Particles and Universe: Particle detectors

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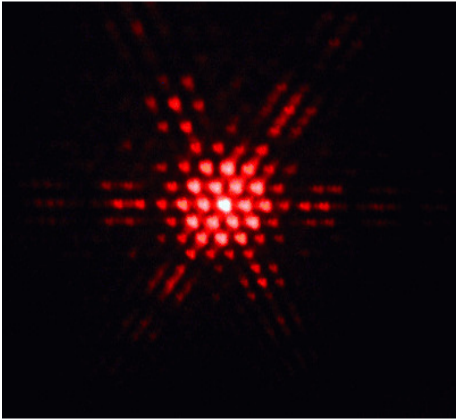
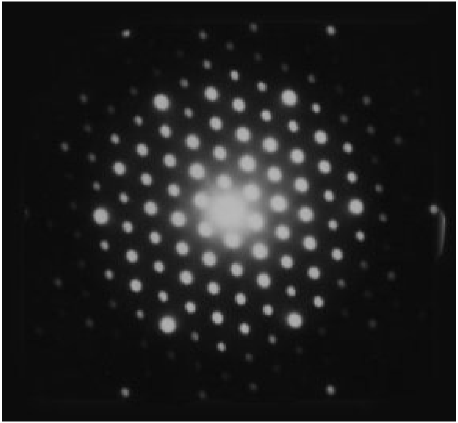
Hypothesis of Luis de Broglie (1923): wave-particle duality

Diffraction on hexagonal structures:

Light



Electrons



Classical Mechanics

If we know initial positions and velocities off all constituents of the system (eg. Solar system objects), we can foresee the future state of the system (as well as determine its history).

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This reasoning fails on the subatomic scales!

Wave-particle duality forces us to look for new methods to describe particle behavior...

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Quantum mechanics

Motion of a particle described as a propagation of probability wave (according to quantum wave equations)

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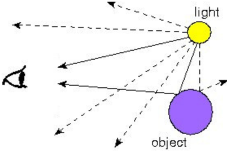
Also, we are not able to measure particle state with infinite precision - uncertainty principle

Particle detection

In the macroscopic world, we are able to make observations which do not interfere with the process under study



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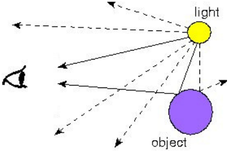

In the particle world, each measurement is related to some interaction.
We are not able to "see" particles without changing their state!

We can not observe particles which do not interact

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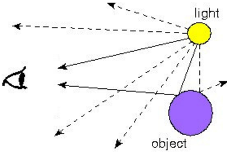

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Main processes used for particle detection:

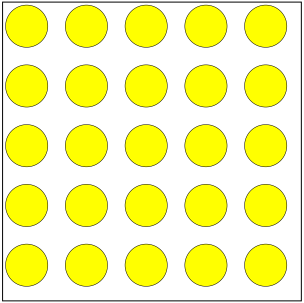
- ionization and scintillation
- photoelectric effect
- Cherenkov radiation

Structure of matter

Properties of different materials depend on the strength of valence electrons bonding with atomic cores.

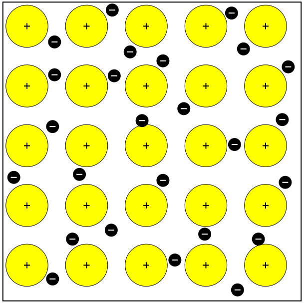
Insulator

All electrons tightly bonded with atoms



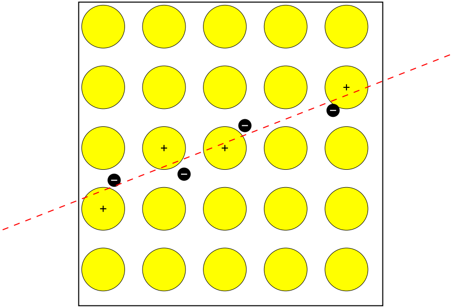
Conductor

Valence electrons can move freely



Ionization

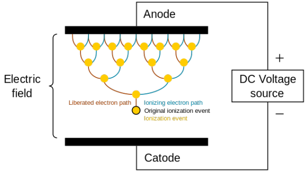
Is the phenomena used in most of the particle detectors



Charged particle passing through the insulator interacts with valence electrons and passes part of its energy to them, sufficient to "liberate" them from their atoms. Free charge carriers are created

Gas detectors

Ionization in gases is very small, of the order of 100 e/cm.
Measurement of the corresponding current is not possible, unless we apply electric field strong enough to create an electron avalanche.



In the uniform field we are not able to obtain large multiplication factors.

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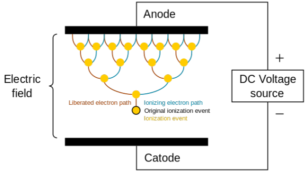
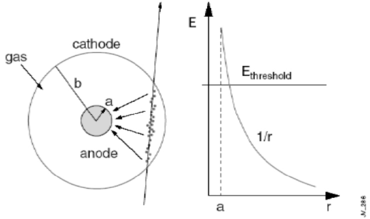




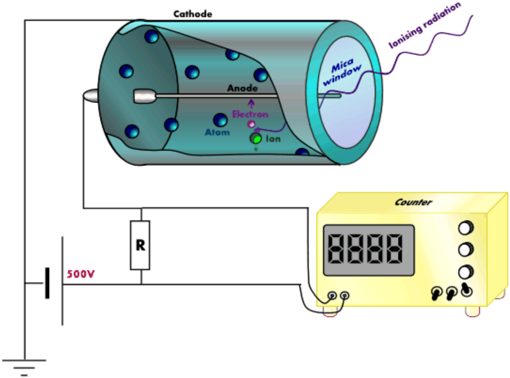
In the uniform field we are not able to obtain large multiplication factors.

Strong electric field resulting in large multiplication can be easily obtained around the thin anod wire.

Detected charge is still very low, but can be measured with sensitive electronics. Charge multiplication is crucial...

Geiger-Müller counter

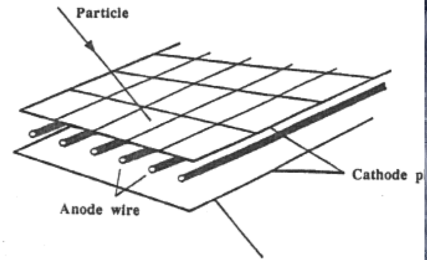
Electrons accelerated in strong electric field (resulting from high voltage applied), can create secondary ionization when scattering off atoms. At highest voltages charge multiplication can lead to almost full ionization of the gas near the wire surface (Geiger-Müller mode).

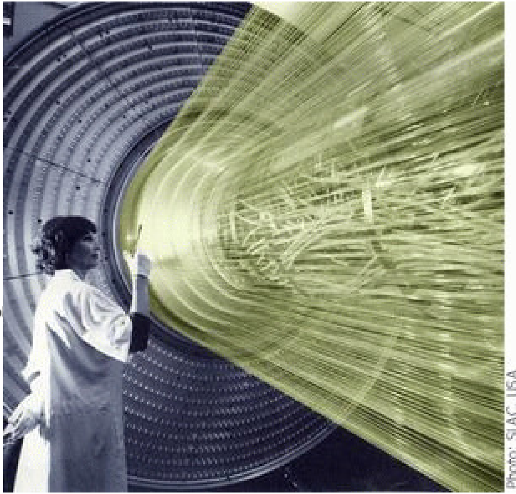


Gas detectors

Multiwire proportional chamber (MWPC)

Georges Charpak 1970
(Nobel 1992)



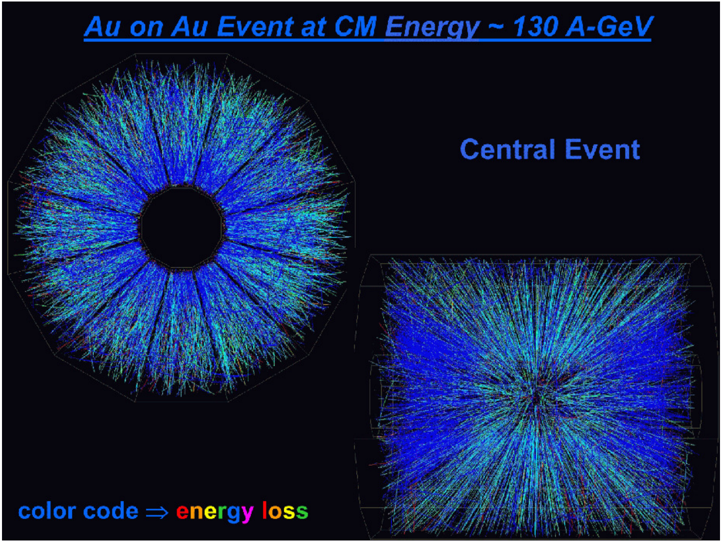


Cheap!
Electronic readout possible!
electronics+computers
$\Rightarrow$ revolution

TPC
Time Projection Chamber

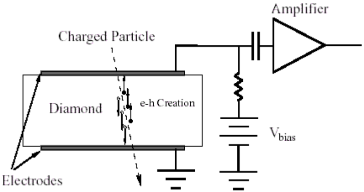
Heavy Ion collision event

STAR detector at RHIC (BNL)



Silicon is much denser than gas.
About 100 electron-hole pairs are created in $1\mu m$.
Charge multiplication not needed, direct charge measurement possible.

Large semiconductor crystals can be used for energy measurement



Semiconductor detectors

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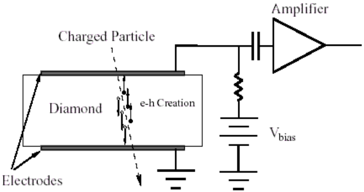
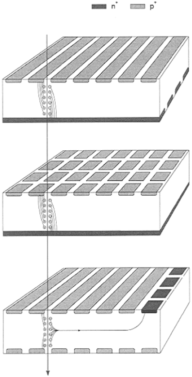


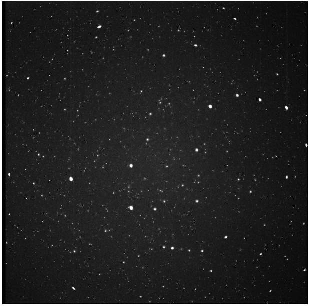
Very precise position measurement possible with proper sensor segmentation



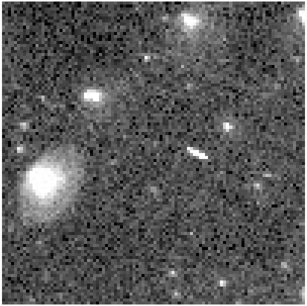
Pixel detectors most precise position measurement
Many different technologies used, including CCD sensors
(as used for digital photography)

Each CCD camera is a particle detector!

Image from astronomic CCD camera:



Enlarged section:

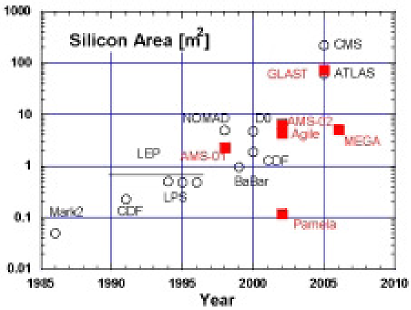


It's not UFO. It's a particle...

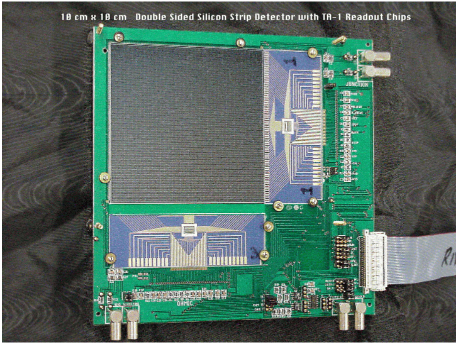
Rapid development

Silicon detectors give very high measurement precision.
They are still relatively expensive, but prices decrease fast with technology development.

$\Rightarrow$ more and more widely used

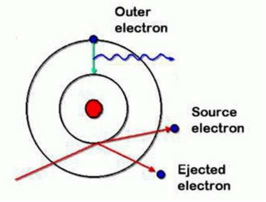


Single pixel sensor



Scintillation

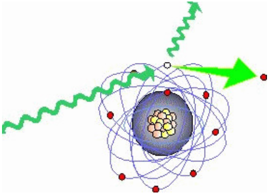
Charged particle passing the medium can ionize or excite the atom.



Return of the atom to its ground state can be accompanied by the photon emission - scintillation

Photons

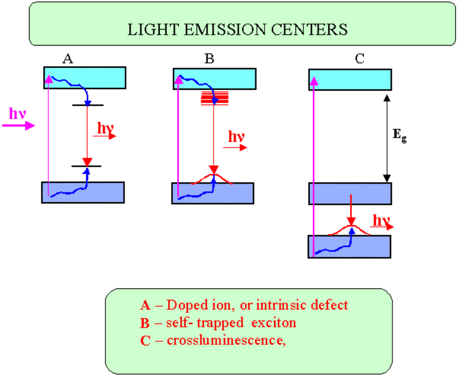
Photons can also interact with electrons in atom.
They can transfer all their energy to single electron (photoelectric effect) or only part of it (Compton effect)



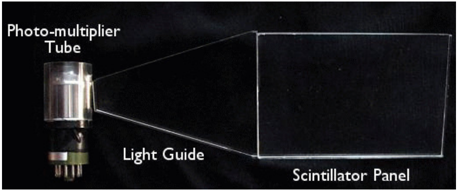
In both cases, electron is "released" from atom.

Scintillation

In some materials, atoms excited by ionizing particle emit photons.



Light produced in scintillator can be measured with photomultiplier.
Classical set-up:



No position measuremen

Very good time measurement

Photomultiplier

Single electrons can release single electrons from photocatode.
We multiply this charge by applying high voltage between subsequent dynodes. When hitting dynodes accelerated electrons produce secondary electrons - charge avalanche.

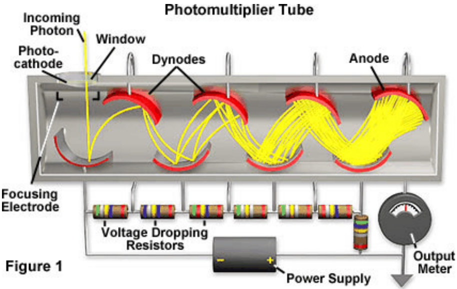
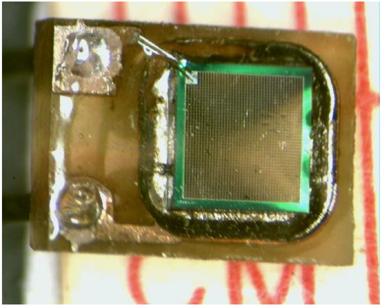


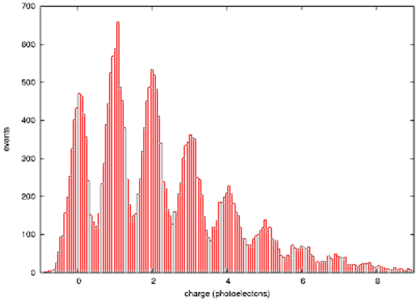
Figure 1

Single photon, if it produces the first electron (photoelectric effect) results in macroscopic charge.

Pixelized Photon Detector (PPD)

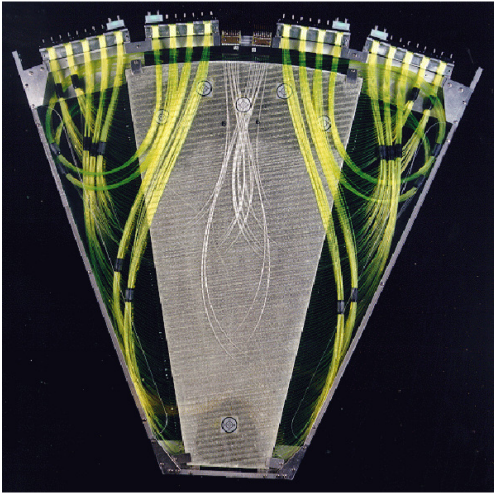
Also called the Silicon Photomultiplier (SiPM).
Large number ($\sim 10^3$) of avalanche photo-diodes on small ($\sim 1mm^2$) surface - possibility of counting single photons





Parameters similar to PMT: $10^5 - 10^6$ gain, response time $\sim 1ns$
Much smaller! Low voltage operation! $\Rightarrow$ more and more popular

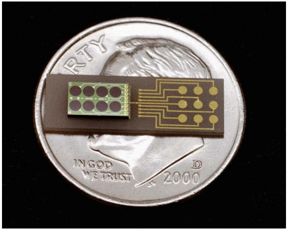
Modern detectors



Classical scintillation detectors not used frequently

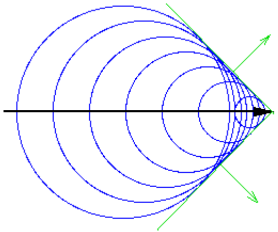
New solution:
$\Leftarrow$ scintillating fibres,

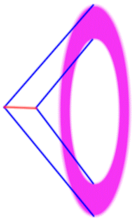
pixelized photon detectors $\Downarrow$



Cherenkov radiation

Emitted by a charged particle traveling with speed larger than the speed of light in given medium.





Light emitted in a cone.
When passing a thin medium layer distinctive annulus shape is obtained on the screen.

Observed in water, ice, air...
Very cheap technology for very large detectors!

Cherenkov radiation

If the particle path in medium is longer, we can use special mirrors to focus produced Cherenkov light

Scheme

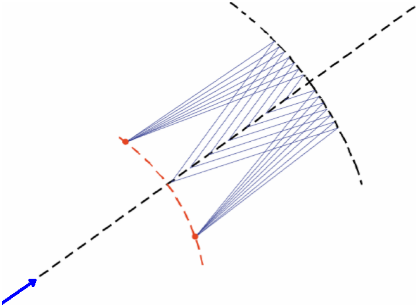
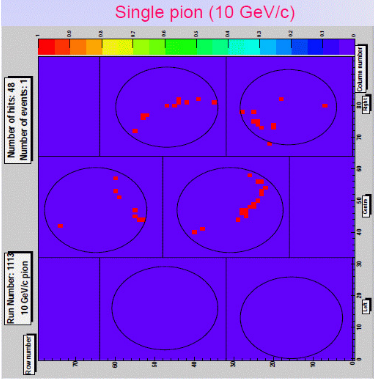


Image in the detector



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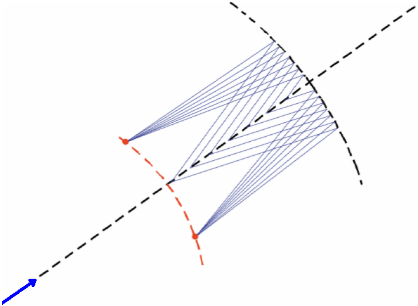

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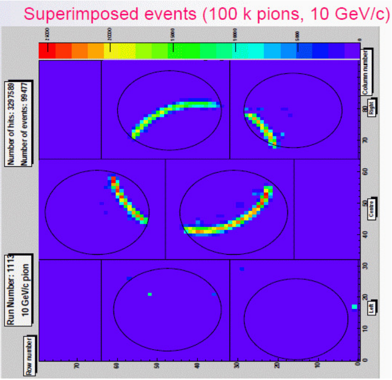


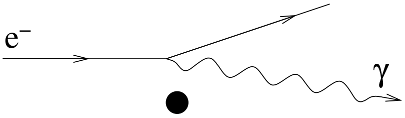
All detectors described so far were designed to measure position of the charged particle ⇒ tracking detectors

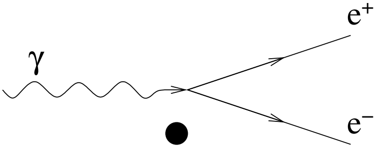
To measure the particle energy, we have to force it to transfer its full energy to the detector ⇒ calorimeters.

Electromagnetic cascade

High energy electrons loose energy in bremsstrahlung

High energy photons convert to e^+ e^- pairs



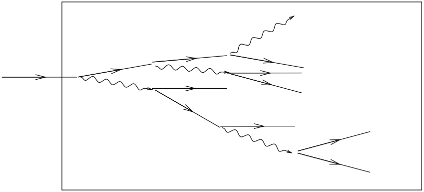


Electromagnetic calorimeters

High energy electron or photon entering the detector creates a cascade of secondaries, with $N \sim E$ particles

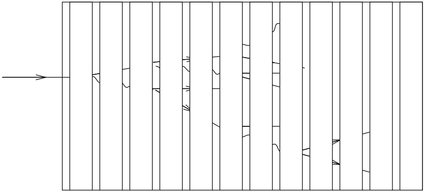
By counting secondaries or measuring their total track length in the detector (total ionization) we can determine the energy of primary particle.

Uniform calorimeter



eg. scintillating cristal

Sampling calorimeter

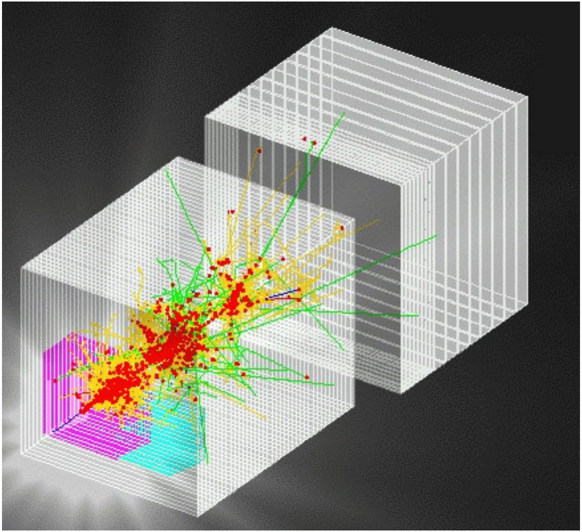


detector layers interleaved with dense absorber

Hadronic calorimeters

Simulation of the hadronic cascade (proton energy measurement)

Hadronic cascade much longer than the electromagnetic one



Layer structure

Modern universal detectors at particle colliders are build from many different sub-components.

We arrange detectors in such a way as to obtain best measurement for all possible particles, as well as their (partial) identification.

detectors which interact least with produced particles are placed closest to the interaction point - gas detectors, thin silicon sensors

detectors which absorb particles are placed at largest distances from interaction point - calorimeters, muon detectors

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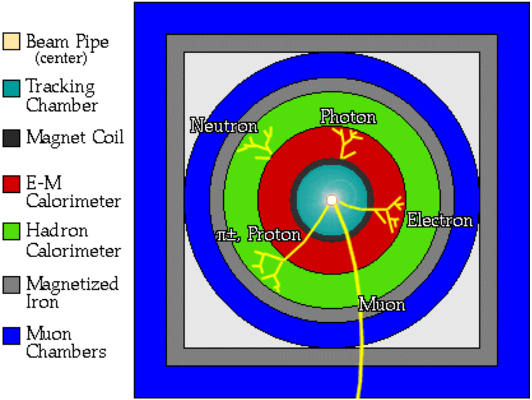

Universal detector

Layout describing most of recent and present-day experiments at colliders (LEP, HERA, Tevatron, LHC, ILC):

Starting from the center of the detector:

- vertex detector
  as close to the beam line as possible, used to measure the exact position of the interaction point, allows for identification of short-lived particles (secondary vertexes)
  silicon pixel detectors

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  as close to the beam line as possible, used to measure the exact position of the interaction point, allows for identification of short-lived particles (secondary vertexes)
  silicon pixel detectors
- tracking detectors
  measure tracks of charged particles, allows to determine their momentum from bending in magnetic field
  gas detectors or silicon strip detectors

Universal detector

- electromagnetic calorimeter
  electron and photon energy measurement
  dense material absorbing EM cascade
  (copper, lead, tungsten)

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  dense material absorbing hadronic cascade; hadronic cascade is many times longer than EM one

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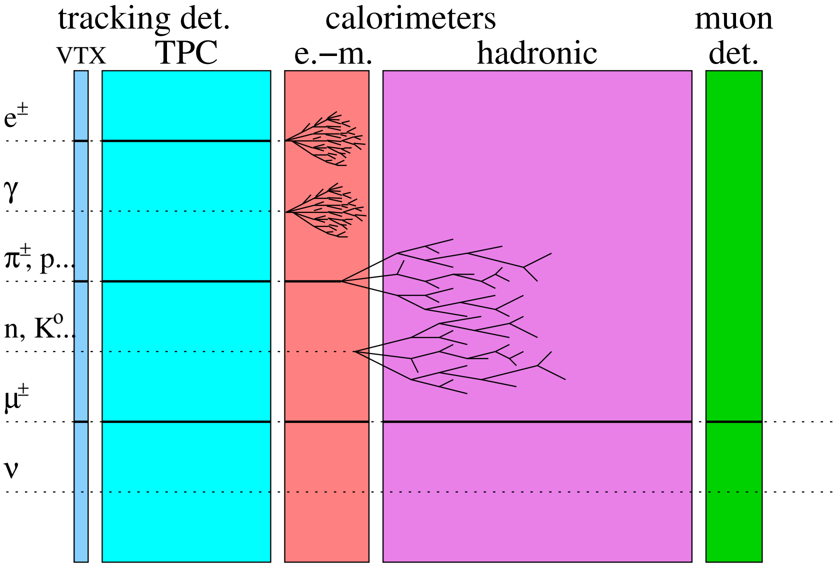
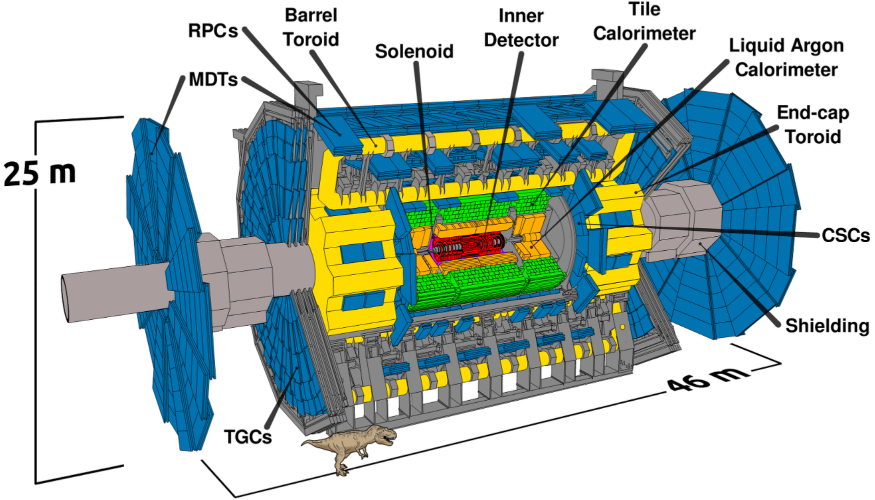
- hadron calorimeter
  hadron energy measurement (protons, neutrons, pions, kaons)
  dense material absorbing hadronic cascade; hadronic cascade is many times longer than EM one
- muon detectors
  identify muons - only charged particles which can pass both calorimeters with small energy losses

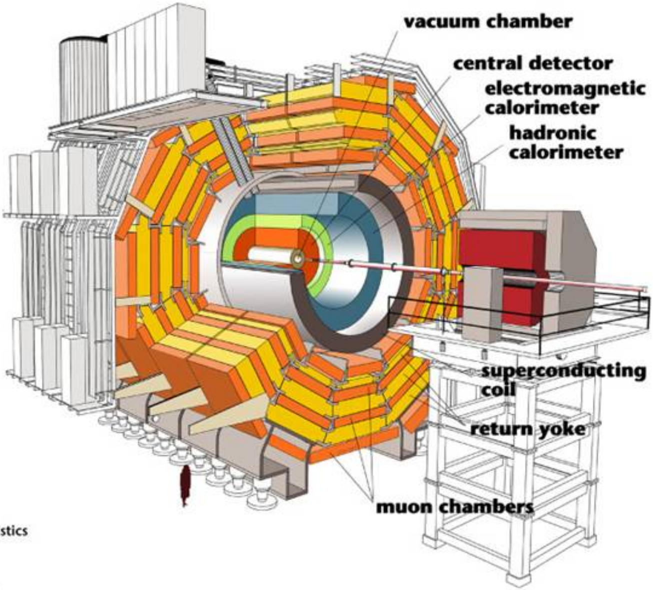
Collider experiments



ATLAS experiment



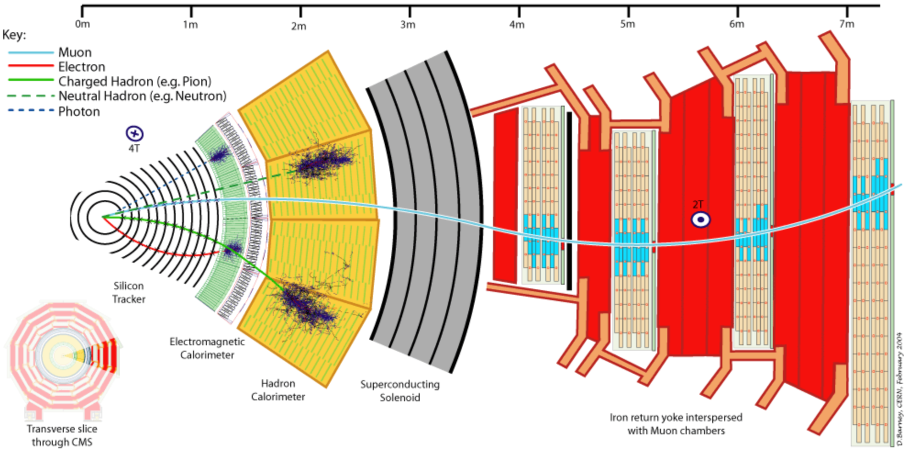
CMS experiment



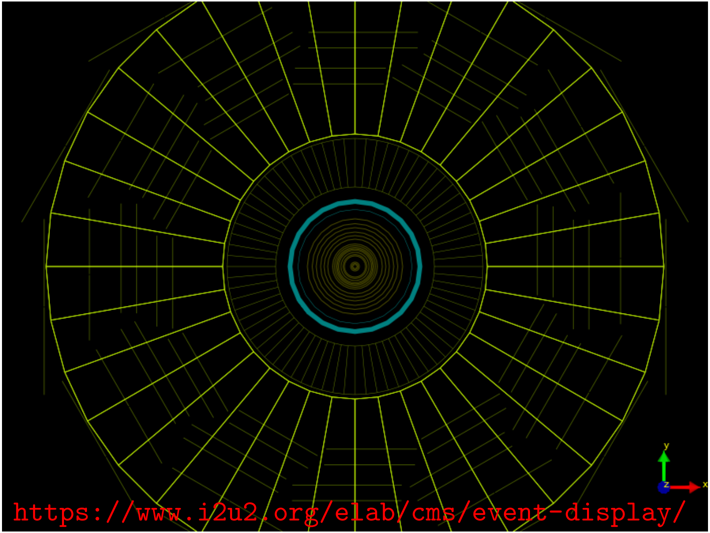
Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t

Compact Muon Solenoid - CMS

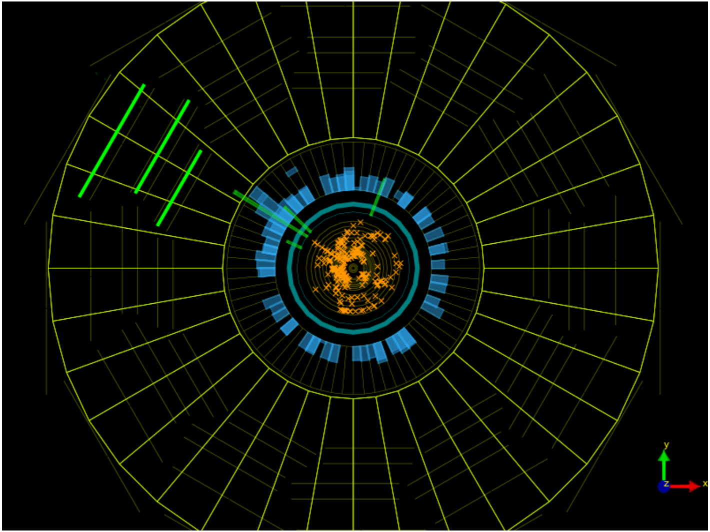


CMS Schematic detector view



Reconstructed events

CMS Single muon event



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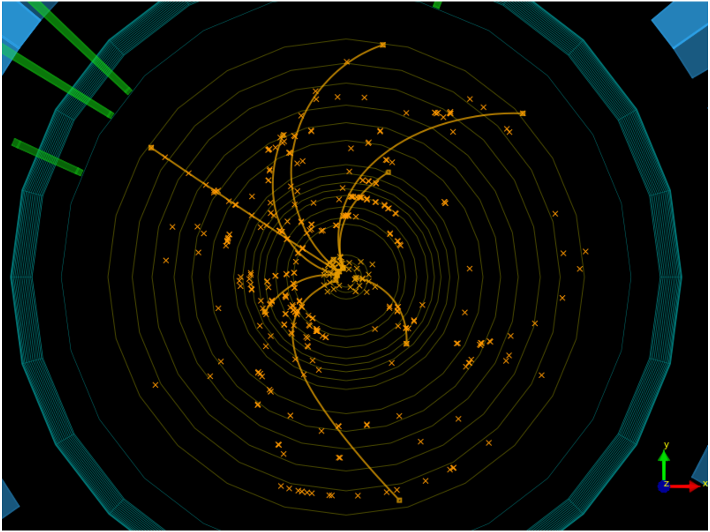
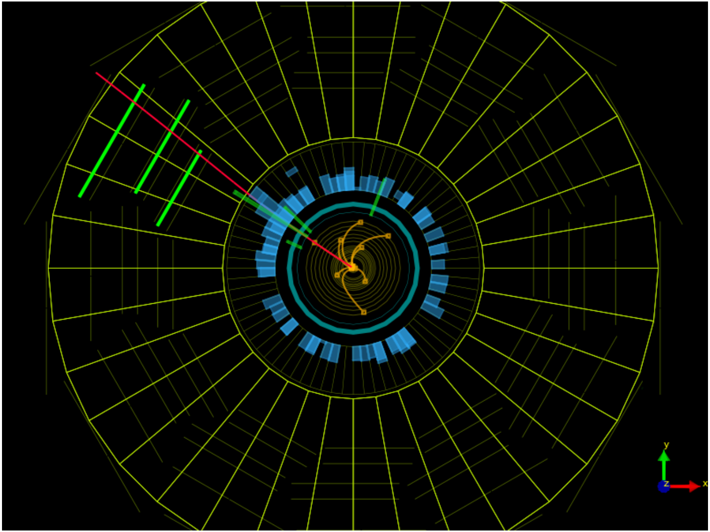
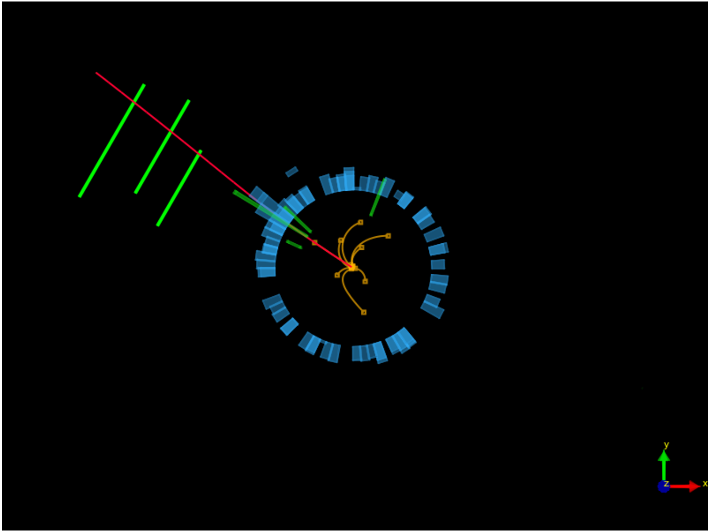


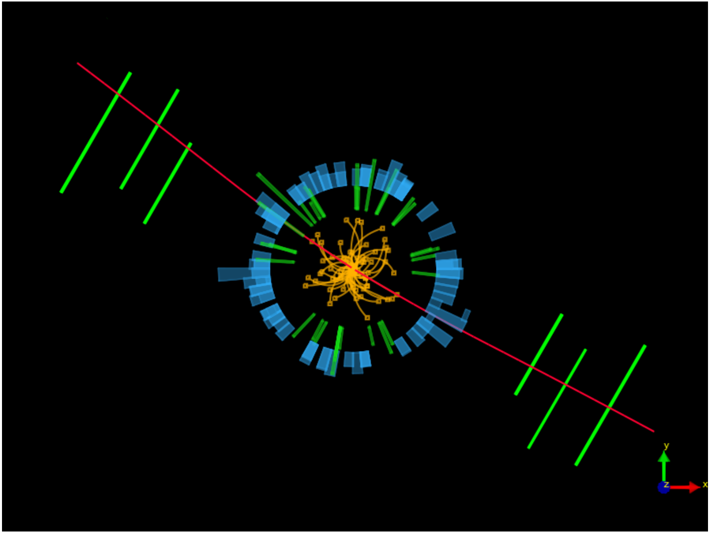
CMS Single muon event



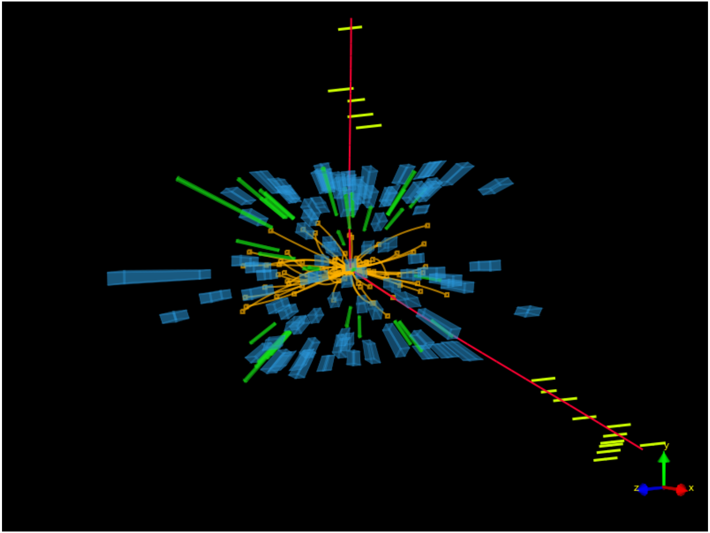
CMS Single muon event



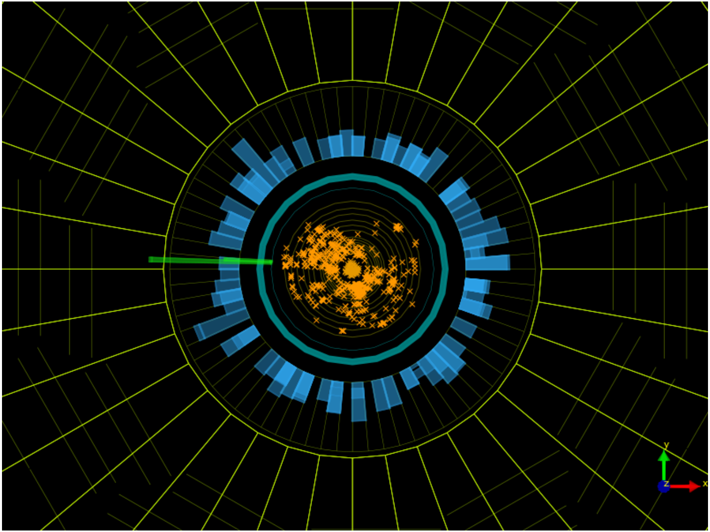
CMS Event with two muons



CMS Event with two muons

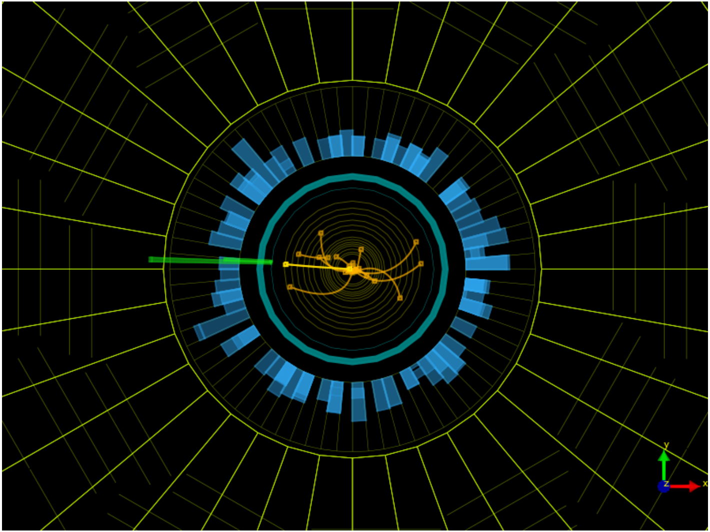


CMS Event with electron production



Reconstructed events

CMS Event with electron production



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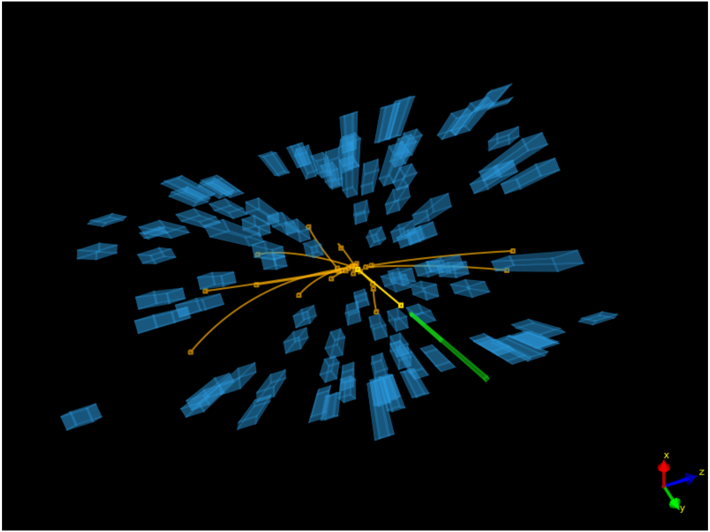
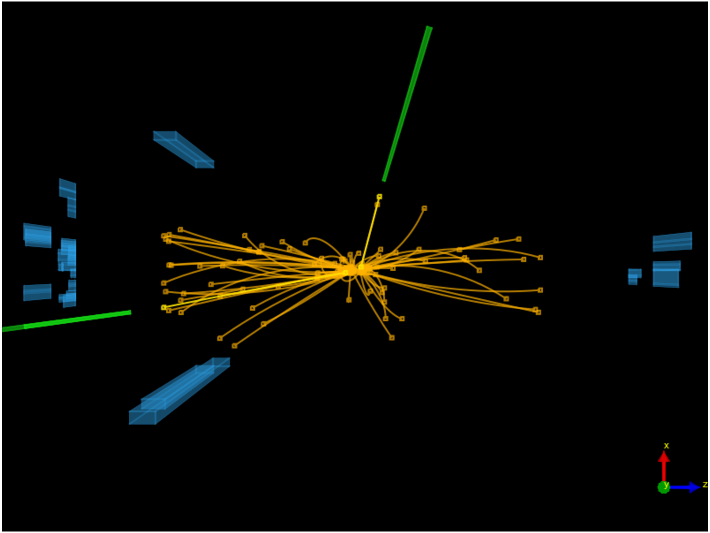
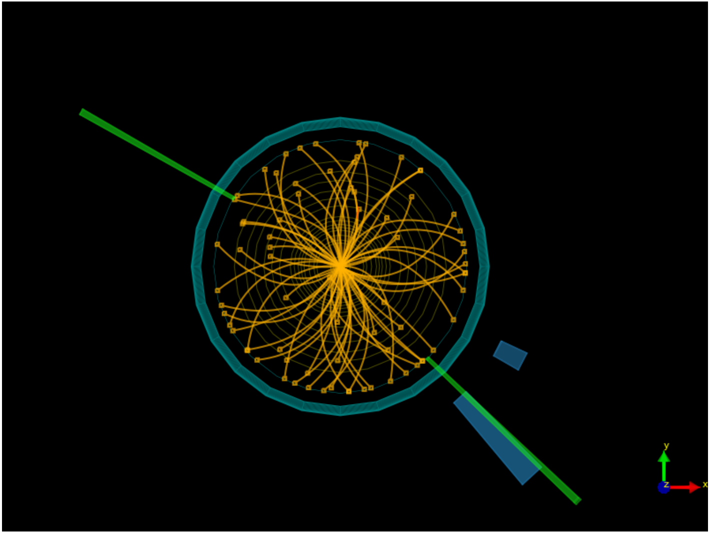


CMS Event with two electrons



CMS Event with two photon production ($H \to \gamma\gamma$ candidate)



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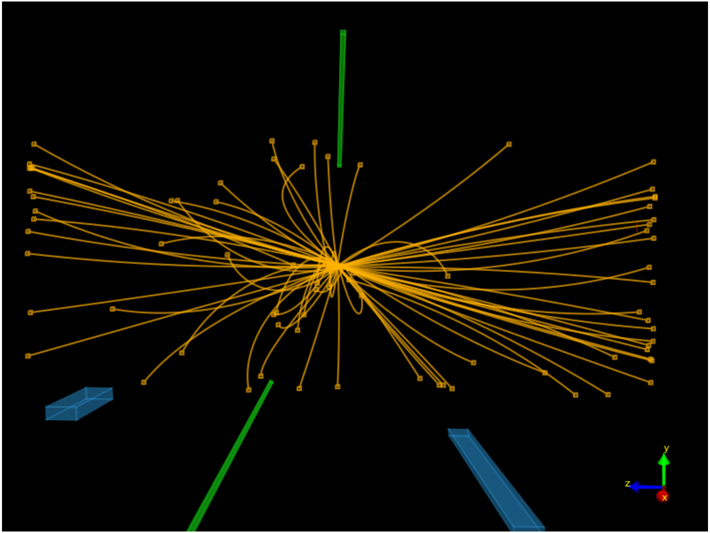
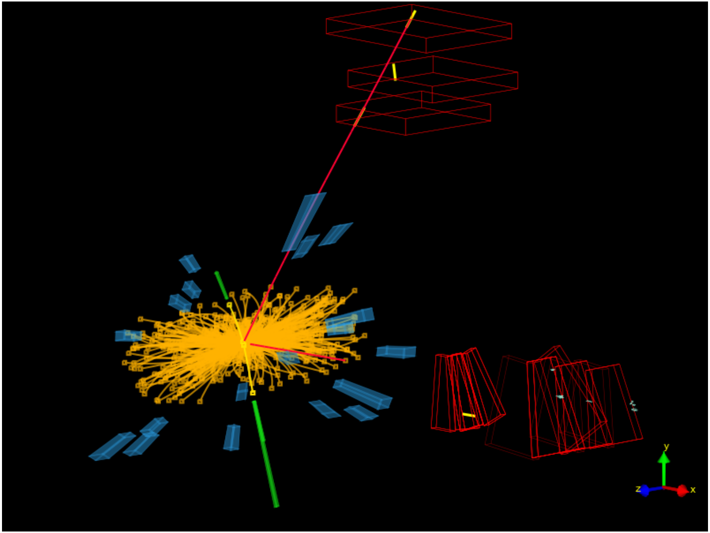


CMS Four lepton event ($H \to ZZ \to e^+e^-\mu^+\mu^-$ candidate)



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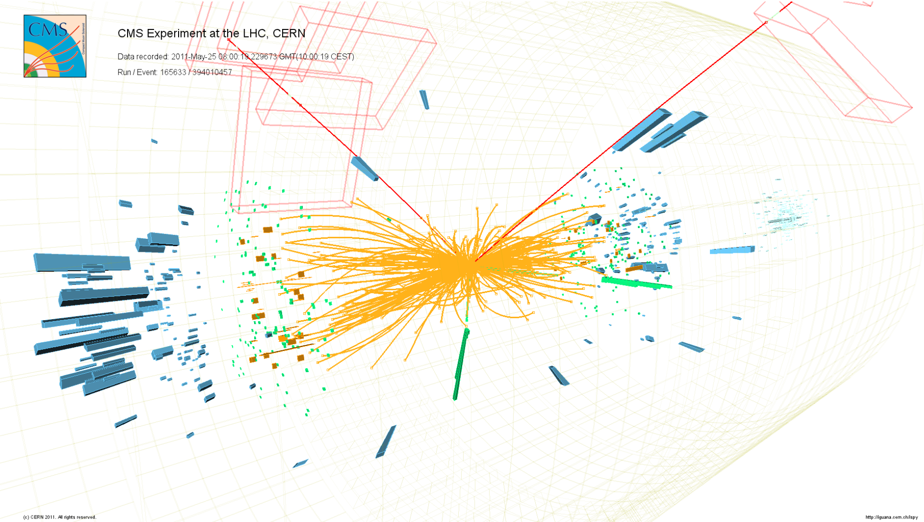
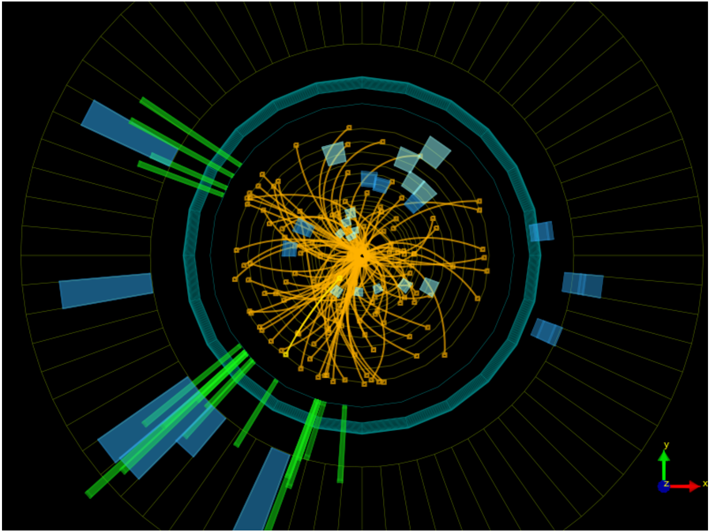


CMS How do we interpret events like this?



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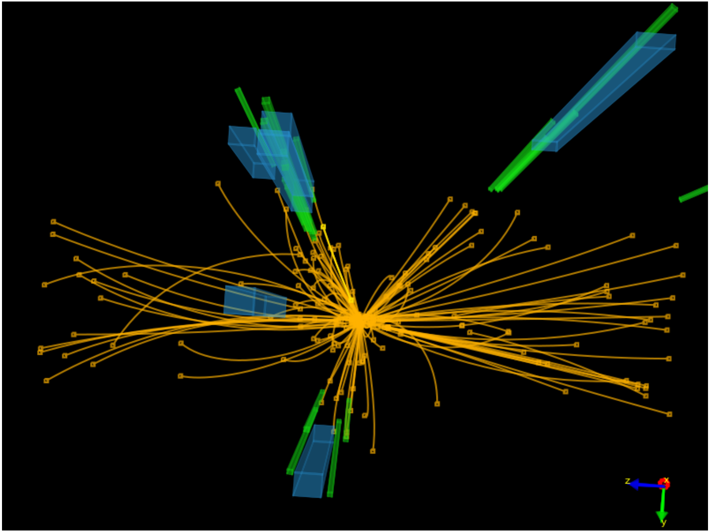

Reconstructed events

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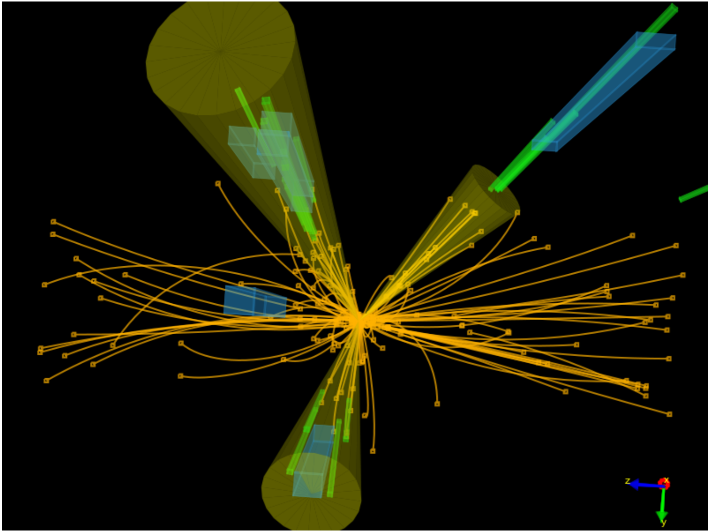
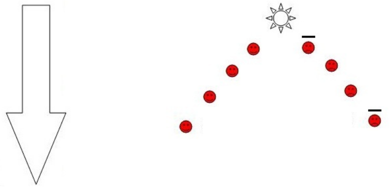
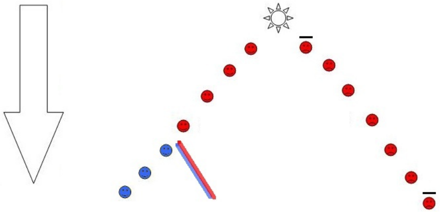


When a pair of quarks is produced in the collision:
$gg \to q\bar{q}$



When a pair of quarks is produced in the collision:
$gg \rightarrow q\bar{q}$

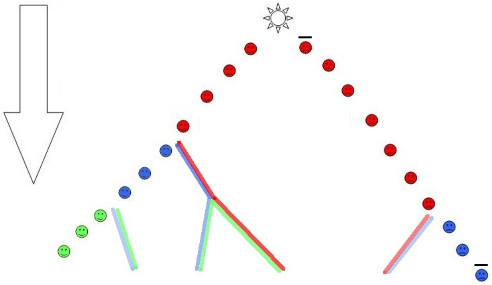
Color field increases between quarks moving apart



When a pair of quarks is produced in the collision: $gg \to q\bar{q}$

Color field increases between quarks moving apart

Gluons are emitted



When a pair of quarks is produced in the collision: $gg \to q\bar{q}$

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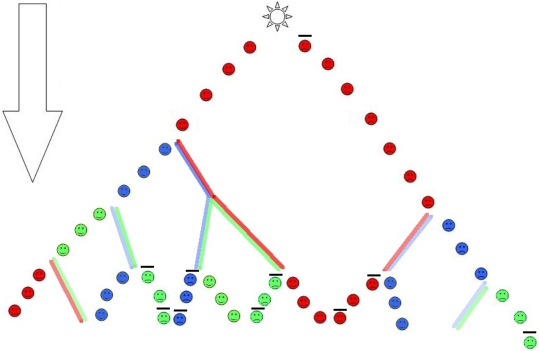
Gluons convert to quark-antiquark pairs



When a pair of quarks is produced in the collision: $gg \to q\bar{q}$

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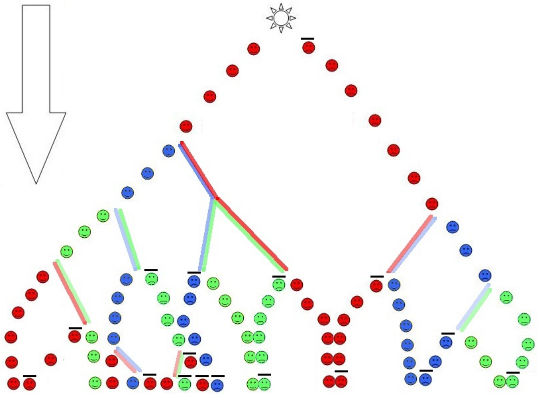
Quarks and antiquarks form "white" hadrons



Hadronization

When a pair of quarks is produced in the collision:
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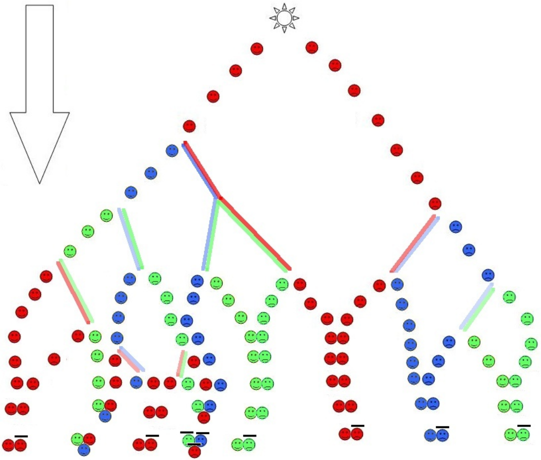
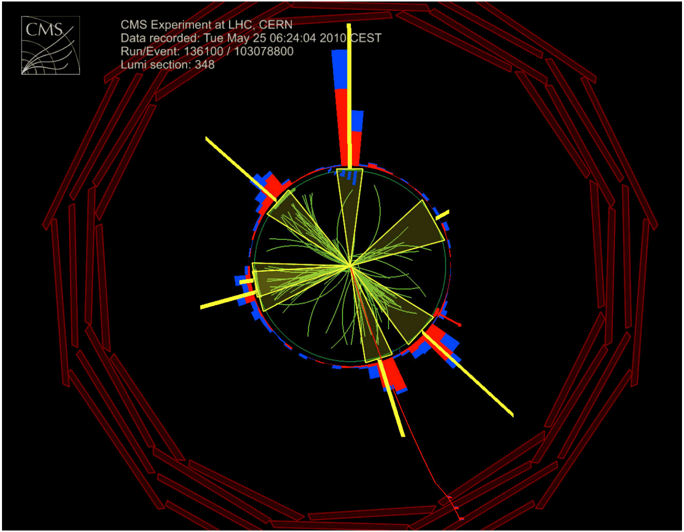
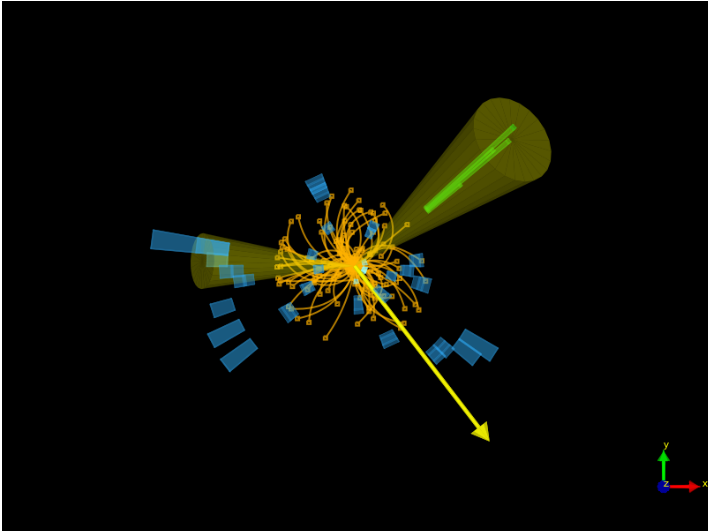


CMS Event with six jet production

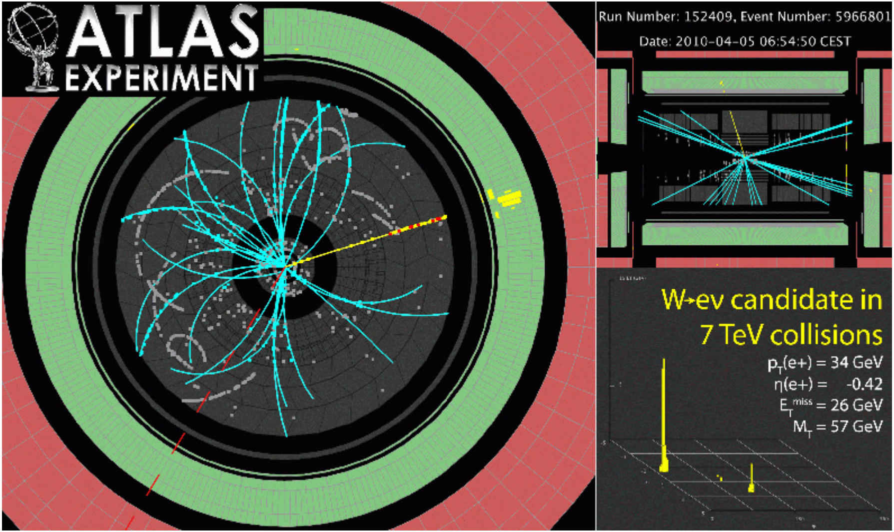


CMS Unbalanced transverse momentum - signature of missing particle



Reconstructed events

ATLAS Event with W^+ boson production ($W^+ \to e^+\nu_e$)



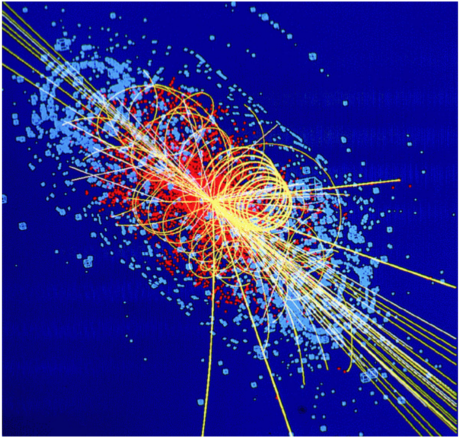
Up to 50 proton pairs collide at LHC at each bunch crossing

New particles are produced at almost each collision

About billion of interactions per second!

We have no possibilities to store more than about 100 events per second!

How to select the interesting ones?



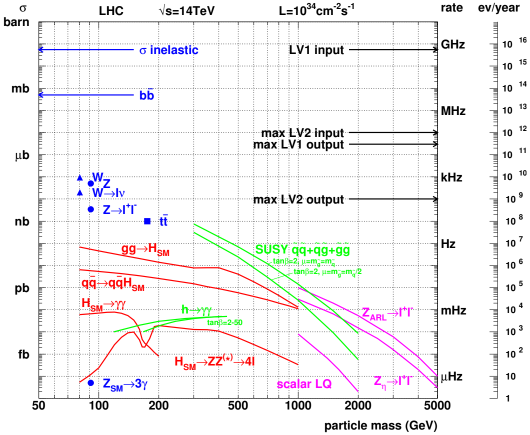
Trigger system

Signals from the detector components are “checked” after each bunch crossing by the dedicated electronics, so called trigger.

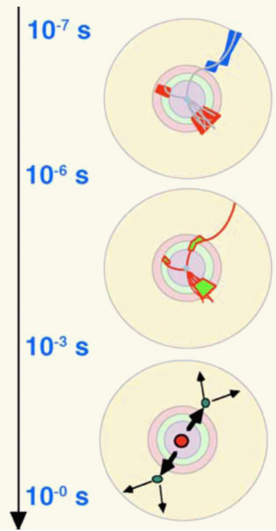
Only “interesting” signals are read from the detector.

These events are then passed through subsequent “filters” - dedicated programs rejecting all “rubbish”

Only events looking interesting are stored to disk!



Trigger system



Final event selection require their very detailed analysis. But no computer could process 40 milion events per second!

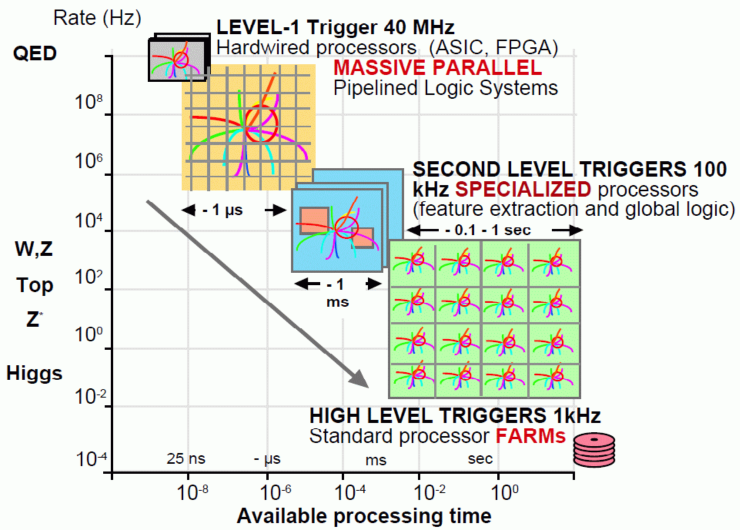
Solution: multilevel trigger system!

Level 1: very fast (dedicated electronics), rejects 99.9% of rubbish

Level 2: checks basic event parameters, selects 1% for final analysis

Level 3: full even analysis and final decision

Trigger system scheme



Simulation

We use very complicated detector systems to measure particle interactions.
We use trigger systems to select events of interest.
We use dedicated algorithms to reconstruct the particle properties.

How do we know how to interpret the measurements?
How to determine the efficiency of event selection?
How to estimate precision of energy or mass measurement?
How to verify that our results are consistent with expectations?

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How to verify that our results are consistent with expectations?

Monte Carlo method

We use simulation methods to model all aspects of the experiment:
beam particle collision, interactions inside the detector, detector response, trigger system decision.

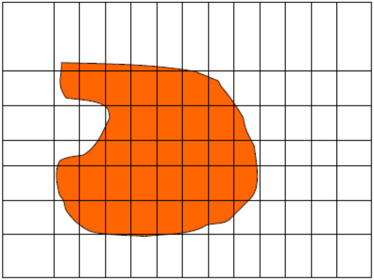
We produce event samples which are equivalent to the actual data.
We can reconstruct them in the same way and compare
$\Rightarrow$ verify our knowledge about physics and detector performance

Monte Carlo method

Simple example: how to calculate the area of an irregular figure?

Defined eg. by a complicated set of mathematical formula

There are two approaches:



We can divide the space into a large number of unit elements and count the elements belonging to the figure

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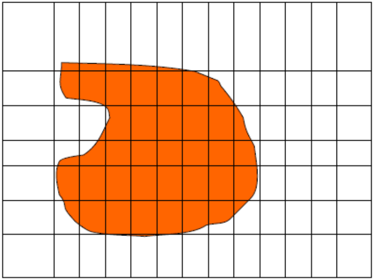

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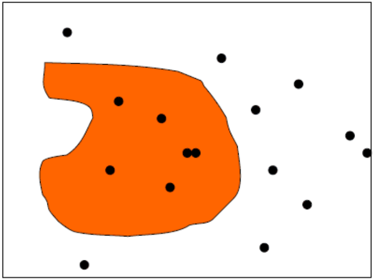

We can generate random points and count those inside the figure

$\Rightarrow$ much more efficient

in large number of dimensions

Simulation

Monte Carlo simulation is just an efficient way to “integrate” all our knowledge on the observed phenomena. It allows to predict the experimental result with arbitrary precision.

But it is not a “magic box” - predictions can be calculated only for the processes which are fully understood!

Examples of Monte Carlo simulation results compared with data: