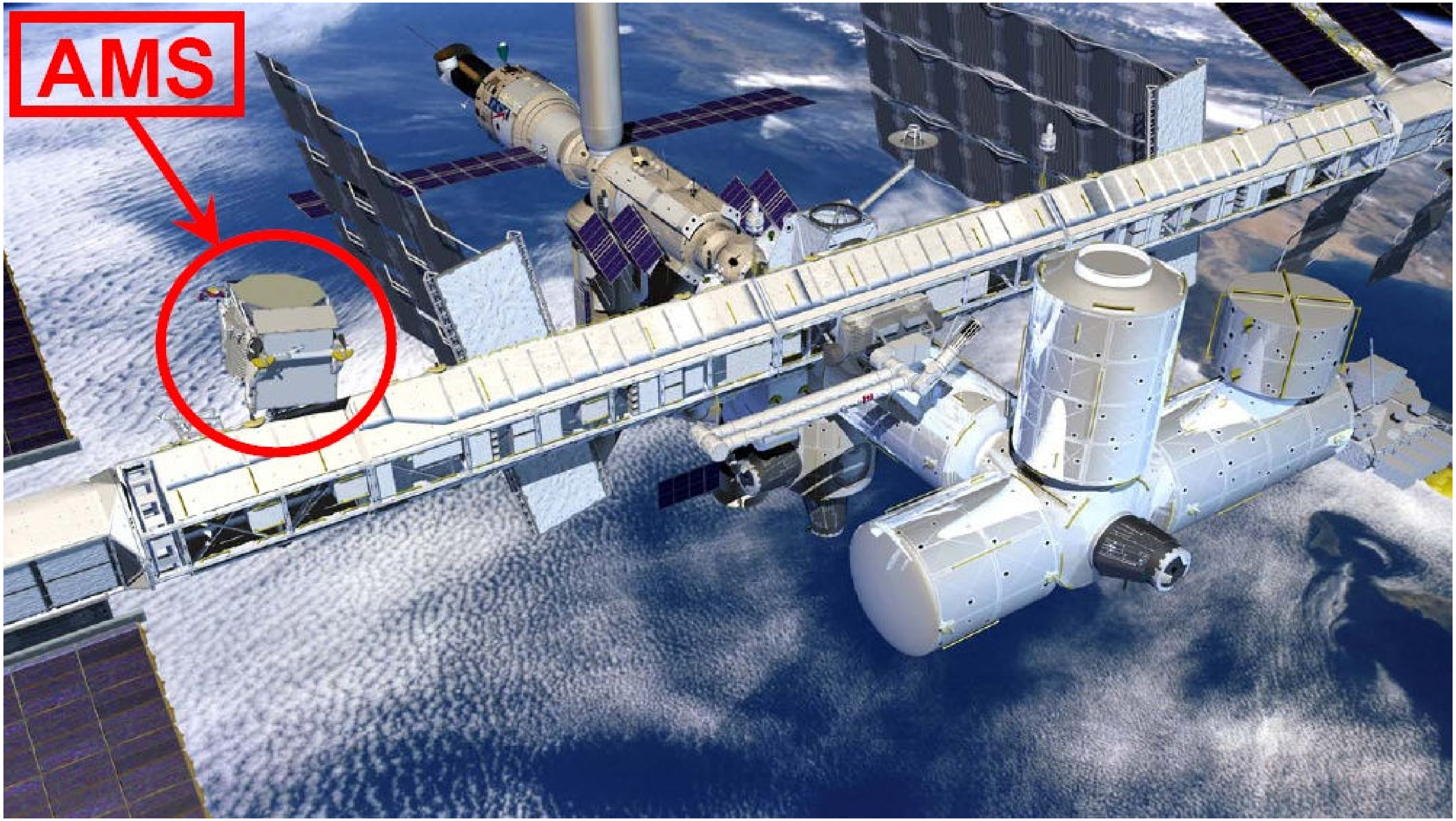
ACORDE
TPC
ABSORBER
MUON FILTER
HMPID
DIPOLE MAGNET
TRIGGER CHAMBERS
PMD
ITS
TRD
TOF
PHOS
L3 MAGNET
TRACKING CHAMBERS

ALICE Particle ID

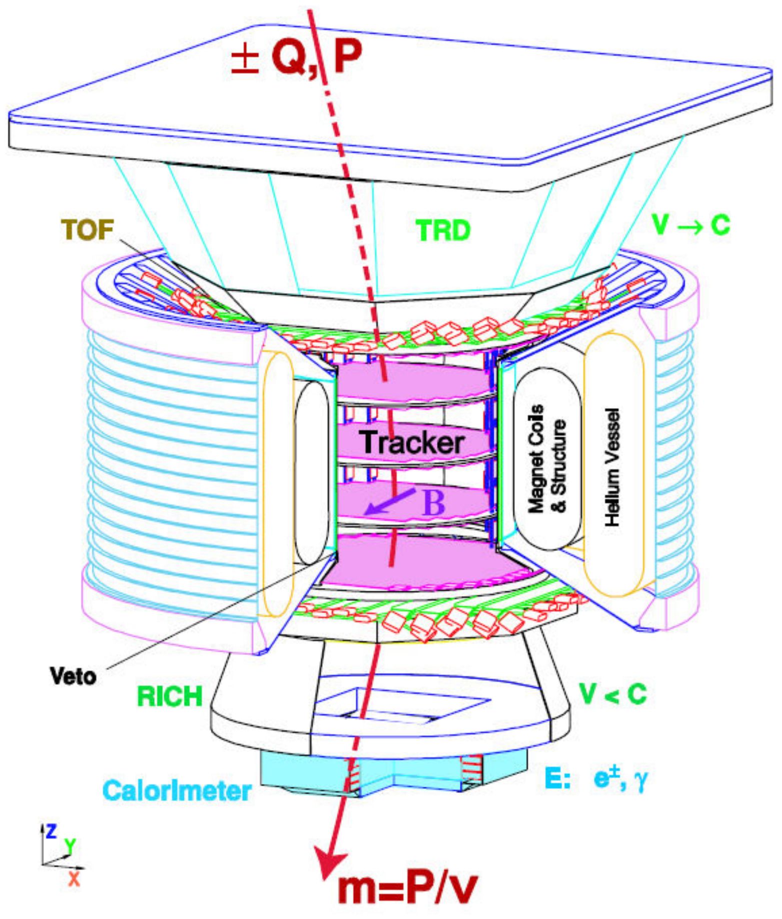


AMS

Will be installed on the space station.

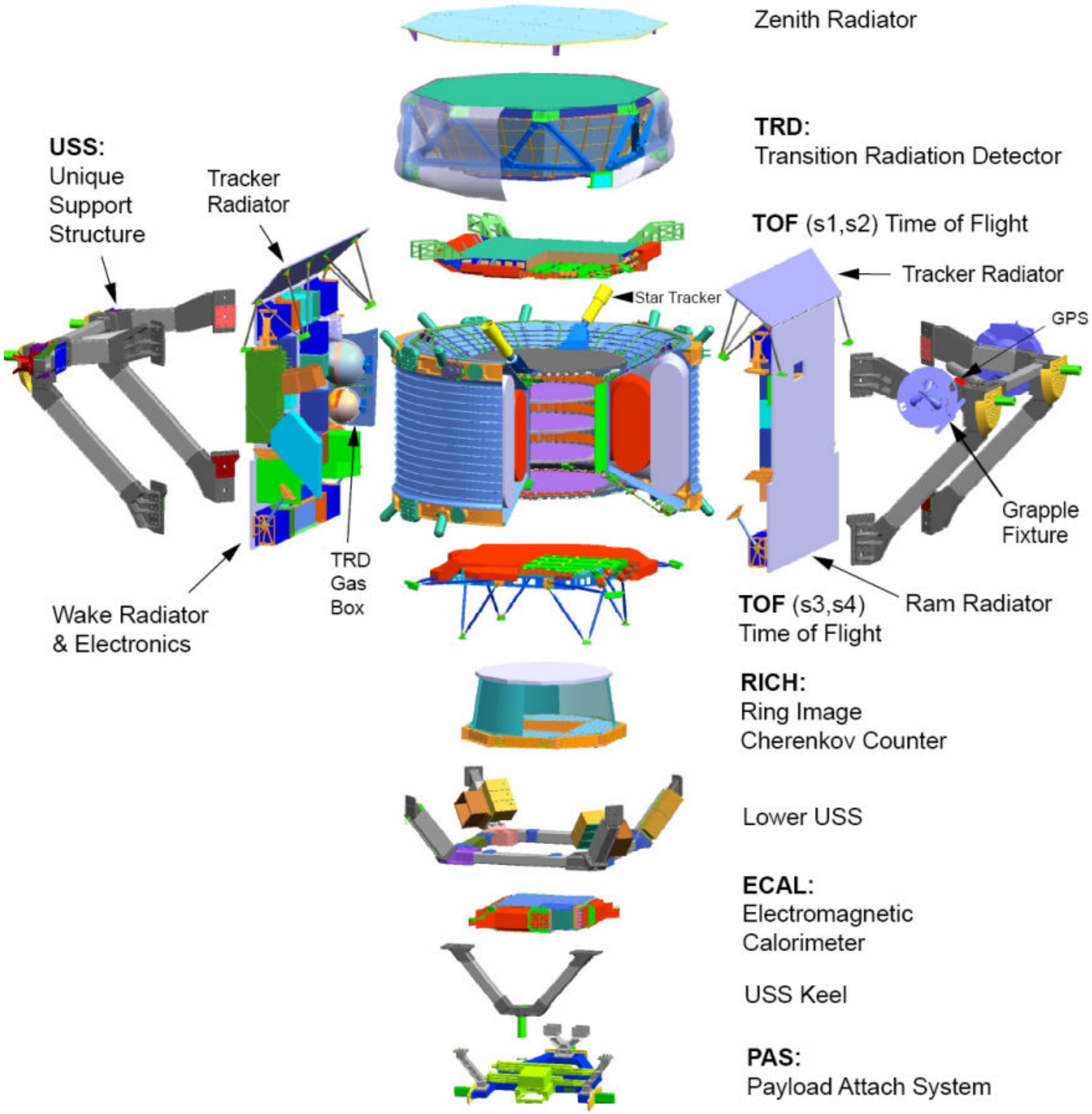


AMS



± Q, P
TOF
TRD
V → C
Tracker
B
Magnet Coils & Structure
Helium Vessel
Veto
RICH
V < C
Calorimeter
E: e±, γ
m=P/v

AMS



Zenith Radiator
TRD:
Transition Radiation Detector
USS:
Unique
Support
Structure
Tracker
Radiator
TOF (s1,s2) Time of Flight
Tracker Radiator
Star Tracker
GPS
Grapple
Fixture
TRD
Gas
Box
Wake Radiator
& Electronics
TOF (s3,s4)
Time of Flight
Ram Radiator
RICH:
Ring Image
Cherenkov Counter
Lower USS
ECAL:
Electromagnetic
Calorimeter
USS Keel
PAS:
Payload Attach System

A few Reasons why you want to become an Experimental Particle Physicist

The Standard Model of Particles Physics, a theory that was established in the early 1970ies, is in excellent agreement with experiments. Especially the LEP experiments verified the theory to impressive precision.

The Higgs Particle, a necessary element of the standard model, is being hunted at LHC.

Although the standard model is perfectly fitting the experiment, we know/think that it cannot be the final answer:

CP violation and the other CKM matrix elements are put into the model explicitly and they are not derived from a theory.

The masses of the particles are also unexplained.

The Matter- Antimatter asymmetry in the Universe cannot be explained by the level of standard model CP violation.

The cosmological constant predicted by the standard model differs by 120 orders of magnitude from the observed one.

The Higgs mass renormalization requires fine tuning operations etc. etc.

A few Reasons why you want to become an Experimental Particle Physicist

Incredible efforts by the smartest theorists did not really advance on these questions and did not touch base with experiment.

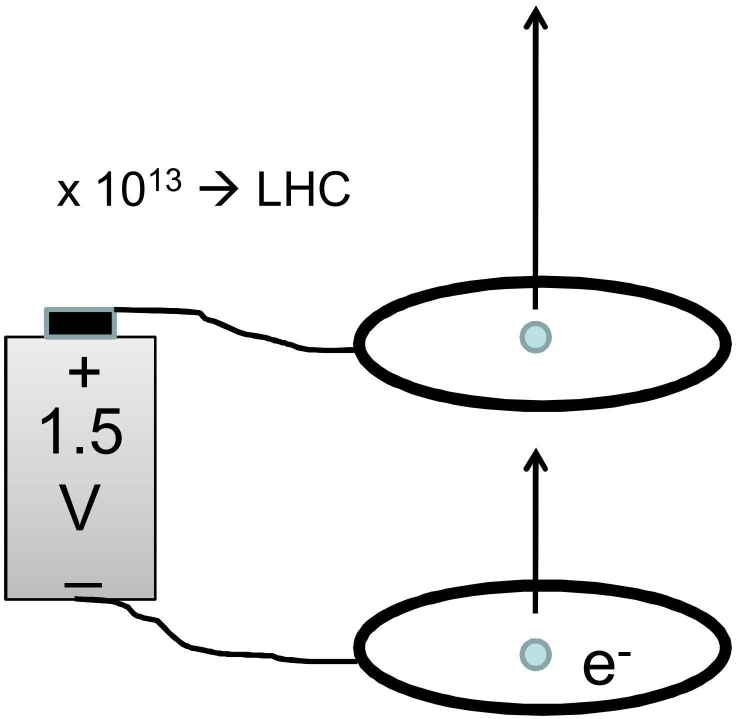
It is very difficult to find out what is wrong with the theory if all experimental results are fitting the theory.

If we would find the standard model Higgs at LHC it would be an very impressive confirmation of the Standard Model, but we would not at all advance on the questions quoted earlier.

Hopefully we find something in contradiction with the Standard Model !!!

The next step in advancing our knowledge will come from Experiment. Maybe LHC or some telescope, or some astrophysics experiment or some other future accelerator …

We have to invent new technologies for future accelerators and experiments !



Physicist 1: How can we build an accelerator with 10 times more energy ?

Physicist 2: Hmm – I have an idea !! We build a 10 times larger accelerator !

You

have to develop the tricks and technologies to advance on the most fundamental questions of Physics !