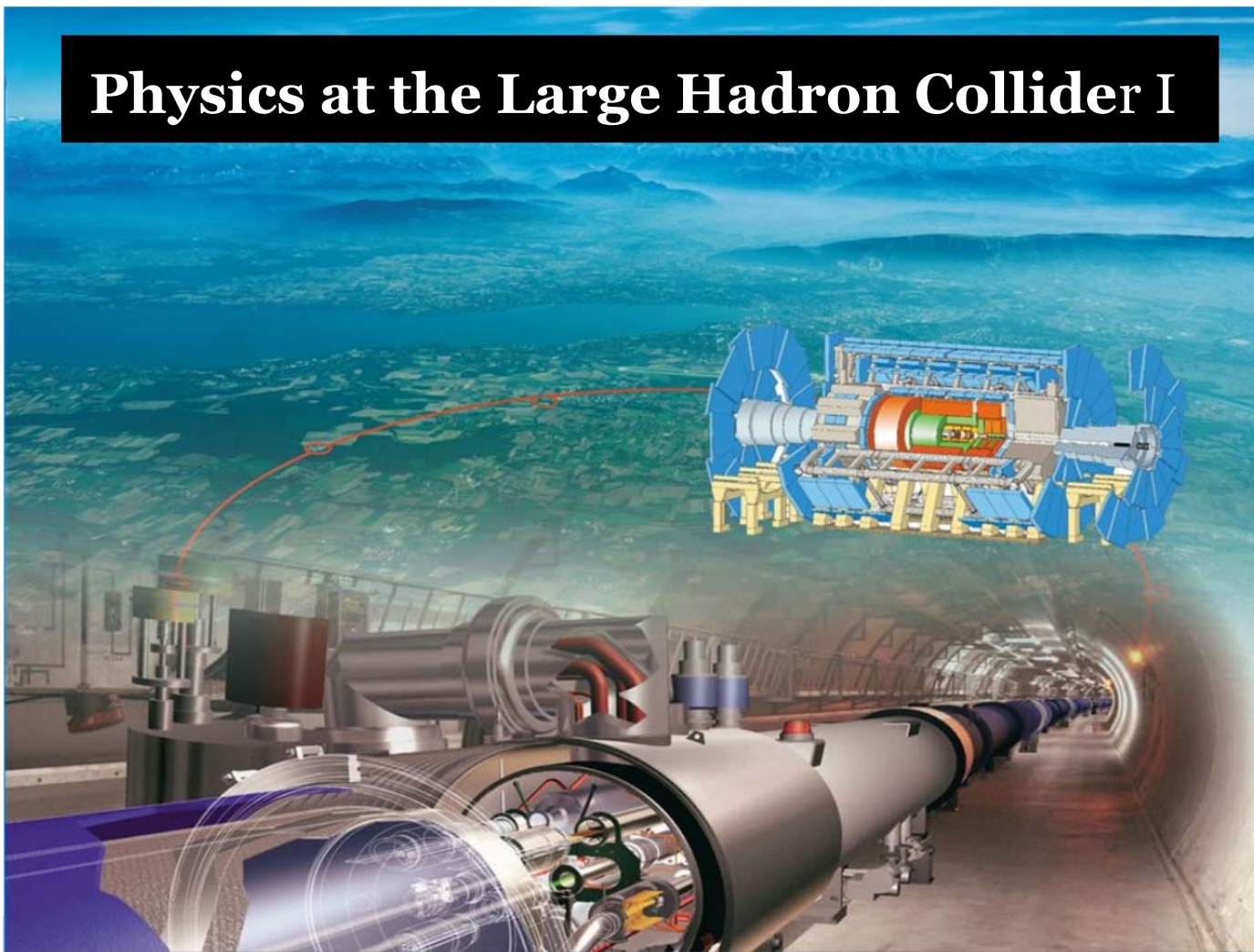


# Testing the Standard Model of Elementary Particle Physics II

First lecture

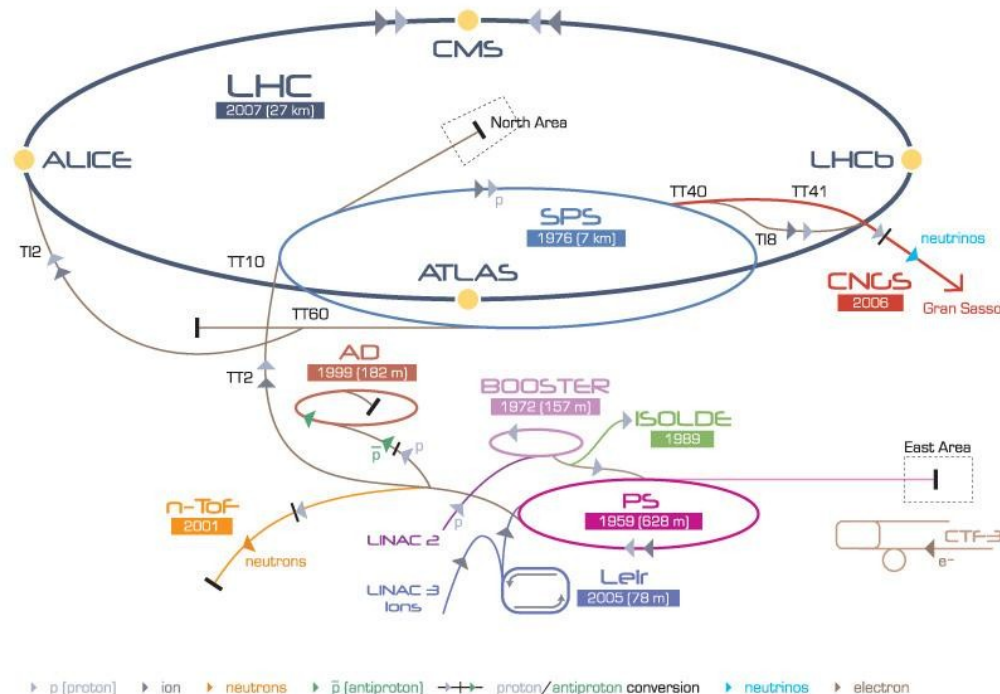
23th April 2020

# Physics at the Large Hadron Collider I



# The Large Hadron Collider

## CERN Accelerator Complex



- Instantaneous luminosity

$$\mathcal{L} = fn \frac{N_1 N_2}{A}$$

$N_1, N_2$  = Number of hadrons per bunch

$n$  = Number of bunches per beam

$f$  = Resolution frequency

$A$  = Beam cross section

- Integrated luminosity

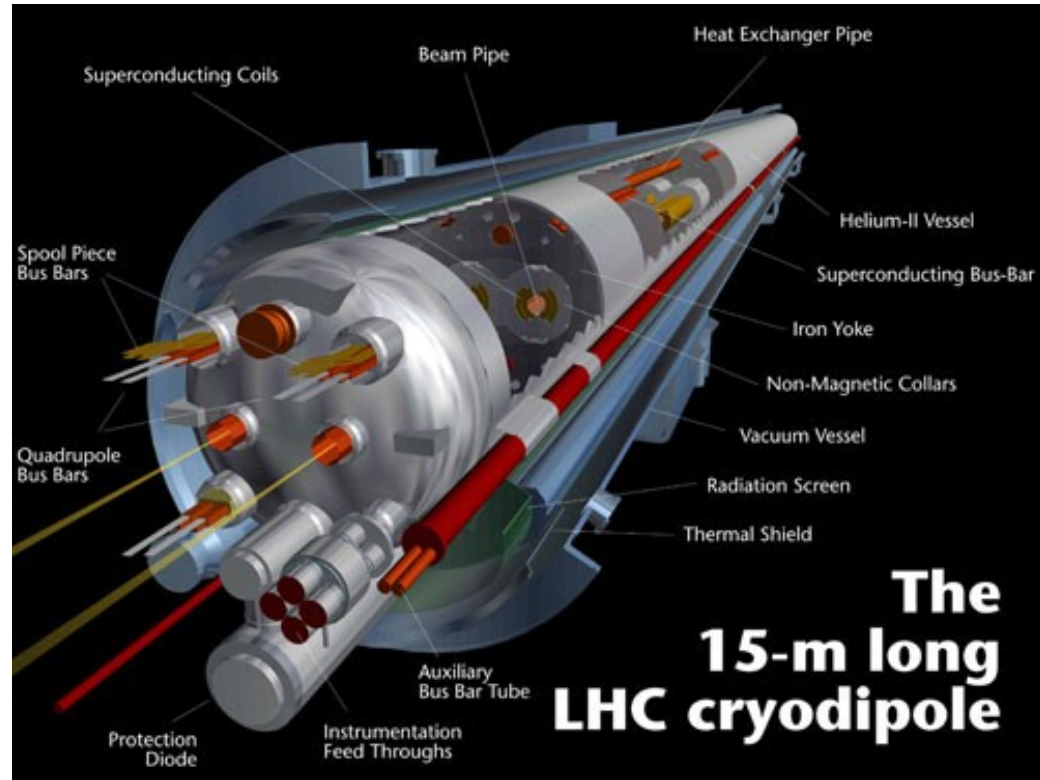
$$L = \int \mathcal{L} dt$$

- CoM energy:  $\sqrt{s}$

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron  
AD Antiproton Decelerator CTF3 Clic Test Facility CNGS CERN Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine Device  
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

# Magnet system

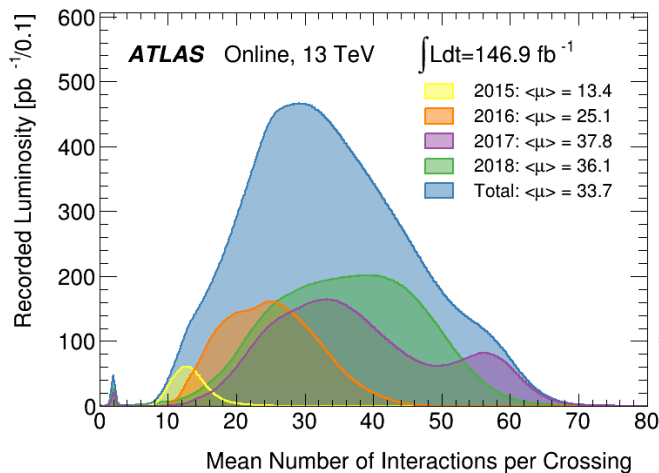
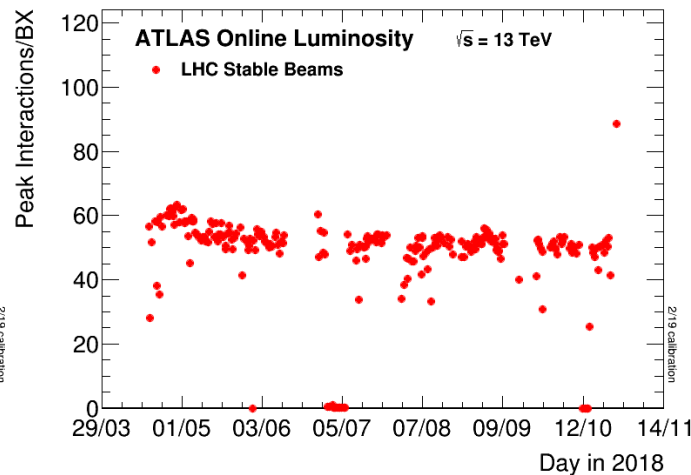
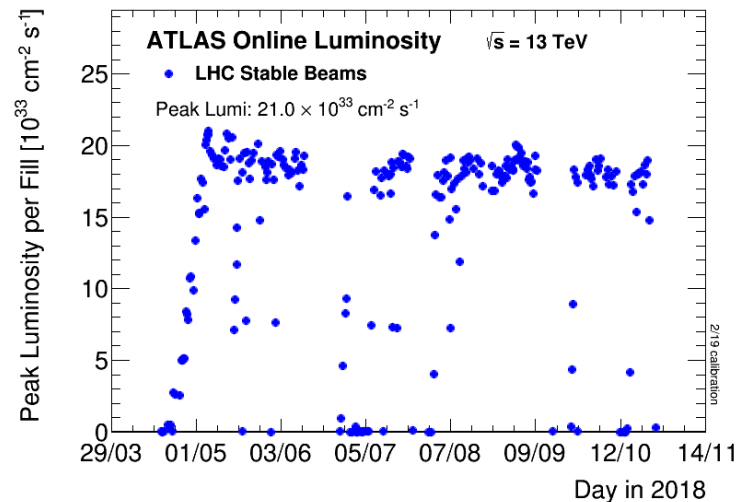
- At the LHC **superconducting dipole magnets** are operated at B-field strength of 8.3 T over their full length
  - Forcing the particle beams to follow the circular pipes
- **Quadrupole magnets** are used to focus the beams
- The LHC magnets are made from niobium-titanium (NbTi) cables.
- LHC is operate at 1.9 K (-271.3°C)



# Luminosity

- Design goal of LHC:
  - $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ 
    - $n = 2835$  proton bunches per beam
    - $f = 40\text{MHz}$
    - $N_1/N_2 = 10^{11}$  protons per bunch

- Already exceeded in Run-II



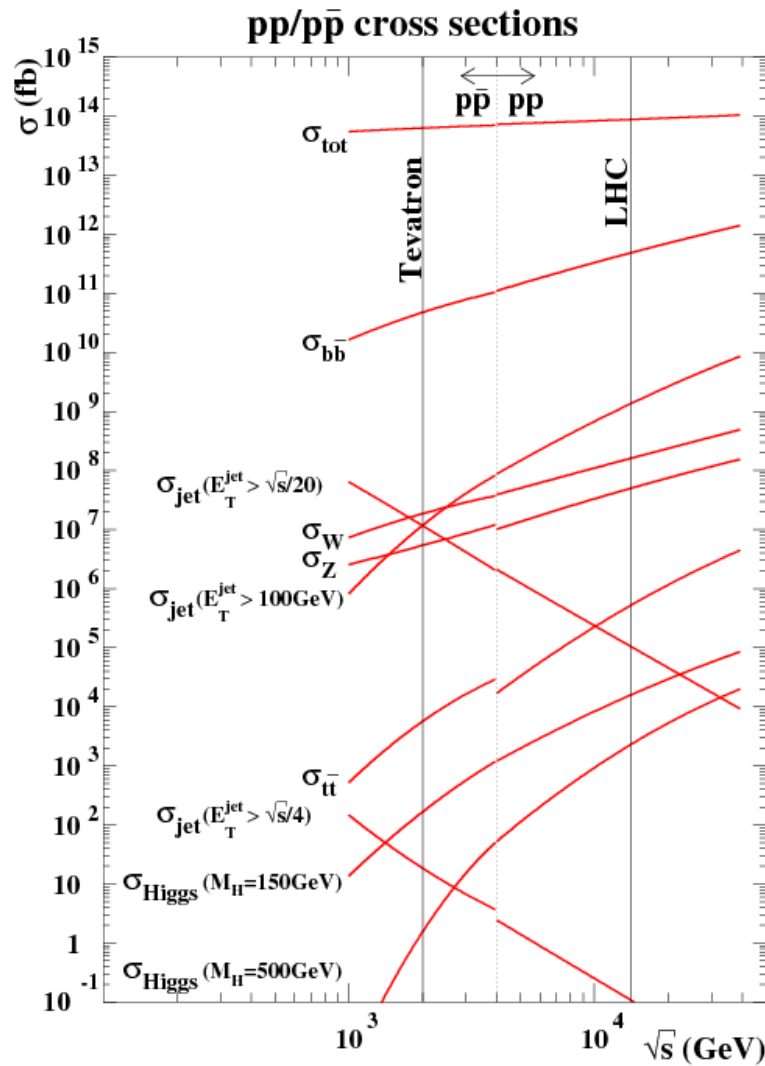
$$\mathcal{L} = f n \frac{N_1 N_2}{A}$$

- Pile-up:
  - Additional interactions next to the hard process

# Event rates/cross sections

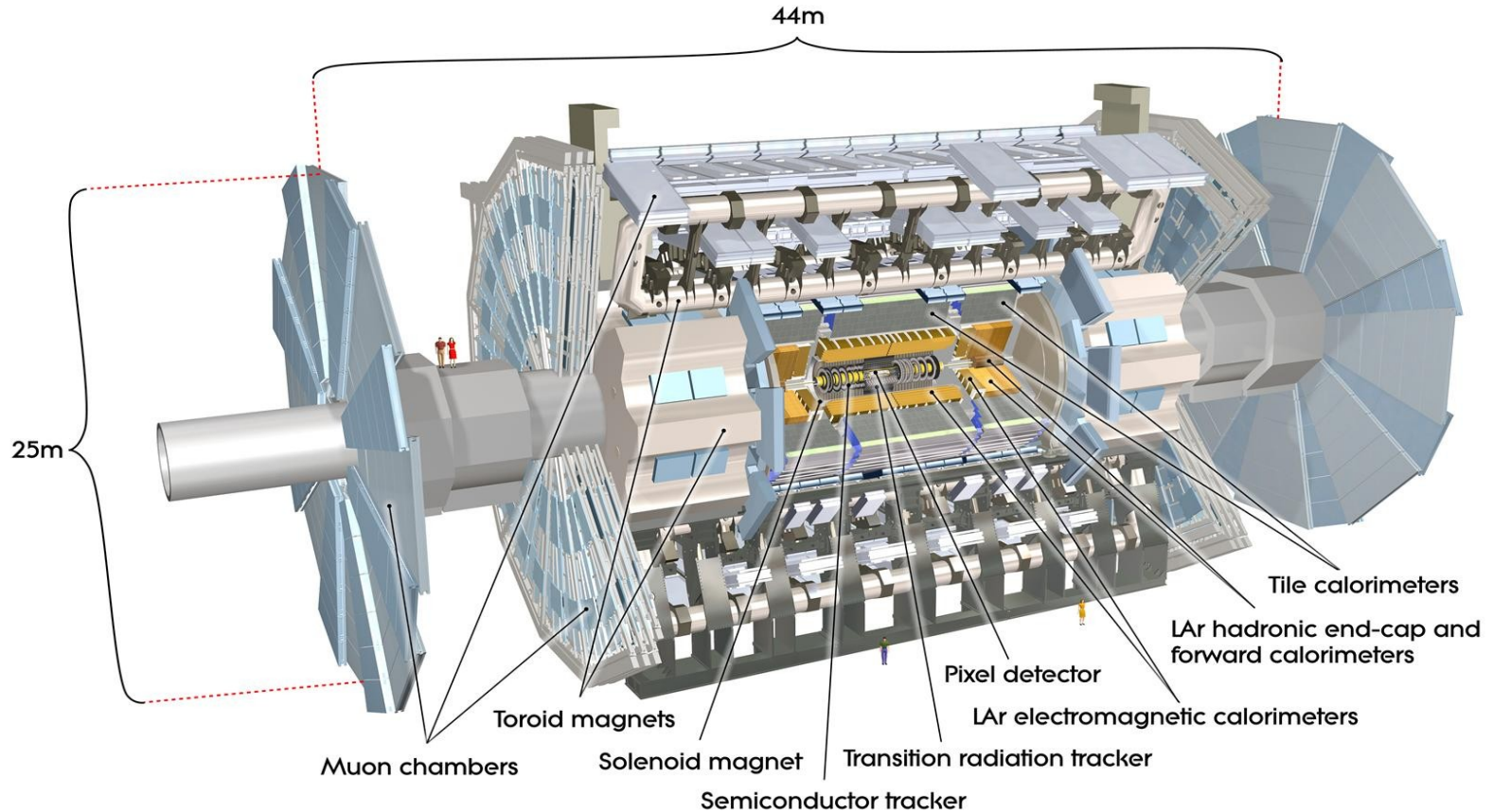
$$\frac{dN}{dt} = \mathcal{L} \cdot \sigma$$

Inelastic pp collisions	$\sim 10^7$ Hz
b-quark production	$\sim 10^4$ Hz
Jet production $E_T > 250$ GeV	$\sim 1$ Hz
$W \rightarrow l\nu$	$\sim 1$ Hz
top-quark production	$\sim 10^{-2}$ Hz
Higgs bosons	$\sim 10^{-4}$ Hz





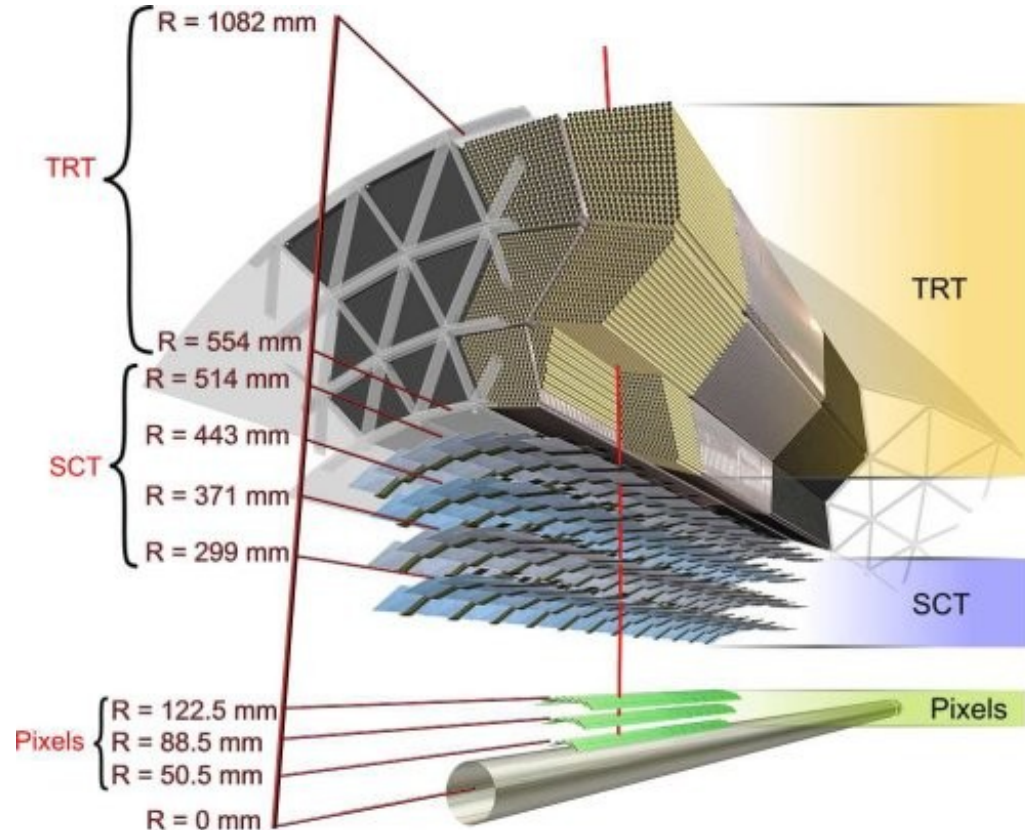
# The ATLAS Detector



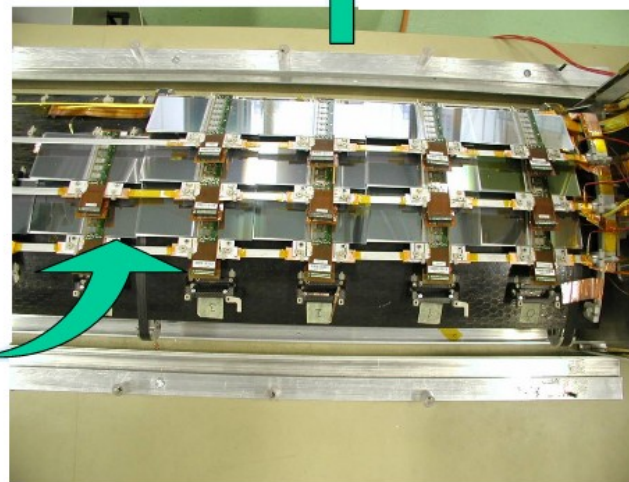
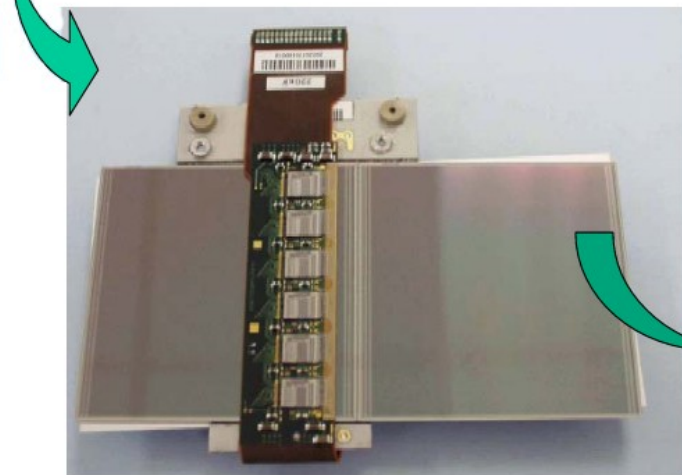
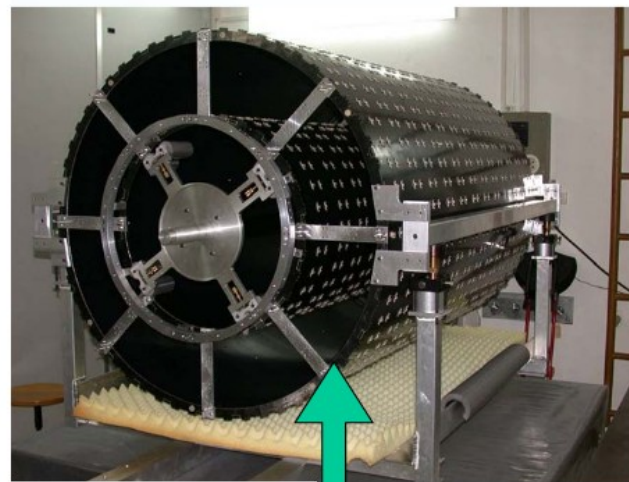
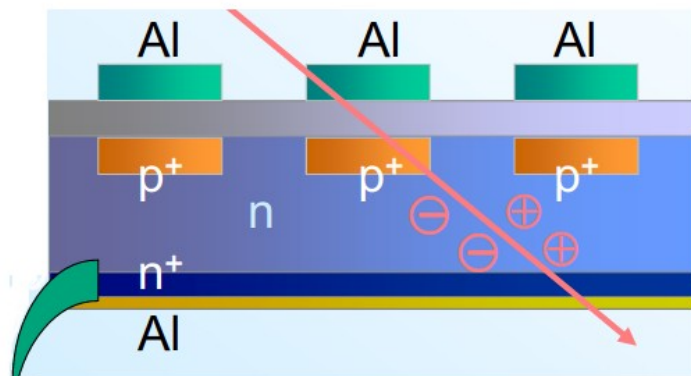
# Inner Detector

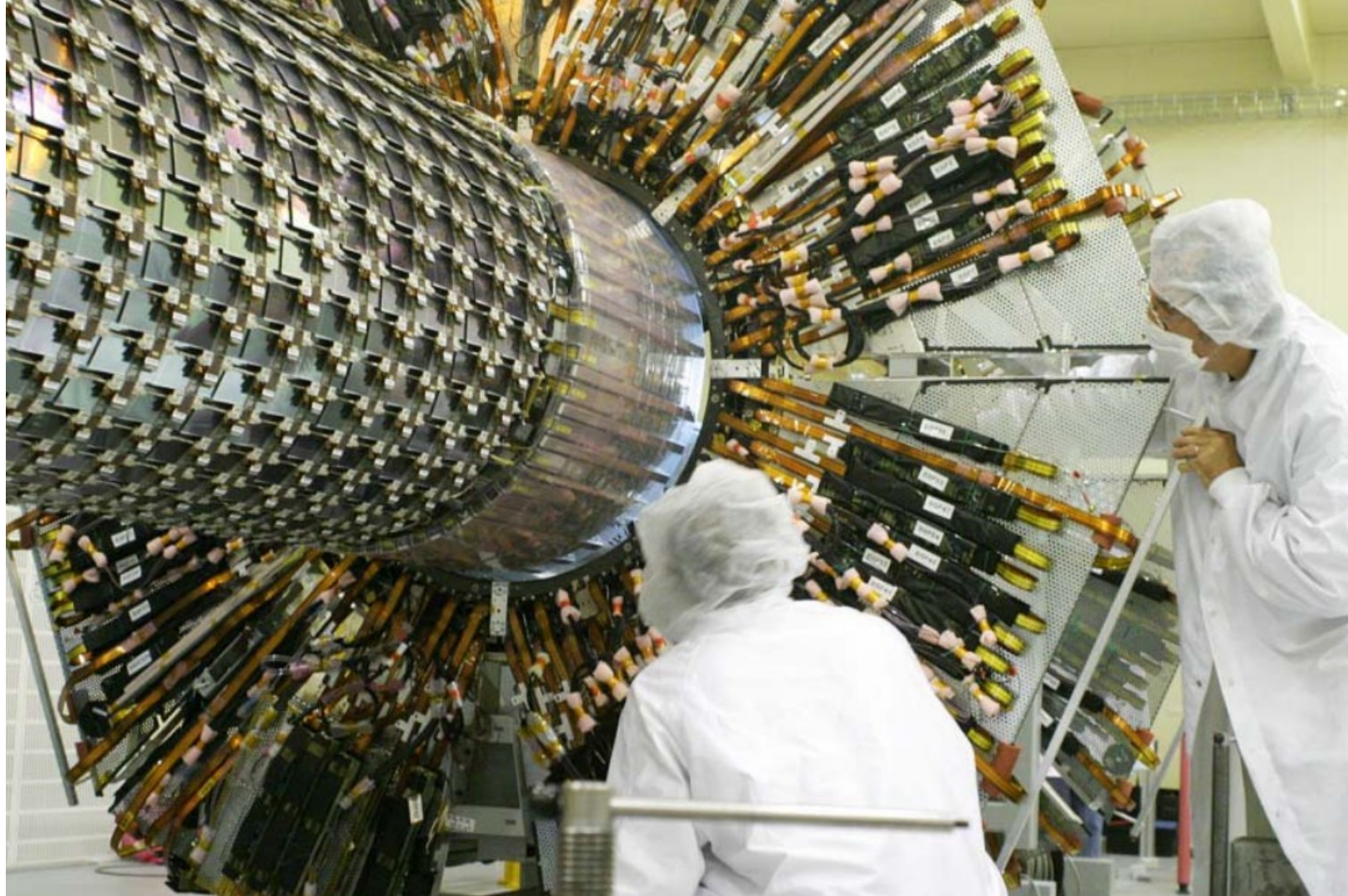
- **Inner Detector** build up by three types of tracking detectors
  - Pixel
  - Semiconductor Tracker (SCT)
  - Transition Radiation Tracker (TRT)
- Dedicated to reconstruct trajectories of charged particles (tracking), charge identification and momentum measurement

$$\frac{\sigma_{p_T}}{p_T} = 0,05\% \cdot p_T \oplus 1\%$$











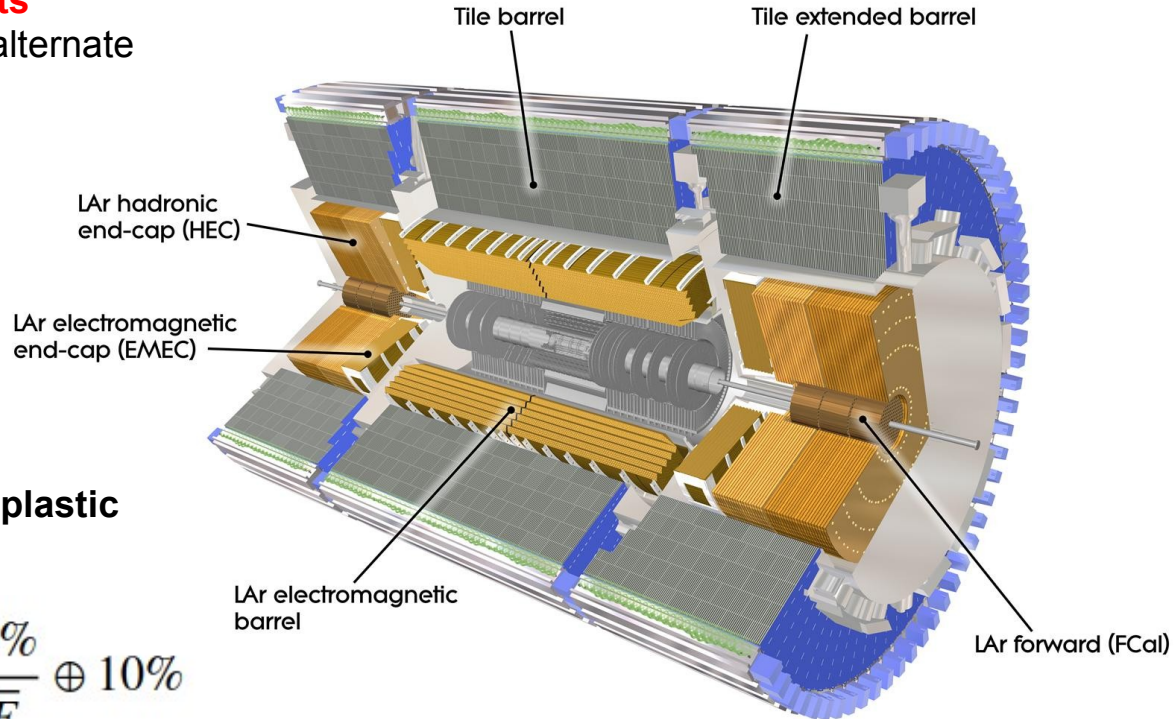
# Calorimeter system

- ATLAS calorimeters use so called sampling technique for **energy measurements**
  - Active material and absorber alternate
- **EM calorimeter:**
  - Active medium: **liquid argon**
  - Absorber: **Lead**

$$\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\%$$

- **Hadronic calorimeter:**
  - Active medium: **scintillating plastic**
  - Absorber: **Steel**

$$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\% \quad \text{and} \quad \frac{\sigma_E}{E} = \frac{100\%}{\sqrt{E}} \oplus 10\%$$



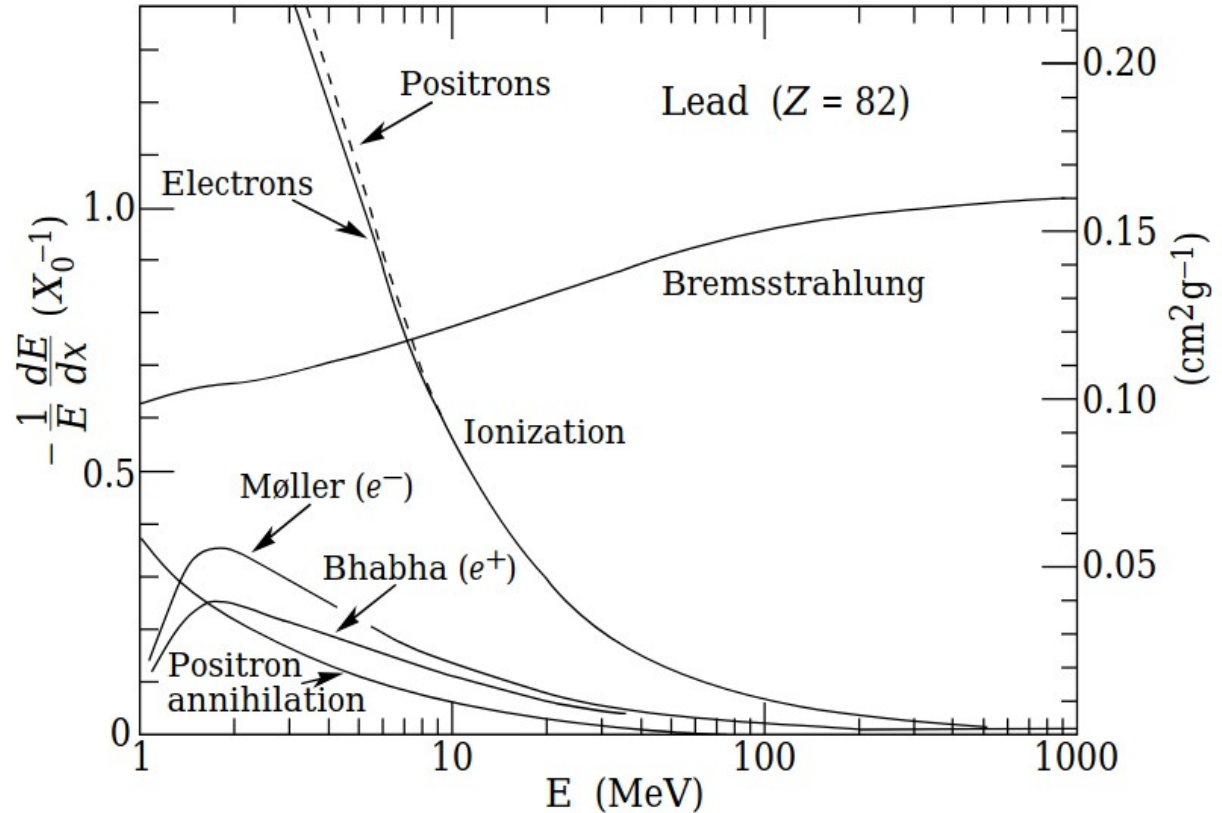
# Calorimetry

$$-\frac{dE}{dx} = \frac{E}{X_0}$$

$$X_0 = \frac{716.4 \cdot A}{Z(Z+1) \log(287/\sqrt{Z})}$$

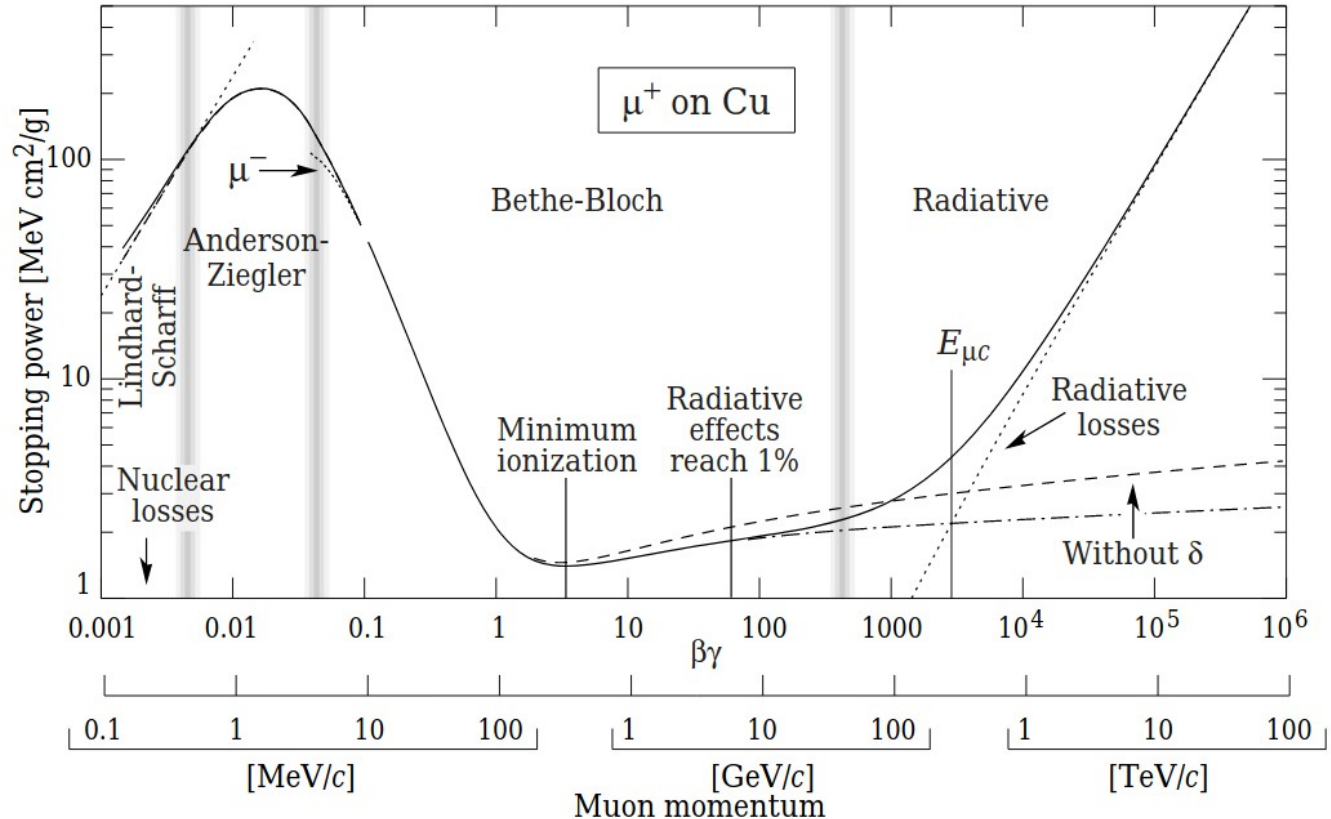
Z = Atomic number of absorber

A = Atomic mass of absorber



# Calorimetry

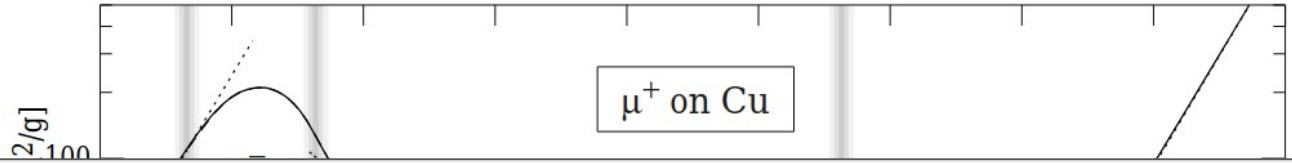
<http://pdg.lbl.gov/2009/reviews/rpp2009-rev-passage-particles-matter.pdf>



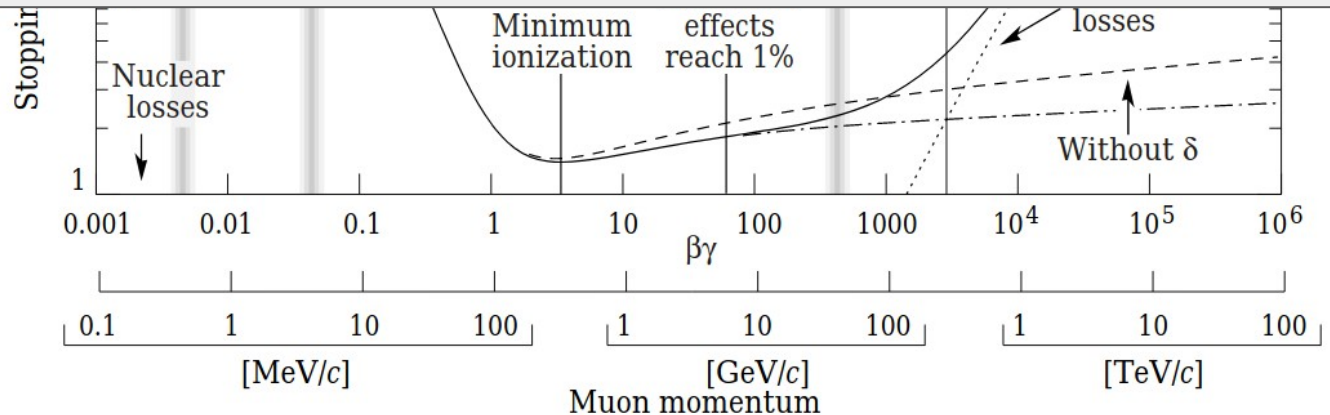


# Calorimetry

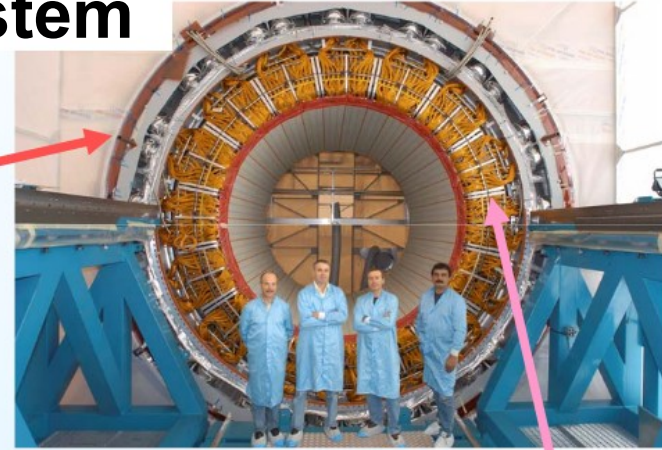
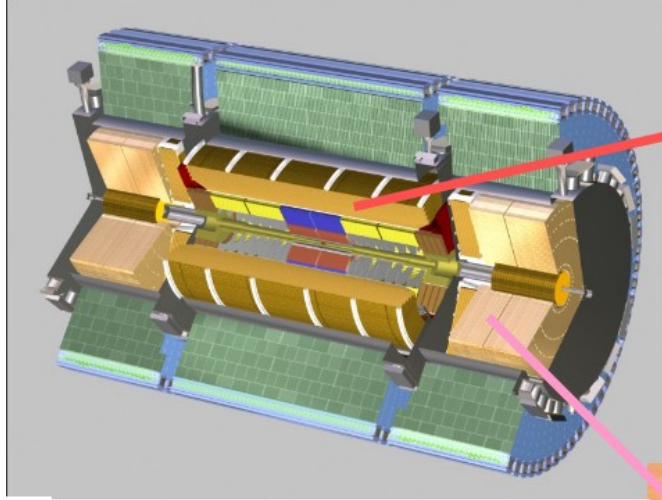
<http://pdg.lbl.gov/2009/reviews/rpp2009-rev-passage-particles-matter.pdf>



$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

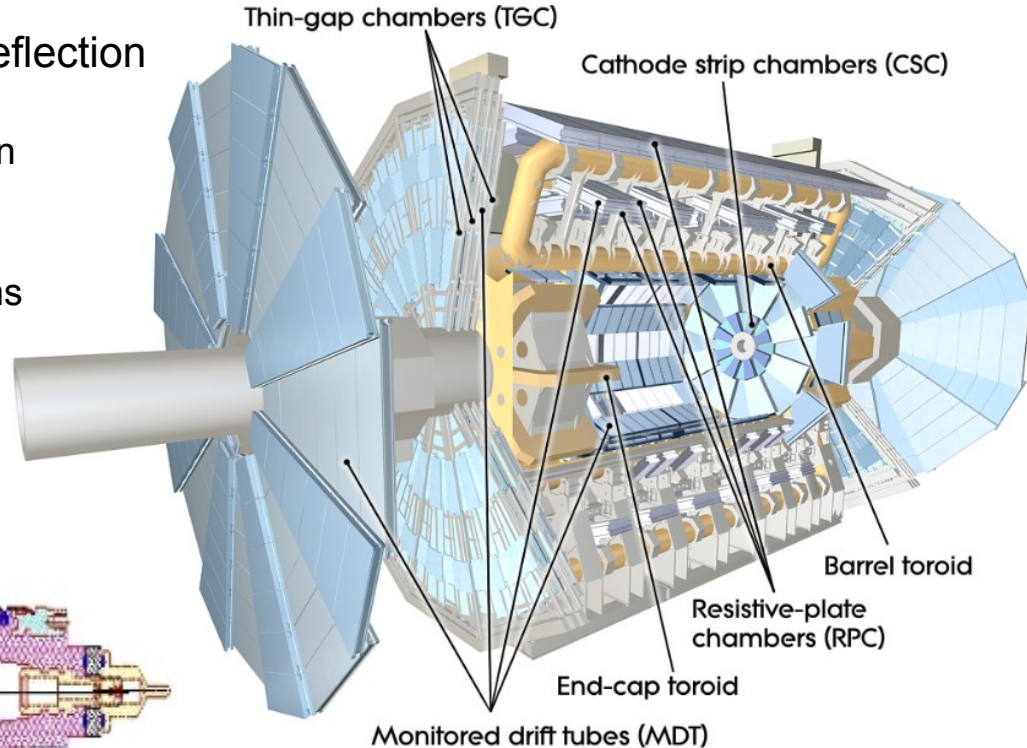


# ATLAS calorimeter system



# Muon spectrometer

- The muon spectrometer measures the deflection of the muon tracks in the magnetic field
  - Based on gaseous detectors for precision tracking and triggering
- Characteristics:
  - Momentum resolution of 2-10% for muons with a  $p_T$  between 10GeV - 1TeV
  - Spatial resolution of 30  $\mu\text{m}$



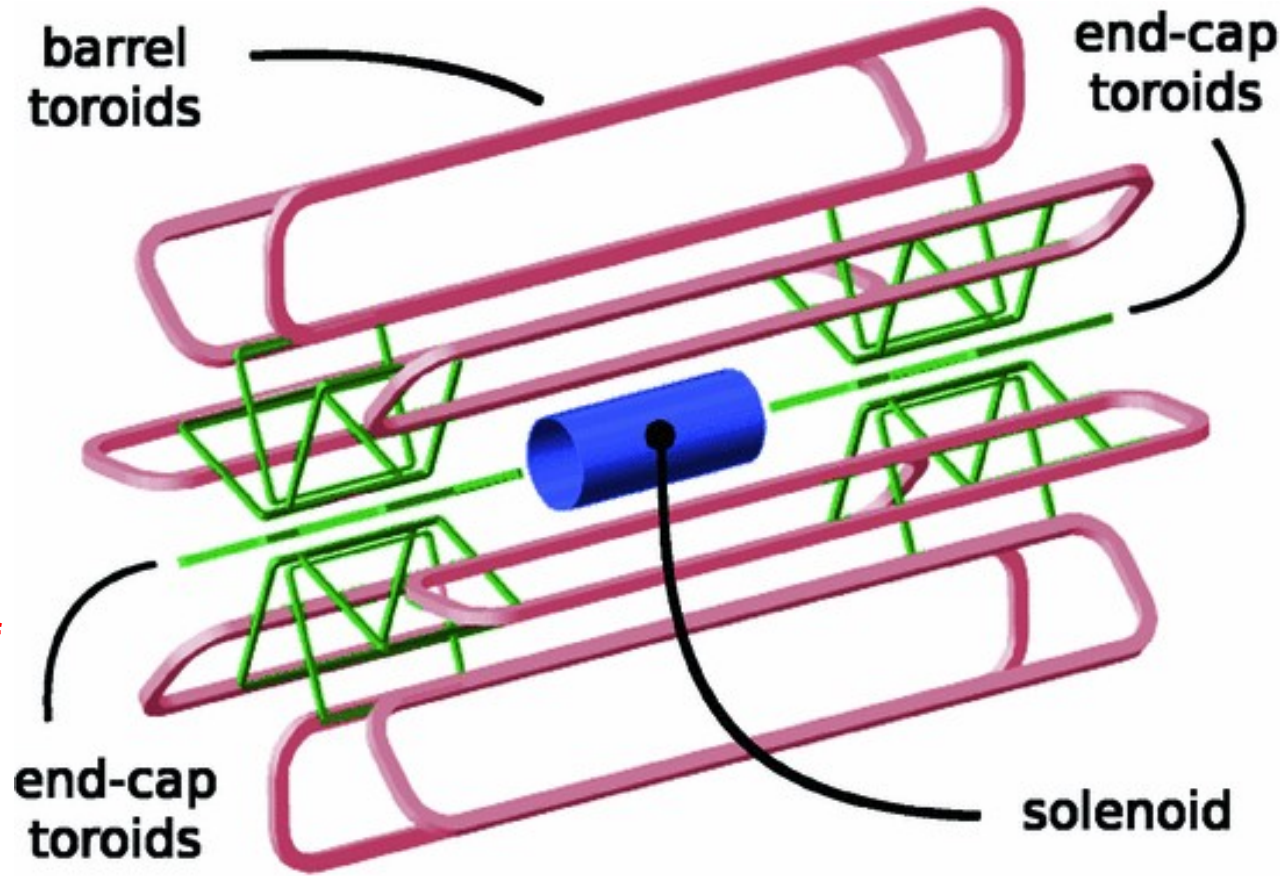


# Construction of muon chambers



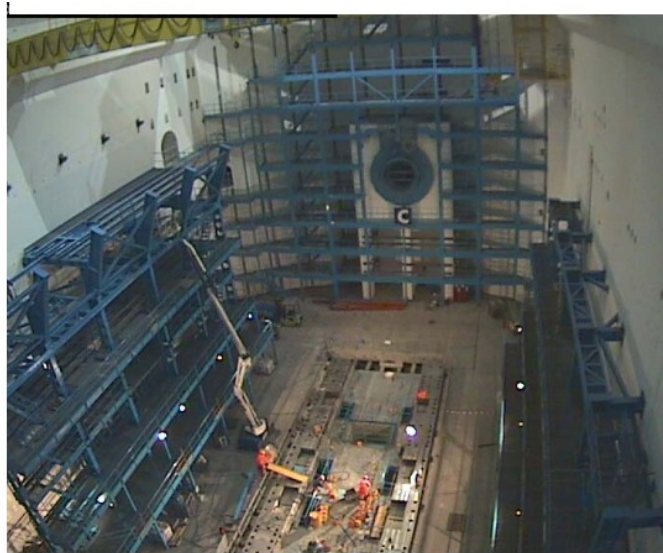
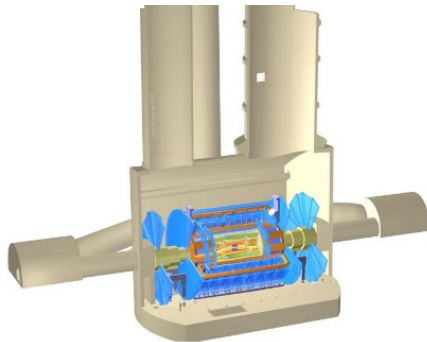
# Magnet system

- **Toroids:**
  - Field strength: 4T
- **Solenoid**
  - Field strength: 2T
- Responsible for bending trajectories of charged particles
  - Enables measurement of momenta





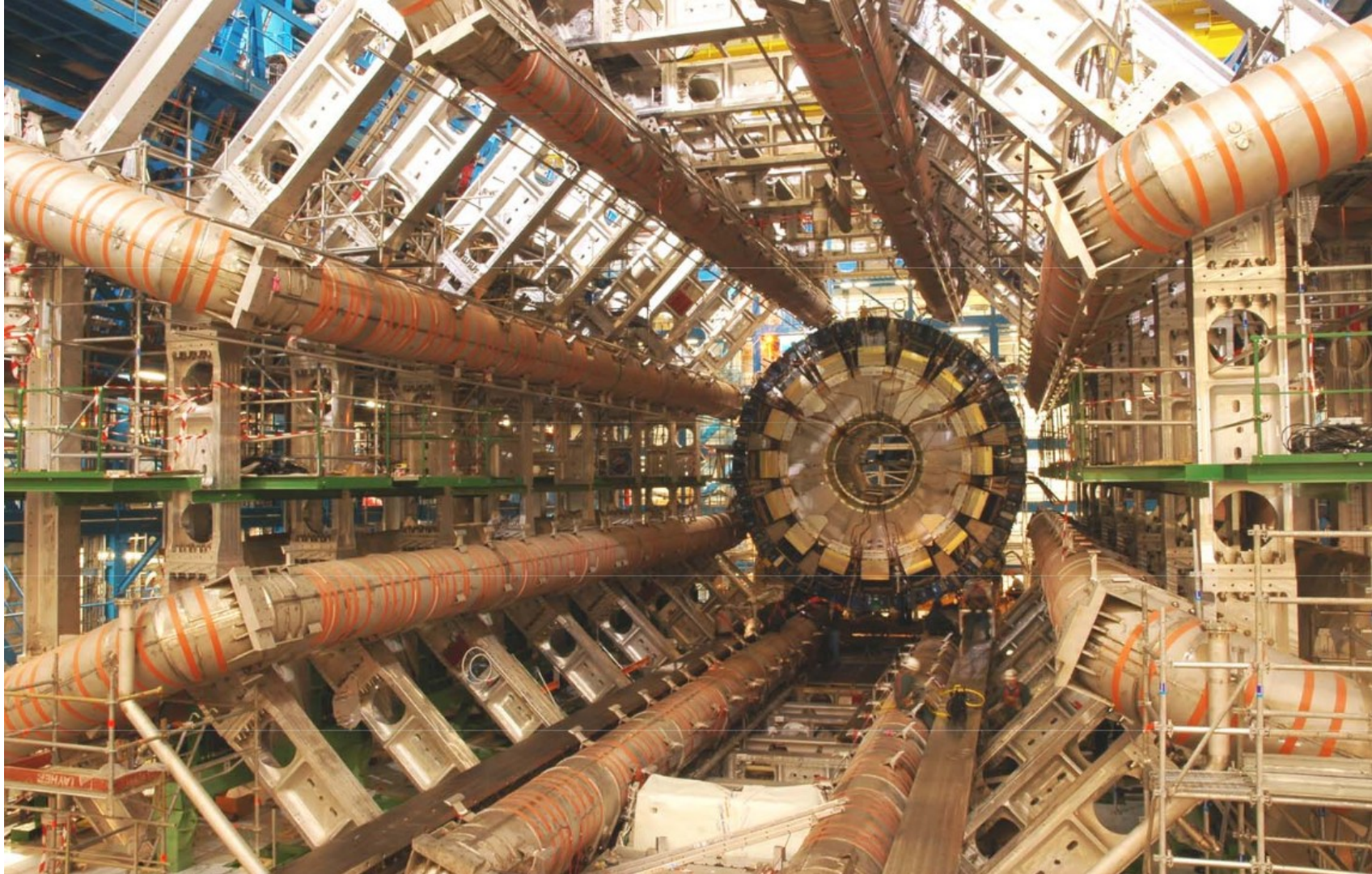
# Construction





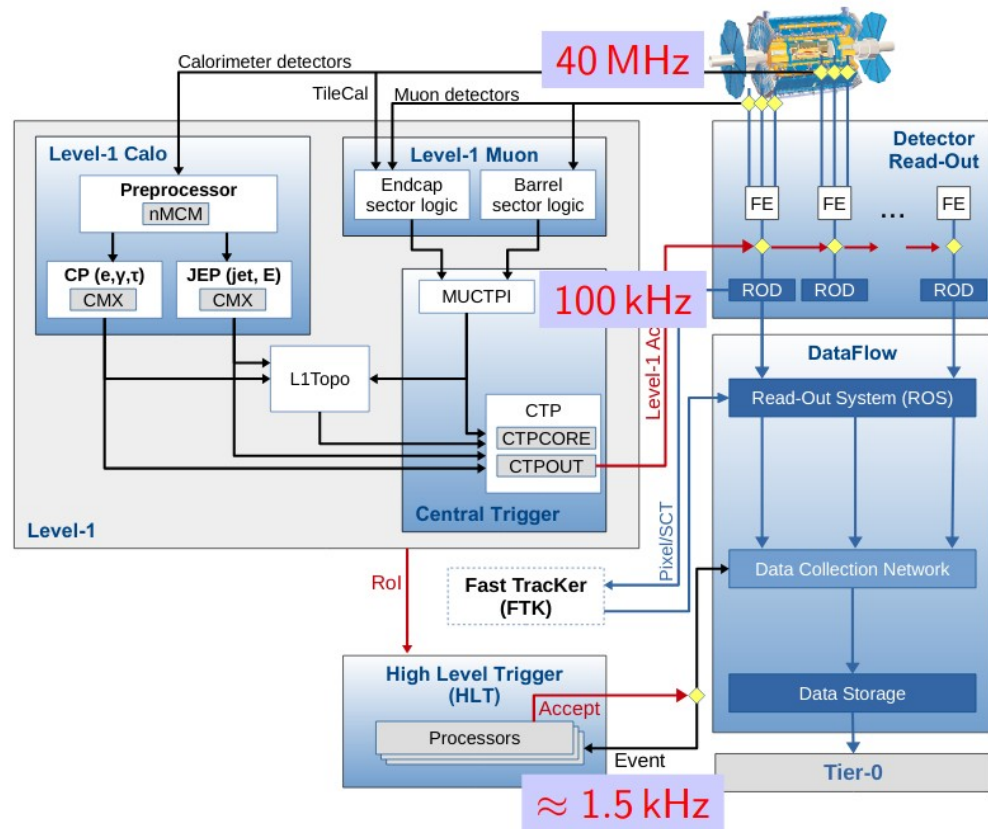
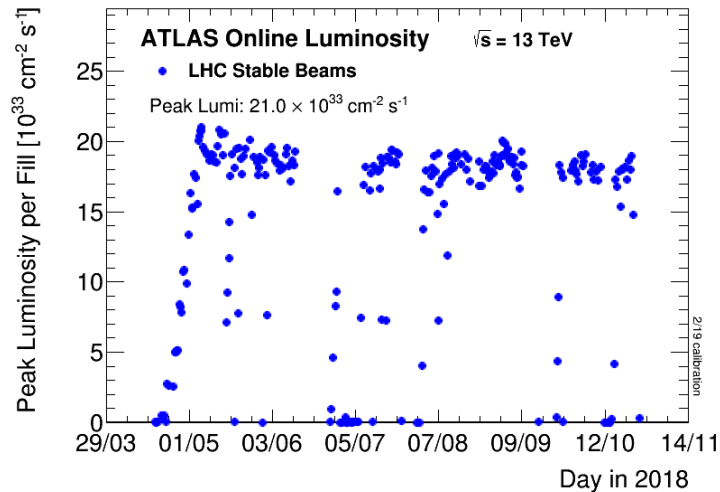




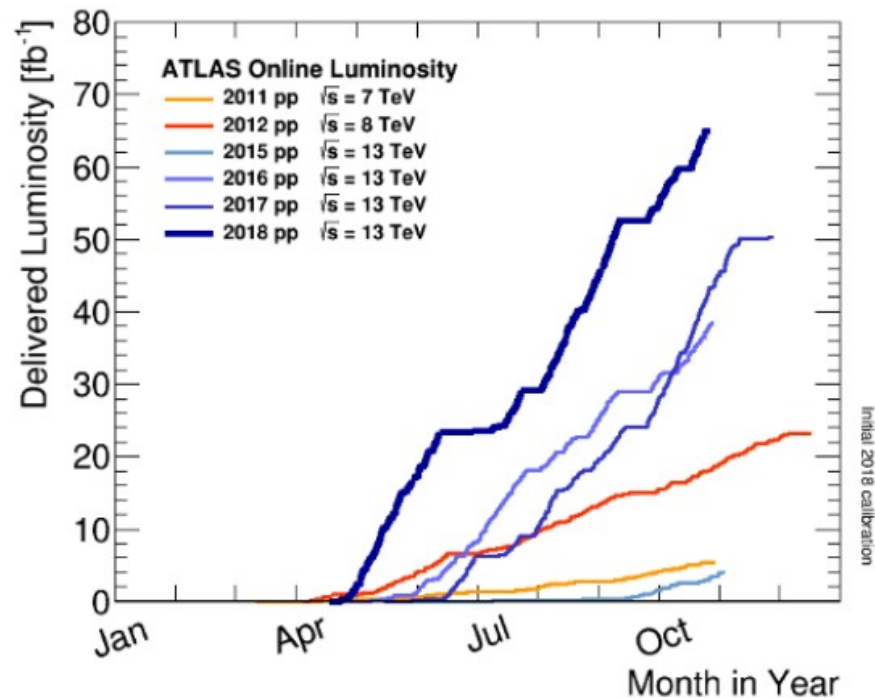
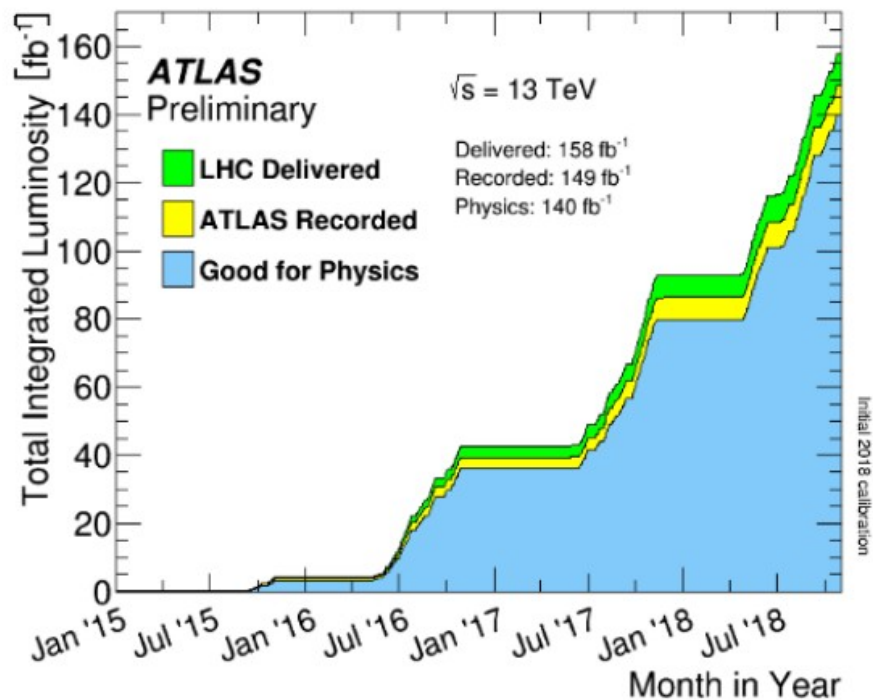


# Trigger system

- **Trigger system filters out potentially interesting events**
  - Reduces the data to a more manageable amount



# Data taking

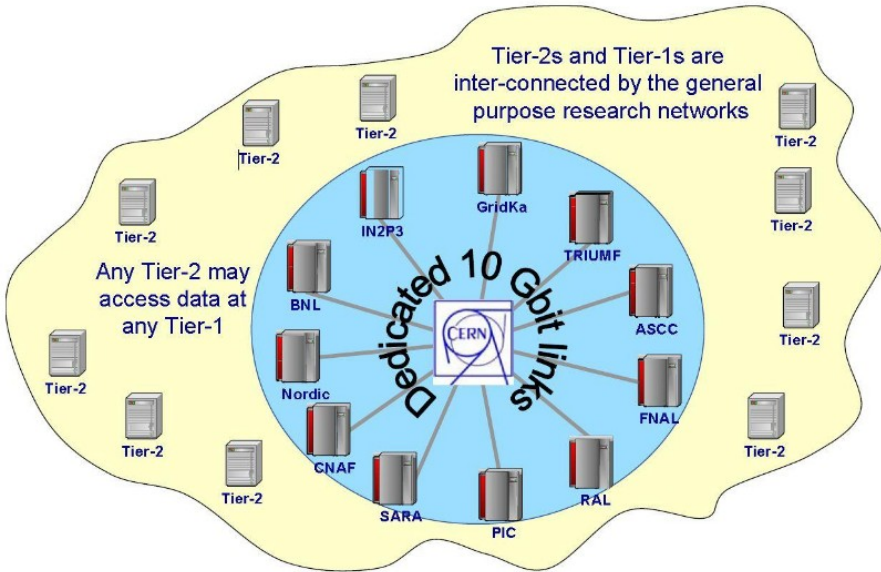


$$N = L \cdot \sigma$$



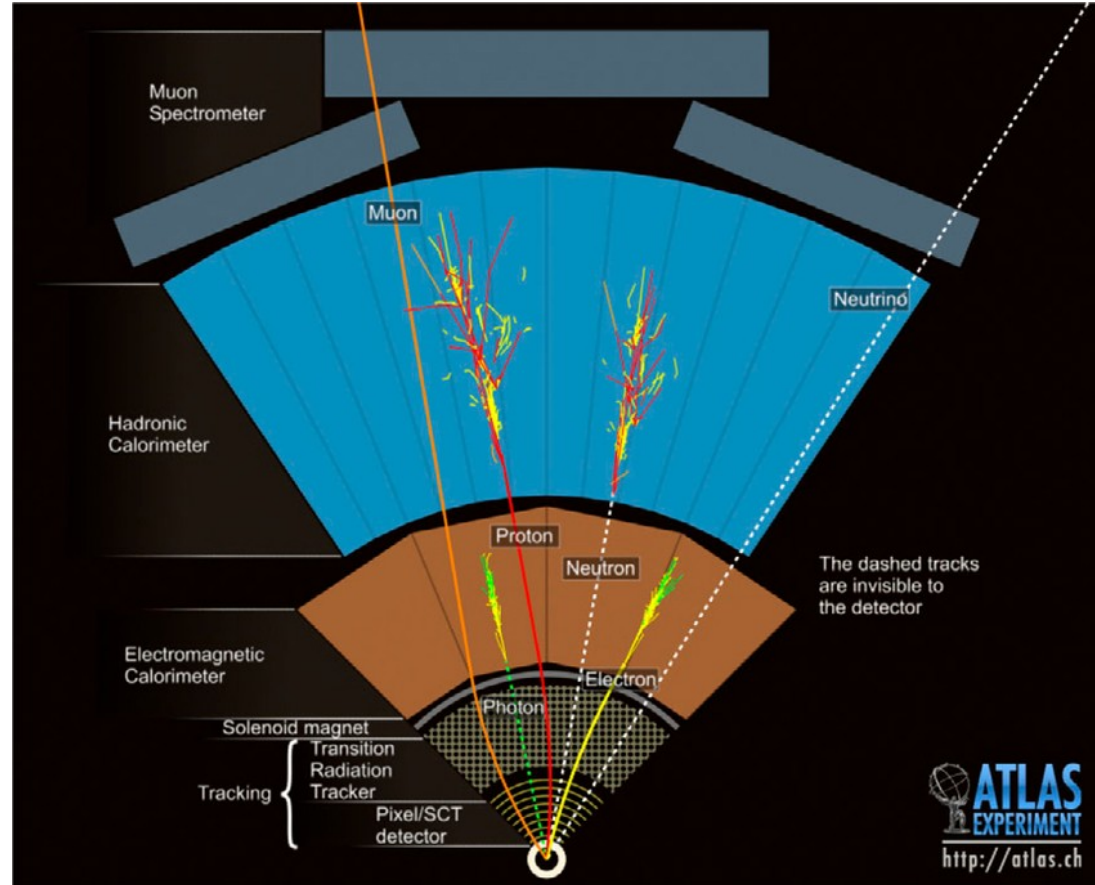
# Grid computing

- Raw data from the experiments are written to tape at the Tier-0 center at CERN.
  - Afterwards the processed data is distributed to the various Tier-1 and Tier-2 centers.
    - Users send their software around the globe rather than downloading it to local facilities



# Particle identification

- **Hadronic particle shower**
  - Cone shaped jets build from calorimeter clusters or tracks
- **Muons**
  - Combined tracks from Inner Detector and Spectrometer
- **Electrons**
  - Inner Detector (ID) track
  - Energy clusters in calorimeter system
- **Taus**
  - Jets with either 1 or 3 ID tracks

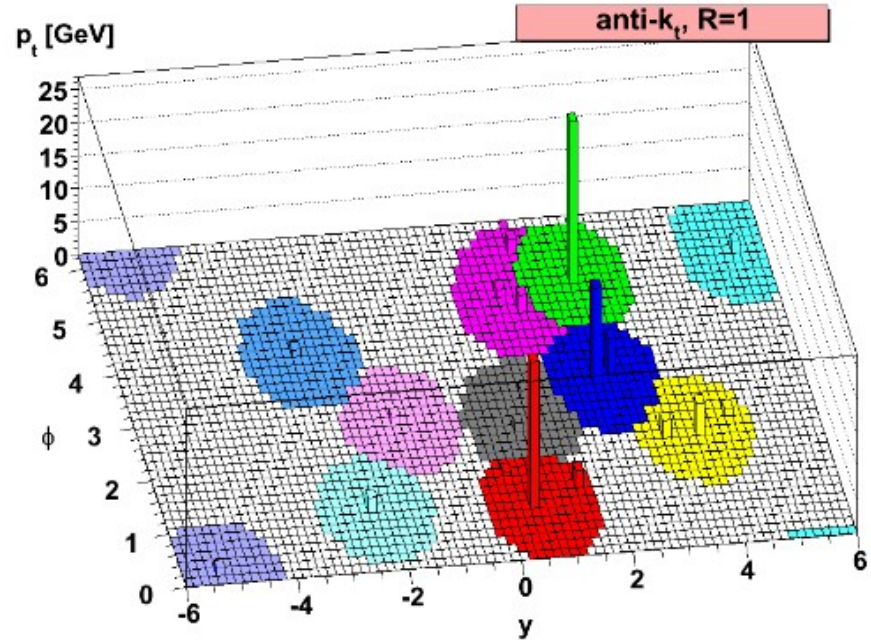


# Jets

- **Jets:** Collimated bunches of stable hadrons, originating from partons (quarks and gluons) after fragmentation and hadronization
- Require collinear- and infrared-safety i.e. jets are unchanged by:
  - Collinear splitting
  - Soft emissions
- LHC experiments preferably use so called **sequential clustering algorithms**
- Application: Calculate for all pairs of particles  $i$  and  $j$ :

$$d_{ij} = \min(k_{i,T}^{2p}, k_{j,T}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = k_{i,T}^{2p}$$



The pair with the smallest  $d$  is clustered if  $d_{ij} < d_{iB}$ , for  $d_{iB} < d_{ij}$  object  $i$  is called a jet

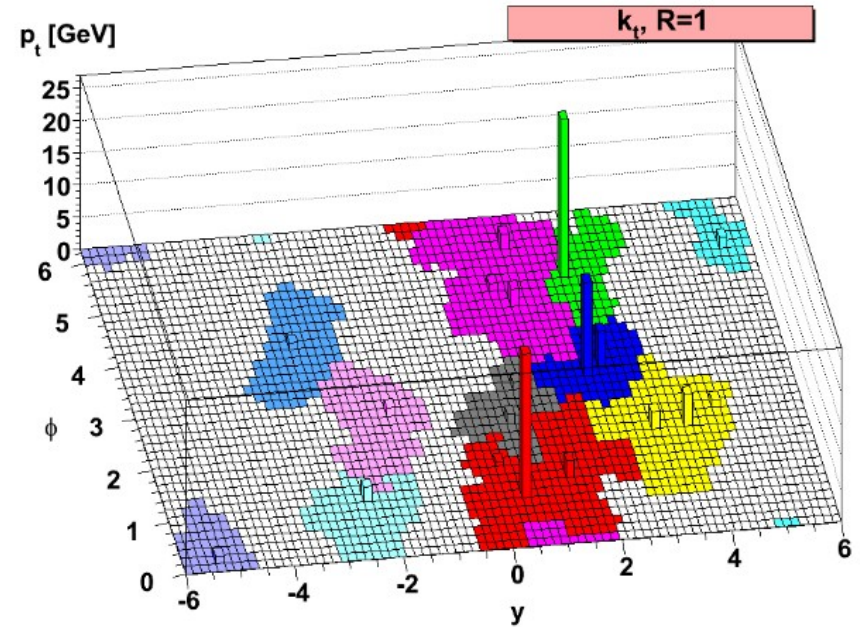


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# The CMS Detector

## CMS DETECTOR

Total weight : 14,000 tonnes  
Overall diameter : 15.0 m  
Overall length : 28.7 m  
Magnetic field : 3.8 T

STEEL RETURN YOKE  
12,500 tonnes

### SILICON TRACKERS

Pixel ( $100 \times 150 \mu\text{m}^2$ )  $\sim 1 \text{ m}^2 \sim 66\text{M}$  channels  
Microstrips ( $80\text{--}180 \mu\text{m}$ )  $\sim 200 \text{ m}^2 \sim 9.6\text{M}$  channels

### SUPERCONDUCTING SOLENOID

Niobium titanium coil carrying  $\sim 18,000 \text{ A}$

### MUON CHAMBERS

Barrel: 250 Drift Tube, 480 Resistive Plate Chambers  
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

### PRESHOWER

Silicon strips  $\sim 16 \text{ m}^2 \sim 137,000$  channels

### FORWARD CALORIMETER

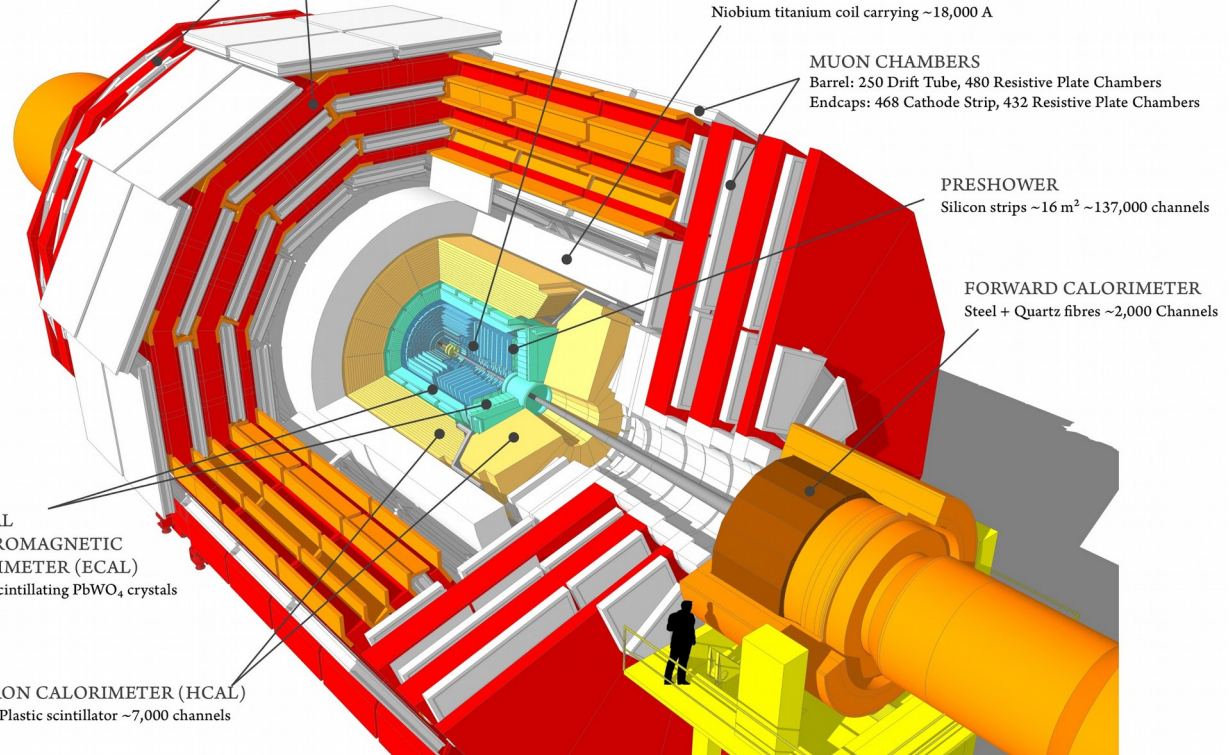
Steel + Quartz fibres  $\sim 2,000$  Channels

### CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)

$\sim 76,000$  scintillating  $\text{PbWO}_4$  crystals

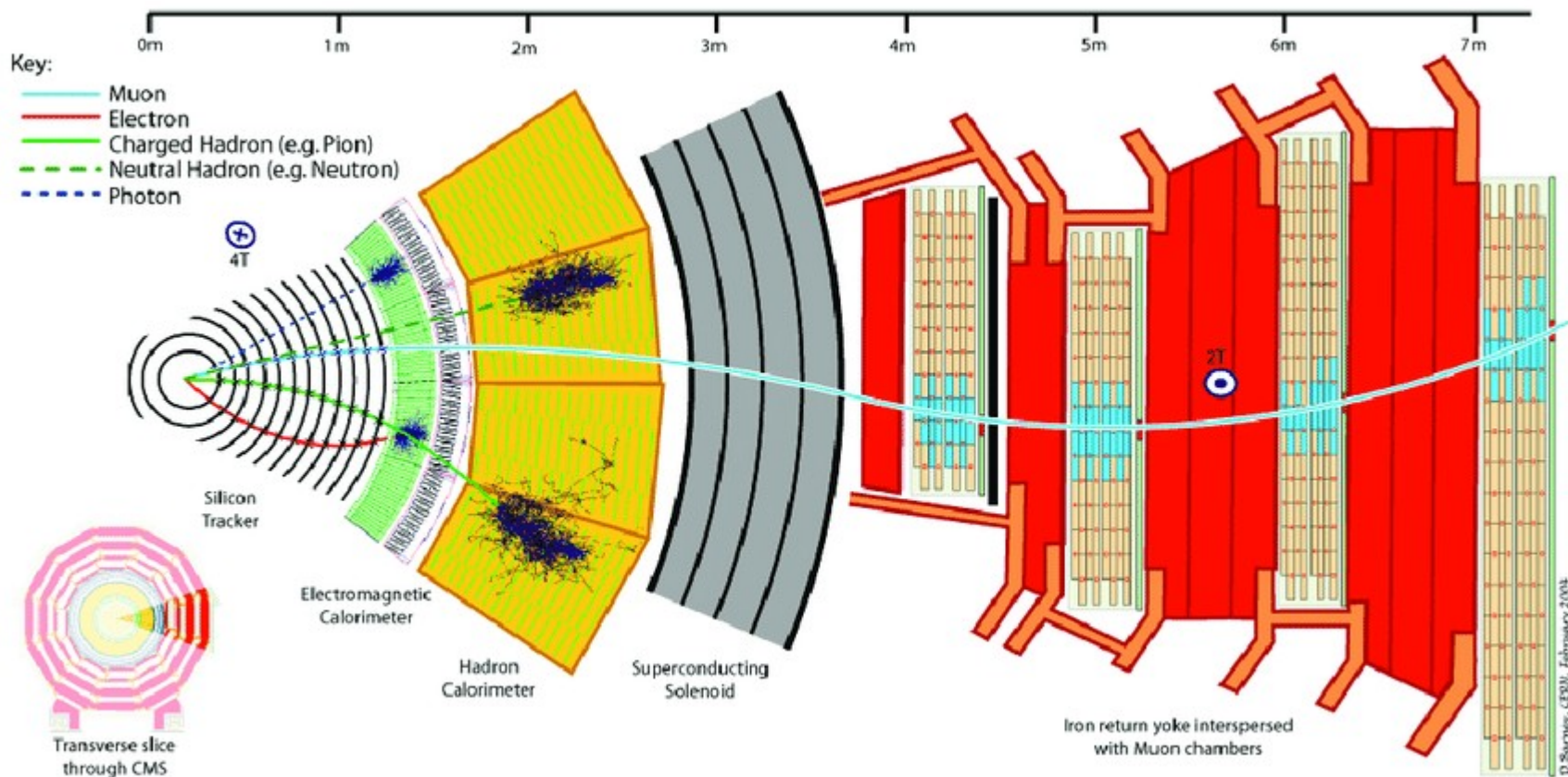
### HADRON CALORIMETER (HCAL)

Brass + Plastic scintillator  $\sim 7,000$  channels





# The CMS Detector



# The LHCb Detector



## LHCb Detector

Weight: 5,600 tonnes  
Height: 10 m  
Length: 20 m

