

# Particles and Universe: Particle detectors

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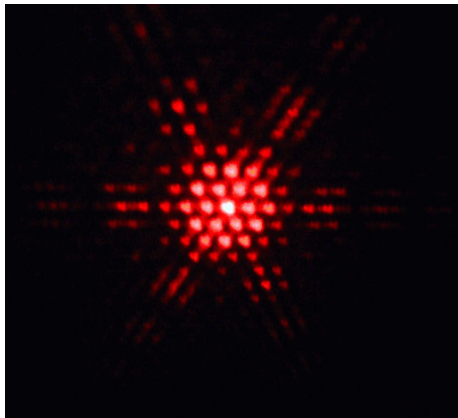
March 31, 2015

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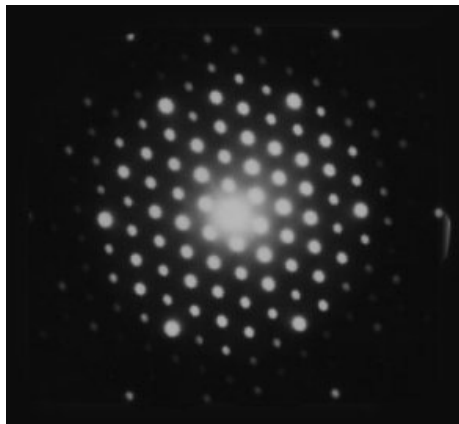
Hypothesis of Luis de Broglie (1923): wave-particle duality

Diffraction on hexagonal structures:

**Light**



**Electrons**



## Classical Mechanics

If we know initial positions and velocities of 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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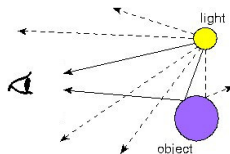
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Also, we are not able to measure particle state with infinite precision - **uncertainty principle**

## Particle detection

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



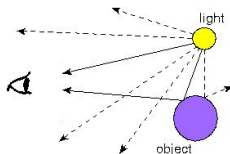
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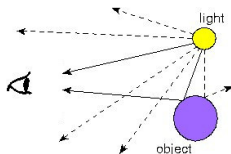


In the particle world, each measurement is related to some interaction. We are not able to “see” particles without changing their state!

We can not observe particles which do not interact

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Main processes used for particle detection:

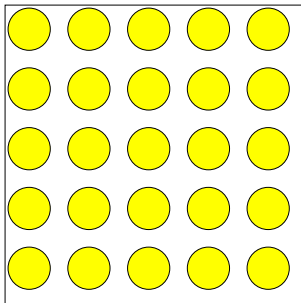
- ionization and scintillation
- photoelectric effect
- Cherenkov radiation

## Structure of matter

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

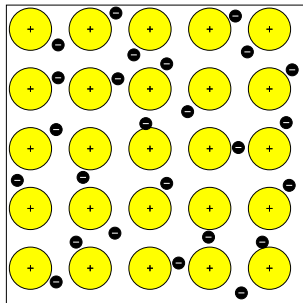
### Insulator

All electrons tightly bonded with atoms



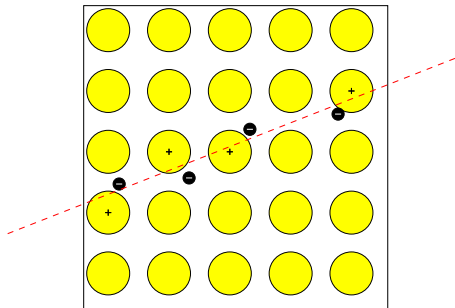
### Conductor

Valence electrons can move freely



## Ionization

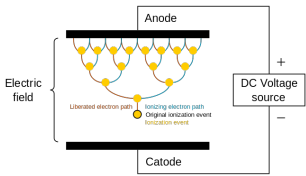
Is the phenomena used in most of the particle detectors



**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**.



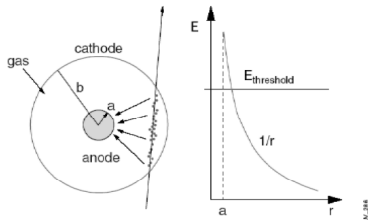
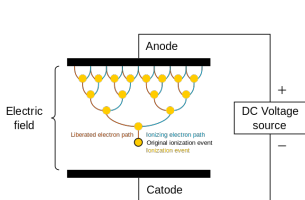
In the uniform field we are not able to obtain large multiplication factors.



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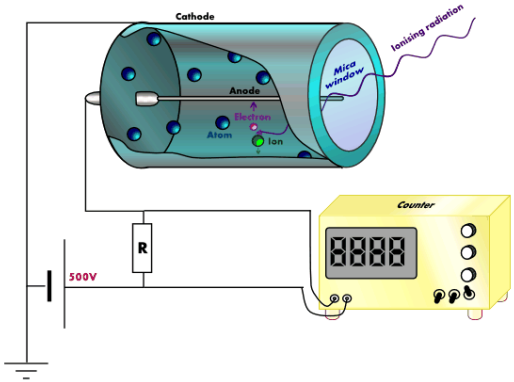
Strong electric field resulting in large multiplication can be easily obtained around the thin anode wire.

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

# Gas detectors

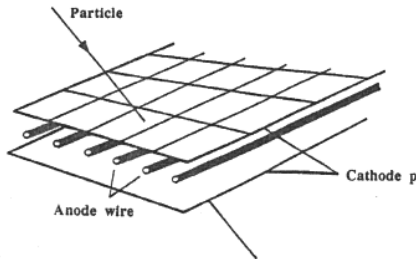
## Geiger-Müller counter

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).



## Multiwire proportional chamber (MWPC)

Georges Charpak 1970  
(Nobel 1992)



Cheap!  
Electronic readout possible!  
electronics+computers  
⇒ revolution

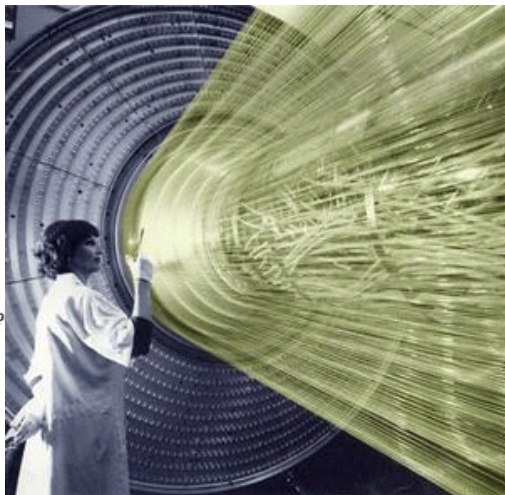


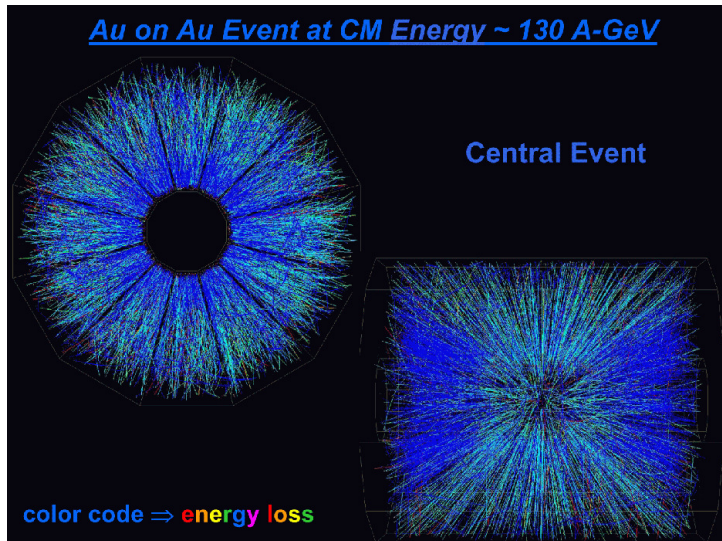
Photo: SLAC, USA

## TPC

Time  
Projection  
Chamber

Heavy Ion  
collision event

STAR detector  
at RHIC (BNL)

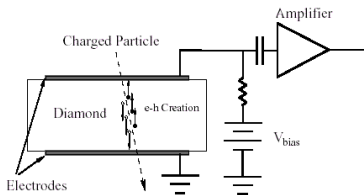


**Silicon** is much denser than gas.

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

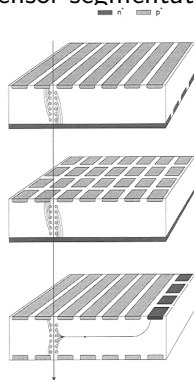
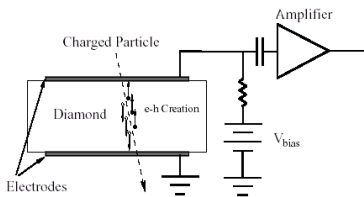
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Very precise position measurement possible with proper sensor segmentation



**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...

# Silicon detectors

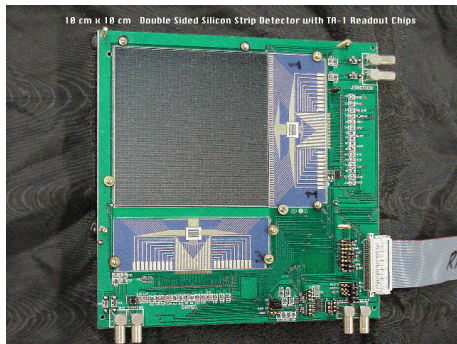
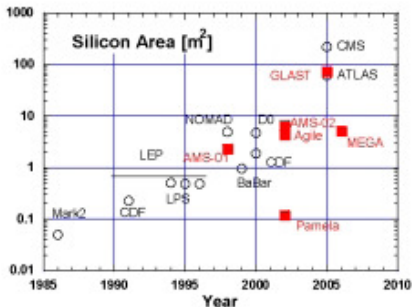
## Rapid development

Silicon detectors give very high measurement precision.

They are still relatively expensive, but prices decrease fast with technology development.

⇒ more and more widely used

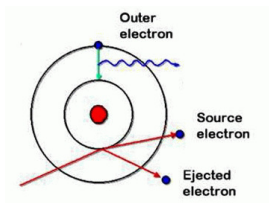
Single pixel sensor





## Scintillation

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

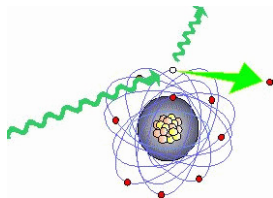


**Return** of the atom to its ground state can be accompanied by the photon emission - **scintillation**

## Photons

Photons can also interact with electrons in atom.

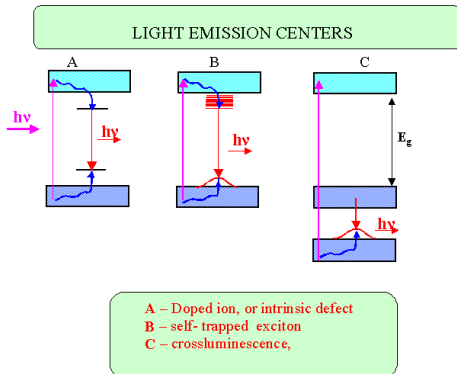
They can transfer all their energy to single electron (**photoelectric effect**) or only part of it (**Compton effect**)



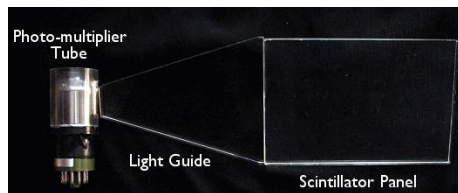
In both cases, electron is **“released”** from atom.

## Scintillation

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



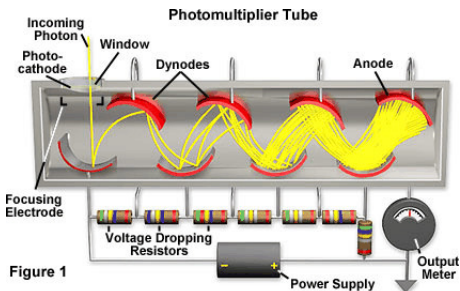
Light produced in scintillator can be measured with photomultiplier.  
Classical set-up:



No position measurement  
Very good time measurement

## Photomultiplier

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

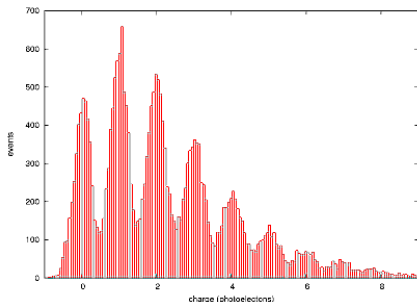
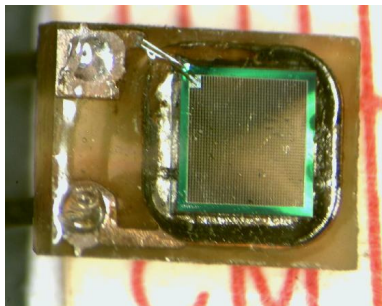


Single photon, if it produces the first electron (photoelectric effect) results in macroscopic charge.

## Pixelized Photon Detector (PPD)

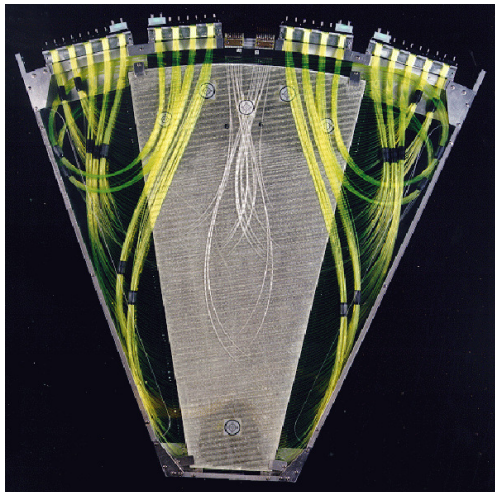
Also called the **Silicon Photomultiplier (SiPM)**.

Large number ( $\sim 10^3$ ) of avalanche photo-diodes on small ( $\sim 1\text{mm}^2$ ) surface - possibility of **counting single photons**



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

## Modern detectors

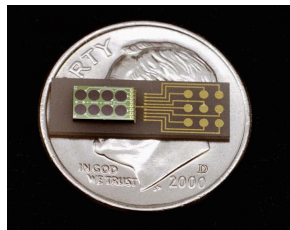


Classical scintillation detectors  
not used frequently

New solution:

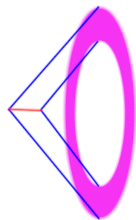
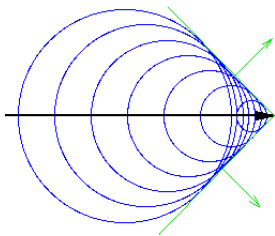
← scintillating fibres,

pixelized photon detectors ↓



## 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...

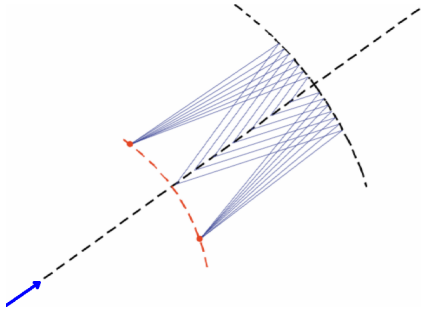
Very cheap technology for very large detectors!

# Cherenkov detectors

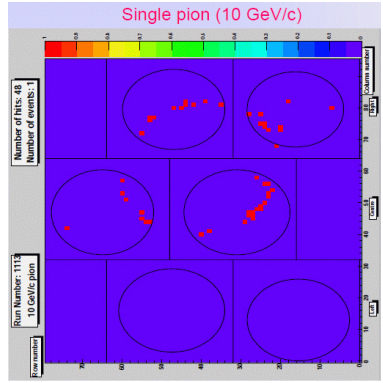
## Cherenkov radiation

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

### Scheme



### Image in the detector

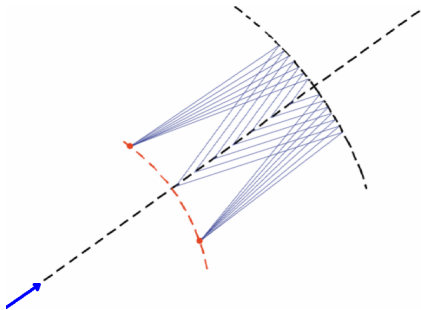


# Cherenkov detectors

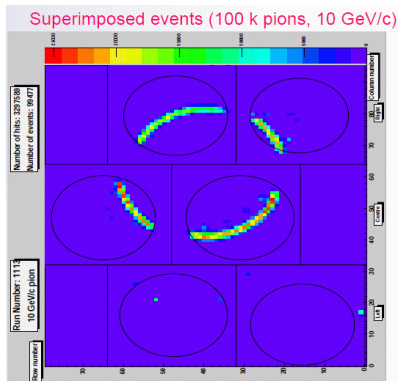
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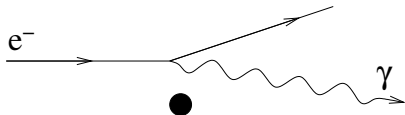
# Calorimeters

All detectors described so far were designed to measure position of the **charged** particle  $\Rightarrow$  tracking detectors

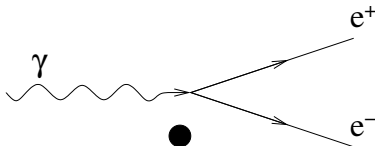
To measure the particle energy, we have to force it to transfer its full energy to the detector  $\Rightarrow$  **calorimeters**.

## Electromagnetic cascade

High energy electrons  
 loose energy in **bremsstrahlung**



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



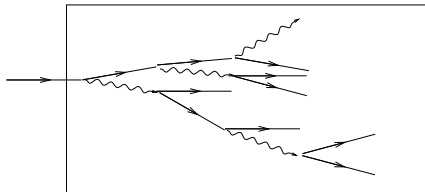
# Calorimeters

## Electromagnetic calorimeters

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

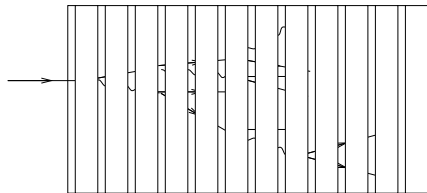
By counting secondaries or measuring their total track length in the detector (total ionization) we can determine the energy of primary particle.

Uniform calorimeter



eg. scintillating cristal

Sampling calorimeter

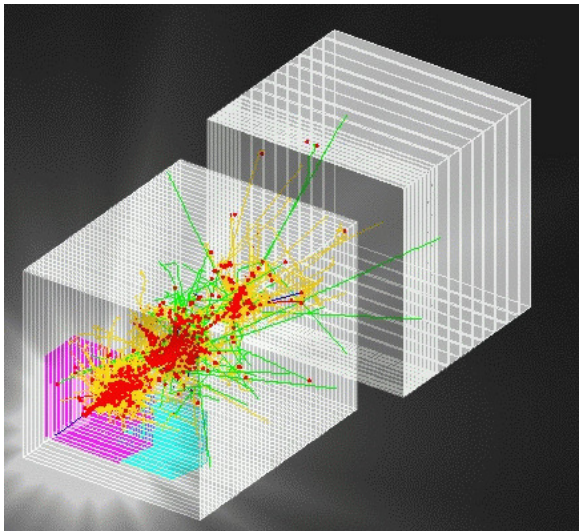


detector layers interleaved with dense absorber

## 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**.

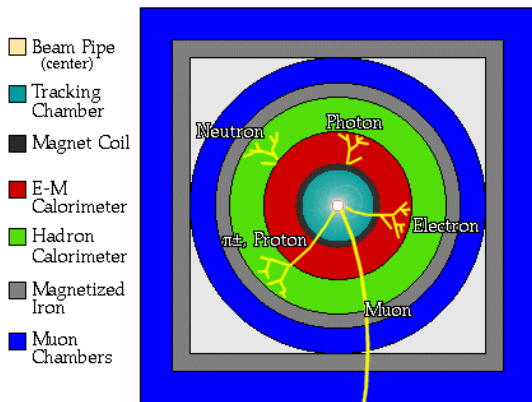
We arrange detectors in such a way as to obtain **best measurement** for all possible particles, as well as their (partial) **identification**.

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

## Layer structure

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



## 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)

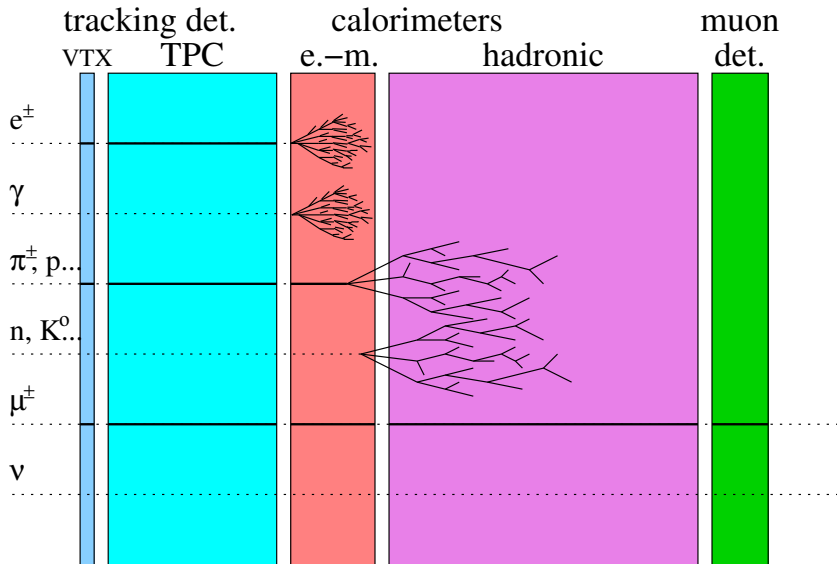


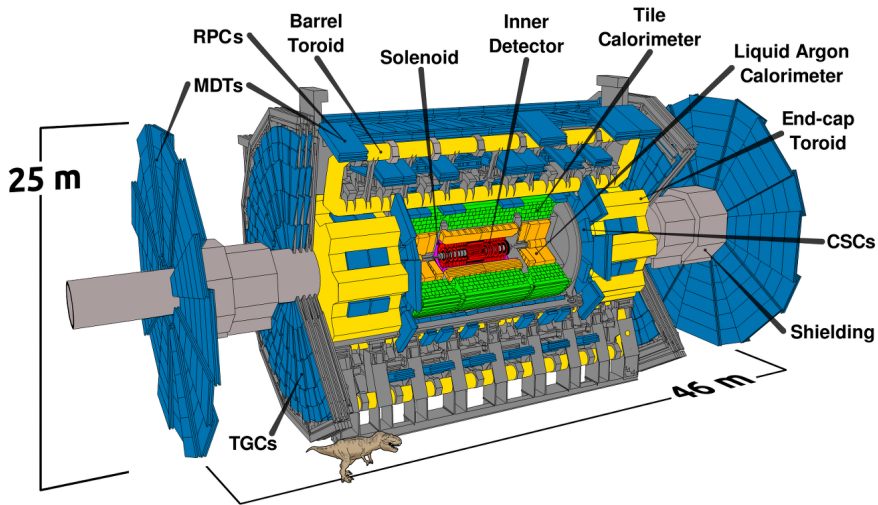
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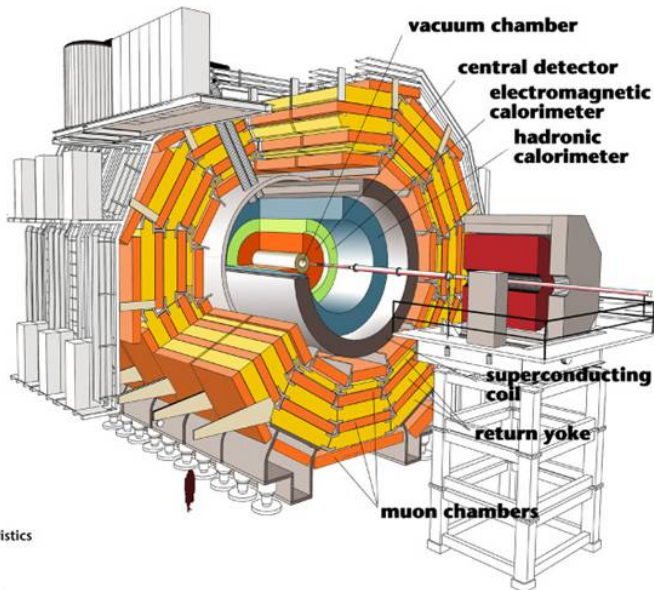
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- hadron calorimeter  
hadron energy measurement (protons, neutrons, pions, kaons)  
dense material absorbing hadronic cascade; hadronic cascade is many times longer than EM one

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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



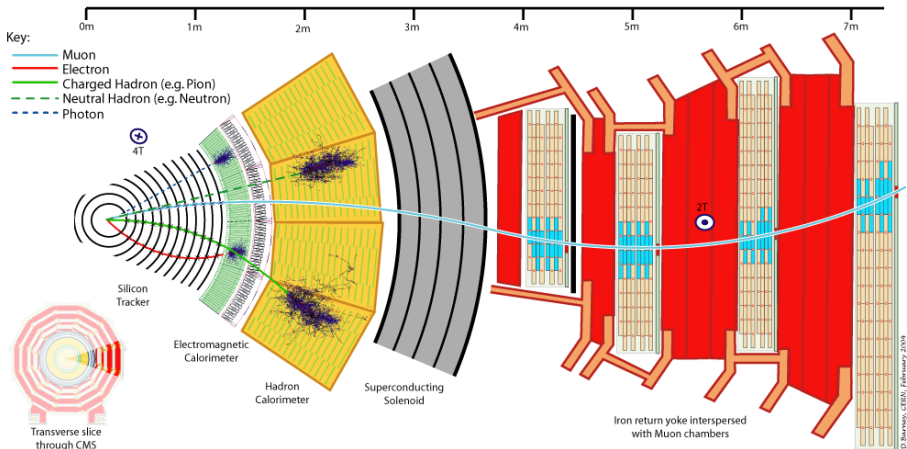




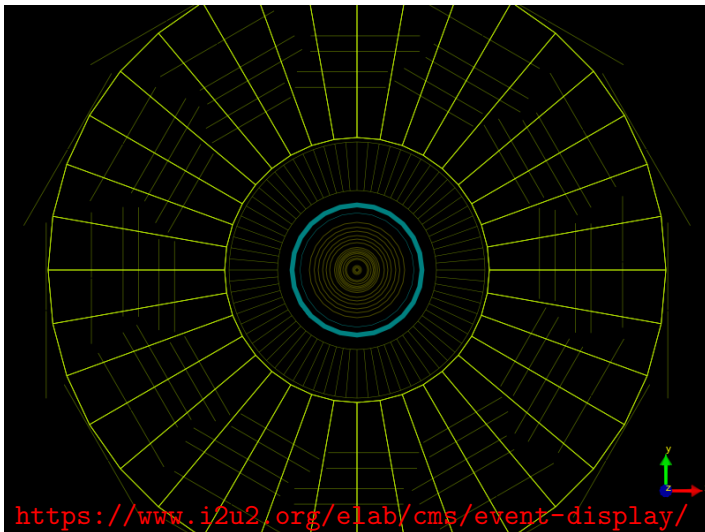
## Detector characteristics

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

## Compact Muon Solenoid - CMS

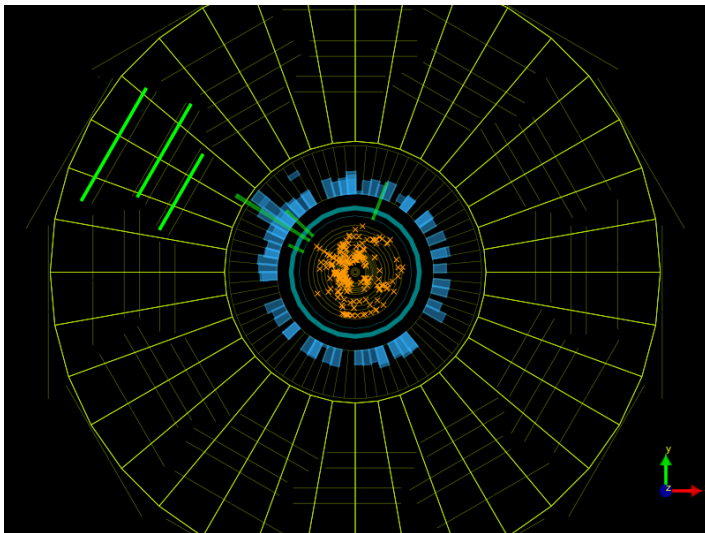


## CMS Schematic detector view



**CMS**

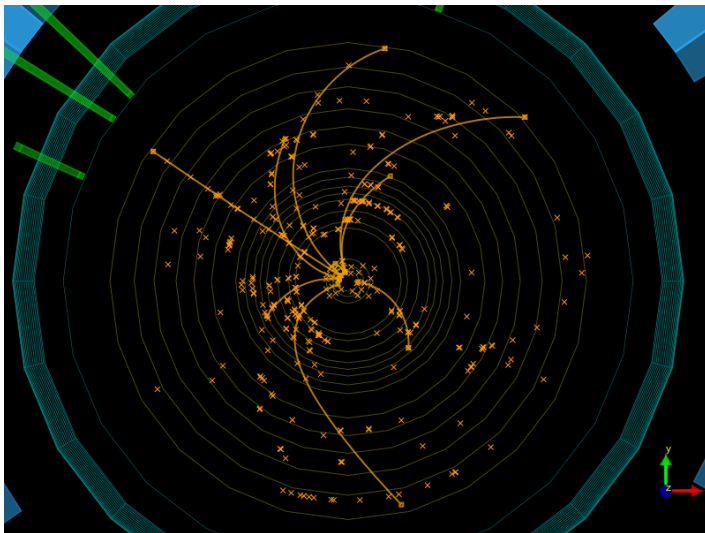
Single muon event





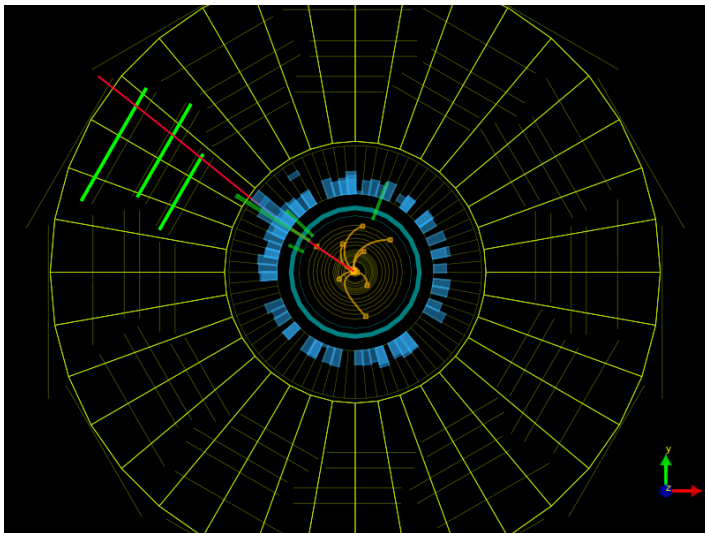
**CMS**

Single muon event



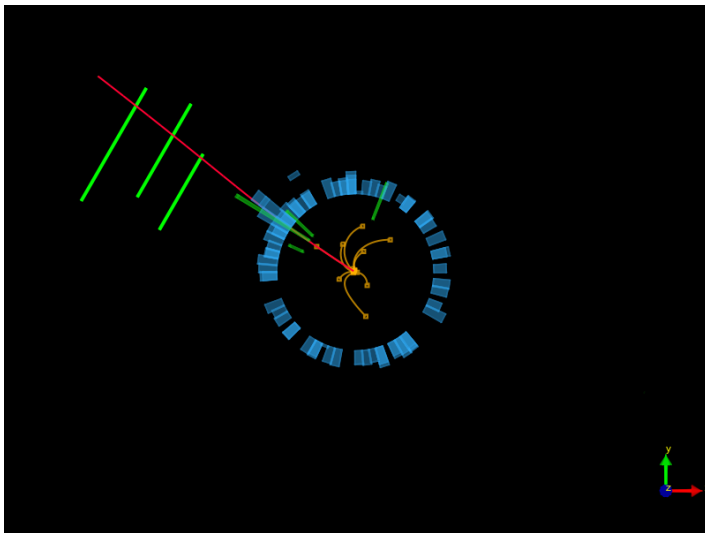
**CMS**

Single muon event

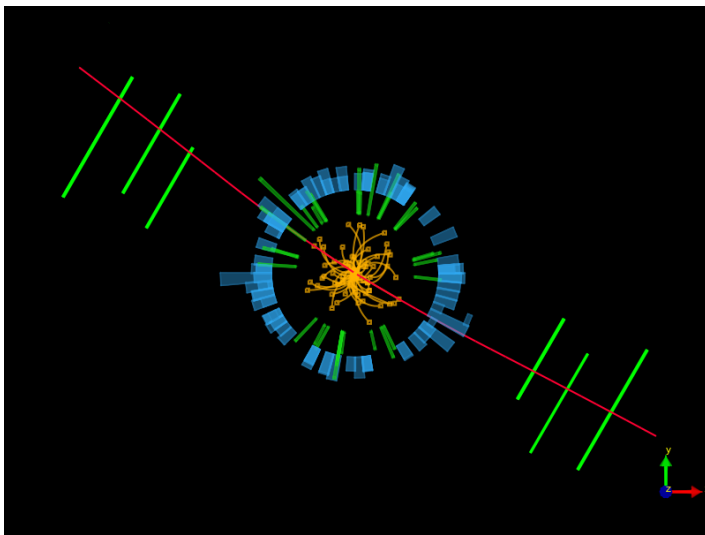


**CMS**

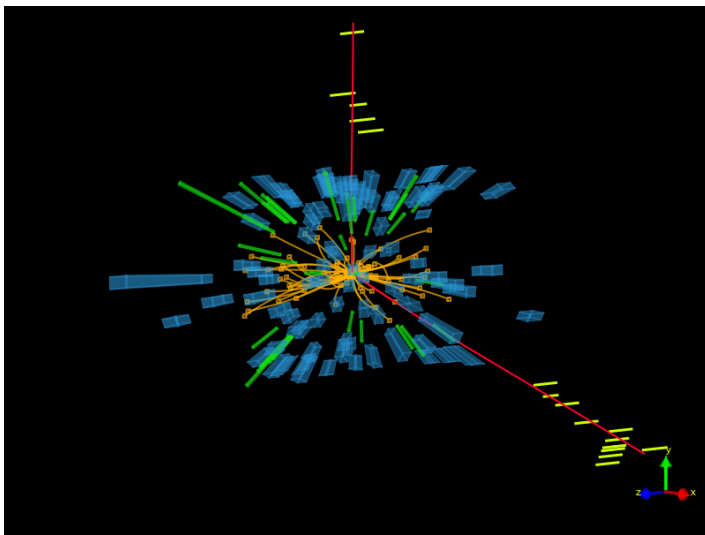
Single muon event



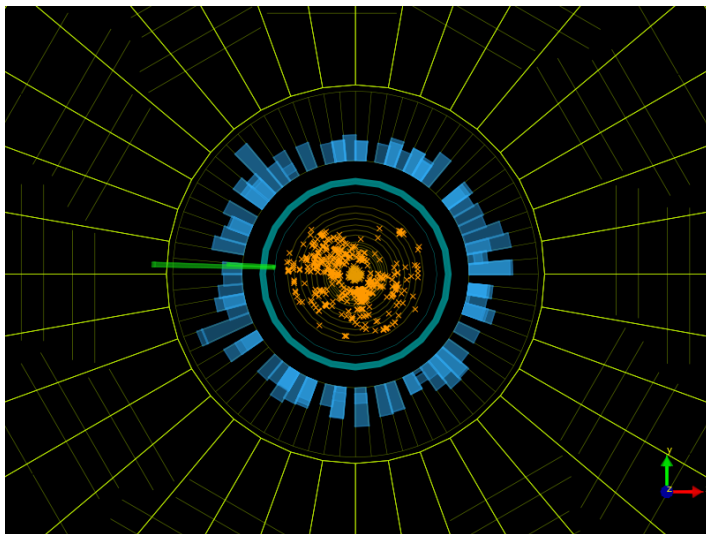
## CMS Event with two muons



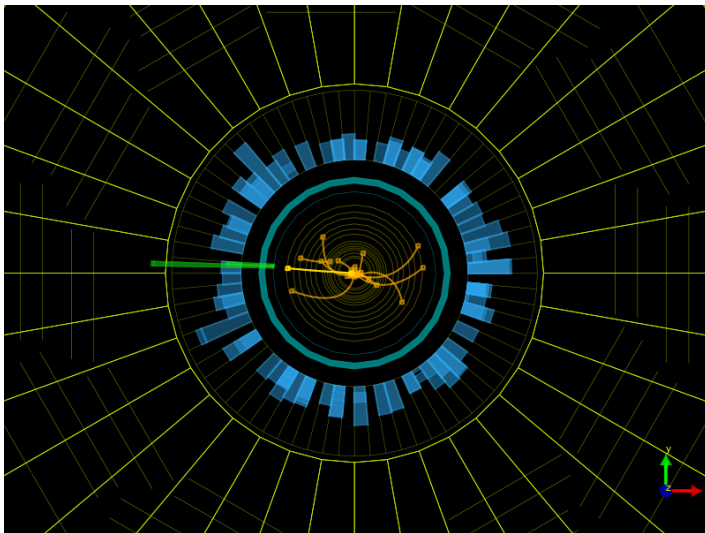
## CMS Event with two muons



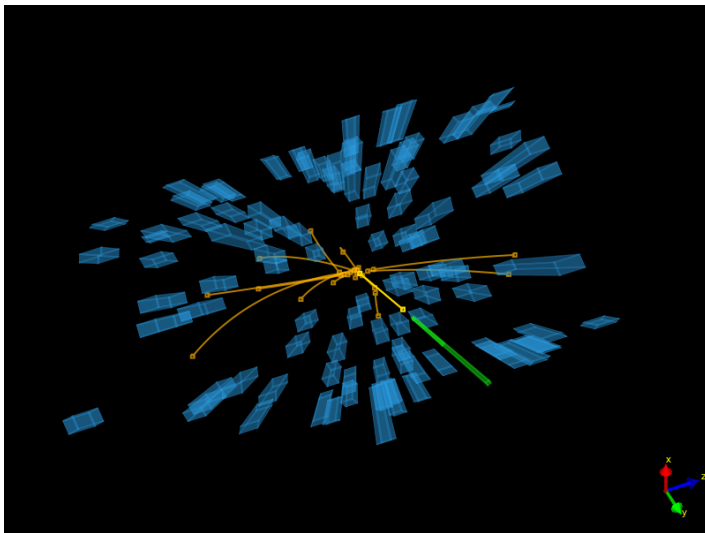
## CMS Event with electron production



## CMS Event with electron production

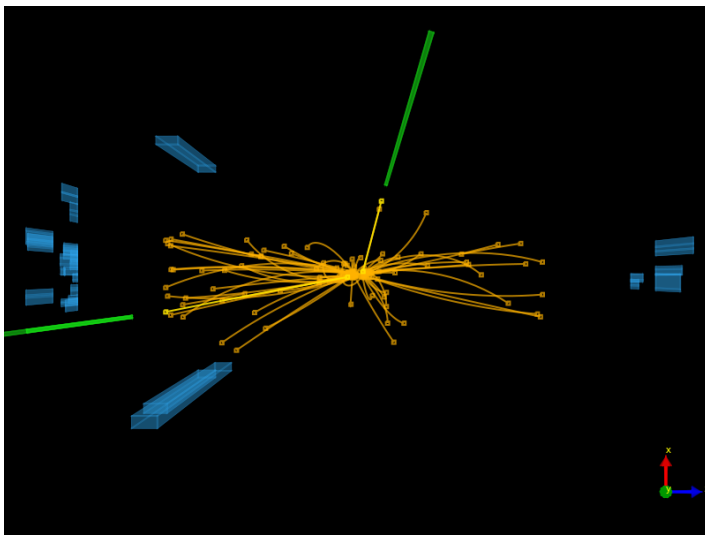


## **CMS** Event with electron production

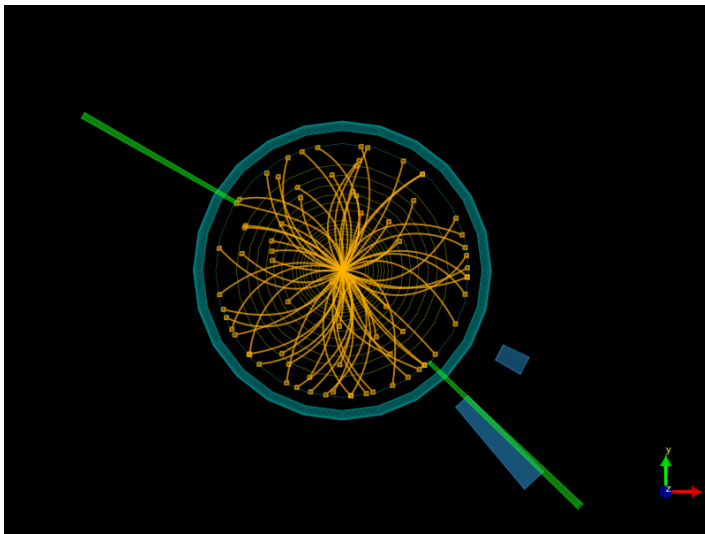




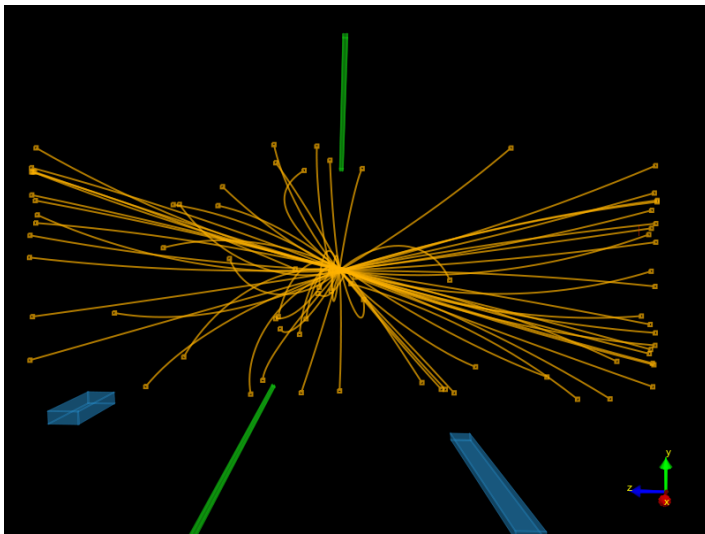
## CMS Event with two electrons



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



## **CMS** Event with two photon production ( $H \rightarrow \gamma\gamma$ candidate)





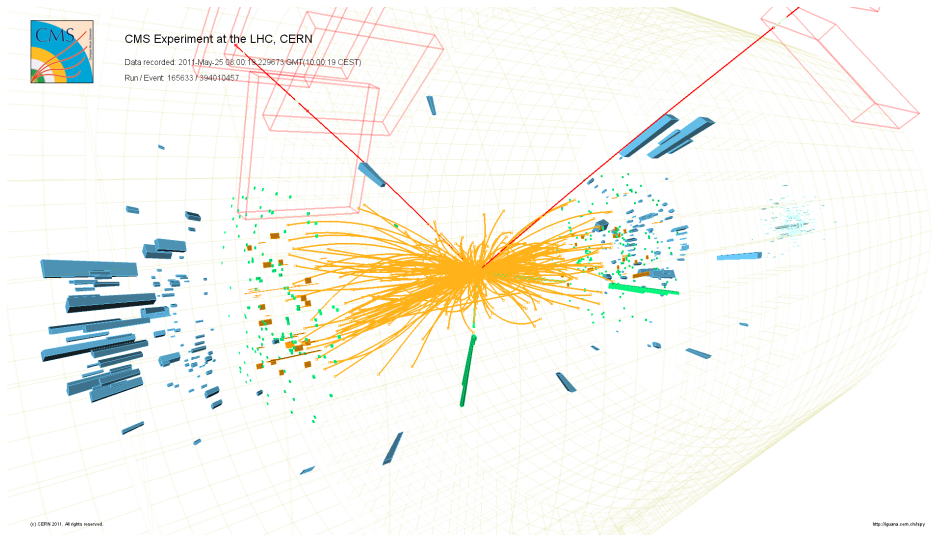
## CMS Four lepton event ( $H \rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^-$ candidate)



CMS Experiment at the LHC, CERN

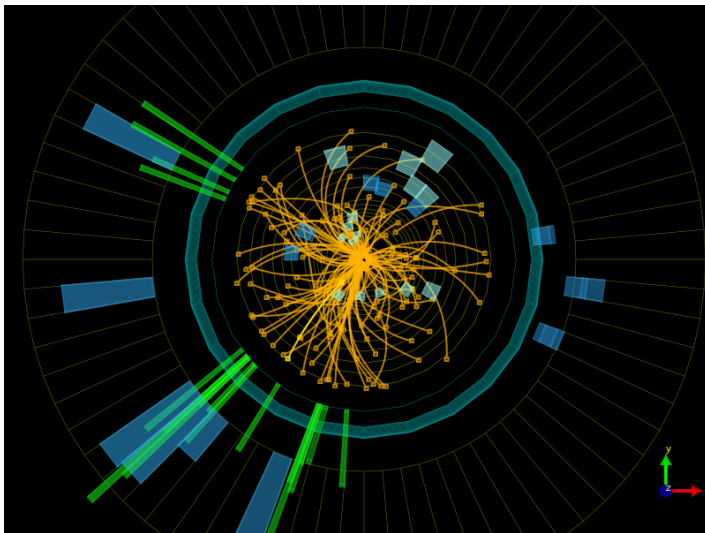
Data recorded: 2011-May-25 06:00:19.229673 GMT(+00:00:19 CEST)

Run/Event: 165633/394010457

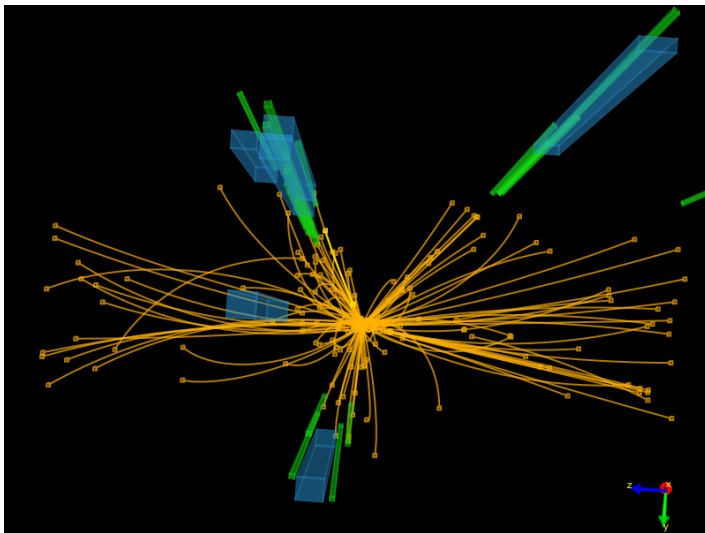


**CMS**

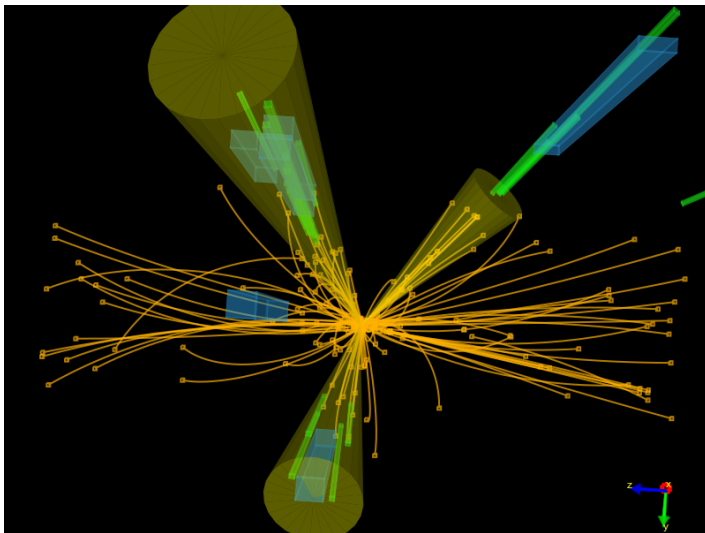
How do we interpret events like this?



**CMS** How do we interpret events like this?



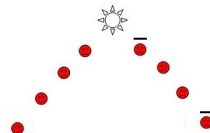
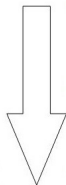
**CMS** How do we interpret events like this?





When a pair of quarks is produced in the collision:

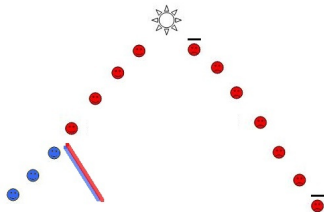
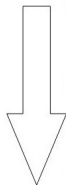
$$gg \rightarrow q\bar{q}$$



When a pair of quarks is produced in the collision:

$$gg \rightarrow q\bar{q}$$

Color field increases between quarks moving apart

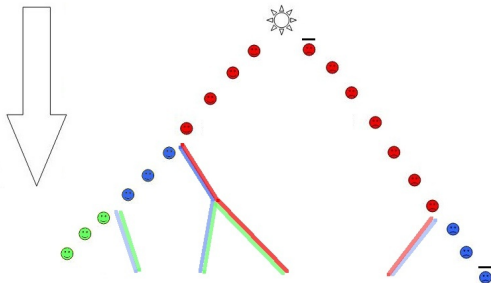


When a pair of quarks is produced in the collision:

$$gg \rightarrow q\bar{q}$$

Color field increases between quarks moving apart

Gluons are emitted



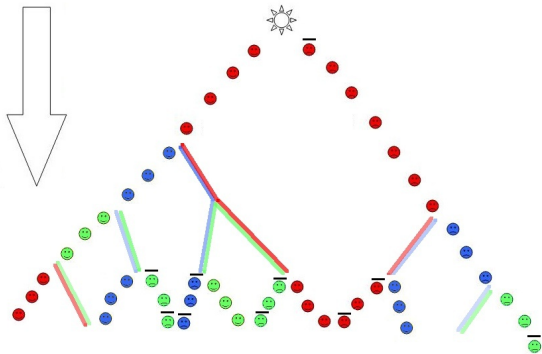
When a pair of quarks is produced in the collision:

$$gg \rightarrow q\bar{q}$$

Color field increases between quarks moving apart

Gluons are emitted

Gluons convert to quark-antiquark pairs



# Hadronization

When a pair of quarks is produced in the collision:

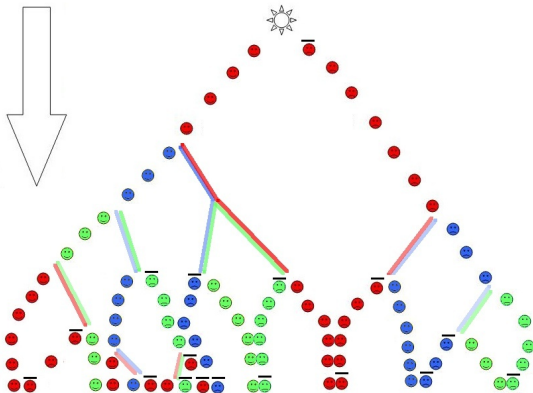
$$gg \rightarrow q\bar{q}$$

Color field increases between quarks moving apart

Gluons are emitted

Gluons convert to quark-antiquark pairs

Quarks and antiquarks form "white" hadrons



When a pair of quarks is produced in the collision:

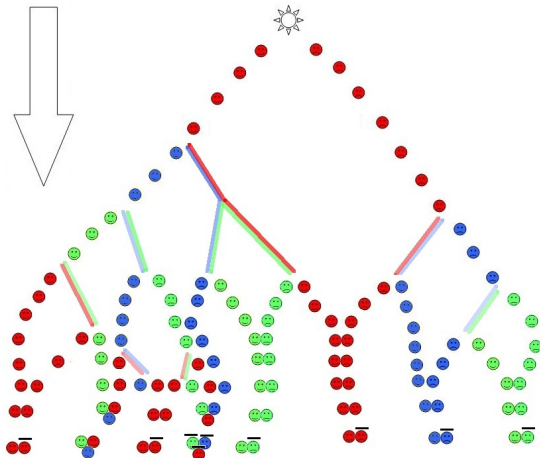
$$gg \rightarrow q\bar{q}$$

Color field increases between quarks moving apart

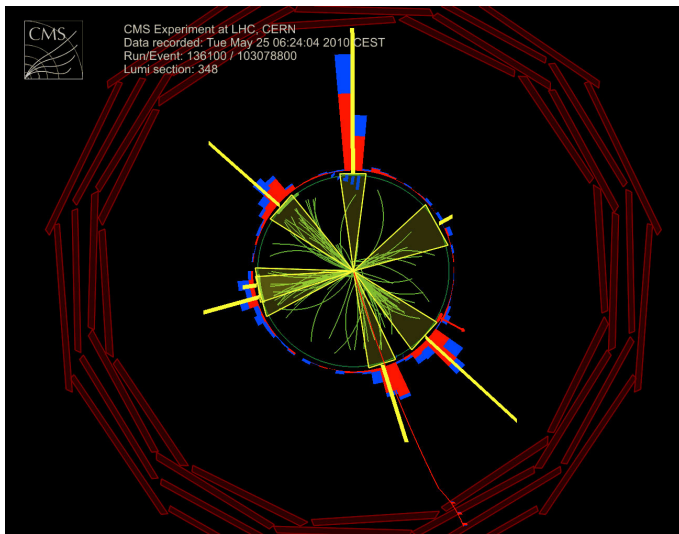
Gluons are emitted

Gluons convert to quark-antiquark pairs

Quarks and antiquarks form “white” hadrons

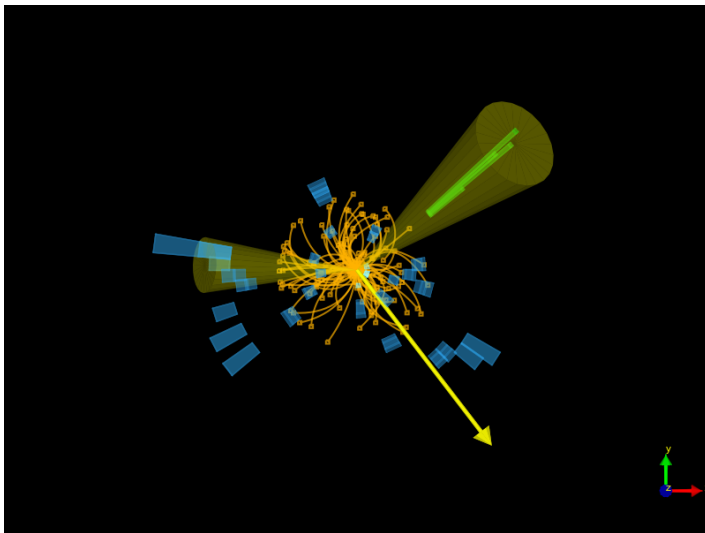


## CMS Event with six jet production



**CMS**

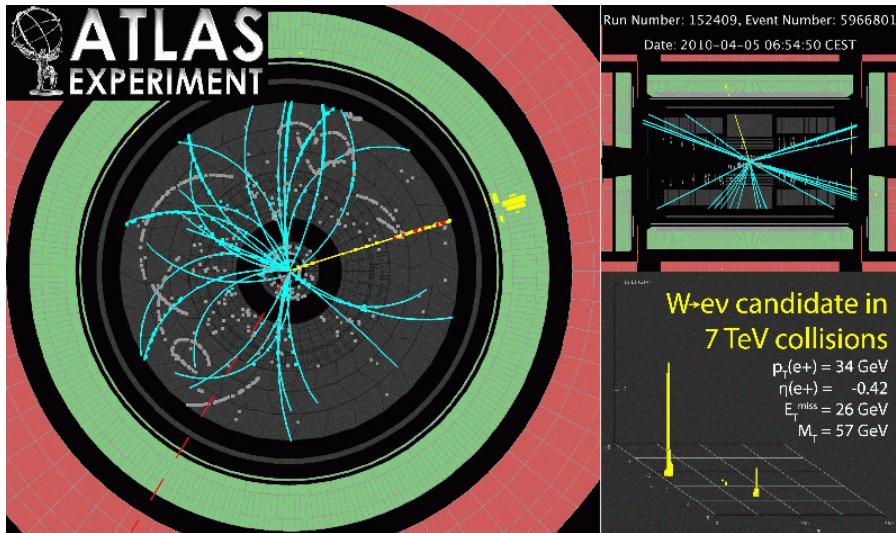
Unbalanced transverse momentum - signature of missing particle





# Reconstructed events

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



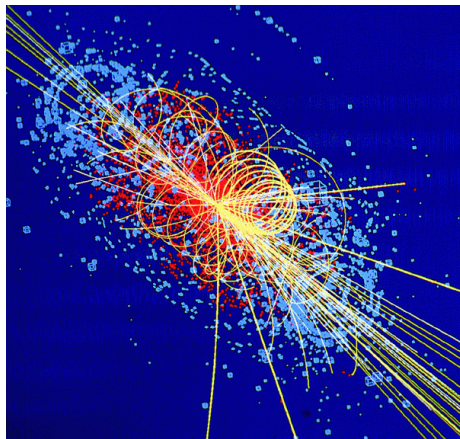
Up to 50 proton pairs collide at LHC at each bunch crossing

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?



# Event selection

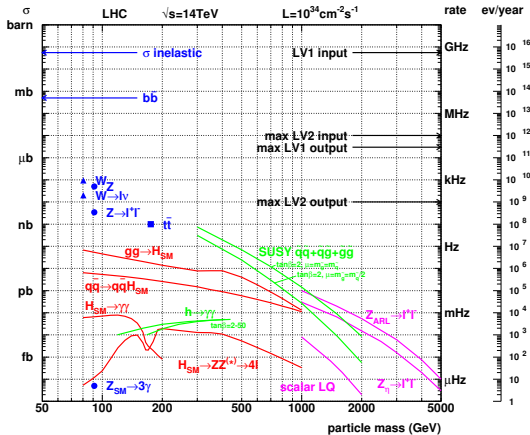
## Trigger system

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

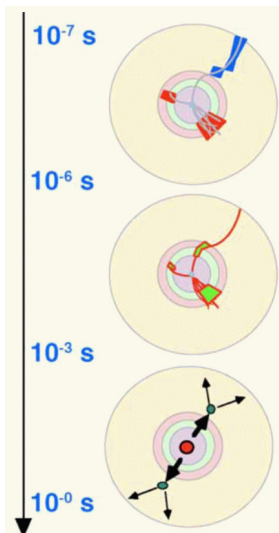
Only “interesting” signals are read from the detector.

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 million 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

# Event selection

## Trigger system scheme

