Introduction to Particle Detectors

Mar Capeans
CERN July 7th 2017
• Detector Technologies
• How detectors are designed and used in HEP experiments, taking into account system aspects
• R&D trends, Future detectors

• For an in-depth, more academic exposure please see:
  – CERN Summer students lectures (5 h on detectors): https://indico.cern.ch/event/632096/
  – Semiconductor Radiation Detectors - Device Physics, G.Lutz, Springer
  – Calorimetry, R. Wigmans, Oxford Science Publications, 2000
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...
LHC Detectors Context

- **p-p Beam Energy**: $7 \times 10^{12}$ eV
- **Luminosity**: $10^{34}$ cm$^{-2}$ s$^{-1}$
- **Nb of bunches**: 2835
- **Nb p/bunch**: $10^{11}$

Bunch collisions 40 million/s

~25 interactions / Bunch crossing overlapping in time and space

$10^9$ events/s

> 1000 particle signals in the detector at 40MHz rate

1 interesting collision in $10^{13}$
**Past vs LHC**

- Dozens of particles/s vs. $10^9$ collisions/s
- No event selection vs. Registering $1/10^{12}$ events
- ‘Eye’ analysis vs. GRID computing

**LHC … Very Difficult Environment**

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, ….)
Artistic Event

Higgs

q, g

mar.capeans@cern.ch
7/7/2017
• **Particle Detection**

• Usually we can not ‘see’ the reaction itself, but only the end products of the reaction

• In order to reconstruct the reaction mechanism and the properties of the involved particles, we want the maximum information about the end products

• **The ideal particle detector should provide...**
  – Coverage of full solid angle (no cracks, fine segmentation)
  – Measurement of momentum and/or energy
  – Detect, track and identify all particles (mass, charge)
  – Fast response, no dead time

  – Practical limitations: technology, space, budget
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)
Interactions

Structure within the Atom

Quark
Size $< 10^{-19}$ m

Electron
Size $< 10^{-18}$ m

Neutron and Proton
Size $= 10^{-15}$ m

Nucleus
Size $= 10^{-14}$ m

Atom
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</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acts on:</td>
<td>Mass - Energy</td>
<td>Flavor</td>
<td>Electric Charge</td>
<td>Color Charge</td>
</tr>
<tr>
<td>Particles experiencing:</td>
<td>All</td>
<td>Quarks, Leptons</td>
<td>Electrically charged</td>
<td>Quarks, Gluons, Hadrons</td>
</tr>
<tr>
<td>Particles mediating:</td>
<td>Graviton (not yet observed)</td>
<td>$W^+$, $W^-$, $Z^0$</td>
<td>$\gamma$</td>
<td>Gluons, Mesons</td>
</tr>
<tr>
<td>Strength relative to Electroweak</td>
<td>$10^{-41}$</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>for two u quarks at:</td>
<td>$10^{-41}$</td>
<td>Not applicable to quarks</td>
<td>25</td>
<td>Not applicable to quarks</td>
</tr>
<tr>
<td>for two protons in nucleus</td>
<td>$10^{-36}$</td>
<td>Not applicable to hadrons</td>
<td>60</td>
<td>20</td>
</tr>
</tbody>
</table>

EM
Strong
Weak
Gravity
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 produced and 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 ($m_0 >> m_e$), e.g. proton, k, π, μ

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

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

• 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: \( \sigma \) goes as \( 1/m^2 \)
Neutral Particles

Contrary to charged particles that deposit energy continuously due to ionization, photons usually suffer one-off interactions producing charged particles.

- **Photoelectric effect** ($Z^5$); absorption of a photon by an atom **ejecting an electron**.
  
  *Used in various detector technologies (very imp. In medical imaging)*

- **Compton scattering** ($Z$); scattering of a photon against a free electron (Klein Nishina formula). It results **in a decrease in energy of the photon**. Part of the energy of the photon is transferred to the recoiling electron.

- **Pair-production** ($Z^2+Z$); essentially bremsstrahlung, **photon creating an electron-positron pair near a nucleus**. Dominates at a high energy, threshold at $2m_e = 1.022$ MeV
  
  *Most important in our field, Initiates EM shower in calorimeters*
Neutrinos interact only weakly, tiny cross-sections

To detect neutrinos, we need first a charged particle (again)
  - Possible reactions:

\[
\begin{align*}
\nu_e + n &\rightarrow e^- + p \\
\bar{\nu}_e + p &\rightarrow \ell^+ + n
\end{align*}
\]

The cross-section or the reaction \( n_e + n \rightarrow e^- + p \) is of the order \( 10^{-43} \text{ cm}^2 \) (per nucleon, \( E_n \sim \text{few MeV} \)), therefore
  - Detection efficiency \( e_{\text{det}} = s \times N_{\text{surf}} = s \times r \times N_A \frac{d}{A} \)
  - 1m Iron: \( e_{\text{det}} \sim 5 \times 10^{-17} \)

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

- Tracking
- Calorimeter
- Muon Filter

Collider Geometry

- Beam
- Target
- Magnet

- Beam
- Endcap
- Barrel
- Endcap
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) ~16m² ~66M channels
- Microstrips (80x180 μm) ~200m² ~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 ~16m² ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO₄ crystals

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

  **Semiconductors**
  
  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**
  
  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 ....
• Tracking •

Tracking chamber
Electromagnetic calorimeter
Hadron calorimeter
Muon detector

photons
electron positron
muons
pions proton

neutrinos...
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 TRT, 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

- Barrel
- Endcap

Dimensions:
- 6.2 m
- 2.1 m
• **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
  \[\sigma \sim 10 \, \mu m\]
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**

- Typically $\sim 100$ pairs/cm, and they are not easy to detect as the typical noise of an amplifier is $\sim 1000$ $e^-$
- **Need to MULTIPLY the electrons**
• **Amplification**

• Multiplication requires fields where the $e^-$ energy occasionally is sufficient to ionise

**Thin Anode Wire**

- **Cathode radius** $b$
- **Anode radius** $a$

**Electric Field and Potential**:

\[
E(r) = \frac{CV_0}{2\pi\varepsilon_0} \frac{1}{r}
\]

\[
V(r) = \frac{CV_0}{2\pi\varepsilon_0} \ln \frac{r}{a}
\]

\[
C = \frac{2\pi\varepsilon_0}{\ln(b/a)}
\]

Capacitance per unit length
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

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

Thin metal-coated polymer foils
70 µm holes at 140 mm pitch
• New LHC Detectors with newest technologies (GEM) •

Exploded view of a long GE1/1 triple-GEM:

CMS GE1/1
@ LS2

285 mm
1283 mm
510 mm
Gas Detectors

- Good spatial resolution
- Good dE/dx
- Good Rate capability
- Fast & Large Signals
- Low radiation length
- Large area coverage
- Multiple configurations, flexible geometry

Gas detectors perform well where a precision of a few tens of microns is required.

At very large radius, where large areas have to be covered, e.g. the muon chambers, it is unrealistic to use anything other than gas detectors.

In the intermediate region between about 20 cm and 2 m radius silicon and micropattern gas detectors meet as rivals, as both fulfill all the necessary requirements concerning precision, rate capability and radiation hardness.
Semiconductors

- 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.
  
  - 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
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: $4.5 \times 10^8$ per detector/cm$^2$

**Please watch this fun video on transistors**
https://www.youtube.com/watch?v=IcrBqCFLHIY
DC coupled strip detector
Through going charged particles create $e^-$ $h^+$ pairs in the depletion zone (about ~25000 pairs in standard detector thickness).
These charges drift to the electrodes.
The drift (current) creates the signal which is amplified by an amplifier connected to each strip.
From the signals on the individual strips the position of the through going particle is deduced.
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 mm) result in $3.2 \times 10^4$ e-/hole pairs

- Si high density reduces the range of secondary e, thus good spatial resolution
  - 10 mm, the best ~1 mm

- The granularity can also be very high

- Thin, therefore can be positioned close to the interaction point

- Industrial process (high yield, continuous development... )
Strips VS Pixels

**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

mar.capeans@cern.ch

7/7/2017
**ATLAS, Barrel SCT module**

**Hybrid assembly**
- with readout chips

**4 Silicon sensors**
- 280 μm thick
- 2.3° stereo angle
- Overlap in $\phi$ & $z$ 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 [$\phi$ pitch] x 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
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
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

**Scintillating fibres**

mar.capeans@cern.ch
• **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
**Photo-detectors**

**Purpose:** Convert light into detectable electronic signal

**Principle:** Use photoelectric effect to ‘convert’ photons (g) 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 → highest tendency to release electrons.
SciFi in numbers

- 250 micron diam fibers
- 1152 mats, 144 modules
- 360 m$^2$ total area
- almost 11,000 km of fibre
- $\sim$590’000 SiPM channels

Fi-based downstream tracking stations
Single technology that can perform similarly to a silicon tracker, but cost-effective enough to cover the 30m$^2$ of acceptance of each layer. The result is a light and uniform tracking detector without the need for cooling or signal cables entering into the detector acceptance.
Calorimetry

Diagram showing different particles and their paths through a calorimeter. Neutrinos are indicated at the end.
Calorimeters

- Experimental technique in nuclear and particle physics where the detection of a particle and the measurement of its properties is based on total or partial absorption in the detector volume.

- It is a destructive process: particle’s energy is converted in a detectable signal until the particle is absorbed (or leave the detector).

- First calorimeters in Particle Physics appeared in the ‘70s as need to measure energies of all particles, charged and neutrals, except muon (heavy) & neutrinos (weak interaction).

Calorimeters measure charged and neutral particles (g, e, jets (q,g), missing transverse energy i.e. neutrinos), performance improves with energy and is ~constant over 4p, high rate capabilities and fast making them suitable for trigger applications.
Calorimeters

1. An incident particle interacts with the calorimeter passive and active material

2. A cascade process is initiated: shower development depends on particle type and on detector material

3. Visible energy - heat, ionization, excitation of atoms, Cherenkov light - deposited in the active media of the calorimeter produces a detectable signal

4. Signal produced is proportional to the total energy deposited by the particle

5. Calorimeter’s calibration establishes a precise relationship between the ‘visible energy’ detected and the energy of the incoming particle
Calorimeter Types

By Particle Type

<table>
<thead>
<tr>
<th>Electromagnetic Calorimeter</th>
<th>Hadronic Calorimeter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons and electron showers ($\gamma, e, \pi^0$)</td>
<td>Charged and neutral hadrons, jets ($\pi, p, n$)</td>
</tr>
</tbody>
</table>

EM Shower
Energy losses result from different mechanisms, at high energy the most important processes:
- Electron/Positrons: Bremsstrahlung
  \[ \frac{dE_{e^\pm}}{E_{e^\pm}} = - \frac{dx}{X_0} \]
- Photons: Pair productions
  \[ \frac{dE_\gamma}{E_\gamma} = - \frac{(7/9)dx}{X_0} \]

Hadronic Shower
They develop as result of inelastic interaction with the media nuclei through a cascade process
A multitude of effects are produced in the shower development which make the hadron calorimeters a more complicated detector to optimize and with a significantly worse intrinsic resolution.
## Calorimeter Types

<table>
<thead>
<tr>
<th>By Construction Type</th>
<th>Homogenous Calorimeter</th>
<th>Sampling Calorimeters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Homogenous Calorimeter</strong></td>
<td>Full absorption detectors, fully active medium for both energy degradation and signal generation</td>
<td>Alternating layers of absorber material to degrade the particle energy and active media to provide detectable signals</td>
</tr>
<tr>
<td><strong>Sampling Calorimeters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scintillation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semiconductor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cherenkov</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ionization (Common: LAr)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Common absorbers are Pb, Fe, Cu, U</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Calorimeters**

**Homogeneous EM Calorimeter (CMS)**
- **Clear advantage:** good energy resolution, good linearity
  - 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)
  - Cost

**Sampling EM Calorimeter (ATLAS)**
- Only a fraction of the energy deposited is detectable: less precision
- Typical sampling calorimeters use iron or lead absorber material, variety of detectors in between possible
- ATLAS is using LAr with “accordion” shaped steel absorbers (accordion geometry to provide better uniformity of response, less cabling, and fast signal extraction)
Calorimeter Systems

Homogenous ECAL based on scintillating Lead/Tungstate crystals.

HCAL: The hadron barrel (HB) and hadron endcap (HE) calorimeters are sampling calorimeters with 50 mm thick copper absorber plates interleaved with 4 mm thick scintillator sheets. Hadron Forward (HF) is a SS absorber and quartz fibers emitting Cherenkov light.

ECAL based on liquid argon sampling calorimeter; Lead absorber. In the forward regions (FCAL), used Cu rods.

HCAL is a sampling calorimeter using iron as absorber material and scintillating tiles as active material. The HEC (End-Cap calo) is an LAr sampling calorimeter with Cu plate absorbers.
Muon Systems

- Tracking chamber
- Electromagnetic calorimeter
- Hadron calorimeter
- Muon detector

- Photons
- Electron positron
- Muons
- Pions proton

neutrinos...
• **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.

**ATLAS**, 12 000 m², 1.1 Mchannels
Alignement precision <±30 mm
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 ($\sim 1\,\text{ns}$)
Resistive Plate Chambers

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

**RPC developments for LHC**
- Large Area Coverage (> 5000 m²) – Industrialization
- Increased Rate Capability (~kHz/cm²)
- Large Background Radiation

**Diagram Description**
- **HV**
- **GND**
- **READOUT STRIPS X**
- **READOUT STRIPS Y**
- **2 mm**
- **2 mm**
- **GAS GAP**
- **INSULATOR**
- **RESISTIVE ELECTRODES:**
  - BAKELITE PLATE with $\rho \sim 10^9 \, \Omega \cdot \text{cm}$
  - (linseed oil)
  + GRAPHITE COATING
**Muon Spectrometer**

**DRIFT TUBES (DT)**
Central coverage
Tracking (100 mm) & trigger

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

**RESISTIVE PLATE CHAMBERS (RPC)**
Central and forward coverage
Redundant Trigger (3 ns)
612 detectors
Signals

- Energy
- Light
- Current
- Voltage
- Bits

Energy → Light → Current → Voltage → Bits → Light

Partícula → PbWO₄ Crystals → APD VPT → Floating-Point Preamp → ADC → Fiber Readout

Upper-Level VME Readout Card (in Counting Room)

Digital Trigger S

Detector → Electrónica → Adquisición

mar.capeans@cern.ch

7/7/2017
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>

Tier O: Worldwide LHC Computing Grid
**HEP Detectors**

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 increased in size and complexity at least a factor 10
- The data flow and data processing is unprecedented
- Projects span over 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>37</td>
<td>154</td>
<td>~1500</td>
</tr>
<tr>
<td>ATLAS</td>
<td>38</td>
<td>182</td>
<td>~3000</td>
</tr>
<tr>
<td>CMS</td>
<td>46</td>
<td>182</td>
<td>~3500</td>
</tr>
<tr>
<td>LHCb</td>
<td>16</td>
<td>69</td>
<td>~800</td>
</tr>
</tbody>
</table>
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
• LHC Tracker Upgrades •

+ IBL PIXEL

+ New PIXEL

NEW TRACKER

NEW TRACKER

NEW TRACKER

NEW TRACKING SYSTEM (VELO, UT, SciFi)

LS1

2013 2014 2015 2016 2017 2018

2019 2020 2021 2022 2023 2024 2025

LS2

LS3

mar.capeans@cern.ch
• Tracker Upgrades

Challenges for HL-LHC
• Maximum leveled instantaneous luminosity of $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Currently $\sim 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
• 3,000 fb-1 Integrated luminosity to ATLAS/CMS over ten years of operation
• 200 (mean number of) proton-proton interactions per bunch crossing. Design was 23, recently extended capability to $> 50$ pp interactions per bunch crossing

• Higher particle fluences: increased radiation tolerance
• Higher occupancies: finer segmentation
• Larger Area ($\sim 200 \text{ m}^2$ for strips and 16 m$^2$ for pixels): cheaper sensors, ease of construction, distributed production
• Low noise and power

<table>
<thead>
<tr>
<th></th>
<th>Silicon Area (m$^2$)</th>
<th>MChannels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel</td>
<td>8.2</td>
<td>638</td>
</tr>
<tr>
<td>Strip</td>
<td>193</td>
<td>74</td>
</tr>
</tbody>
</table>
• **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 ($\geq 10$ Gbps)

• **Trigger/DAQ/Offline computing**
  – New trigger strategies, processing, networks, storage, CPU, CLOUD-computing...
• **Diverse R&D**
  
  Driven by Study Projects

• **LCD**
  
  – The Linear Collider Detector focuses on physics and detector studies for a future e+e- collider at the TeV-scale

• **FCC**
  
  – The Future Circular Collider Study explores different designs of circular colliders (100 TeV) for the post-LHC era

• **Neutrino Platform**
  
  – Fundamental research in neutrino physics at particle accelerators worldwide
**CLIC Detector**

**LHC:** high rates of QCD backgrounds, need of complex triggers and high levels of radiation.

**Linear colliders** imply collisions $e^+e^-$ that are pointlike, with initial state well-defined and therefore with a clean experimental environment: possible trigger-less readout, and most important, low radiation levels. **Makes it easier to use new technologies.**
Neutrino Detectors

DUNE Overview

- four identical cryostats deep underground
- staged approach to four independent 10 kt LAr detector modules
- Single-phase and dual-phase readout under consideration

high precision near detector at 574m

Wide band, high purity $\nu_\mu$ beam with peak flux at 2.5 GeV operating at $\sim$1.2 MW and upgradeable
**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 m$^3$ fire at a ~1 km distance

Experimental testing is the key to discover and advance knowledge.

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

Development of integrated designs is carried out in close collaboration with physicists, microelectronics experts, mechanical/thermal engineers, material/micro/nano technology scientists...

Message for your students

Experimental physicists contribute to the complete cycle

• Messages for your students •

mar.capeans@cern.ch 7/7/2017
Thanks for your attention!
• *The Particle Detector BriefBook* [http://www.cern.ch/Physics/ParticleDetector/BriefBook/](http://www.cern.ch/Physics/ParticleDetector/BriefBook/)

• CERN summer student lectures by W. Riegler: [http://indico.cern.ch/conferenceDisplay.py?confId=134370](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](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 Multiwires Proportional and Drift Chambers, CERN 77-09
Spare Slides
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>

mar.capeans@cern.ch  7/7/2017
Detectors interleaved with the magnet yoke steel layers
• Distributed/Collaborative Projects •

Example, the ATLAS Transition Radiation Tracker (non-exhaustive list!)

- 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
  - CERN, US

- Tests
  - CERN, RU, US

- Integration
  - CERN

- Installation

- Commissioning

- All

mar.capeans@cern.ch

7/7/2017