High School Teacher Programme 2016

https://indico.cern.ch/e/HST2016

Particle Detectors

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CERN EP-DT
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Particle Detectors

OUTLINE

1. Particle Detector Challenges at LHC
2. Interactions of Particles with Matter
3. Detector Technologies
4. How HEP Experiments Work
• Particle Physics Tools

• Accelerators
  ▪ Luminosity, energy…

• Detectors
  ▪ Efficiency, granularity, resolution…

• Trigger/DAQ (Online)
  ▪ Efficiency, filters, through-put…

• Data Analysis (Offline)
  ▪ Large scale computing, physics results…
• Imaging Events•

50’s – 70’s  
LEP: 88 - 2000  
LHC
LHC

- **p-p Beam Energy**
- **Luminosity**
  - Nb of bunches
  - Nb p/bunch

- Bunch collisions 40 million/s
- ~25 interactions / Bunch crossing overlapping in time and space
  - 1000 x 10^6 events/s

- > 1000 particle signals in the detector at 40MHz rate
- 1 interesting collision in 10^{13}
• **Past VS LHC**

Dozens of particles/s  
No event selection  
‘Eye’ analysis  

**VS**  

10⁹ collisions/s  
Registering 1/10¹² events  
GRID computing

At each bunch crossing ~1000 individual particles to be identified every 25 ns …. High density of particles imply high granularity in the detection system …

Large quantity of readout services (100 M channels/active components)

Large neutron fluxes, large photon fluxes capable of compromising the mechanical properties of materials and electronics components. Induced radioactivity in high Z materials (activation) which will add complexity to the maintenance process

Large Magnetic Fields in large volumes, which imply usage of superconductivity (cryogenics) and attention to magnetic components (electronics components, mechanical stress, ….)

• **Very Difficult Environment**
Artistic Event
• Only a few of the numerous known particles have lifetimes that are long enough to leave tracks in a detector
• Most of the particles are measured through the decay products and their kinematic relations (invariant mass)
• Some short lived particles (b,c –particles) reach lifetimes in the laboratory system that are sufficient to leave short tracks before decaying → identification by measurement of short tracks
• Detectors are built to measure few charged and neutral particles (and their antiparticles) and photons: \(e^\pm, \mu^\pm, \pi^\pm, K^\pm, K^0, p^\pm, n, \Upsilon\)
• Their difference in mass, charge and interaction is the key to their identification
Particle Detectors

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Interactions

Structure within the Atom

Quark
Size < 10^{-19} m

Electron
Size < 10^{-18} m

Neutron and Proton
Size ≈ 10^{-15} m

Atoms
Size ≈ 10^{-10} m

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Properties of the Interactions

<table>
<thead>
<tr>
<th>Property</th>
<th>Gravitational</th>
<th>Weak (Electroweak)</th>
<th>Electromagnetic</th>
<th>Strong Fundamental</th>
<th>Strong Residual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles experiencing:</td>
<td>All</td>
<td>Quarks, Leptons</td>
<td>Electrically charged</td>
<td>Quarks, Gluons</td>
<td>Hadrons</td>
</tr>
<tr>
<td>Particles mediating:</td>
<td>Graviton (not yet observed)</td>
<td>W^+ W^- Z^0</td>
<td></td>
<td>Gluons</td>
<td>Mesons</td>
</tr>
<tr>
<td>Strength relative to electron for two u quarks at:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10^{-18} m</td>
<td>10^{-41}</td>
<td>0.8</td>
<td>1</td>
<td>25</td>
<td>Not applicable to quarks</td>
</tr>
<tr>
<td>3 x 10^{-17} m</td>
<td>10^{-41}</td>
<td>10^{-4}</td>
<td>1</td>
<td>60</td>
<td>Not applicable to hadrons</td>
</tr>
<tr>
<td>for two protons in nucleus</td>
<td>10^{-36}</td>
<td>10^{-7}</td>
<td>1</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>
Interaction with the atomic electrons. The incoming particle loses energy and the atoms are excited or ionized.

Interaction with the atomic nucleus. The particle is deflected (scattered) causing multiple scattering of the particle in the material. During this scattering a Bremsstrahlung photon can be emitted.

In case the particle’s velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produce a X ray photon, called Transition radiation.
Heavy Charged Particles

Bethe-Bloch formula gives the mean rate of energy loss (stopping power) for a heavy charged particle ($m_0 \gg m_e$), e.g. proton, k, π, μ.

$$\langle \frac{dE}{dx} \rangle = -4\pi N A r_e^2 m_e c^2 Z \frac{1}{A \beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \gamma^2 \beta^2}{I^2} T^{\max} - \beta^2 - \frac{\delta}{2} \right]$$

N: Avogadro’s Nb
m_e: e- mass
Z, A: medium Atomic, Mass
I: effective ionization potential
B: projectile velocity
• **Electrons and Positrons**

- Electrons/positrons; modify Bethe Bloch to take into account that incoming particle has same mass as the atomic electrons
- Bremsstrahlung (photon emission by an electron accelerated in Coulomb field of nucleus) in the electrical field of a charge Z comes in addition: \( \frac{\gamma}{m^2} \) goes as \( 1/m^2 \)

Deceleration of a charged particle when deflected by another charged particle, typically an electron by an atomic nucleus
Neutral Particles

- **Photoelectric effect** \((Z^5)\); absorption of a photon by an atom ejecting an electron. The cross-section shows the typical shell structures in an atom.

  *Used in various detector technologies (very imp. In medical imaging)*

- **Compton scattering** \((Z)\); scattering of a photon against a free electron (Klein Nishina formula). This process has well defined kinematic constraints (giving the so called Compton Edge for the energy transfer to the electron etc.) and for energies above a few MeV 90\% of the energy is transferred (in most cases).

- **Pair-production** \((Z^2+Z)\); essentially bremsstrahlung; threshold at \(2 \, m_e = 1.022 \, \text{MeV}\). Dominates at a high energy.

  *Most important in our field, Initiates EM shower in calorimeters*
• Interactions in the Detector

Low density → High density
High precision → Low precision
High granularity → Low granularity

momentum measurement by curvature in magnetic field

energy measurement by creation and total absorption of showers

muon detection with improved momentum measurement (long lever arm)

photons
electron positron
muons
pions proton

Low density → High density
Neutrinos interact only weakly, tiny cross-sections

To detect neutrinos, we need first a charged particle (again)

- Possible reactions:

  \[ \nu_e + n \rightarrow e^- + p \]
  \[ \bar{\nu}_e + p \rightarrow e^+ + n \]

  \[ \ell = e, \mu, \tau \]

- The cross-section or the reaction \( \nu_e + n \rightarrow e^- + p \) is of the order \( 10^{-43} \) cm\(^2\) (per nucleon, \( E_n \sim \) few MeV), therefore

  - Detection efficiency \( \varepsilon_{\text{det}} = \sigma \times N_{\text{surf}} = \sigma \rho N_A \frac{d}{A} \)

  - 1m Iron: \( \varepsilon_{\text{det}} \sim 5 \times 10^{-17} \)

- Neutrino detection requires big and massive detectors (kT) and high neutrino fluxes

- In collider experiments, fully hermetic detector allow to detect neutrinos indirectly: we sum up all visible energy and momentum, and attribute missing energy and momentum to neutrino
Detector Systems

Fix Target Geometry

Collider Geometry

Tracking Calorimeter Muon Filter
• Particle Detectors •

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Detector Technologies

- How are reactions of the various particles with detectors turned into electrical signals. We would like to extract position and energy information channel by channel from our detectors.
- Three effects/technologies are usually used:

**Ionisation detectors | Semiconductors | Scintillators**

If a particle has enough energy to ionize a gas atom or molecule, the resulting electrons and ions cause a current flow which can be measured. When a charged particle traverses Si, it produces ionizing and non-ionizing E Loss. The latter produces radiation damage, while ionization loss causes the creation of e-hole pairs which produces the signal. Scintillators are materials that produce sparks or scintillations of light when ionizing radiation passes through them. The charged particle excites atoms in the scintillator, e- returns to ground state by emitting a photon.

and these are used for different functions: tracking and/or triggering, energy measurements, photon detectors for Cherenkov or TRT, etc and from then on, it is all online (trigger, DAQ) and offline treatment and analysis ....
• ATLAS Detector •

- Muon chambers
- Toroid magnets
- Solenoid magnet
- Transition radiation tracker
- Pixel detector
- LAr electromagnetic calorimeters
- LAr hadronic end-cap and forward calorimeters
- Tile calorimeters
- Semiconductor tracker

Dimensions:
- 44m
- 25m
CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm) ~16m^2 ~66M channels
Microstrips (80x180 μm) ~200m^2 ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
Silicon strips ~16m^2 ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO_4 crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels
- **Trackers**

- **Measure charged particles as they emerge from the interaction point, disturbing them as little as possible**
- Measure the **trajectory** of charged particles
  - Measure several points (hits) along the track and fit curves to the hits (helix, straight line)
- Determine their **momentum**
  - From their curvature in a magnetic field
- **Extrapolate back** to the point of origin
  - Reconstruct primary vertices
- Reconstruct **secondary vertices**
  - Long-lived particles have a measurable displacement between primary vertex and decay
- **Match tracks** with showers in the calorimeters or tracks in the muon systems
- Trackers also contribute to **particle identification** (PID)
  - Measuring rate of energy loss (dE/dx) in the tracker
  - Using dedicated detectors to distinguish different particle types (TR, TOF, RICH)

Want a compact detector, inside a magnetic field, to register as many hits as possible but light to minimise interactions of charged (and neutral) particles before they reach the calorimeter systems
ATLAS Tracker

TRT (Straws-Gas)
- 350 kchannels
- 36 track points
- $\sigma \sim 130 \, \mu m$

SCT (Silicon strips)
- 6.2 Mchannels
- 4 track points
- $\sigma \sim 16 \, \mu m$

Pixel (Silicon pixels)
- 80 Mchannels
- 3 track points
- $\sigma \sim 10 \, \mu m$
ATLAS ID elements crossed by two charged particles of 10 GeV pT

- A particle at $|\eta| = 1.4$ traverses the beam-pipe, 3 pixel layers, 4 SCT disks with double layers of sensors, and approximately 40 straws in the TRT end-cap.
- A particle at $|\eta| = 2.2$ traverses the beam-pipe, only the first pixel layer, 2 end-cap pixel disks and the last 4 disks of the SCT end-cap.
Gaseous Detectors

Any charged particle traversing a gas will lose energy due to interactions with the atoms of the gas. This results in:

- **Excitation**, the particle passes a specific amount of energy to a gas atom
- **Ionization**, the particle knocks an electron off the gas atom, and leaves a positively charged ion

Resulting primary $e^-$ will have enough kinetic energy to ionize other atoms of gas. The sum is called **Total Ionization**.
**Ionization**

**Energy Loss of Charged Particles in Gases**

<table>
<thead>
<tr>
<th>Gas</th>
<th>Density, mg cm(^{-3})</th>
<th>(E_x), eV</th>
<th>(E_I), eV</th>
<th>(W_i), eV</th>
<th>(\Delta E/dx)(_{\text{min}}) keV cm(^{-1})</th>
<th>(N_p) cm(^{-1})</th>
<th>(N_T) cm(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ne</td>
<td>0.839</td>
<td>16.7</td>
<td>21.6</td>
<td>30</td>
<td>1.45</td>
<td>13</td>
<td>50</td>
</tr>
<tr>
<td>Ar</td>
<td>1.66</td>
<td>11.6</td>
<td>15.7</td>
<td>25</td>
<td>2.53</td>
<td>25</td>
<td>106</td>
</tr>
<tr>
<td>Xe</td>
<td>5.495</td>
<td>8.4</td>
<td>12.1</td>
<td>22</td>
<td>6.87</td>
<td>41</td>
<td>312</td>
</tr>
<tr>
<td>CH(_4)</td>
<td>0.667</td>
<td>8.8</td>
<td>12.6</td>
<td>30</td>
<td>1.61</td>
<td>37</td>
<td>54</td>
</tr>
<tr>
<td>C(_2)H(_6)</td>
<td>1.26</td>
<td>8.2</td>
<td>11.5</td>
<td>26</td>
<td>2.91</td>
<td>48</td>
<td>112</td>
</tr>
<tr>
<td>iC(_4)H(_10)</td>
<td>2.49</td>
<td>6.5</td>
<td>10.6</td>
<td>26</td>
<td>5.67</td>
<td>90</td>
<td>220</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>1.84</td>
<td>7.0</td>
<td>13.8</td>
<td>34</td>
<td>3.35</td>
<td>35</td>
<td>100</td>
</tr>
<tr>
<td>CF(_4)</td>
<td>3.78</td>
<td>10.0</td>
<td>16.0</td>
<td>54</td>
<td>6.38</td>
<td>63</td>
<td>120</td>
</tr>
</tbody>
</table>

\(n_p = 25\) ion pairs/cm

\(n_T = \Delta E/W_i = 2.5\) keV/cm / 25 eV = 100 ion pairs/cm

- 100 pairs are not easy to detect, typical noise of an amplifier is ~1000 e\(^-\)

- **Need to MULTIPLY the electrons**
• **Amplification**

• Multiplication requires fields where the $e^-$ energy occasionally is sufficient to ionise
Noble gases require the lowest electric field for formation of avalanches.
De-excitation of noble gases occur only via emission of photons
Quencher Gases

A polyatomic gas acts as a QUENCHER, i.e., absorbs photons in a large energy range due to the large amount of non-radiative excited states (rotational and vibrational)

- Most organic compounds in the HC and -OH families. The quenching efficiency increases with the nb of atoms in the molecule
- Freons, BF$_3$
- CO$_2$: non flammable, non polymerizing, easily available
## Gas in LHC detectors

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Sub-Detector</th>
<th>Gas Mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE</td>
<td>TPC, TRD, PMD</td>
<td></td>
</tr>
<tr>
<td>ATLAS</td>
<td>CSC, MDT, TRT</td>
<td></td>
</tr>
<tr>
<td>CMS</td>
<td>DT</td>
<td>Noble Gas + CO₂</td>
</tr>
<tr>
<td>LHCb</td>
<td>OT straws</td>
<td></td>
</tr>
<tr>
<td>TOTEM</td>
<td>GEM, CSC</td>
<td></td>
</tr>
<tr>
<td>LHCb</td>
<td>MWPC, GEM</td>
<td>Ar – CO₂ - CF₄</td>
</tr>
<tr>
<td>CMS</td>
<td>CSC</td>
<td></td>
</tr>
<tr>
<td>ATLAS, CMS, ALICE</td>
<td>RPC</td>
<td>C₂H₂F₄ - iC₄H₁₀ - SF₆</td>
</tr>
<tr>
<td>ATLAS</td>
<td>TGC</td>
<td>CO₂ – n-pentane</td>
</tr>
<tr>
<td>LHCb</td>
<td>RICH</td>
<td>CF₄ or C₄F₁₀</td>
</tr>
</tbody>
</table>
• MWPC •

- Fast position-sensitive detectors (1968)
- Continuously active
- Efficient at particle fluxes up to several MHz/cm²
- Sub-mm position accuracy
- **First electronic device allowing high statistics experiments!!**

MWPC… Rate capability limited by space charge defined by the time of evacuation of positive ions

G.Charpak, Noble Prize in 1992
Increasing Cell Granularity

STRAW TUBES
Anode-cathode distance: 2 mm
Spatial resolution ~ 130-300 μm

MICRO STRIP GAS CHAMBERS (MSGC - A.Oed, 1988)
Semiconductor industry technologies
Anode-cathode distance: 40 μm
Spatial resolution ~ 40 μm

MSGC… Very high rate capability due to small pitch and fast ion collection, but delicate structures with very high fields in electrodes edges… sparks
• Decoupling Multiplication from Charge Collection •

Micro Strip Gas Chamber

Spatial resolution ~ 50 µm
Time resolution better than 10 ns

Charge collection

Multiplication

Thin metal-coated polymer foils
70 µm holes at 140 mm pitch

200 µm

400 µm

GEM foil
**GEM Detectors**

- Primary electrons are released by ionizing radiation in the gas (E-field between drift plane and GEM)

- By applying a suitable voltage difference between the two metal sides of the GEM, an electric field with an intensity as high as 100kV/cm is created inside the holes which act as multiplication channels

- Readout electrodes are at ground potential; electron charge is collected on strips or pads, ions are partially collected in the bottom of the GEM foil
• Multi-GEM detectors

Cylindrical geometries have an important limitation: Primary electrons have to drift close to the wire before the charge multiplication starts. Limit in the time resolution $\sim 0.1\mu s$.

In a parallel plate geometry the charge multiplication starts immediately because all the gas volume is active (uniform and very intense field). This results in much better time resolution ($\sim 1\text{ ns}$).
Developed in the 80s as an **affordable, robust, large area detector** with:

- **Fast timing**: < 1 ns to ps for MRPC
- **Space resolution**: ~mm
- **Rate capability**: up to ~100 Hz/cm²

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**RPC developments for LHC**

- **Large Area Coverage** (> 5000 m²) – Industrialization
- **Increased Rate Capability** (~kHz/cm²)
- **Large Background Radiation**
• **Semiconductors**

- Used in nuclear physics for Energy measurements since the 50ies
- Appear in HEP in the 70ies
- In the 80ies, planar technique of producing silicon radiation sensors, permitting segmentation of one side of the junction and the use of signals recorded on the segments to determine particle positions

- Solid state ionization chamber, member of the large family of ionization detectors. A Si detector takes advantage of the special electronic structure of a semi-conductor
Basic element of a solid state (silicon) detector is... a **diode**

p-type (more holes) and n-type (more electrons) doped silicon material is put together

**For particle detectors**: reverse bias the diode to create an active detection layer

Depletion layer: zone free of mobile charge carriers
- no free holes, no electrons so that we can observe the ionization charge
- thickness of depletion region depends on voltage, doping concentration

Typically 20000 - 30'000 electron/hole pairs in Si

300 µm

Compare to intrinsic Si: $4.5 \cdot 10^8$ per detector/cm²
• Semiconductors

• Very attractive in HEP because of:
  – Good intrinsic energy resolution
    • Silicon: 1 e-hole pair for every 3.6 eV released by a crossing particle. In Gas: 30 eV required to ionize a gas molecule
    • High primary ionization (larger signal), no amplification: typical detector thickness (300 μm) result in 3.2 x10⁴ e-/hole pairs
  – Si high density reduces the range of secondary e, thus good spatial resolution
    • 10 μm, the best ~1 μm
  – The granularity can also be very high
  – Thin, therefore can be positioned close to the interaction point
  – Industrial process (high yield, continuous development….)
Strips

- Each strip is connected to one electronic readout channel
- First prototypes: ~ 1980
- Strip pitch: ~10-100 µm
- Position resolution: ~few µm due to charge sharing between neighbouring strips

Pixels

- 2D resolution
- First prototypes ~1990
- Can be used for tracking or imaging:
  - particle tracking = detection of individual charged particles
  - imaging = count / integrate particles or photons
Silicon Detectors at LHC

ALICE Pixel Detector

LHCb VELO

ATLAS Pixel Detector

CMS Pixel Detector

ALICE Drift Detector

ALICE Strip Detector

ATLAS SCT Barrel

CMS Strip Tracker IB
**Hybrid Pixels**

Development closely linked to progress in microelectronics and interconexión technologies (sensor & chip)

- Each pixel cell in the sensor is connected to a pixel cell in the readout chip via a bump bond
- Sensor and readout are optimized separately

- “Large” signal (sensor~200-300µm x 80 e-h pairs: 16000-24000 e-h)
- Thinning of readout wafers (~150µm at LHC)
- Mature technology employed in all LHC experiments

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Slide: P. Riedler, CERN
**ATLAS, Barrel SCT module**

- **Hybrid assembly** with readout chips

- **4 Silicon sensors**
  - 280 μm thick
  - 2.3° stereo angle
  - Overlap in φ & z to adjacent modules

- **Be module baseboard** with mounting points & central TPG
  - TPG (thermal pyrolytic graphite) plate for sensor cooling

- **Connector**
  - Power & data

- **12.8 cm**

- **6 binary readout chips on either sensor side; sig:noise = 14:1**

- **768 p⁺ microstrips Cell size: 80 μm [φ pitch] × 13 cm [z]**
  - Overall 6.3 \(10^6\) channels

- **Fully equipped double sided electrical module with baseboard and readout hybrids**
• Systems

• How to efficiently cover large surfaces? Ladders (modules)
  - sensor size limited by wafer size and bump bonding requirements (flatness!), LHC experiments today: ~7cm x 2cm
  - chip size limited by process rules (larger chip means lower yield in production)
What is a system?
- Sensor
- Readout electronics
- Interconnection
- Mechanical supports
- Cooling, thermal aspects
- Power supplies
- Services: cables, pipes, fiber links...
- Monitoring, sensors, alignment
**Goal:** get low mass, highly granular silicon pixel detectors without interconnection to a sensor.

⇒ Integrate charge generation volume into the readout chip.

“**Disadvantages**”

- Signal ~ 80e⁻⁻⁻h/µm: <1000 e⁻⁻⁻h
- Less radiation tolerant compared to hybrid pixel
- New technology
Silicon detectors, Trends

ALICE ITS Upgrade: Inner Layer Stave

Light weight, compact modules to minimize material budget:

- **Monolithic sensors**: integrated sensor and electronics
- **Integrated** mechanical support and cooling
- 50 µm silicon sensors connected via solder points *(direct on chip laser soldering)* to a 2-layer Al(Cu)-polyimide flex cable
- Power and signal connections to each chip
Scintillation Particle Detector

Scintillators are materials that produce sparks or scintillations of light when ionizing radiation passes through them. The charged particle excites atoms in the scintillator, e- returns to ground state by emitting a photon.

Detector Principle
- $dE/dx$ converted into visible light
- Detection via photosensor [e.g. photomultiplier, SiPM, human eye ...]

Main Features
- Sensitivity to energy
- Good linearity over large dynamic range
- Fast time response
- Pulse shape discrimination
Scintillators

Different types of scintillators
- Inorganic crystalline scintillators (NaI, CsI, BaF$_2$...)
- Nobel Gas (Ar)
- Organic (Liquids or plastic scintillators)

Many different geometries

The amount of light produced in the scintillator is very small. It must be amplified before it can be recorded as a pulse or in any other way.

External wavelength shifters and light guides are used to aid light collection in complicated geometries; must be insensitive to ionising radiation and Cherenkov light.
**Purpose:** Convert light into detectable electronic signal

**Principle:** Use photoelectric effect to ‘convert’ photons ($\gamma$) to photoelectrons (pe)

Details depend on the type of the photosensitive material. Many photosensitive materials are semiconductors, but photoeffect can also be observed from gases and liquids.

Photon detection involves often materials like K, Na, Rb, Cs (alkali metals). They have the smallest electronegativity $\rightarrow$ highest tendency to release electrons.
SciFi in numbers

Fibre mat × 8
SciFi Module × 12
Detector Layer × 4 (stereo angles 0°, +5°, -5°, 0°)
Tracking Station × 3

Scintillating Fibre Tracker

- 250 micron diam fibers
- 1152 mats, 144 modules
- 360 m² total area
- almost 11,000 km of fibre
- ~590'000 SiPM channels
Calorimeters

- Goal is to measure energy of incoming particle
  - **Detect E of neutral or charged particles.** Stop particles (absorb all the energy), except muon (heavy) & neutrinos (weak interaction).
  - The interaction of the incident particle with the detector (through electromagnetic or strong processes) produces a shower of secondary particles with progressively degraded energy.
    - Measure the integral of energy loss per depth
    - Sample the energy loss at several points

- Two types of calorimeters
  - Electromagnetic (photon and electron showers)
  - Hadron (pion, proton, neutron …)
**Calorimeters**

**Homegeneous EM Calorimeter (CMS)**

- Absorber = active detector
- Clear advantage: good energy resolution
  - the entire shower is kept in active detector material (no shower particle is lost in passive absorber)
- Disadvantages
  - limited granularity, no information on shower shape in longitudinal direction (along particle flight direction)

**Sampling EM Calorimeter (ATLAS)**

- Absorber interleaved with detector
- Typical sampling calorimeters use iron or lead absorber material, variety of detectors in between possible: gas detectors (MWPCs), plastic scintillators, liquid noble gases (LAr, LKr)
- ATLAS is using LAr with “accordeon” shaped steel absorbers
Muon Systems

- Function: muon detection; Muons are charged particles that are just like electrons and positrons, but 200 times heavier. Because muons can penetrate several metres of iron without interacting, unlike most particles they are not stopped by calorimeters. Therefore, chambers to detect muons are placed at the very edge of the experiment where they are the only particles likely to register a signal.

- Detection principle: Ionization detectors (gas), similar to precision trackers but usually of lower spatial resolution.

- They are fast detectors and are part of the Trigger system to select events.
Muon Spectrometer

DRIFT TUBES (DT)
Central coverage
Tracking (100 μm) & trigger

CATHODE STRIP CHAMBERS (CSC)
Forward coverage (6000 m2)
Tracking (1mm) & trigger
540 detectors, 0.5 MChannels

RESISTIVE PLATE CHAMBERS (RPC)
Central and forward coverage
Redundant Trigger (3 ns)
612 detectors
Most detectors rely critically on low noise electronics. A typical Front-End is shown below, where:

- Detector is represented by the capacitance $C_d$
- Bias voltage is applied through $R_b$
- Signal is coupled to the amplifier though a capacitance $C_c$
- $R_s$ represents all the resistances in the input path

The preamplifier provides gain and feed a shaper which takes care of the frequency response and limits the duration of the signal.
Data Acquisition, Storage, Distribution and Processing is as complex as the detector itself

- Large data production (~PB/sec) versus storage capability (~GB/sec) forces huge online selection
- 3 levels of triggers (first level fully electronics based)
- Data distribution for offline processing using GRID system

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Método</th>
<th>Entrada Sucesos/s</th>
<th>Salida Sucesos/s</th>
<th>Factor de reducción</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nivel 1</td>
<td>HW (Í, Calo)</td>
<td>40 000 (10^3)</td>
<td>100 (10^3)</td>
<td>400</td>
</tr>
<tr>
<td>Nivel 2</td>
<td>SW (RoI, ID)</td>
<td>100 (10^3)</td>
<td>3 (10^3)</td>
<td>30</td>
</tr>
<tr>
<td>Nivel 3</td>
<td>SW</td>
<td>3 (10^3)</td>
<td>0.2 (10^3)</td>
<td>15</td>
</tr>
</tbody>
</table>
Last generation of HEP detectors are incredibly complex and state of the art pieces of technology

- Large use of (semiconductors/gas) radiation hard technology for trackers
- Calorimeters precise as never before
- Cryogenics for detectors and magnet systems
- Detector systems have increased in size and complexity at least a factor 10
- The data flow and data processing is unprecedented
- Projects span over a lifetime of 3-4 decades, involving thousands of scientists

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Countries</th>
<th>Institutions</th>
<th>Scientists</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE</td>
<td>36</td>
<td>131</td>
<td>~1200</td>
</tr>
<tr>
<td>ATLAS</td>
<td>38</td>
<td>177</td>
<td>~ 3000</td>
</tr>
<tr>
<td>CMS</td>
<td>42</td>
<td>182</td>
<td>~ 3000</td>
</tr>
<tr>
<td>LHCb</td>
<td>16</td>
<td>65</td>
<td>~ 700</td>
</tr>
</tbody>
</table>
Example, the ATLAS Transition Radiation Tracker (non-exhaustive list!)

- Distributed/Collaborative Projects

- R&D
  - Module Construction: RU, US
  - Electronics: CERN, US, DK, SE
  - Procurement in Firms: EU, US, RU, FR, etc
  - Services (gas, cooling, cables, sensors, etc): CERN, US, DK, RU, SE, PO

- Design Prototyping
  - RU, US
  - CERN, US

- Installation

- Tests
  - CERN, RU, US

- Integration
  - CERN

- Commissioning

- All
CERN’s priority is the exploitation of the LHC to its maximum potential… 2035

- Run1: 2008 – 2013 7-8 TeV ~ 2000 Higgs
- Run2: 2015 – 2018 13-14 TeV
- Run3: 2021 – 2023 > Luminosity
Further Detector Upgrades

The discovery of the Higgs boson is the start of a major programme of work to measure this particle’s properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier

- Must replace inoperable detector elements (rad damage)
- Must upgrade electronics to cope with increased rates

Trackers R&D Efforts

- Improved radhard
- Optimization of sensor thickness (reduced leak current) and geometry (better overlap, less material)
- 3D sensors
- Combine sensor and electronics in one chip (MAPS on CMOS)
- On detector thermal management (CO₂)
- Scintillating Fiber Tracker (LHCb)
Detector Upgrades

**Calorimeters R&D Efforts**, towards rad tolerant systems
- Rad-tolerant crystal scintillators (LYSO, YSO, Cerium Fluoride), WLS fibres in quartz capillaries, rad-tolerant photo-detectors (e.g. GaInP), change layout of tile calorimeter using WLS fibres within scintillator to shorten the light path length, High granularity Particle flow / Imaging Gas Calorimetry (CALICE)...
- *Electronics upgrades*: On-detector front-end electronics with sufficient resolution and large dynamic range

**Muon systems R&D Efforts**
- Improved rate capability and timing, using novel detector technologies (e.g. MPGD)

**Electronics**
- Development of new front-end chips to cope with increased channel densities, develop high density interconnects, optimize power distribution, develop High speed links (≥10 Gbps)

**Trigger/DAQ/Offline computing**
- New trigger strategies, processing, networks, storage, CPU, CLOUD-computing…
Detector Trends

Sensors & FE
- Increased position resolution (~μm level)
- Increased timing accuracy (~ns)
- Low mass
- Increased radiation hardness
- Integration sensors&electronics

Engineering
- Interconnect technologies
- Powering, Cooling
- Services, Light-weight supports
- New materials
- Alignment, Stability…

Development of integrated designs, carried out in close collaboration with physicists, microelectronics experts, mechanical/thermal engineers, material/micro/nano technology scientists…
Other Fields of Application

- Fast and Therma Neutron Detection
  Non-destructive diagnostic, Biology, Nuclear plants, …

- Xray Low Energy
  Radioactive waste…

- Pixelated GEMs
  Microdosimetry, Direct measurements with real tissue, Radon monitors…

- Gamma High Fluxes
  Radiotherapy…

- High Intensity Beam Monitors
  Hadrontherapy, Ions beam monitoring…

Highly sensitive GEM-based UV flame and smoke detector

RETGEM-based detectors are able to reliably detect a 1.5 m³ fire at a ~1 km distance

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

There is a very close relationship between physics discoveries and developments in instrumentation: Accelerators, Detectors, Electronics and Computing.
Thanks for your attention!
• The Particle Detector BriefBook http://www.cern.ch/Physics/ParticleDetector/BriefBook/
• CERN summer student lectures by W. Riegler: http://indico.cern.ch/conferenceDisplay.py?confId=134370
• ICFA Schools on Instrumentation
  • The last one: http://fisindico.uniandes.edu.co/indico/conferenceTimeTable.py?confId=61#20131125

• BOOKS:
  • K. Kleinknecht - Detectors for Particle Radiation, C.U.P. 1990
  • R. Fernow - Introduction to Experimental Particle Physics, C.U.P. 1986
  • W.R. Leo - Techniques for Nuclear and Particle Physics Experiments, Springer-Verlag 1987

• CERN Notes:
  • F. Sauli - Principles of Operation of Multiwire Proportional and Drift Chambers, CERN 77-09
Spare Slides
Detectors interleaved with the magnet yoke steel layers