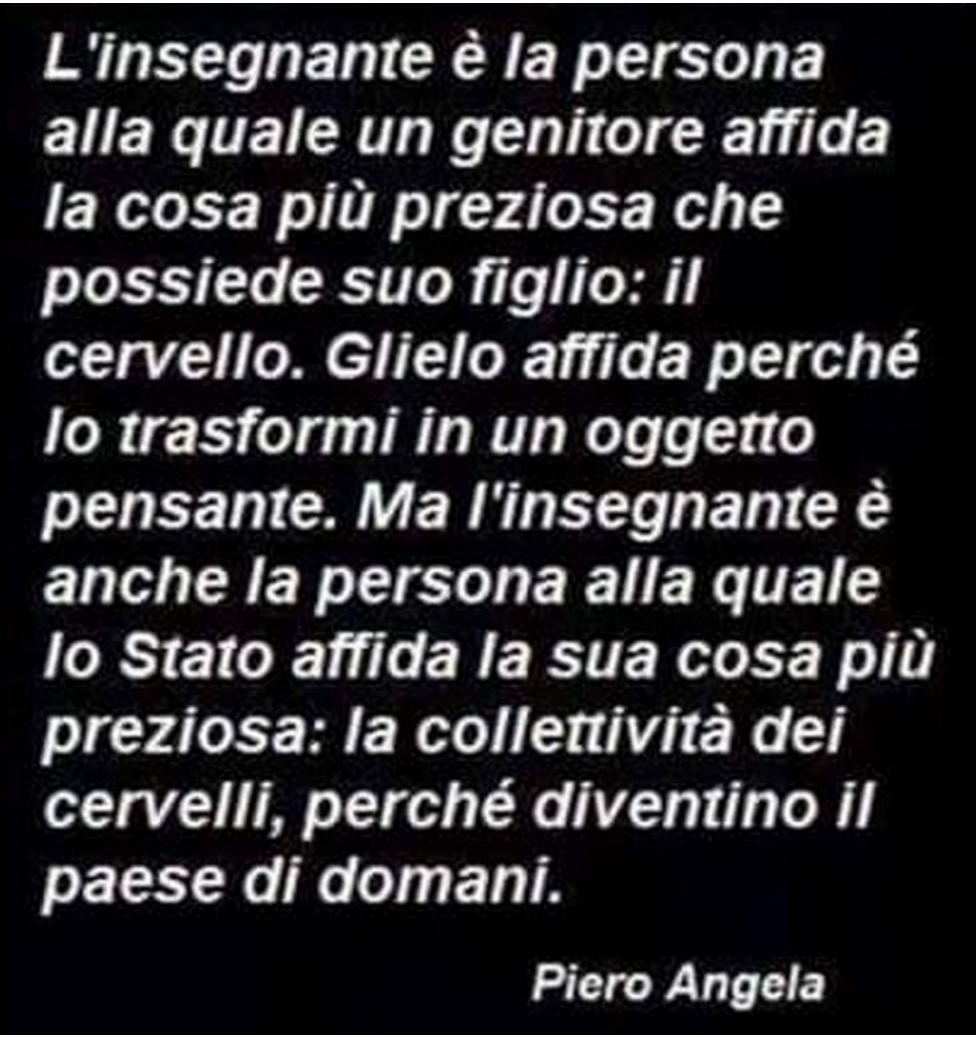
Introduction to Particle Detectors

Chiara Mariotti

CERN, 11 July 2019

The teacher



L'insegnante è la persona alla quale un genitore affida la cosa più preziosa che possiede suo figlio: il cervello. Glielo affida perché lo trasformi in un oggetto pensante. Ma l'insegnante è anche la persona alla quale lo Stato affida la sua cosa più preziosa: la collettività dei cervelli, perché diventino il paese di domani.

Piero Angela

The teacher is the person to whom a parent entrusts the most precious thing that his child possesses: the brain.
He entrusts it to him to transform it into a thinking object.
But the teacher is also the person to whom the State entrusts its most precious thing:
the community of brains,
so that they become the country of tomorrow.

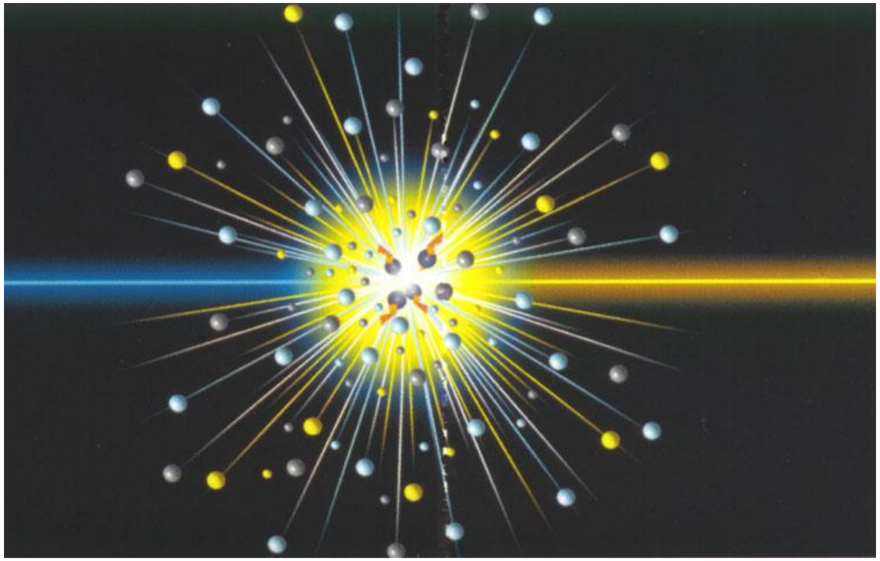
Piero Angela

At CERN

We accelerate particles bringing them to very high energies for ther make them collide:

- to study what happens during the interaction at $<10^{-13}$ cm
- to produce new particles thanks to $\mathbf{E = mc^2}$

$$\boxed{E=mc^2}$$



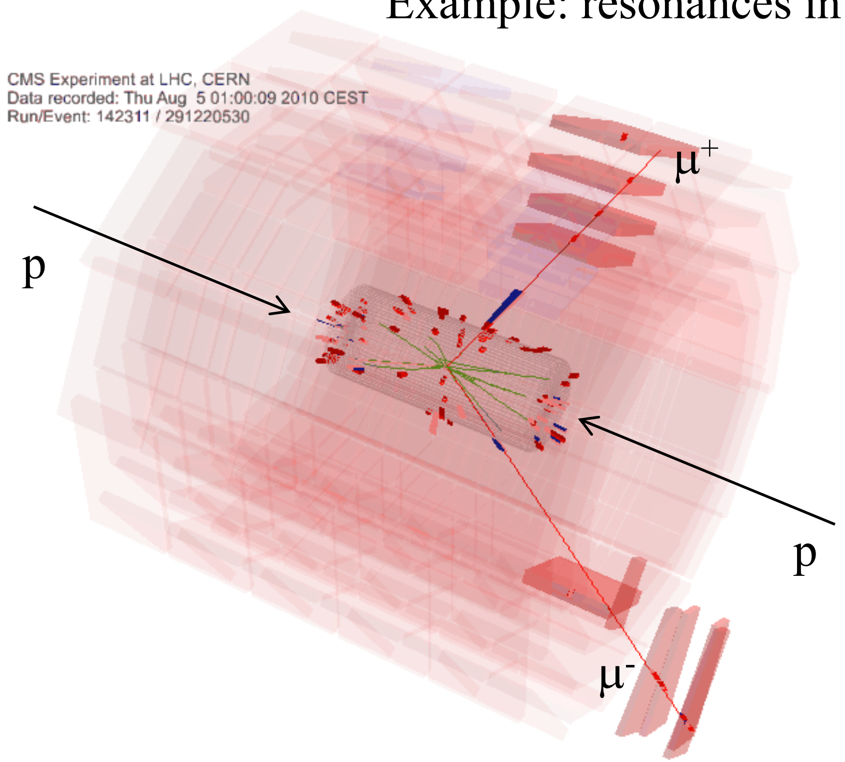
Studying the particles produced (how many there are, what are they, their characteristics, etc.) we can understand what happened at the moment of the collision and understand the fundamental processes that govern nature

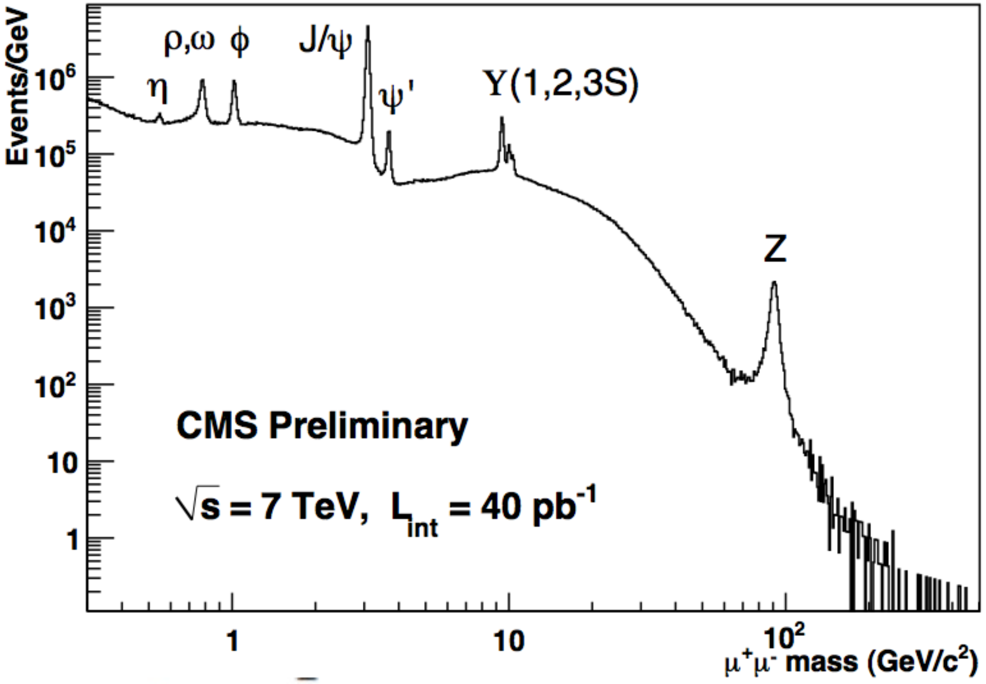
Events

The "interesting" particles decay rapidly

- We need to look for their decay products
- Often in a background of similar events produced from already-known processes

Example: resonances in the spectrum $\mu^+\mu^-$ in pp collisions

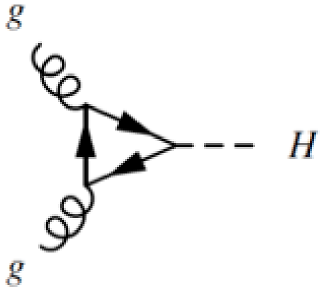




$$M_X^2 = E_1^2 + E_2^2 + 2E_1E_2 - p_1^2 - p_2^2 - 2p_1p_2\cos\theta$$

Production and decay of the Higgs Boson

The Higgs boson can be produced in the fusion of 2 of the gluons that are inside the proton:

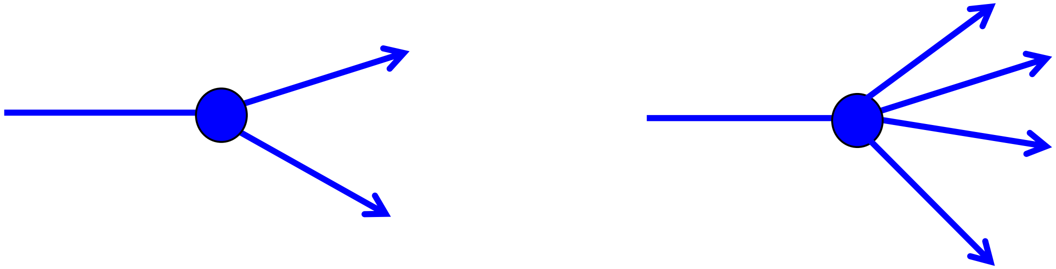


The Higgs boson is not a stable particle

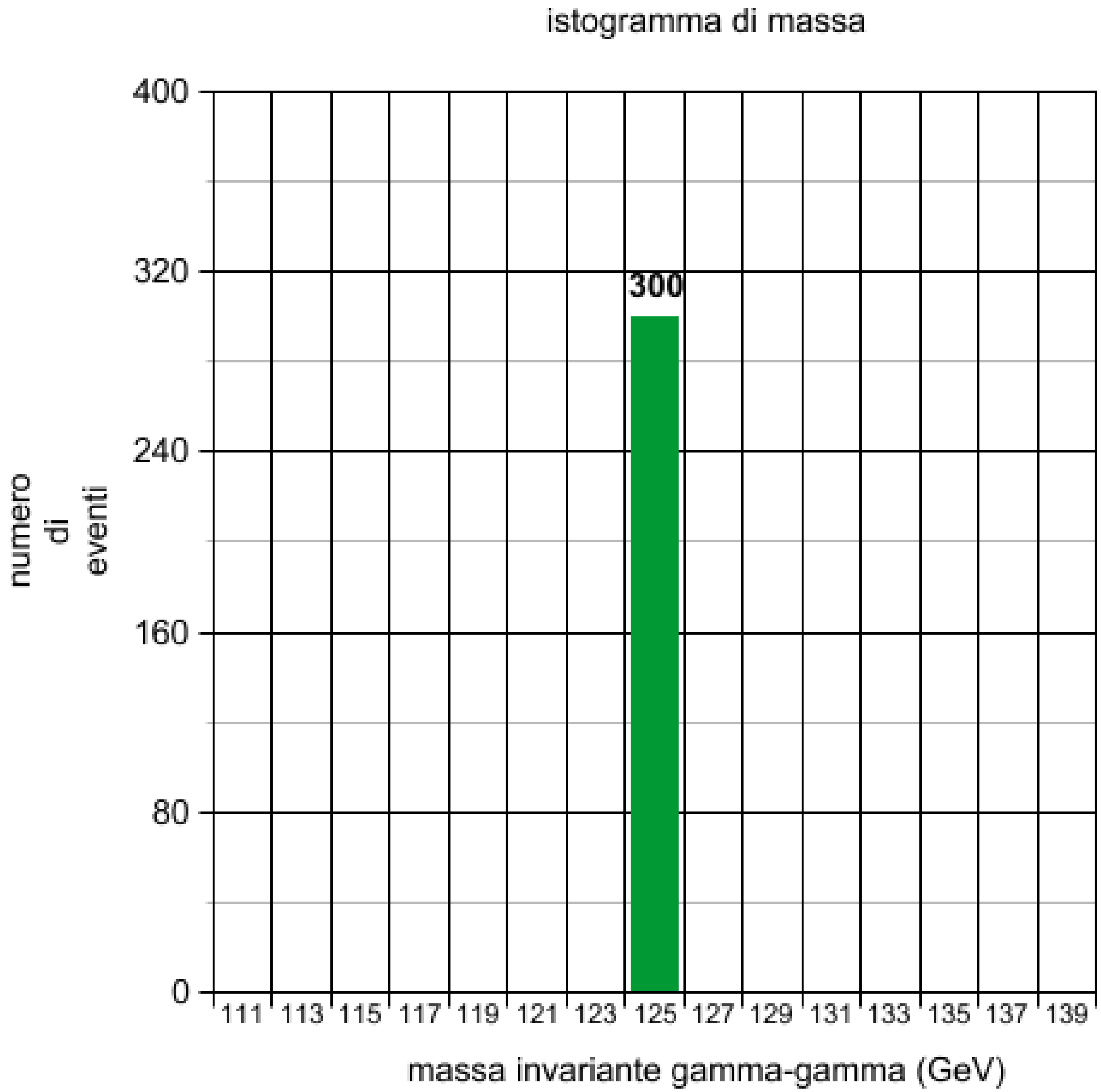
Decade in the lightest elementary particles

The "final states" are manifold; the most important are:

- H→ two fotons (H→γγ)
- H→ four leptons (four electrons or four muons…) (H→4l)



Decay of a particle of mass m=125 GeV



This is a simulation

$$p^\mu = \begin{pmatrix} E/c \\ p^1 \\ p^2 \\ p^3 \end{pmatrix} = \begin{pmatrix} p^0 \\ p^1 \\ p^2 \\ p^3 \end{pmatrix}$$

$$\boxed{M_H^2 = (p_1 + p_2)^2}$$

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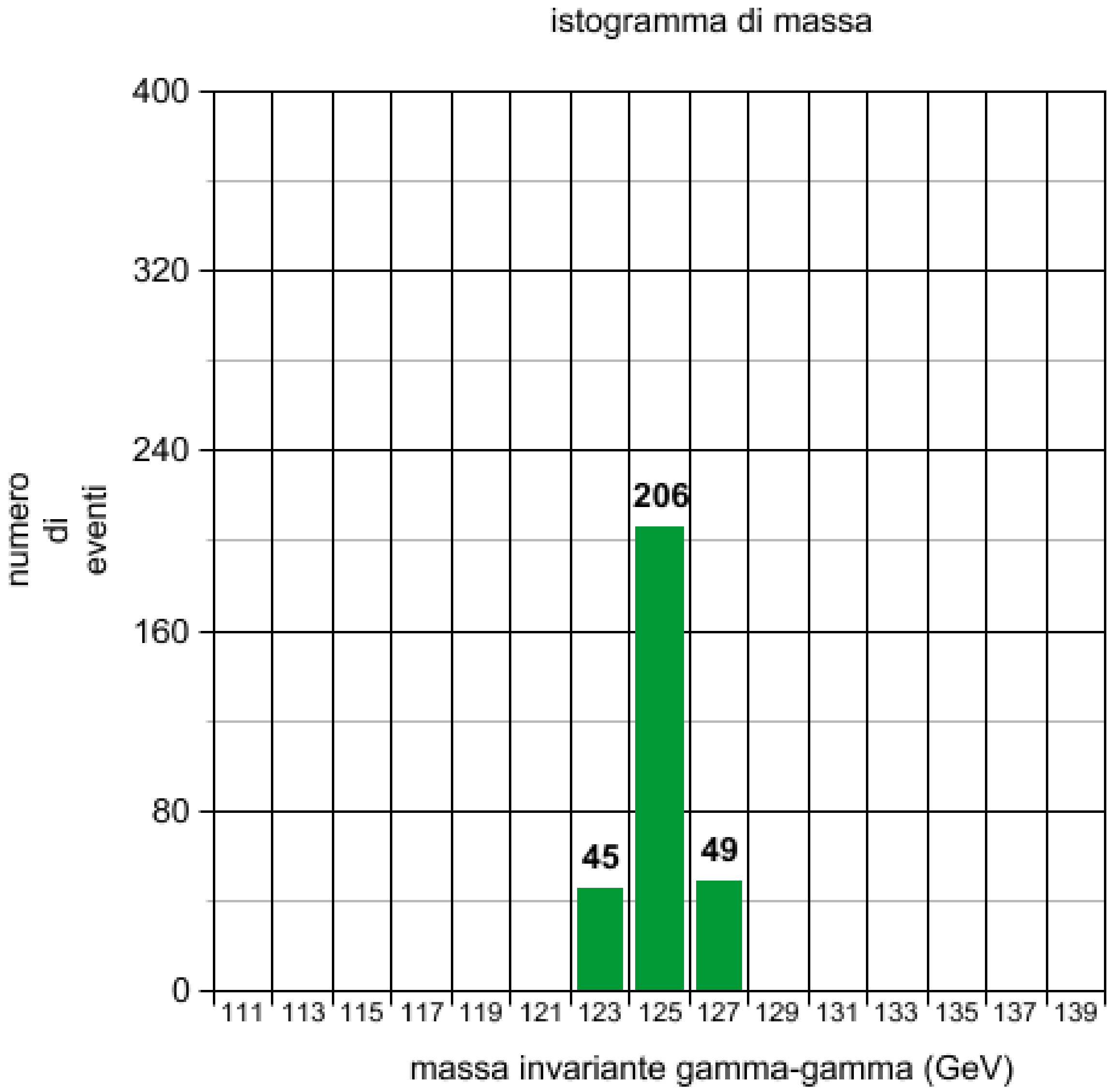

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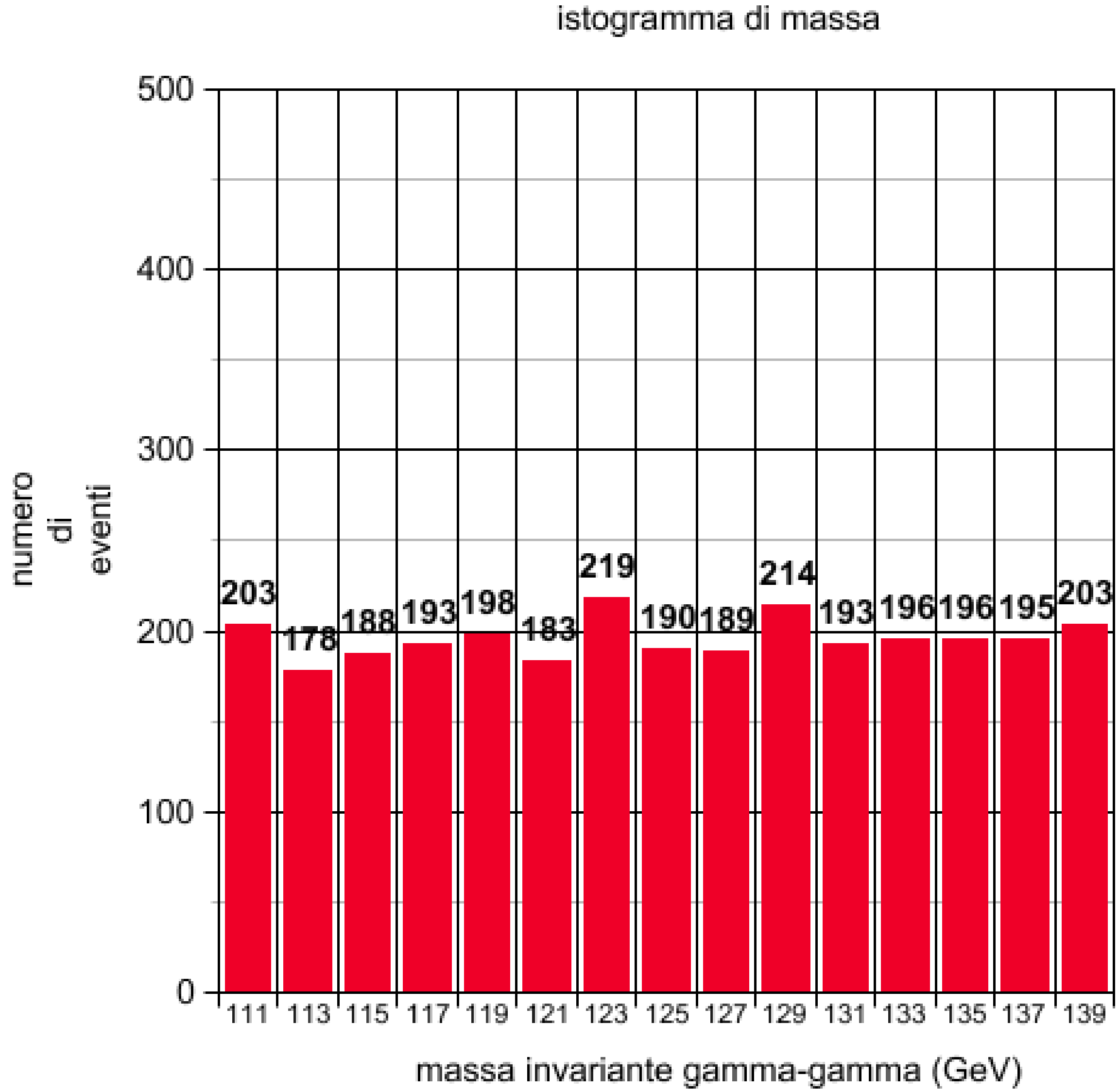
The Background

2 photons invariant mass, they are not coming from the decay of a particle



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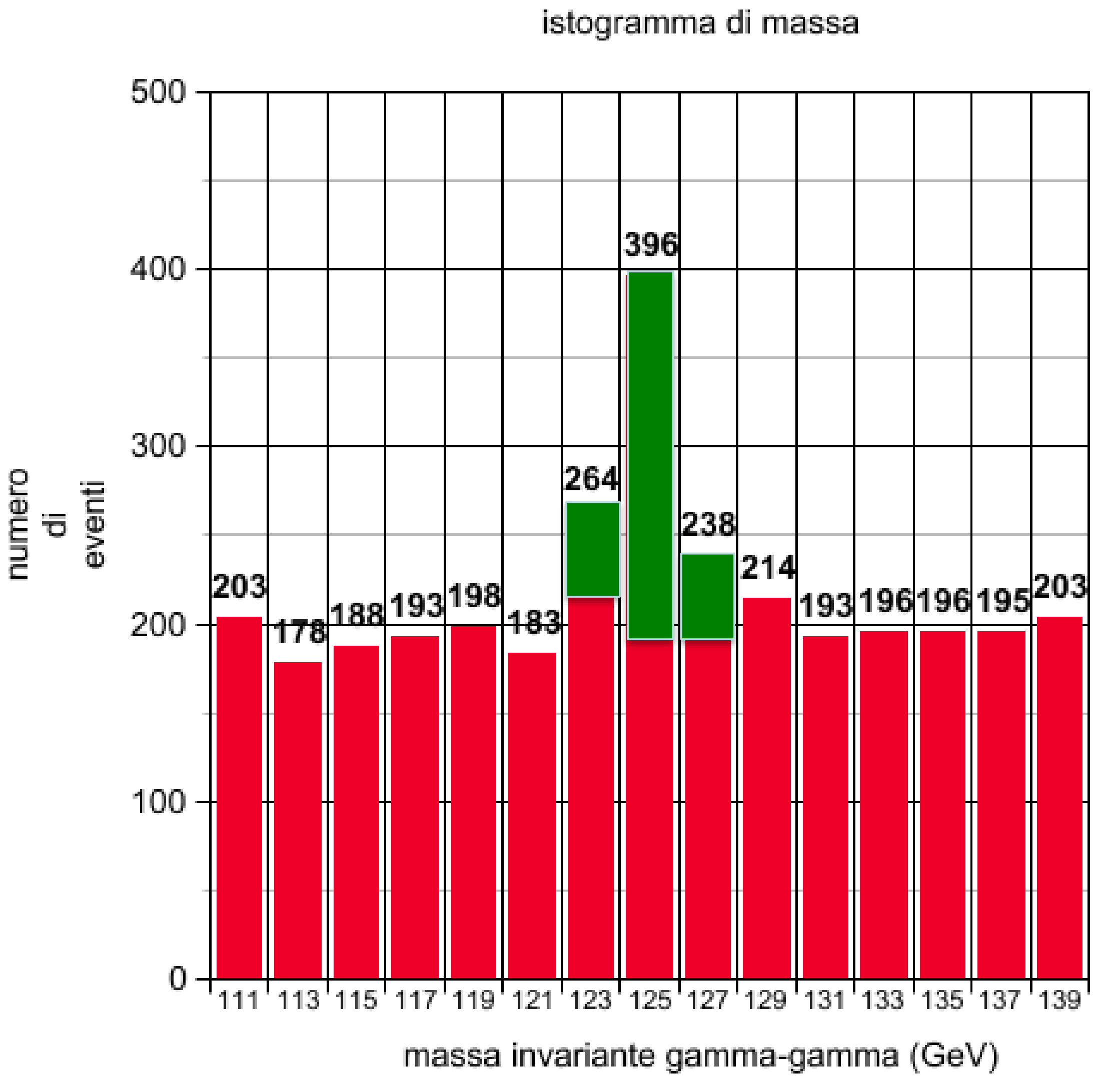
Background and Signal



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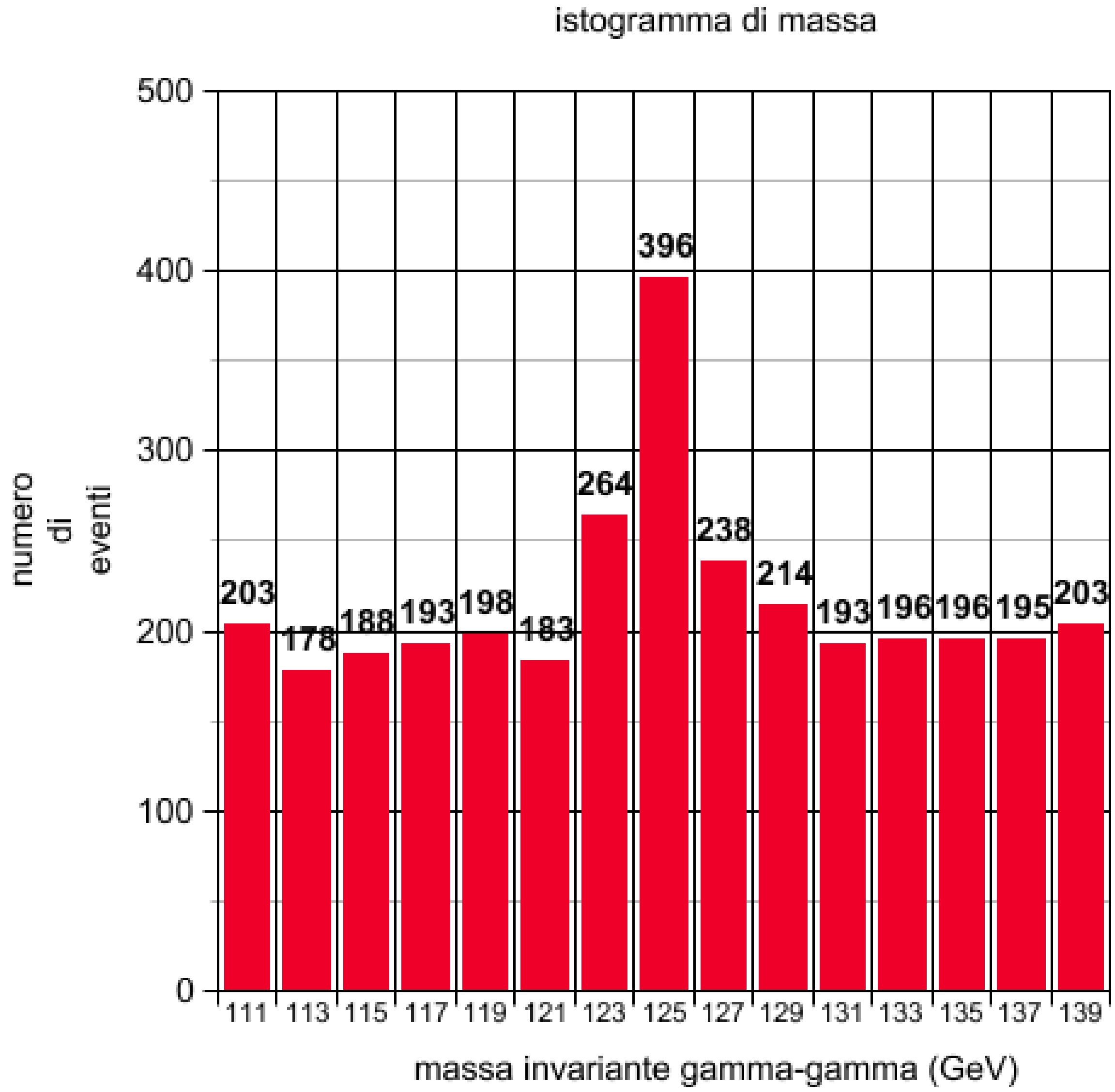

This is a simulation

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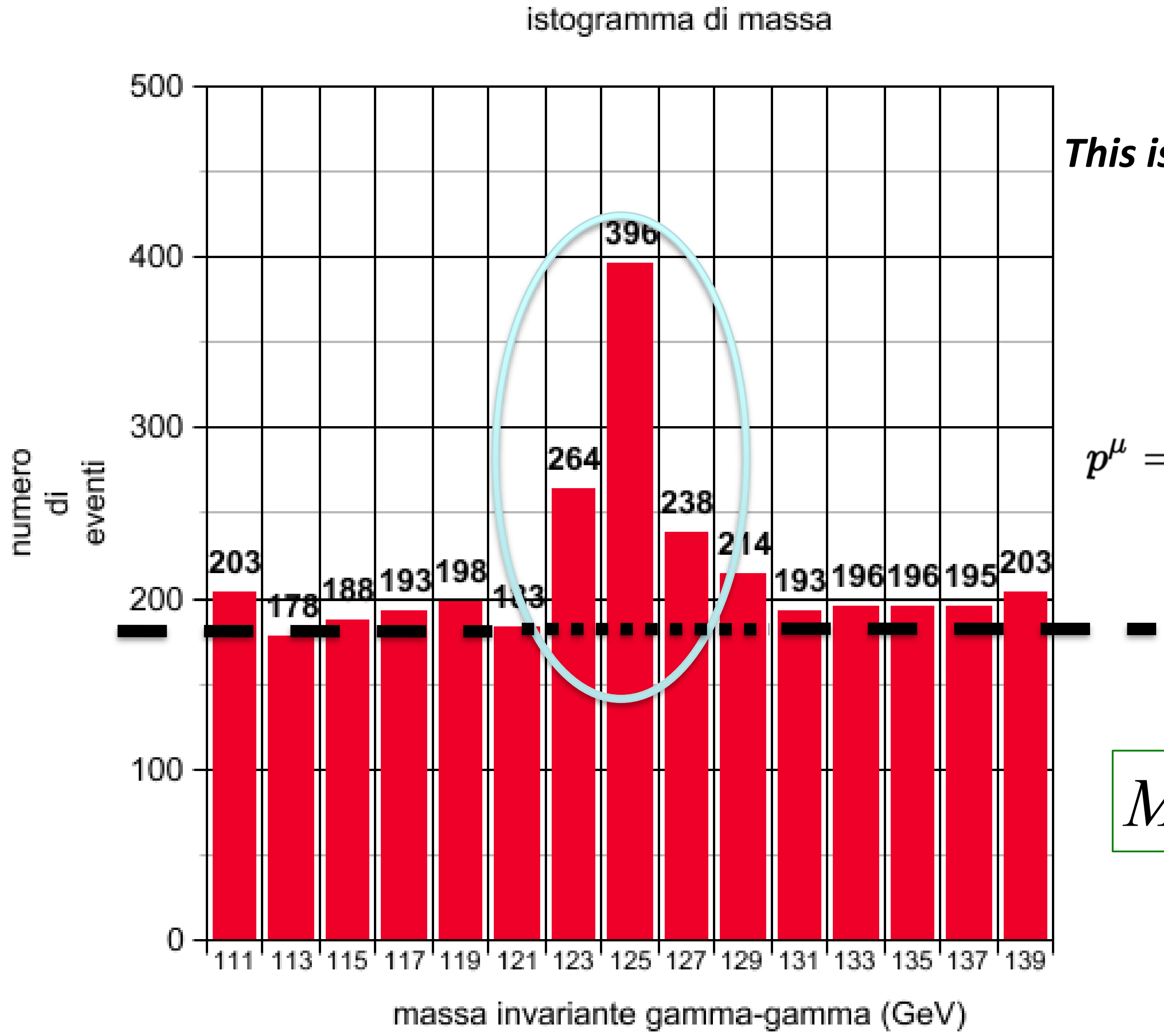

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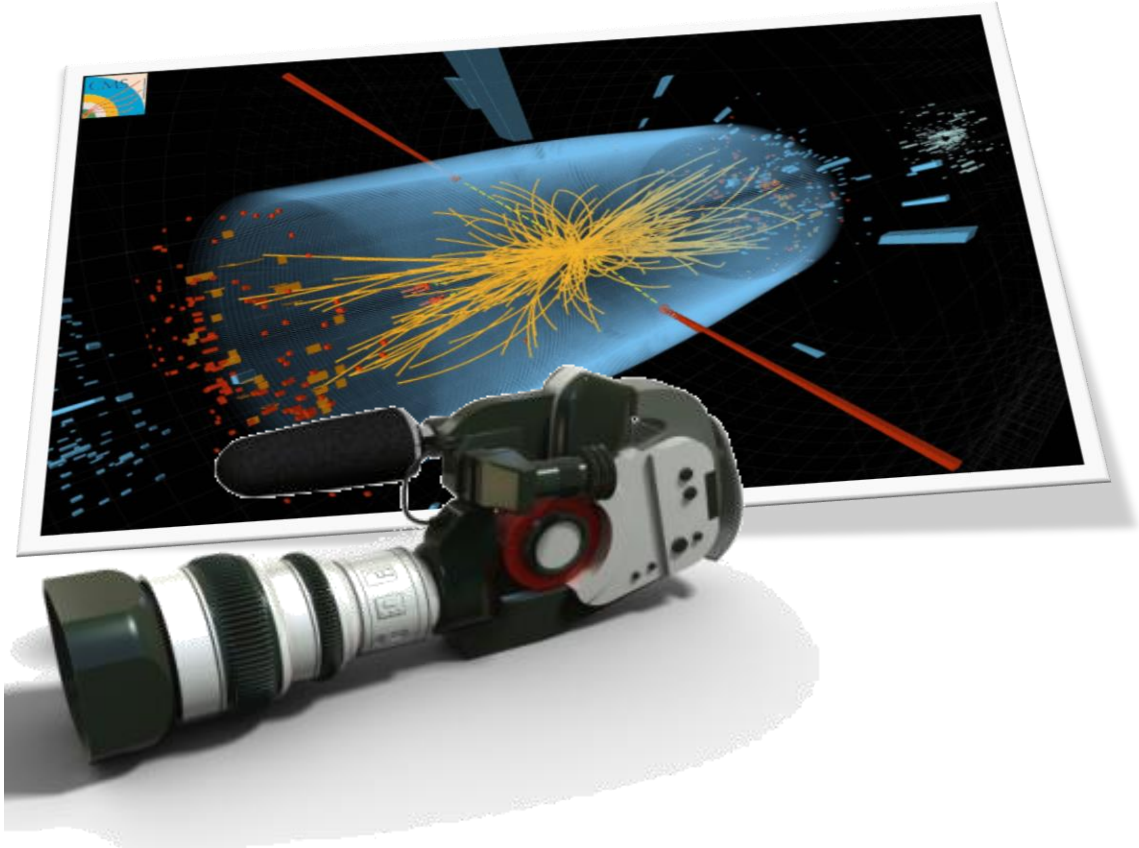
DETECTORS



A detector is not a huge photographic-camera !

System of thousands of specialized sensors:

They exploit the interaction of particles with matter to obtain **independent measurements of position, energy, and momentum**

Measures that must then be put together to reconstruct what happened

The Detectors

To reconstruct what happened at the time of the interaction between the two protons, we must reconstruct all the particles that they were produced in the final state.

Of these we want to measure everything:

- mass, therefore identity (electrons, photons, muons, type of hadron ...)
- momentum (or speed) and energy
- trajectory, therefore angles and directions

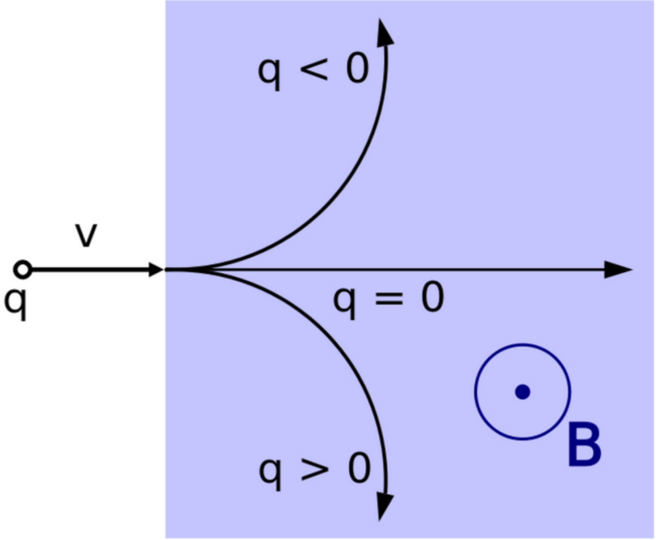
To do this we combine the information of many detectors places in succession.

We also want FAST detectors because we want to analyze very rare events (and therefore record many interactions)
And PRECISE detectors, to be more efficient.

quick review on the detectors
the LHC detectors

Magnetic fields

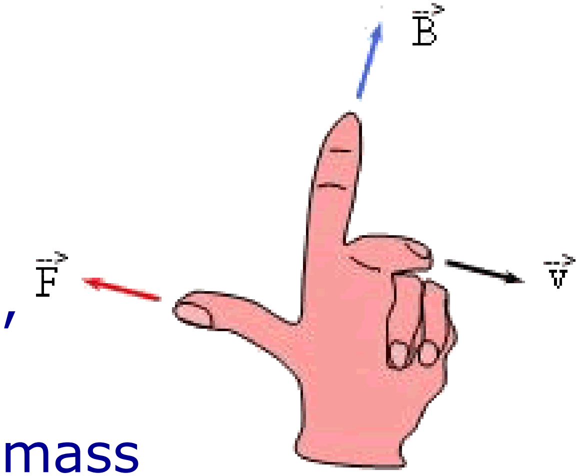
The magnetic field curves the **charged** particles:



The Lorentz force

$$F = q \cdot v \cdot B = m \cdot \frac{v^2}{R}$$

$$\Rightarrow q \cdot B \cdot R = m \cdot v = \left| \vec{p} \right|$$



A magnetic field allows:

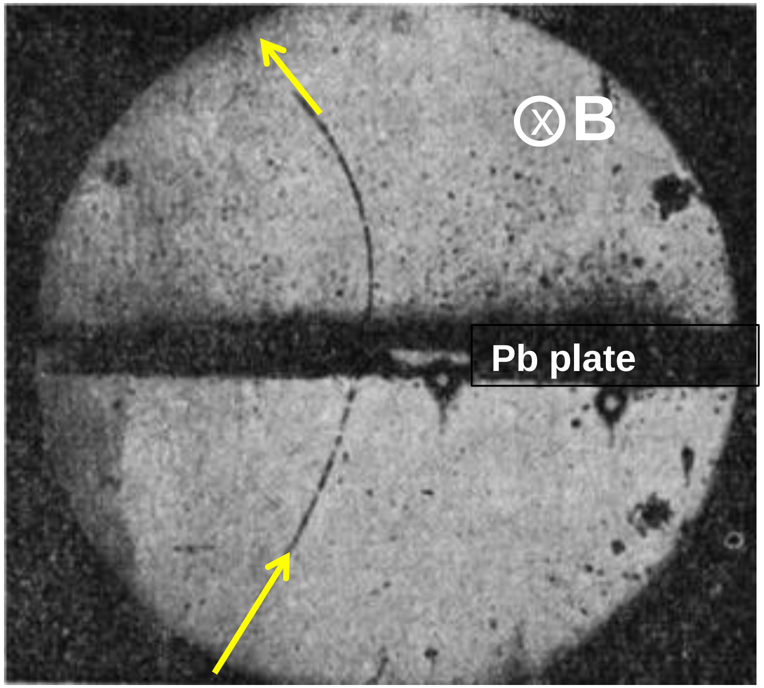
- determine the charge of a particle,
- given R the radius of curvature and m,
  determine p (the impulse)
- or known the impulse determines the mass

How do we "see" particles?

Taking advantage of the mechanisms with which they interact with matter

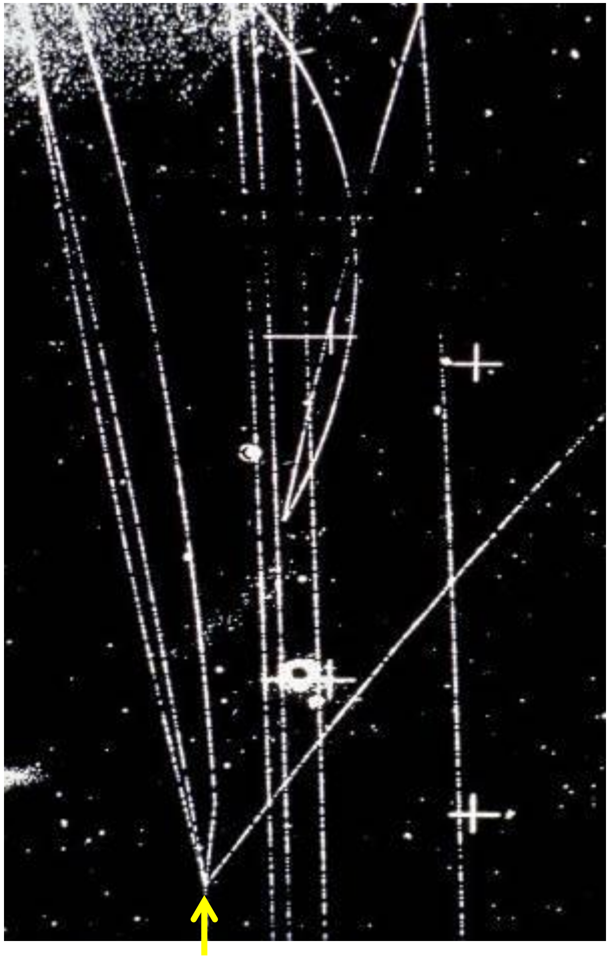
- Example: charged particles ionize matter as they pass

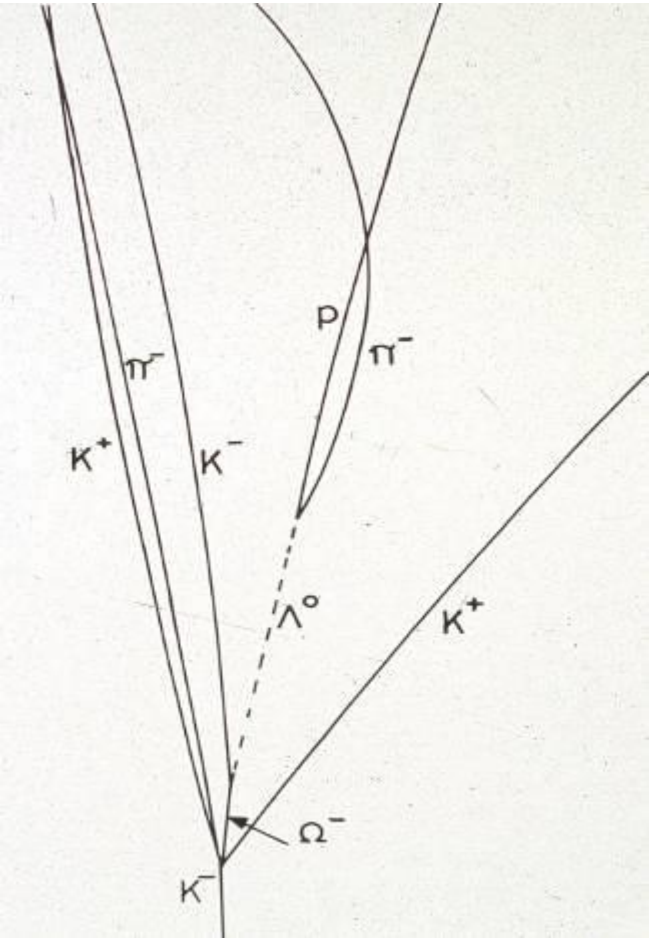
Claud chamber (Wilson, 1911; Nobel prize 1927): Chamber filled with saturated steam which condenses as a result of ionization, making the trace visible



Discovery of the positron (e+)
(Anderson, 1932; Nobel Prize 1936): Observing cosmic rays through a cloud chamber immersed in a magnetic field that curves its trajectory, with a lead plate to absorb part of the energy
(1928 Dirac introduced the anti-matter)

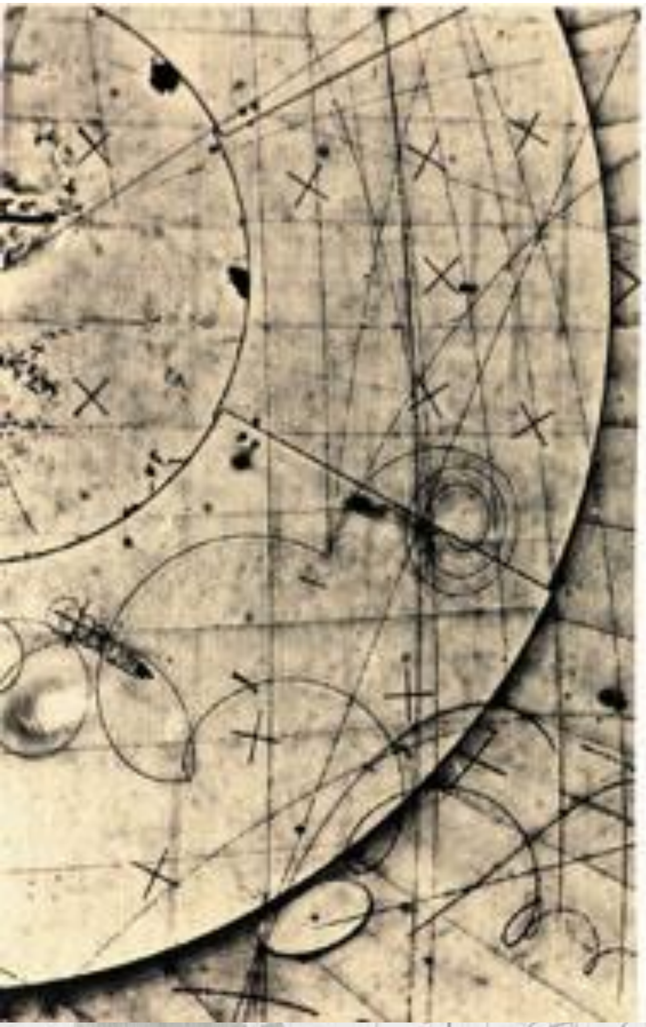
The first detectors: bubbles chambers

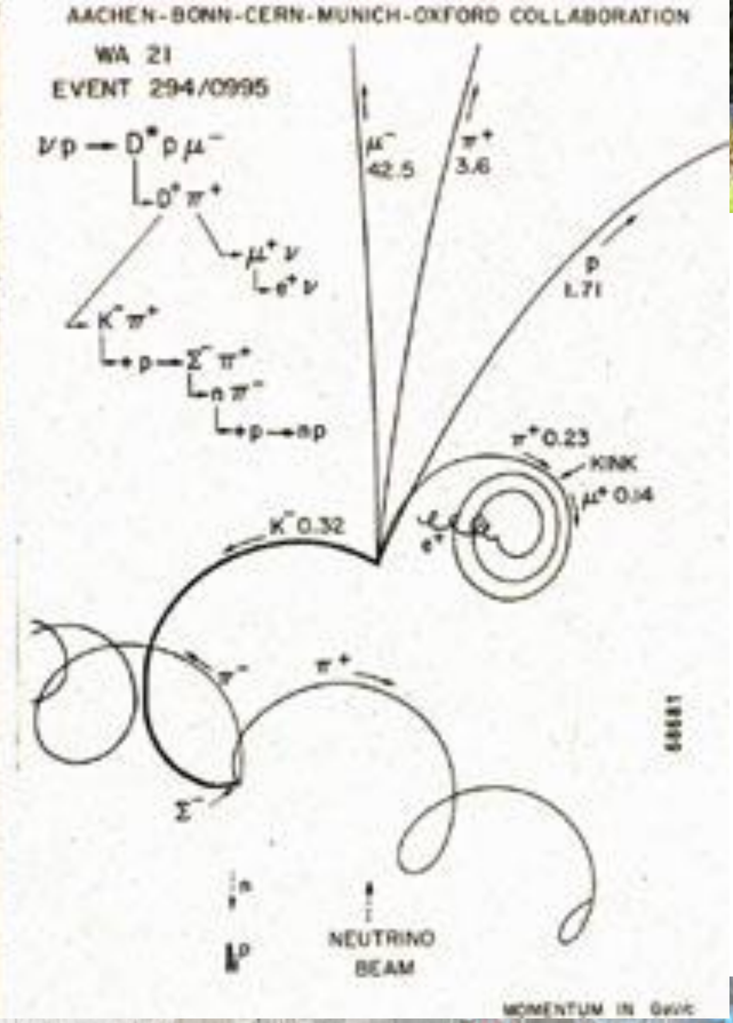




Millions of collisions photographed and studied one by one ..

Gargamelle



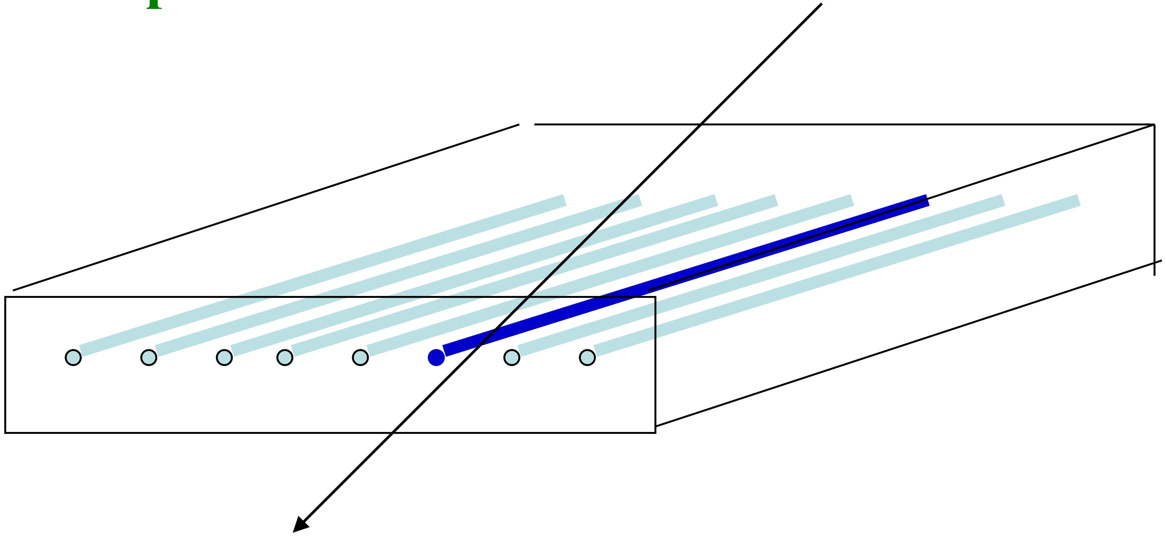

AACHEN-BONN-CERN-MUNICH-OXFORD COLLABORATION
WA 21
EVENT 294/0995
$\nu p \to D^{*} p \mu^-$
$\llcorner D^0 \pi^+$
$\llcorner \mu^+ \nu$
$\llcorner e^+ \nu$
$\llcorner K^- \pi^+$
$\llcorner p \to \Sigma^- \pi^+$
$\llcorner n \pi^-$
$\llcorner p \to np$
μ^- 42.5
π^+ 3.6
p 1.71
π^+ 0.23
KINK
μ^+ 0.14
e^+
K^- 0.32
π^-
π^+
Σ^-
n
p
NEUTRINO BEAM
MOMENTUM IN GeV/c

Rivelatori elettronici

Photos of bubble chambers: slow process both for acquisition and for reading

1968: Georges Charpak at CERN invents the

Proportional Multi-Wire Chamber

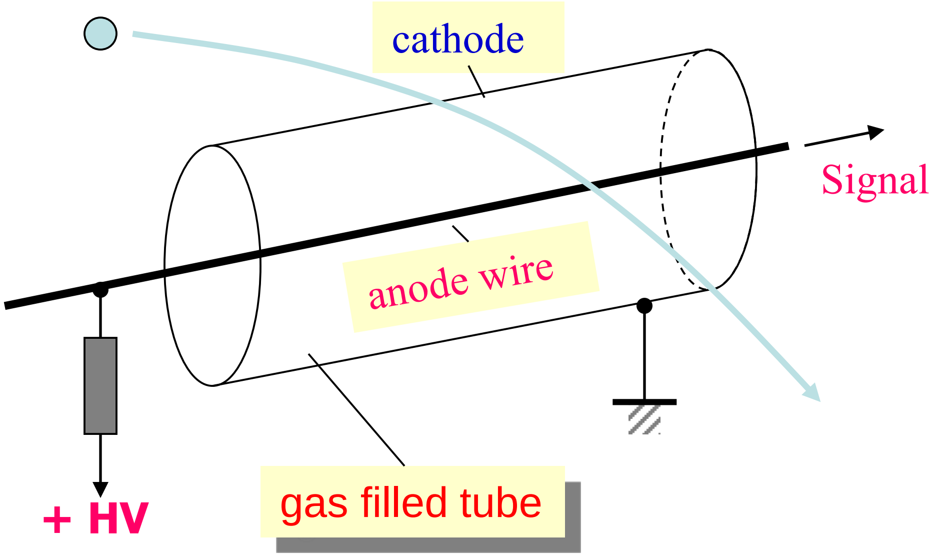


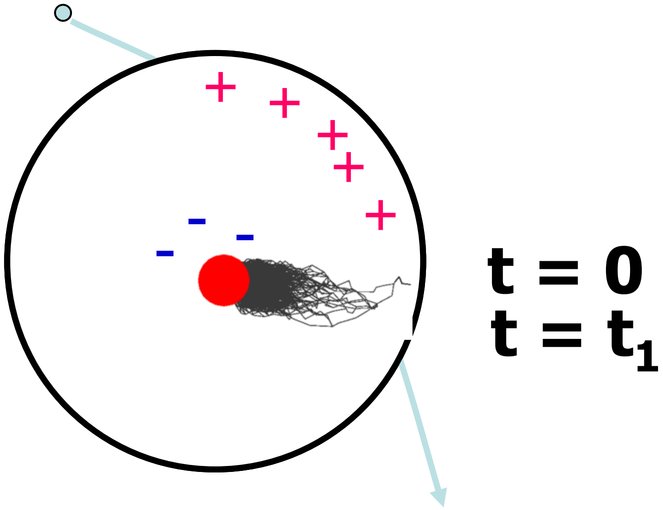
Chamber with gas + wires under high voltage
particle ionizes the gas →
the charges are collected from the nearest wire
→electronic signal

Nobel prize 1992

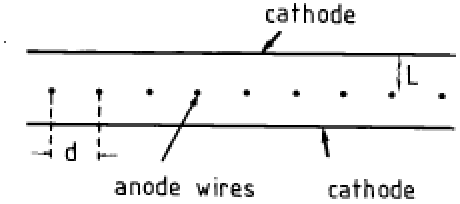
We move into the totally electronic era:
- Quick acquisition
- Possibility of computer processing

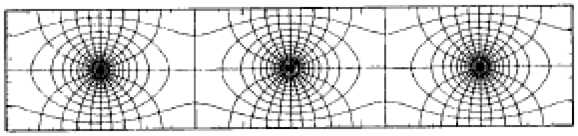
Gas detectors





- **Geiger-Counter**: Binary response
- **Proportional Counter**:
- **MWPC:** Multi Wire Proportional Chamber
- e altri….





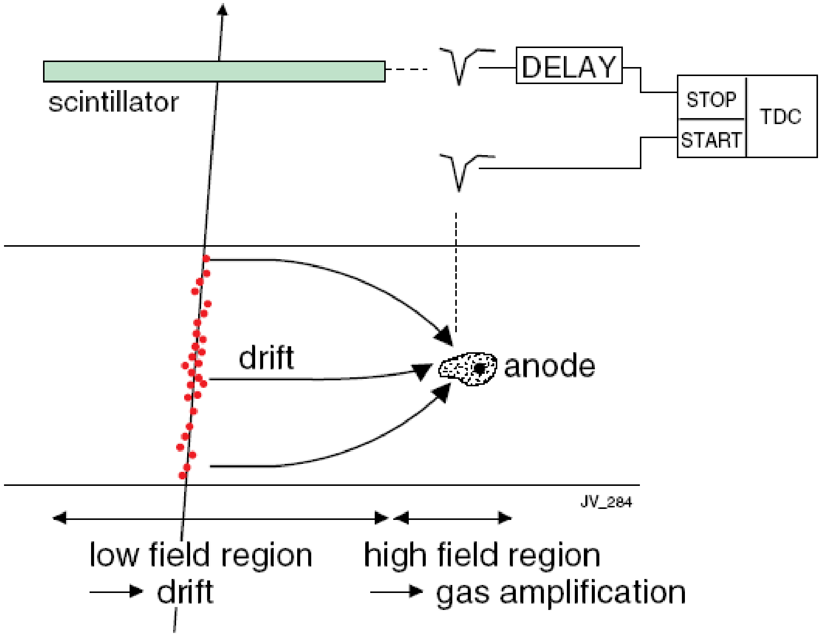
field lines and equipotentials around anode wires

Drift Chamber

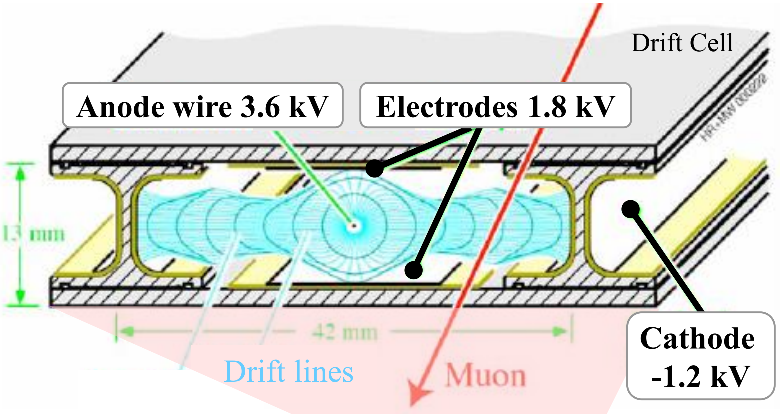
The standard wire chambers are limited in the accuracy of the trajectory measurement by the distance between the wires.

Drift chambers (drift chambers) measure the drift time of the charges improving the resolution.

However, the time ot which the particle cross the detector must be known.

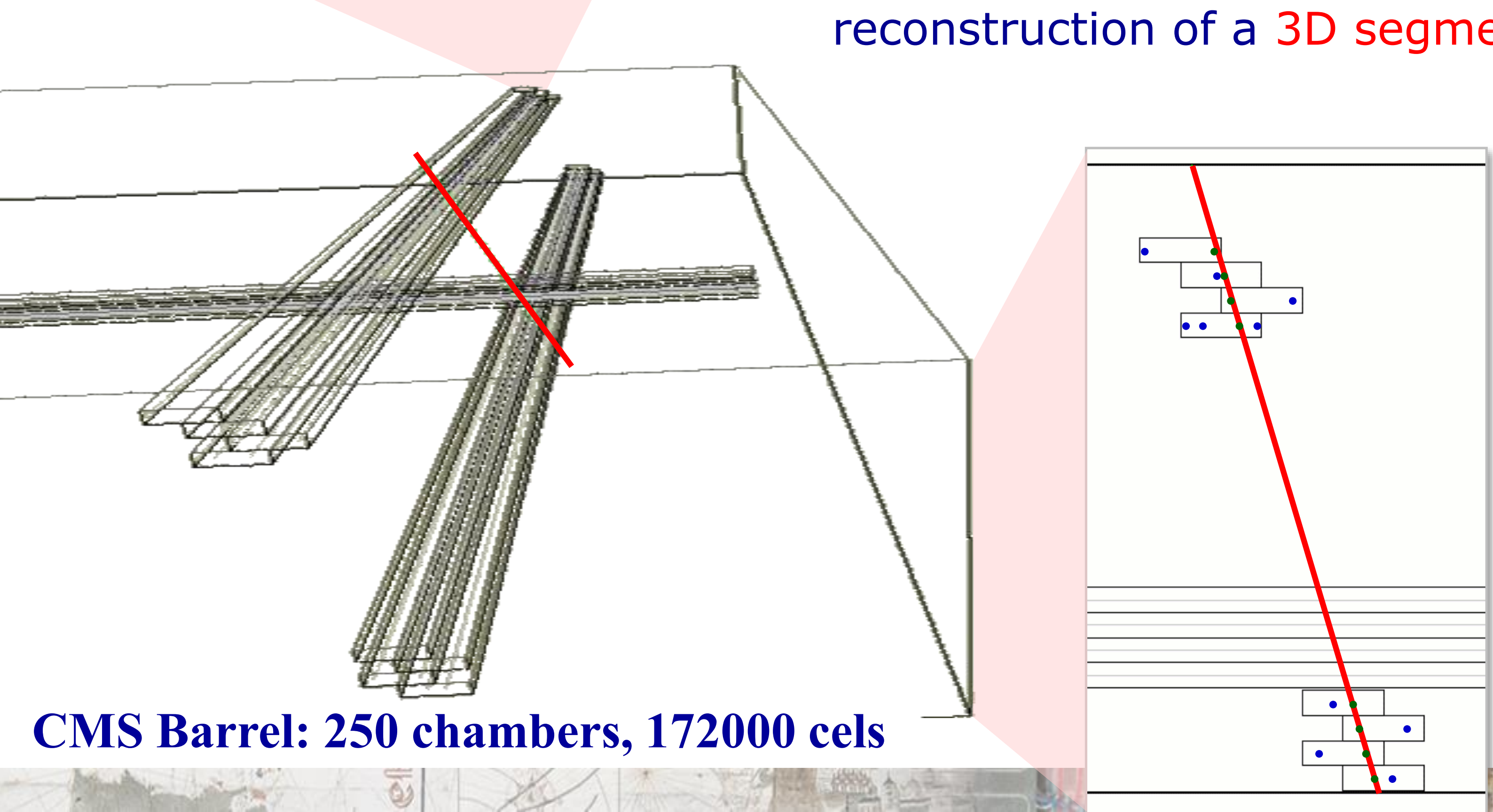


Muon chambers : p.es. Drift Tubes



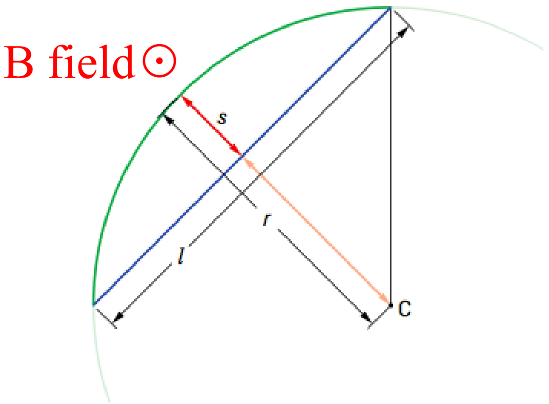
Overlapping layers of independent cells

- Measurement of the position from the drift time of the charges produced by ionization
- Resolution ~ 200 mm
- Groups of orthogonal layers allow the reconstruction of a 3D segment



CMS Barrel: 250 chambers, 172000 cels

Compact MUON Solenoid

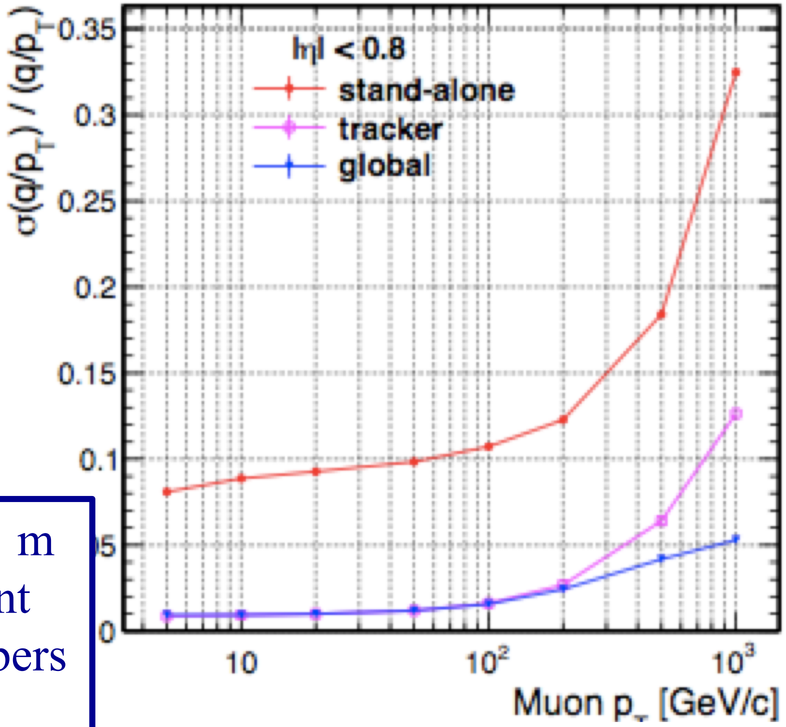


$$r = \frac{\ell^2}{8s} + \frac{s}{2} \;\underset{highP_t}{»}\; \frac{\ell^2}{8s}$$

$$P_t \,\mu\, 0.3 \times B \times r$$

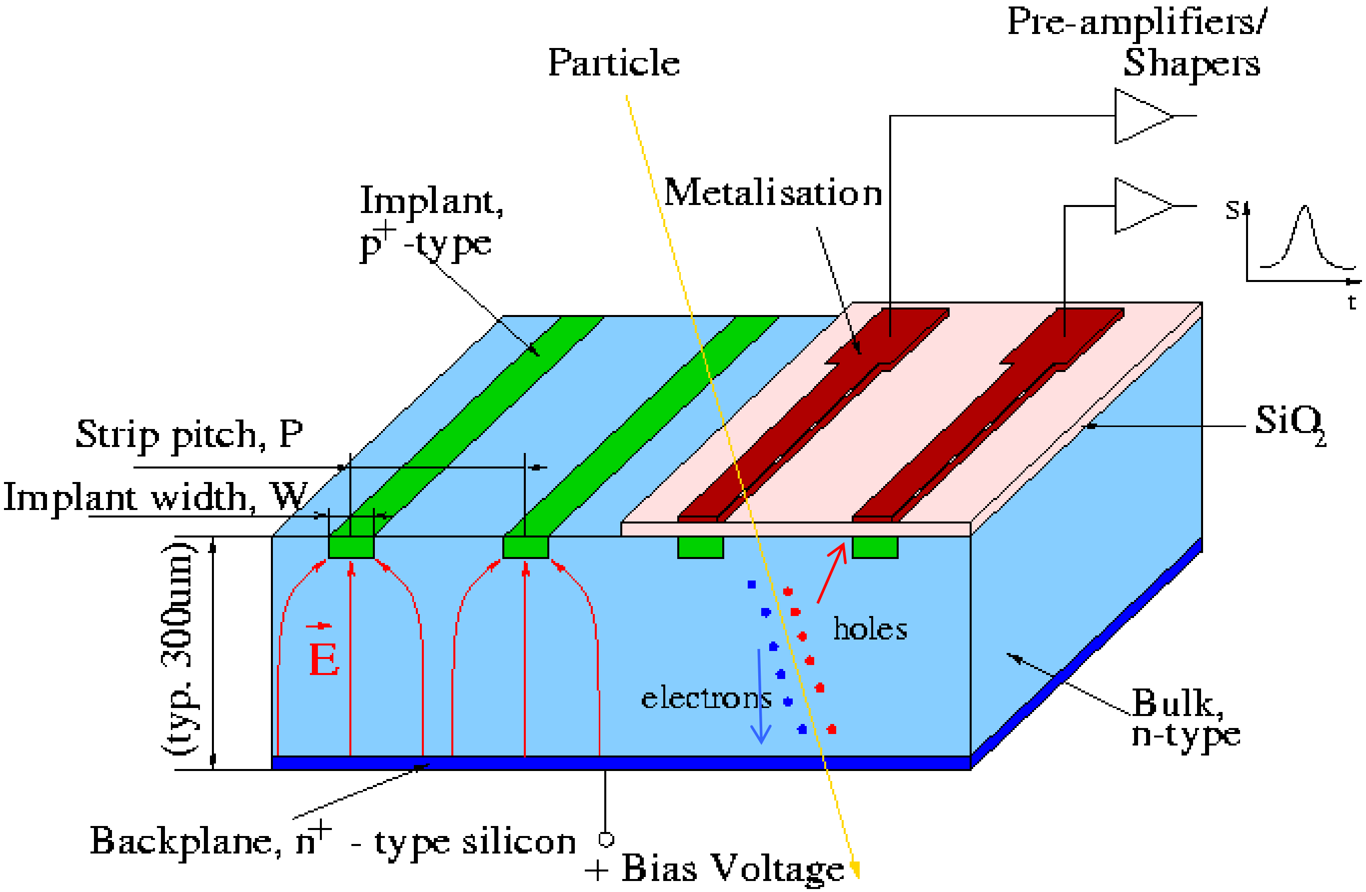
$$\frac{\Delta P_t}{P_t} \propto \frac{\Delta s}{\boxed{\ell^2}} + ...$$

ℓ (path length in uniform B) is ~1.1 m for the Si-tracker, but more important is the first layer of the Muon chambers (~3m)



Silicon detector

Instead of a gas, a semiconductor material is used: silicon, properly doped and processed.



Vertex detectors

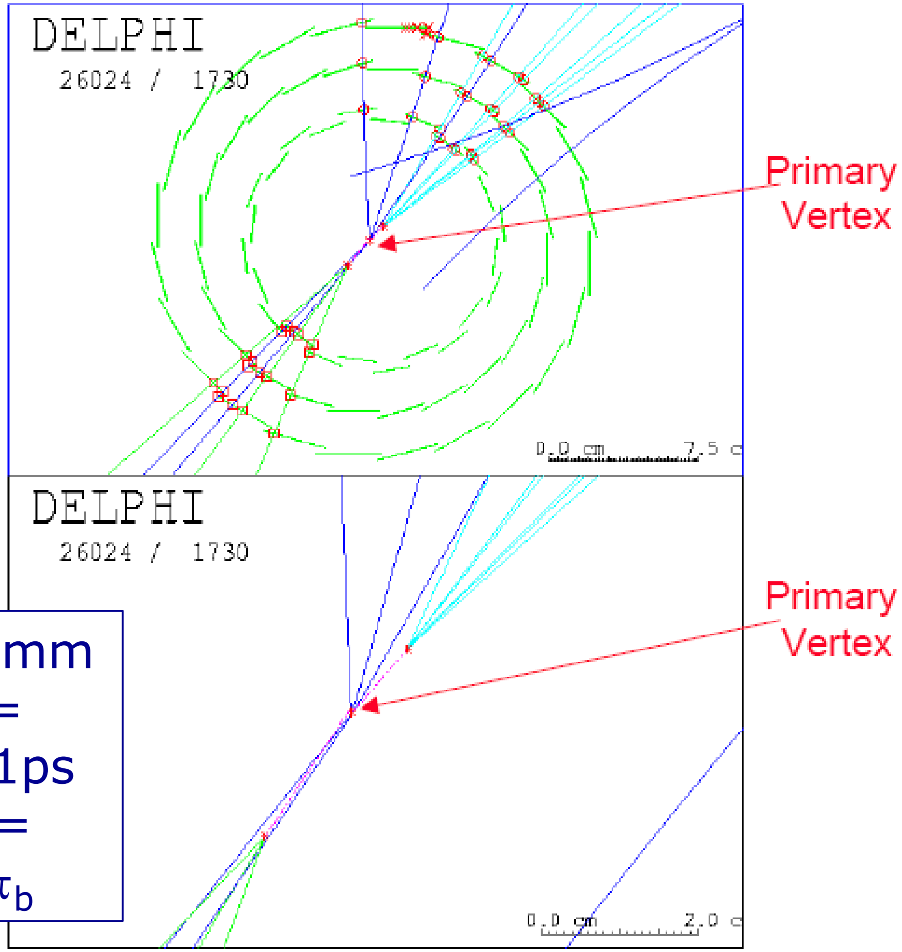
The silicon detectors allow position measurements with very high precision (~ 10mm)

They are ideal for measuring the vertex interaction and any secondary vertices of particles with long average life-time.

They are very expensive (~ 8 euros / cm2) and are used only in areas near the interaction vertex.

Reconstructed B-mesons in the DELPHI micro vertex detector

$\tau_B \approx 1.6$ ps $\quad l = c\tau\gamma \approx 500\ \mu\text{m}\cdot\gamma$



~3 mm
=
~1ps
=
τ_b

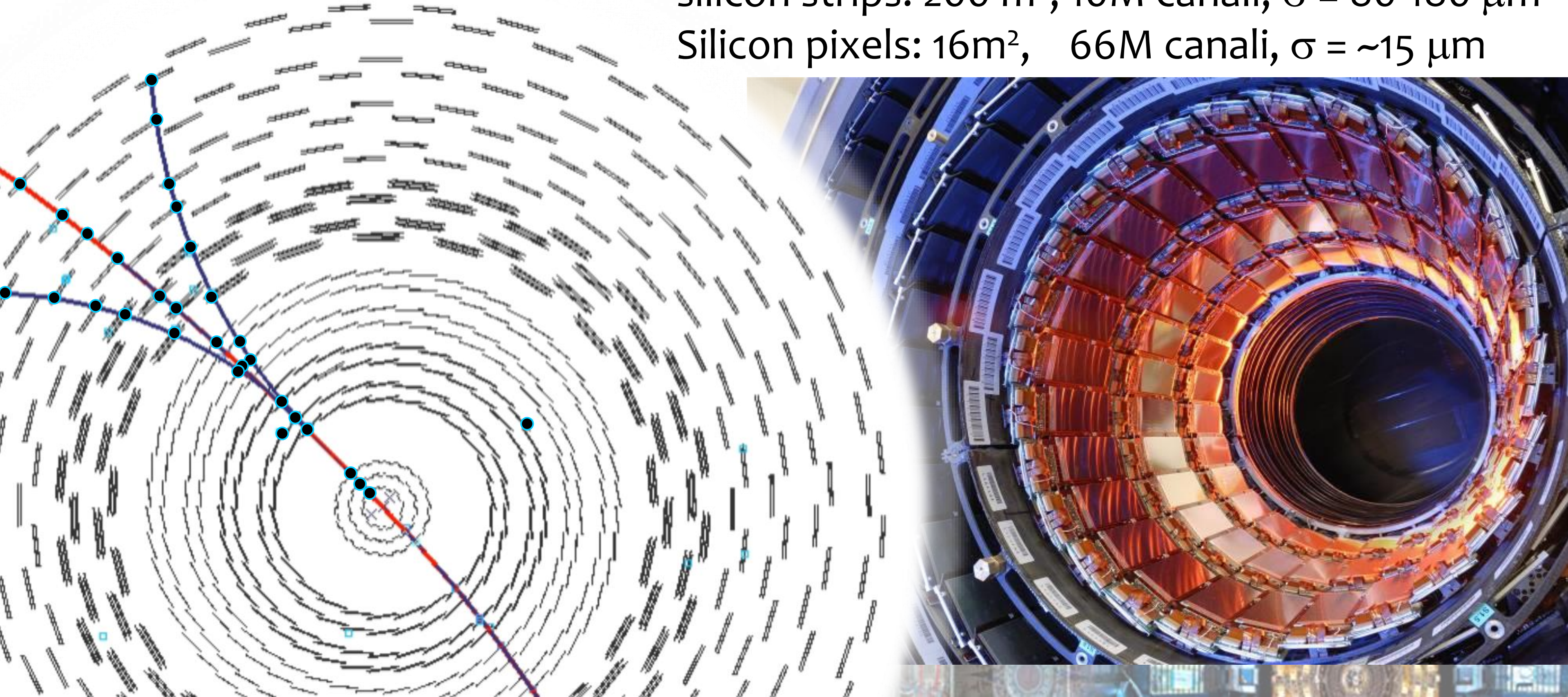
The Tracker: measurement of the trajectory

- Reconstruction of the trajectory: from the "points" in successive layers
- Momentum measurement: from the curvature in the magnetic field

CMS Tracker:

silicon strips: 200 m^2, 10M canali, σ = 80-180 μm

Silicon pixels: 16m^2, 66M canali, σ = ~15 μm



The calorimeter: measurement of the energy

Energy measurement via total absorption
(destructive measure)

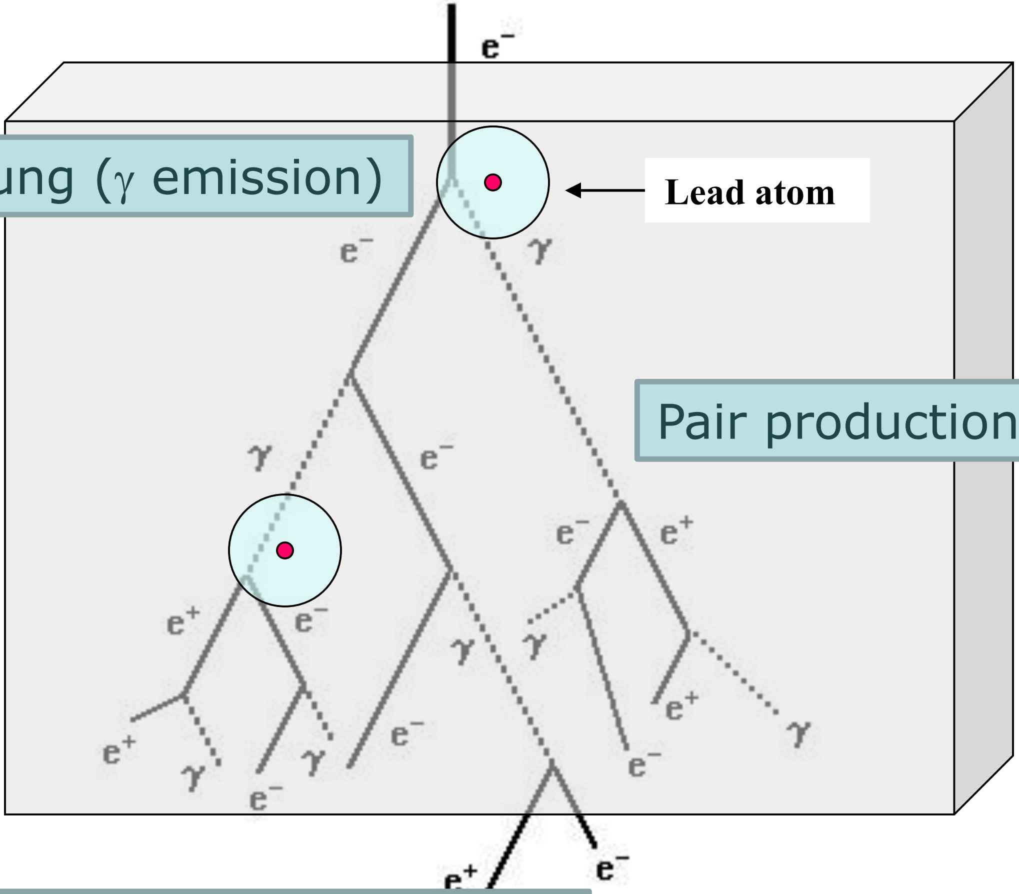
The response of the detector must be **proportional to E** per
- Charged particles: electrons and hadrons
- Neutral particles: photons and neutrons

Measuring principle:
- Electromagnetic shower (electromagnetic particle interactions with the material)
- Hadron shower (dominated by strong particle interactions with the material)

The signal we read is the conversion of ionization or excitation – caused by the shower particles - of the detector material: current and voltage are measured.

The number of particles produced is proportional to the incident energy

Elettromagnetic shower



Bremsstrahlung (γ emission)

Pair production (electron-positron

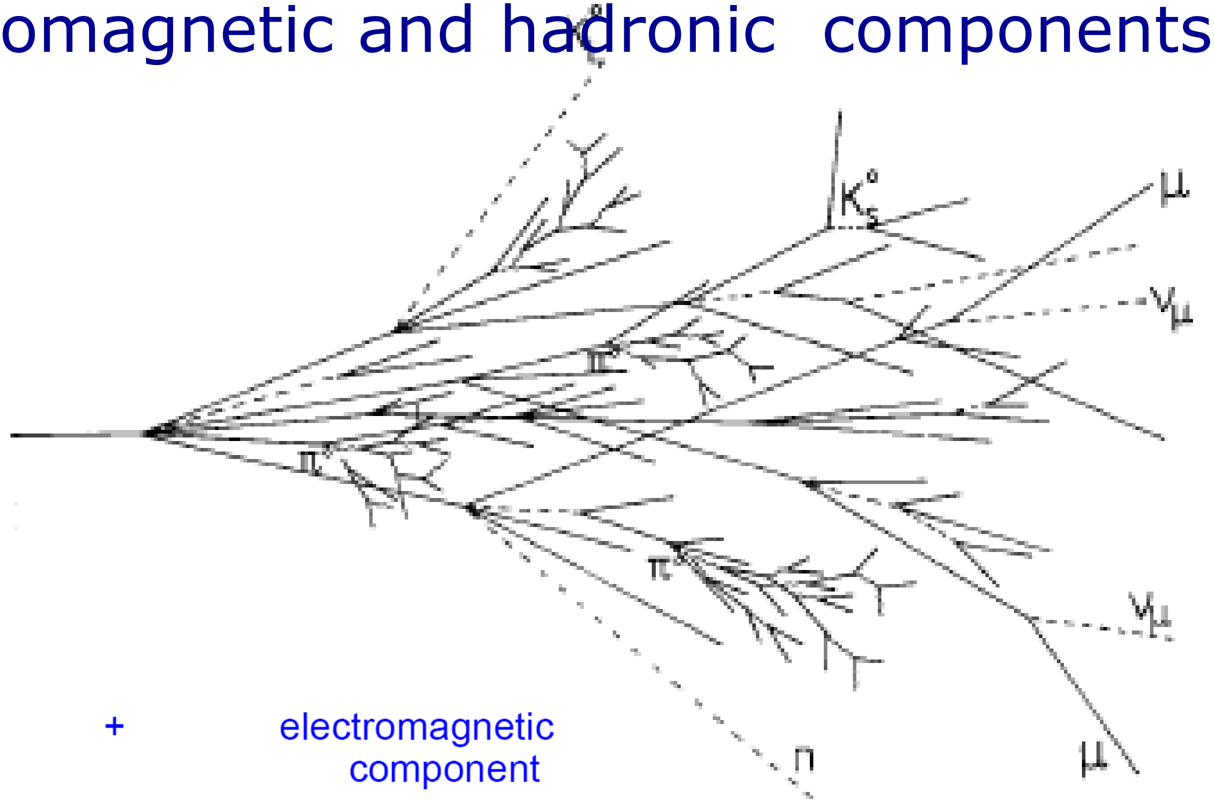
etc.

Until all particle energy is spent ;-)

Radiation length: X_0 = Length, where 1/e particle energy is emitted via Bremsstrahlung

Hadronic shower

Particle cascade with
electromagnetic and hadronic components



(Grupen)

Hadronic + electromagnetic component

↓ ↓

charged pions, protons, kaons ….
Breaking up of nuclei
(binding energy),
neutrons, neutrinos, soft γ's
muons …. → invisible energy

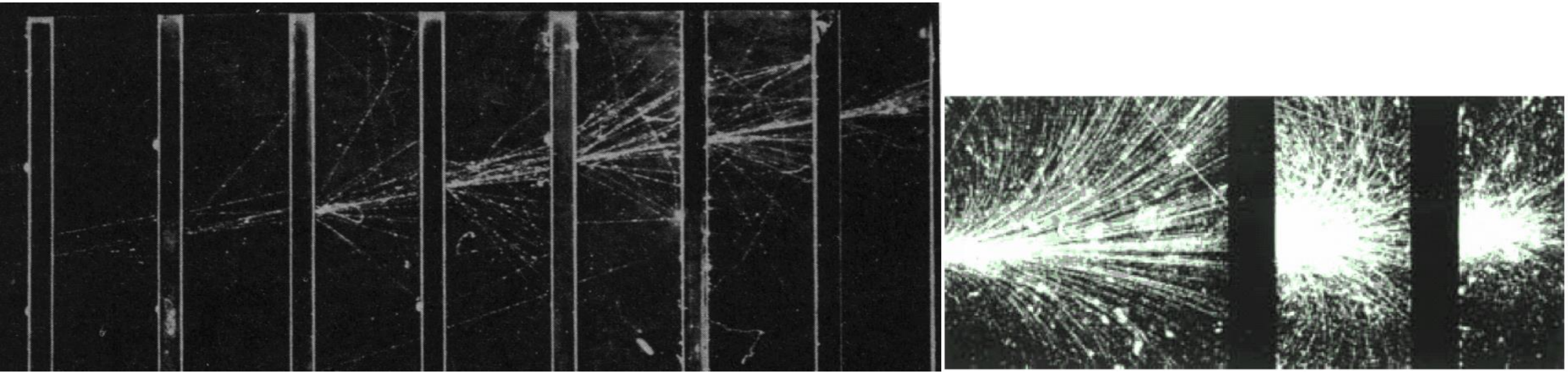
neutral pions → 2γ →
electromagnetic cascade

$$n(\pi^0) \approx \ln E(GeV) - 4.6$$

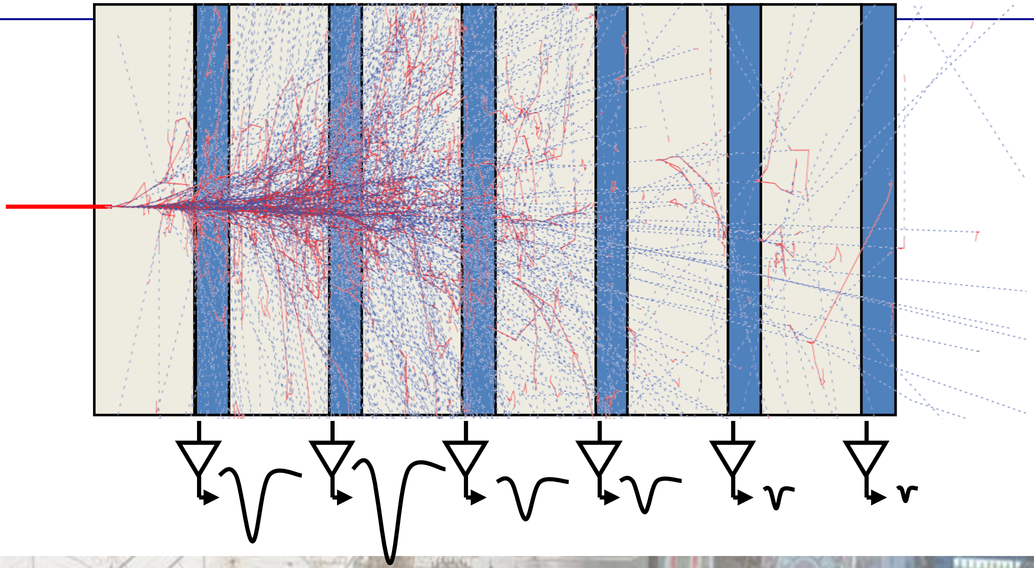
example 100 GeV: $n(\pi^0) \approx 18$

Energy measurement is less precise than electromagnetic calorimeters, due to large fluctuations in hadronic showers

Showers: energy is proportional to the number of particles produced

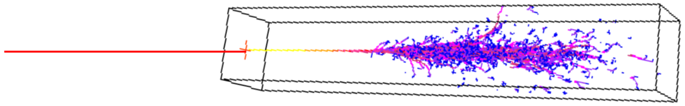


They can be composed of **passive absorbers** (which make the particles showering) alternated with **sensitive elements** (which allow the "particle" to be "read")



... Calorimeters can also be composed of a homogeneous material that acts simultaneously as an absorber and a sensitive material

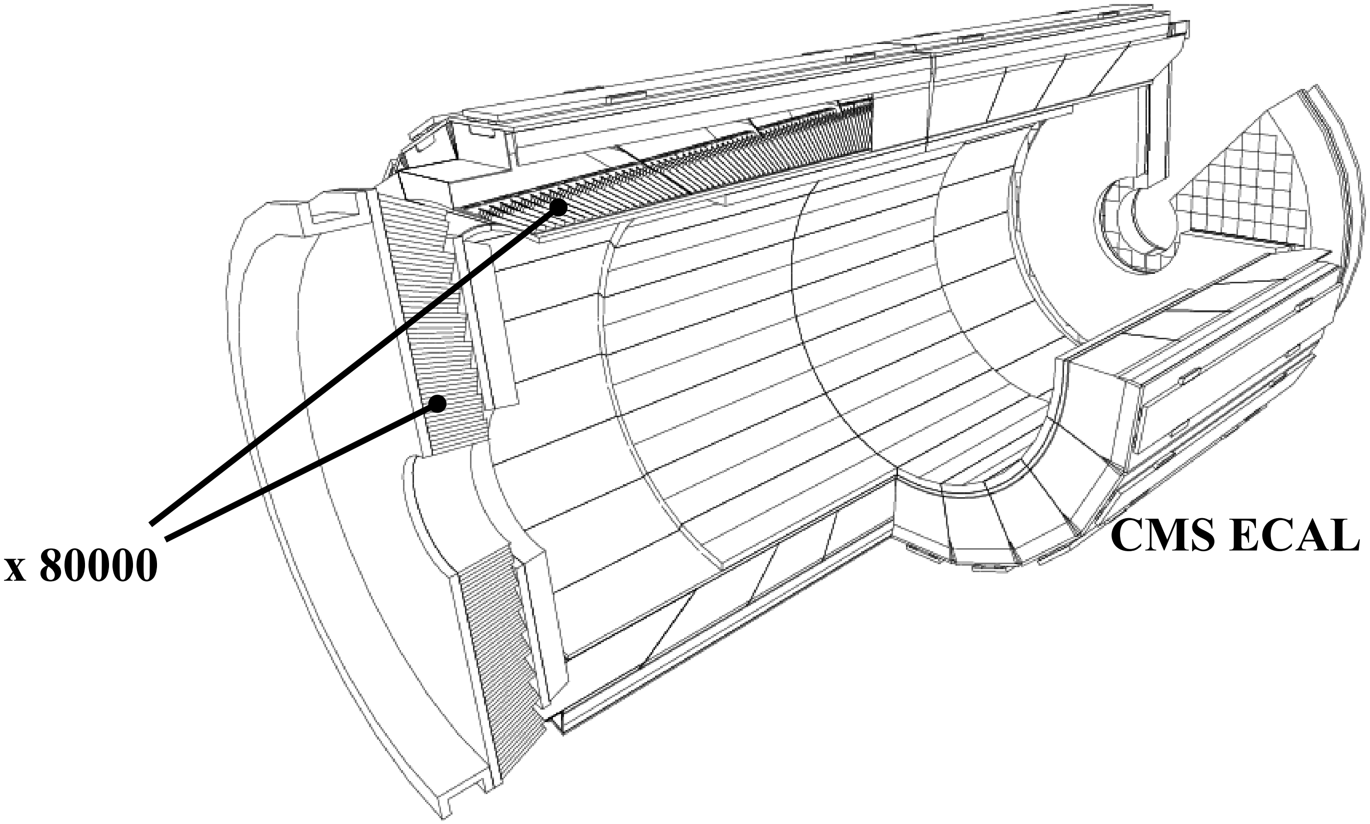
The material must be special: high "A" to make the particles shower, but transparent, to allow the light generated by these to reach the photocathode.



Elettromagnetic calorimeter of CMS

80000 crystals of $PbWO_4$

They point towards the vertex of the proton-proton interaction



The different particles

Particles interact differently with matter:

All charged particles are "traceable", ionizing a gas or silicon.

The electrons shower in an "electromagnetic" way (they feel the electromagnetic and weak force but not the strong force)

The photons are neutral: they are not traceable and they shower only electromagnetically (they feel only the electromagnetic force)

Muons: they interact very little with matter (they feel electromagnetic and weak force): they can pass through thick layers of material - they do not shower, but ionize a gas.

Hadrons shower hadronically: they feel the strong force.

Neutrinos "do not" interact (only the feel the weak force) and exit the detector

Energy loss for Bremmstrahlung (photon emission)

- la sezione d'urto è proporzionale a $1/m^2$

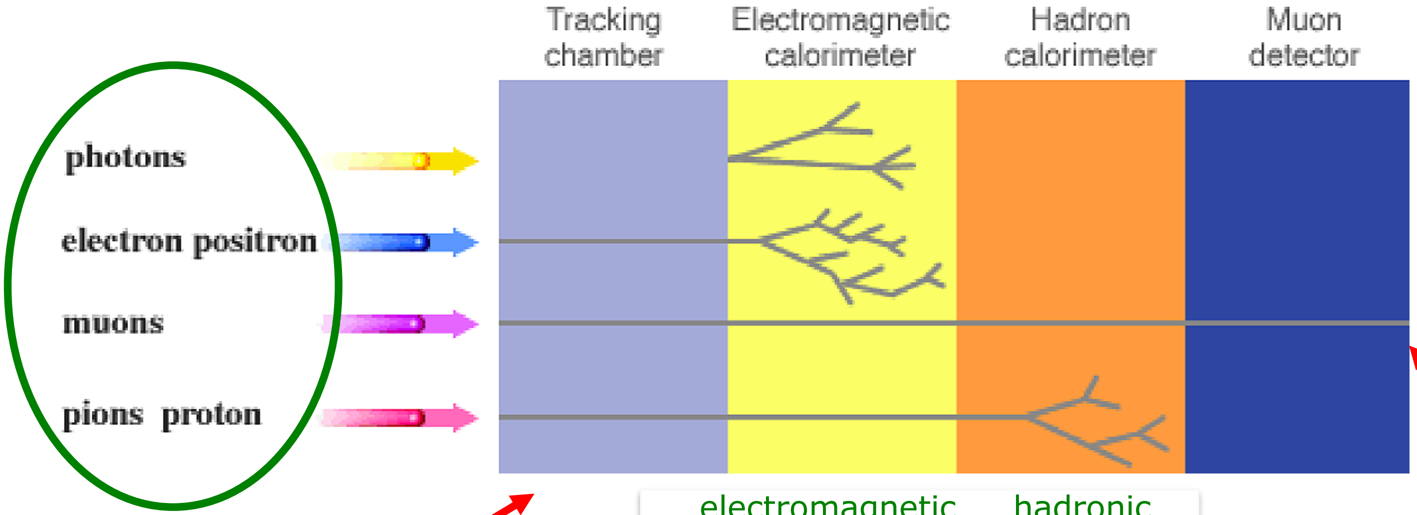
$$\sigma \propto \left(\frac{e^2}{mc^2} \right)^2$$

  - a energie inferiori a qualche centinaio di GeV, solo gli elettroni perdono sensibilmente energie per radiazione
  - $m_e/m_\mu \approx 200$
  - fattore 40.000 in probabilità di radiazione

- L'effetto principale è dovuto allo scattering con il campo elettrico dei nuclei

Il passaggio delle particelle

measurement by missing energy



undetected neutrinos...

electromagnetic hadronic shower

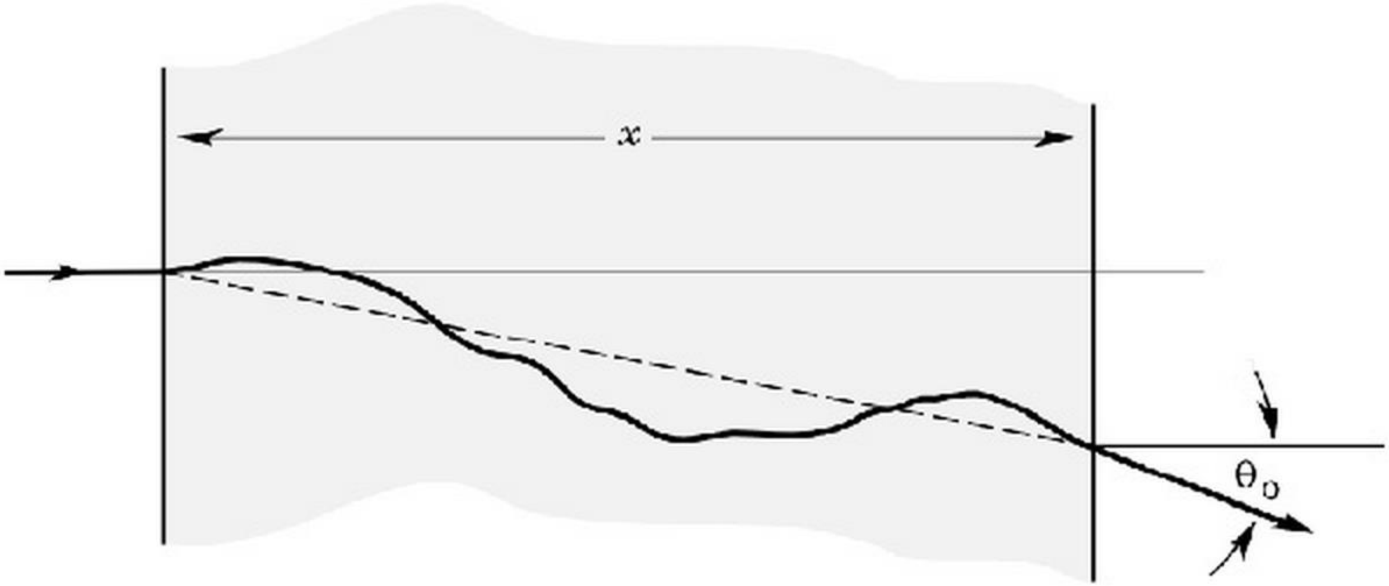
momentum measurement via curvature in the magnetic field

energy measurement via creation and total shower absorption

muon detection that have crossed the full detector.
Long lever arm: momentum measurement

Multiple scattering

As we move away from the vertex of interaction, we use detectors with less intrinsic precision - and less expensive! - because the particles interact with the material of the detectors they cross, and their position is thus known with an "error”.

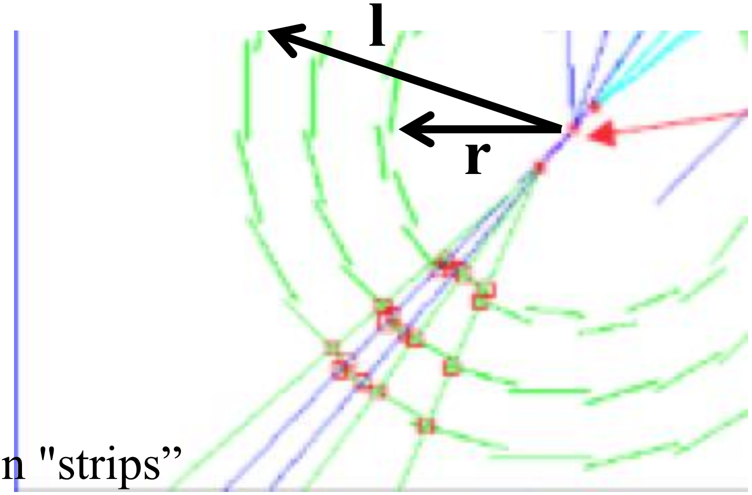


The needed precision

It is necessary to estimate well the precision you need from each detector given the measurement you want to perform and the surrounding conditions.

For example: the vertex detector are built to measure particles that decay in 1.5 ps, i.e. that decay after 3mm from the primary vertex; "intrinsic" precision of ~ 10μm is required. The detector must be positioned as close as possible to the interaction point (small r=radius), and have at least 3 layers to determine the track ...

$$\sigma_{res}^2 = \sigma_{\text{int}}^2 \times \sqrt{1 + 2\frac{r}{l} + 2\frac{r^2}{l^2}} + \sigma_{MS}^2$$



σ_{int} is given by the distance between the active silicon "strips"

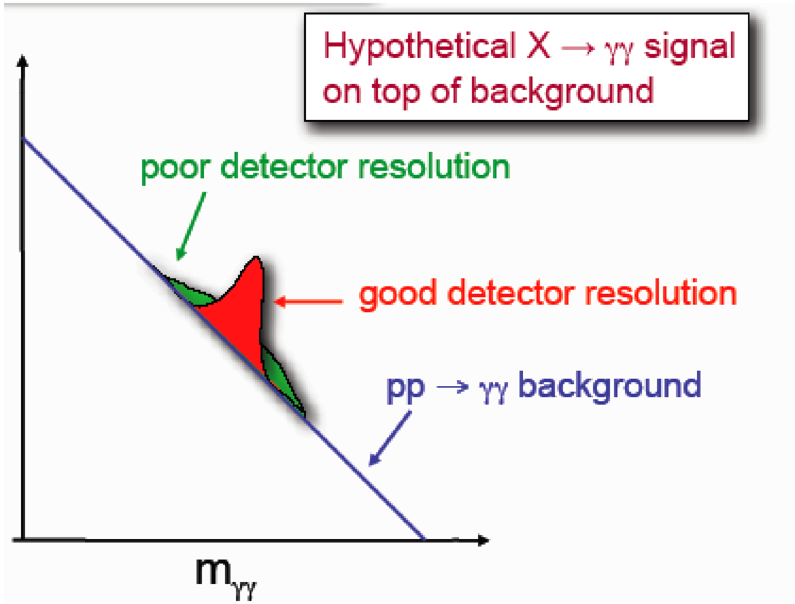
σ_{MS} (multiple-scattering) ~ $a^2 + b^2/p^2 \sin\theta^{3/2}$

The needed precision

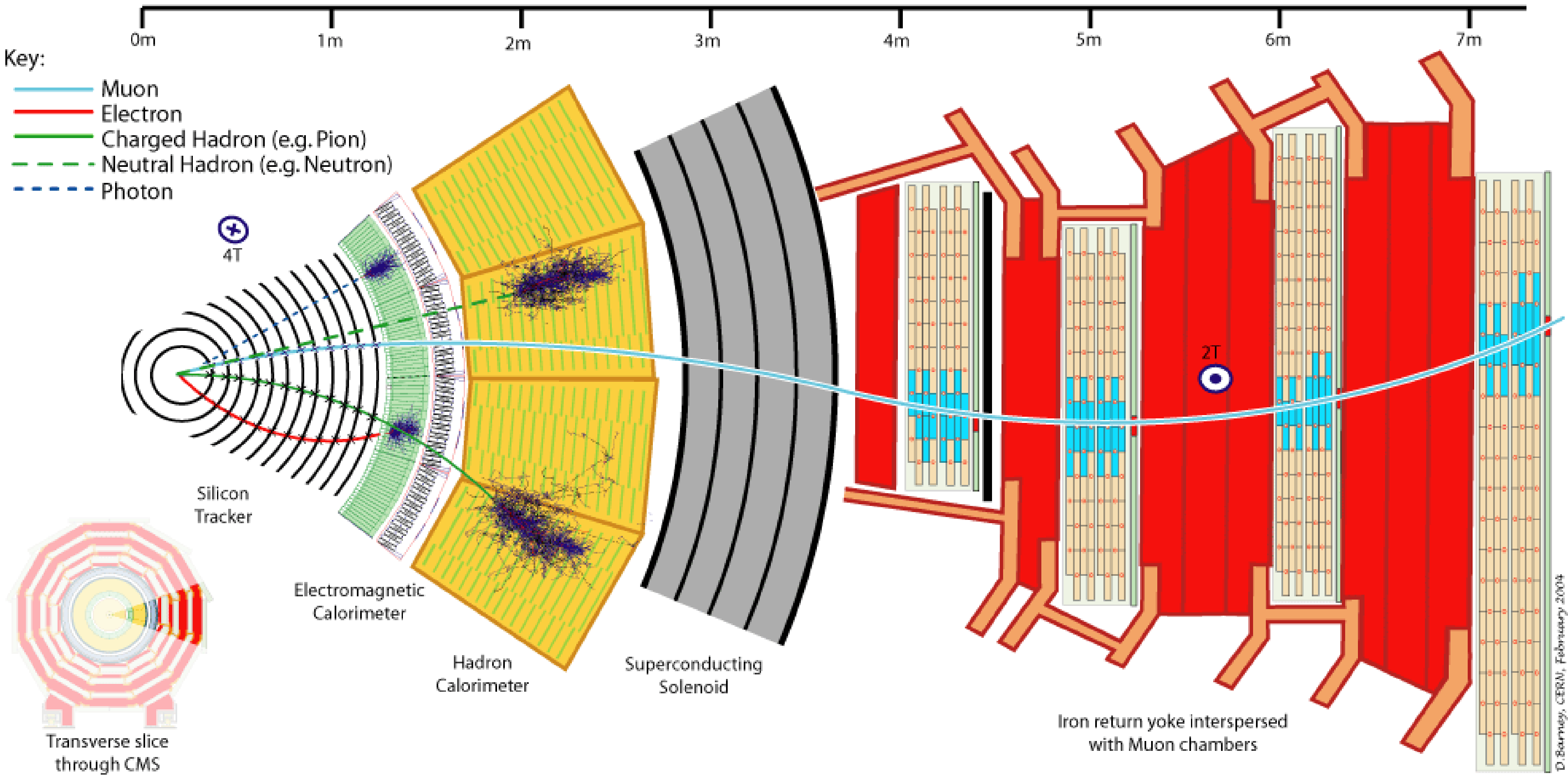
If we want to reveal H → γγ and have a “narrow” peak in mass, our calorimeter will have to have an excellent, and constant over time, resolution in energy

$$m^2_{©©} = 2E_1E_2(1-\cos\langle\ )$$

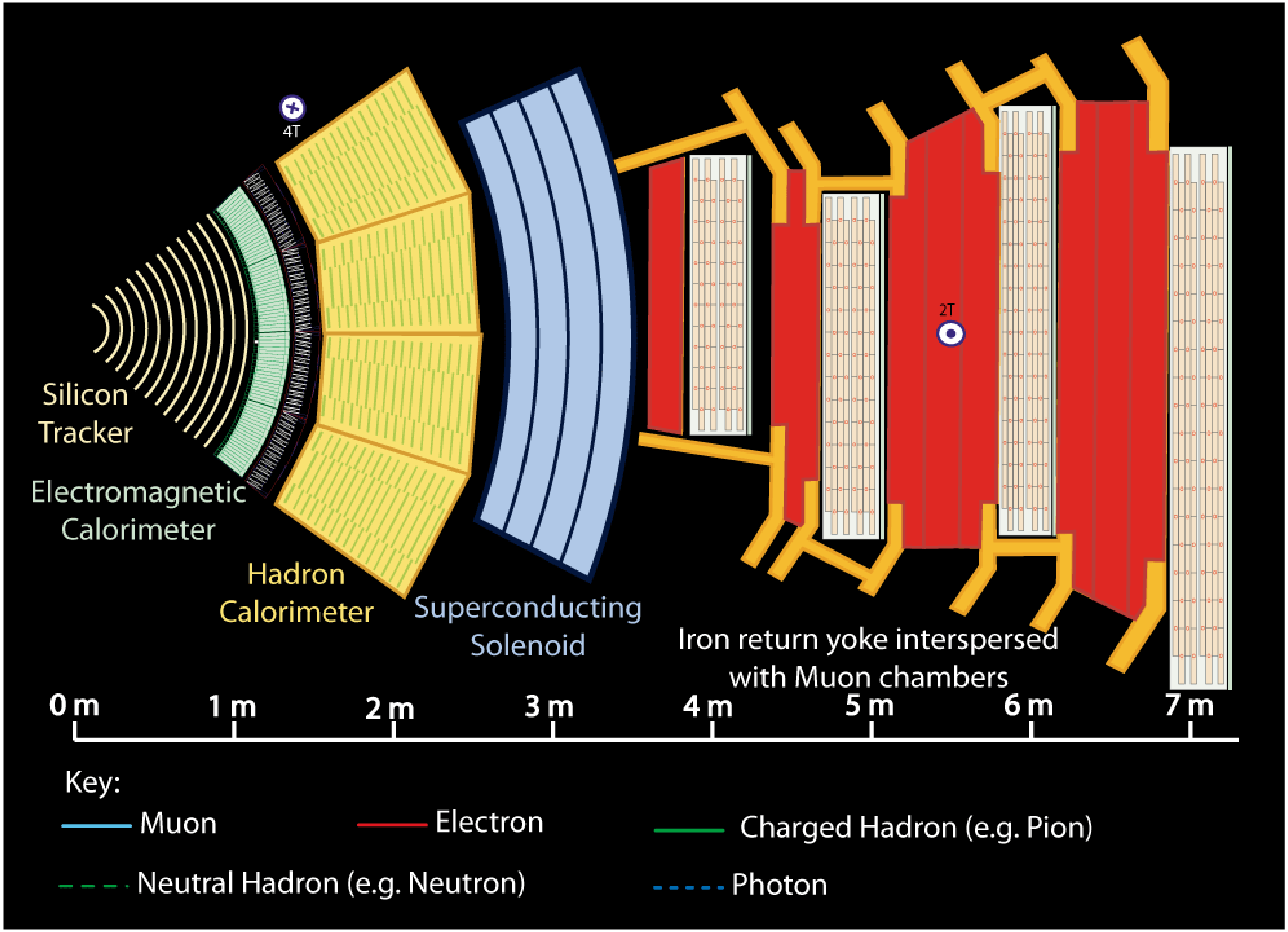
Uncertainty on m ←
Uncertainty over photon energy
and on the direction of photons



CMS at LHC

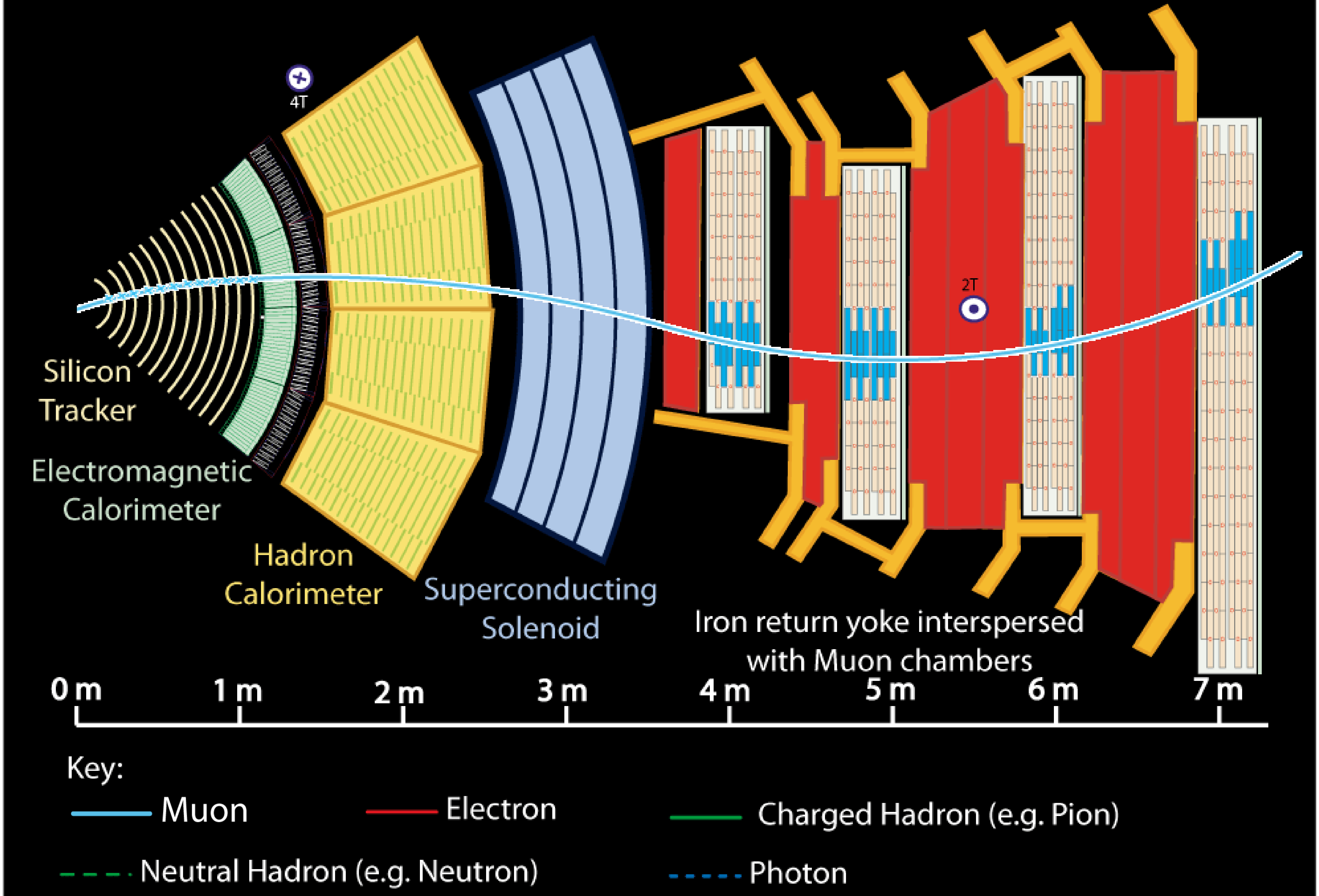


D.Barney, CERN, February 2004



Key:

- Muon
- Electron
- Charged Hadron (e.g. Pion)
- Neutral Hadron (e.g. Neutron)
- Photon



Silicon Tracker

Electromagnetic Calorimeter

Hadron Calorimeter

Superconducting Solenoid

Iron return yoke interspersed with Muon chambers

Key:

- Muon
- Electron
- Charged Hadron (e.g. Pion)
- Neutral Hadron (e.g. Neutron)
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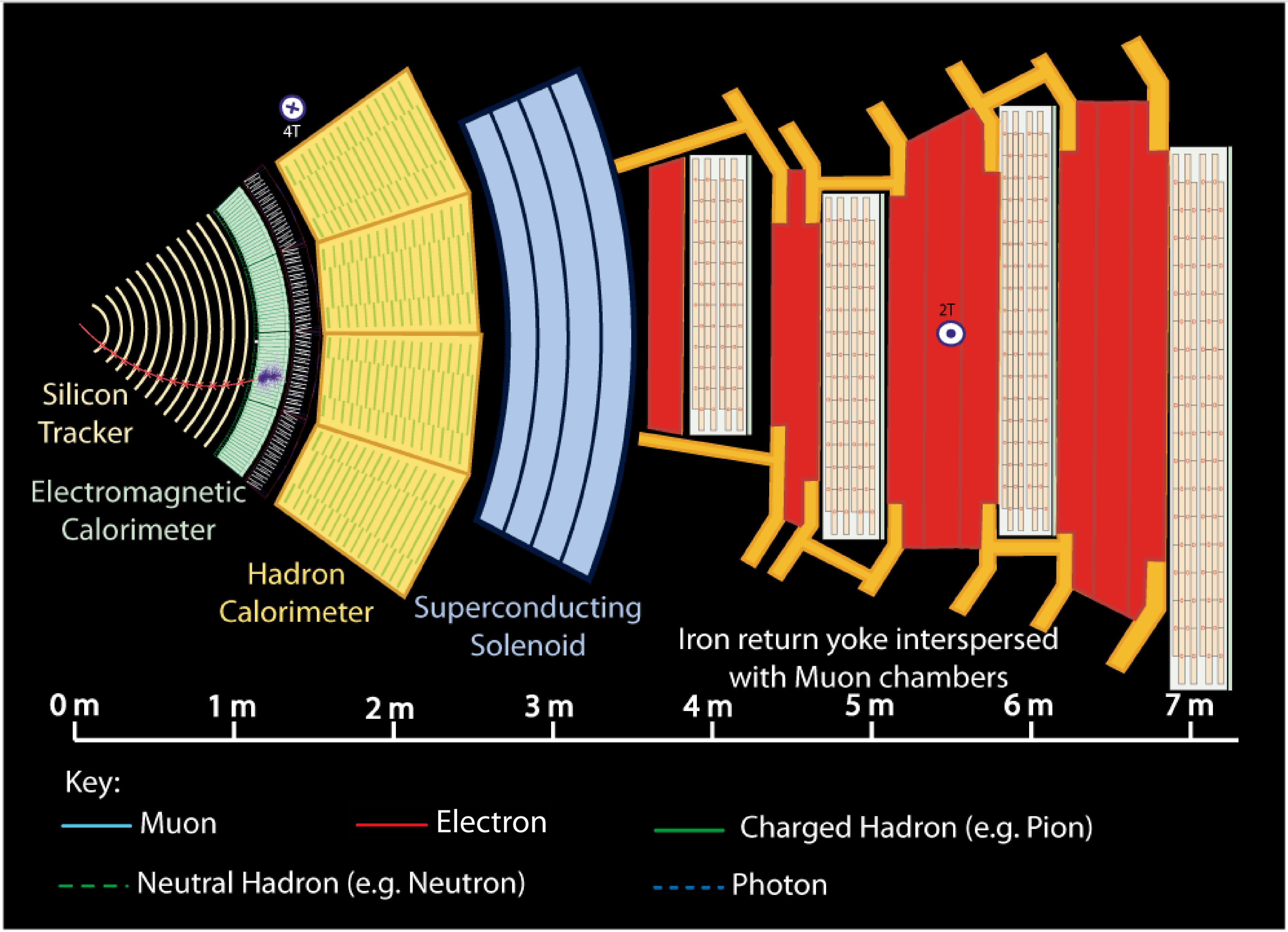
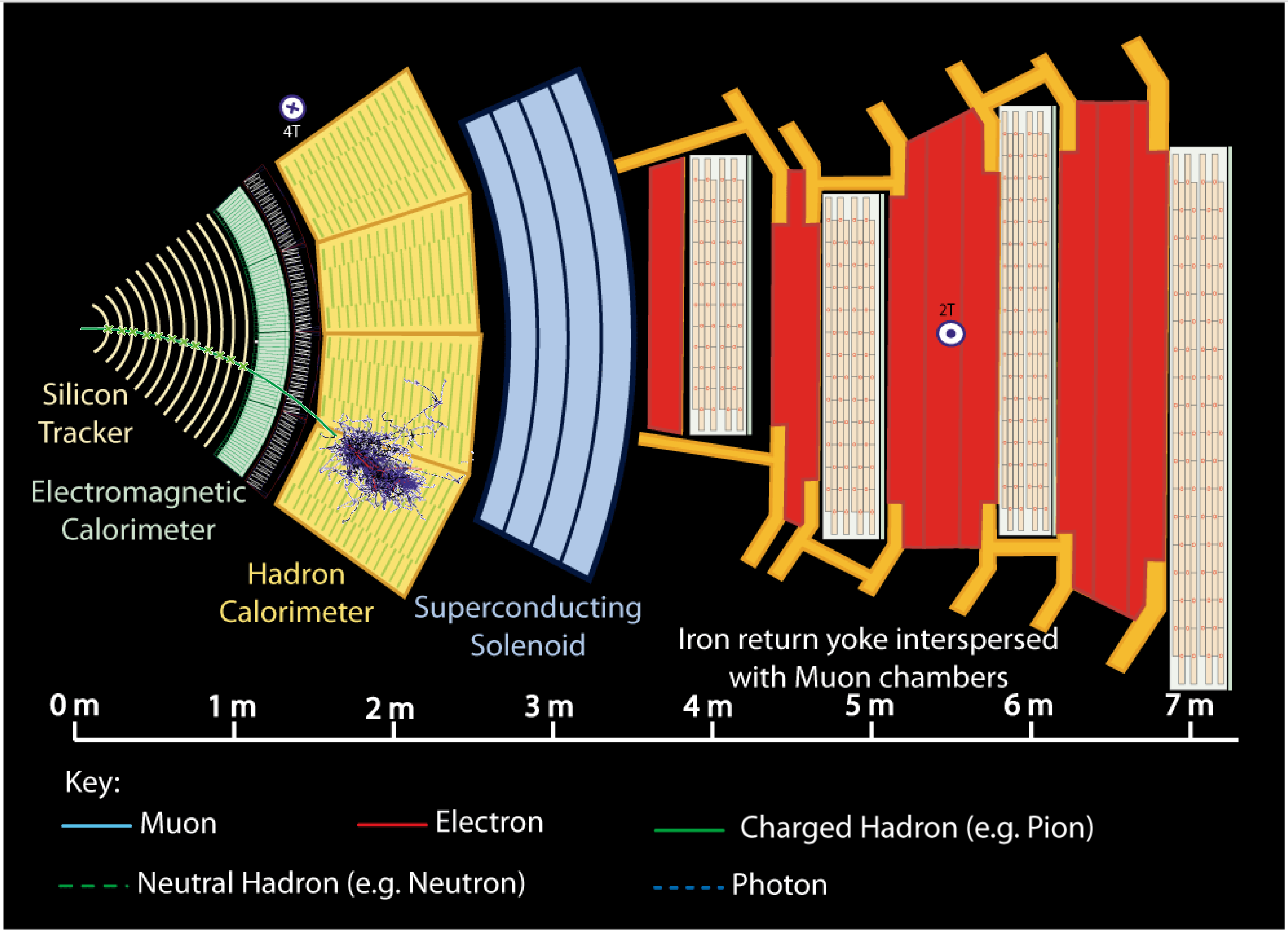


4T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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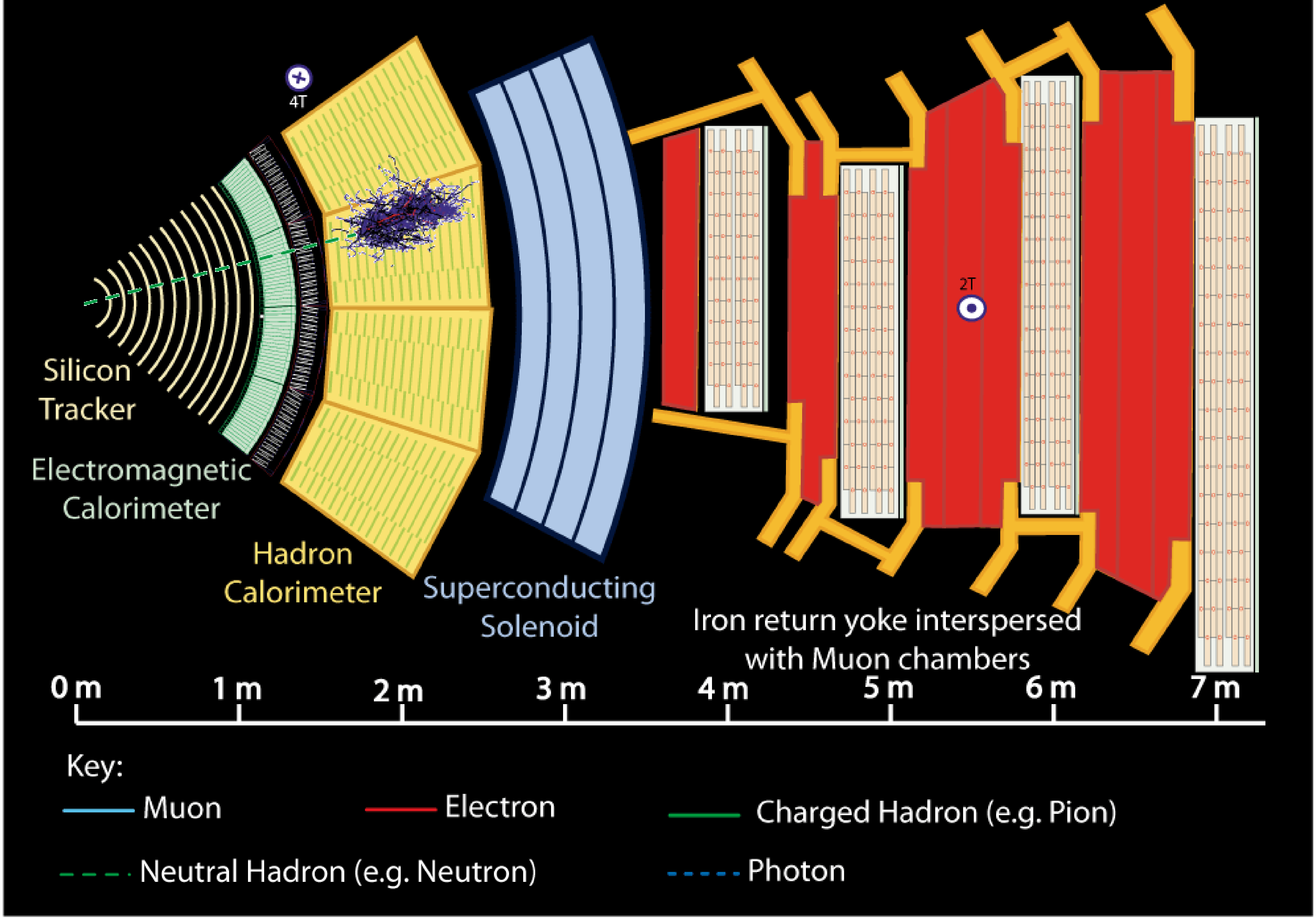
4T
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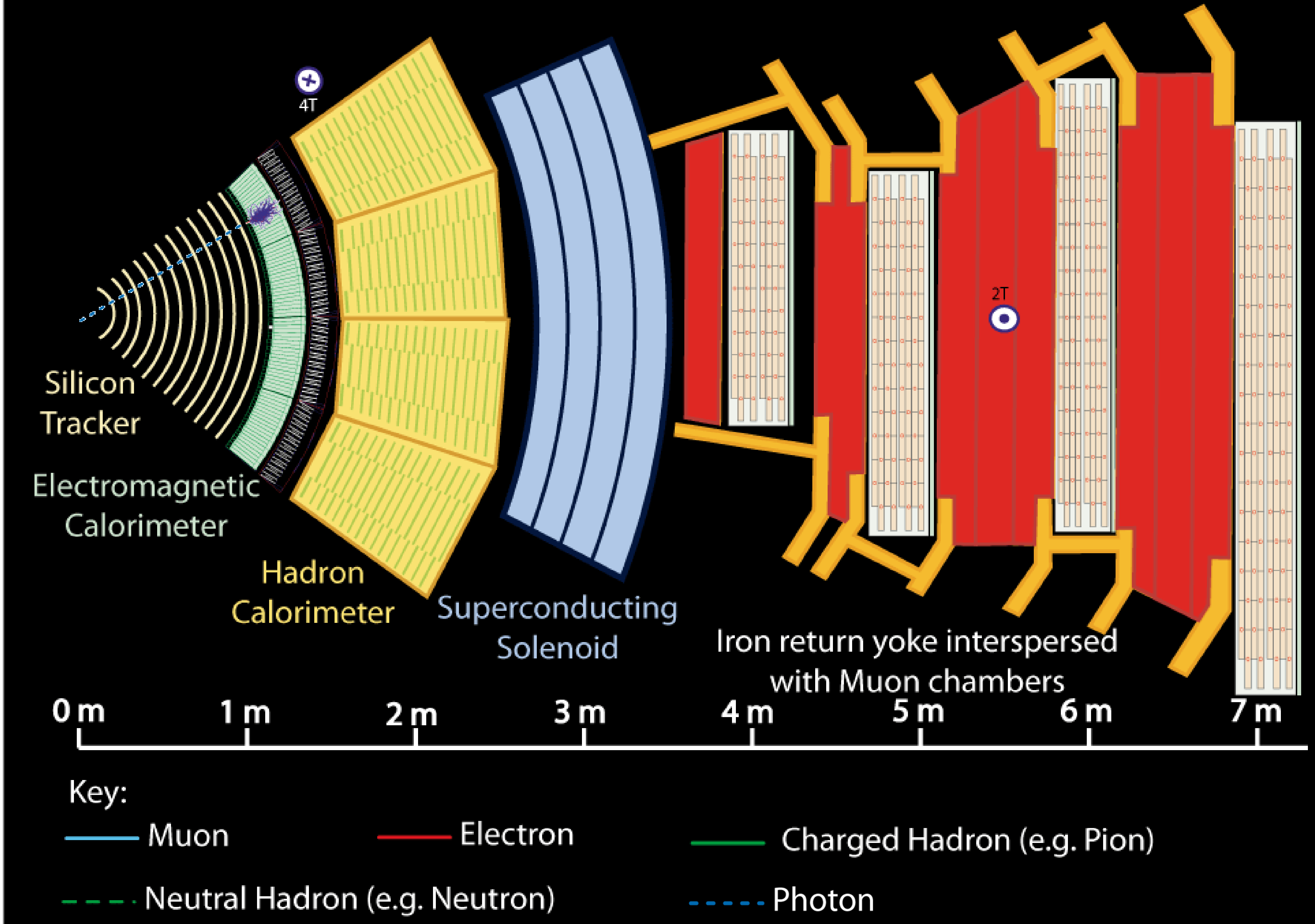
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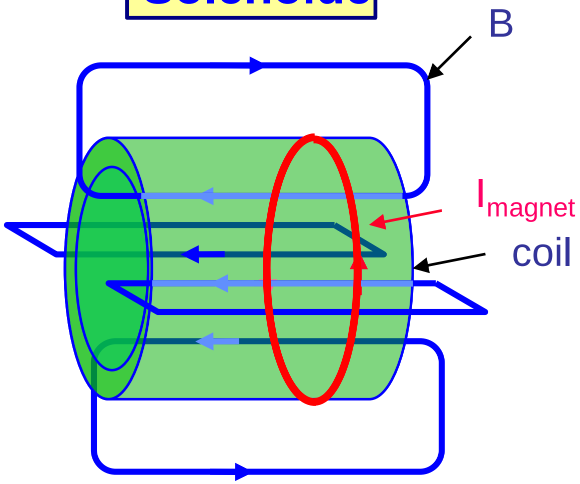
Neutral Hadron (e.g. Neutron)
Photon

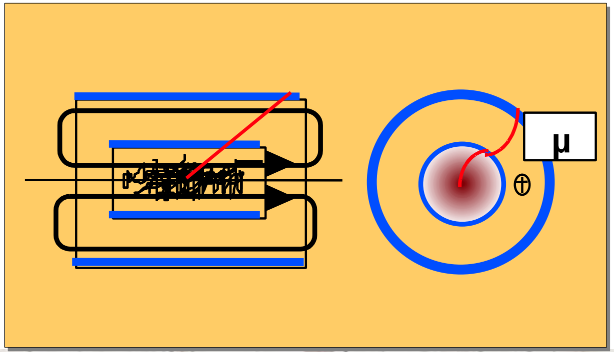
The magnets of ATLAS and CMS

Solenoide

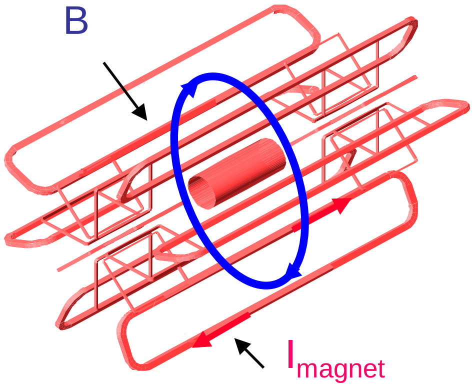


+ strong and homogeneous field in solenoid
- massive iron return yoke necessary
- limited in size (cost)
- solenoid thickness (radiation length)

CMS, ALICE, LEP Detectors

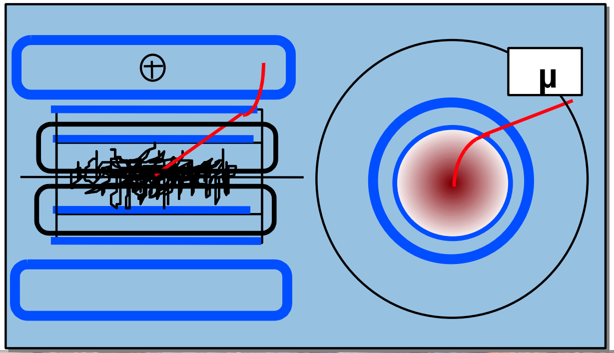


(air-core) Toroide

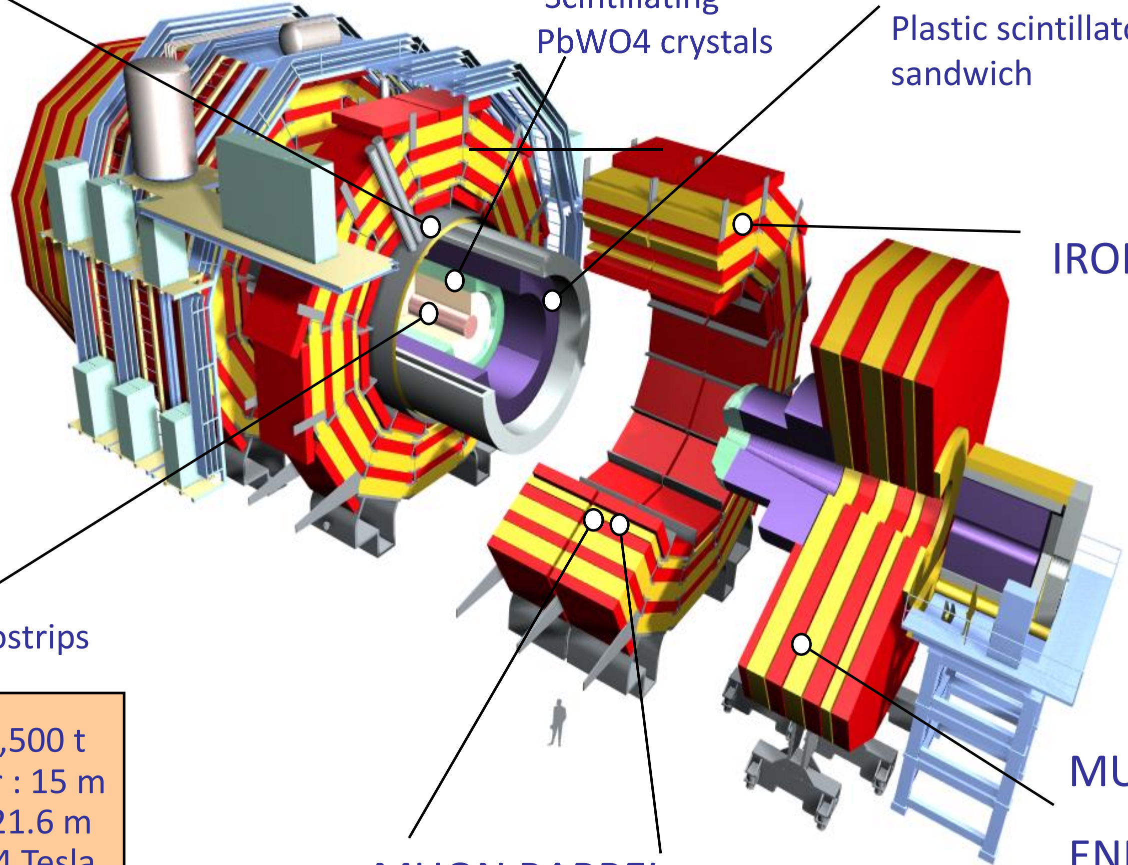


+ large air core, no iron, low material budget
- additional solenoid in the inner parts necessary
-- inhomogeneous field
- complex structure

ATLAS



Exploded View of CMS



SUPERCONDUCTING COIL

CALORIMETERS

ECAL

Scintillating PbWO4 crystals

HCAL

Plastic scintillator/brass sandwich

IRON YOKE

TRACKER

Silicon Microstrips

Pixels

Total weight : 12,500 t

Overall diameter : 15 m

Overall length : 21.6 m

Magnetic field : 4 Tesla

MUON BARREL

Drift Tube Chambers

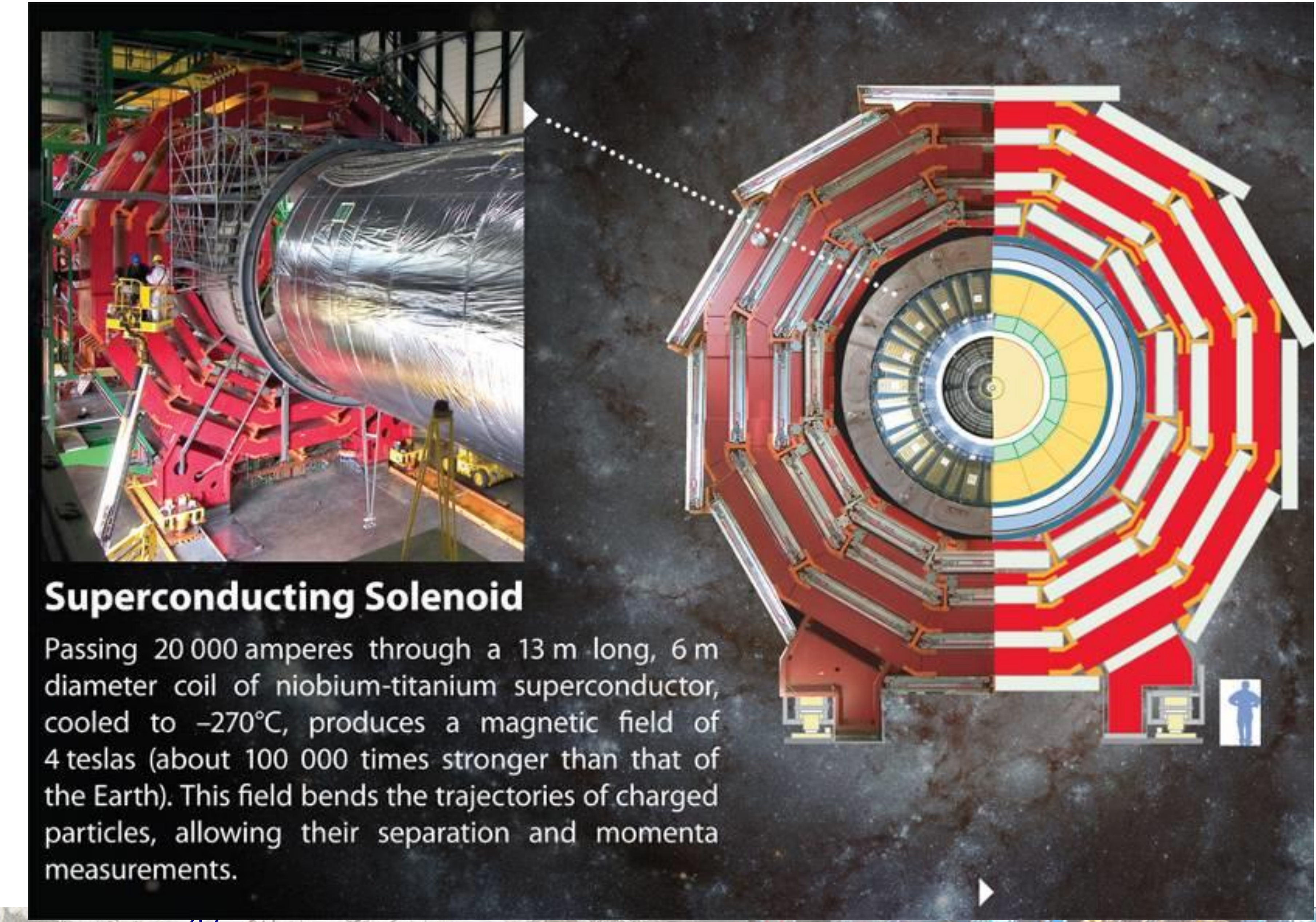
Resistive Plate Chambers

MUON ENDCAPS

Cathode Strip Chambers

Resistive Plate Chambers

The superconductive magnet of CMS

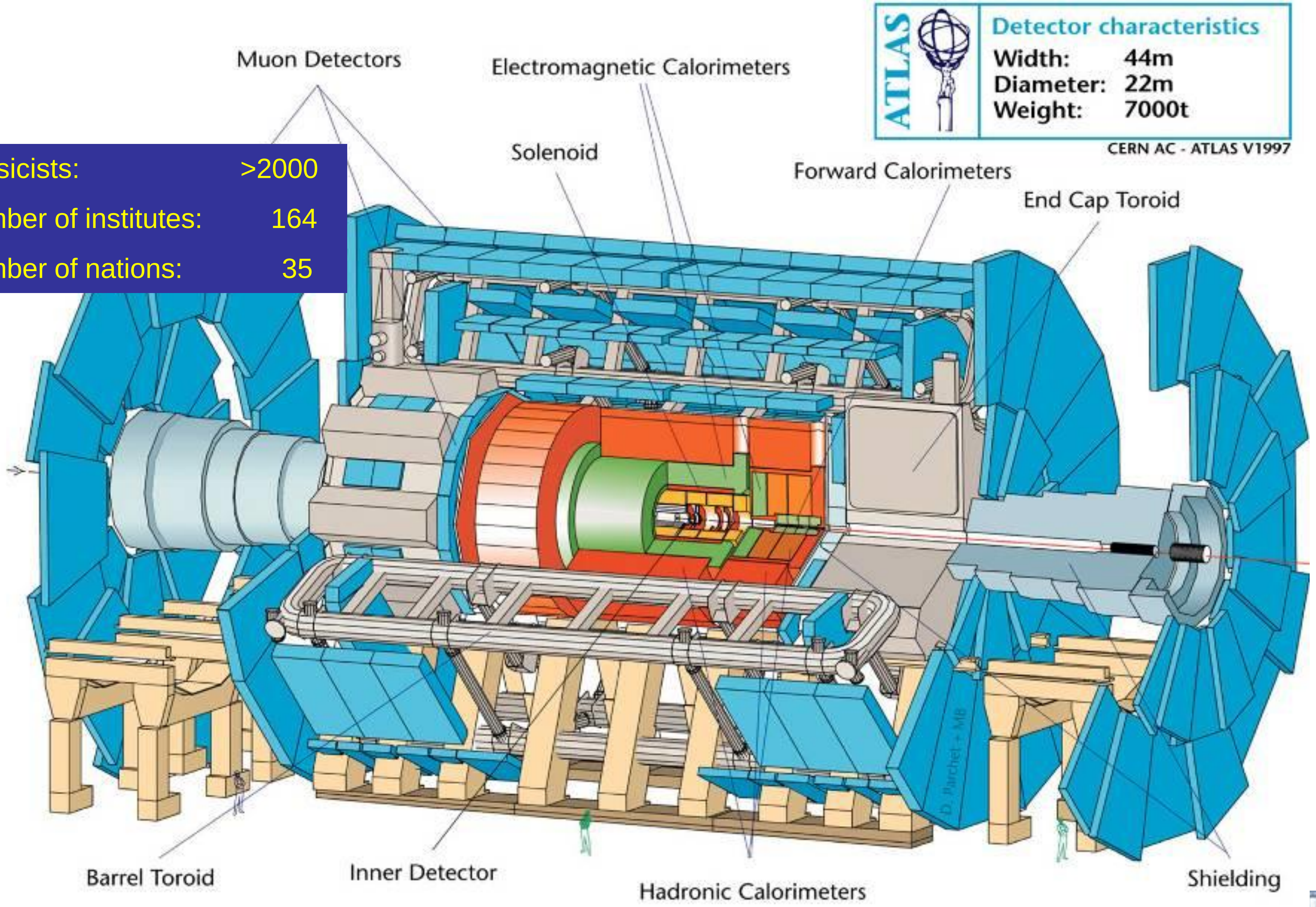


Superconducting Solenoid

Passing 20 000 amperes through a 13 m long, 6 m diameter coil of niobium-titanium superconductor, cooled to –270°C, produces a magnetic field of 4 teslas (about 100 000 times stronger than that of the Earth). This field bends the trajectories of charged particles, allowing their separation and momenta measurements.

ATLAS

Physicists:	>2000
Number of institutes:	164
Number of nations:	35



ATLAS and CMS detectors

Object reconstruction

Each detector gives a "partial" information on the particle.

- the "tracker" detects the charged particles, measures their momentum, charge, and direction.

- The electromagnetic calorimeter: measures the energy of the electron or photon

→ tracker + EM cal = distinction between electron and photon

- The hadronic calorimeter measures the energy of other particles (hadrons).

→ Tracker + HAD cal = distinction between neutral and charged hadron

- The muon detector identifies the particle as a muon: it is the only charged particle that manages to pass through the previous detectors.

→ electrons, photons, muons and hadrons

Neutrinos

The neutrino is not detectable because it interacts very little with matter,
→ manifests itself as lack of energy and moment,
its characteristics can be reconstructed from the kinematics of the event:

We add up all the particles (energies and moments): what we get
it must be the same as the one we started from (proton proton interaction).
If energy or momentum is missing -> a neutrino has been produced
and escaped the detector.

$$\boxed{\begin{aligned}
&E(protone-protone)=\sum Energia(particelle)\\
&Pz(protone-protone)=\sum Pz(particelle)\\
&Px(protone-protone)=\sum Px(particelle)=0\\
&Py(protone-protone)=\sum Py(particelle)=0
\end{aligned}}$$

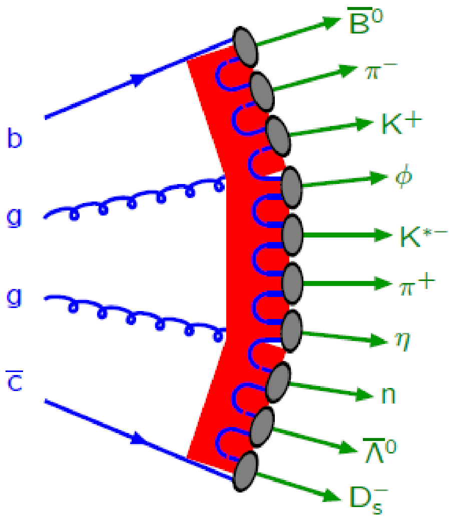
$$\boxed{\begin{aligned}
&E(neutrino)=E(protone-protone)-\sum Energia(particelle)\\
&Px(neutrino)=0-\sum Px(particelle)\\
&Py(neutrino)=0-\sum Py(particelle)
\end{aligned}}$$

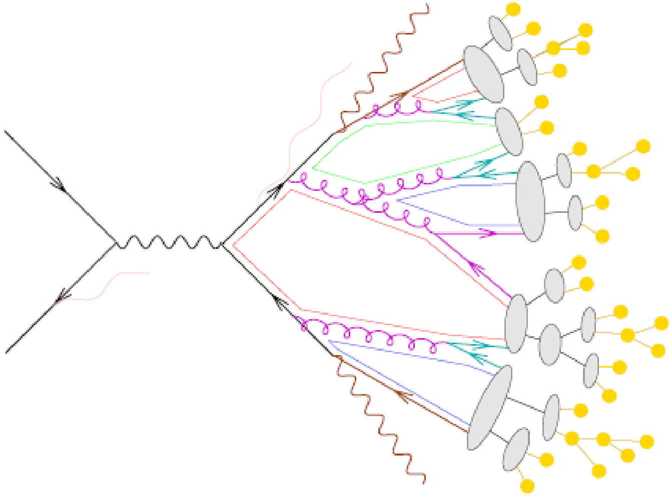
Jet Reconstruction

In reality we observe hadrons, since quarks cannot exist "free", but only aggregated inside the hadrons

(mesons: particles composed of 2 quarks, baryons: particles composed of 3 quarks)

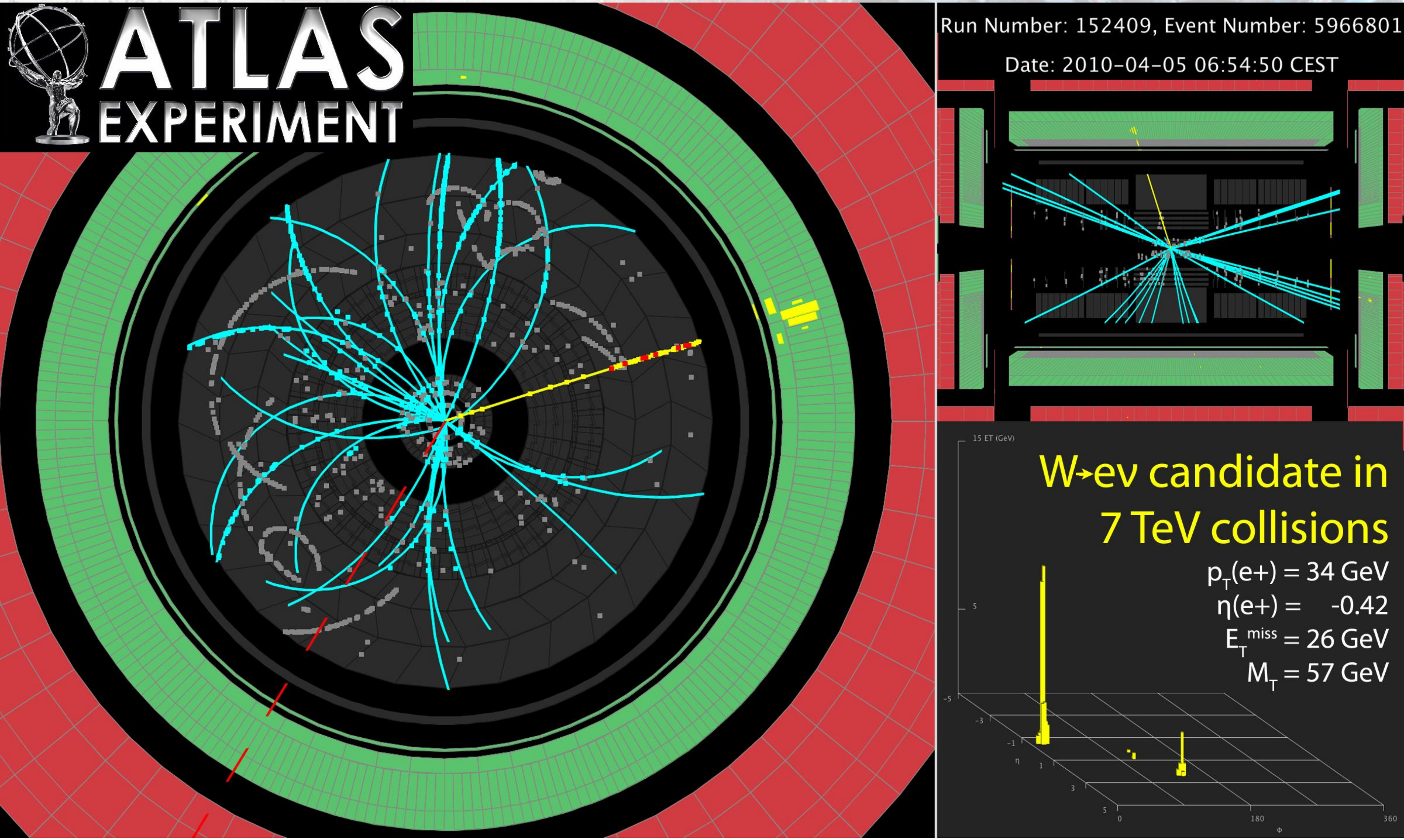
It is possible to obtain information on the quark or gluon that participated to the interaction by studying the hadrons that have been generated:





The hadrons that come from an initial quark tend to go in the same direction and therefore to associate to the other particles and create JETS of particles.
JETs are therefore made up of hadrons, electrons, muons, neutrinos, photons etc ...

Exercise:
recognize the different particles
in the following events



Run Number: 152409, Event Number: 5966801

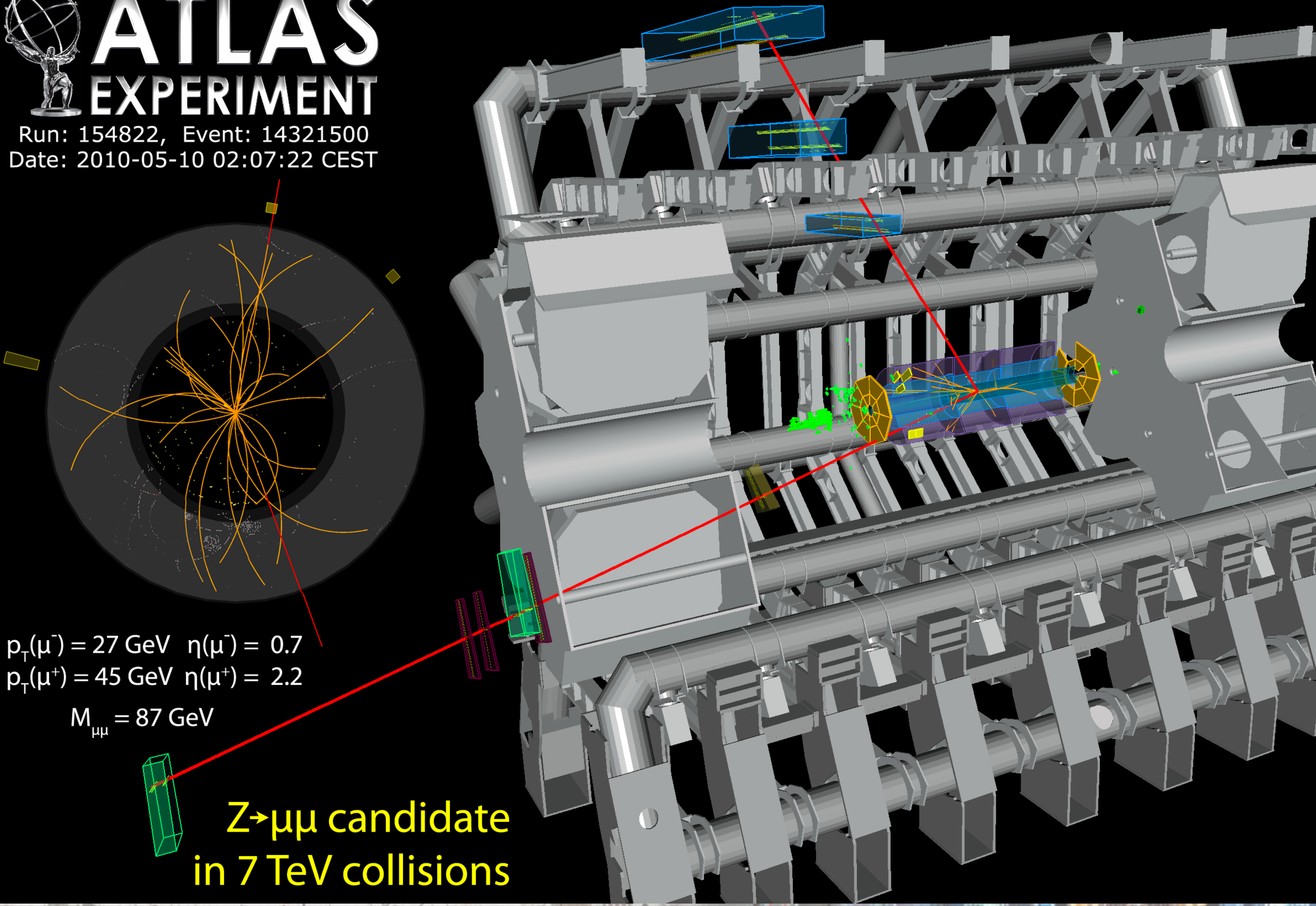
Date: 2010-04-05 06:54:50 CEST

W→eν candidate in 7 TeV collisions

$p_T(e+) = 34$ GeV
$\eta(e+) = -0.42$
$E_T^{miss} = 26$ GeV
$M_T = 57$ GeV

ATLAS EXPERIMENT

Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST



$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$

$M_{\mu\mu} = 87$ GeV

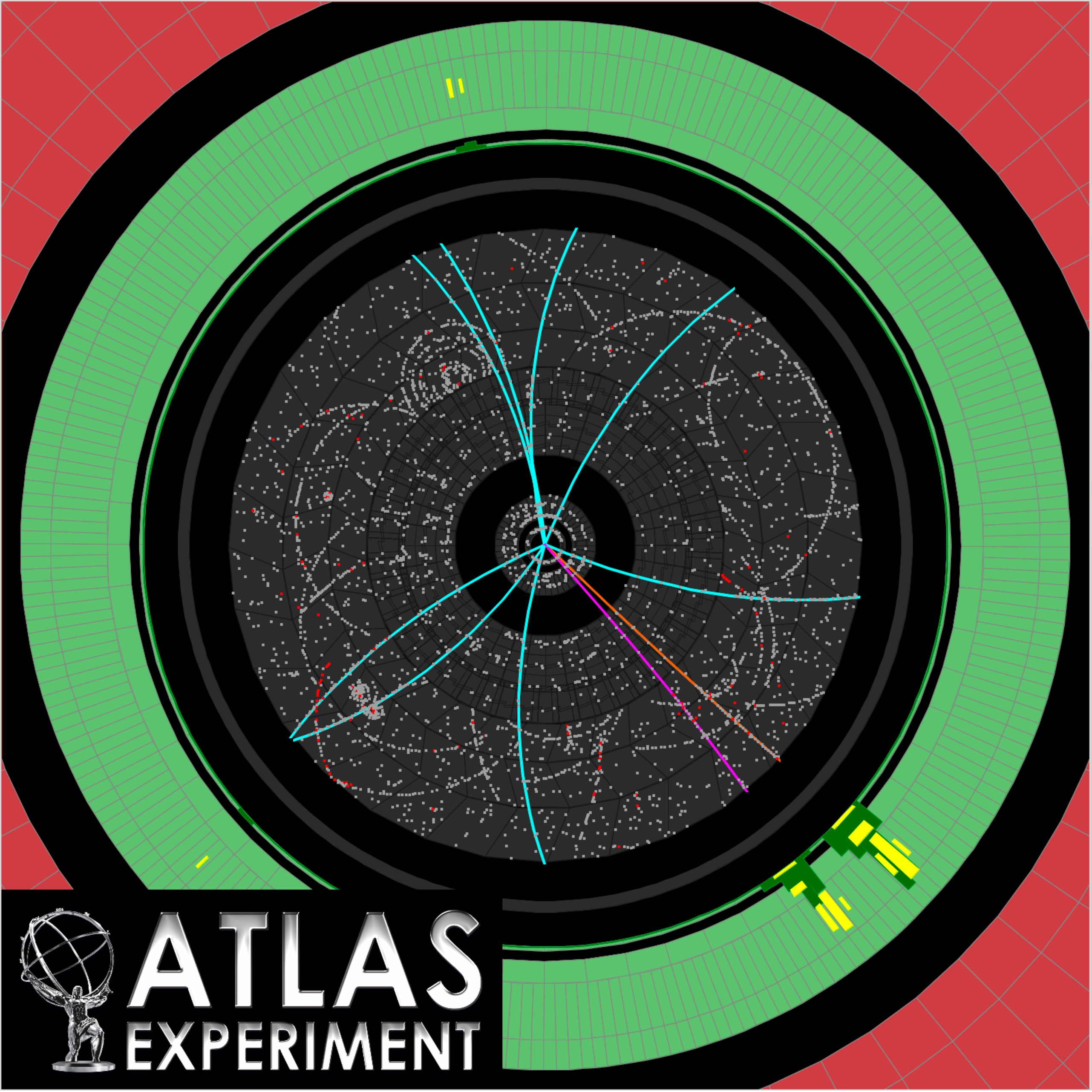
Z→μμ candidate in 7 TeV collisions

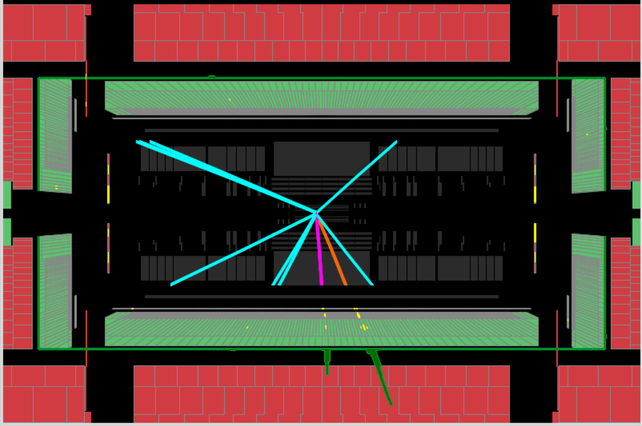
Run Number: 160736, Event Number: 3446804

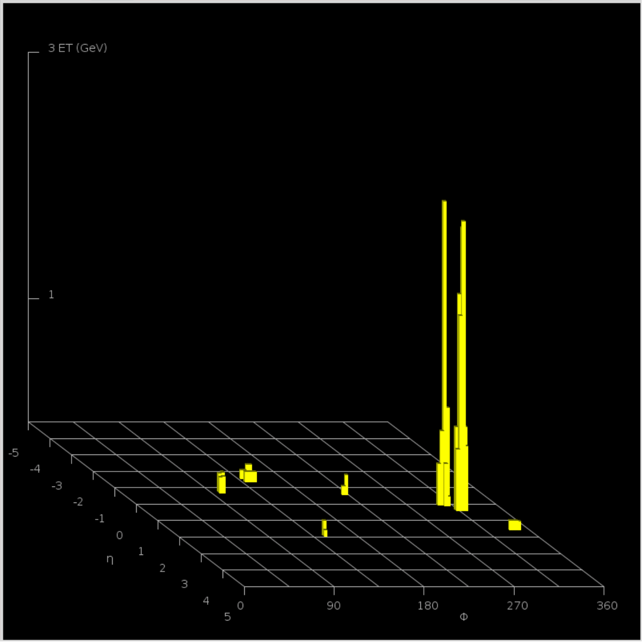
Date: 2010-08-04 05:18:18 CEST

J/ψ→ee candidate in 7 TeV collisions

M_{ee} = 3.17 GeV



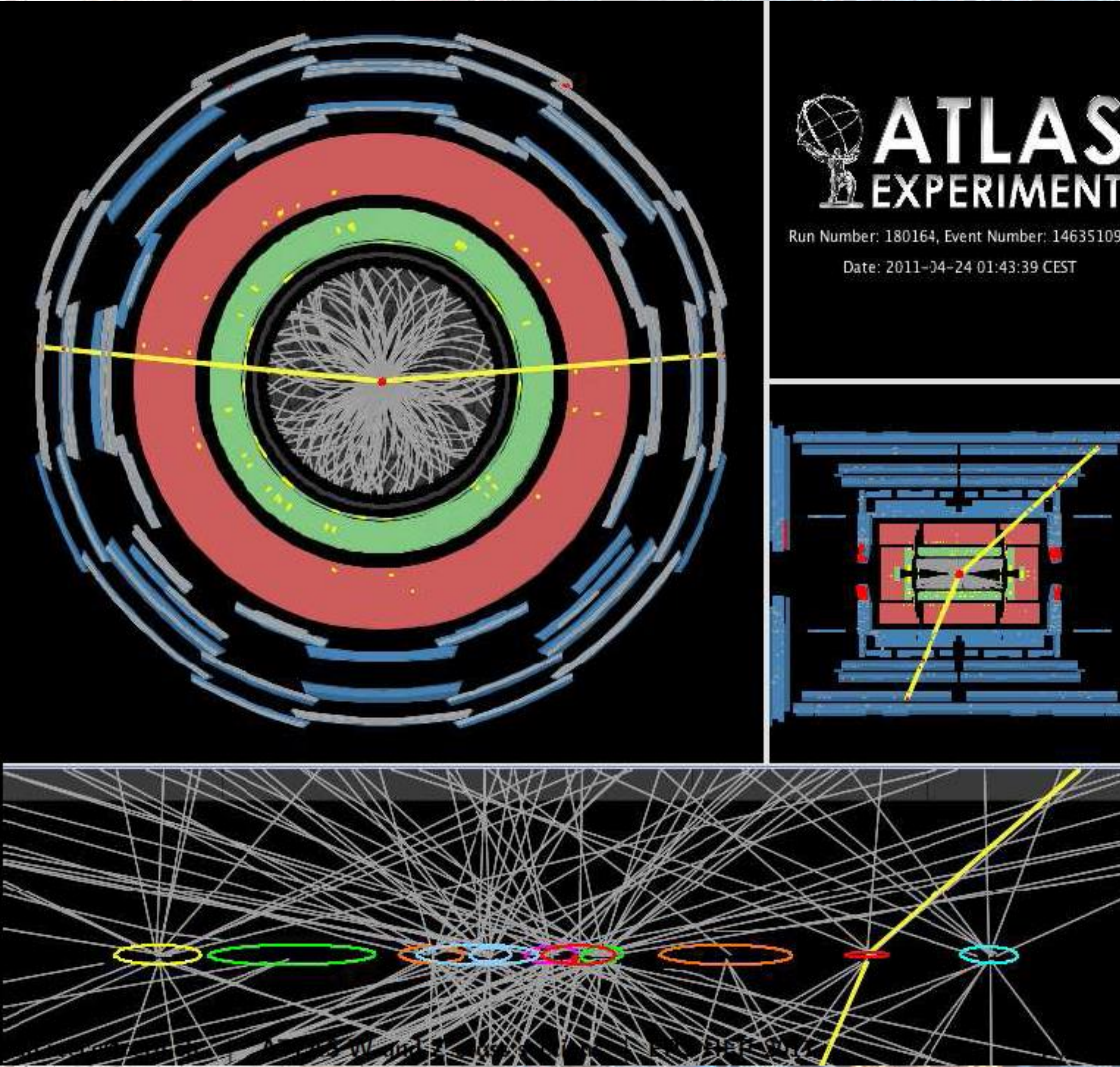


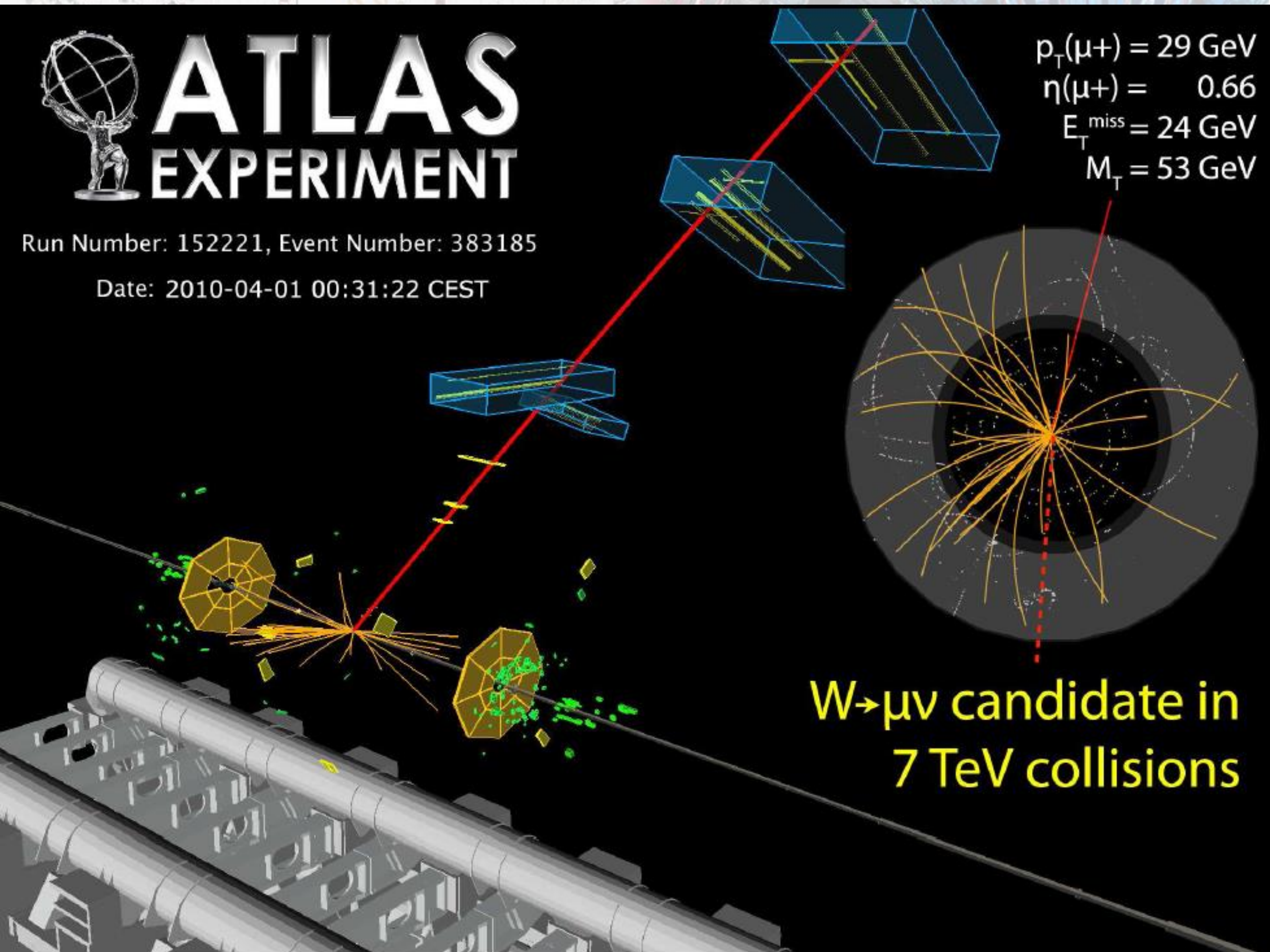


$Z \to \mu\mu$ candidate with 10 additional soft "pile-up" interactions.

High p_{T} leptons allow us to select the interesting EW events.

Conversely, W/Z provide events for understanding high p_{T} lepton performance.





ATLAS EXPERIMENT

Run Number: 152221, Event Number: 383185

Date: 2010-04-01 00:31:22 CEST

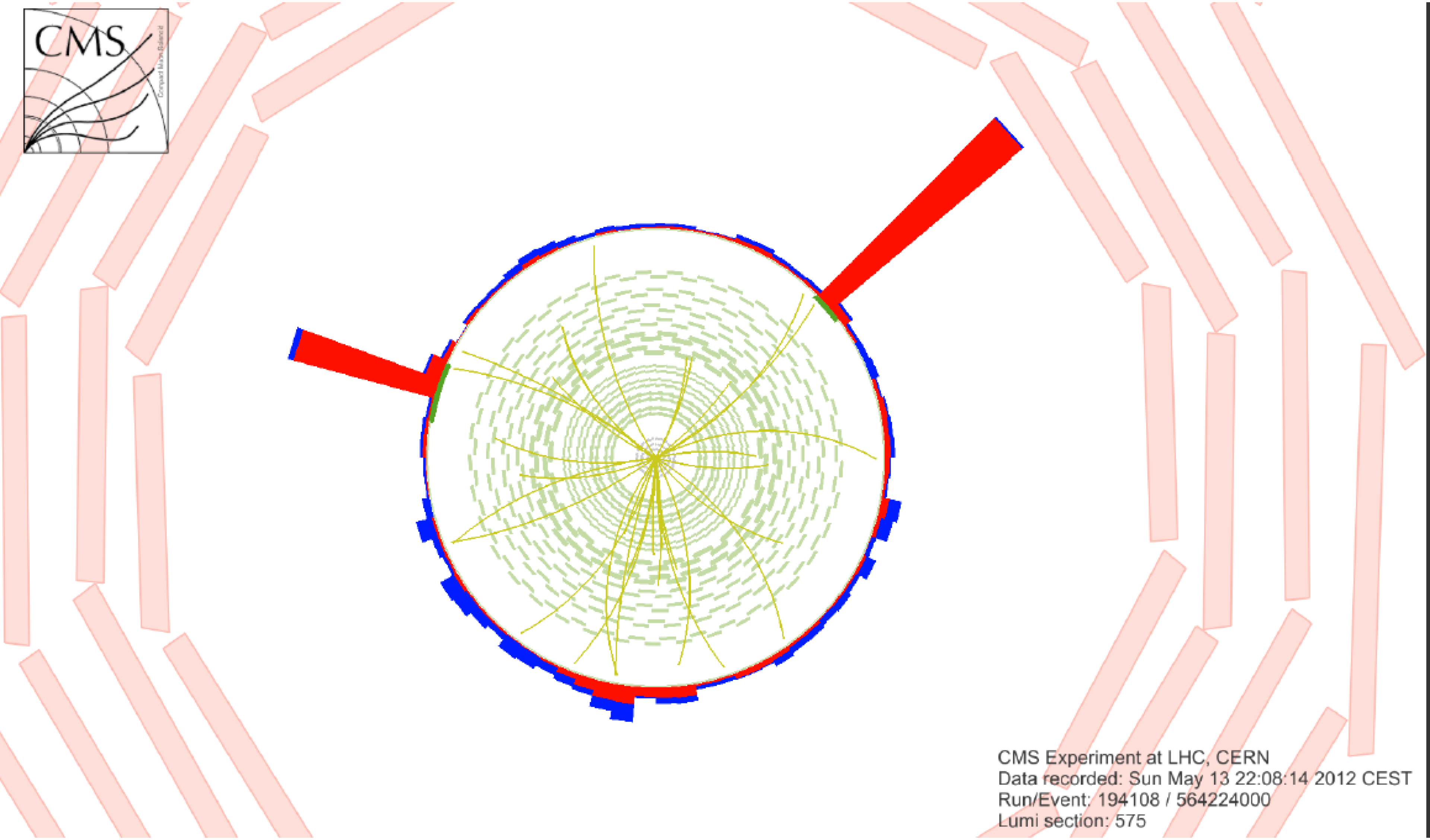
$p_T(\mu+) = 29$ GeV

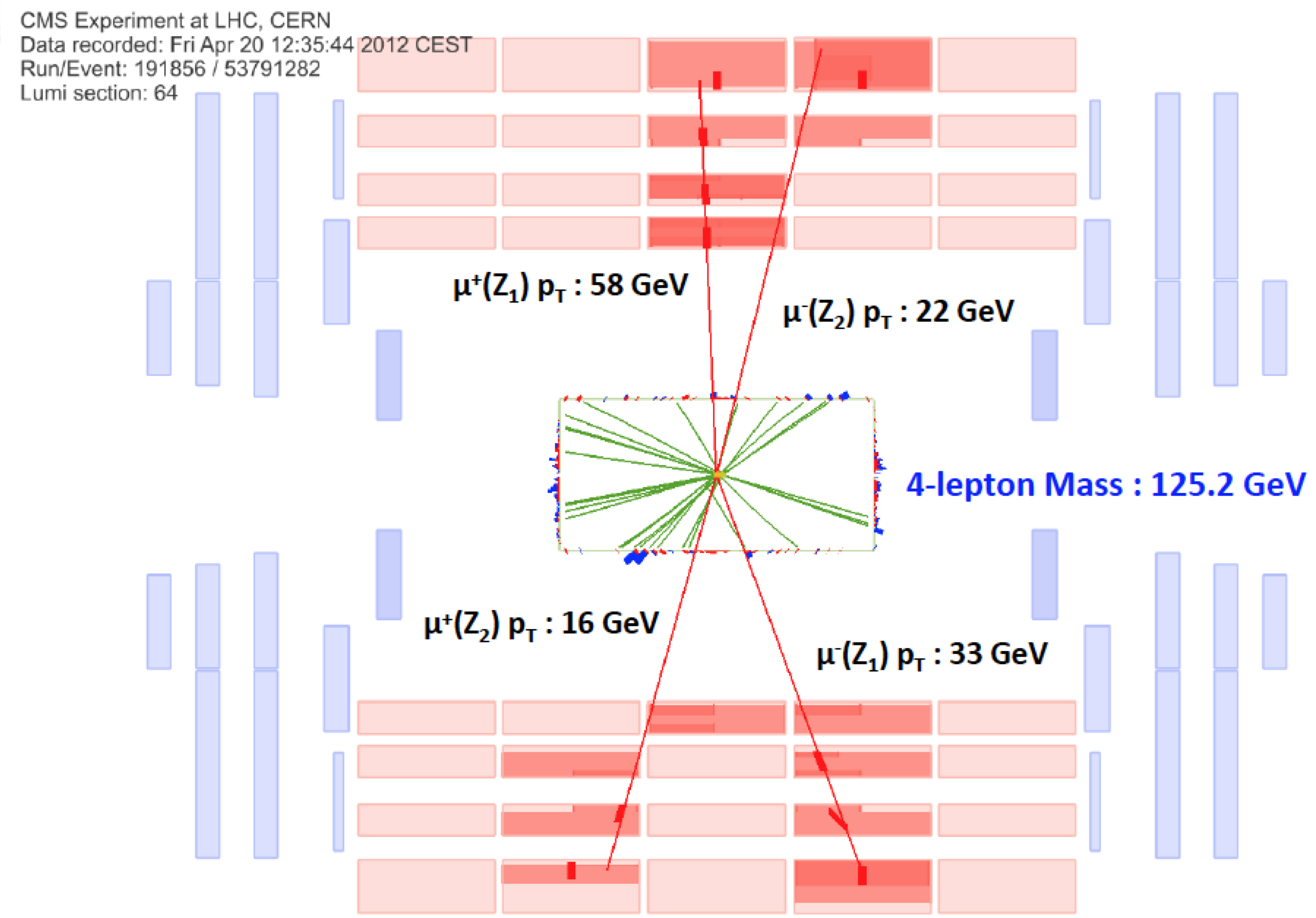
$\eta(\mu+) = 0.66$

$E_T^{miss} = 24$ GeV

$M_T = 53$ GeV

W→μν candidate in 7 TeV collisions


CMS
CMS Experiment at LHC, CERN
Data recorded: Sun May 13 22:08:14 2012 CEST
Run/Event: 194108 / 564224000
Lumi section: 575



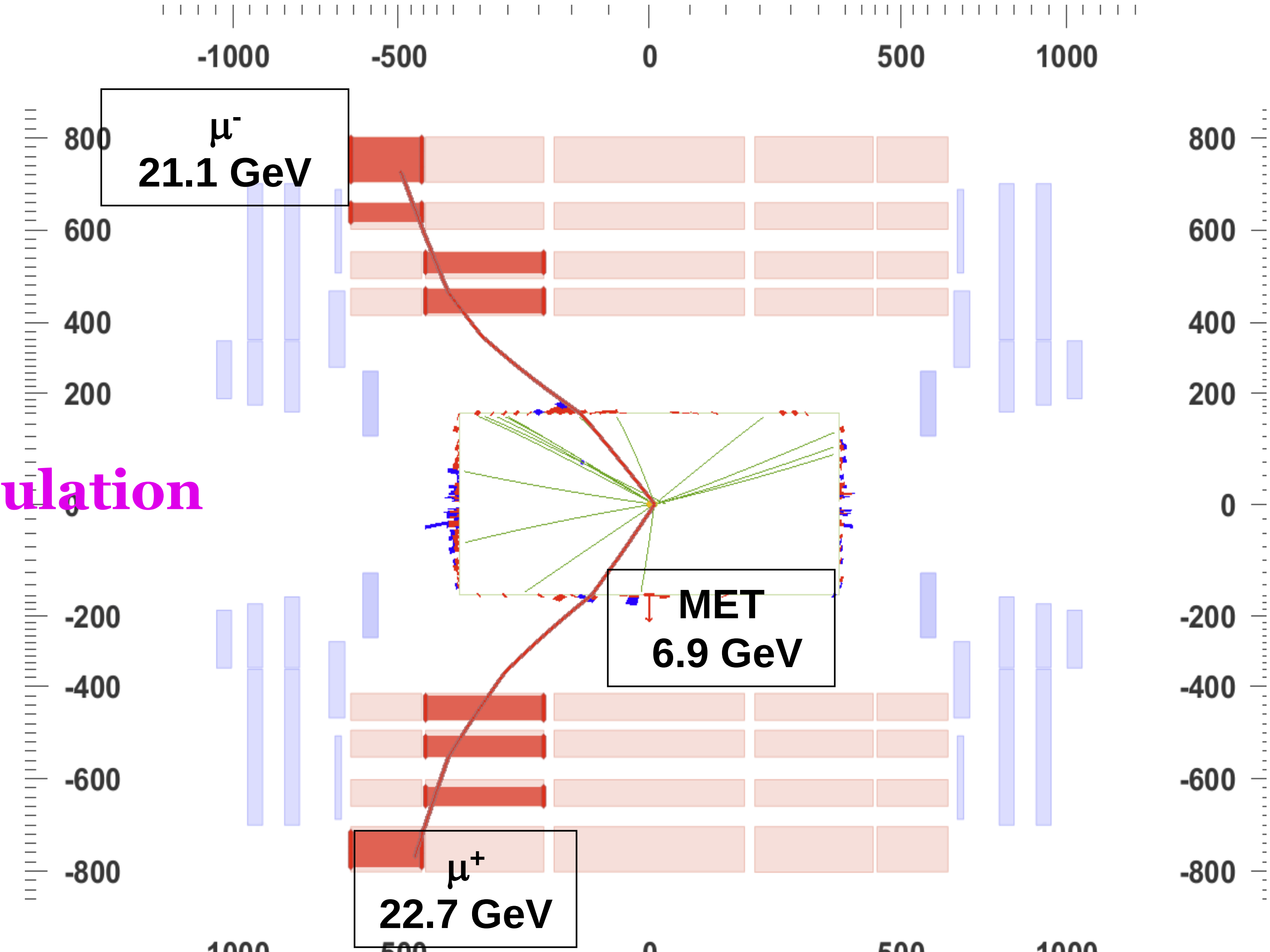
$\mu^+(Z_1)$ p_T : 58 GeV

$\mu^-(Z_2)$ p_T : 22 GeV

4-lepton Mass : 125.2 GeV

$\mu^+(Z_2)$ p_T : 16 GeV

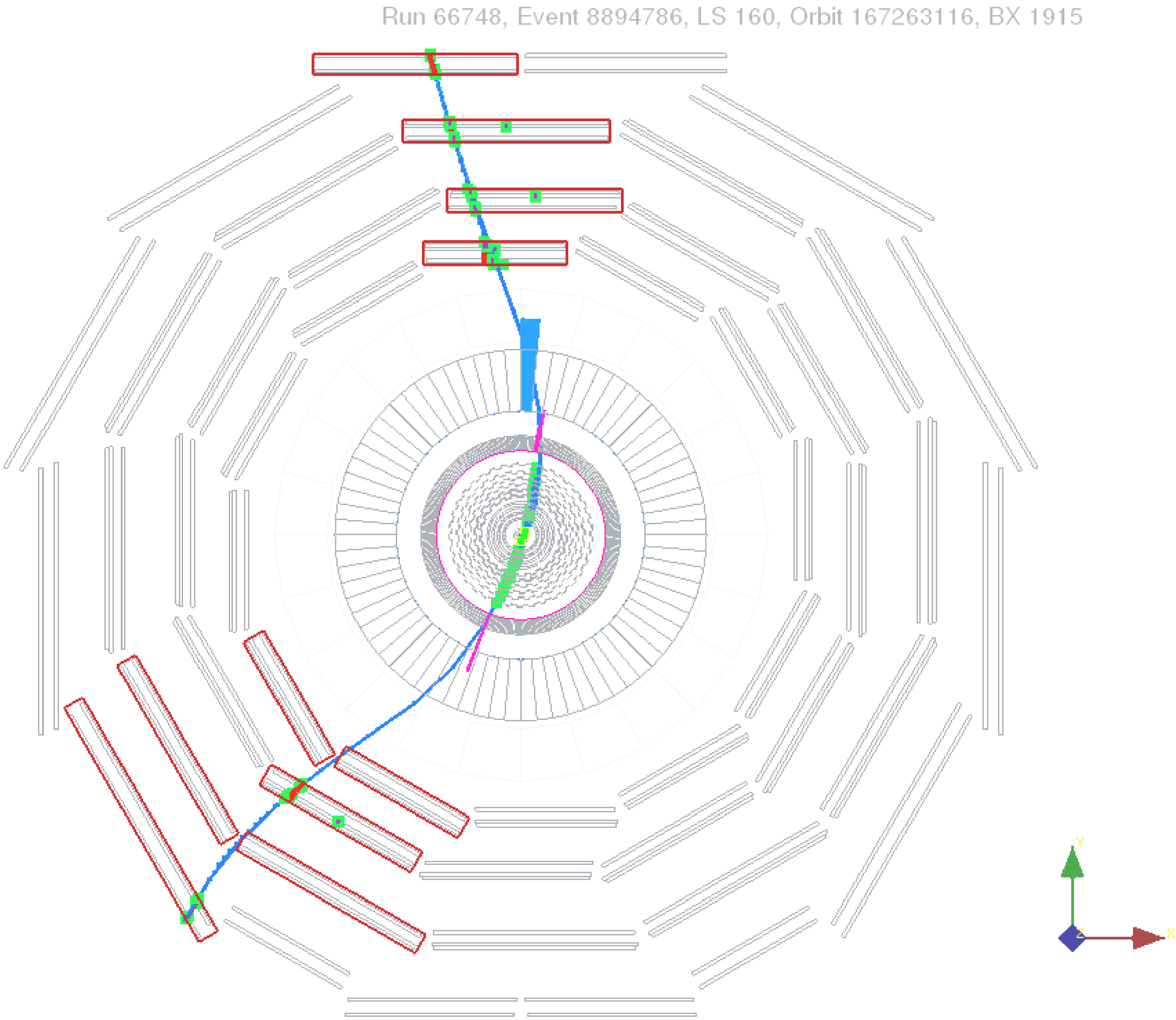
$\mu^-(Z_1)$ p_T : 33 GeV



Simulation

drastically reduced by requiring MET in the event

CRAFT event Cosmic Ray Four Tesla

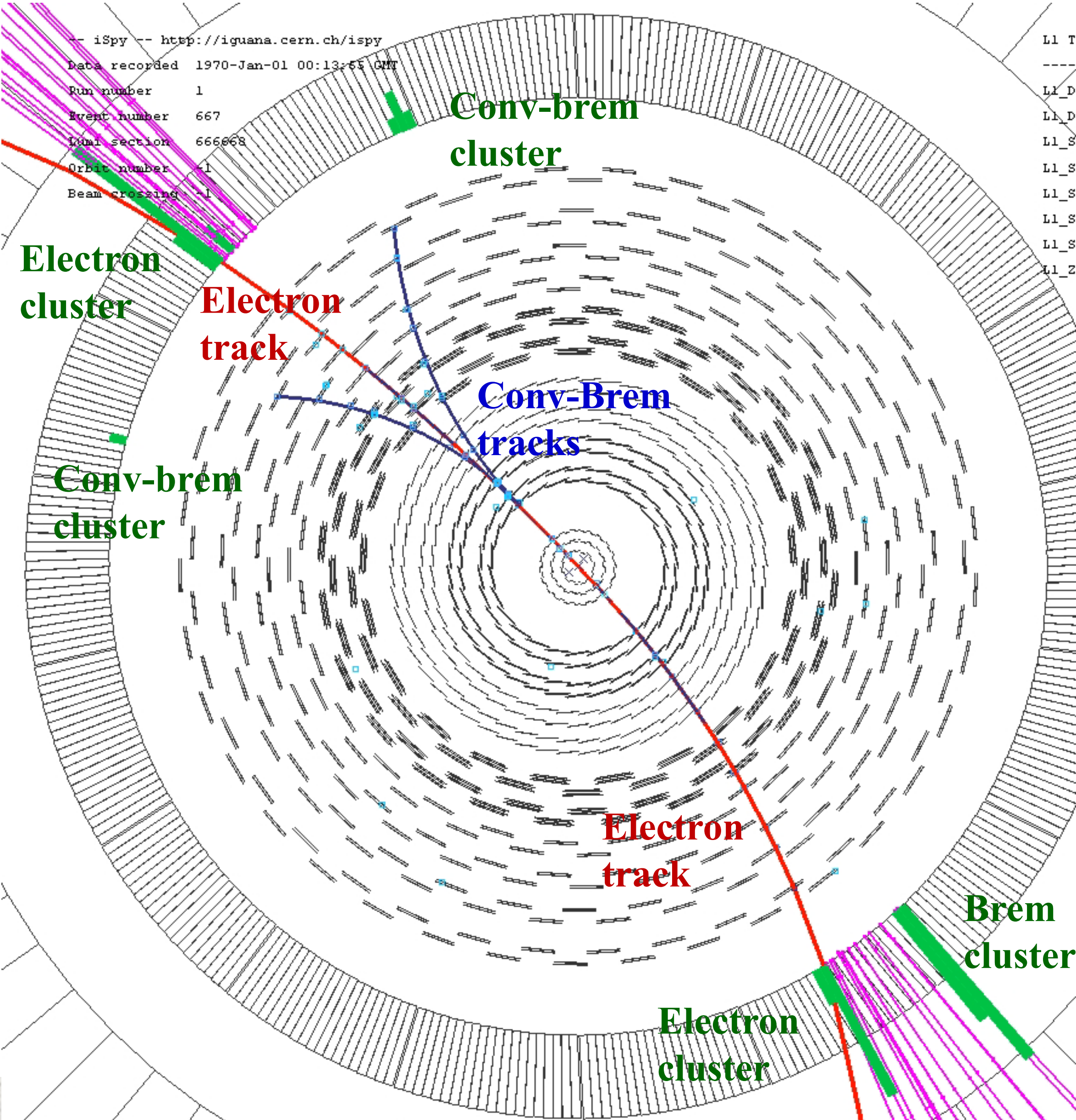


Before start of LHC beams

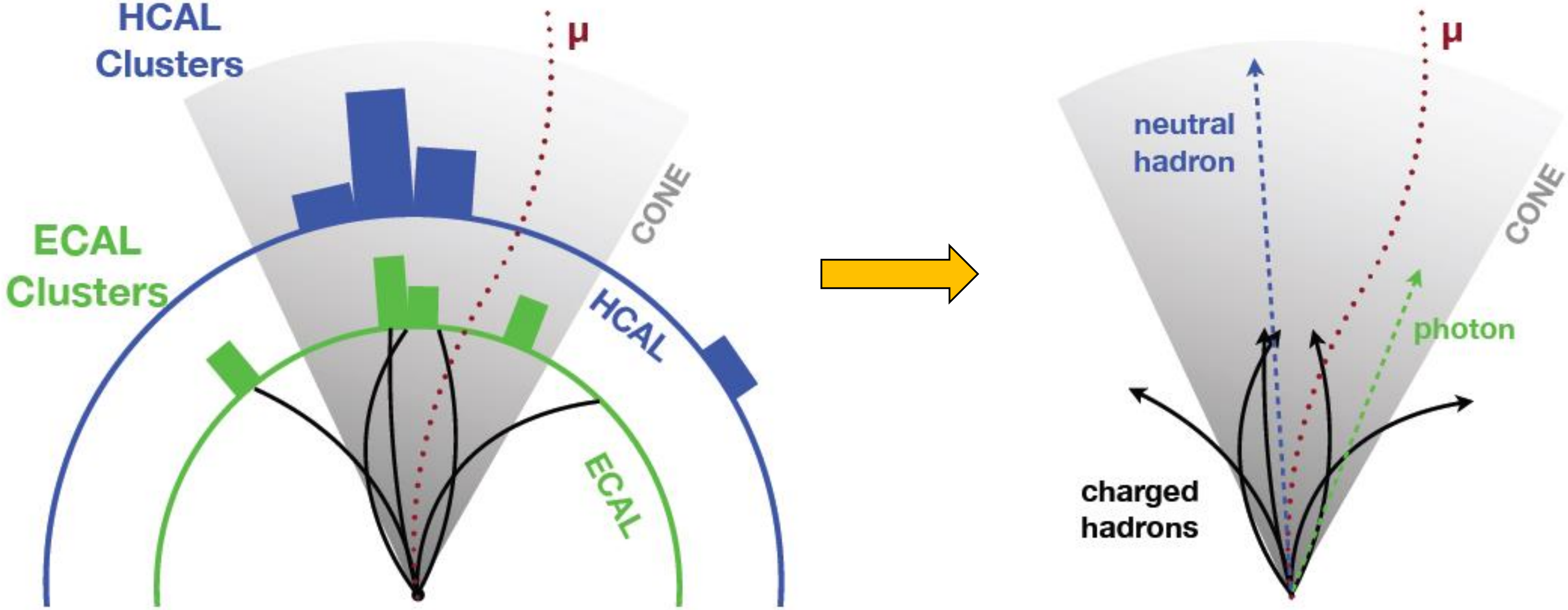
Recostruction Algorithms

Sophisticated algorithms to reconstruct the objects of the event starting from thousands of individual independent measurements

- Pattern recognition
- Track fitting
- Clustering
  - association of information of different detectors, resolution of ambiguity
- Estimate of physical quantities



Global event description



Associate all available information in a global description of the event

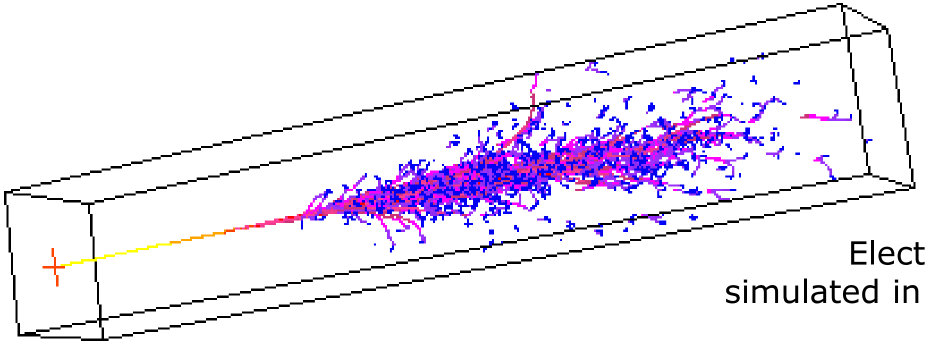
→List of hits → list of tracks / clusters → List of muons, electrons, photons, charged and neutral hadrons → jets and missing energy

Detector Simulation

In order to interpret the collected data, it is necessary to compare them with simulations of the already known physical processes, and those hypothesized

1. Simulated physical events: Monte Carlo generators
2. Simulation of the interaction of particles with the detector
    1. Each particle is followed through the detector (GEANT) in a detailed model of the whole apparatus
3. Simulation of the signals produced in the detectors

Result: simulated data identical to the real ones



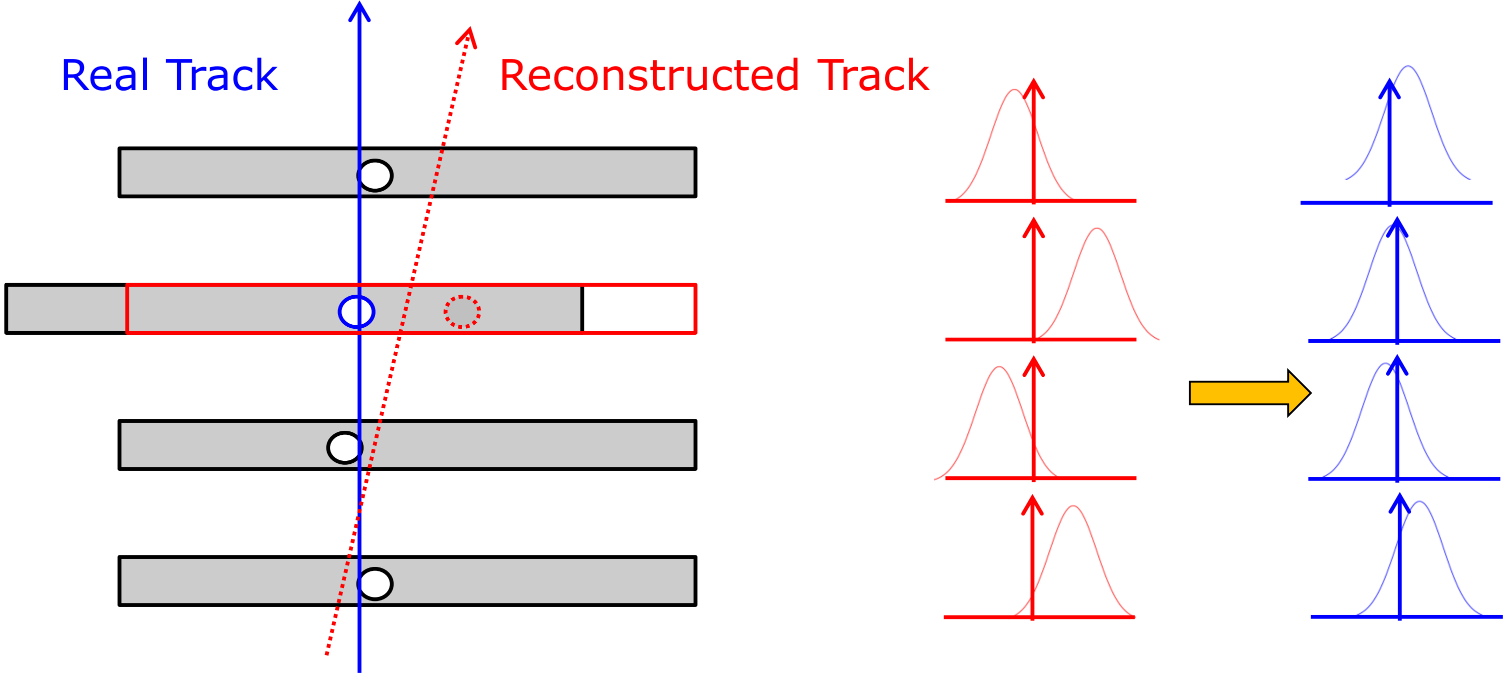
Electromagnetic shower simulated in a crystal of $PbWO_4$

Understanding the detector using the data

Events produced by "known" processes are valuable for studying and improving the detector's performance

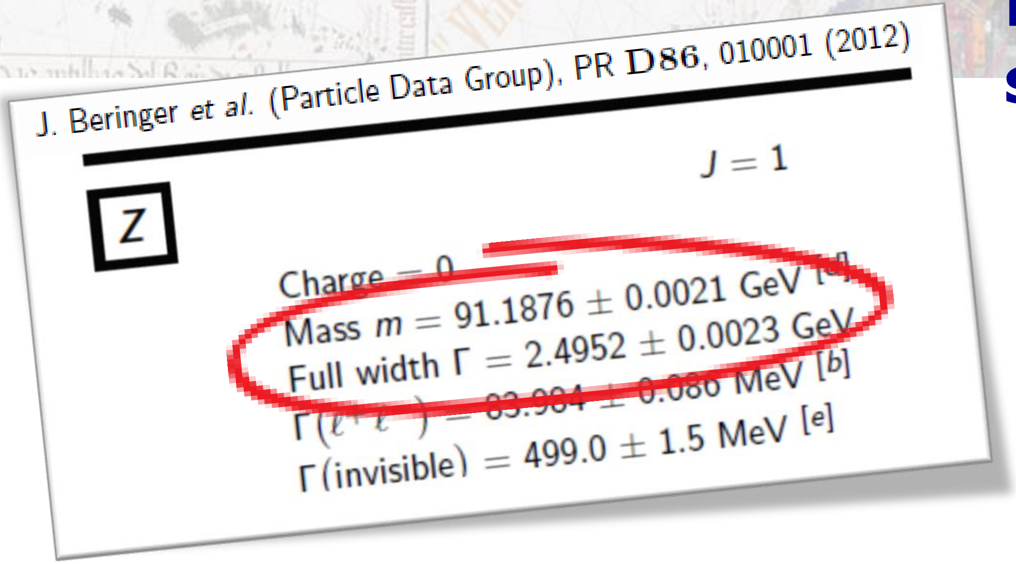
→ Calibrations, alignments, measurements of data efficiencies

Example: Alignment of trackers



I get alignment parameters from the residuals
(= measurement - position of the trace)

Example: momentum scale



J. Beringer *et al.* (Particle Data Group), PR **D86**, 010001 (2012)

Z

$J = 1$

Charge = 0

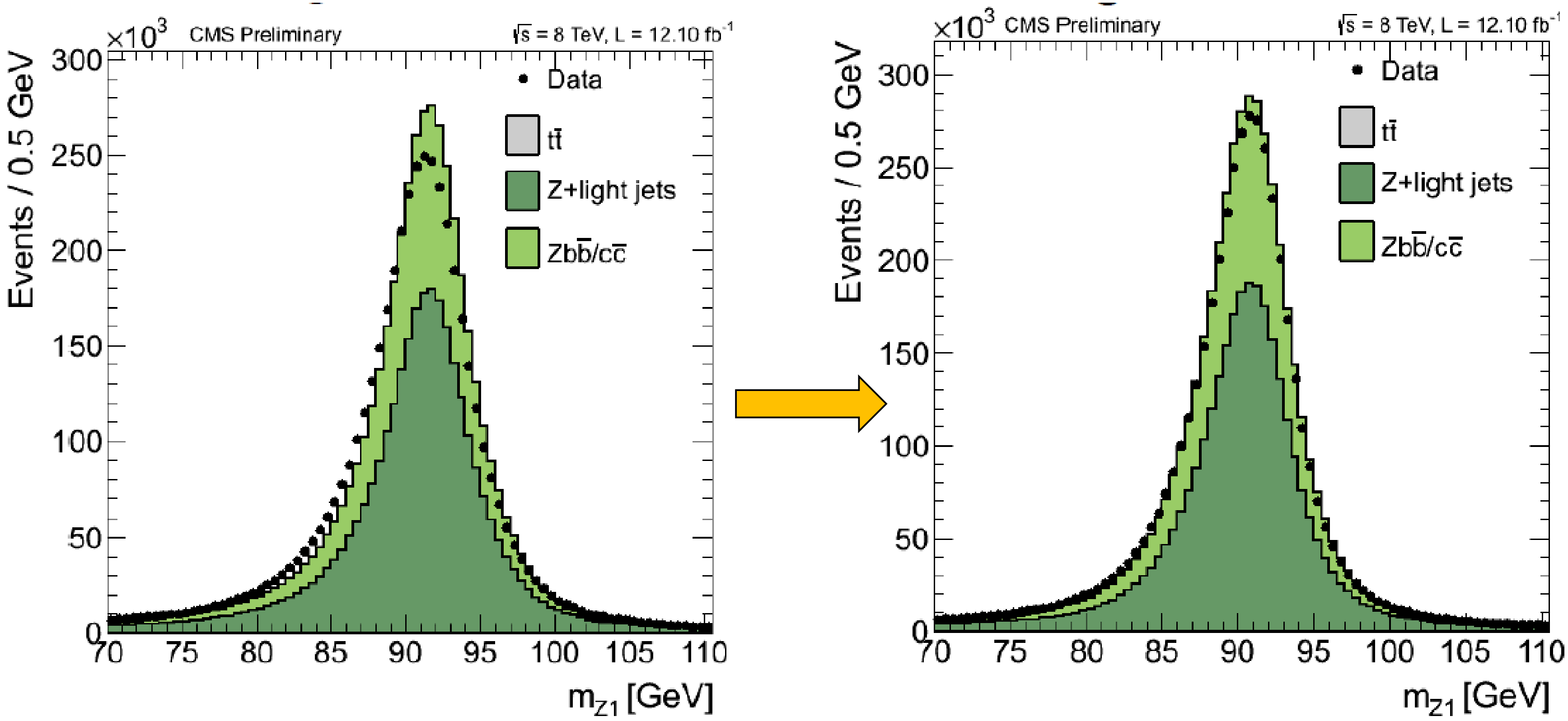
Mass $m = 91.1876 \pm 0.0021$ GeV [a]

Full width $\Gamma = 2.4952 \pm 0.0023$ GeV

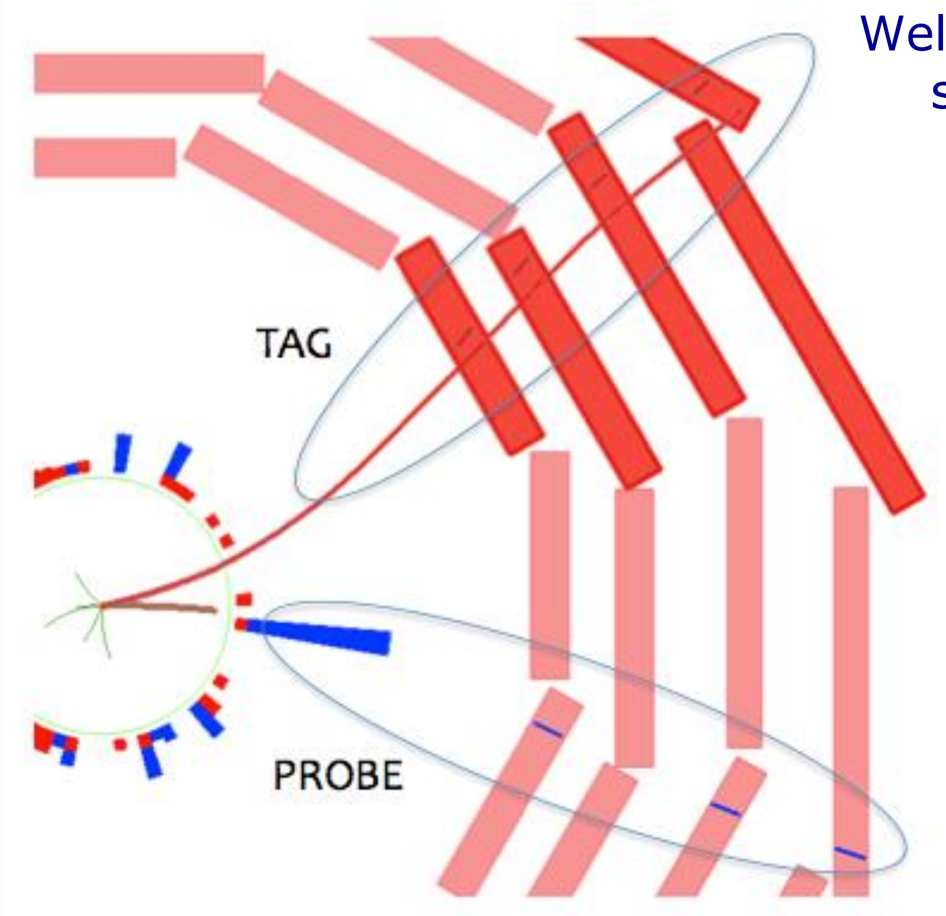
$\Gamma(\ell^+\ell^-) = 83.984 \pm 0.086$ MeV [b]

$\Gamma(\text{invisible}) = 499.0 \pm 1.5$ MeV [e]

Z→ee events: to force the energy scale of the electrons



Efficiency measurement using data: "Tag-and-probe"



Well known resonances (Z, J/ψ, Υ→ℓℓ) selected using $m_{\ell\ell}$

- requiring two tracks of which at least one satisfies identification criteria ("TAG").
- study of the identification efficiency using the other track ("PROBE")