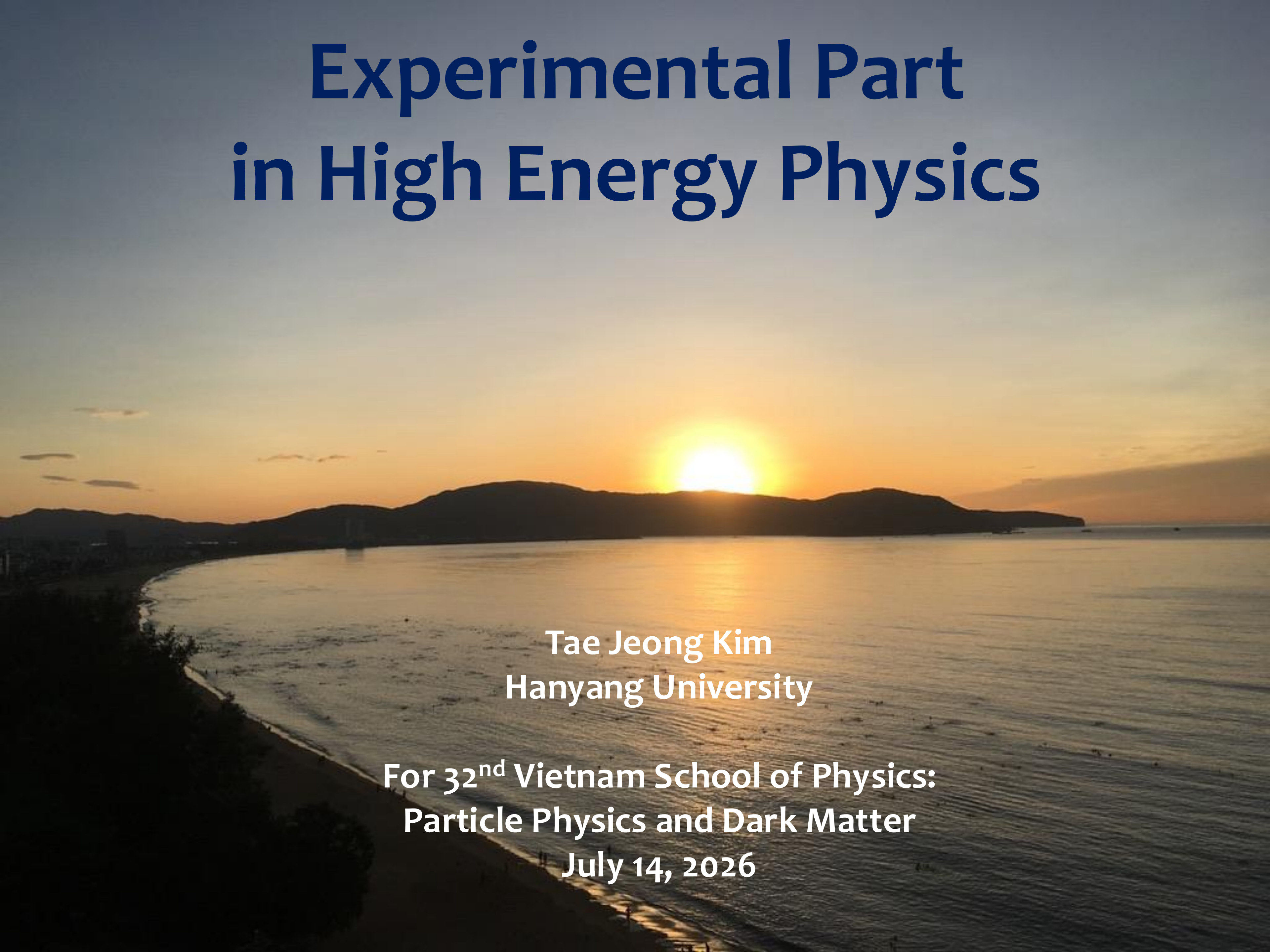


Experimental Part in High Energy Physics

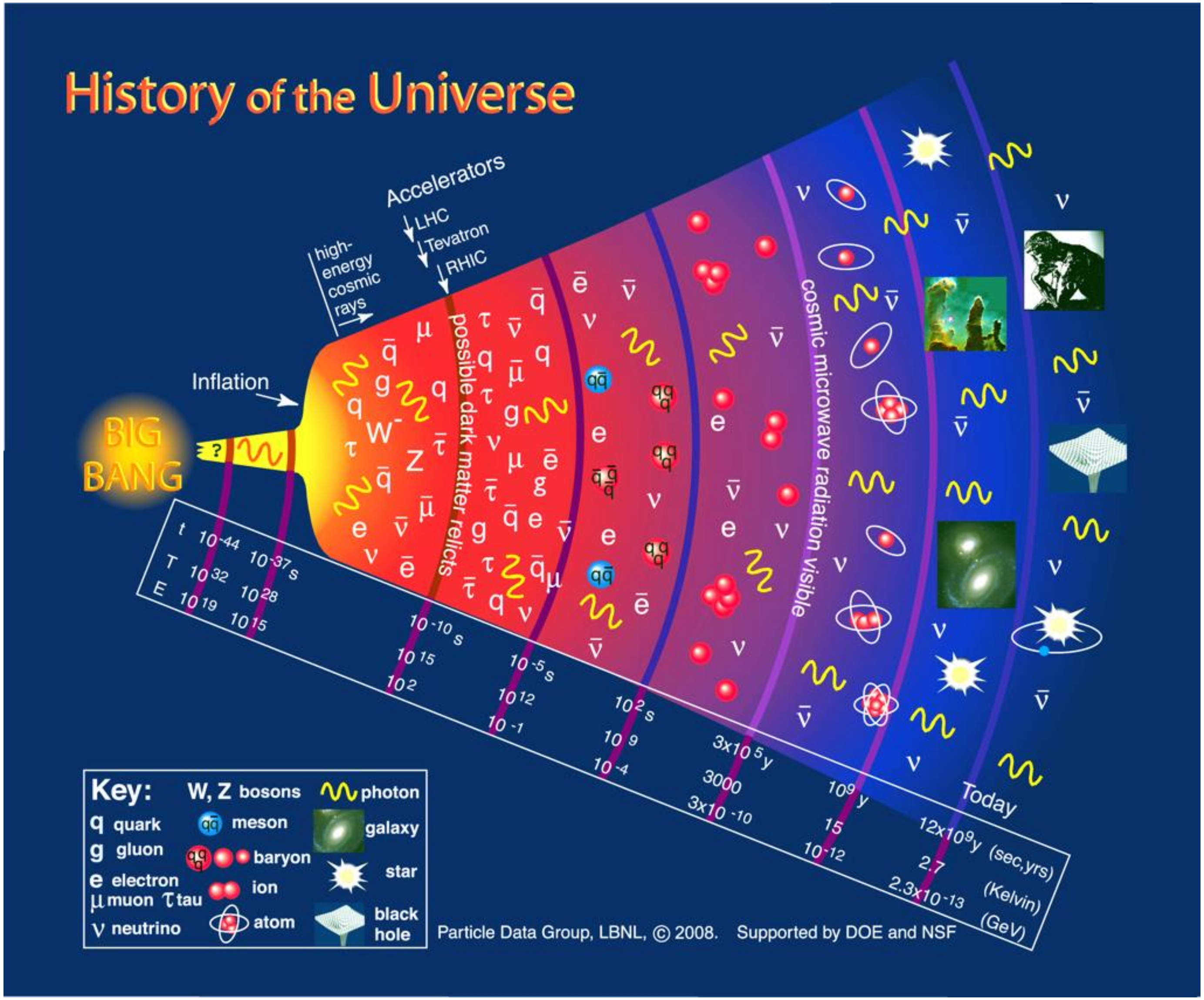
Tae Jeong Kim
Hanyang University

For 32nd Vietnam School of Physics:
Particle Physics and Dark Matter
July 14, 2026

Disclaimer

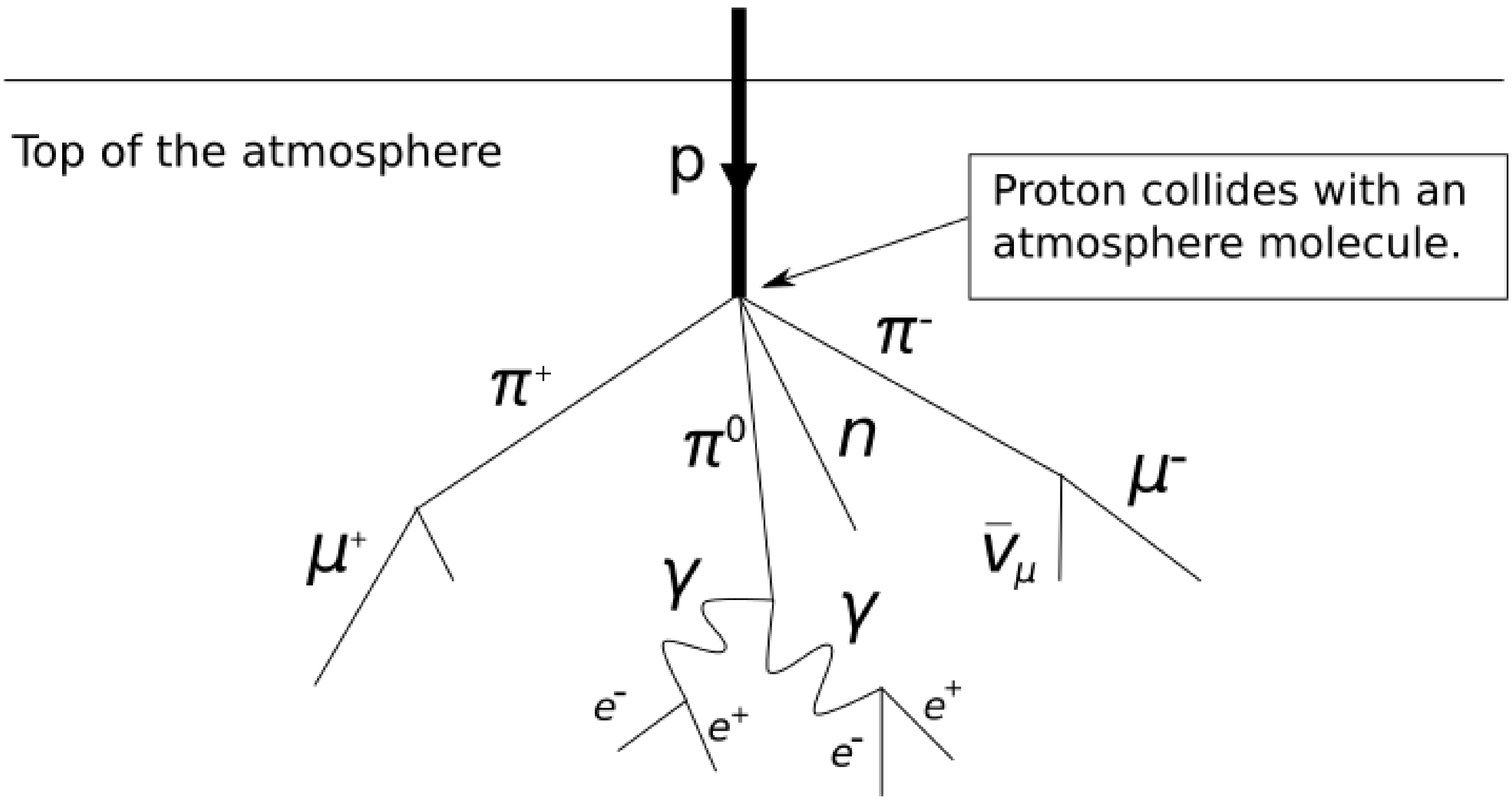
- Some of materials are from the CMS induction course and various introductory slide in CMS
- Since I am from CMS, the slide material is based on the CMS detector

High Energy Physics



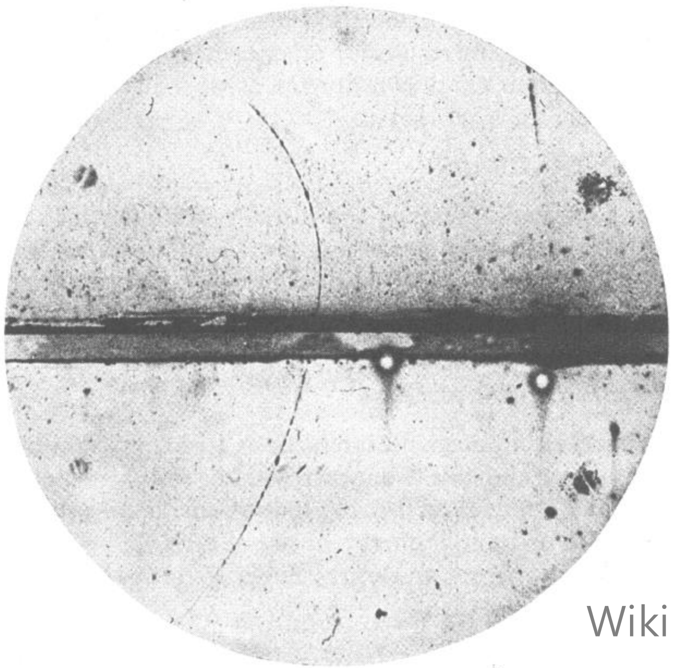
Cosmic Rays

At the beginning of High Energy Physics:



Cloud chamber

- Filled with a supersaturated vapor of alcohol.
- The passage of a charged particle condenses the vapor into tiny droplets.
- These droplets produce a visible trail marking the particle's path.

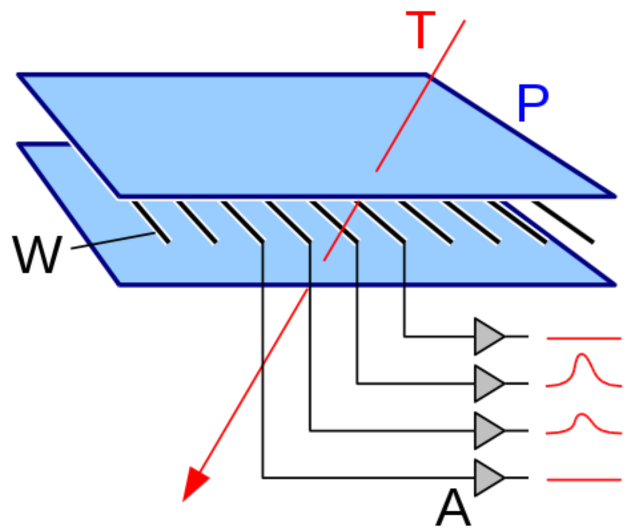


Wikipedia

Cloud chamber at home

Multi-wire proportional chamber

- In 1969, Georges Charpak invented the multi-wire proportional chamber (MWPC)
- He was awarded Nobel prize in Physics in 1992
- Electronic signal for particle detection
- 1000 particles per 1s



Wikipedia

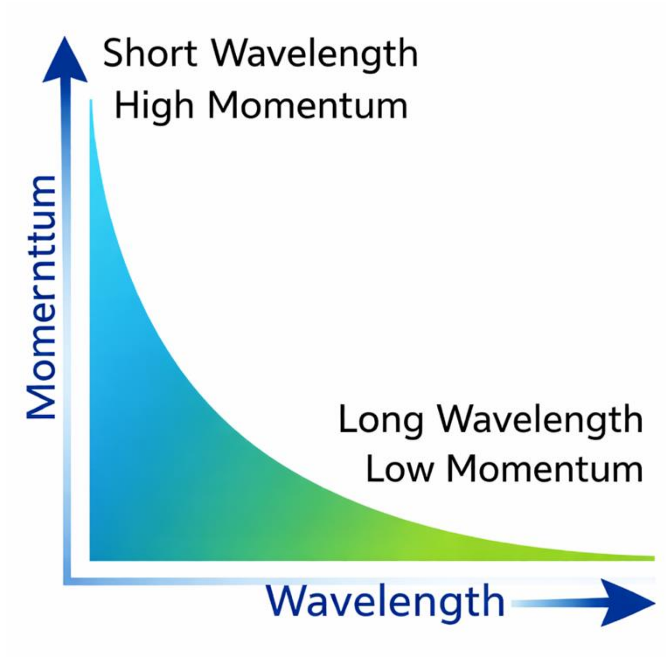
The physics tool: the accelerator

- **To probe** smaller particles, **we need to decrease the wavelength. How?**
- A particle's momentum and its wavelength are inversely related.

$$\boldsymbol{\lambda = \frac{h}{p}}$$

- This High Energy is also used to create the massive particles

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



Colliding beam experiment

- The center-of-mass energy $\sqrt{s}$ is from Lorentz Invariant quantity

$$s = (\Sigma E_i)^2 - (\Sigma p_i)^2 \text{ where c=1.}$$

- In a colliding-beam experiment, two beams of high-energy particles are made to cross each other

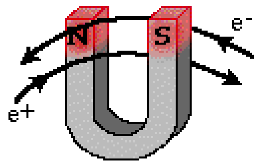
$$\sqrt{s} = E_p + E_p = 2E_p$$

- A collision between them is more likely to produce a higher mass particle than would a fixed-target collision at the same energy.

$$s = \left(E + m_p\right)^2 - p^2 = 2m_p^2 + 2m_pE \approx 2m_pE \ \rightarrow \sqrt{s} = \sqrt{2m_pE}$$

What makes particles go in a circle?

- To keep any object going in a circle, there needs to be a constant force on that object towards the center of the circle.
- Large magnets provide necessary inward force to bend the particle's path in a circle.
- The magnetic field only bends the particles' paths along the arc of accelerator not adding or subtracting energy from the particles.

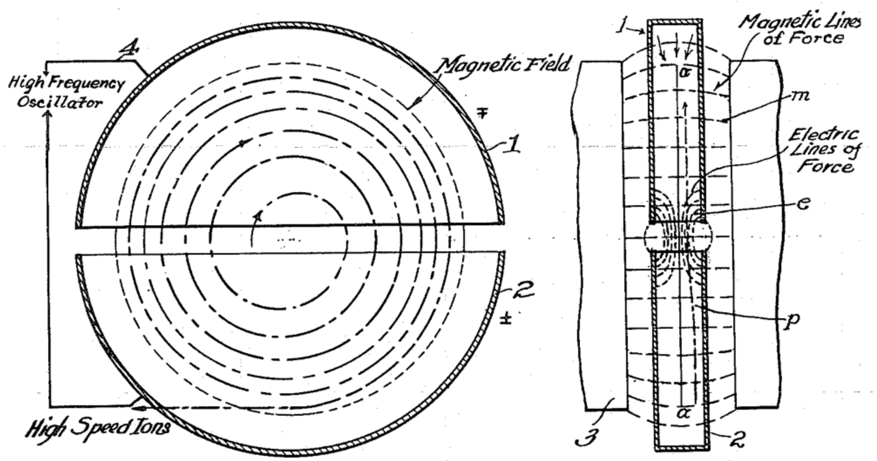


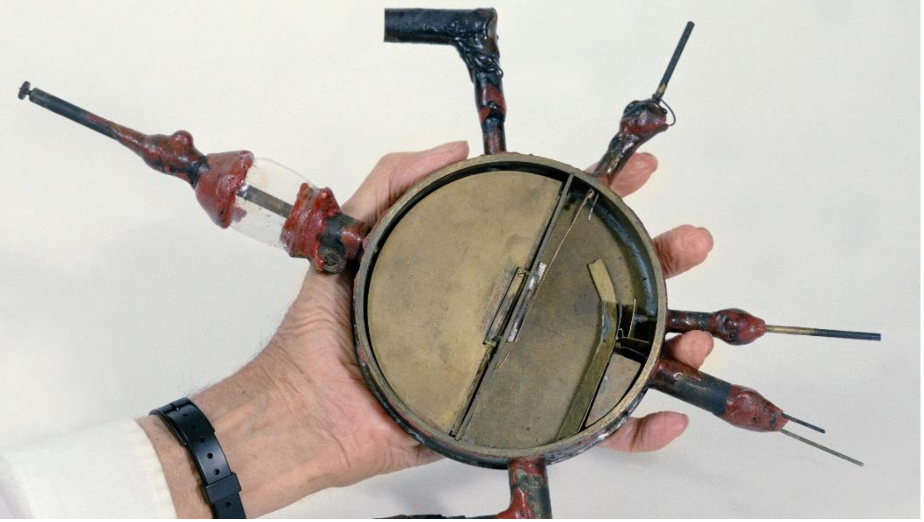
If a magnetic field makes electrons go clockwise, in which direction does it make positrons go?

Cyclotron

- Ernest Lawrence invented cyclotron
- **The magnetic field only bends the particles and the electric field increases the speed of the particles**
- The first cyclotron is only 10 cm (see the photo below)
- **This was the beginning of a big science because the cyclotron needs to be bigger and bigger in order to obtain particles of high energy**

Lawrence Berkeley National Laboratory Photo Archives





Cyclotron

For the circular motion, centripetal force is Lorentz force

Particle reaches its maximum energy at r=R

$$F_c = \frac{mv^2}{r} \qquad F_B = qvB$$

$$F_C = F_B$$

$$\frac{mv^2}{R} = qvB \rightarrow v = \frac{qBR}{m}$$

Frequency $$f = \frac{1}{T} = \frac{qB}{2\pi m}$$

Energy of the particle $$E = \frac{1}{2}mv^2 = \frac{q^2B^2R^2}{2m}$$

Relativistic considerations

The relativistic mass

$$m = \frac{m_0}{\sqrt{1-(v/c)^2}} = \frac{m_0}{\sqrt{1-\beta^2}} = \gamma m_0$$

m_0 is the particle rest mass

Relativistic cyclotron frequency and angular frequency

$$f = \frac{qB}{2\pi\gamma m_0} = \frac{f_0}{\gamma} = f_0\sqrt{1-\beta^2} = f_0\sqrt{1-(\frac{v}{c})^2}$$

$$\omega = 2\pi f = \frac{qB}{\gamma m_0} = \frac{\omega_0}{\gamma} = \omega_0\sqrt{1-\beta^2} = \omega_0\sqrt{1-(\frac{v}{c})^2}$$

Synchrotron

- For the cyclotron, we have a limitation on the radius and need to take in to account the relativistic considerations

- To get High Energy while keeping the radius r, the magnetic field should also increase

$$B = \frac{vm}{qR}$$

- The magnetic field and the frequency are increased from their initial values B_i and ω_i to final values B_f and w_f

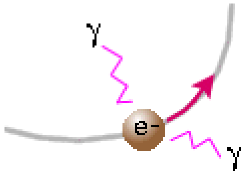
  → Synchrotron

- The energy of the bunch of particles is increased during this process from the injection energy E_i to the final energy E_f

Advantages of accelerator design

- The advantage of a circular accelerator over a liner accelerator:
  - Can provide very high-energy by going around many times
  - Many times around also means higher probability for collisions

- The advantage of a linear accelerator:
  - Easier to build
  - When a charge particle is accelerated, it radiates away energy. This is Bremsstrahlung radiation
  - Much worse for accelerating electrons



Synchrotron radiation

- A particle moving in a circular orbit in a magnetic field radiates away energy in the form of photons

$$\Delta E = \frac{4\pi q^2 \beta^3 \gamma^4}{3\rho}$$ ρ=radius

- For highly relativistic particles,

$$\beta \approx 1 \quad E = \gamma m_0 c^2$$

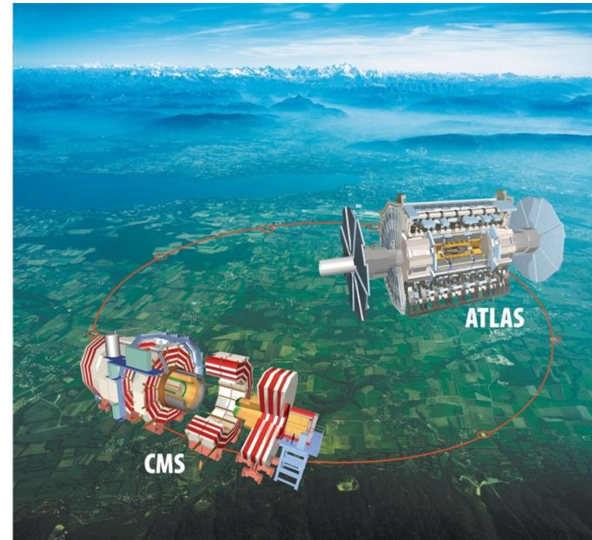
energy loss is inversely proportional to the fourth power of the particle's mass

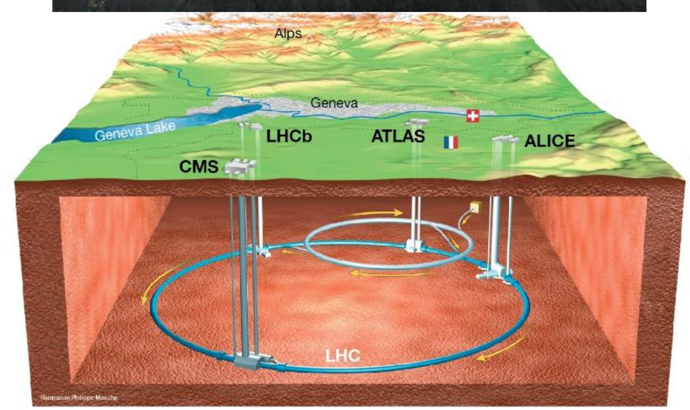
- The losses for electrons are very severe
  - Electron mass ~ 0.5 MeV
  - Proton mass ~ 938 MeV

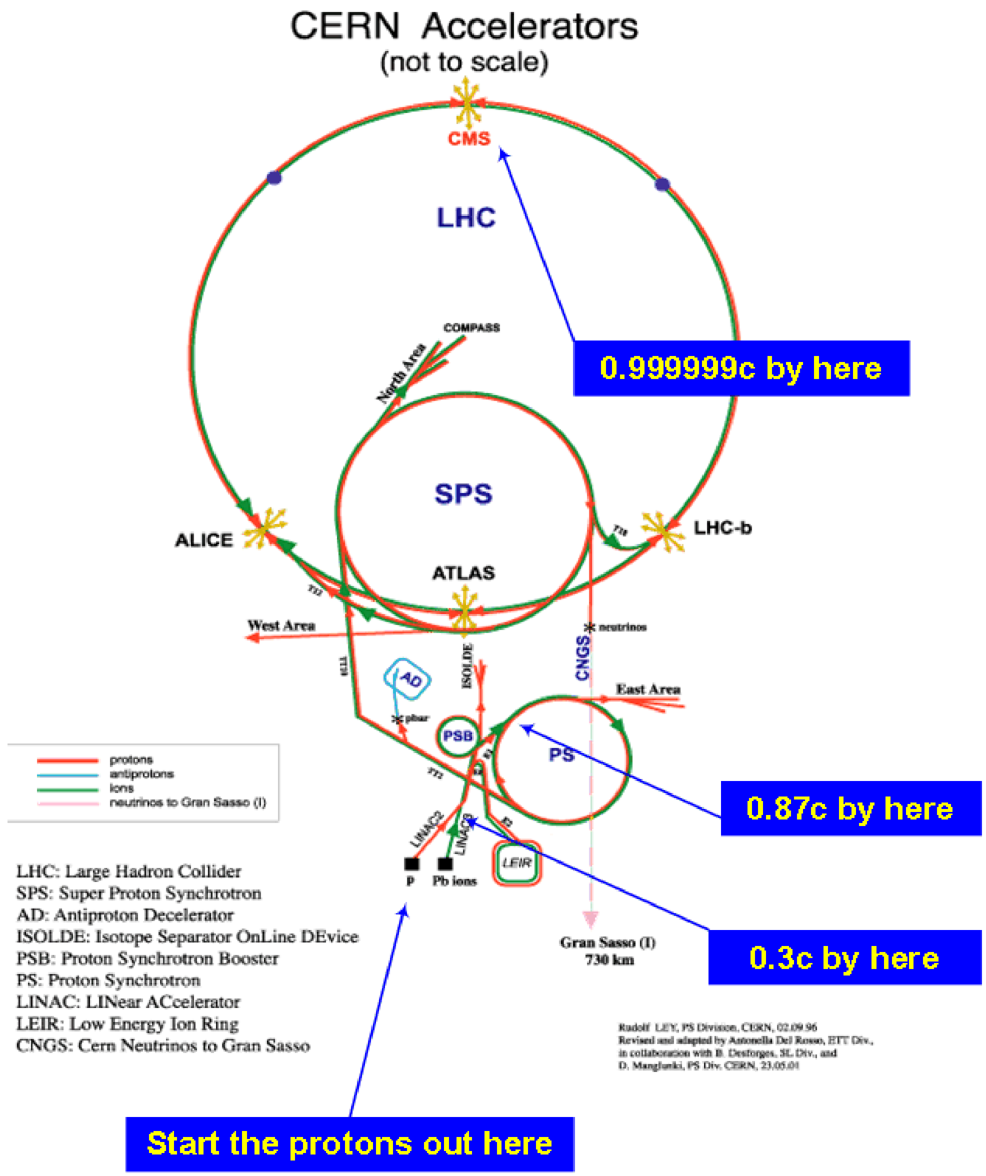
→ $$\frac{\Delta E_e}{\Delta E_p} \approx 10^{13}$$

Large Hadron Collider (LHC)

- Circumference 27 km
- Detectors 100 meters below
- 9593 magnets at 1.9 K
- Helium 120 tonnes
- Protons travel at the speed of light
- 2808 bunch/beam
- 1.14×10^{11} protons/bunch
- Proton beams circulate 11245 times/sec
- 100 million collisions per second
- Instant. Luminosity = $\sim 10^{34}\ \mathrm{cm}^{-1}\mathrm{s}^{-1}$
- Center of the mass energy 13.6 TeV
  - Can create new particles





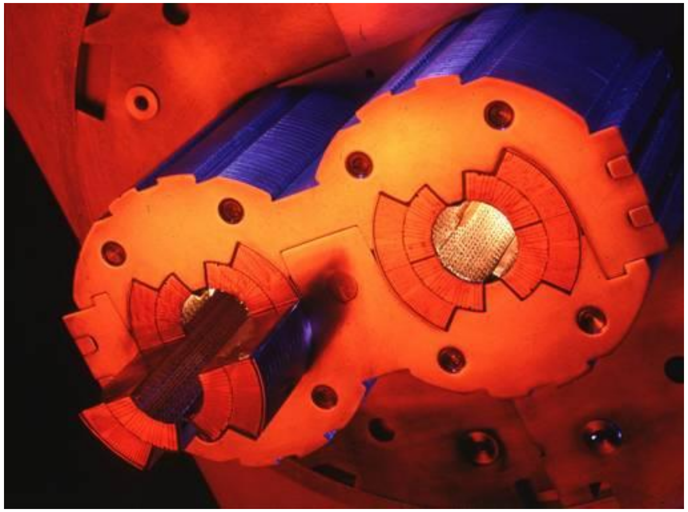


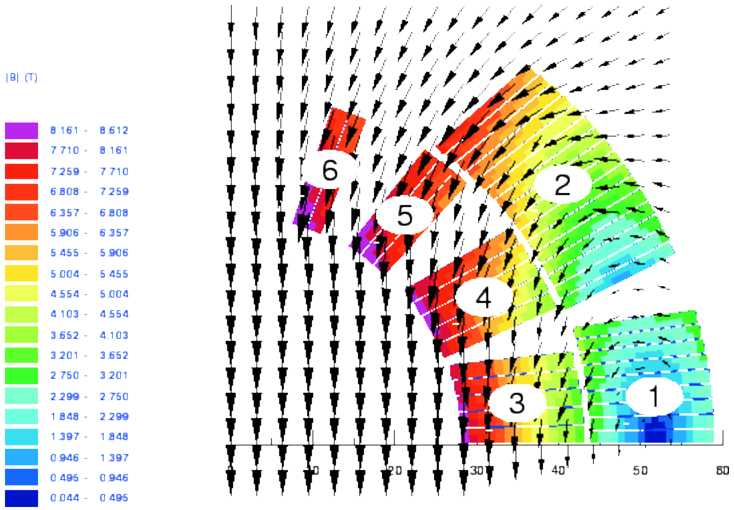
https://lhc-machine-outreach.web.cern.ch

LHC tunnel

Main dipole at the LHC

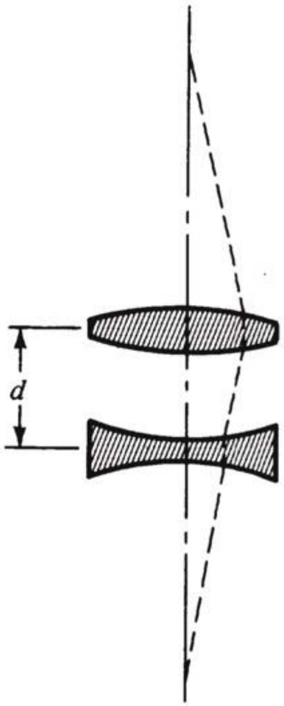
- To bend protons
- 8 Tesla at 1.9 K
- Each one is 14.3 meters long
- A total of 1232 are needed





https://lhc-machine-outreach.web.cern.ch

Focusing magnets



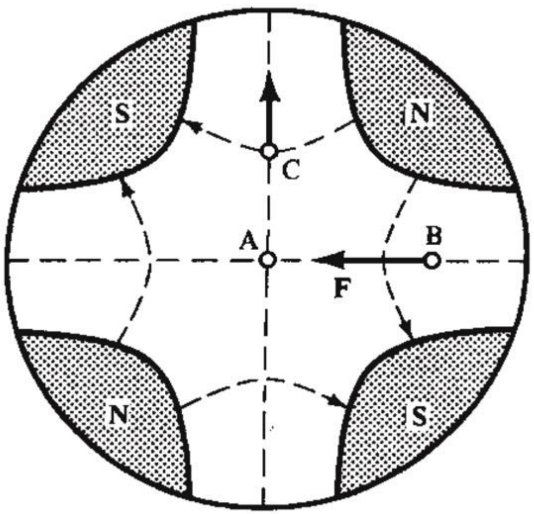
- Combination of a focusing and a defocusing lens with equal focal lengths is always focusing

$$f_{comb} = \frac{f^2}{d}$$

- A train of focusing and defocusing magnets has a net focusing effect

QF – QD – QF – QD -…

Defocusing plane



Focusing plane

Quadrupole magnet

Measurements at particle accelerators

- Two important features of an accelerator.
  - Its center of mass energy
  - Instantaneous luminosity L, which determines the event rates.
- Number of interactions

$$N = \sigma \int \mathcal{L} dt$$

- Usual units of cross-section are barns
  - 1 barn = 1 b = 10^{-28} m^2
- Typical cross-section, for example, $\sigma(t\bar{t})$ = 924 pb at $\sqrt{s}$=13.6 TeV
- Let's assume that we have the integrated luminosity of

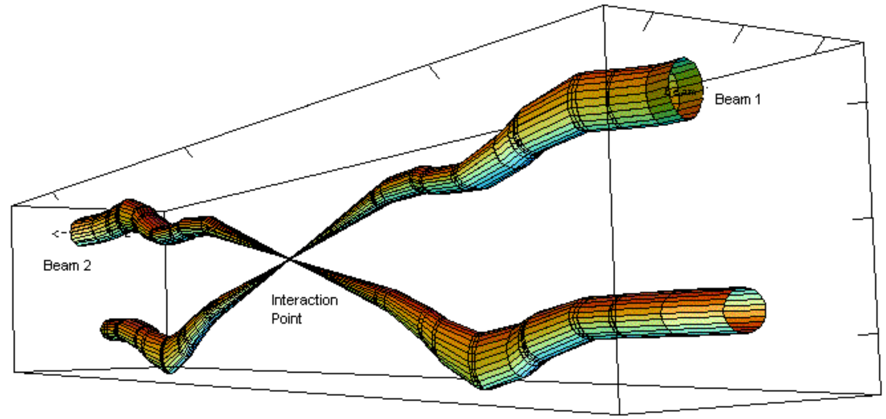
$$\int_0^t \mathcal{L}\ dt = 100\ fb^{-1}$$

- Number of $t\bar{t}$ events N = 924 pb × 100 fb^{-1} = 92,400,000 events

Collisions

- After an accelerator has pumped enough energy into its particles, they collide either with a target or each other

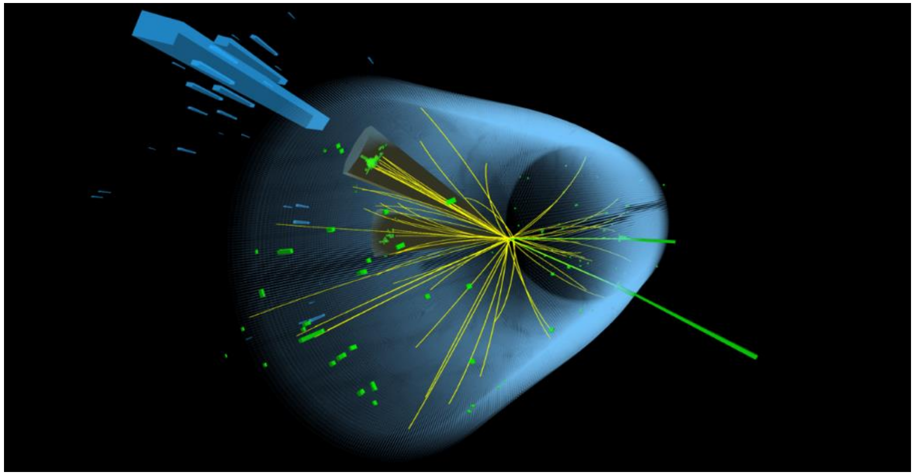
squeeze the beam size down as much as possible at the collision point



Relative beam sizes around IP1 (Atlas) in collision

- For example, 100,000 million protons per bunch down to 64 microns (a human hair) → around 20 collisions per crossing
- At the LHC, bunches cross every 25 ns

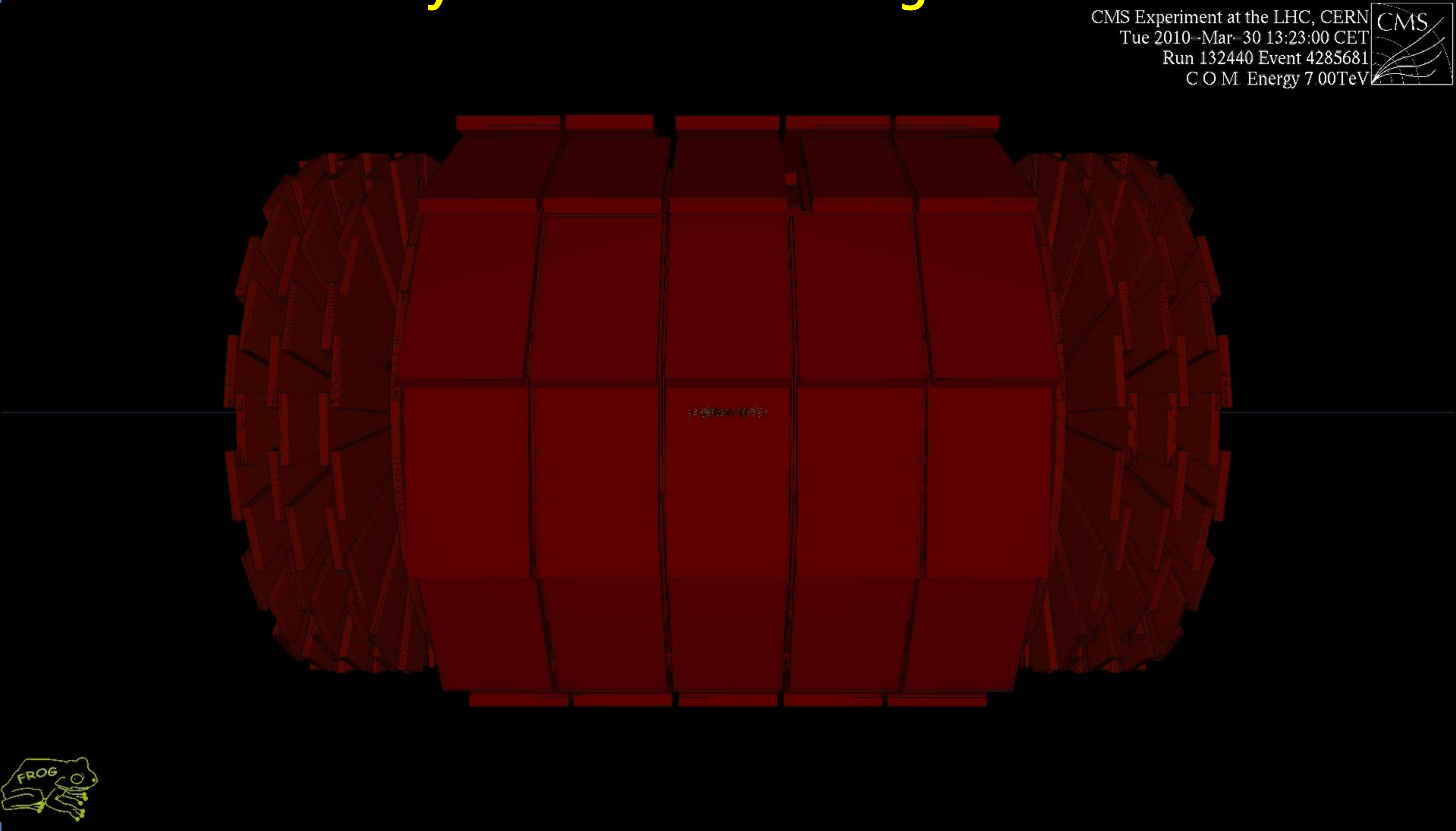
The event



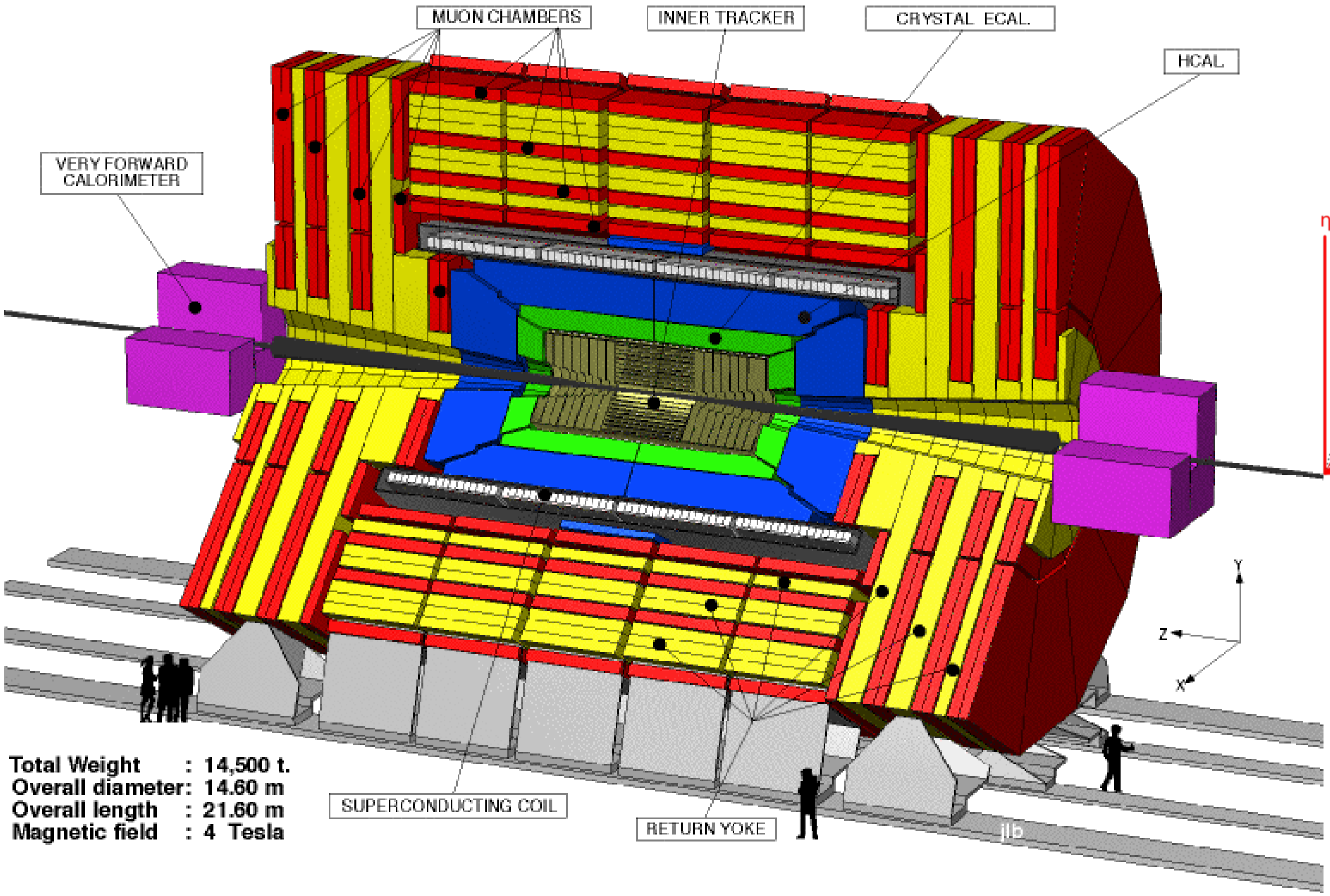
- After an accelerator has pumped enough energy into its particles, they collide either with a target or each other.
- **Each of these collisions is called an event.**
- Each event is very complicated since lots of particles are produced.
- Most of these particles have lifetimes so short that they go an extremely short distance before decaying into other particles and therefore leave no detectable tracks.

A pp interaction at CMS

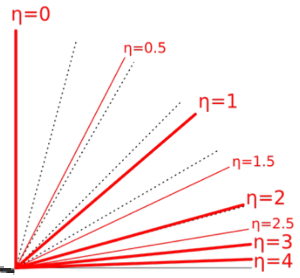
This is where your data are coming from!



Compact Muon Solenoid

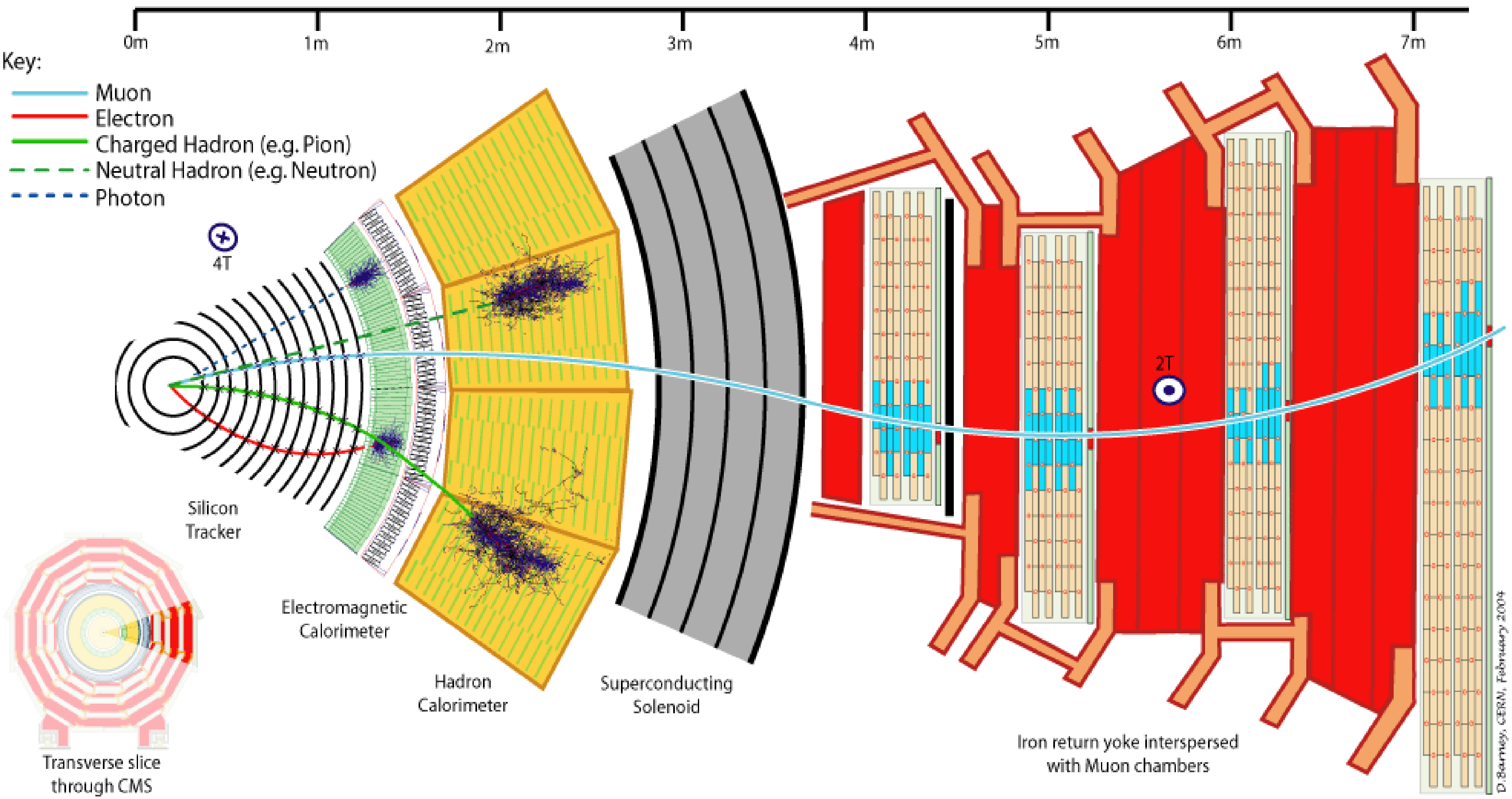


$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

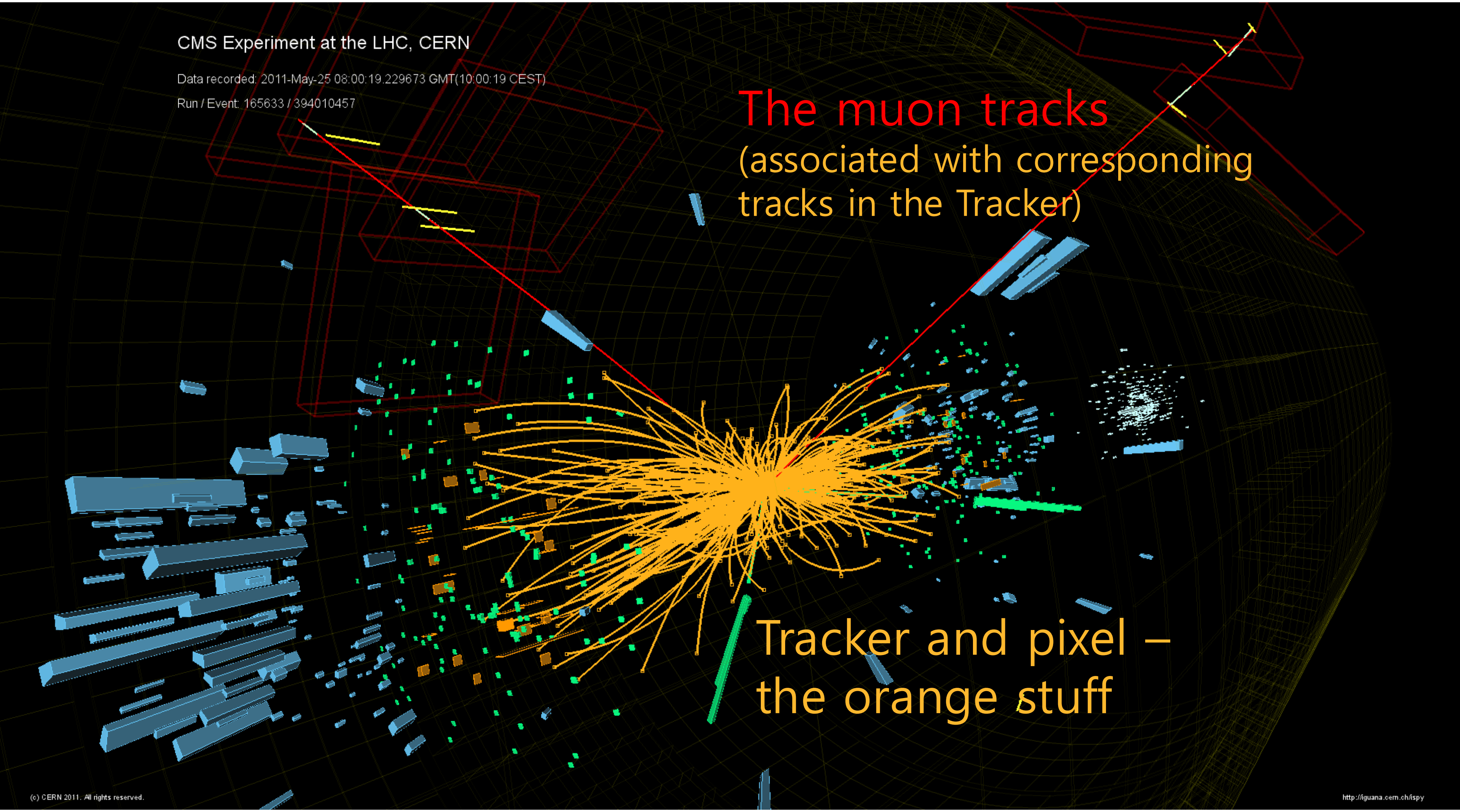


Wikipedia

Detector cross section

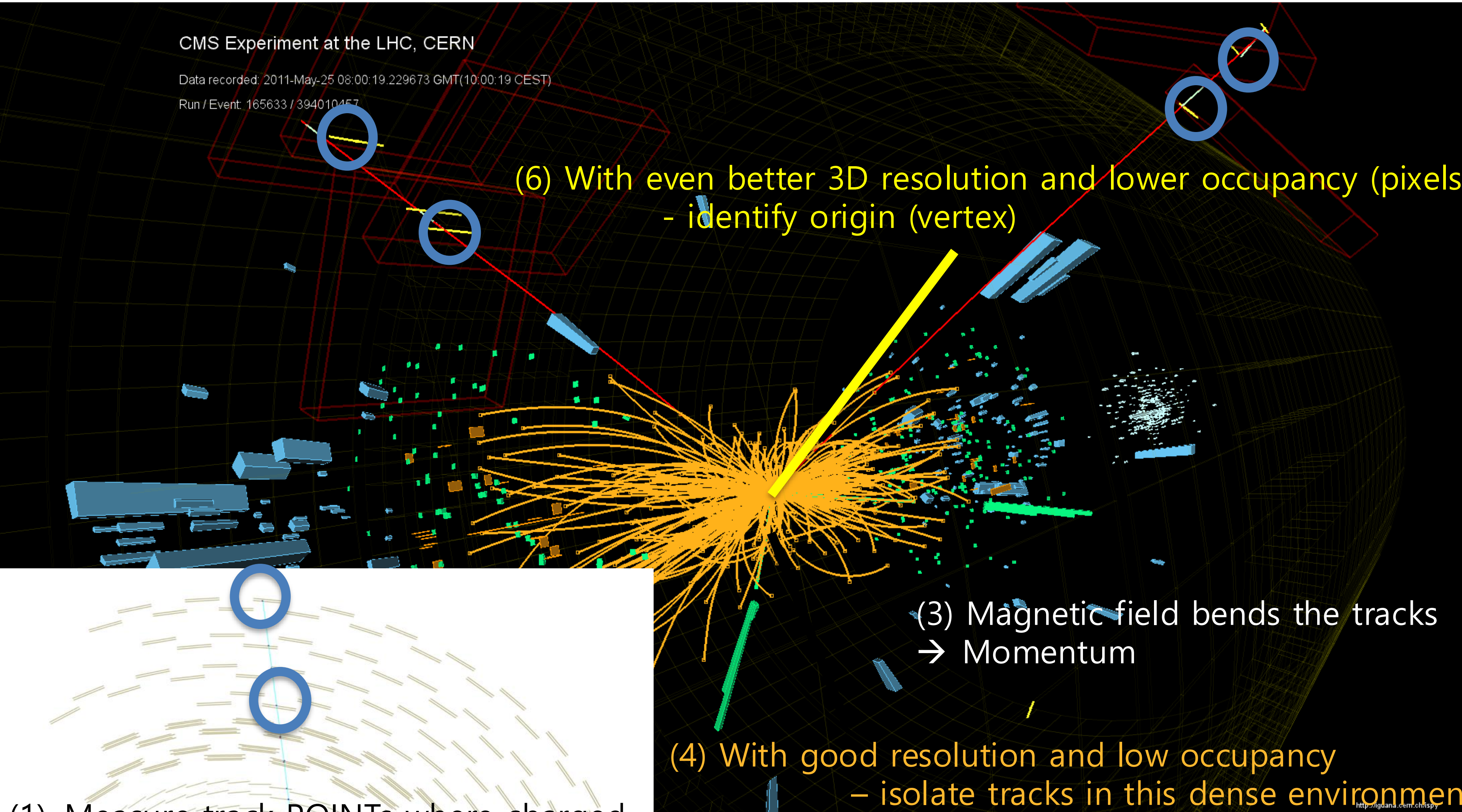


Tracking component of the events



What are the ingredients to get that?

What is the task of these detectors?



(6) With even better 3D resolution and lower occupancy (pixels) - identify origin (vertex)

(3) Magnetic field bends the tracks → Momentum

(4) With good resolution and low occupancy – isolate tracks in this dense environment

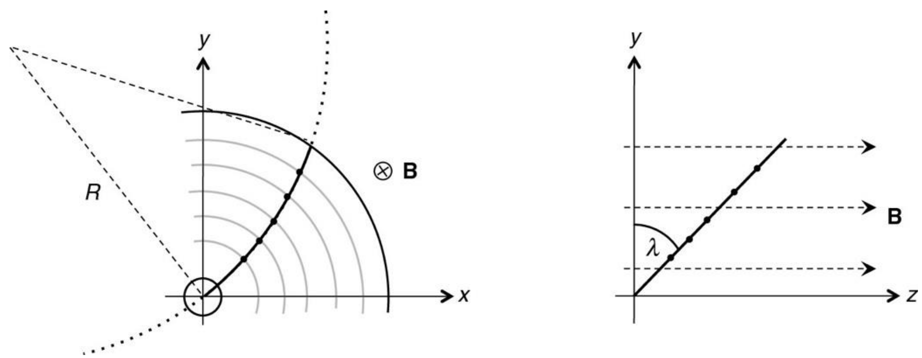
(1) Measure track POINTs where charged particles traverses

(2) Reconstruct tracks (interpolate points)

(5) In conjunction with calorimeters identify particle type

Measuring charge & momentum

- One important function of the detector is to measure a particle's charge and momentum. For this reason, there is a strong field in the inner parts of detector.

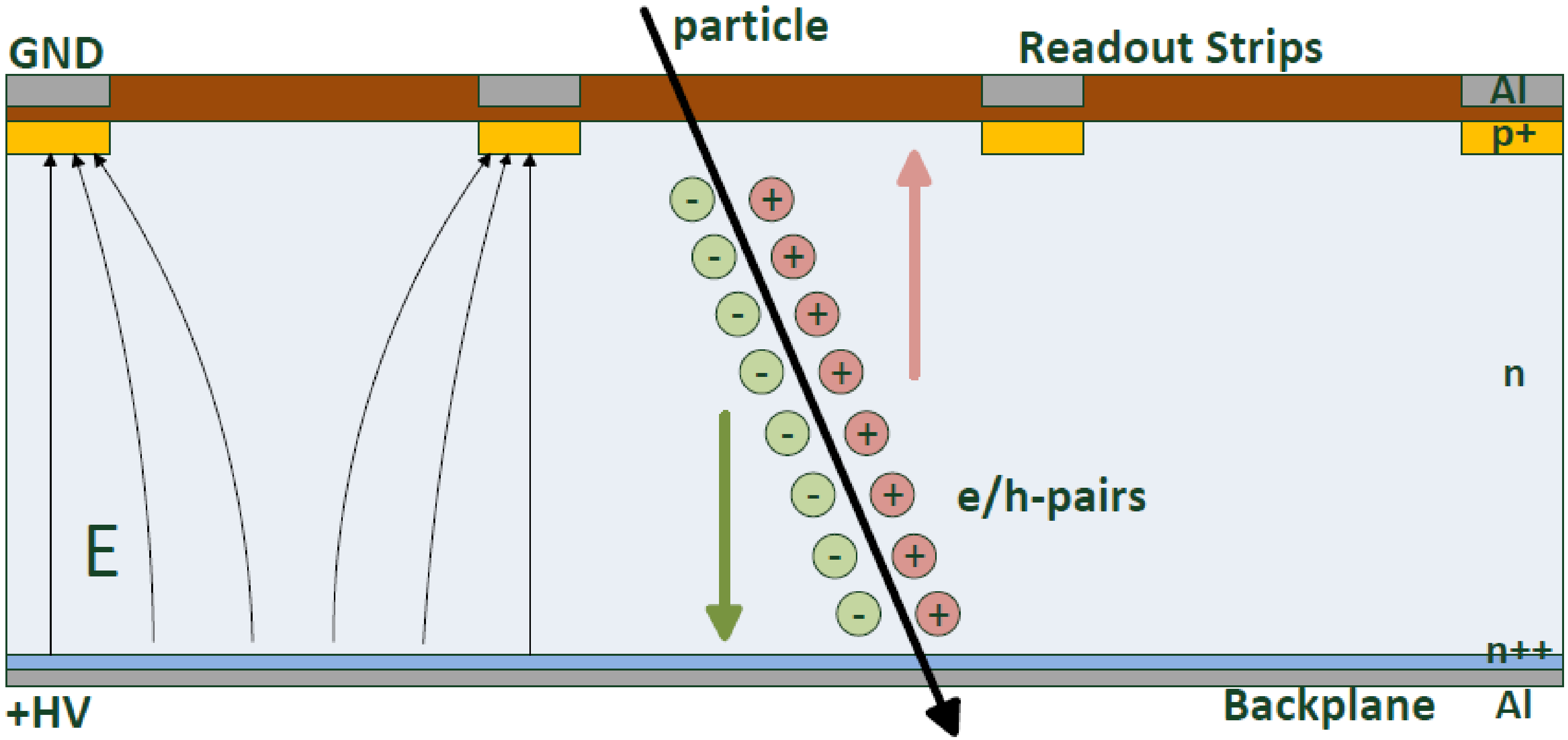


- The signs of the charged particles can be easily reconstructed from their path.
- The momenta of particles can be calculated with its curvature:

$$\boldsymbol{p = 0.3 \cdot B \cdot R}\ \left(\frac{\boldsymbol{GeV}}{\boldsymbol{c}}\right)$$ (B=magnetic field, R=curvature)

Principles of Silicon tracker

- Electron-hole-pairs generated by ionizing particles traversing the silicon are separated by E-field and ‘drift’ to the electrodes
- Most probable MIP signal is ≈22,500 e/h pairs for 300 μm silicon



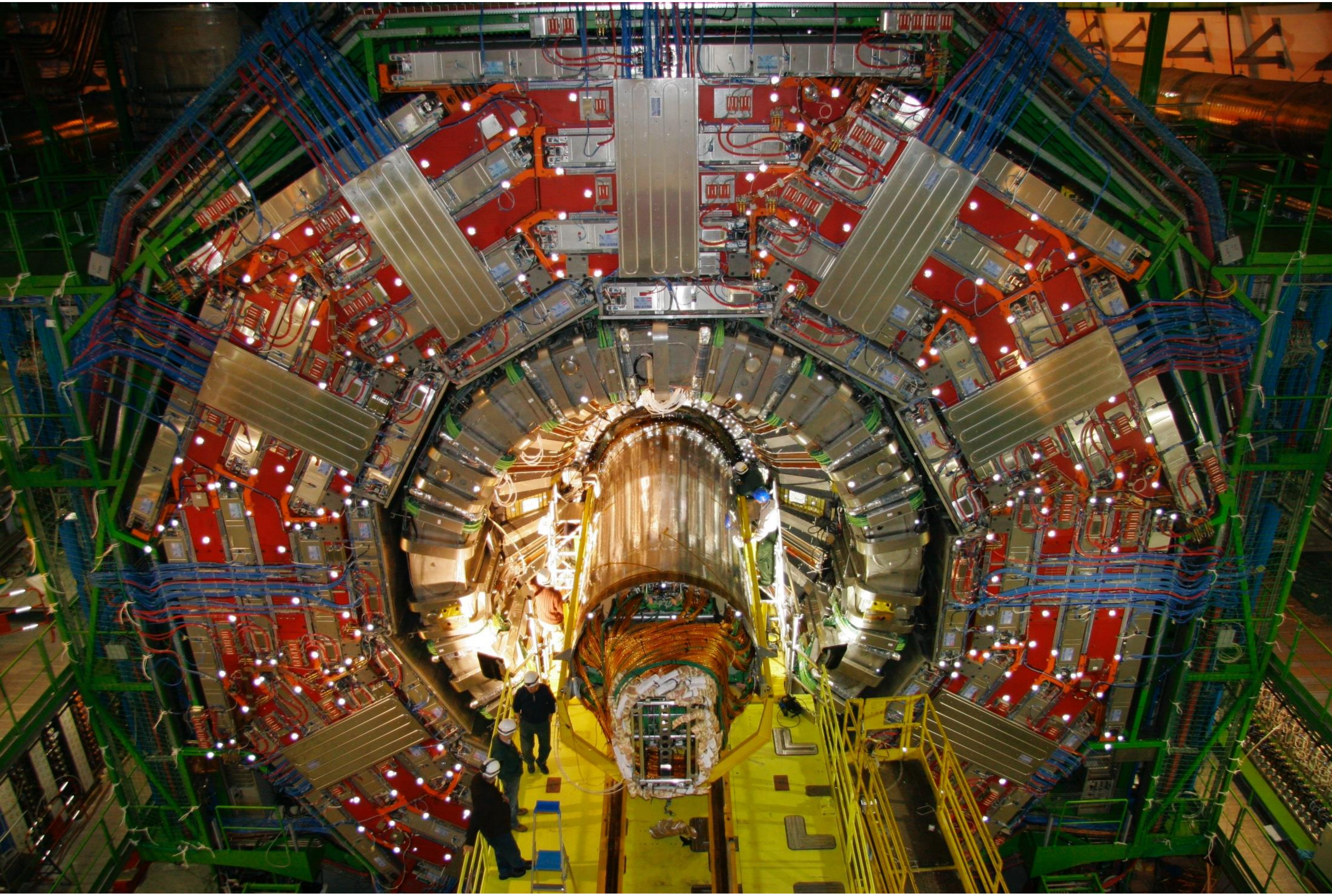
R. Eber, ELECTRIC FIELDS AND CHARGE CARRIER DRIFT IN HIGHLY IRRADIATED SILICON PARTICLE DETECTORS, PhD, IEKP, KIT, 2013

Basically, the same for pixels and strips

- Strips ‘collect’ holes
- Pixels ‘collect’ electrons

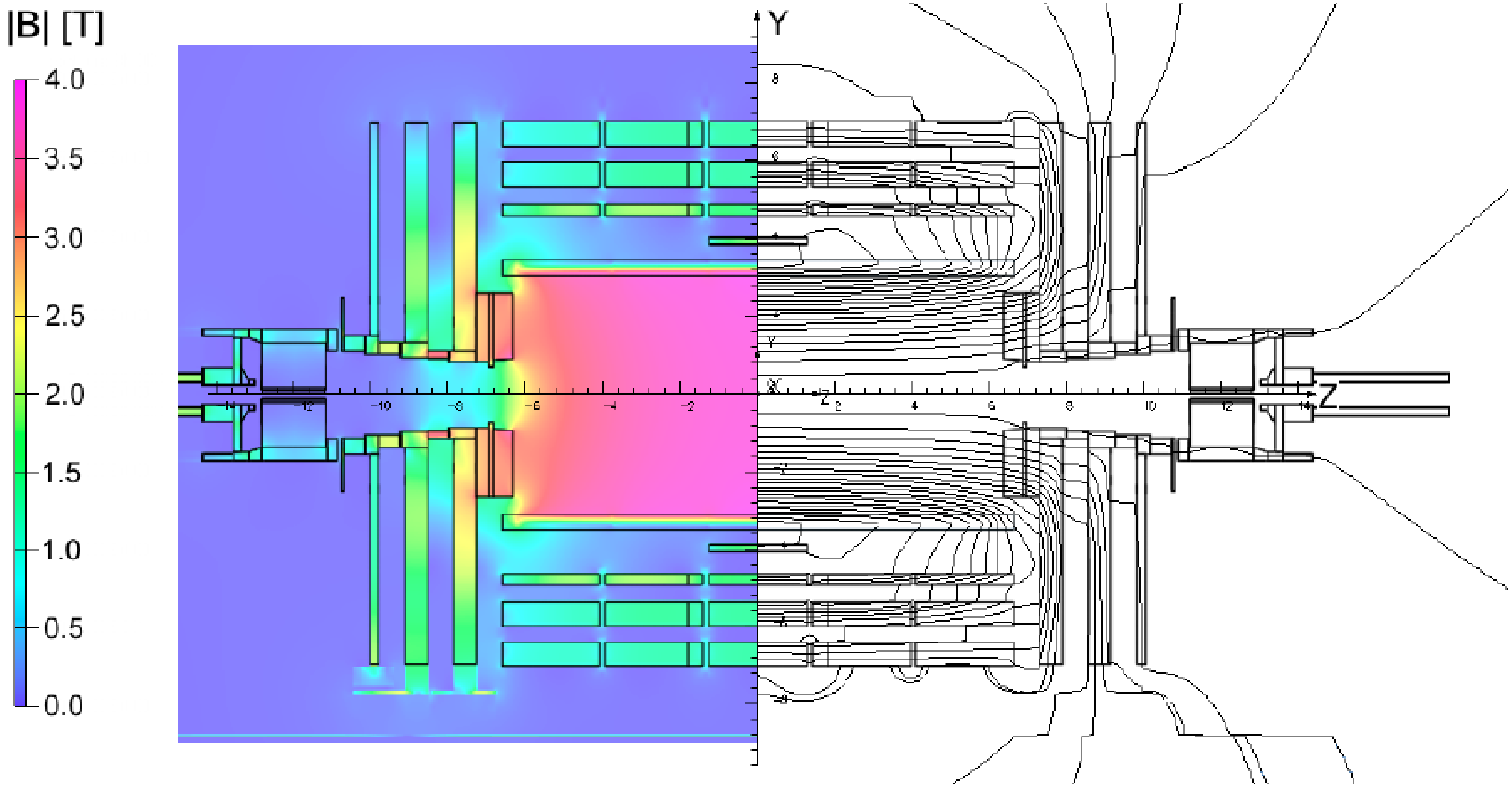
} Depends on ‘polarity’ of implants

Insertion of the CMS Tracker into the Heart of CMS



CMS magnetic field

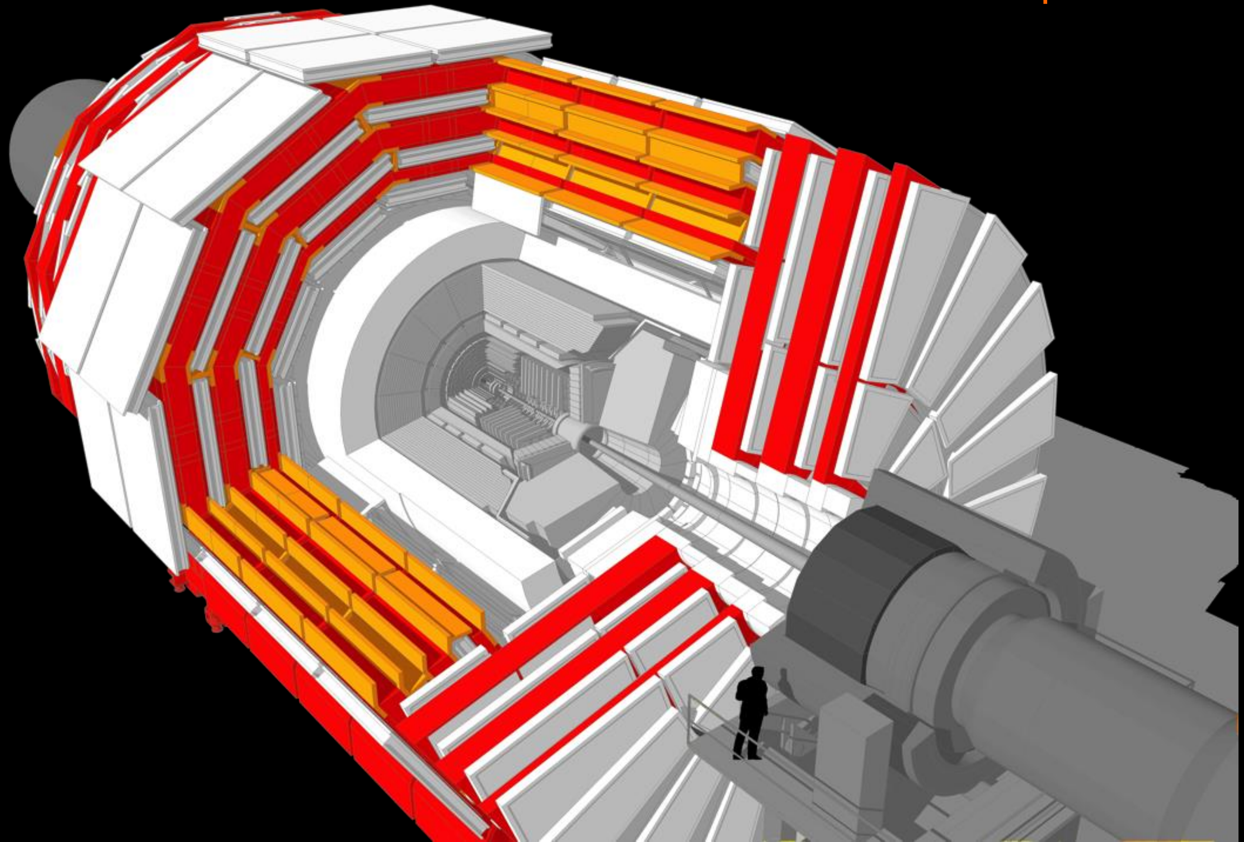
- 3.8T coil is outside of the hadronic calorimeter
  - Tracking detectors are inside the coil
  - Muon detectors are outside the coil



The Layers of CMS: MUON

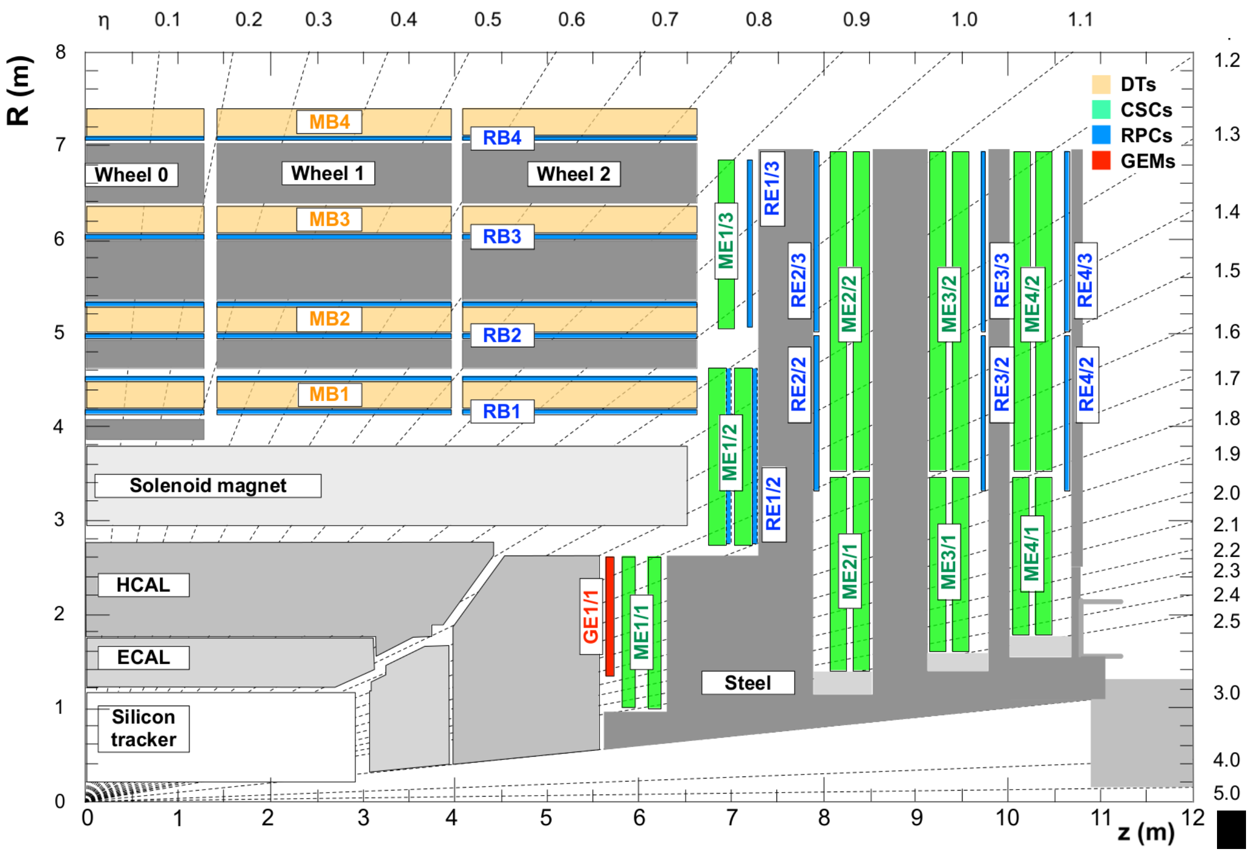
To identify muons (essentially heavy elect rons) and measure their momenta, CMS uses four types of detectors:

- Drift Tubes – **DT**
- Cathode Strip Chambers – **CSC**
- Resistive Plate Chambers – **RPC**
- Gas Electron Multipliers – **GEM**



Cross section of CMS (r-z)

- Four types of detector:
  - Precise position measurement and triggering by Drift Tubes (DT) in the barrel, and Cathode Strip Chambers (CSC) and Gas Electron Multipliers (GEM) in the endcap
  - Redundant triggering, and bunch tagging by Resistive Plate Chambers (RPC)



Barrel: $0 < |\eta| < 1.2$

5 wheels / 4 stations instrumented with DTs and RPCs

Endcap: $0.9 < |\eta| < 2.4$

3 discs / 4 stations instrumented with CSCs and RPCs

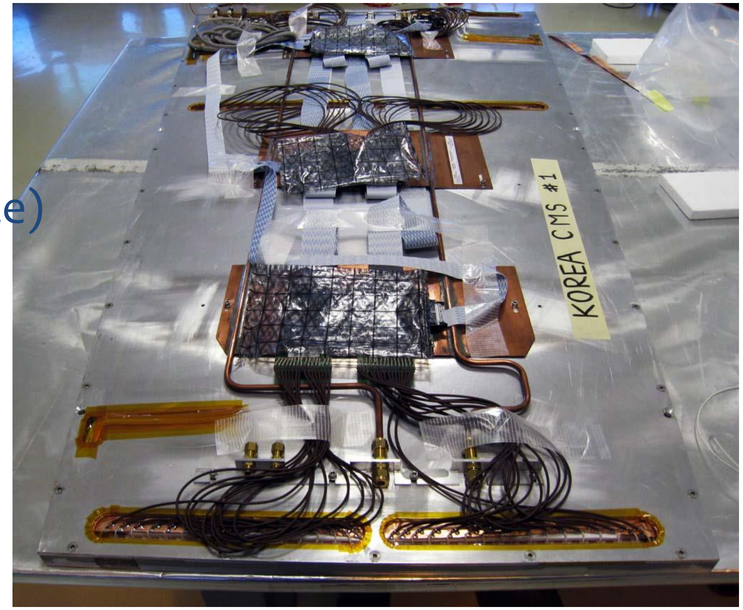
Spatial resolution 75-150 μm /station

Muon detector

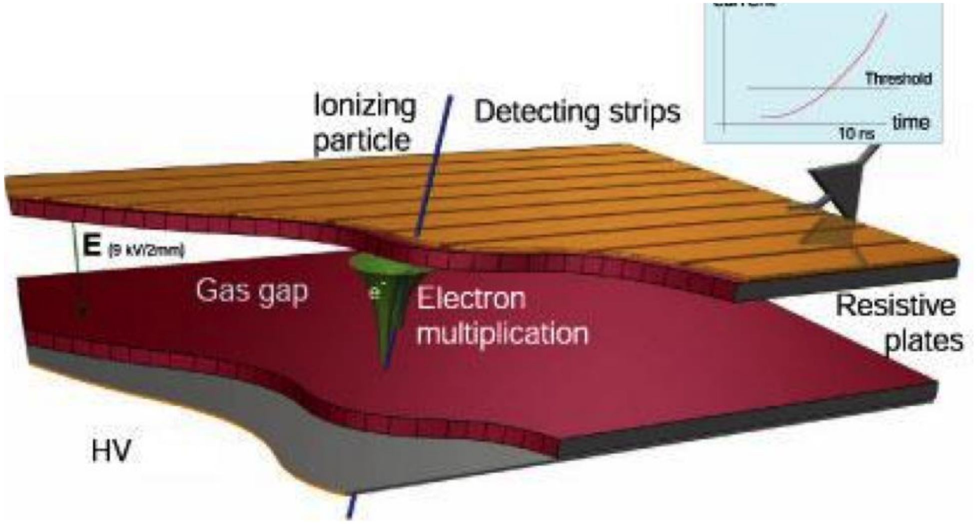
- One of muon detector is Resistive Plate Chamber (RPC).
- Fast gaseous detectors that provide a muon trigger system.
- Consist of two parallel plates, a positively charged anode and a negatively-charge cathode, both made of a very high resistivity plastic material separated by a gas volume.

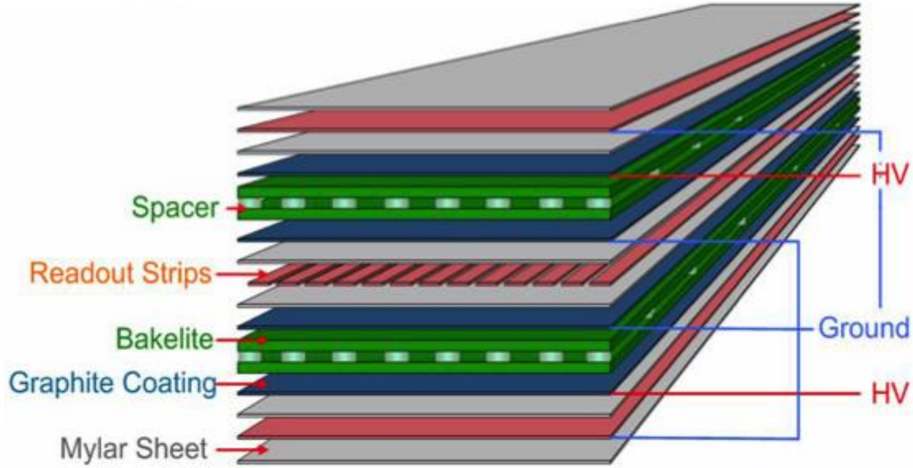
CMS Resistive Plate Chambers (RPC)

- **480 barrel** and **576 endcap** chambers in CMS
- Charge induced onto external strips
- Consist of two parallel plates: Resistive layer (Bakelite) with $\rho \sim 10^{10}\ \Omega$ cm is transparent to signal, quenches avalanche
- Spatial resolution 0.8-1.2 centimeters
- Double gap, each 2 mm, 9.6 kV, for high efficiency
- Fast - triggering



General RPC principle

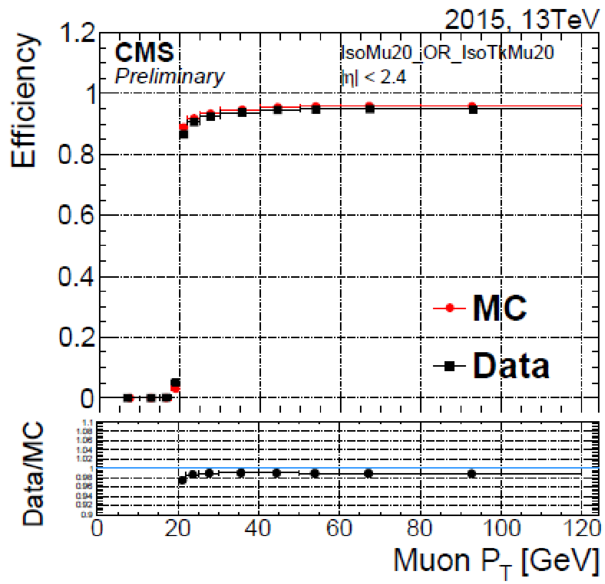


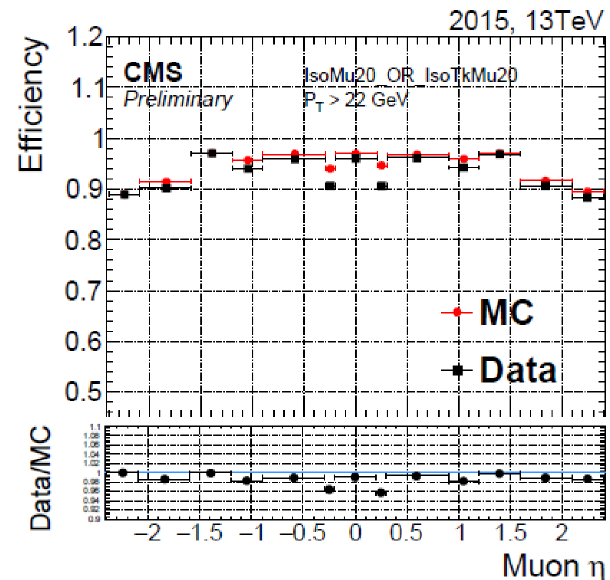


Muon trigger and offline efficiencies

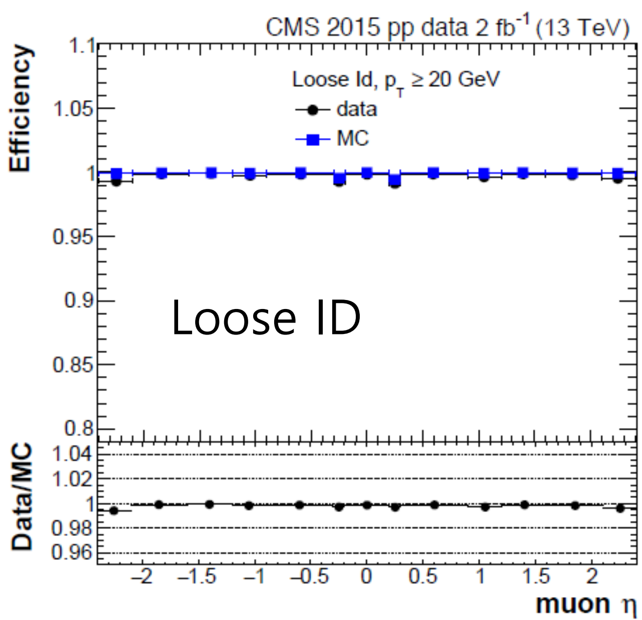
versus momentum | **versus pseudorapidity**

High-Level trigger

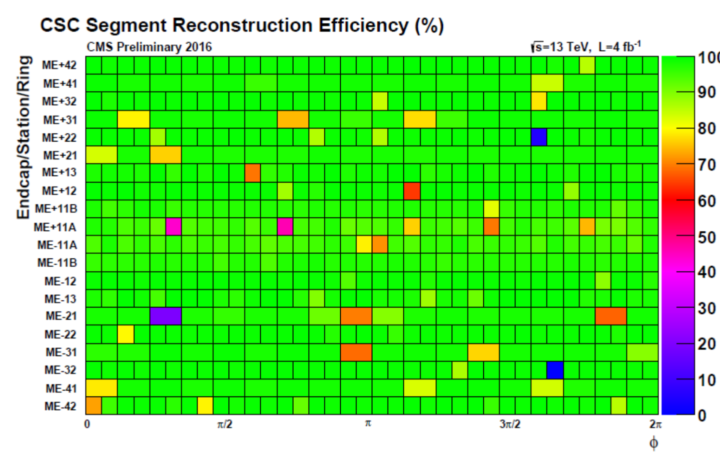




Reconstruction + ID efficiency vs η -- simulation

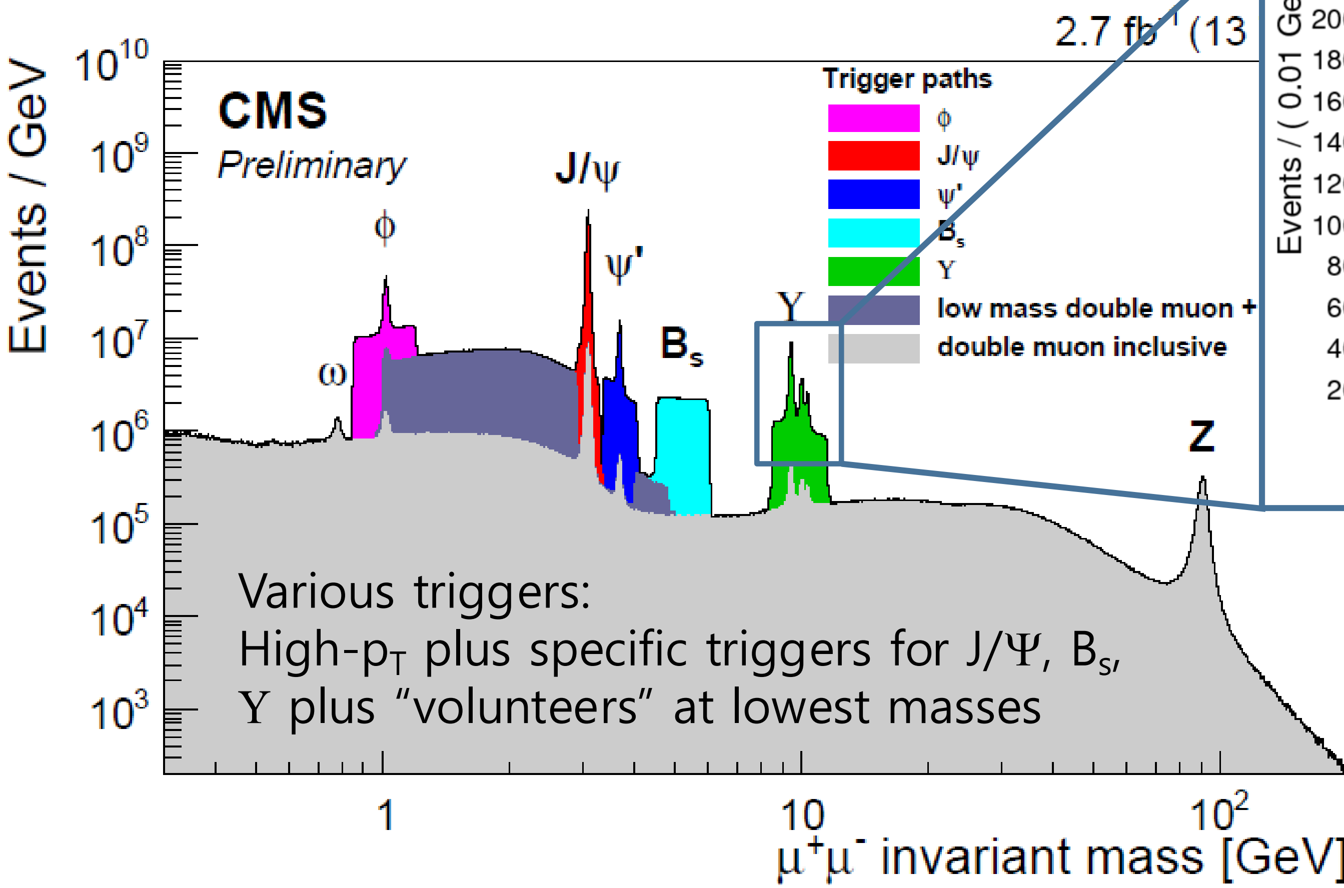


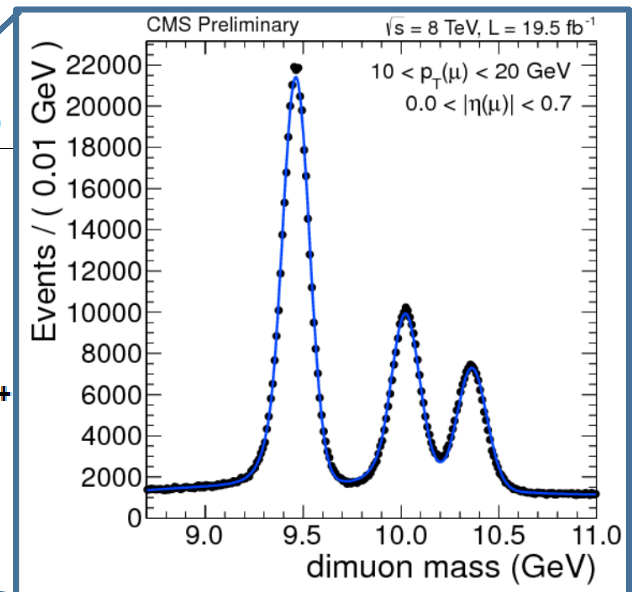
Example: CSC segment effi ciency, per chamber



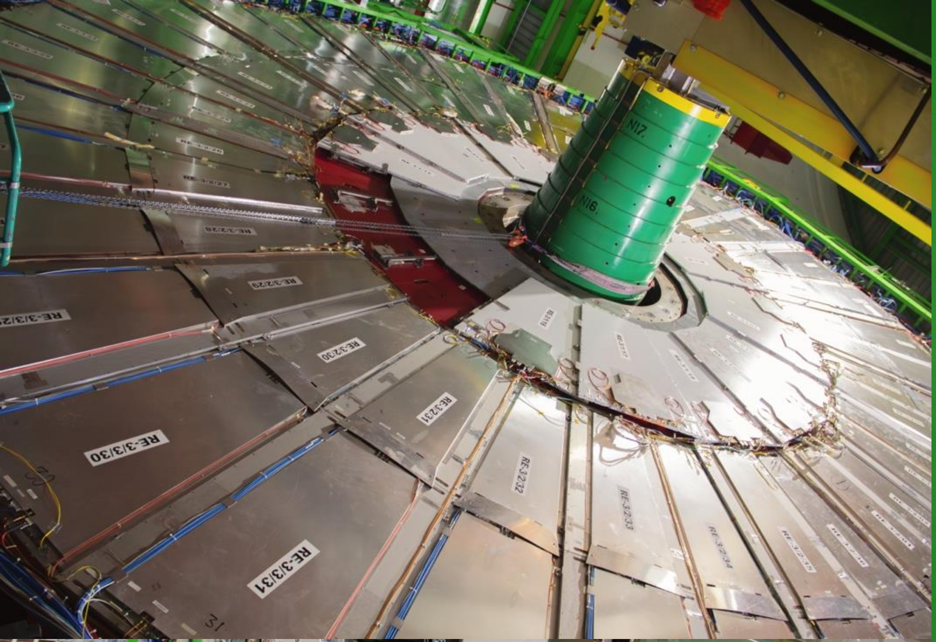
Physics example: dimuon mass spectrum

- Trigger CMS readout on muon pairs of various types
- Verify high muon quality by matching muon hits with silicon tracker tracks; use momentum vectors from the silicon tracker fitting
- Form invariant mass of muon pair
- Several Nobel prizes in this one plot:

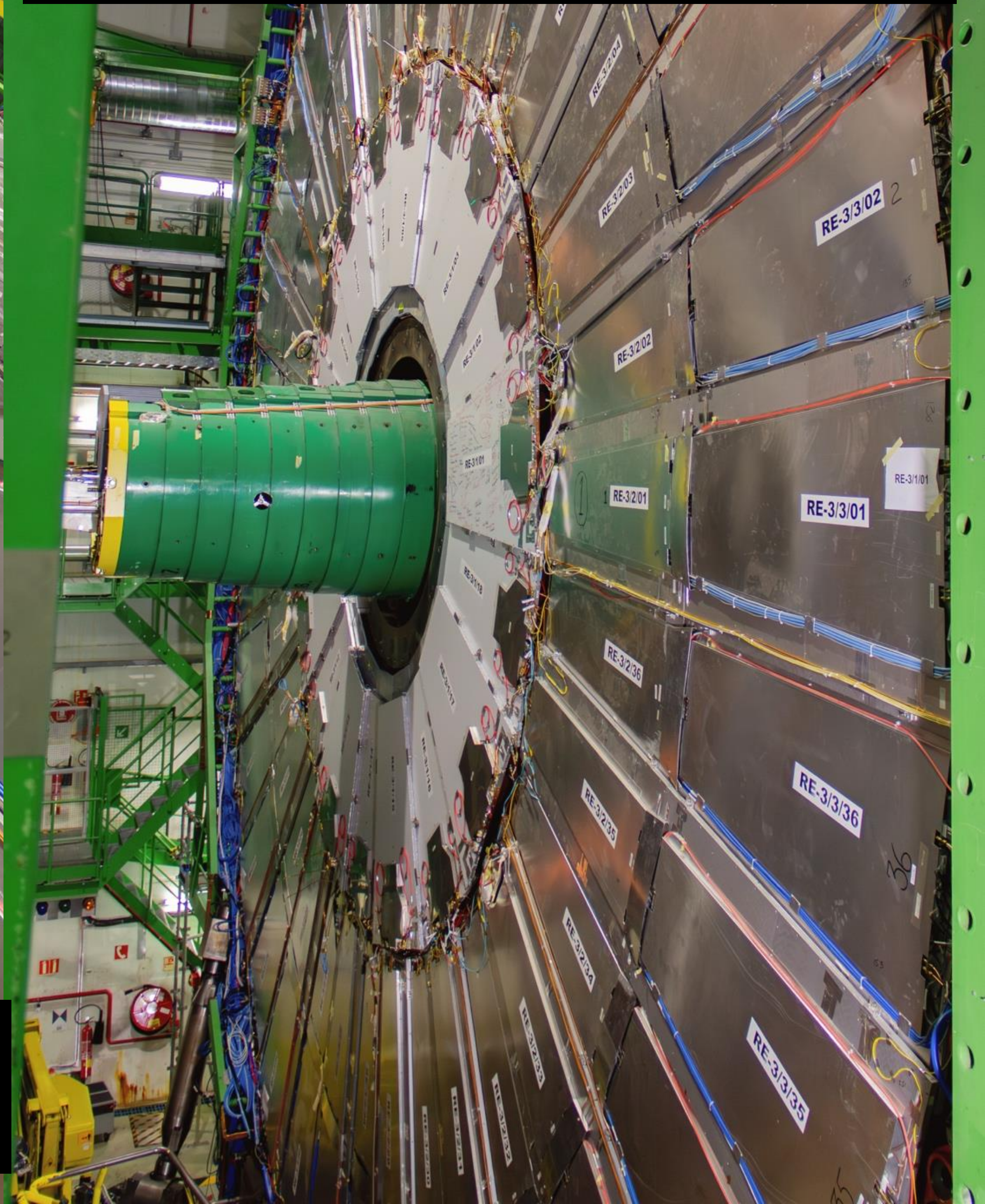




The full power of the CMS tracking detectors and the CMS magnet in one plot



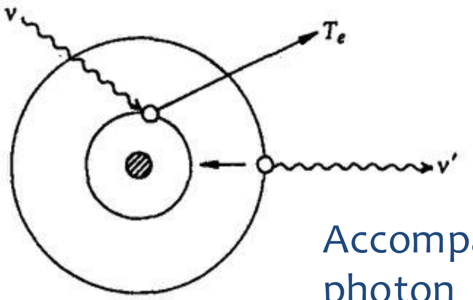
Installation of the RE3/1 Chamber
Complete!



Installation of the RE3/1 Chamber
January 2025

Interactions of photon with Matter

- **Photoelectric effect (below~1 MeV)**



Accompanied by an X-ray photon

$$E_\gamma = h\nu = I_B + T_e$$

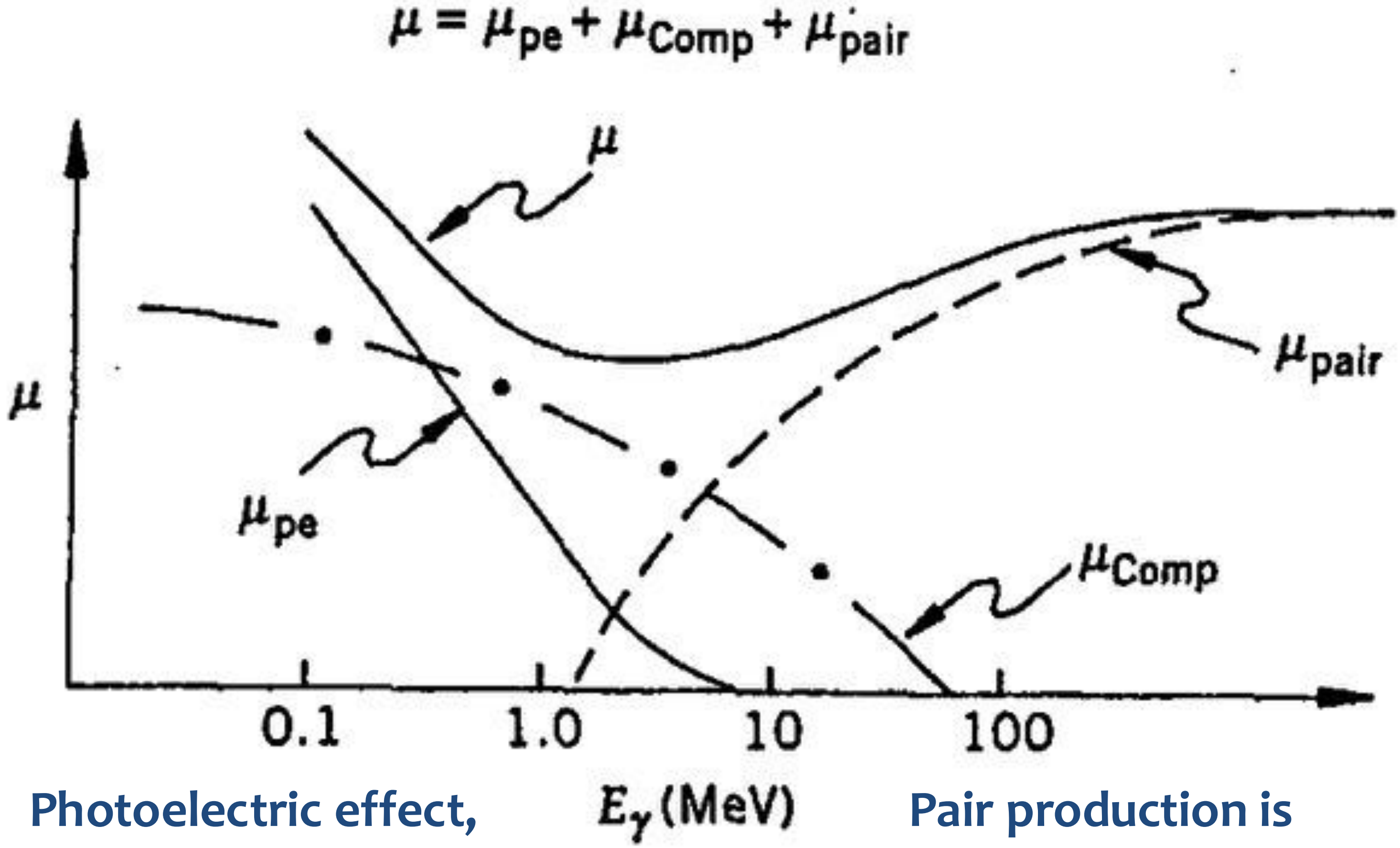
or

$$T_e = h\nu - I_B$$

- **Compton scattering (0.1~10 MeV)**

$$\nu' = \frac{\nu}{1+\frac{h\nu}{mc^2}(1-\cos\theta)}$$

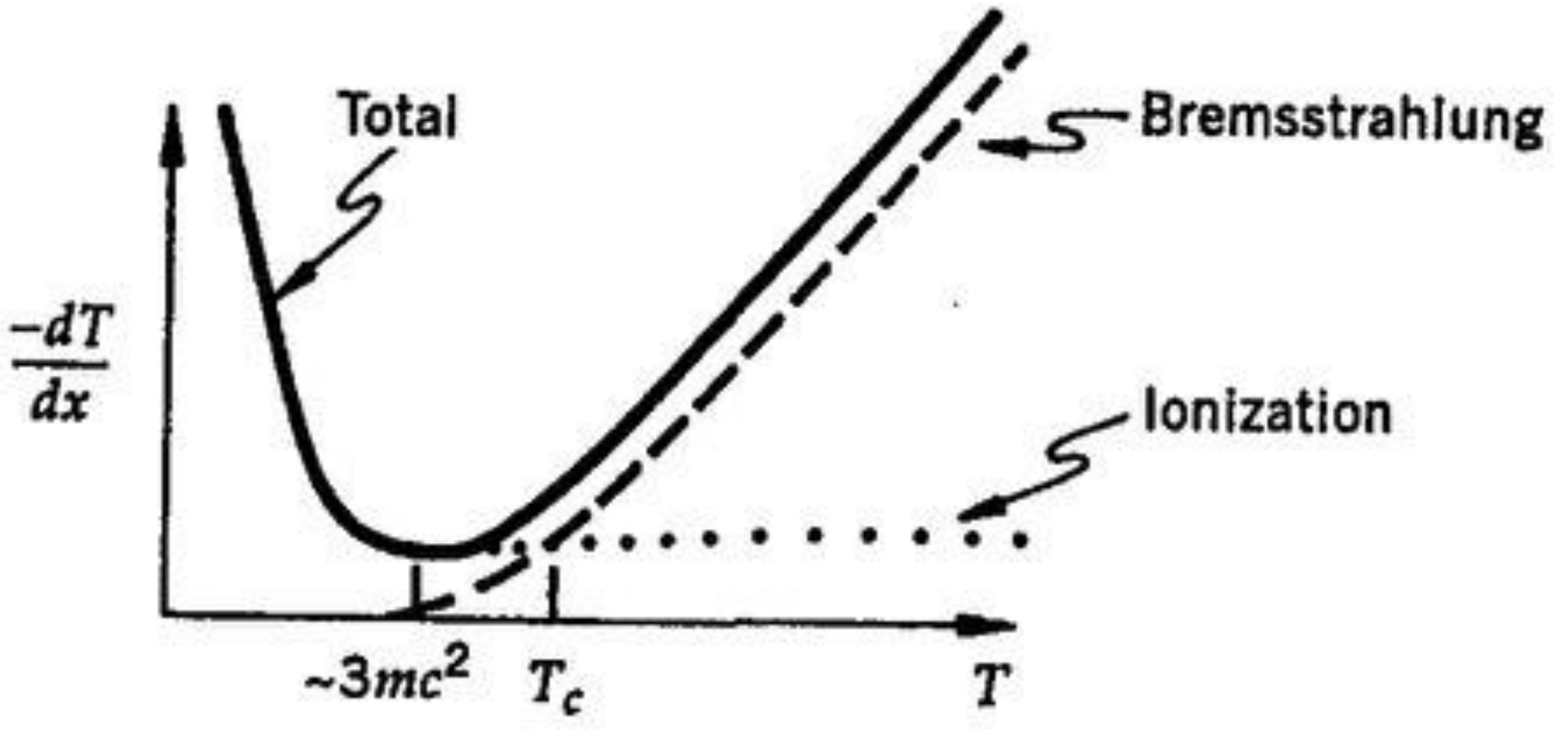
Photon energy loss



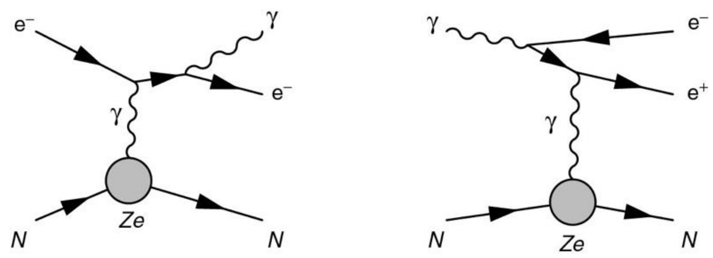
Photoelectric effect, Compton scattering (low energy)

Pair production is dominant in high-energy (E_γ>1 GeV)

Electron energy loss

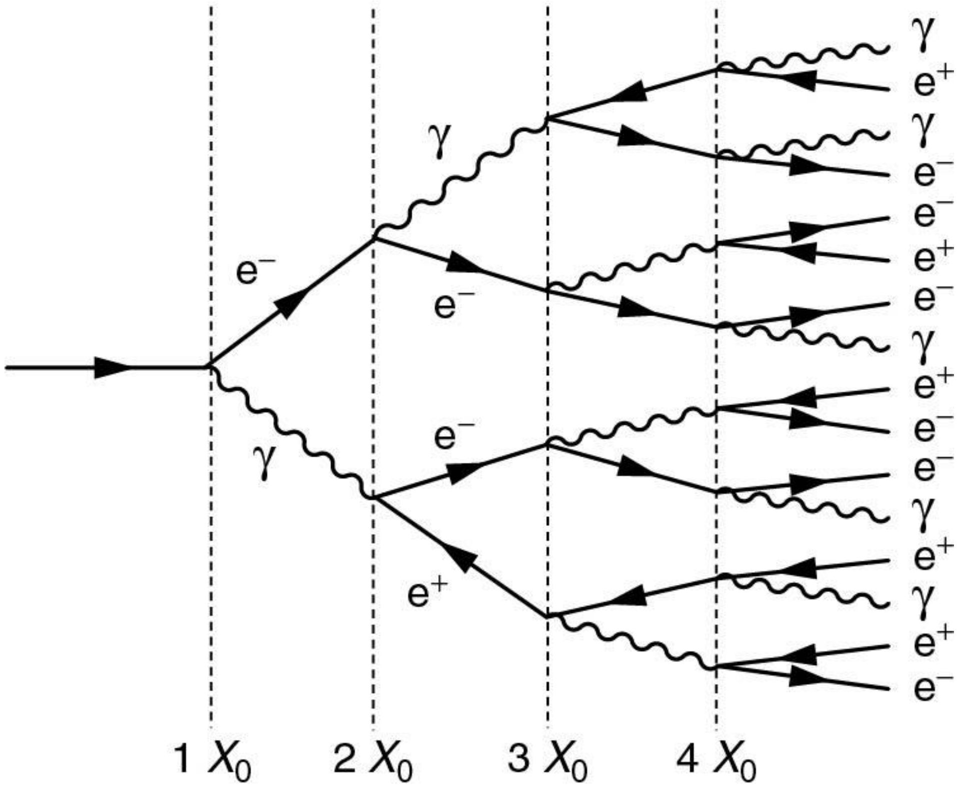


Electron and photon in high energy



- The radiation length (X_0) is defined as the distance over which a high-energy electron or positron loses, on average., 63.2% $(1 - e^{-1})$ of its energy to bremsstrahlung.
- For example, high-energy electrons lose the same fraction of their energy in 18 cm of water (0.5 X_0) as in 2.8 mm of lead (0.5 X_0).

Electron-photon showers



- Average Energy after x radiation length

$$\langle E \rangle \approx \frac{E}{2^x}$$

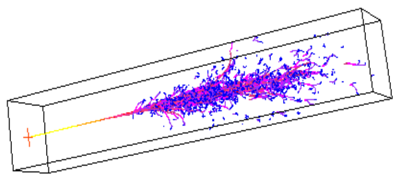
- Radiation length

$$x_{max} = \frac{\ln(E/E_c)}{\ln 2}$$

- Electrons: irradiate photons until their energy becomes less than the cr itical energy (E_c) – material dependent
- Photons: pair productions occurs until $E_\gamma < 2m_e$

Electromagnetic Calorimeter

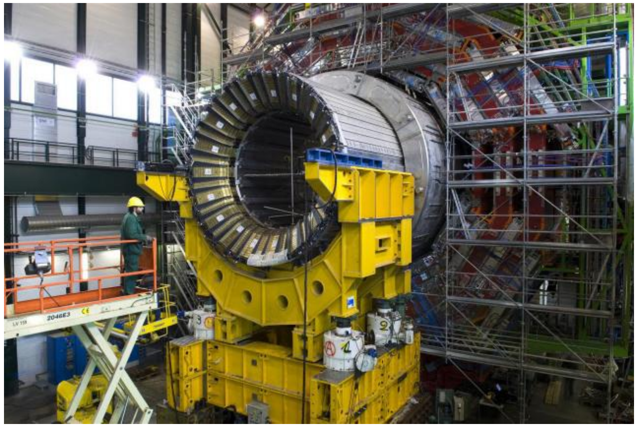
- Electrons/photons are measured using an electromagnetic calorimeter (ECAL).
- CMS ECAL: Homogenous lead-tungstate ($\mathbf{PbWO_4}$) crystal - Highly transparent and scintillate when electrons and photons pass through it.
- It produces light in proportion to the particle's energy.
- Photodetectors are glued onto the back of each of the crystals to detect the scintillation light and convert it to an electrical signal that is amplified and sent for analysis.



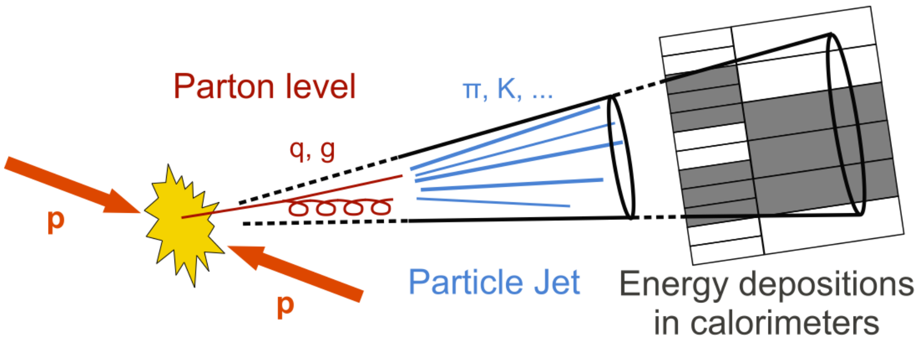
- Lead tungstate ($PbWO_4$) crystals each weigh 1.5 kg for a volume of a small coffee cup.
- Radiation length ~ X_0=0.85 cm
- Contains nearly 80000 such crystals.

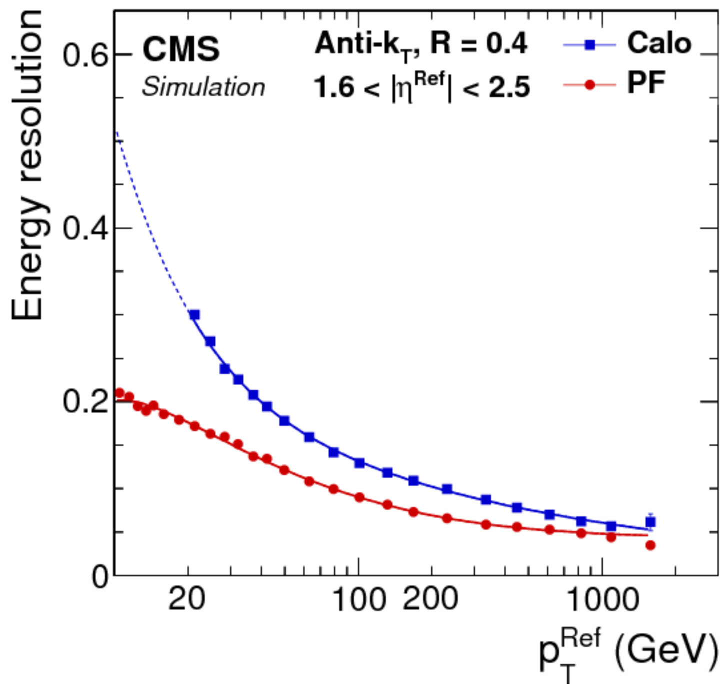
Hadron calorimeter

- Charged Hadrons (Neutrons, protons, pions, etc.) interact with nuclei through the strong interaction.
- The interaction length (λ_{int}) is the average distance a high-energy hadron has to travel inside that medium before a nuclear interaction occurs.
- CMS Hadron calorimeter
  - Sample calorimeter with brass sandwiched with plastic scintillator
  - has ~5 λ_{int}
  - The particles pass through the active scintillation material causing them to emit blue-violet light.



Jets





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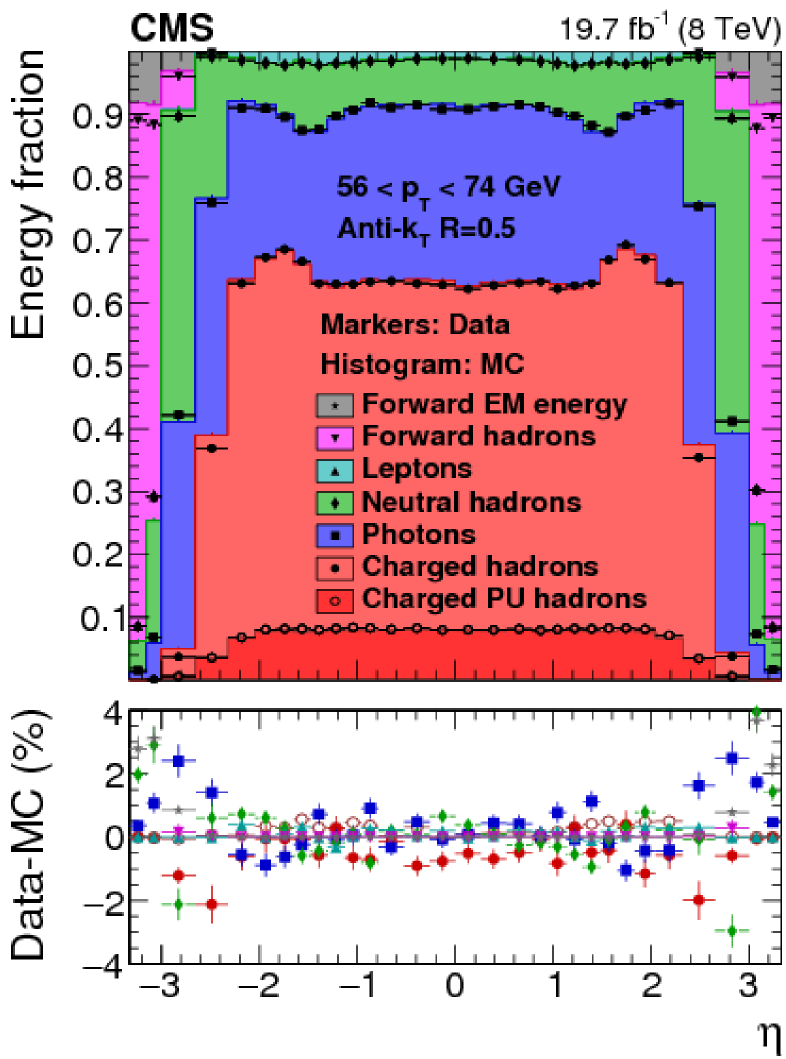
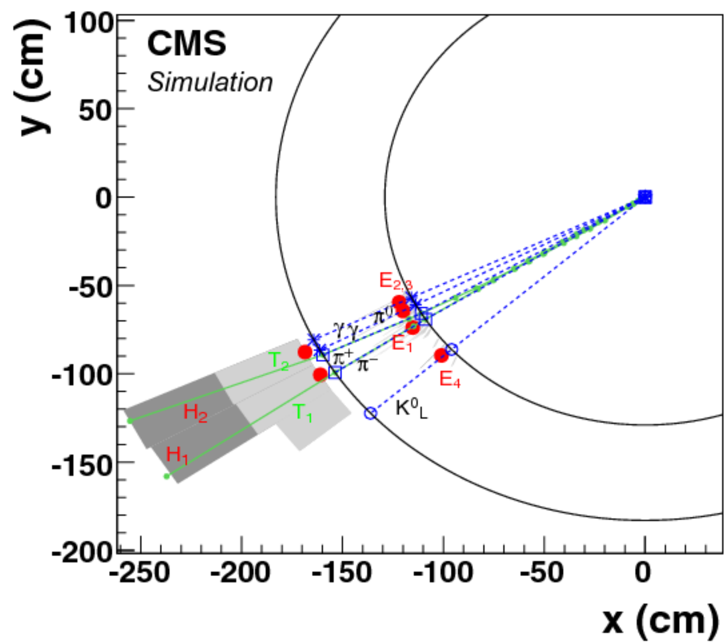
- Quarks and Gluons go through Hadronization (confinement process)
- Jets: Clustering of energy of stable particles in a calorimeter
- Jet energy resolution gets better when the energy is higher with $1/\sqrt{E}$ (Stochastic term)

Particle Flow Jet



- Charged particle ~ 65%
- Photons ~ 25%
- Neutral particle ~ 10%

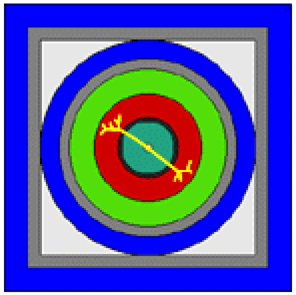


- Replace charged particle energy by track momentum

Quiz

- There are 6 possible decays of a Z particle
- Try to identify the particles that left these tracks

1



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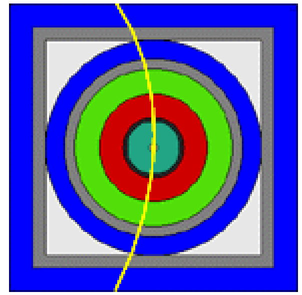

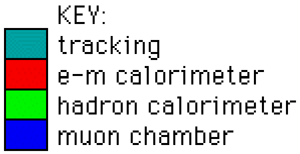

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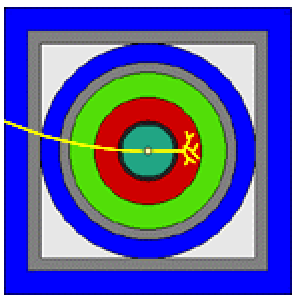

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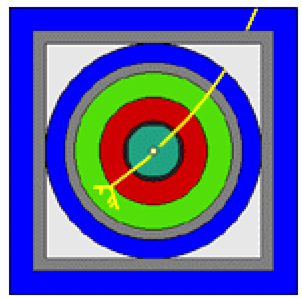

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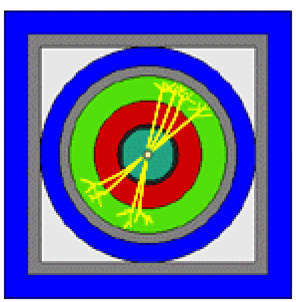

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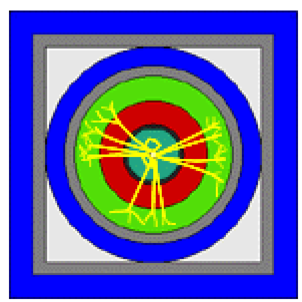

The ultimate Pile-Up, so far