Aspects of HEP – Detectors and Data Reconstruction (1)

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Particle Detection

- Particles that exist long enough to fly and reach our detector:
  - p, e, γ, ν are stable.
    - But ν hardly interacts...
  - n, μ, K^0_L, π, $K^\pm$ all live for at least 10 ns.
    - 10 ns $\times\ c =$ 3 m
- There are two divisions to be done:
  - Charged (p, e, μ, π, $K^\pm$) vs. neutral (γ, ν, n, K^0_L)
  - Hadrons (p, n, π, $K^\pm$, K^0_L) vs. others (e, γ, μ, ν)
- Other particles have to be **reconstructed** from the particles we detect.
  - $Z \to e^+e^-$, $t \to Wb \to \mu\nu b$
- To detect the particles, we have to make them interact with **bulk matter**.
- After they interact, we have electric / light signals – to **reconstruct** the particles from the data is a different problem, that will be tackled in the next lecture.

Energy Loss of Charged Heavy Particles (1)

- The dominant energy loss is collision with atoms.
  - Mainly excitation and ionisation.

Bethe-Bloch formula:

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

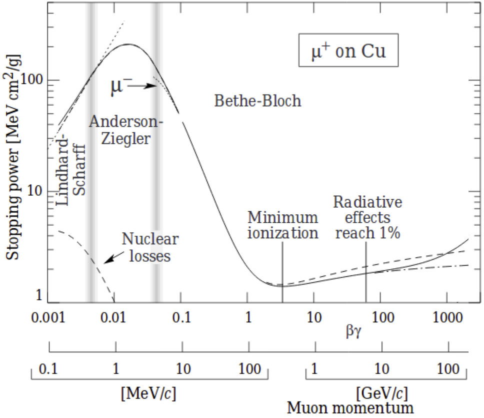
$\gamma = \dfrac{1}{\sqrt{1-\beta^2}}$: Lorentz factor, and $\beta = v/c$; $r_e = \dfrac{1}{4\pi\epsilon_0}\dfrac{e^2}{m_e c^2}$;

z: Charge of penetrating particle;
Z and A: Atomic and nuclear numbers of the target;
ρ: Target density;
N_A: Avogadro constant;

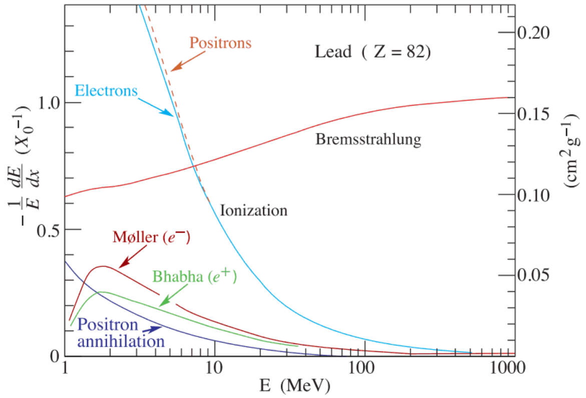
I: mean excitation energy;
W_{max}: Maximal energy transfer in a single collision;
δ: Density correction;
C: Shell correction.

Energy Loss of Charged Heavy Particles (2)

- The $\frac{dE}{dx}$ curve following Bethe-Bloch is a good description for $0.1 < \gamma\beta < 1000$.
- Three regions:
  - At low energies $\frac{dE}{dx}$ drops to a minimum. Particles at this energy are called **minimum ionizing particles** (mip);
  - At higher energies a logarithmic rise follows;
  - At very high energies a plateau is reached. . .
  - . . . but soon a new process comes into play!



Energy Loss of Charged Light Particles: Electrons and Positrons



To the energy loss through collision it is necessary to add effects from **bremsstrahlung**:

$$-\left(\frac{dE}{dx}\right)_{tot} = -\left(\frac{dE}{dx}\right)_{coll} - \left(\frac{dE}{dx}\right)_{rad}.$$

- Ionisation losses decrease logarithmically with E (and increase linearly with Z);
- Bremsstrahlung increases appr. linear with E (and quadratically with Z);
- **Bremsstrahlung is the dominant process for high energies** (> 1 GeV).
  - Critical energy E_C: electron ionisation losses become equal to bremsstrahlung.

$$E_C \simeq \frac{610(710)\mathrm{MeV}}{Z + 1.24(0.92)} \text{ for solids (gases)}$$

Bremsstrahlung Approximation and Radiation Length

For high energies the energy loss through radiation can be approximated as:

$$-\left(\frac{dE}{dx}\right)_{rad} = 4\alpha\rho N_A \frac{Z(Z+1)}{A} z^2 r_e^2 E \ln\left(183 Z^{\frac{1}{3}}\right)$$

So,

$$-\left(\frac{dE}{dx}\right)_{rad} \propto \frac{E}{m^2}$$

Rewriting the previous expression:

$$-\left(\frac{dE}{dx}\right)_{rad} = \frac{E}{X_0}.$$

Then,

$$X_0 = \frac{A}{4\alpha\rho N_A Z(Z+1) z^2 r_e^2 \ln\left(183 Z^{-\frac{1}{3}}\right)}.$$

Integrating over it:

$$E(x) = E_0 \cdot \exp\left[-\frac{x}{X_0}\right].$$

The radiation length X_0 is the distance in which the energy of the particle is reduced by $1/e$ due to bremsstrahlung.

Interactions of Photons – Low Energy

Photoelectric Effect

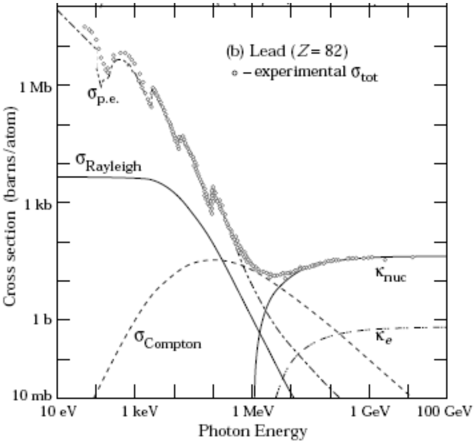
- $\gamma + \mathrm{Atom} \rightarrow \mathrm{e}^- + \mathrm{Ion}^+$
- $E_\mathrm{e} = h\nu - E_\mathrm{binding}$
- Cross-section (approximation for "high energy" photons):

$$\sigma_\mathrm{photon} = \frac{3}{2}\alpha^4\sigma_0 Z^5 \frac{m_e c^2}{E_\gamma},$$

Compton Scattering

- $\gamma + \mathrm{Atom} \rightarrow \gamma + \mathrm{e}^- + \mathrm{Ion}^+$
- $E_\gamma = h\nu_0 - h_\nu = h\nu\left[\frac{\gamma(1-\cos\theta)}{1+\gamma(1-\cos\theta)}\right]$
- Cross-section (approximation for "high energy" photons):

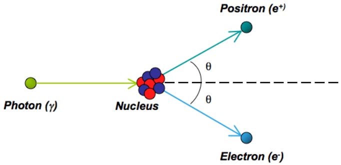
$$\sigma_\mathrm{total} = \frac{2\pi\alpha^2}{s}\log\left(\frac{s}{m_e^2}\right), \quad s = E^2_\mathrm{CM}(e\gamma)$$

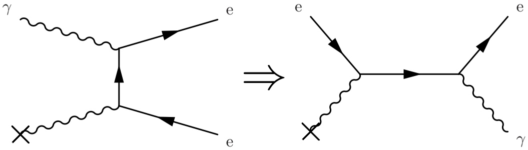


Interactions of Photons – High Energy – Pair Production

- Generation of an electron positron pair by a photon in the field of a nucleus or an electron.

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





- The kinetic energy transferred to the target:

$$E_\gamma > 2m_e c^2,$$

$$E_\gamma = h\nu \approx 1.022\ \text{MeV}.$$

- In the high energy approximation the cross section reaches an energy independent value:

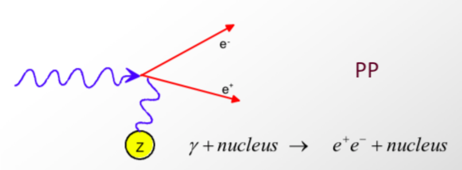
$$\sigma_{\text{pair}} \approx \frac{7}{9}\left(4\alpha r_e^2 Z^2 \ln\frac{183}{Z^{\frac{1}{3}}}\right) = \frac{7}{9}\frac{A}{X_0\,N_A}.$$

  - X_0 appears here again because there is a symmetry between the relevant diagrams!

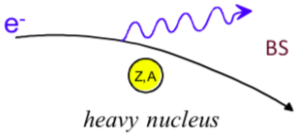
Electromagnetic Shower

Dominant processes at high energies:

- photons: pair production (PP)

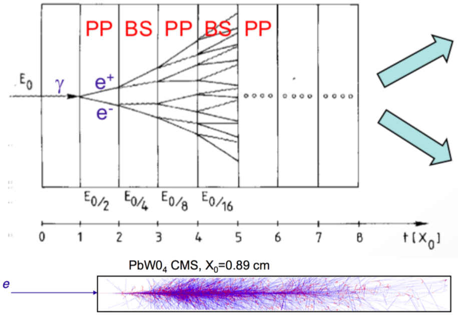


- electrons/positrons: Bremsstrahlung (BS)



Introduce the scale variables

$$t = \frac{x}{X_0} \quad , \quad y = \frac{E}{E_c}$$



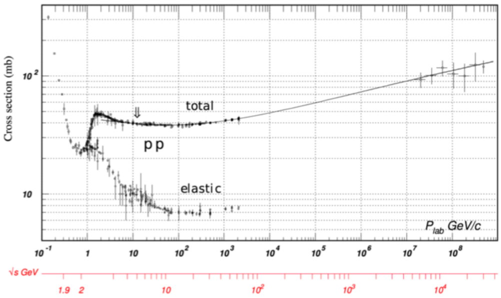
Interaction of Hadrons with Matter (1)

Interaction of a hadron with nucleus

- elastic: $p + N \to p + N$ ($\sigma_{\text{el}} \sim 10$ mb)
- inelastic: $p + N \to X$ (σ_{inel})
  - at high energies also diffractive contribution
- total: $\sigma_{\text{tot}} = \sigma_{\text{el}} + \sigma_{\text{inel}}$
  - dominated by inelastic part: $\sigma_{\text{el}} \sim 10$ mb and $\sigma_{\text{inel}} \propto A^{2/3}$

The total cross section can be approximated:

$$\sigma_{\text{tot}} = \sigma_{\text{tot}}(pA) \approx \sigma_{\text{tot}}(pp) \cdot A^{2/3}$$



Interaction of Hadrons with Matter (2)

Hadronic interaction length:

$$\lambda_{\text{int}} = \frac{A}{\sigma_{\text{tot}}(pp) A^{2/3} \cdot \rho N_A} \sim A^{1/3}$$

- Interaction length characterises both longitudinal and transverse profile of hadronic showers
- Similar to the electromagnetic case, but for N particles

$$-\frac{dN}{dx} = \frac{N}{\lambda_{\text{int}}}$$

$$N = N_0 \exp\left(-x/\lambda_{\text{int}}\right)$$

Interaction length x Radiation length:

$$X_0 \sim \frac{A}{Z^2}, \qquad \lambda_{\text{int}} \sim A^{1/3}$$

Dividing one by another

$$\frac{\lambda_{\text{int}}}{X_0} \sim A^{4/3} \rightarrow \lambda_{\text{int}} \gg X_0$$

Hadronic calorimeter needs to be larger than electromagnetic calorimeter (more layers).

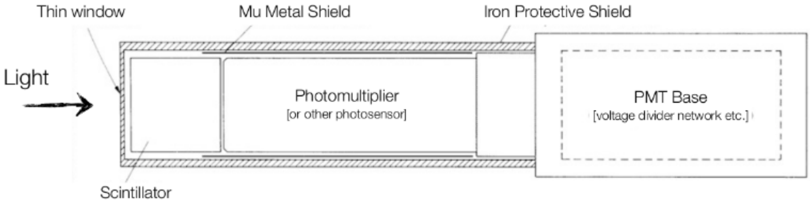
	C	LAr	Fe	U	Scint.
λ_A(cm)	38.8	85.7	16.8	11.0	79.5
X_0(cm)	19.3	14.0	1.76	0.32	42.4

Working principle

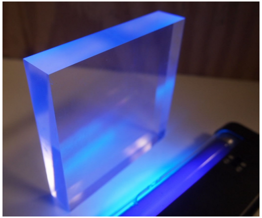
A scintillator is a material that converts the energy of the passage of a particle into light that will be collected by a photosensor.

This process is possible because of fluorescence, an effect that happens when an excited electron moves from a higher energy level, to a lower one.

The scintillator material must be transparent to its own fluorescent light, the conversion must be efficient, and the light needs to be detectable by photosensors.



Types and applications



There are some very important uses for the scintillators:

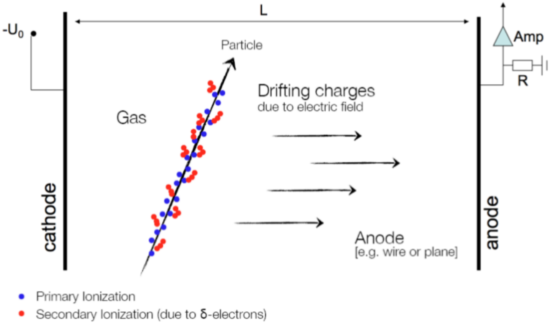
- Particle counters;
- Image displays;
- Energy measurements (at very high rate);
- Trackers (need multiple layers, or can be used as a type of trigger, as will be seen later).

Three types of scintillators can be used, each one with its advantages or disadvantages:

- Inorganic scintillators;
- Liquid noble gases scintillators;
- Organic scintillators.

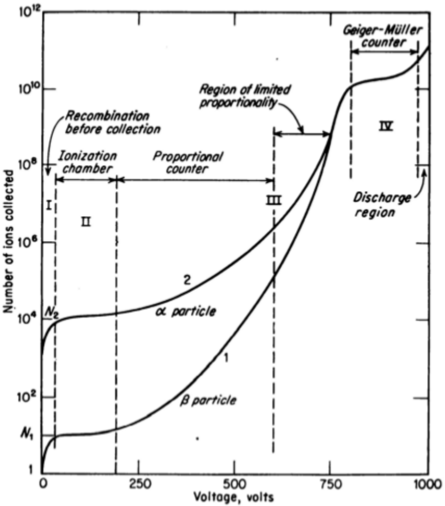
Working principle

The gas chamber detection principle is based on ionisation. A **charged particle** ionises the gas (gas mixtures are commonly used), the electrons and ions drift through the gas (external $\vec{E}$ applied) and generate an electric signal.



The gain of the electric signal is improved by an avalanche of ions and electrons from secondary ionisation (delta electrons).
Some relevant effects are:

- Recombination and electron attachment;
- Delta electrons;
- Diffusion;
- Mobility of charges;
- Avalanche process.

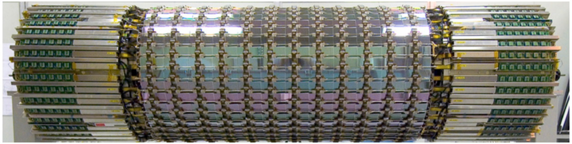


Working principle

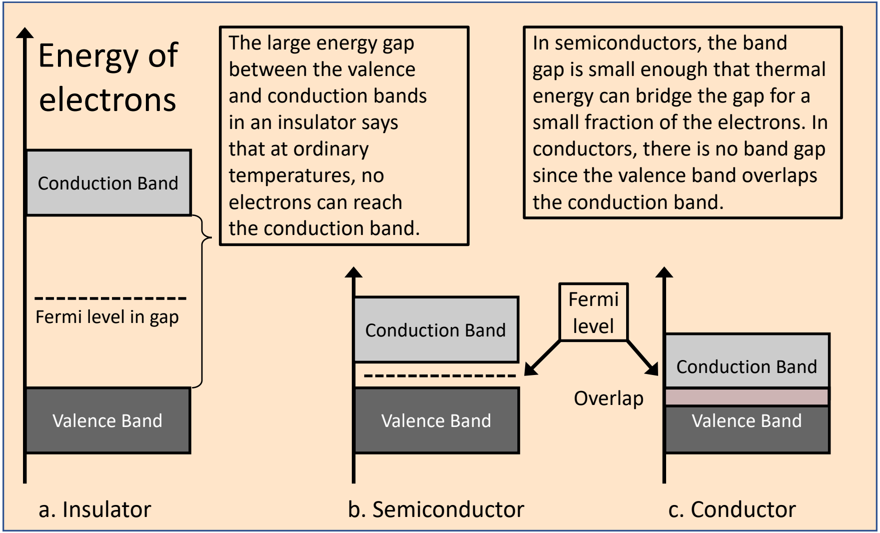
A semiconductor detector is a **radiation damage resistant** type of detector, which can be produced with a few micrometers of precision but at a higher cost.

Its signal is generated by the passage of a **charged particle**, producing electron-hole pairs that will be collected by the readout electronics.

A crystalline material can be modelled by the energy bands, that are separated as conduction band and valence band, and the energy gap of the electrons energy.



Energy Bands

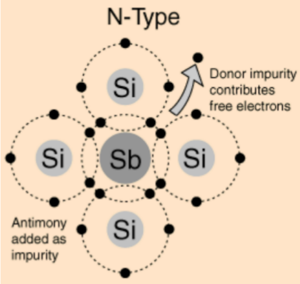


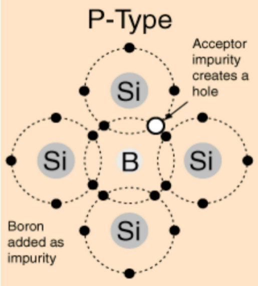
n-type and p-type Semiconductors

Using Si as an example from now on. It's a tetravalent element that will form covalent bonds with the other atoms in a lattice.

It's possible to insert other elements in the lattice to improve its detection capabilities (doping).

Doping the semiconductor is extremely important to increase the resolution of the detector. These materials are called N-type or P-type (increased number of electrons or holes).

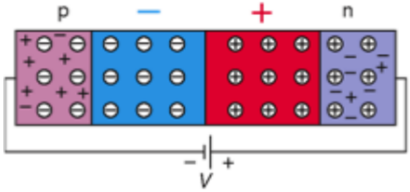


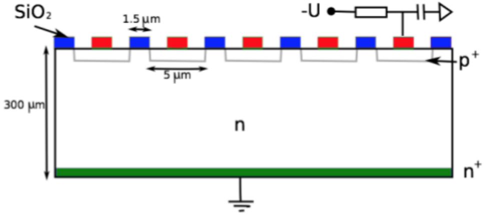


pn Junction and Depletion Region

By putting a n-type material in contact with a p-type material, a depletion region is created, altering the semiconductor conductivity.

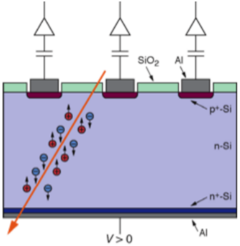
If an external voltage is applied with the cathode connected to the p-type and the anode to the n-type, the depletion zone is enlarged, which makes the current across the junction very small (to improve the resolution). Right figure is an example of a Si detector in the form of microstrips.





Charge Carrier Mobility and Drift Velocity

When a charged particle passes through the detector, it will generate several electron-hole pairs. The drift velocity of those charge carriers in an external electric field is



$$\vec{v}_D = \frac{e\vec{E}}{2M}\tau = \mu\vec{E}, \text{ and } v_D^h \approx \frac{v_D^e}{2} \text{ (distinct from gases);}$$

where the mobility μ was measured as:

$\mu \simeq$ const for $E < 10^3$ V/cm;

$\mu \propto {}^1/\sqrt{E}$ for 10^3 V/cm $< E < 10^4$ V/cm;

$\mu \propto {}^1/E$ for $E > 10^4$ V/cm,

and τ is the mean time between collisions, also defined as $\tau = {}^{\lambda}/v_{\text{thermal}}$ with λ = mean free path. v_D saturates at approximately 10^7 cm/μs.

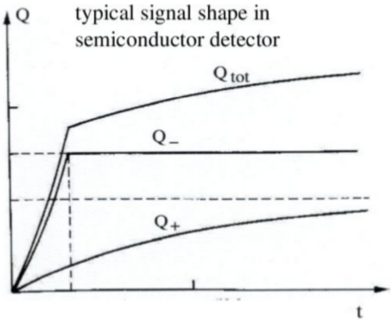
In some detectors, the goal is to achieve constant v_D, to determine the drift time $\Delta t = {}^L/v_D$. For a typical v_D in 100 μm, the drift time is 10 ns.

Signal Rise Time

Another important property that come from v_D is the signal rise time, which will be something of the order of 1 ns for Si detectors, allowing a very high rate.

There are some details:

- $\mu_\pm$ are not constant;
- Loss of charges;
- The charge is distributed over a surface, and some mismeasurements can happen.



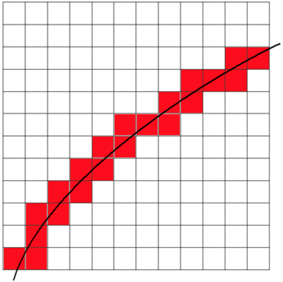
Trackers and Calorimeters

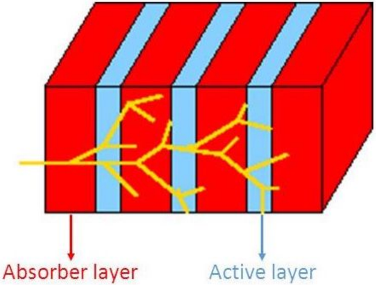
Tracker

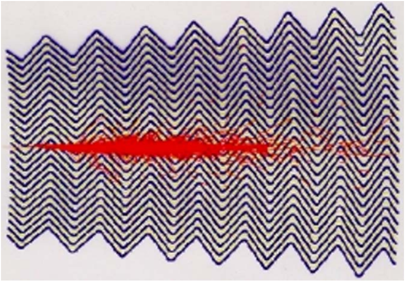
- Measures charged particle tracks in a **non-destructive way** and it usually has:
  - a medium that will produce one or more signals as the particles pass through it;
  - a strong surrounding $\vec{B}$ field to determine particles' charges and momenta.
- (At least) two types:
  - Semiconductor tracker: use for high particle rates (closer to interaction point), more expensive.
  - Gas tracker: use for lower particle rates (farther away), cheaper.
  - (Other possibilities also exist, of course. Extensive R&D!)

Calorimeter

- Measures the energy of charged or neutral particles in a **destructive** way, since it totally absorbs the particles after the shower.
  - Made of dense material to produce particles' interaction.
  - Made of active material to produce measurable quantity.
- Two types:
  - Sampling calorimeter: alternated layers of passive absorbers and active detectors.
  - Homogeneous calorimeter: absorber and active detector at same time.





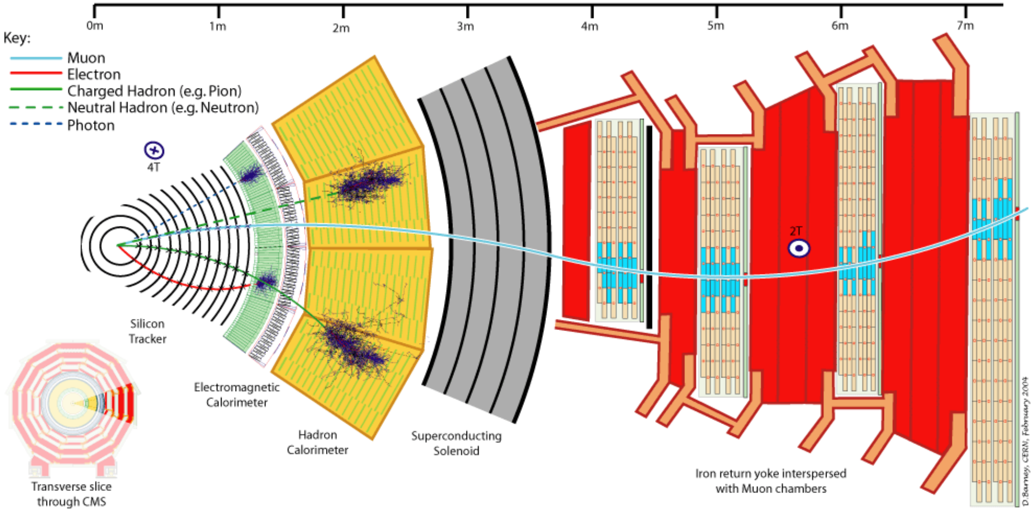


Left: Cartoon of tracker hits. Center: Sampling calorimeter scheme. Right: simulated shower in ATLAS LAr calorimeter.

Integrating All Detectors

- Ideally, we want to measure $(E, \vec{p})$, q, m of all particles produced in the collision.
- Take non-destructive measurements before destructive measurements.
  - Observe the passage of the particle without disturbing it much – small X_0, small λ_{int}.
  - In other words, **track** the particle and measure its momentum.
  - Then, make it undergo a shower in bulk material – in a **calorimeter** – and measure the total deposited energy.
- Special case 1: muons!
  - Muons have very high range – need $\sim$12 meters of pure copper to stop a 20 GeV muon.
  - Alternative: build calorimeters that let the muon pass through, re-track them at the end.
- Special case 2: neutrinos!
  - Interact only through the weak interaction – very small cross-section!
  - Dedicated experiments – Super-Kamiokande, MiniBooNE, DUNE . . .

Multipurpose Detectors



Tools of the Trade

Geant4 is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science.

Delphes is a C++ framework, performing a fast multipurpose detector response simulation. The simulation includes a tracking system, embedded into a magnetic field, calorimeters and a muon system.

We managed to detect the particles. . .

. . . time to reconstruct the data!

Introduction to Reconstruction

After our particles have interacted with our detector, we have to "read out" that information, and format it in such a way that we can understand it. Generally, that entails some sort of transducer that converts the energy deposited in our detector elements and transforms it into electrical signals. It is also customary to digitise the signals for further data processing.

- **Local reconstruction** starts with the detector readout (e.g., channel #28 has 7 ADC counts), and transforms it into intelligible data – a "hit". This is usually low-level information localised to one subsystem, e.g., for a tracker detector it represents not much more than "a charged particle passed through this sensor".
- **Global reconstruction** starts with the hits and tries to group them at a higher-level. Connecting the hits in a silicon detector to reconstruct the trajectory of a charged particle, or clustering the hits in a scintillator to reconstruct the deposit of a photon, fall in this category.
- **Global event description** uses the high-level objects to describe the event as a whole, ready to be connected to a physics process interpretation. Connecting energy clusters to a track to try to reconstruct an electron or a charged hadron, or connecting tracks in two different tracker systems to reconstruct a muon, fall in this category.

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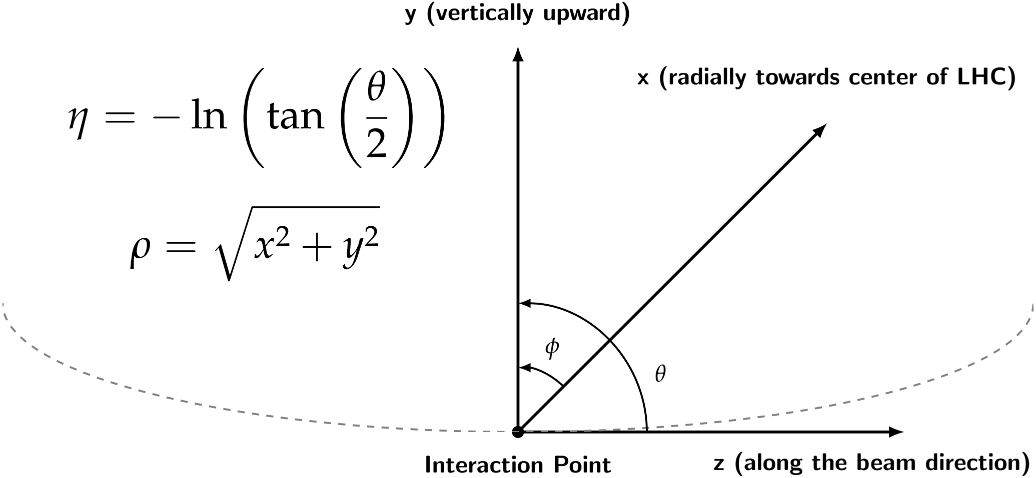
Coordinate System

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

$$\rho = \sqrt{x^2 + y^2}$$



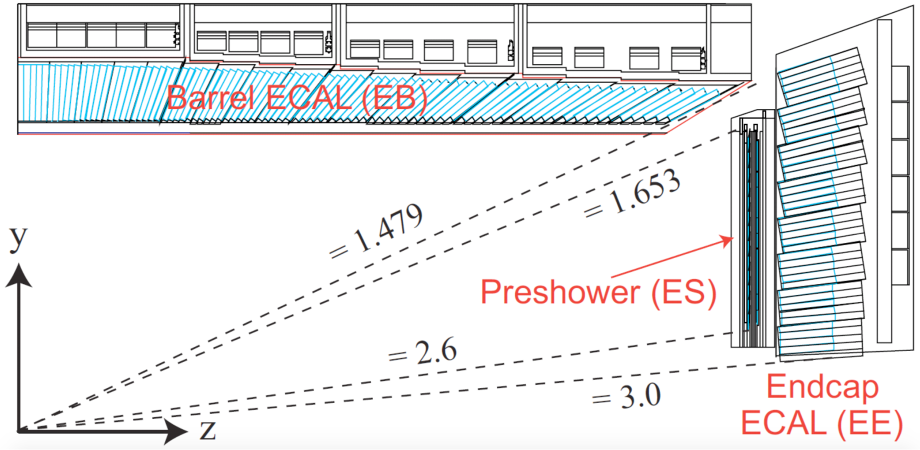
Local Reconstruction: Calorimetry as Example

Local reconstruction is very dependent on the detector implementation details. We will use CMS's crystal electromagnetic calorimeter (ECAL) as an example.

ECAL

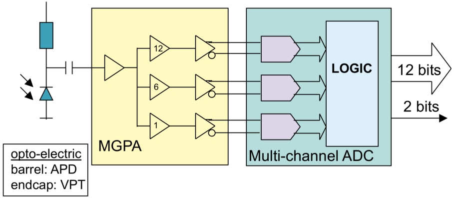
- Around 80000 $PbWO_4$ (lead glass) scintillating crystals.
  - High density (8.3 g/cm^3), short radiation length (0.89 cm), small Molière radius (2.2 cm).
  - 80% of the light is emitted in 25 ns, $\sim$420 nm wavelength, 4.5 photoelectrons per MeV.
- Readout: avalanche photodiodes (APDs) and vacuum phototriodes (VPTs) for barrel ($|\eta| < 1.479$) and endcap ($1.479 < |\eta| < 3.0$) regions, respectively.
  - APDs exploit the photoelectric effect in an avalanche mode diode to convert light to electricity.
  - VPTs are single stage (cathode–anode–dynode) photomultipliers.

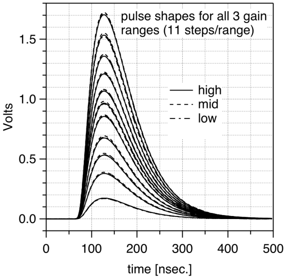
ECAL Geometry



ECAL Readout Chip

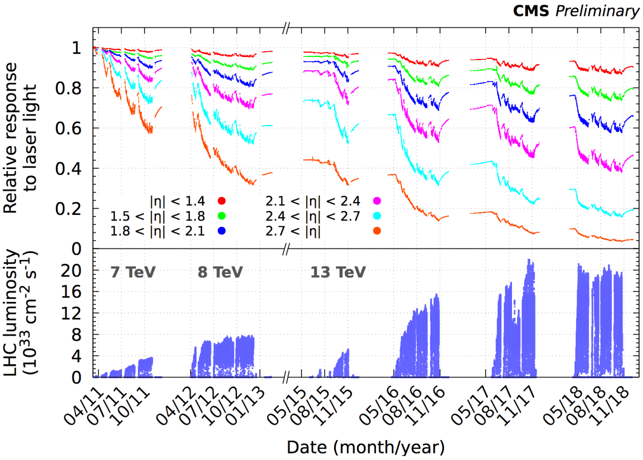
- ECAL readout and precision performance requirements ⇒ front end signals digitised to better than 12 bits.
- Strategy: multiple gain ranges ($\times 12$, $\times 6$, $\times 1$) to span the overall dynamic range.
  - Digitise and transmit the signals only for the highest unsaturated range.
  - 12-bit analog-to-digital converter (ADC) is now sufficient.
  - Parallel gain channels in a multi-gain pre-amplifier (MGPA), coupled to a multi-channel ADC.
  - "Channel-in-range" decision taken by digital logic following the conversion stages.





ECAL Response vs Integrated Luminosity

Radiation damage leads to transparency loss!



ECAL Local Reconstruction

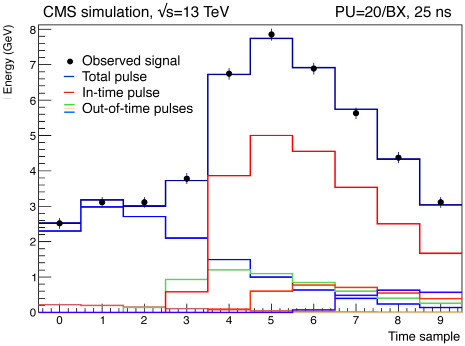
Hit reconstruction refers to the process of estimation of (energy, time, position) of an energy deposit in an ECAL crystal.

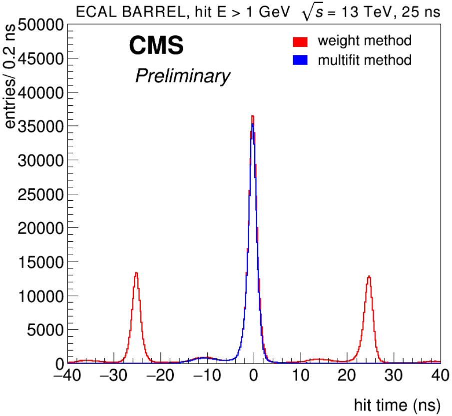
At a given time sampling: 12-bit word for ADC counts + bits to encode the gain ($\times 12$, $\times 6$, $\times 1$). For a given event we want to save, we take 10 time samples: 3 readings before the selected bunch-crossing and 7 readings afterwards. That information comprises a "digi",

From an ECAL "digi", we want to reconstruct four quantities: amplitude (the peak of the pulse shape), pedestal (the baseline), jitter (the time when the maximum of the pulse shape occurs) and χ^2 of the fit (see next slides). After that we still want a global scale factor (ADC counts to GeV) and intercalibration constants.

Reconstruct the Pulse

The multifit method allows for better timing information on the pulse.





Calibrate the Energy

- Use particles of very well known mass to calibrate the detector.
  - $\pi^0 \to \gamma\gamma$, mass of 135 MeV.
  - $\mathrm{Z} \to \mathrm{ee}$, mass of 91.1876 GeV.
- Exploit detector ϕ-symmetry to intercalibrate crystals.
- Exploit $E/p \simeq 1$ for high-energy electrons.