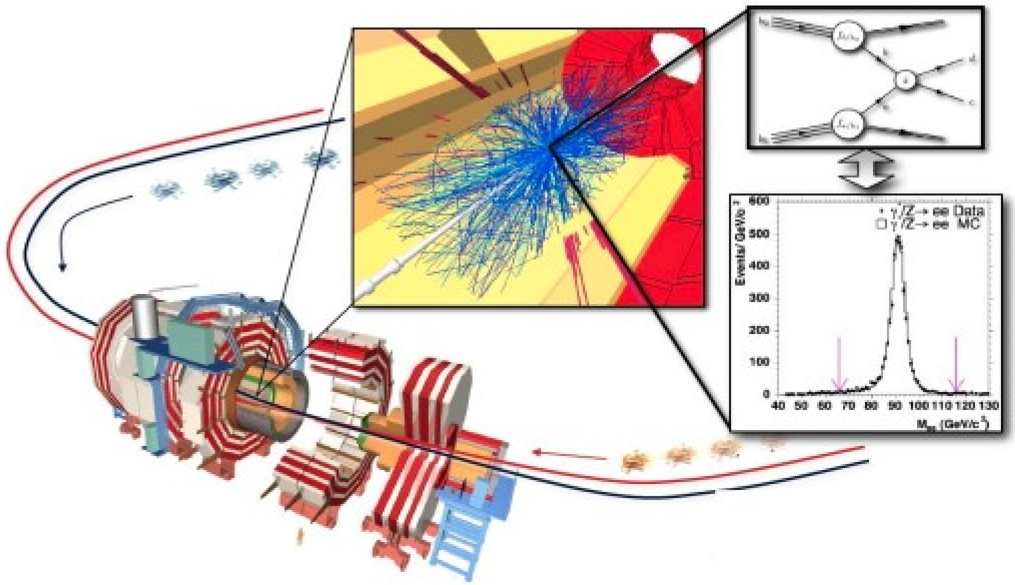
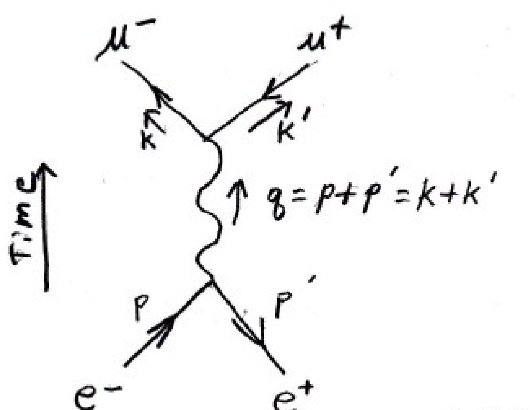


Experimental Z mass measurement with the CMS detector

G71 Física de Partículas Elementales

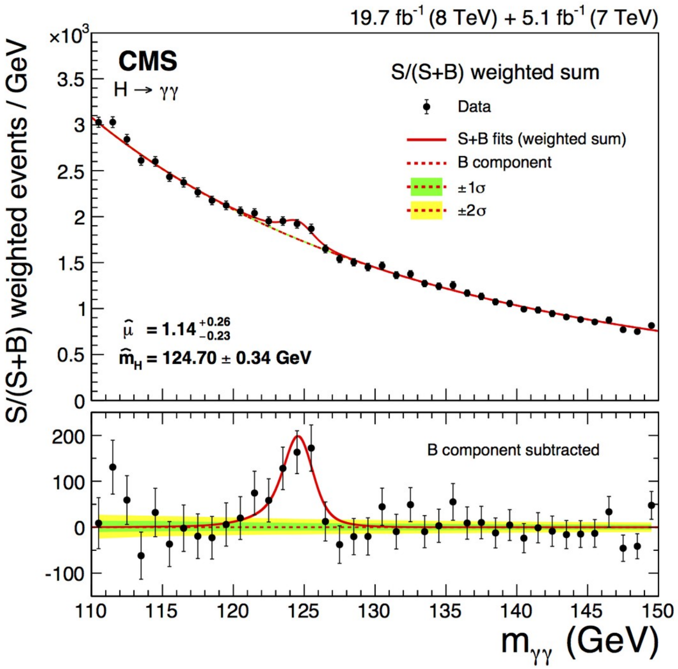
Prelude: Theory vs Experiment

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + h.c. + \bar{\Psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$



$\langle \text{final state} | H_I | \text{initial state} \rangle$

$\mathcal{M} \sim \langle \mu^+\mu^- | H_I | \gamma \rangle^\mu \langle \gamma | H_I | e^+e^- \rangle_\mu$

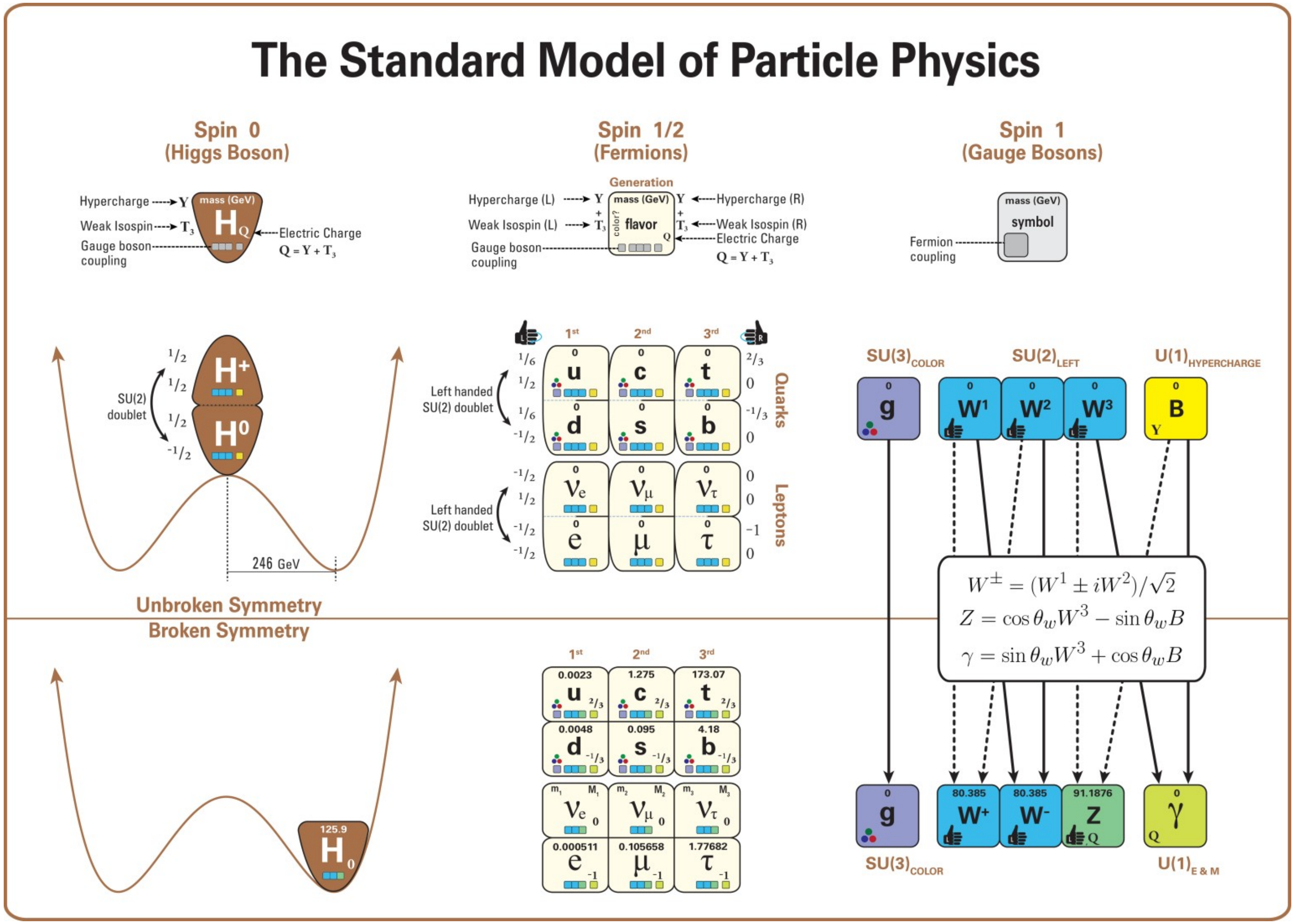


Outline

- The Z boson: a brief theoretical introduction
- Experimental Setup:
    - The CMS detector
    - Data analysis in particle physics
        - Muon reconstruction
        - Di-lepton invariant mass observable
- Experimental results

The Z boson:
A brief theoretical description

The Standard Model of Particle Physics



- Describes particles and its interactions using (special) relativity and quantum field theory
  - Gauge group: SU(3)xSU(2)xU(1)
  - General relativity NOT included

Our target: The Z Boson

- The W and Z bosons **MEDIATE** the weak interaction
- Z boson **decays always** into a fermion and its anti-particle

DPG

Mass:

VALUE (GeV)
91.1876±0.0021 OUR FIT

Width:

VALUE (GeV)
2.4952±0.0023 OUR FIT

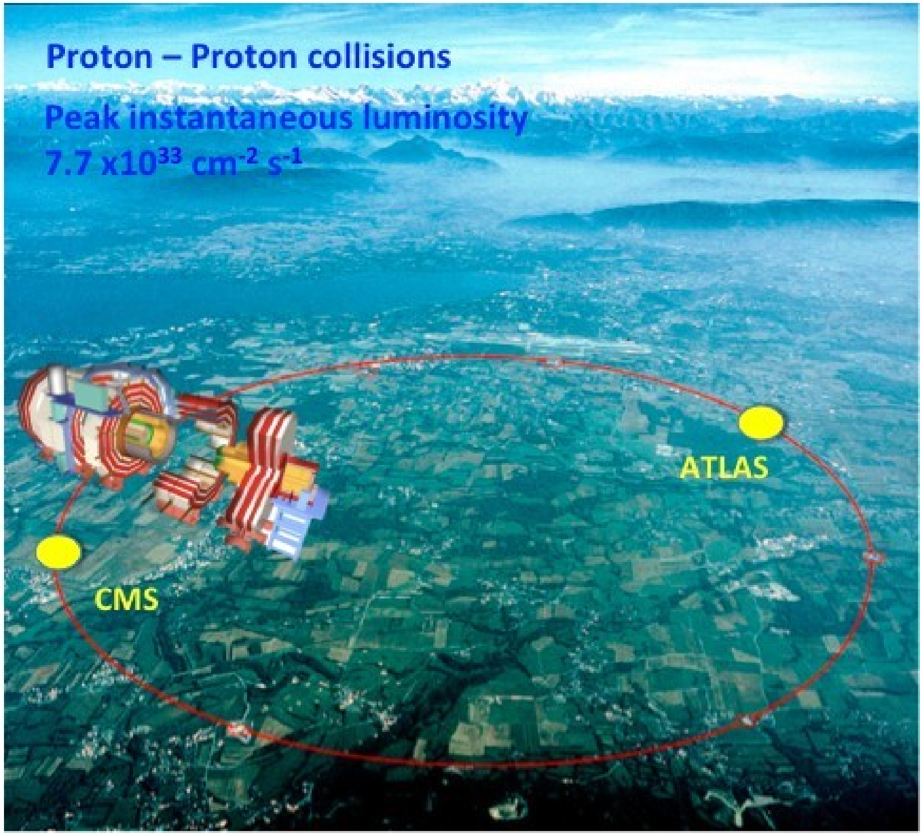
Decay width (lepton universality)

Γ_1	e^+e^-		(3.363 ± 0.004) %
Γ_2	$\mu^+\mu^-$		(3.366 ± 0.007) %
Γ_3	$\tau^+\tau^-$		(3.370 ± 0.008) %
Γ_4	$\ell^+\ell^-$	[a]	(3.3658 ± 0.0023) %

Z boson has a lifetime of 3x10-25 s → Difficult to detect

Z production: LHC

Z bosons are not found in natural conditions → We have to produce them



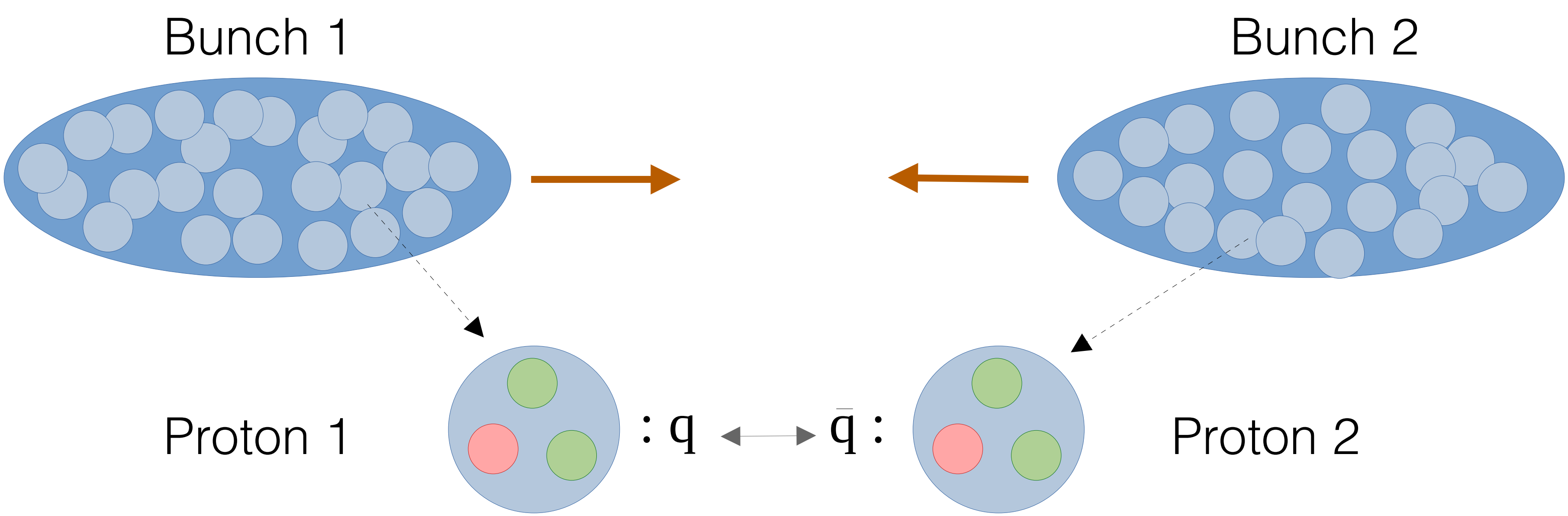
In the LHC, protons are accelerated in bunches (~ 10^{11} protons) up to 13 TeV: **proton-proton collisions.**

Protons have internal structure (uud), we get the quarks of the protons to interact with each other.

New particles are produced from this interaction.

** In our lab we will work with data taken in 2010.
The energy at that time was 7 TeV

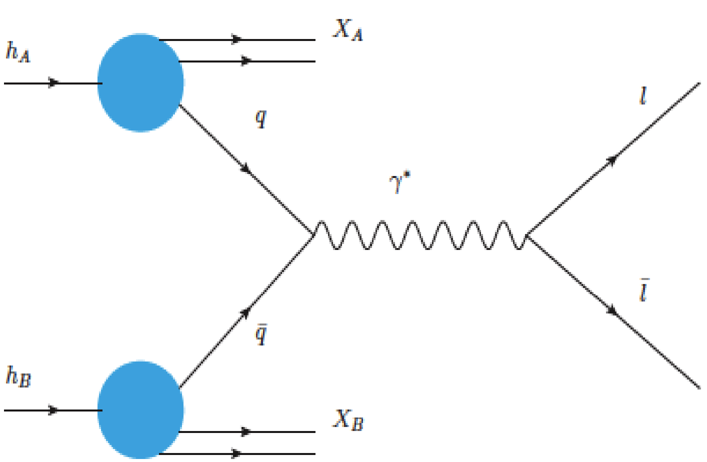
Z production: LHC



The Drell-Yan mechanism:

An electroweak process in which one quark from one of the protons and an anti-quark from the other annihilate into a vector boson (photon or Z) with a large invariant mass.

$$q\bar{q} \to (Z/\gamma)X \to l^+l^-X$$

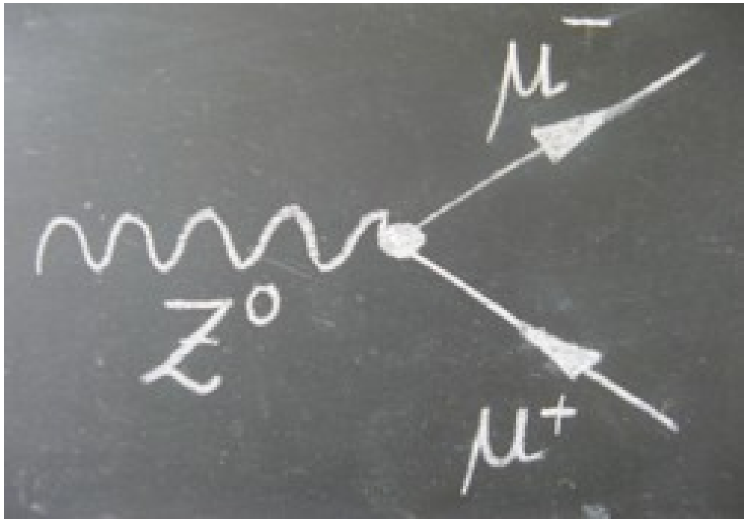


Z boson decays

- Gauge bosons play the role of (virtual) particles exchanged between fermions

- Weak vector bosons (W,Z) are massive, and therefore, very short lived
  → **Cannot be seen in the detectors**

- Can be inferred from their decay products: → We will see how
  - Charged lepton anti-lepton: 10%
  - Neutrino anti-neutrino pair: 20%
  - Quark anti-quark: 70%



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Study of decays

Definition: Particle decay
Spontaneous process of one unstable particle transforming into multiple other particles.

- Decay rate Γ: Probability per unit time that a particle decays.

$$\boxed{dN = -\Gamma N dt \quad \Rightarrow \quad N(t) = N(0)e^{-\Gamma t}}$$

- Lifetime τ: Average time it takes to decay (at rest frame).

$$\boxed{\tau = 1/\Gamma}$$

- If there are several decay modes, the total decay rate can be defined in terms in the decay rates of the different modes:

$$\boxed{\Gamma_{tot} = \sum_i \Gamma_i \quad \text{and} \quad \tau = 1/\Gamma_{tot}}$$

- And we can define the Branching Ratio BR as:

$$\boxed{\mathrm{BR}(\text{decay mode i}) = \Gamma_i / \Gamma_{tot}}$$

Γ as decay width

Heisenberg's uncertainty principle

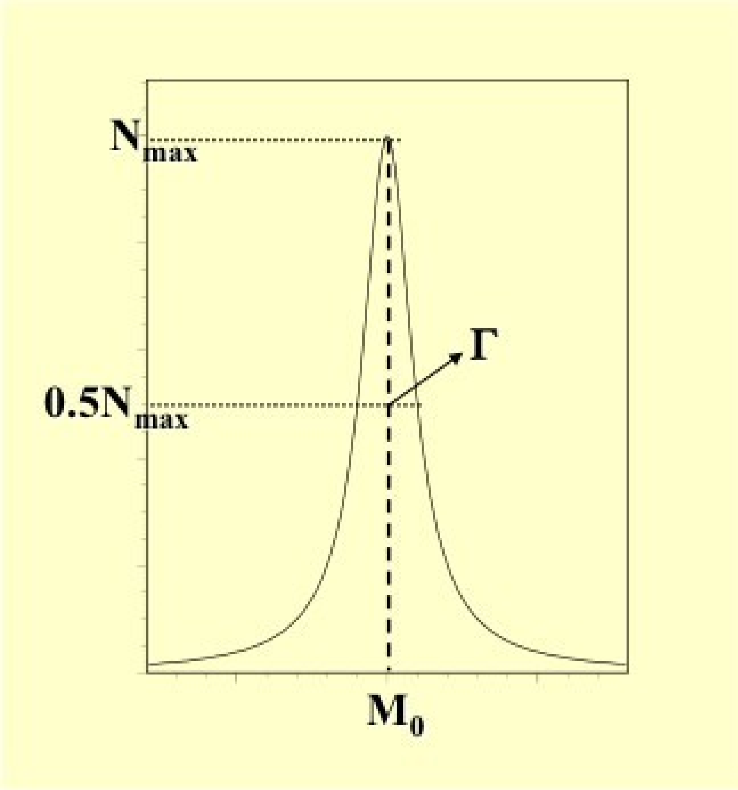
Asses a fundamental limit to the accuracy with which the values for certain pairs of physical quantities of a particle can be determined.

- It can be stated in terms of the energy and time. Unstable particles do not have fixed mass due to uncertainty principle:

$$\boxed{\Delta m \times \Delta t \approx \hbar}$$

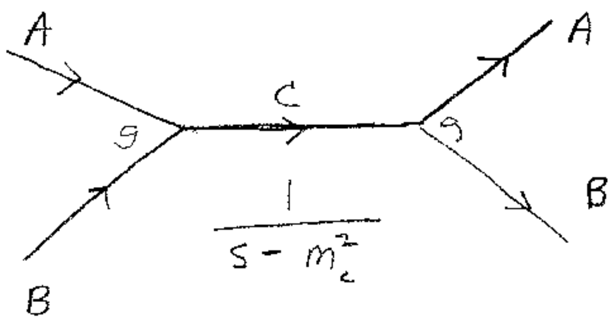
- The mass is instead distributed following a Breit-Wigner function:

$$\boxed{N(m) = N_{max} \frac{(\Gamma/2)^2}{(m - M_0)^2 + (\Gamma/2)^2}}$$



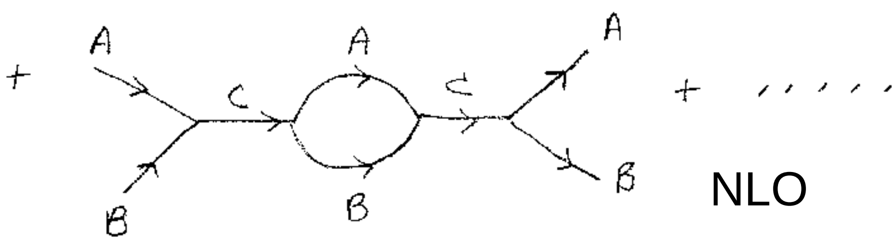
- We can use this to measure mass and width / decay rate of a particle.

Invariant mass

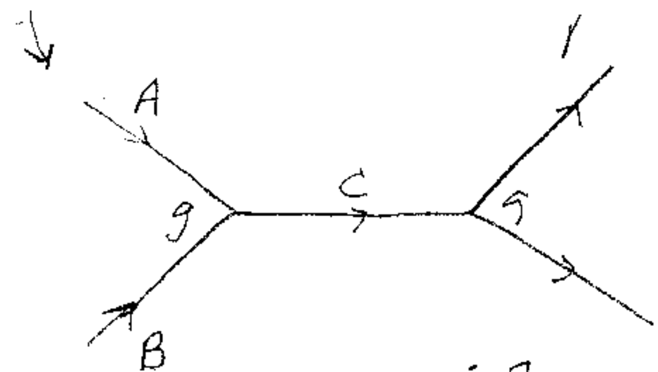


$$\frac{1}{s - m_c^2}$$

LO



NLO



$$m_c = m_0 - i\frac{\Gamma}{2} \Rightarrow \frac{1}{s - (m_0 - \frac{i\Gamma}{2})^2}$$

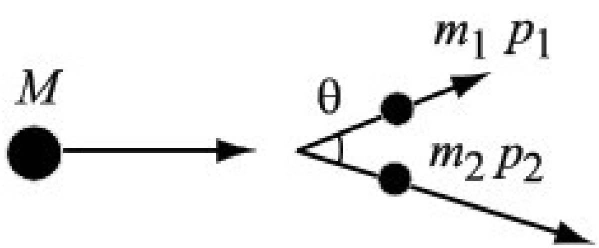
Invariant mass

Definition: Invariant mass

A characteristic of the total energy and momentum of a particle or a system of particles that is <u>the same in all reference frames</u>.

$$p^{\mu}p_{\mu} = \left(\sum_{i=1}^{n} E_i\right)^2 - \left(\sum_{i=1}^{n} \vec{p}_i\right)^2$$

We can apply this definition to our process: A particle decay into 2 other particles:



$$M^2 = m_1^2 + m_2^2 + 2(E_1E_2 - p_1p_2\cos\theta)$$

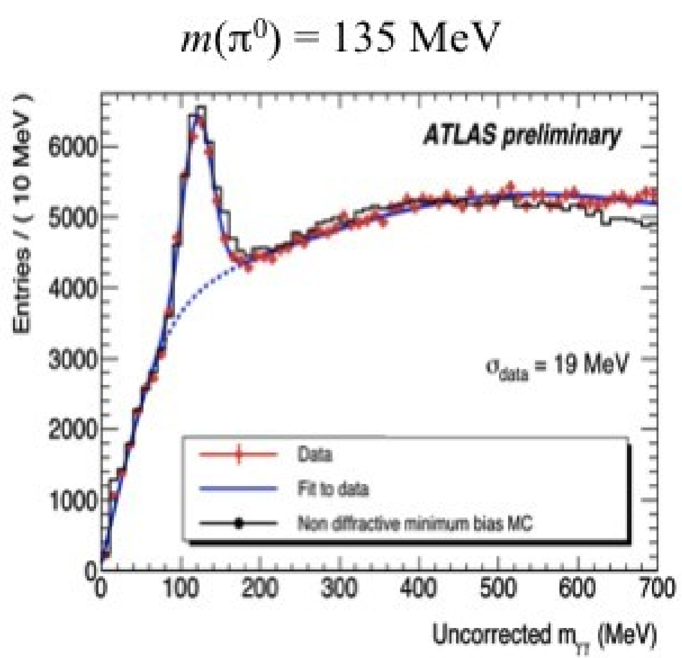
Through this definition we can relate the mass of the mother particle M, with the type of particle (m_1, m_2), momentum (p_1, p_2) and aperture angle θ of the decay products.

Mass reconstruction

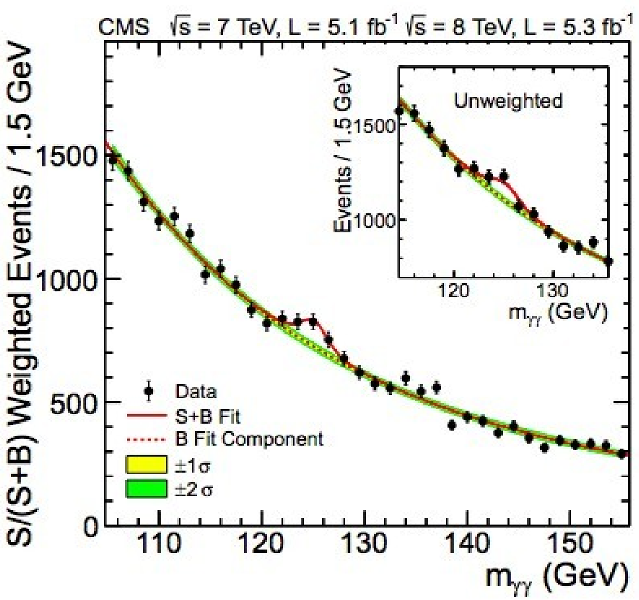
The mass reconstruction of one particle consist of measuring its mass through the measurements of its decay products as described in the previous slide.

- We will apply it to measure the Z mass from the detected muons.
- Also applied to look for more exciting signals, like the Higgs boson.

$\pi^0 \rightarrow \gamma\gamma$



$H \rightarrow \gamma\gamma$



Experimental setup

What can we measure with experiments?

The Z decays very fast ➞ Not detected ➞ we detect the final decay products

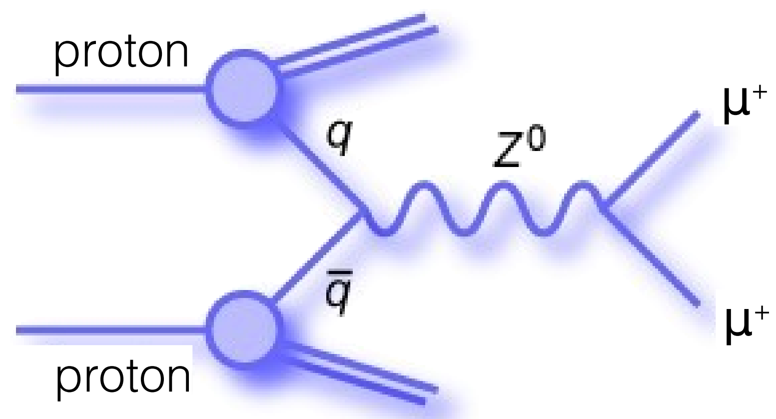
- Ideally we want to measure (E, p_x, p_y, p_z) of each produced particle.

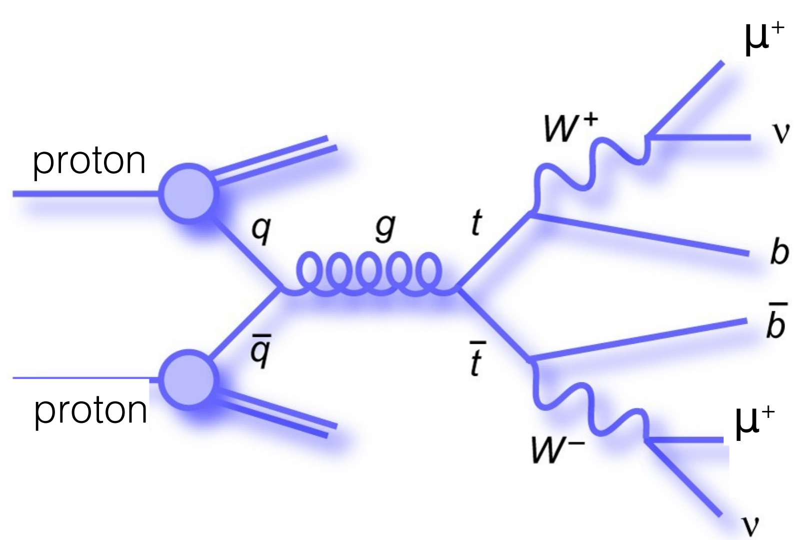
- But careful, Z bosons are not the only particles produced in detectors.

- In each pp collision (**event**) we have a probability (**cross-section**) of producing a particular physical process.

    - We need to go event by event and check if they have two muons compatible with a Z boson decay.

    → Signal vs background discrimination





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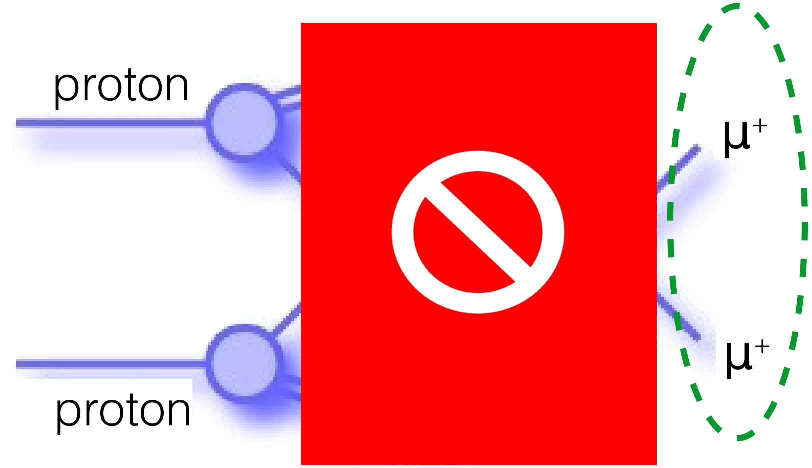
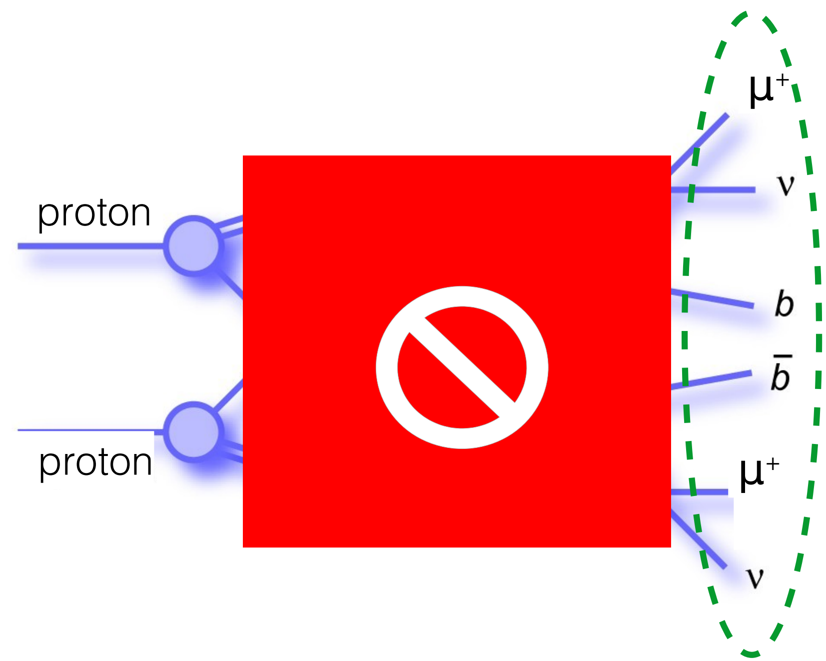


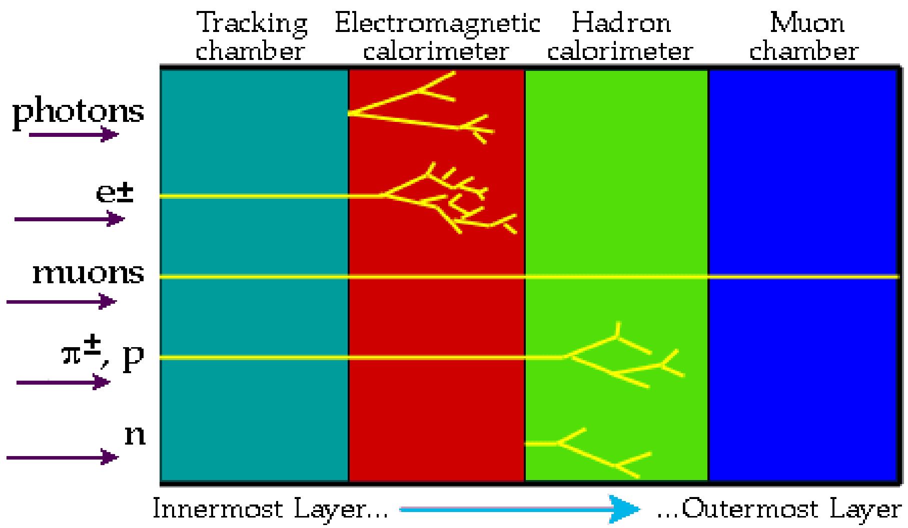


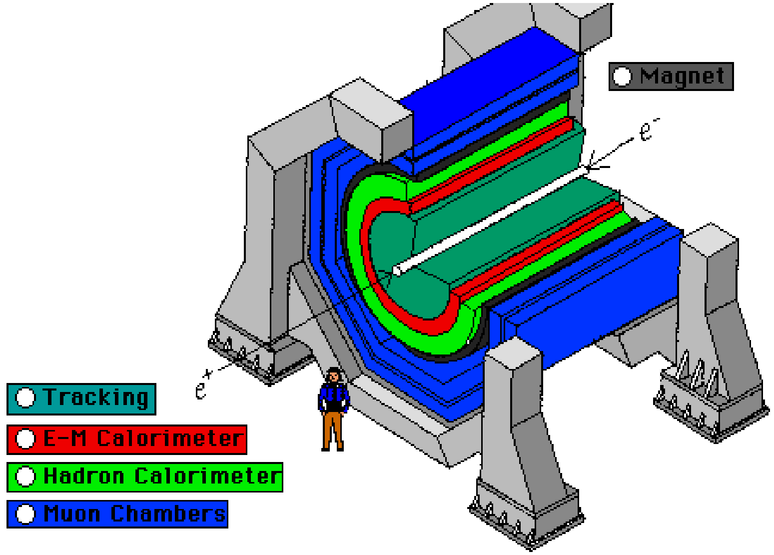
How? Particle detectors

We need to know two things:

- The type of the particles (muons, electrons, photons… etc)
- The values of energy, momentum, direction…

The detectors are composed of layers of subdetectors, specialized in a particular type of particle. There are **three main types** of subdetectors.



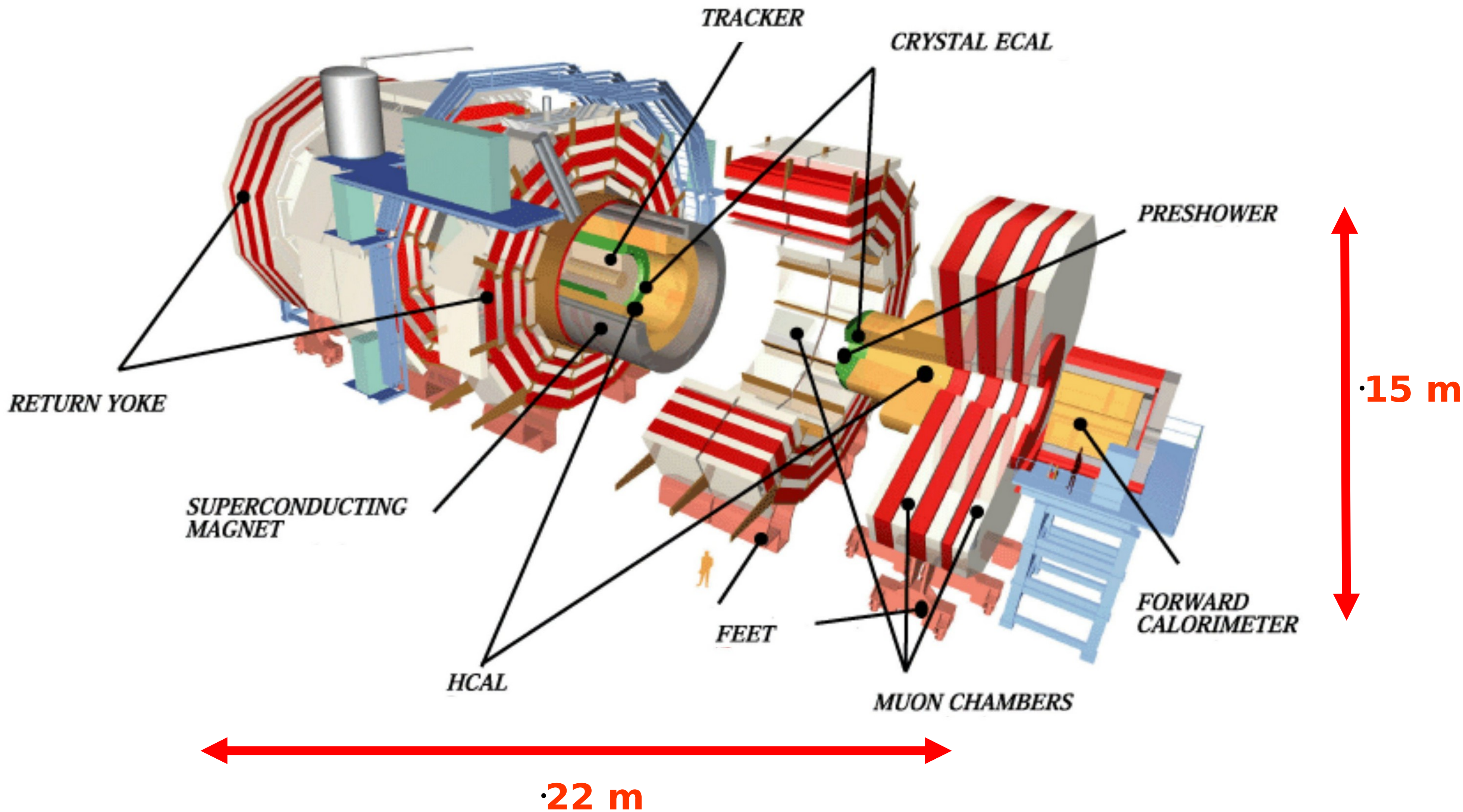


In addition, there is a magnetic field to bend the particle trajectory and measure transverse momentum.

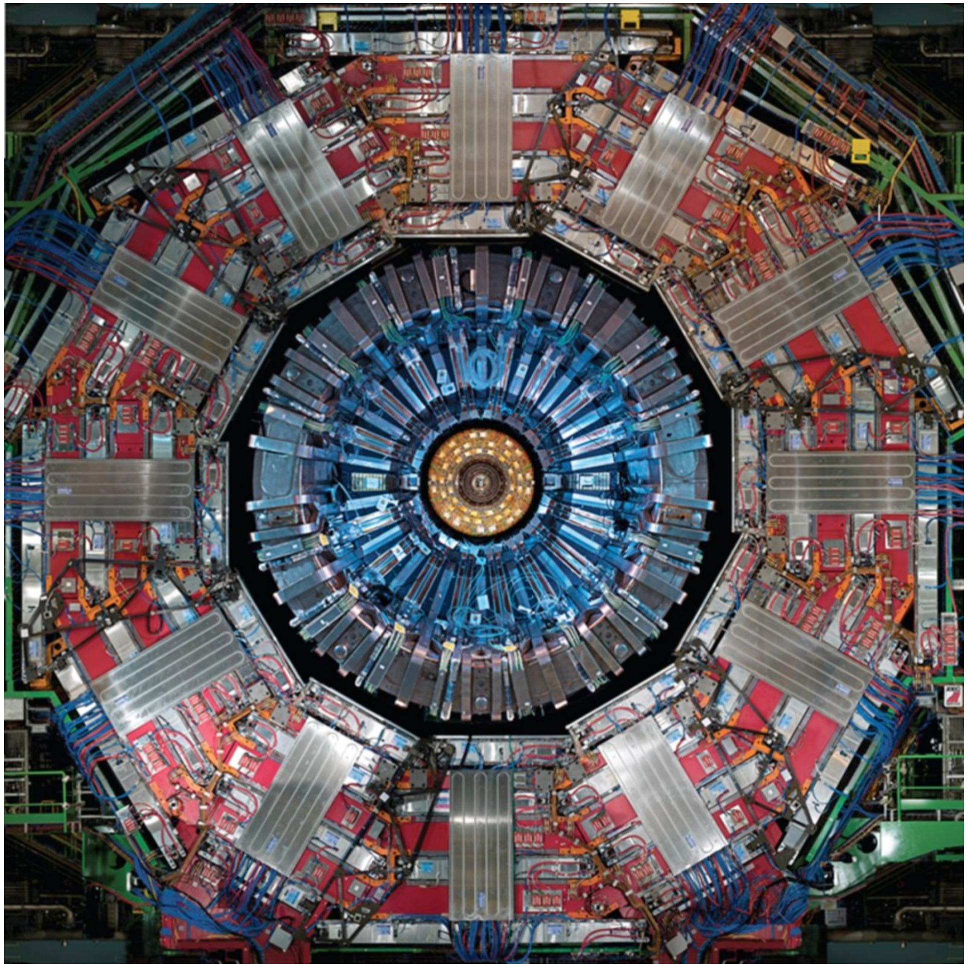
Particle detectors

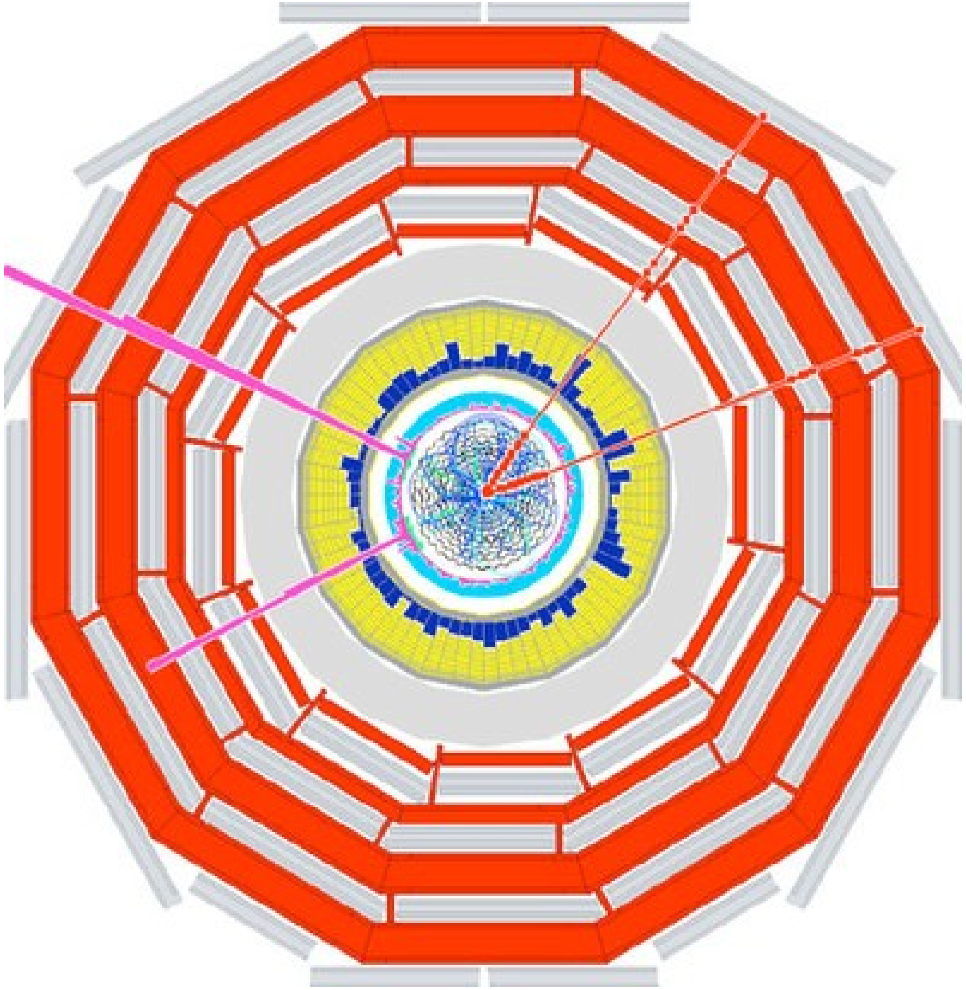
- Tracking detectors (or trackers) = momentum measurement
  - Closest to interaction point: vertex detectors.
    - Measure the interaction primary vertex and secondary vertex from decay particles
  - Main or central tracking detectors
    - Measure the momentum by curvature in magnetic field.
  - Reconstruct the track of charged particles
- Calorimeters = energy measurement
  - Electromagnetic calorimeters (EM particles: electrons, positrons, photons…)
  - Hadronic calorimeters (charged and neutral hadrons)
- Muon detectors = Identification + momentum for muons
  - They are tracking detectors in the outermost detector layer.

CMS: Compact Muon Solenoid

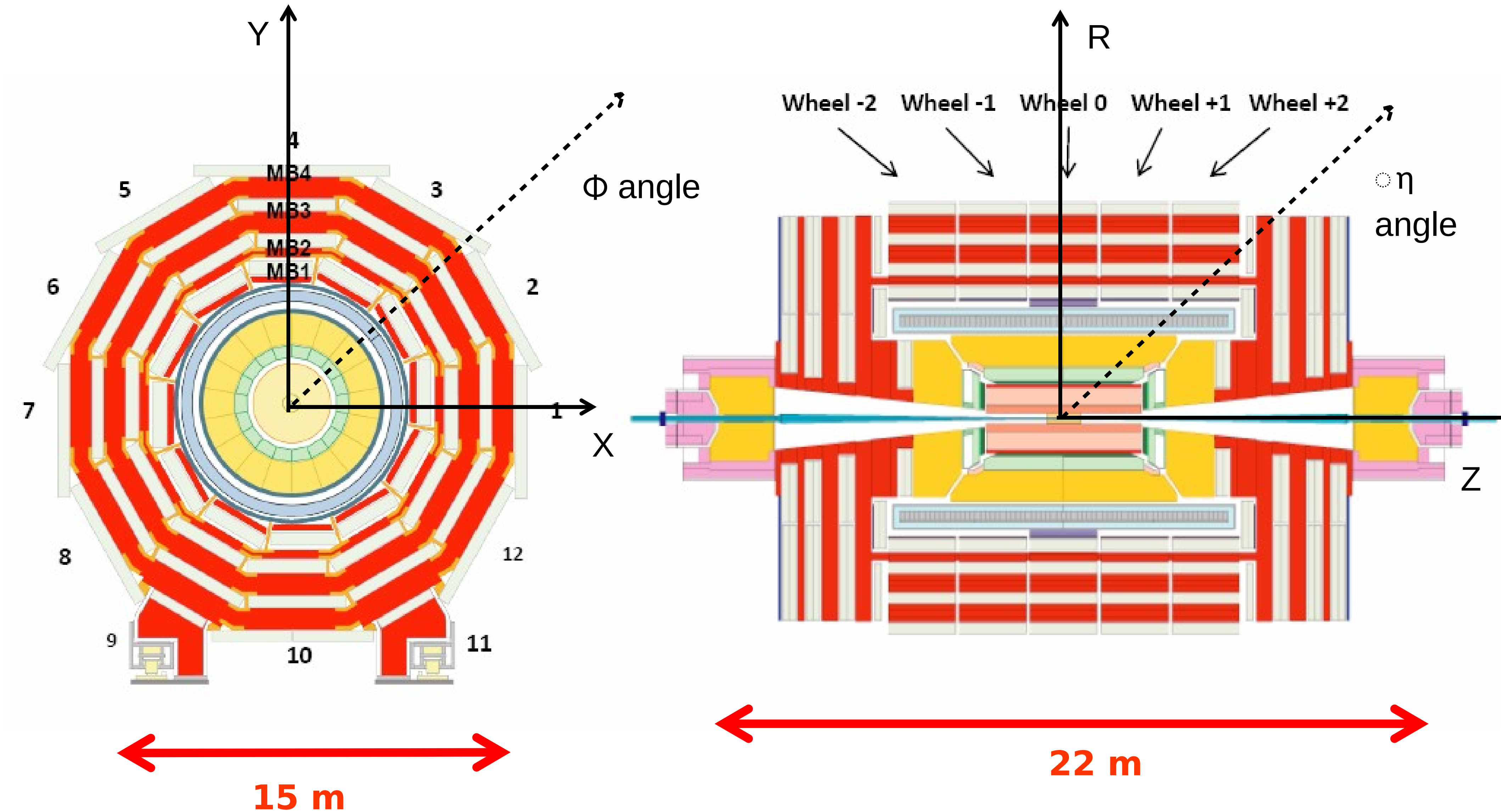


CMS: Compact Muon Solenoid



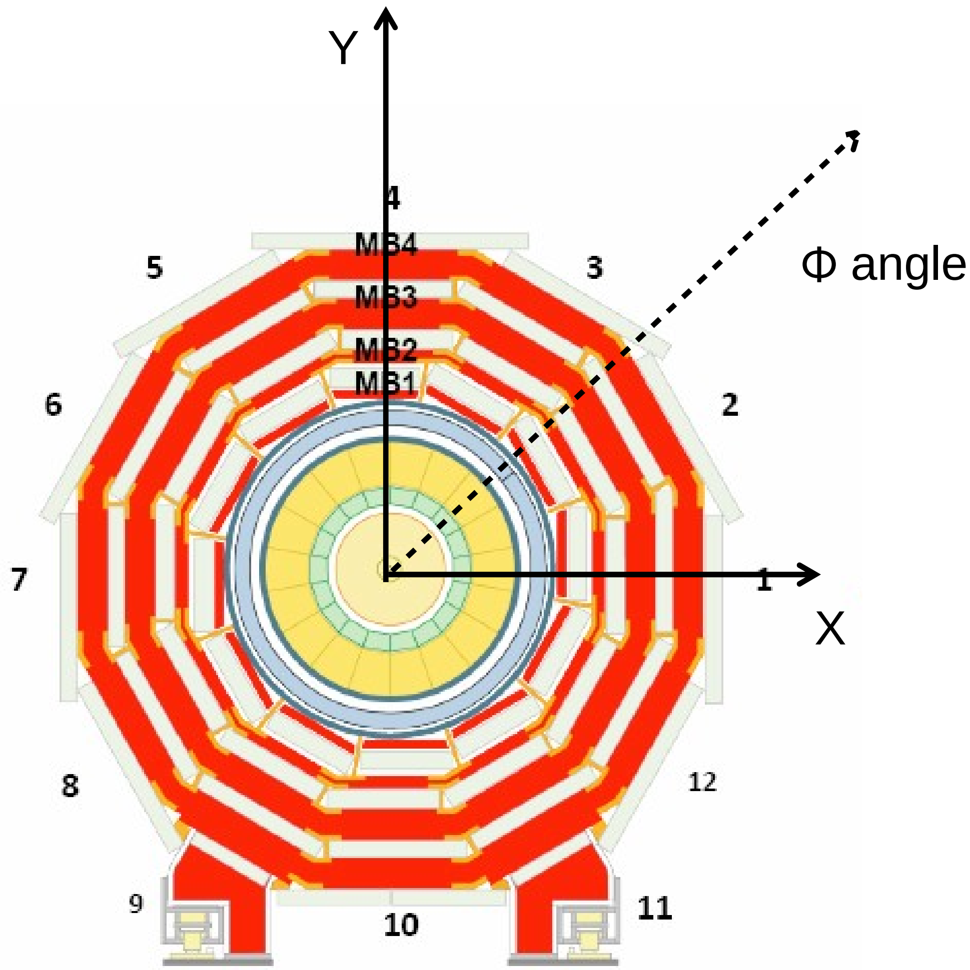


CMS: Compact Muon Solenoid



CMS coordinate system

Due to the geometry of the experimental setup, the appropriate choice is to work with cylindrical coordinates:



<u>Transverse plane:</u>

We measure the Φ angle of the particle in the x-y plane

CMS coordinate system

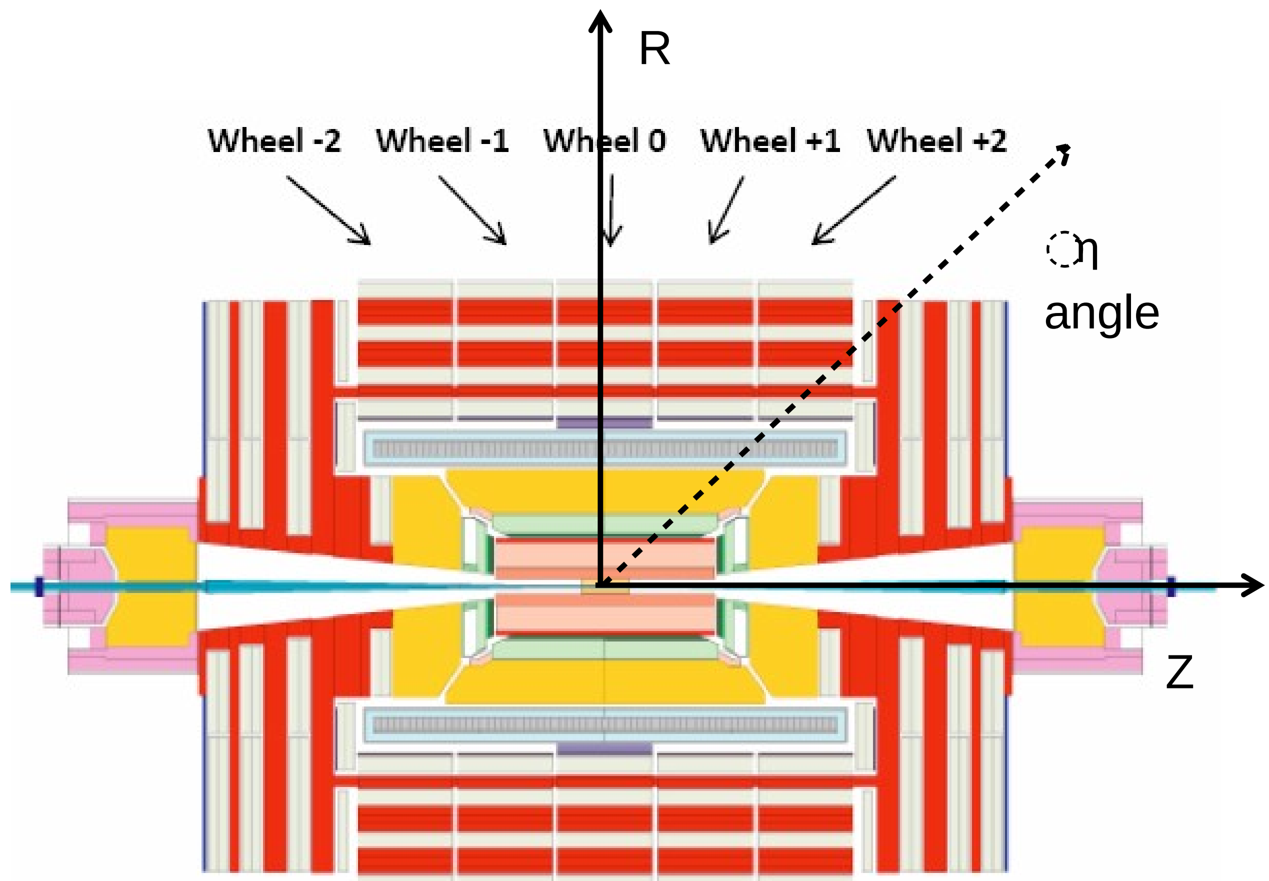
Due to the geometry of the experimental setup, the appropriate choice is to work with cylindrical coordinates:

<u>Longitudinal direction:</u>

We could work with θ

But it is more common to use the pseudorapidity:

$$\eta = -\ln\left(\tan(\theta/2)\right)$$



Which particles can we detect?

A particle is **detected** when it interacts with one (or more) subdetectors and leaves a signal there.

→ Depending on the type of subdetector that returns the signal, we may know which particle is.

There are several **types of particles/objects** we can detect with **CMS**:

- Electrons (tracker + ECAL)
- Photons (ECAL)
- Muons (tracker + Muon system)
- Hadrons (HCAL and tracker if charged)
    - Jets

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We will focus on muons since we will study $Z \to \mu\mu$

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- Electrons (tracker + ECAL)
- Photons (ECAL)
- Muons (tracker + Muon system)
- Hadrons (HCAL and tracker if charged)
    - Jets

Wait… What is this???

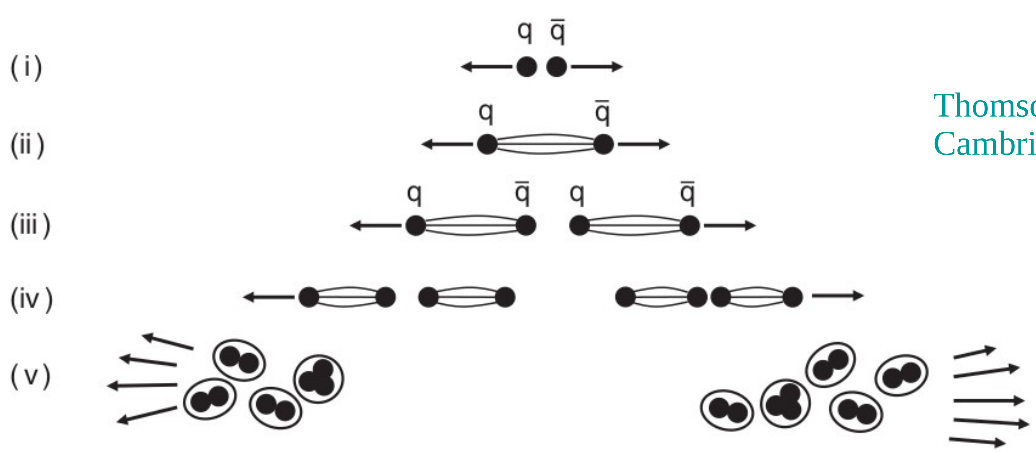
Jets

Definition: Experimental bunch of particles generated by hadronization of a common source (quark, gluon)

→ The strong interaction do not let the quarks and gluons to fly “free” as single states. We find them in more complex structures (mesons and/or hadrons)

e.g. the proton contains 3 quarks: uud

→ We we force the quarks to fly alone, they **hadronize** i.e. they fragment into multiple other particles (that are detected):

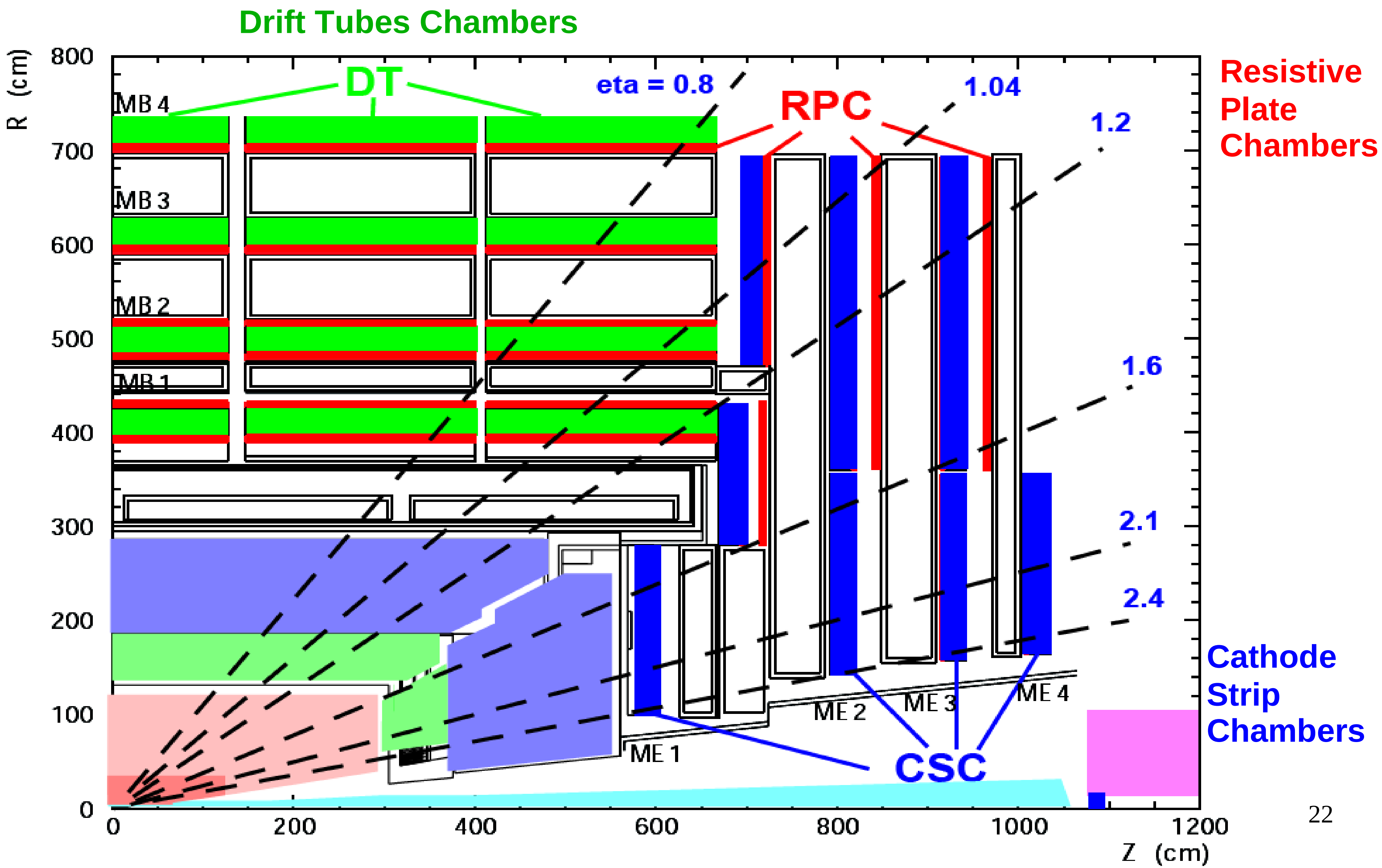


Thomson M. *Modern Particle Physics*, Cambridge University Press. Pag 252

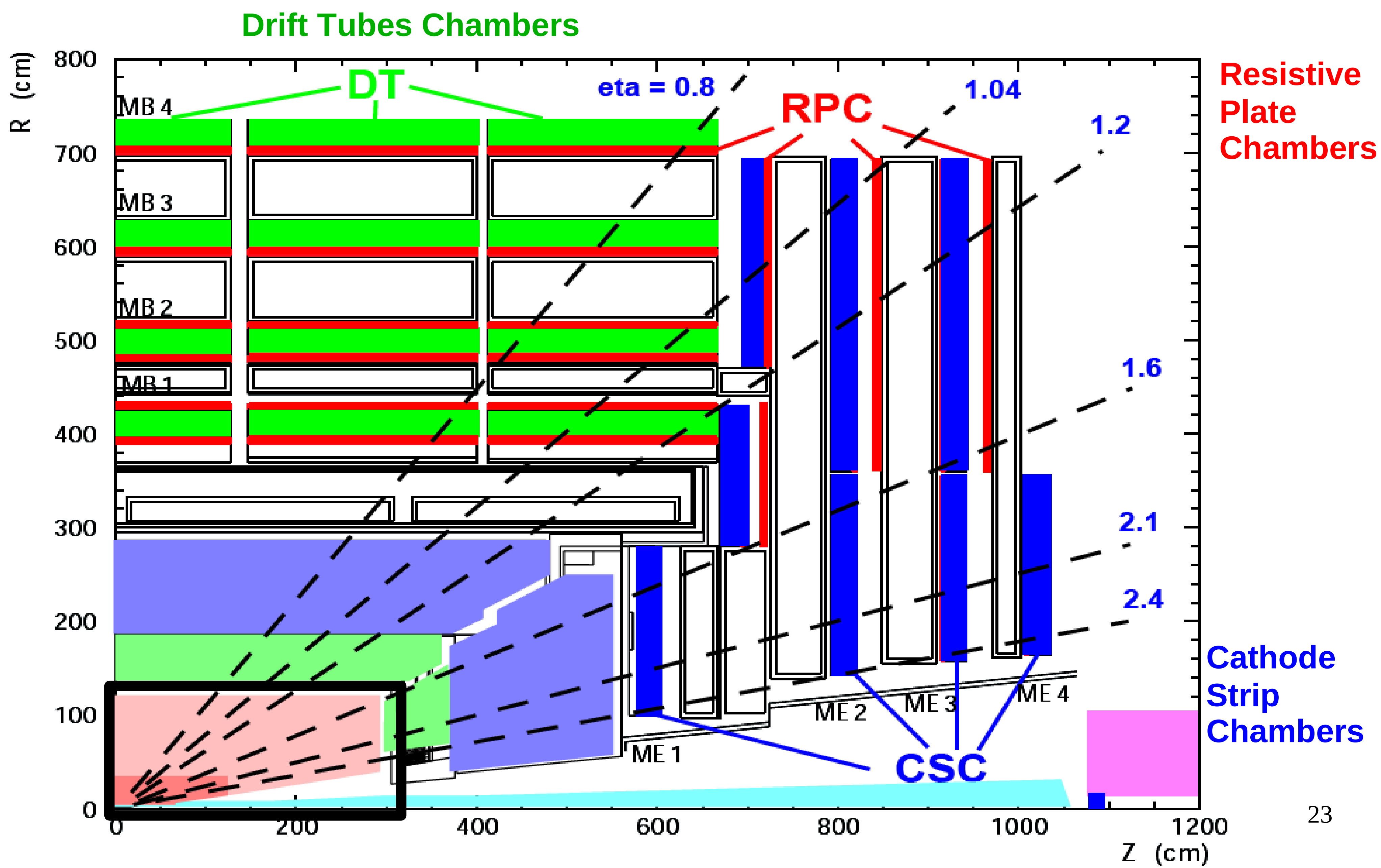
Fig. 10.9 Qualitative picture of the steps in the hadronisation process.

Muons as seen by CMS

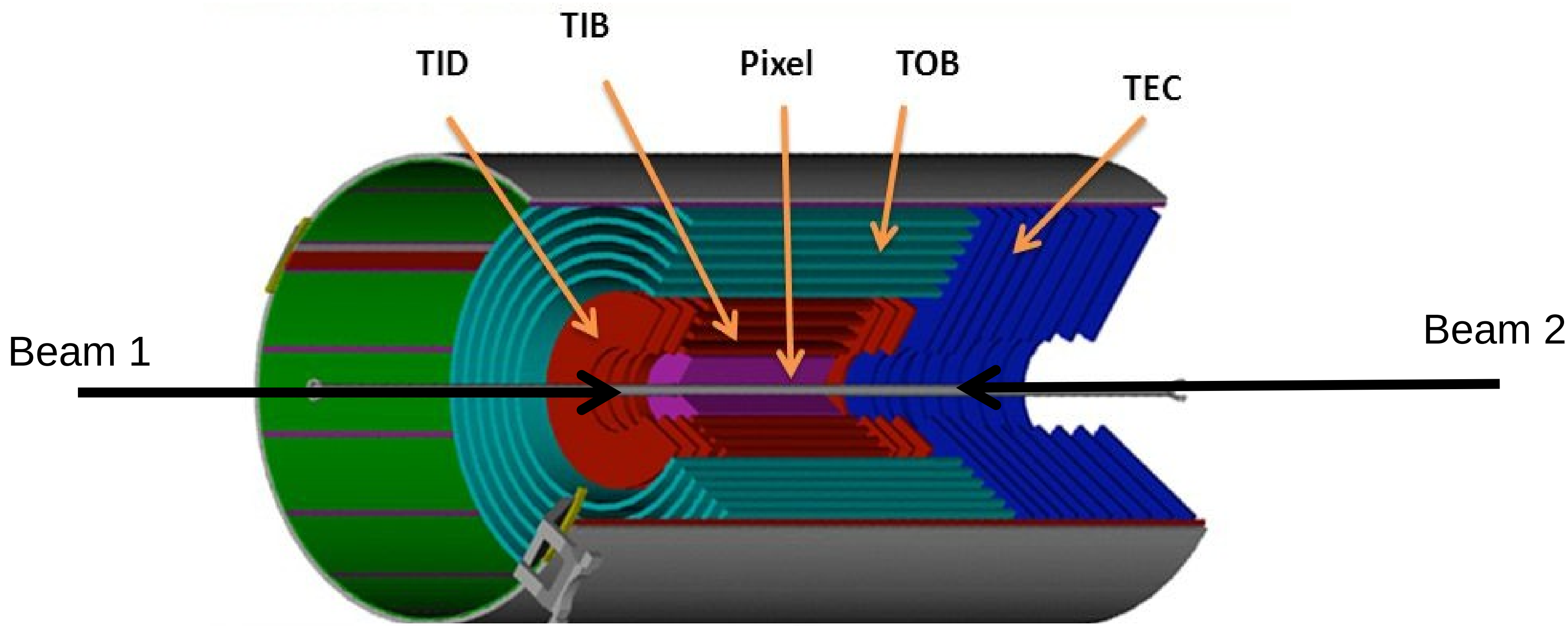
Muons as seen by CMS

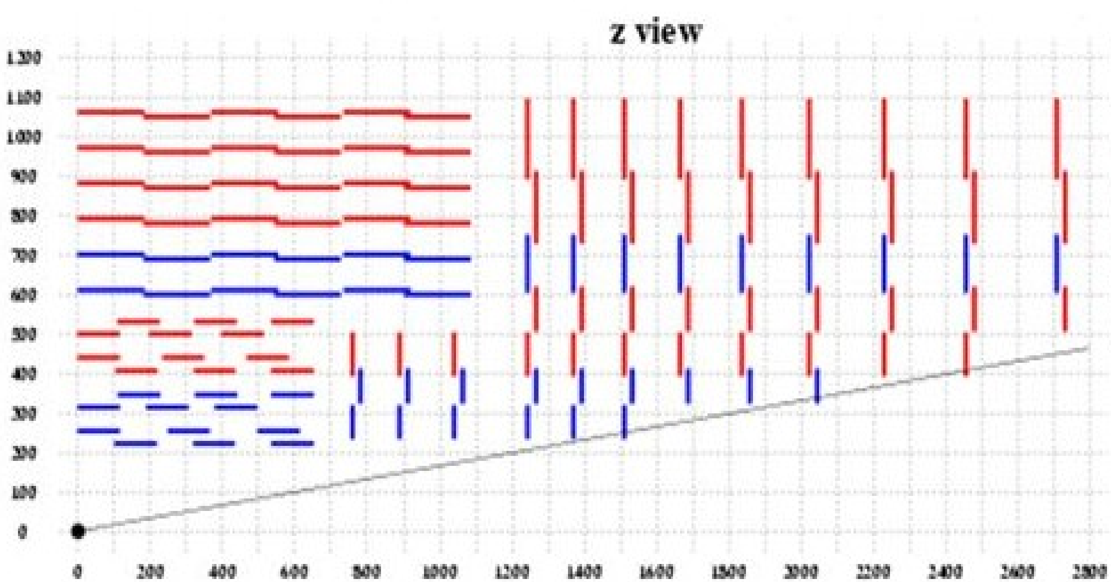


Muons as seen by CMS



CMS silicon tracker





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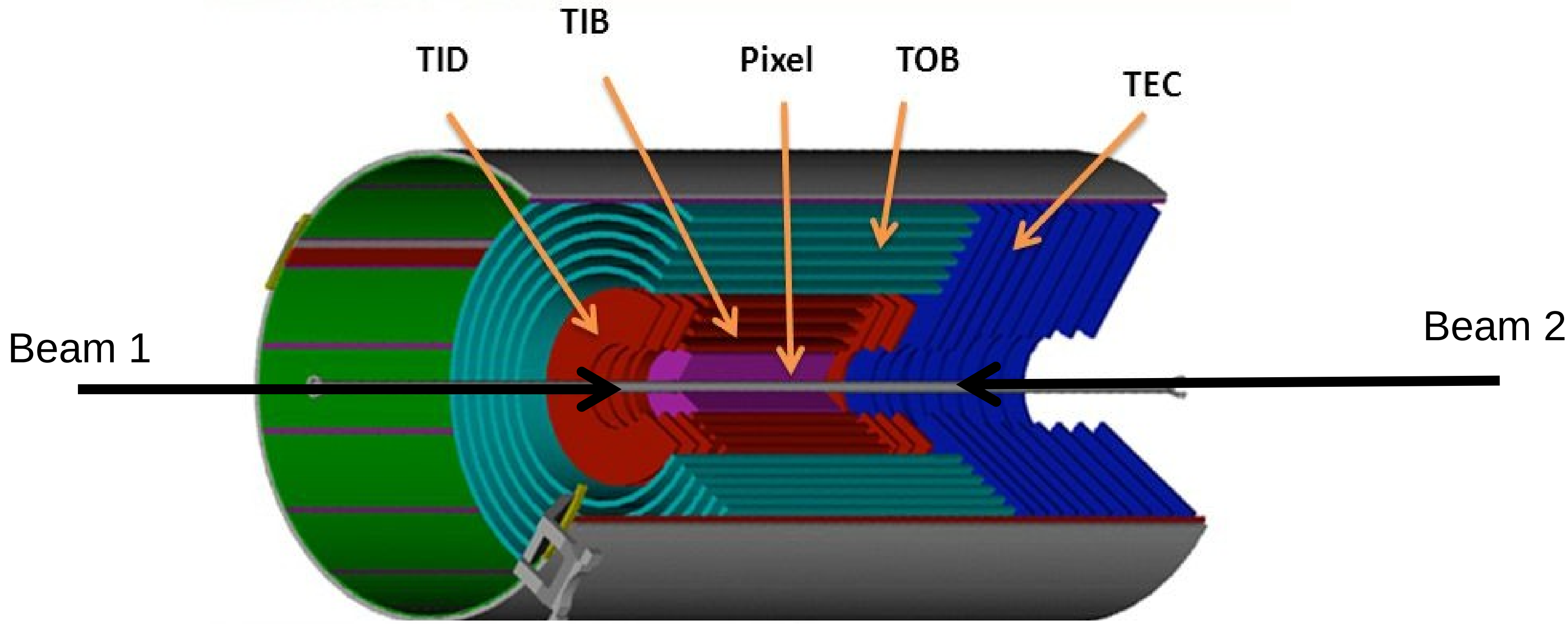
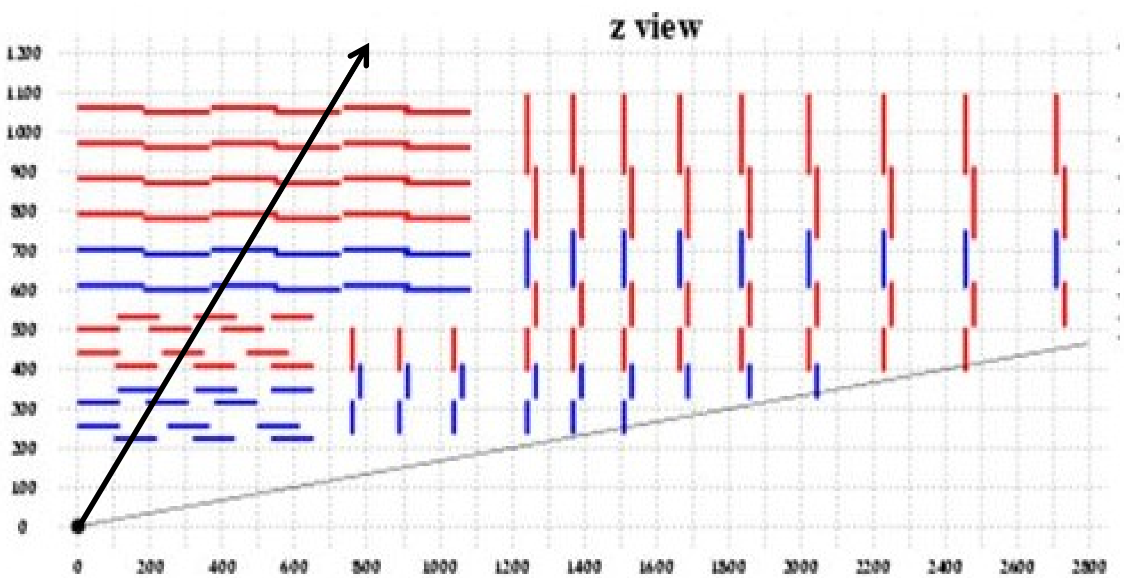
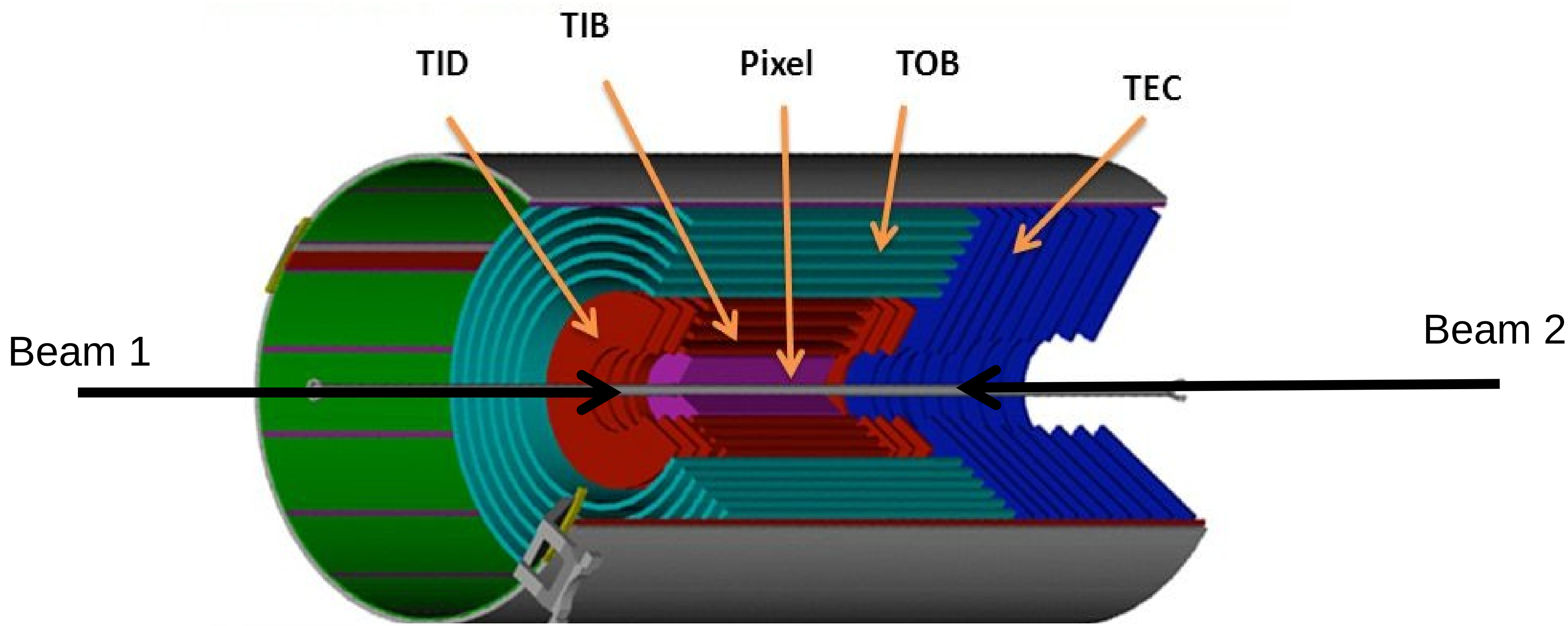
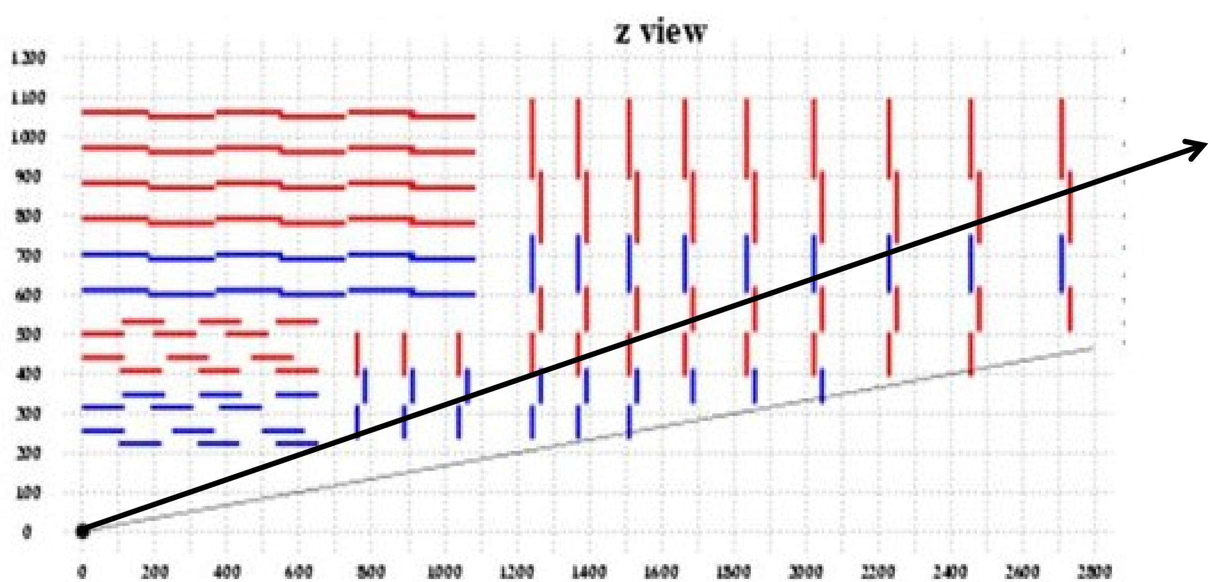




CMS silicon tracker

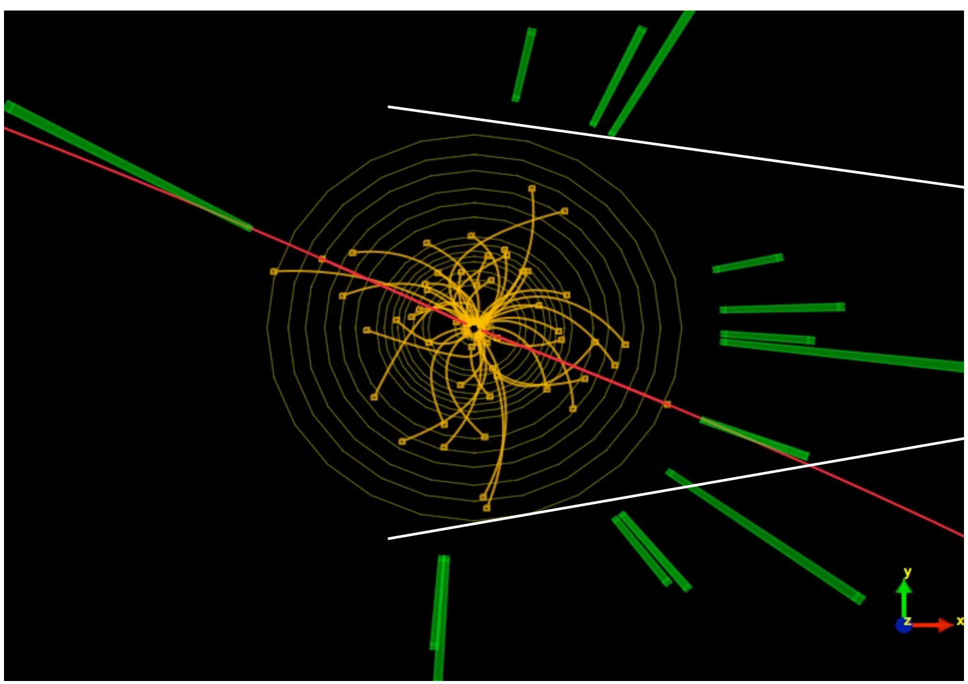


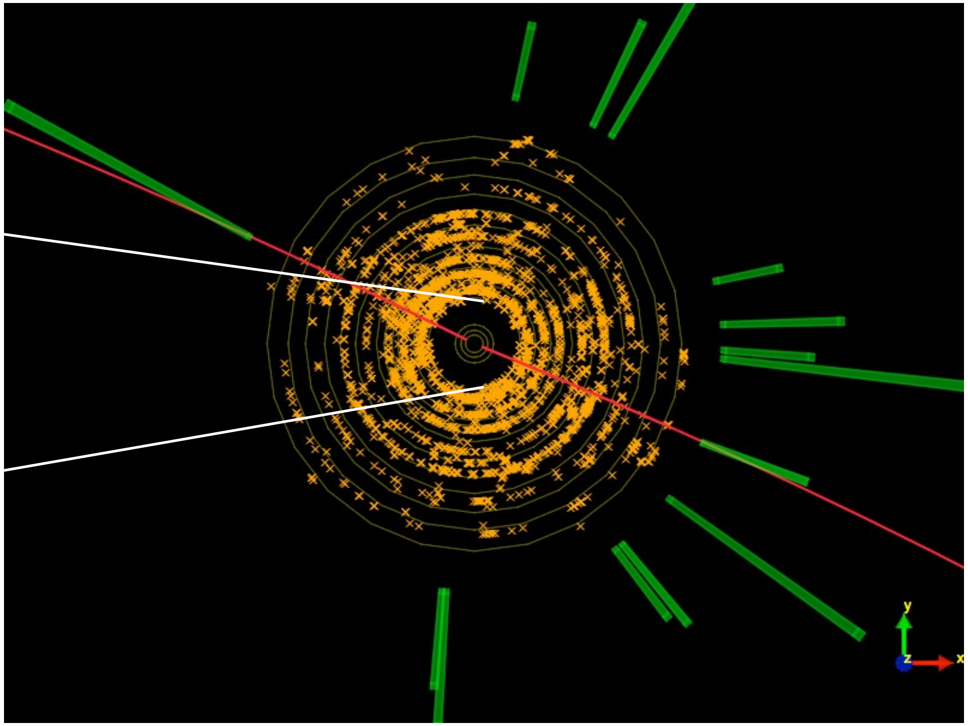


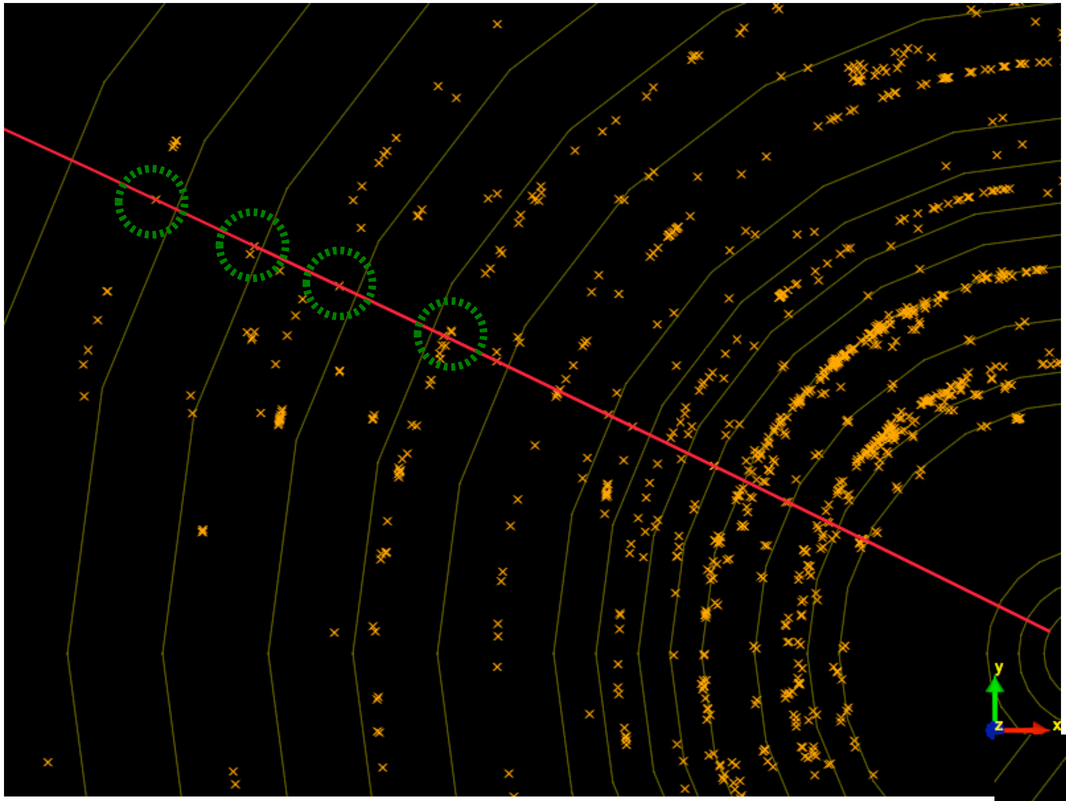
Muon display

We can display real muon events here:
https://www.i2u2.org/elab/cms/event-display/

→ Open Zmumu events, and load from run 148029 the event 21658042

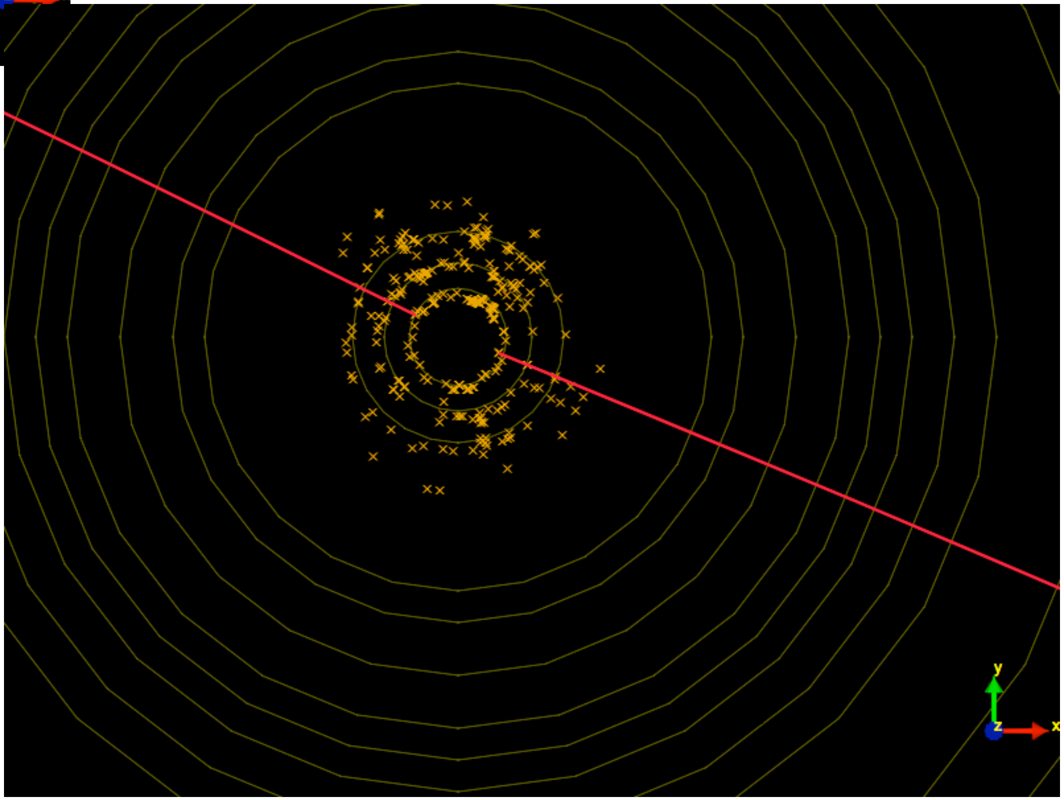






Tracker strips

Tracker pixels



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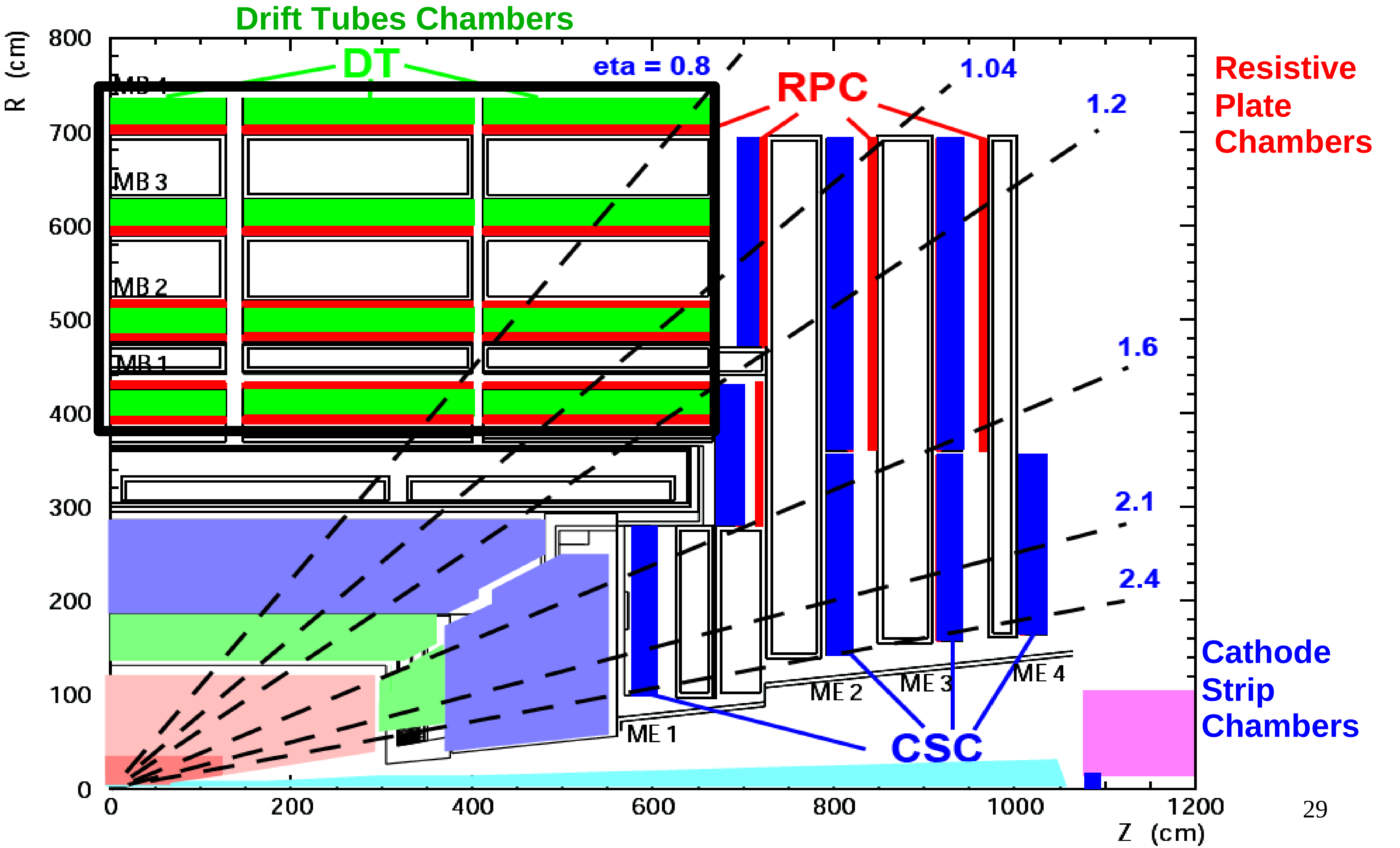
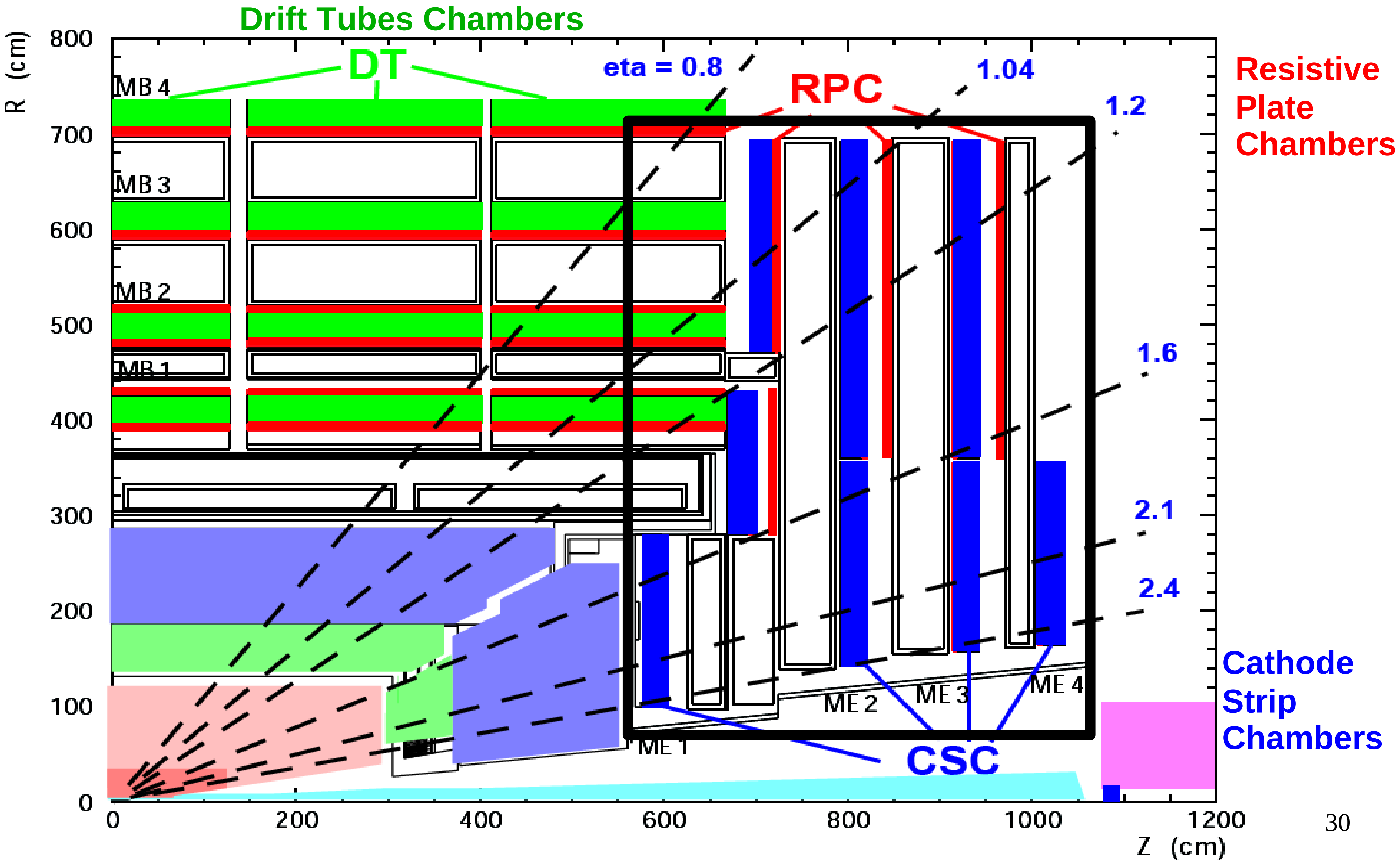
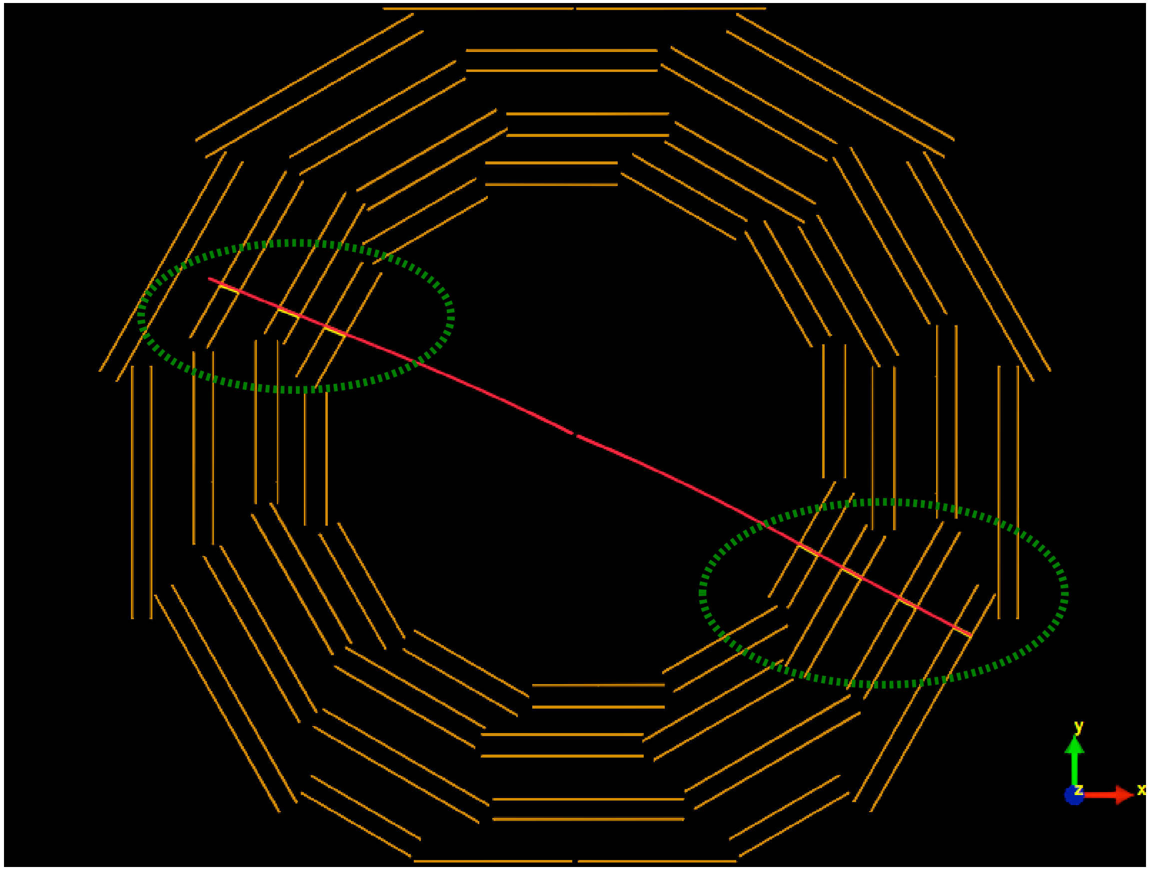
Muons as seen by CMS

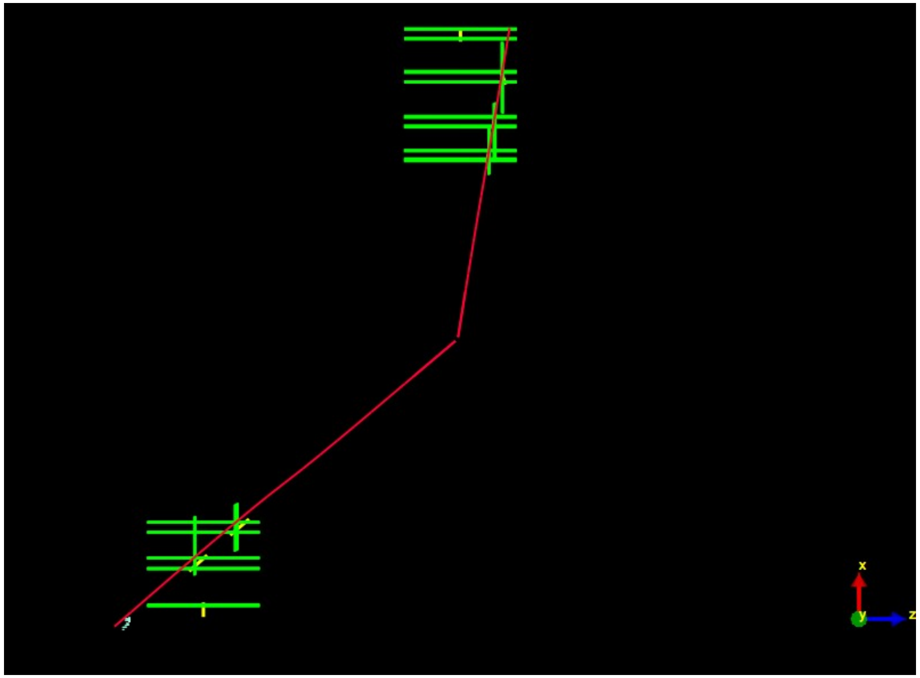


Muons as seen by CMS



Standalone hits and number of muon chambers





Muon reconstruction and identification (ID)

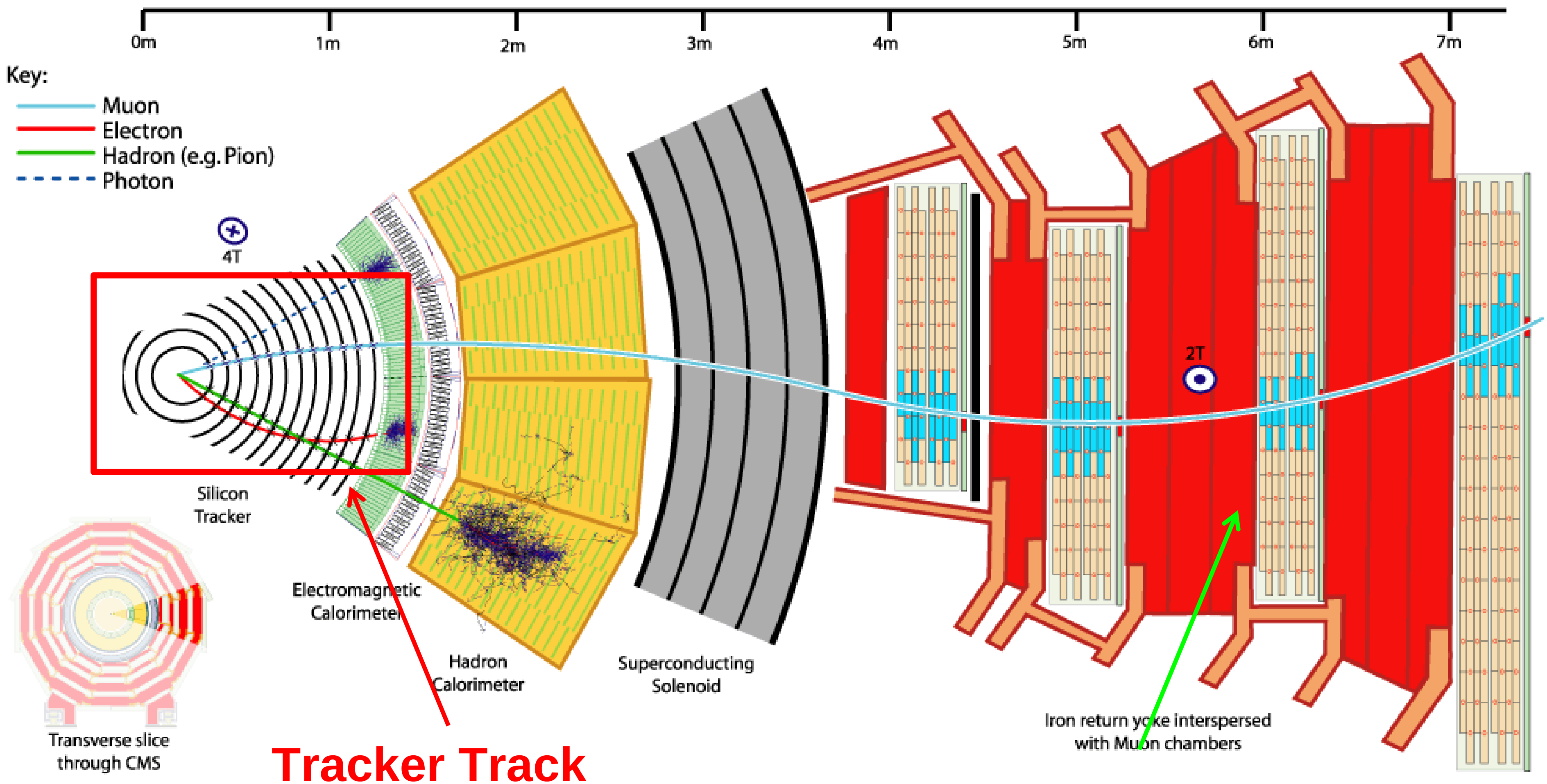
We know which parts of CMS detect the muons but **how do we use that information?**

→ The process of combining all these signals, associate them to a muon and extract its parameters (E, p_T, η, Φ…) is called reconstruction.

→ Several algorithms were developed to that purpose

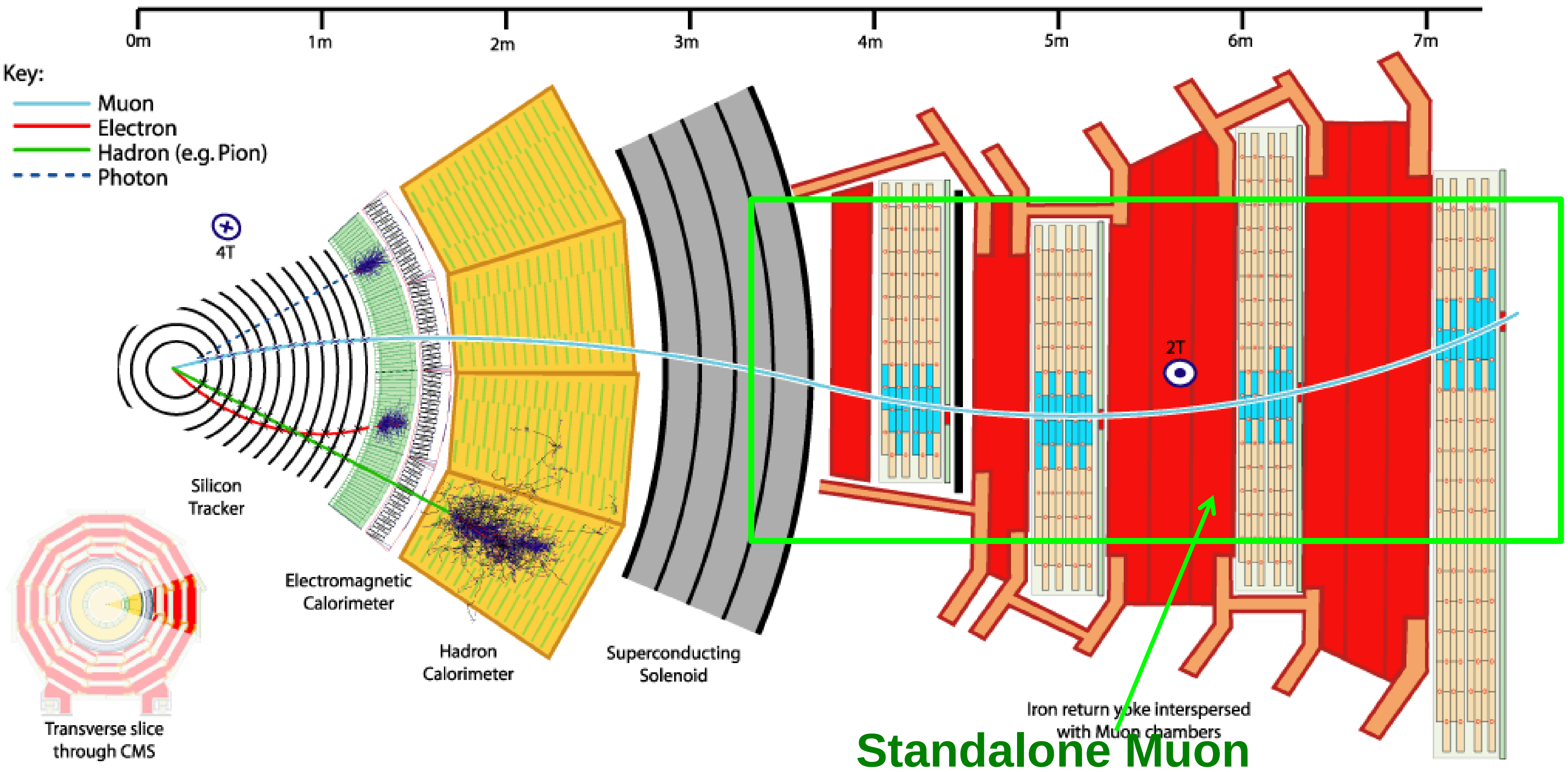
Muon reconstruction: Tracker Muons

Tracker Muons: **Tracker tracks** identified as muons by matching them with a **signal** in the muon system. Based on tracker hits and pixels.



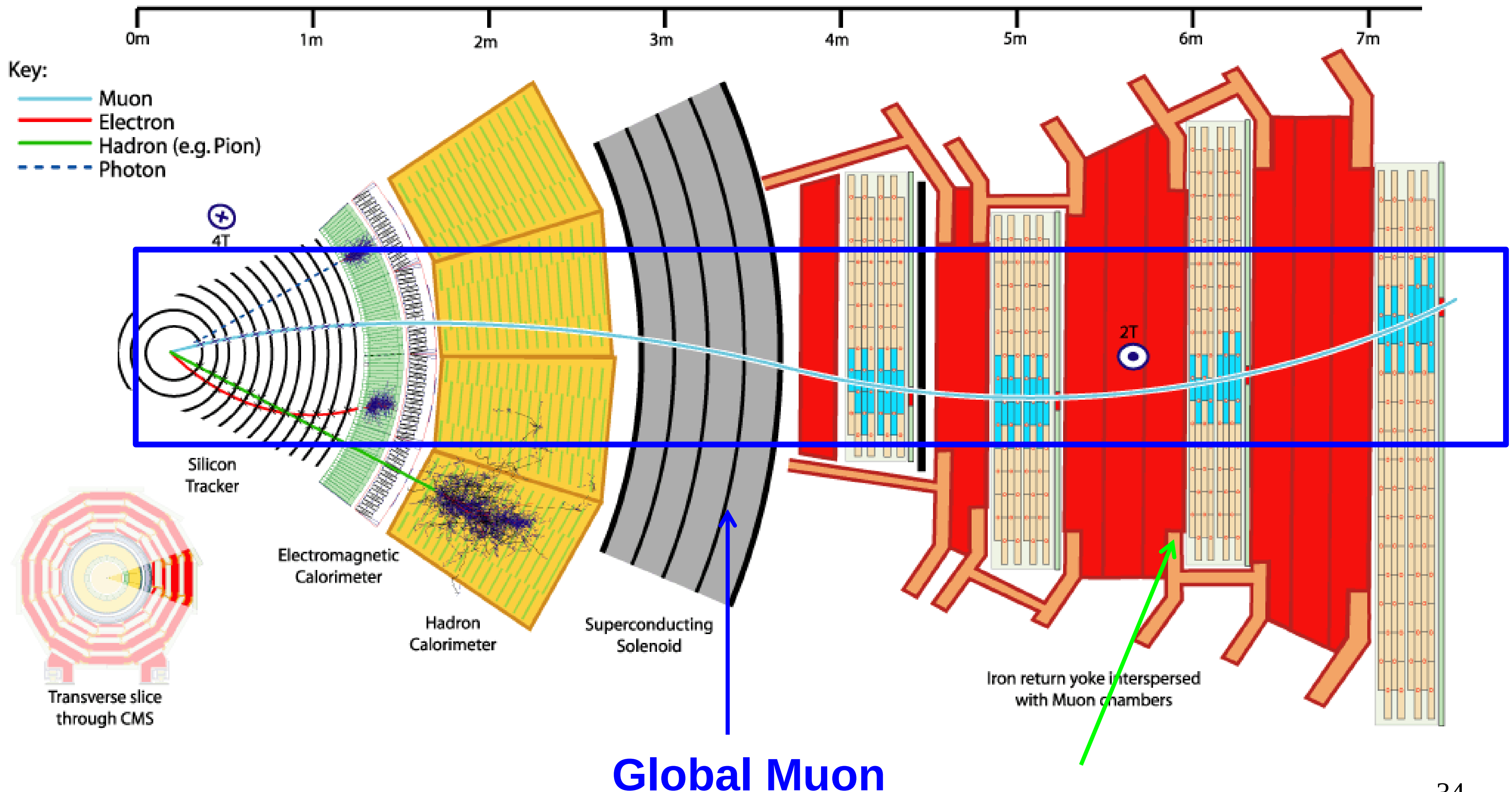
Muon reconstruction: Stand-Alone Muons

Stand-Alone Muons: Muons reconstucted using **only the muon system**.
Based on segment reconstruction in muon chambers.



Muon reconstruction: Global Muons

Global Muons: **Stand-Alone muons** that are combined with **tracks** in the tracker.



Muon ID and selection

We will work with tracker muons, standalone muons and/or global muons.

→ Once the muons are reconstructed…

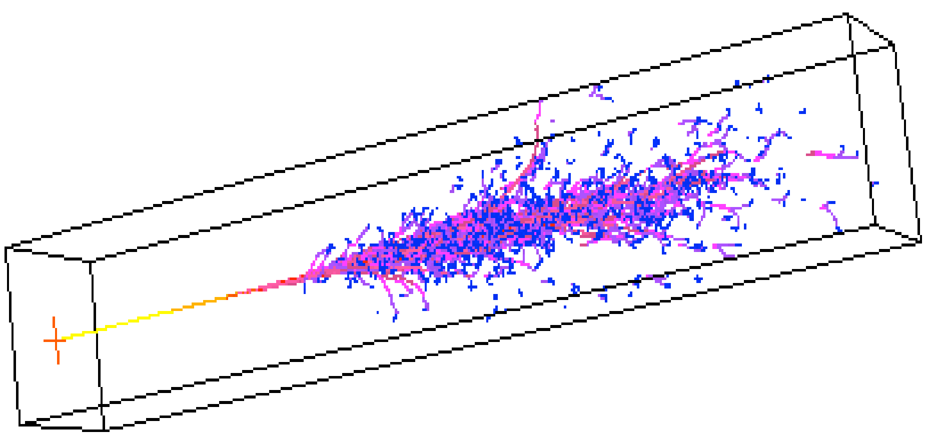
→ We must assure their quality (real muons) (ID)
→ We must identify which muons come from the Z boson
(Signal vs background discrimination)

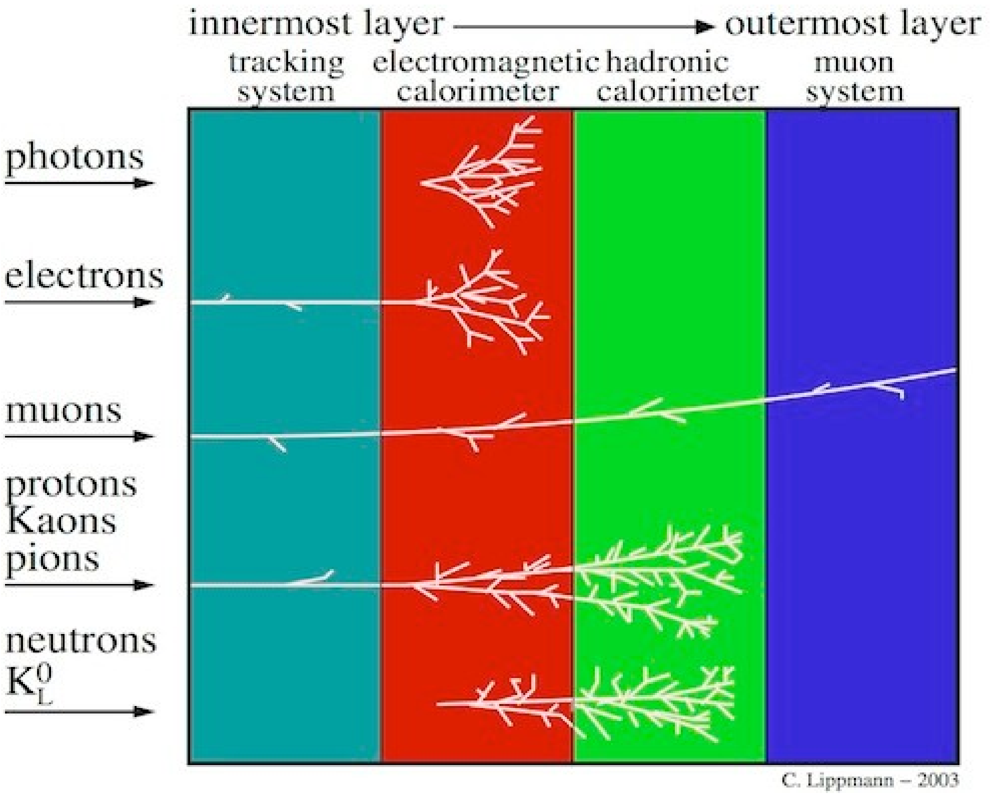
- Select muons that fulfill a set of requirements
  - p_T, η…
  - Number of hits, type of muon…
  - Isolation
  - … etc

CMS: Calorimeters

The particles leave almost all their **energy** in the calorimeters

- Electromagnetic calorimeter: electrons, photons
- Hadronic calorimeter: neutral and charged hadrons (neutrons, pions, protons...)



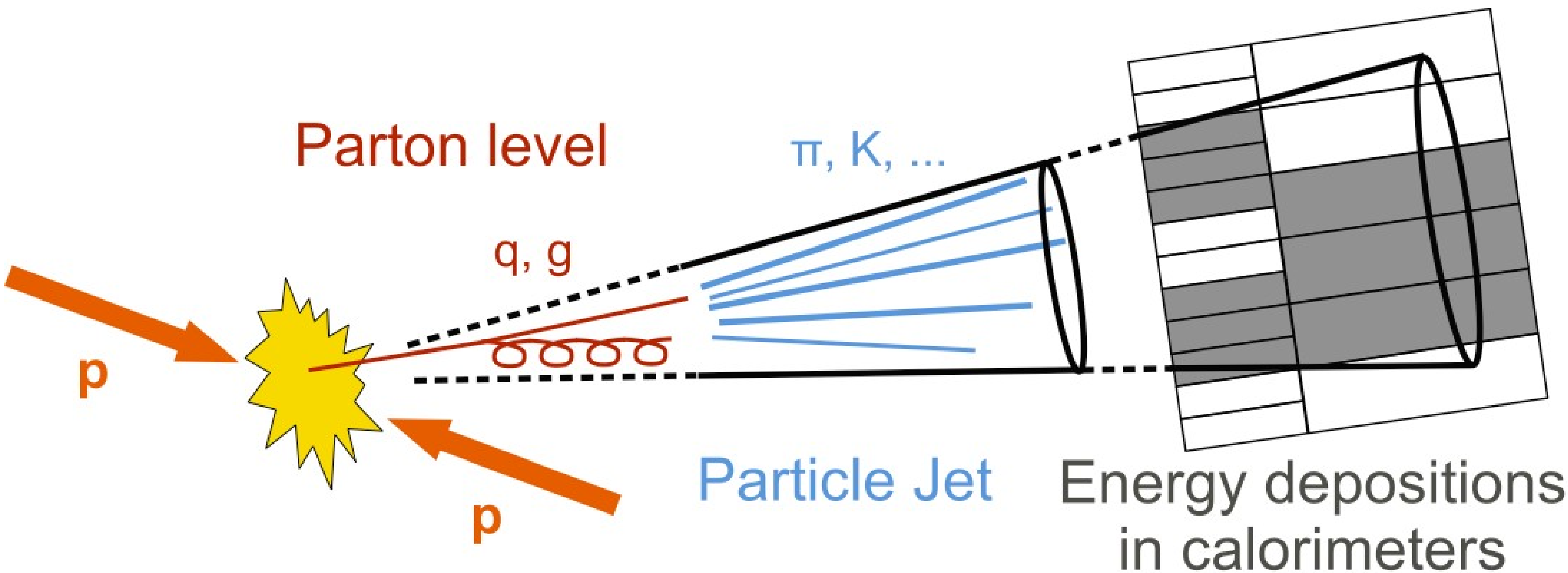


Jets

Remember: Experimental bunch of particles generated by hadronization of a common source (quark, gluon)

→ Experimental signature:

- Energy deposits in both EM and hadronic calorimeters
- Several tracks in the inner detector



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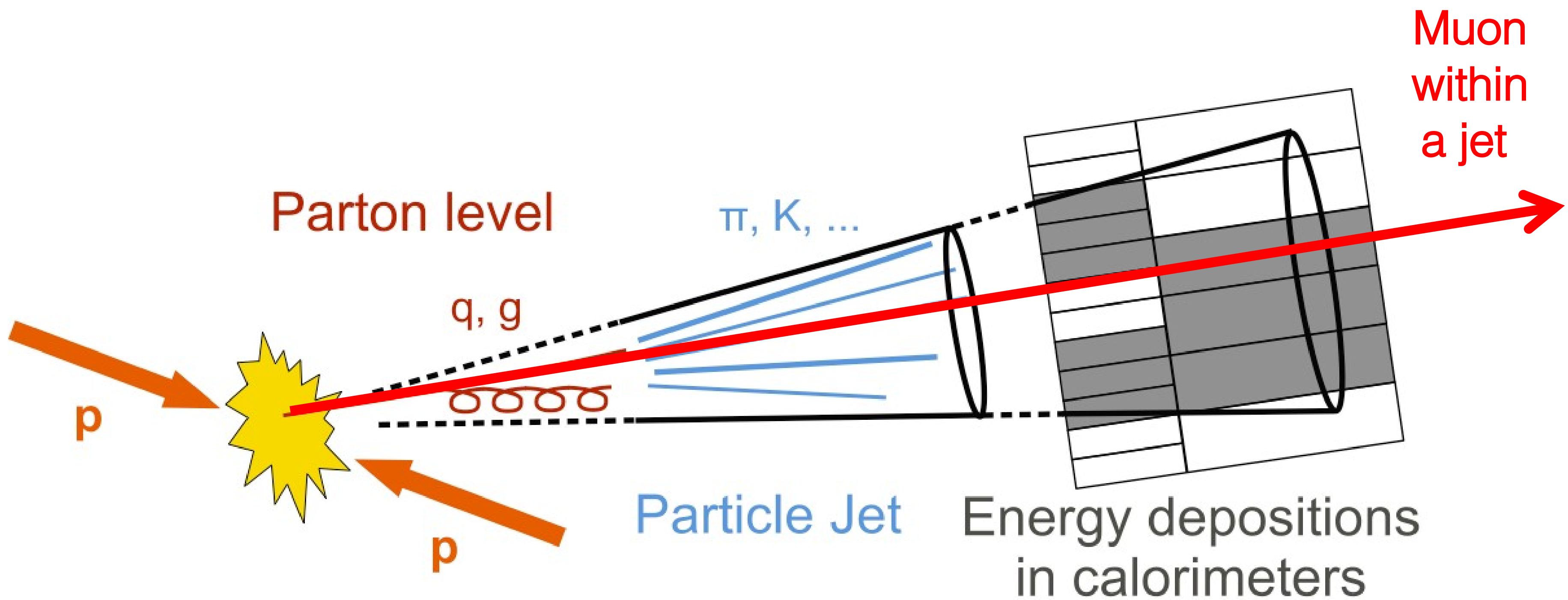
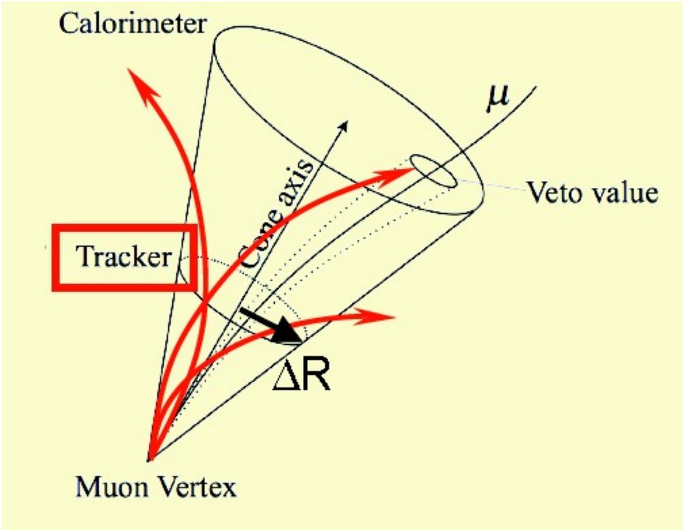


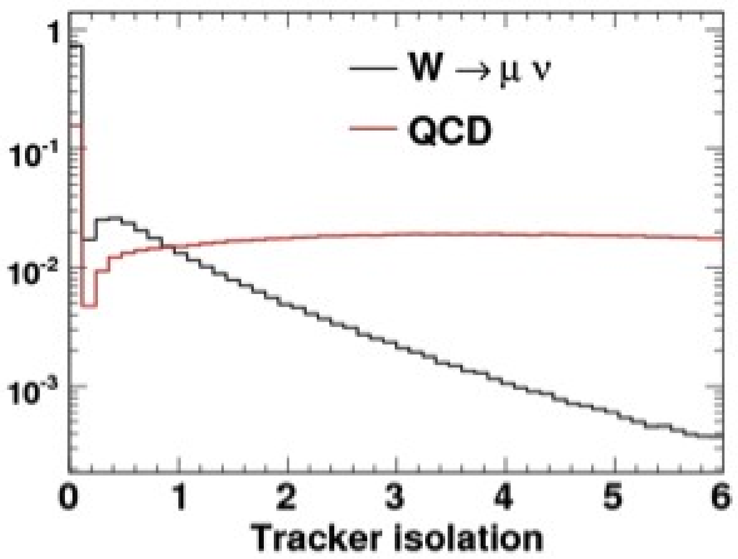
Muon Isolation

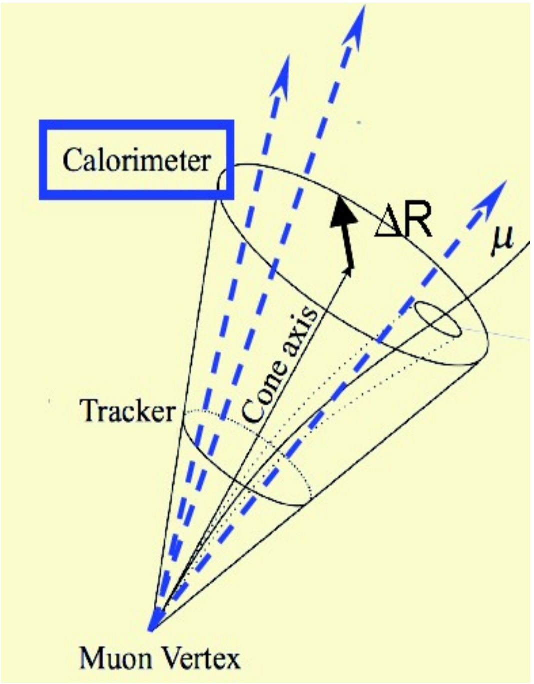
Isolation: Computed magnitude which allows to identify real muons from muons created within jets.

- **Tracker:** Sum the p_T of all the tracks found in a cone around the muon*
- **Calorimeter:** Sum the energy deposits in a cone around the muon*

*The muon is excluded from this computations by applying certain vetoes







Momentum determination

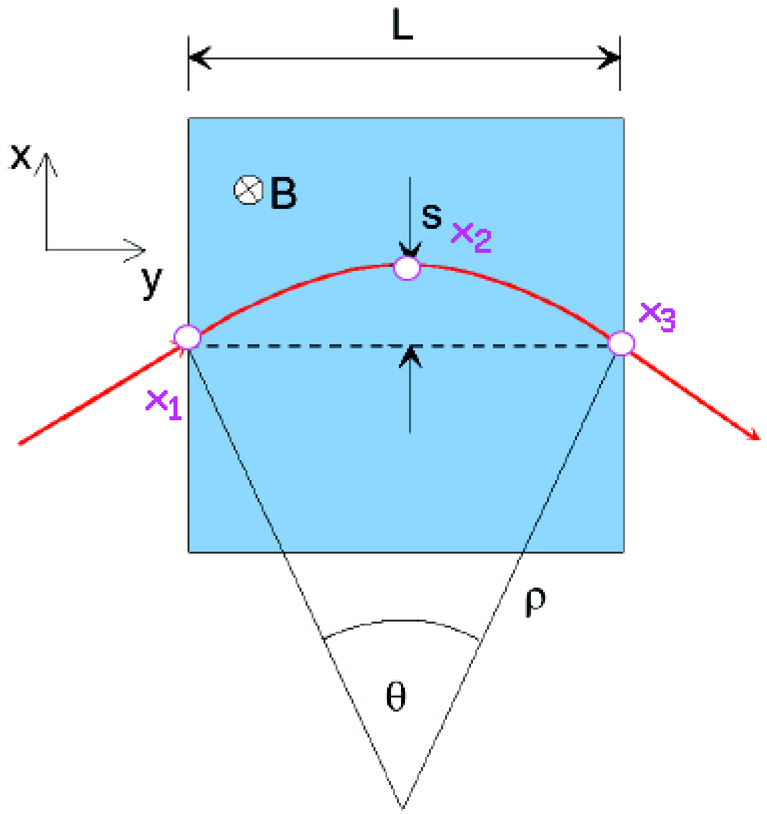
Idea: Use magnetic field to bend trajectory of charged particles.

- **Momentum** is determined by measuring the **track curvature**: k = 1/ρ in the B field.

- For the **transverse momentum** we have:

$$p_T[\mathrm{GeV}] = 0.3B[\mathrm{T}]\rho[\mathrm{m}]$$

(ρ is the bending radius and B the magnetic field)

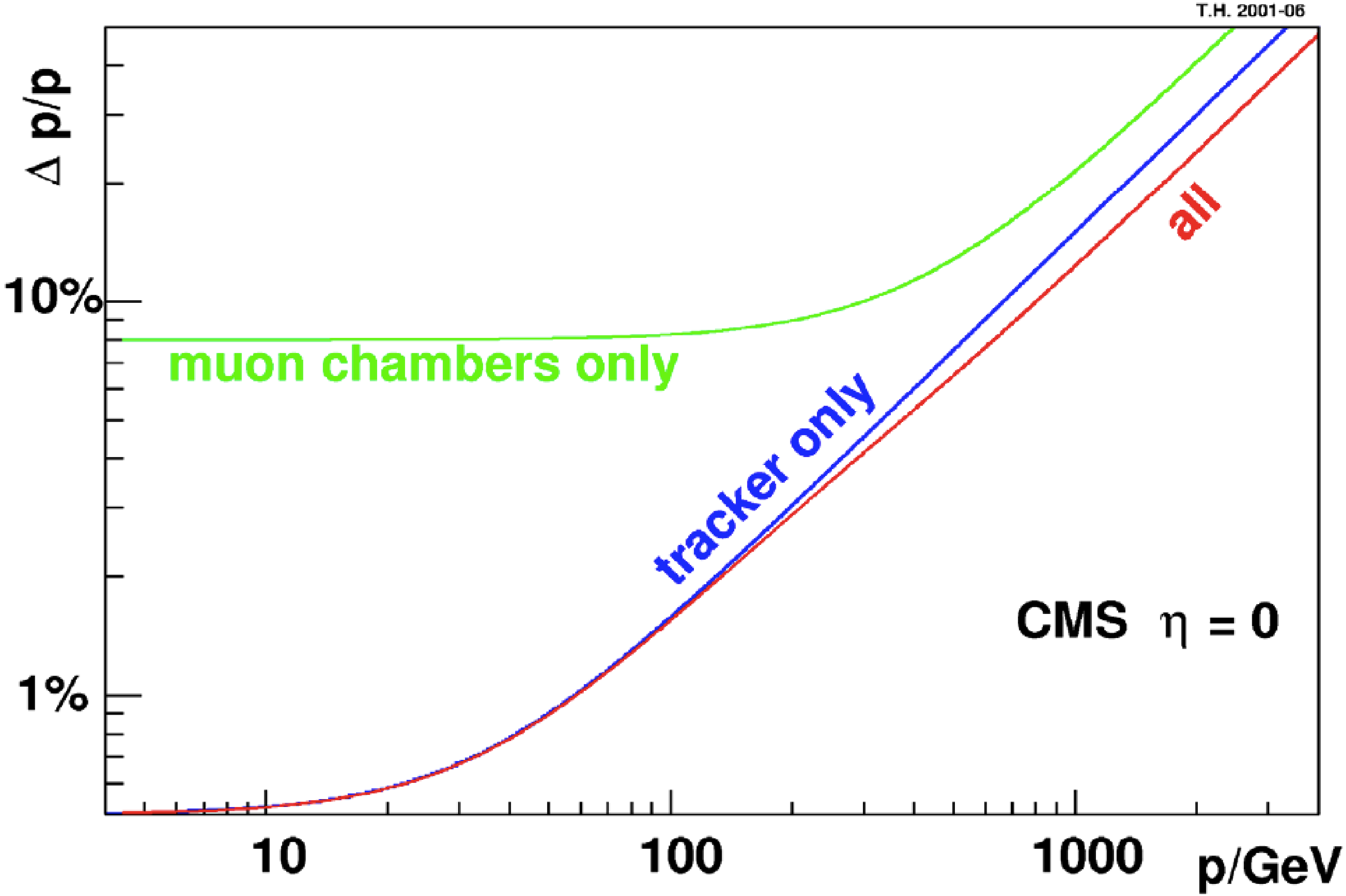


Measurement via Sagitta:

$$\frac{L/2}{\rho} = \sin\frac{\theta}{2} \approx \frac{\theta}{2} \text{ (for small } \theta) \Rightarrow \theta \approx \frac{L}{\rho} = \frac{0.3B \cdot L}{p_T}$$

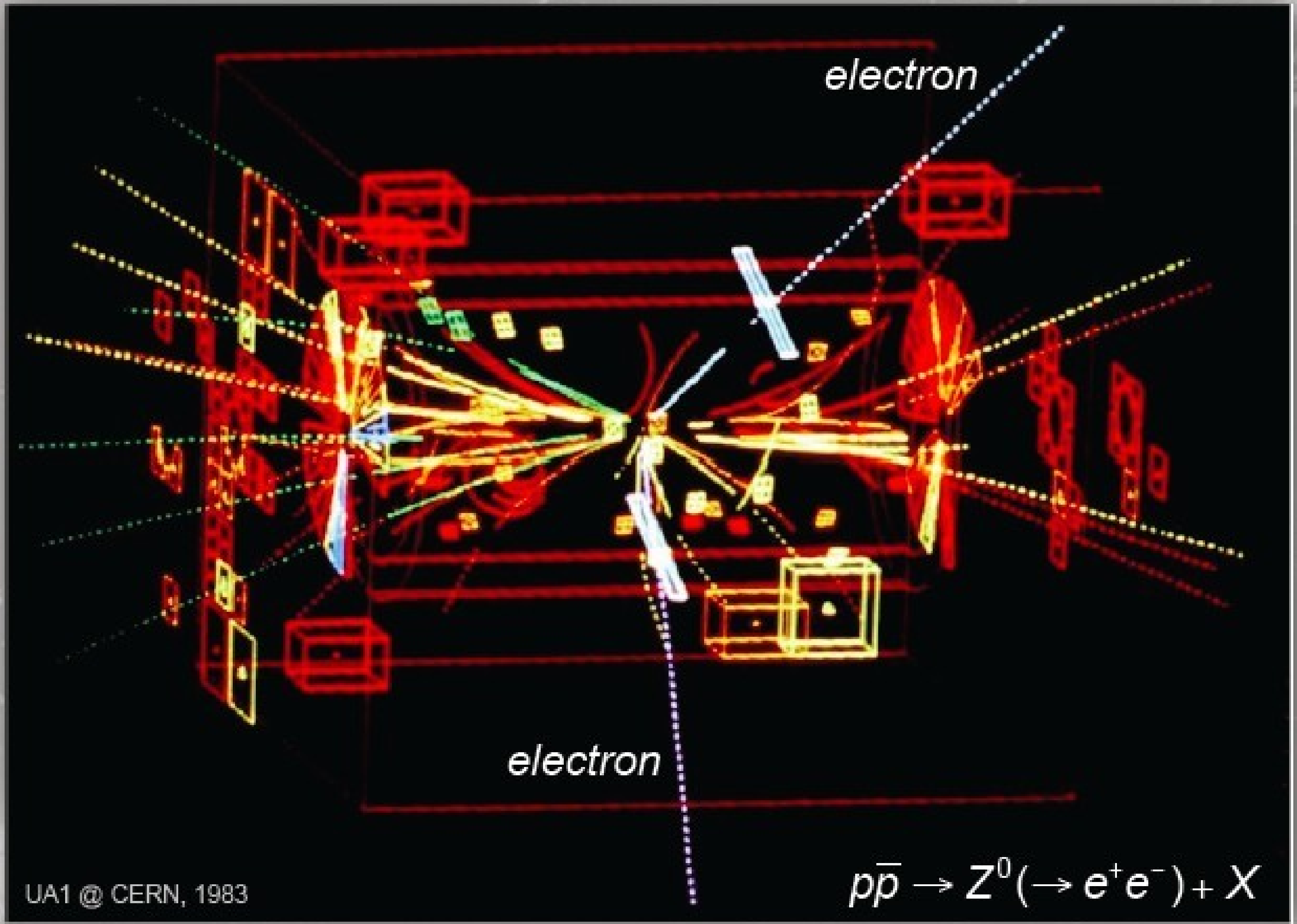
$$s = \rho\left(1 - \cos\frac{\theta}{2}\right) \approx \rho\left(1 - \left(1 - \frac{1}{2}\frac{\theta^2}{4}\right)\right) = \rho\frac{\theta^2}{8} \approx \frac{0.3}{8}\frac{L^2B}{p_T}$$

CMS Muon momentum resolution

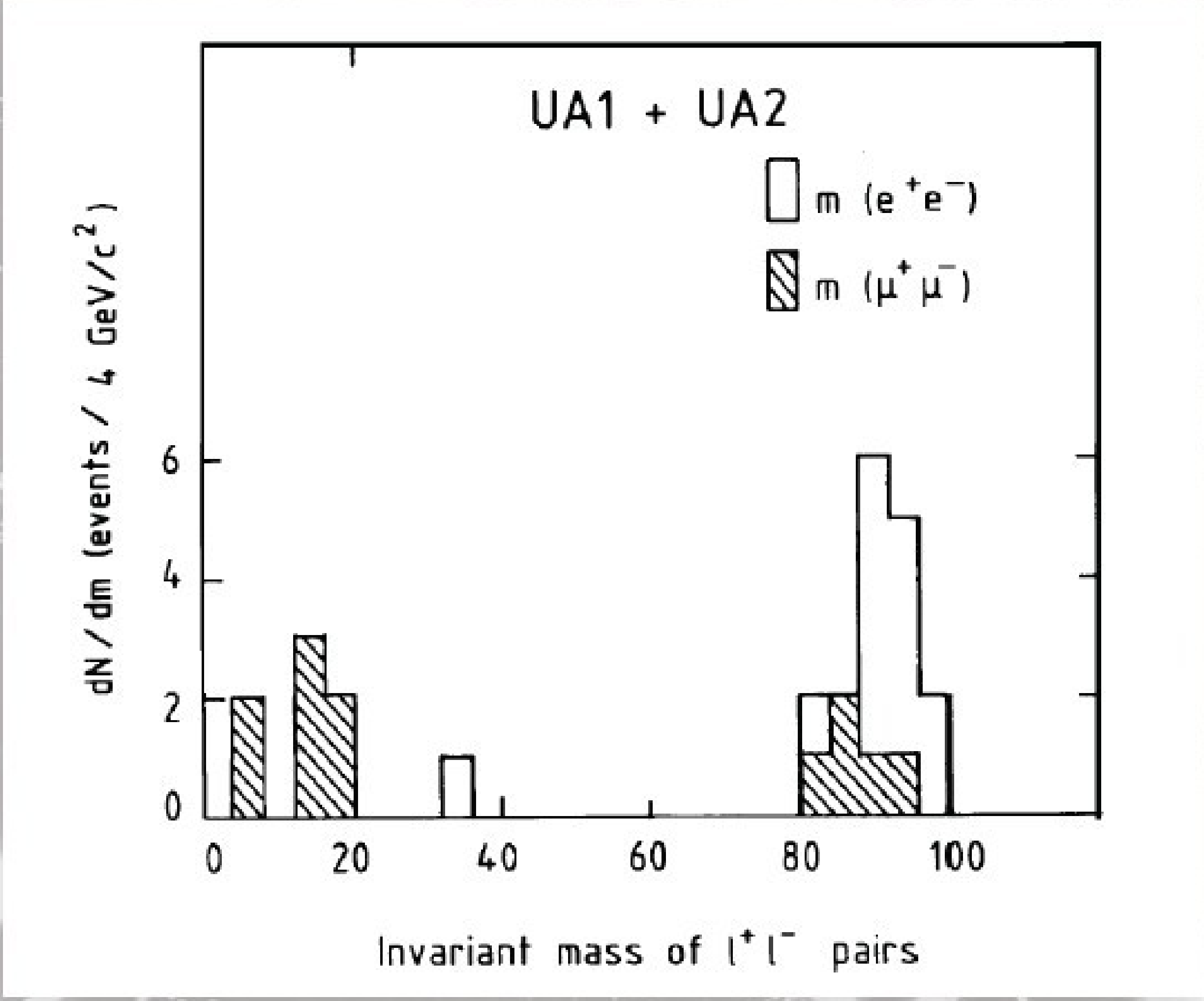


Experimental $Z \to \mu\mu$ results

Z boson production **on the mass shell**, seen in April 1983 by UA1

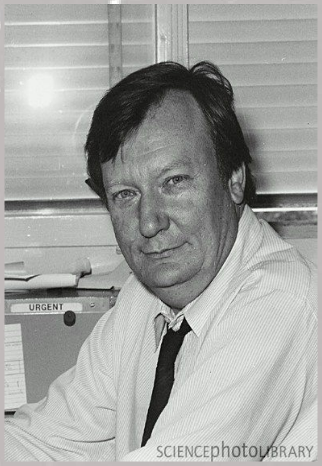


On-shell Z boson discovery 1983



NOBEL Prize in Physics 1984

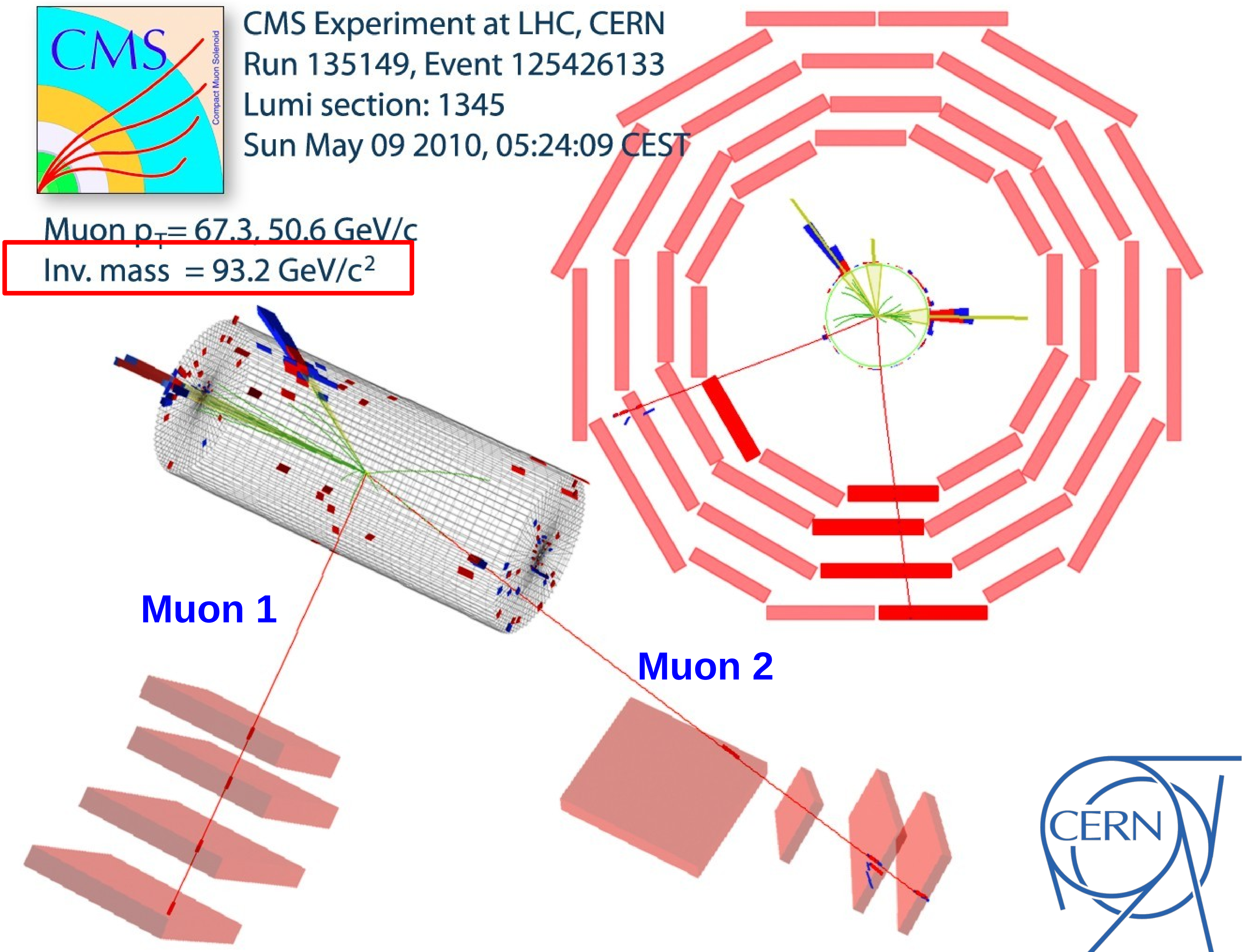
Carlo Rubbia



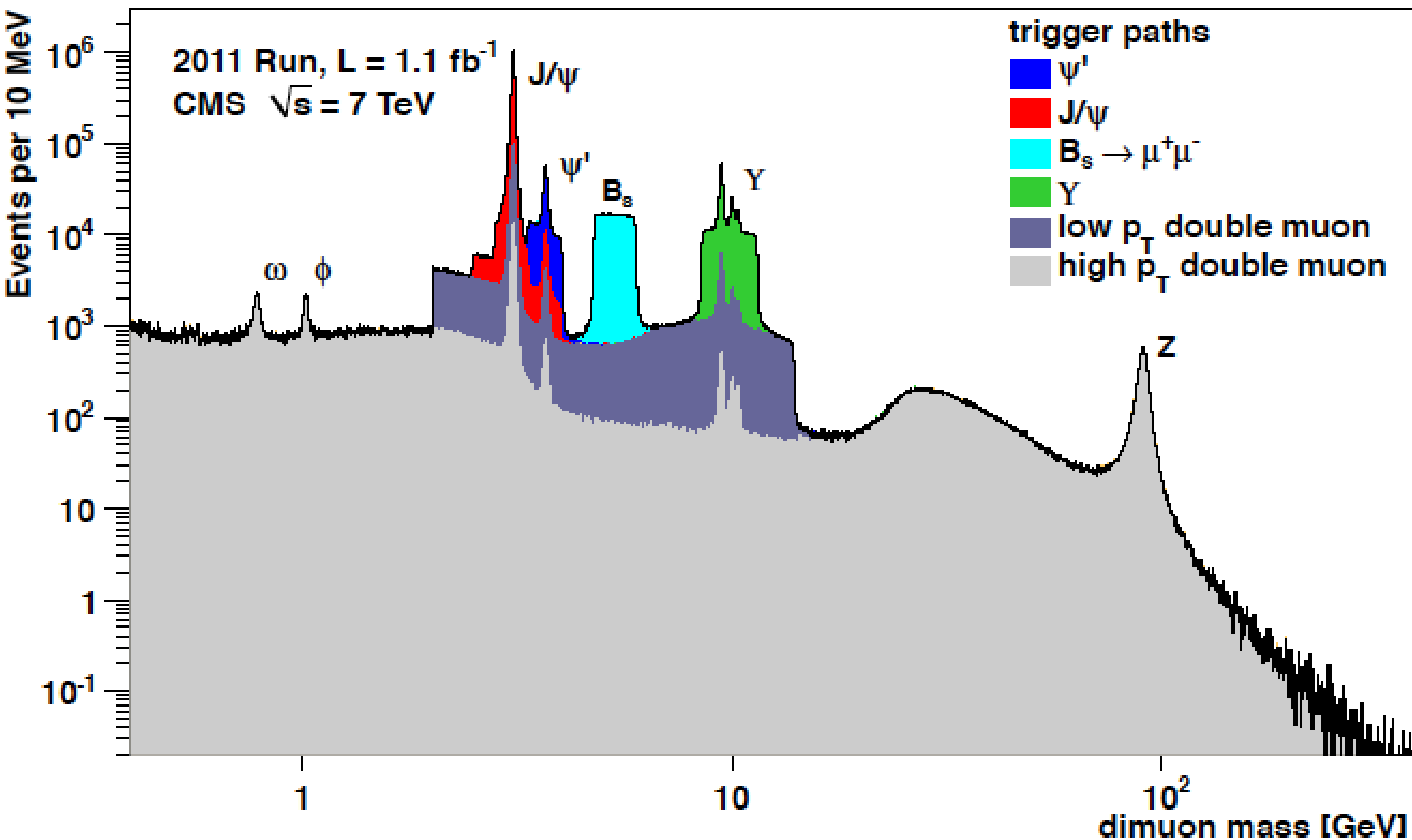
$$M_Z = (95.1 \pm 2.5)\ \text{GeV}$$

See C. Rubbia, Nobel Lecture, 1984

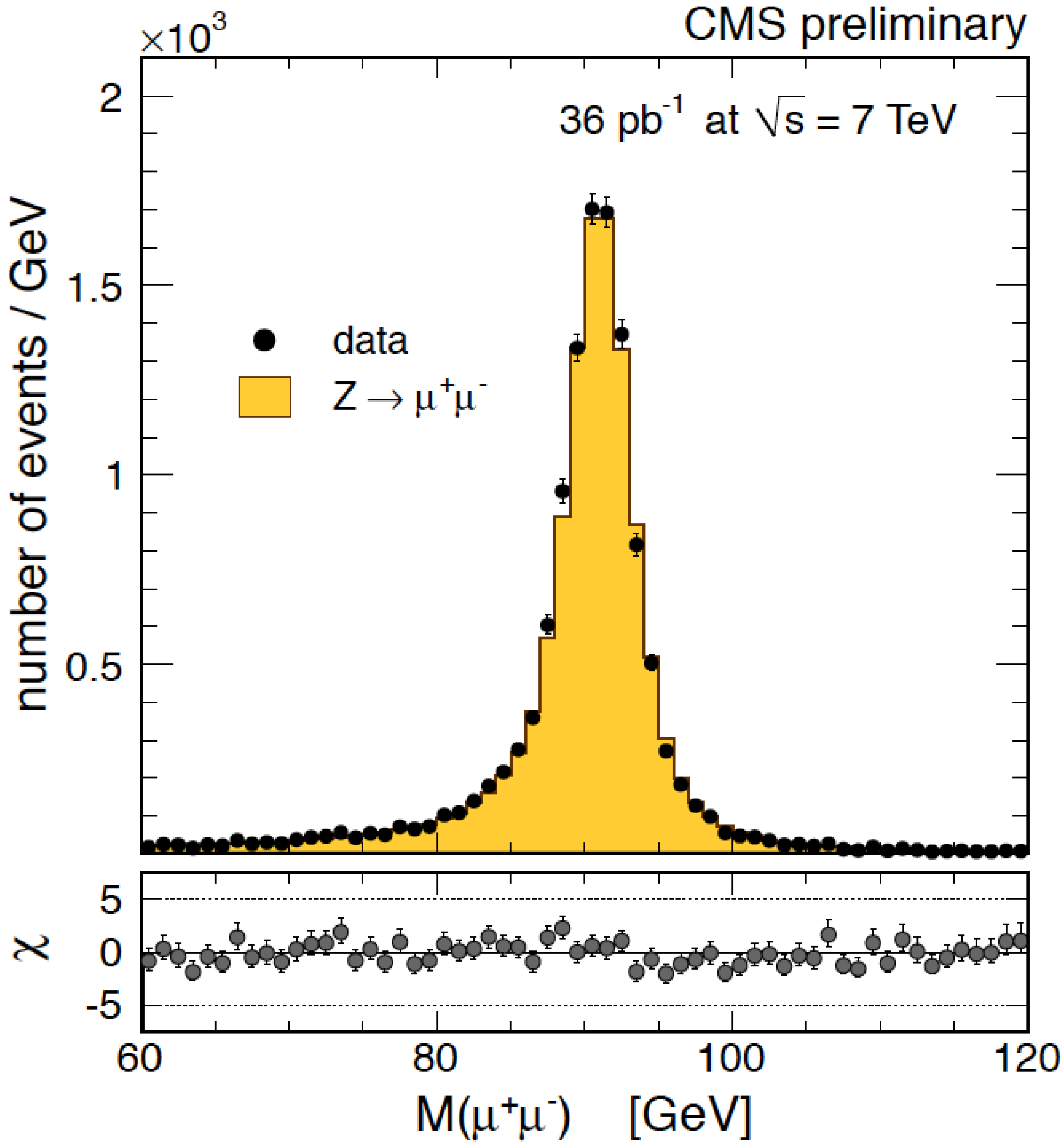
W and *Z* bosons observed at the LHC …


CMS
Compact Muon Solenoid
CMS Experiment at LHC, CERN
Run 135149, Event 125426133
Lumi section: 1345
Sun May 09 2010, 05:24:09 CEST
Muon p_T = 67.3, 50.6 GeV/c
Inv. mass = 93.2 GeV/c^2
Muon 1
Muon 2
CERN

$\mu^+\mu^-$ invariant mass in CMS

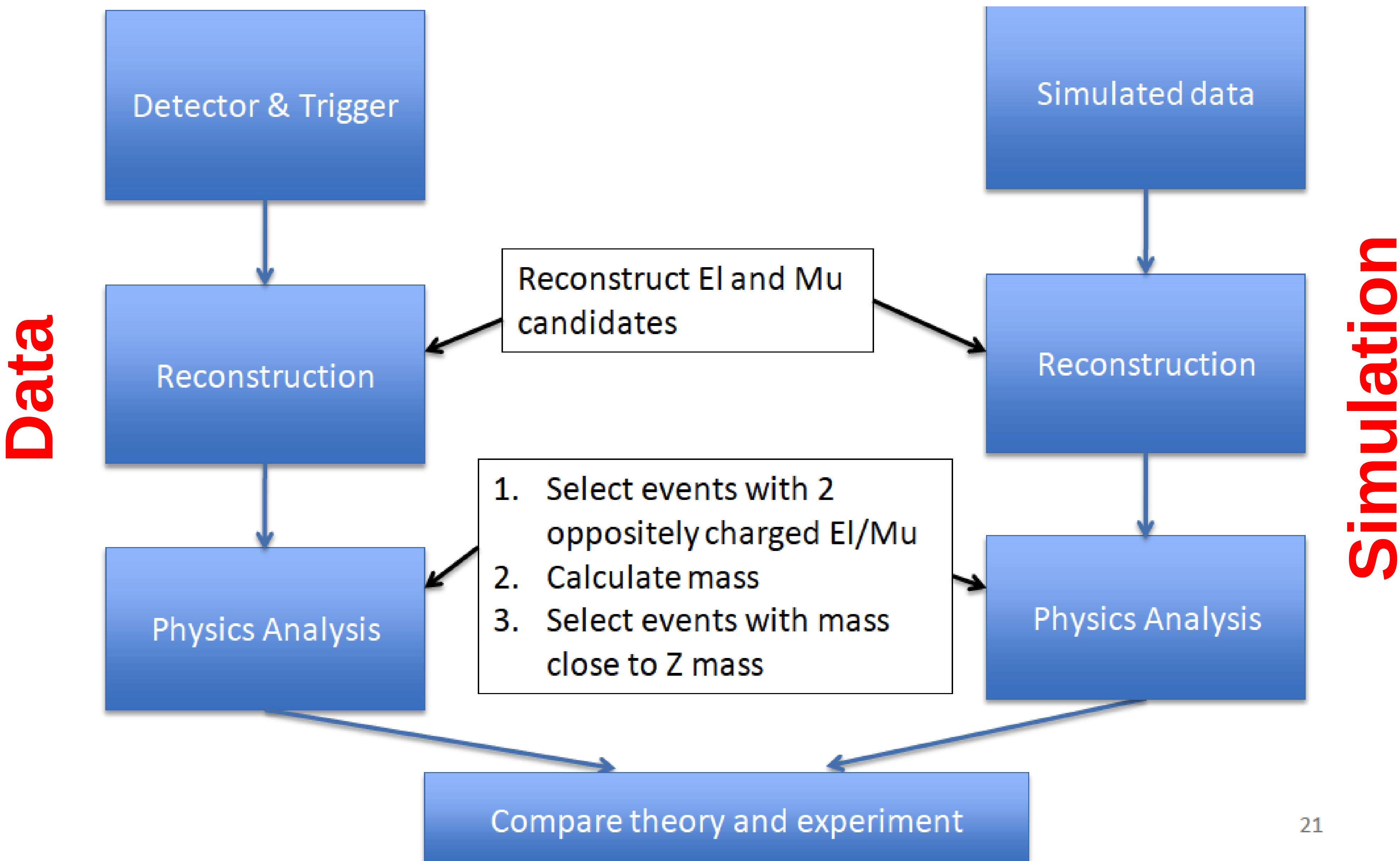


Z boson to $\mu^+\mu^-$



Practical exercise

Analysis flow



Analysis flow