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#### Detectors

Particle detectors are devices where the particles interact allowing us to measure some quantities – position, time, momentum, electric charge, energy, etc



Tracks of alpha particles seen in a cloud chamber at LIP



Track of a cosmic ray seen in a spark chamber at LIP

#### A detector in action



#### Cloud chamber at LIP

#### **Detectors - large and deep neutrino detectors** Examples of Ice Cube in Antartica using the ice as detector and Antares in the Mediterranean using the sea water as detector



#### Ice Cube

#### Both detectors use photmultiplier tubes as photosensors



#### Detectors for cosmic rays - the atmosphere and above



Can send detectors in balloons, put them in orbit (example AMS at the ISS) or lay them in the ground or underground in deep mines (neutrinos again)



#### Detectors - a large detector atmosphere based Auger detector in Argentina uses the atmosphere as a component to study extreme energy cosmic rays





Timing, position and detector size and granularity need to be adequate for the subject

#### Focus on LHC and its general purpose detectors ATLAS and CMS



CMS detector open for maintenance

#### Large Hadron Collider (LHC)

It is a discovery machine, projected to search for: Higgs (found)

SUSY Mont Blanc Dark matter Black holes Particles of many other models New unexpected particles

lake

airport



p-p collider 27 km perimeter Designed for: 7 TeV/beam Luminosity 10<sup>34</sup>cm<sup>-2</sup>s<sup>-1</sup>

These parameters set the working environment for these HEP detectors

ATLAS

#### Signal and background in the LHC package



#### Collisions at the LHC: nominal values



#### Collisions at the LHC: the detectors

Want to see what happens (result) in the collision

Detector built around the collision point, covering as much as possible (depending on the center of mass energy)



#### Collisions at the LHC: the detectors

At the LHC center of mass energy the detectors to contain most of the particles produced in the collisons need to be huge.

Even the "compact" CMS is quite big.



#### ATLAS detector



Based on track detectors in magnetic fields and energy detectors (calorimeters)

#### Transverse momentum ( $p_T$ ) and eta ( $\eta$ )



#### **Detector shape and parameters**

LHC environment (circular collider of 7 TeV protons at a huge rate) and the Physics searched motivated the design of the multi-purpose detectors ATLAS and CMS



In an environment of pile-up of collisions (seen in next slide) With a lot of radiation that damages the detectors

## LHC environment

What do we expect roughly speaking at L =  $10^{34}$  cm<sup>-2</sup>s<sup>-1</sup>?

Assume detector with coverage over  $-3 < \eta < 3$  ( $\theta = 5.7^{\circ}$ )

#### for tracks and $-5 < \eta < 5$ ( $\theta = 0.8^{\circ}$ ) for calorimetry:

- ✓ Most of the energy is not seen! (300000 GeV down the beam pipe)
- ✓ ~ 900 charged tracks every 25 ns through inner tracking
- ✓ ~ 1400 GeV transverse energy (~ 3000 particles) in calorimeters every 25 ns

#### Pile-up

Pile-up is the name given to the impact of the 10-40 uninteresting (usually) interactions occurring in the same bunch crossing as the hard-scattering process which generates



## About neutrinos

One word about neutrinos in hadron colliders:

- since most of the energy of the colliding protons escapes down the beam pipe, one can only use the energy-momentum balance in the transverse plane
  - concepts such as E<sub>T</sub><sup>miss</sup>, missing transverse momentum are used everywhere
- the detector must therefore be quite hermetic
  - -> no neutrino escapes undetected
  - -> no human enters without major work
- (fast access to some parts of the detectors is difficult)

#### **Detector shape and parameters**

Needs very fine granularity near the collision point to identify isolated tracks of each charged particle

Needs coverage to very near the beam pipe to be able to identify missing transverse energy (momentum)

#### Needs to be radiation hard

Needs to be very fast producing a manageable volume of data to record. It is impossible to record all events.

Needs a trigger system able to select the few interesting events to record and reject the uninteresting ones



#### Measuring momentum - bending path of charged particles in magnetic field

ATLAS A Toroidal LHC Apparatus

CMS Compact Muon Solenoid



CMS advantage: 4T (vs 2T in ATLAS inner tracker); much easier to visualize CMS disadvantage: huge amount of iron for return flux produces multiple scattering for the muons decreasing resolution in momentum measurement

## How to measure the momentum of large momentum particles



Momentum resolution

$$\frac{dp}{p} \propto \frac{p}{BL^2}$$

So, optimize  $BL^2$ 

Need a large lever arm L (choice of ATLAS)

or

a large magnetic field B (choice of CMS, B = 4 T)

#### How detectors work - ionization



total ionization is the sum of primary and secondary

ATLAS Liquid Argon calorimeter LArg + Pb Passage of a charged particle through matter releases electrons from the atoms along its path producing ionization



## How detectors work Ionization in a gas filled tube



Voltage, volts

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#### **Muon chambers:**



#### In general, only muons (and neutrinos)

#### that are not detected) arrive here



They leave tracks in stacked long gas filled tubes of the muon detector.

Several planes of chambers allow to reconstruct the track of the particle



#### **Inner trackers**

#### **Inner trackers**



ATLAS – pixels and strips at inner radii followed by a gaseous transition radiation detector at larger radii



#### **Tracking detector**

Immerse in a solenoidal magnetic field

Allows the "visualization" of the charged particles tracks

- Allows the determination of the collision point
- Gives information about secondary vertices
- Inner layers made of semiconductors. In ATLAS, outer layer is transition





## Principle of semiconductor detectors



28

### Calorimeters

### **Calorimeters:**

Participate in the identification of particles

The e.m. calorimeter measures the energy of electrons and photons

The hadronic calorimeter measures the energy of hadrons



#### CMS ECAL

#### Interactions of high energy electrons/positrons

The main way of energy loss for high energy electrons/positrons is bremsstrahlung (braking radiation)

31



Strong deceleration happens when the particle passes near a nucleus

there is emission of photons

energy of the electron that is loosing energy by bremsstrahlung:  $E = E_0 \exp(-x/X_0)$ 

X<sub>0</sub> is the radiation length

## Interaction of high energy photons

The main interaction of high energy photons is the production of electron-positron pairs



happens near a nucleus

photon energy needs to be above 2 x 511 keV

## **Electromagnetic shower**

For high energy photons or electrons/positrons, pair production and bremsstrahlung are respectively the most probable way to loose energy. They will alternate in a particle shower.



number of particles in the shower grows with time

photon origins e+ e- pair

electron/positron radiates photon

proccess repeats when particle energy is high enough

Electromagnetic showers allow the absorption of photons/electrons/positrons in calorimeters

#### **Electromagnetic shower**



After the critical energy shower does not grow.

Shower maximum at  $x_{max} \propto \ln(\frac{E0}{EC})$ 

## ATLAS Liquid Argon e.m. calo



Absorber is lead

Active medium is liquid argon

Shape is accordion to avoid particles crossing only absorber or only active medium

Located inside a cryostat

It is radiation hard

High granularity in front and longitudinal segmentation for better e/gamma identification

Relatively small back cells to be sensitive to energy lost in cryostat

## CMS crystal electromagenetic calo





Homogeneous calorimeter

Lead tungstate (PbWO<sub>4</sub>) crystals create electromagnetic showers and produce scintillation light

High density (8.3 g/cm3), fast decay time allows to collect 80% of light in 25 ns

**Radiation hard** 

Allows excellent energy resolution

#### Hadron calorimeter



## ATLAS TileCal hadron calorimeter



Hadron calorimeter with good performance at low cost

- Scintillating Tiles and WLS optical fibres
- Photomultiplier tubes (PMTs)
- Steel/Tiles, ratio 4.7 : 1 ( $\lambda$  = 20.7 cm)
- 10 k channels (5000 cells)
- Transversal granularity  $\Delta \eta \ x \ \Delta \phi$ =0.1x0.1
- Longitudinal segmentation: 3 layers
- Containment ~ 98% TeV hadrons, jets
- ATLAS jet resolution:  $\sigma_{\rm E}/{\rm E}$  ~ 50-60%/ $\sqrt{{\rm E}}$   $\oplus$  3%

Robust technology for barrel region, but not suited for end-caps (radiation damage)

In end-caps use Liquid Argon technology

### Hadronic showers and jets



## Hadronic showers originate jets of particles

Hadronic showers are similar to electromagnetic ones but much more complex

They originate from the interaction of particles made of quarks or gluons

They have larger intrinsic fluctuations in energy detectable by detectors: there are nuclear interactions taking energy, it may include neutrinos, muons, neutrons, etc that may escape totally or partially, etc

#### How detectors work

#### **Scintillation – organic scintillators**



Hadronic calorimeter Tilecal

Charged particles deposit energy causing excitation of solvent and dopants molecules. Fast de-excitation by fluorescense. Light collected by photodetector.



## Photodetector - PMT example





Photons hitting the photo cathode release electrons (photoelectric effect). Electric fields accelerate electrons to dynodes, multiplying the number of electrons that arrive at the anode.





layers driven by LHC requirements and electronics readout costs

Optics granularity (~ 620k fibres 400k tiles):

- $-\,\Delta\eta$ : 3mm tiles every 9-18mm in Z
- $-\Delta R$ : 11 tiles and 8 fibres in R
- $-\Delta\Phi$ : 20 cm tiles

R

Tile

Ζ, η

## Trigger and Data Acquisition (TDAQ)

## Trigger - online selection

Much of LHC physics means cross sections at least ~10<sup>6</sup> times smaller than total cross section

25ns bunch crossing interval (40 MHz)

Offline storing/processing: ~1000 Hz

#### In one second at design luminosity:

- 40 000 000 bunch crossings
- ~2000 W events
- ~500 Z events
- ~10 top events
- ~0.1 Higgs events
- 1000 events written out

#### The right 1000 events should be written out!



## ATLAS Trigger and Data Acquisition (TDAQ) Run 2



# HEP detectors are quite complex systems

But many times they deliver what we are expecting from them (example of Higgs at ATLAS)

Slide 2008 - forecast



Discovery 2012, ~10 fb<sup>-1</sup>





#### CMS solenoid



Huge solenoid

Length: 12.5 m

B = 4 T

I = 19500 A

Stored energy E = 2.3 GJ (half-a-tonne of TNT equivalent)

## ATLAS toroid coils - they are huge and produce the toroidal magnetic

field of the muon spectrometer



## ATLAS and CMS subdetctor design parameters





## **Principle of semiconductor detectors**



- Large gap: the solid is an insulator.
- No gap: it is a conductor.
- Small band gap: semiconductor
- For silicon, the band gap is 1.1 eV, but it takes 3.6 eV to ionize an atom. The rest of the energy goes to phonon exitations (heat).

## Principle of semiconductor detectors

Silicon can be doped with donors of electrons (e.g. Phosphorus, group V) creating n-type semiconductor

Donors introduce energy levels near the conduction band, almost fully ionized

Electrons are the major carriers

Or

Silicon can be doped with acceptors of electrons (e.g. Boron, group III) creating p-type semiconductor

Acceptors introduce energy levels close to valence band 'absorbing' electrons from it, creating holes

Holes are the major carriers







## Semiconductors p-n junction

- p- and n-doted semiconductor combined
- Gradient of electron and hole densities results in a diffuse migration of majority carriers across the junction.
- Migration leaves a region of net charge of opposite sign on each side, called the depletion region (depleted of charge carriers).



## Semiconductor strip detectors



If the number of particles arriving simultaneously to the detector is small, using strips (in 2 perpendicular directions) allows to know where the particles cross the detector

#### ATLAS SCT has 7 million channels with 10 $\mu$ m precision

#### CMS strip detector has 10 million channels

In case of high particle fluences, ambiguities cause difficulties in the tracks reconstruction, another kind of detector (pixels) is needed

## Semiconductor pixel detectors



ATLAS pixel has 80 million channels – readout is complex

Readout chip mounted on top of pixels – defines the size of the pixel (50 x 400  $\mu$ m)

CMS pixel has 66 million channels, size 100 x 150  $\mu$ m

Pixel detectors allow track reconstruction at high particle rate without ambiguities

## ATLAS Liquid Argon e.m. calo



#### Larg calo response is relatively slow ATLAS LArg calorimeter uses bipolar shaping

Remember that LHC collisions happen every 25 ns

## Timing to help in pile-up rejection



If the timing precision is of the order of ps then pile-up coming from different times during the bunch crossings can be removed

## Timing alignment

When particles are leaving the detector at the speed of light there were already a few more collisions at the center of the detector.

Correct timing in the event is crucial for trigger and offline analysis c=30cm/ns; in 25ns, s=7.5m



## **ATLAS Level 1 architecture**

#### Level 1 uses calorimeter and muon systems only to decide in 2.5 μs

#### Muon spectrometer:

- Dedicated trigger chambers
  - Thin Gap Chambers (endcap) TGC
  - Resistive Plate Chambers (barrel) CSC

#### **Calorimeter:**

- Trigger towers group calorimeter cells in coarse granularity:  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ (EM/Tau);  $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$  (Jets)

#### Identify regions of interest (Rol) and classify them as MU, EM/Tau, Jet

Relevant information is passed to Level 2 / High Level Trigger (in Run 1 / Run 2) where much more detector information is available for decision

