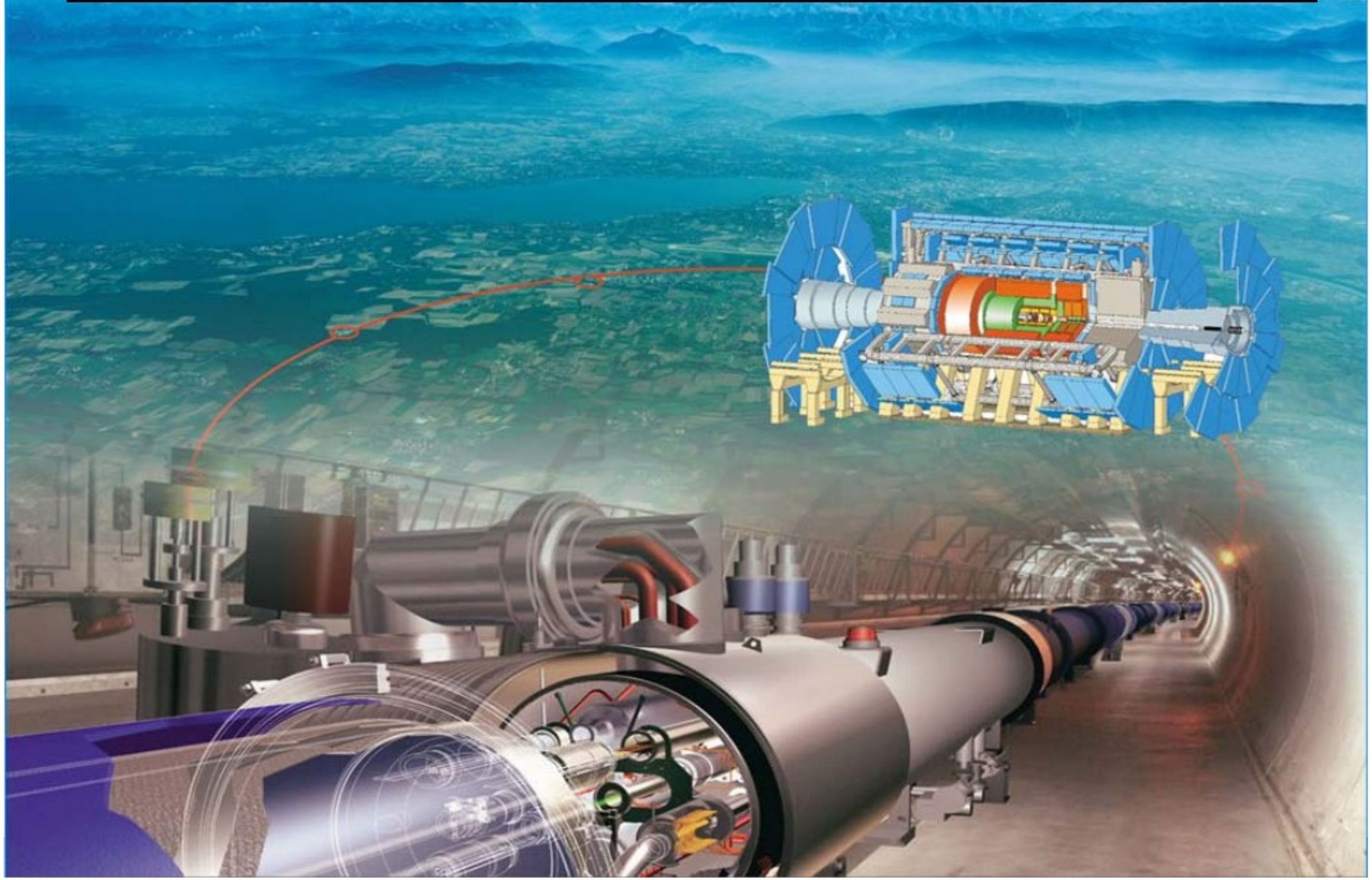
Testing the Standard Model of Elementary Particle Physics II

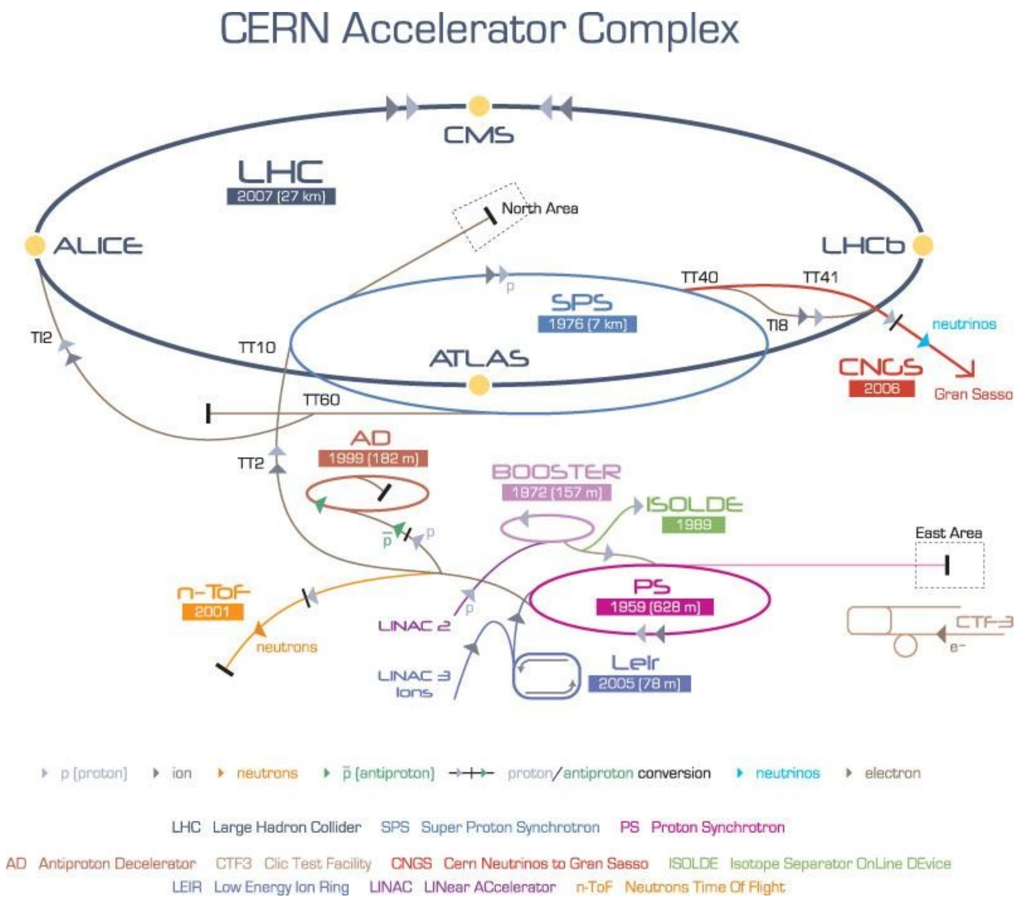
First lecture

23th April 2020

Physics at the Large Hadron Collider I



The Large Hadron Collider



- 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

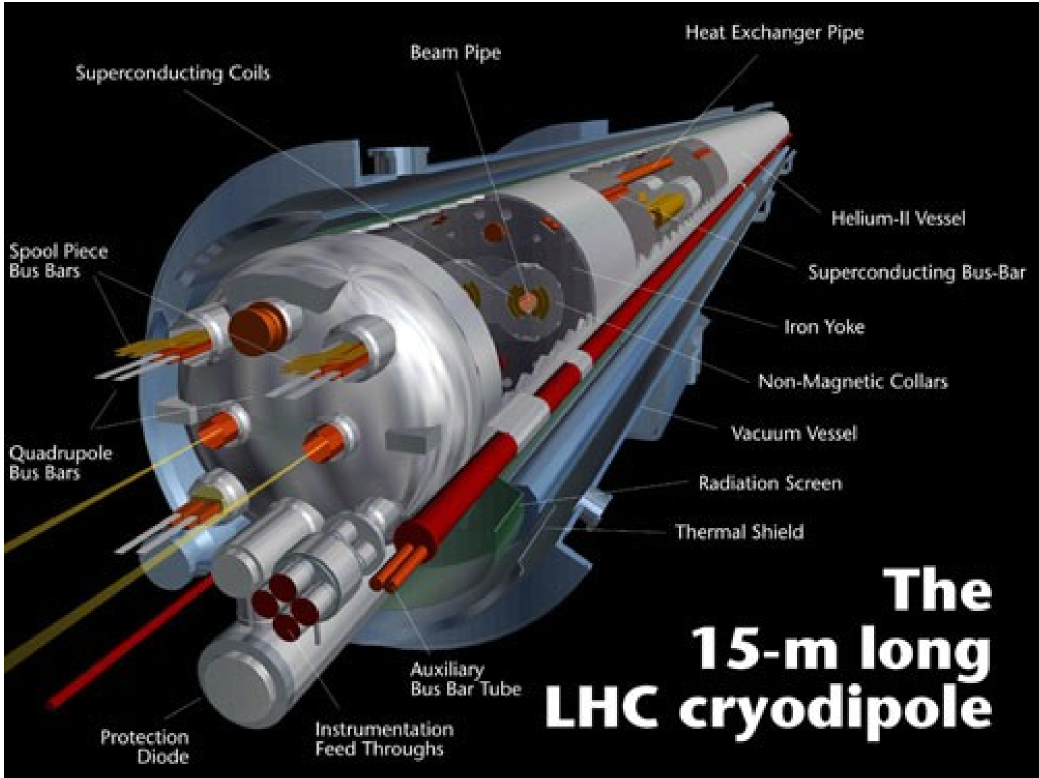
- Integrated luminosity

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

- CoM energy: $\sqrt{s}$

Magnet system

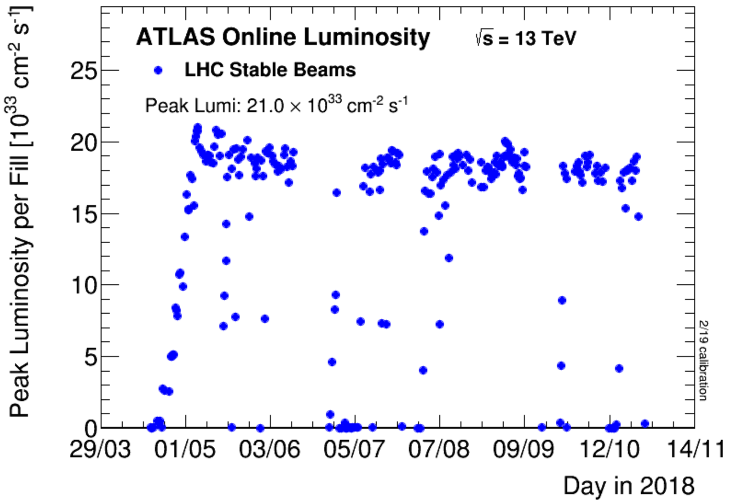
- At the LHC **superconducting dipole magnets** are operated at B-field strength of 8.3 T over their full length
  - Forcing the particle beams to follow the circular pipes
- **Quadrupole magnets** are used to focus the beams



- The LHC magnets are made from niobium-titanium (NbTi) cables.
- LHC is operate at 1.9 K (-271.3°C)

Luminosity

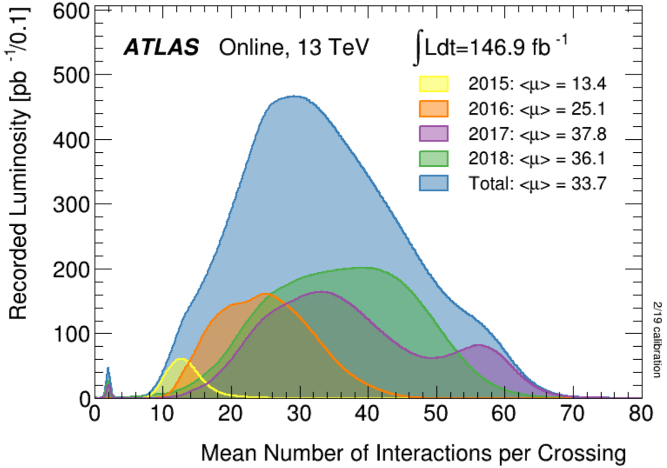
- Design goal of LHC:
  - **10^{34} cm^{-2} s^{-1}**
    - **n = 2835 proton bunches per beam**
    - **f = 40MHz**
    - **$N_1/N_2 = 10^{11}$ protons per bunch**

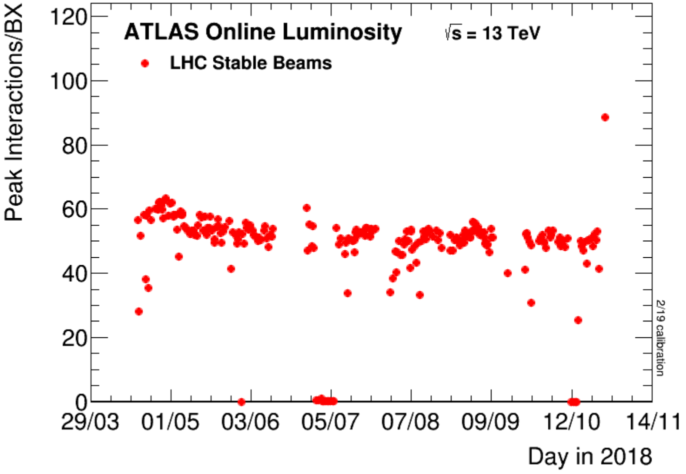


- **Already exceeded in Run-II**

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

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

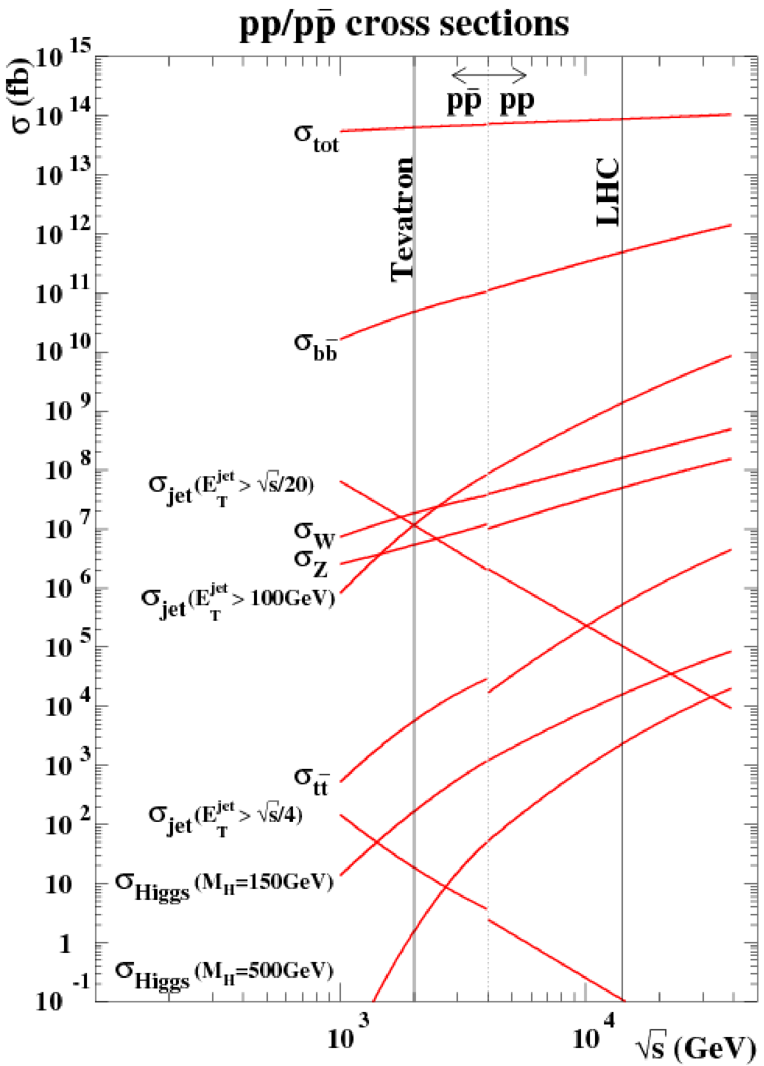




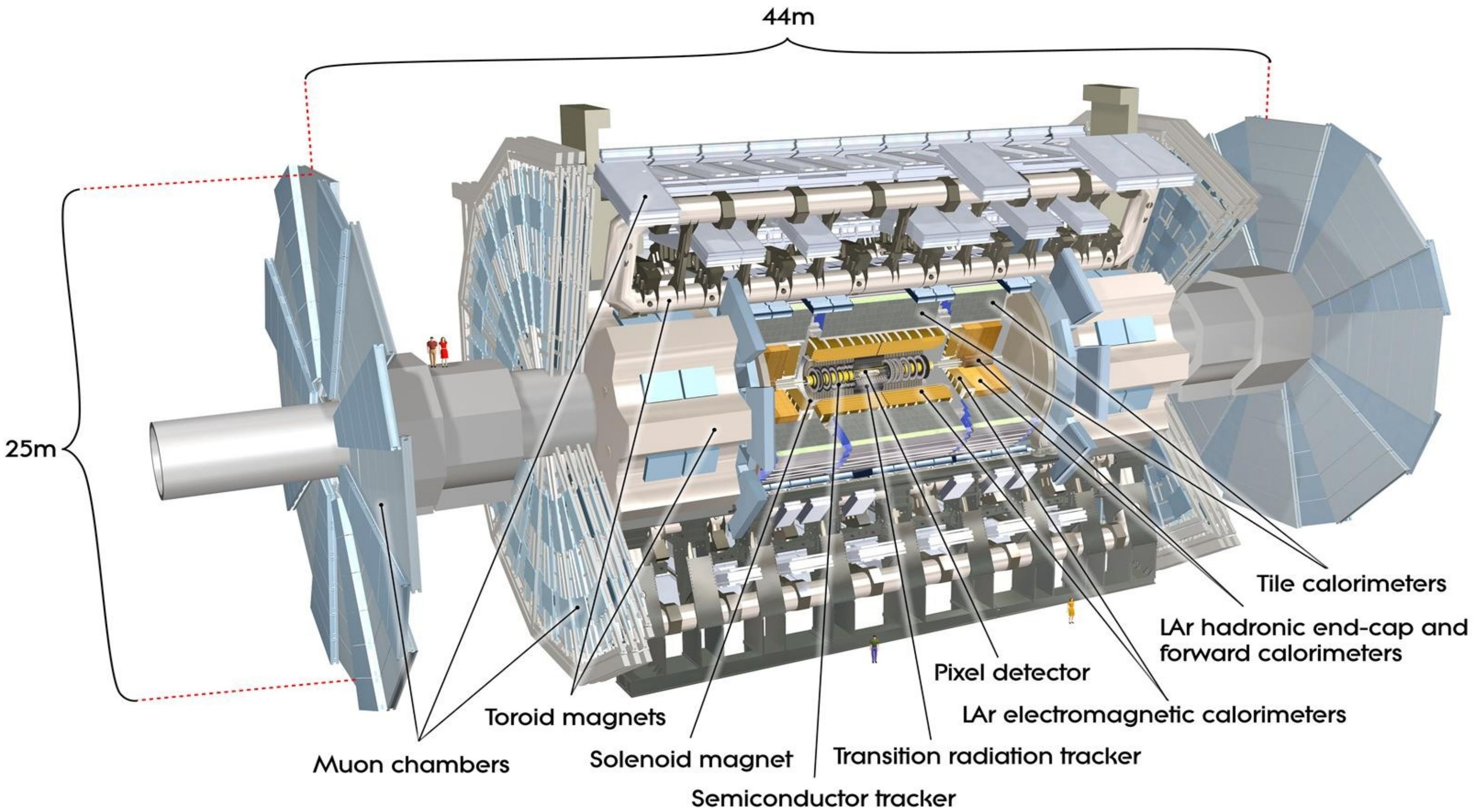
Event rates/cross sections

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

Inelastic pp collisions	~10^7 Hz
b-quark production	~10^4 Hz
Jet production E_T> 250 GeV	~1 Hz
W->lv	~1 Hz
top-quark production	~10^{-2}Hz
Higgs bosons	~10^{-4}Hz



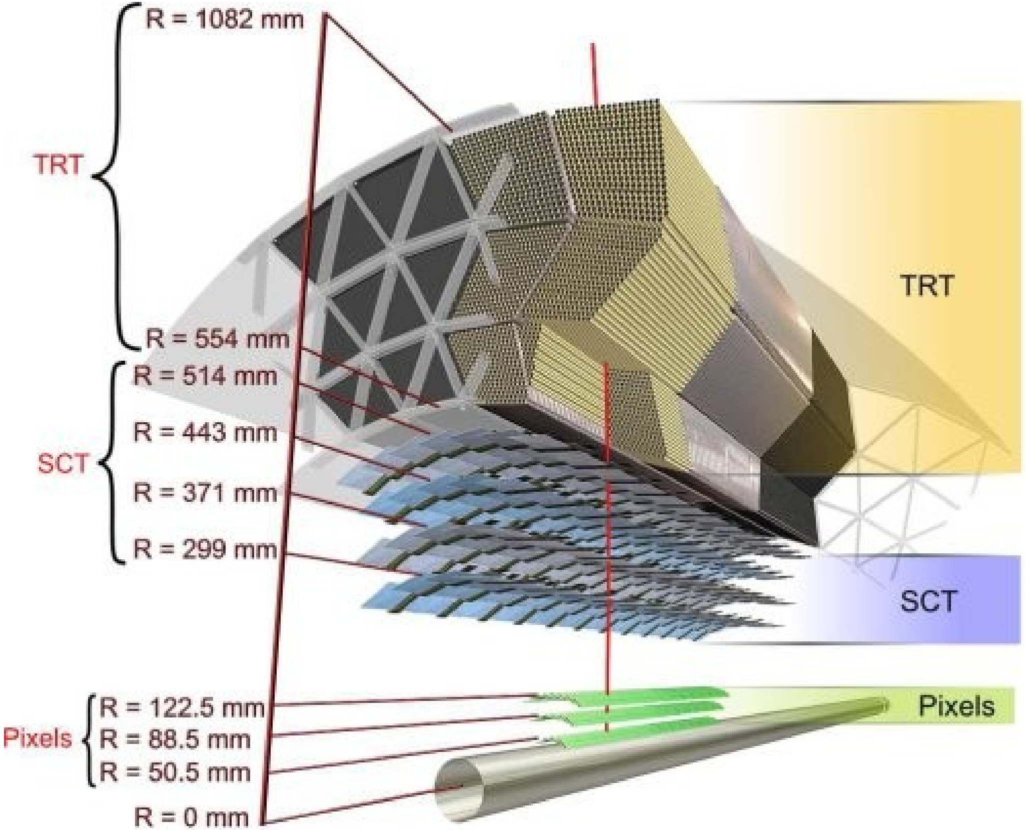
The ATLAS Detector

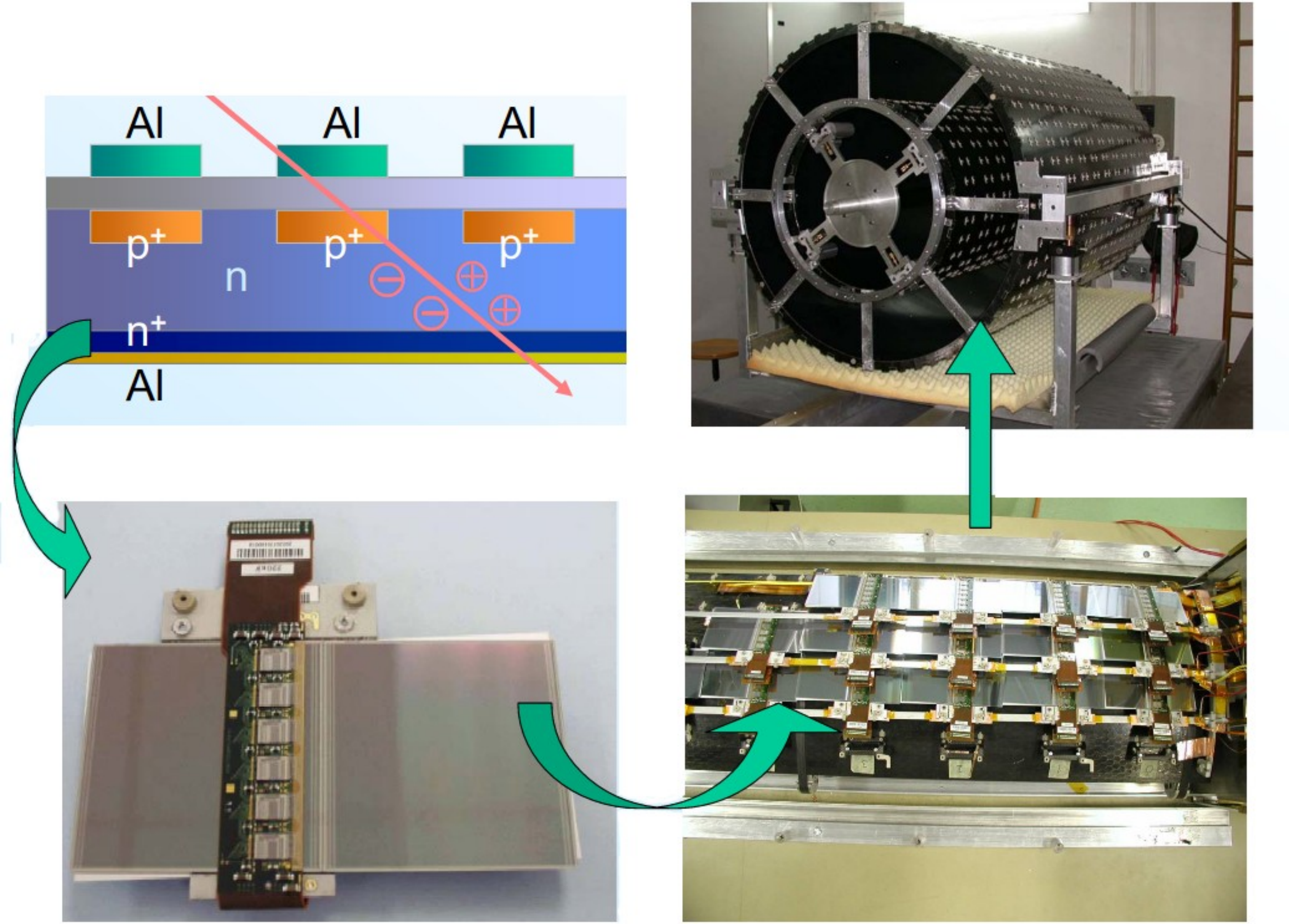


Inner Detector

- **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

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

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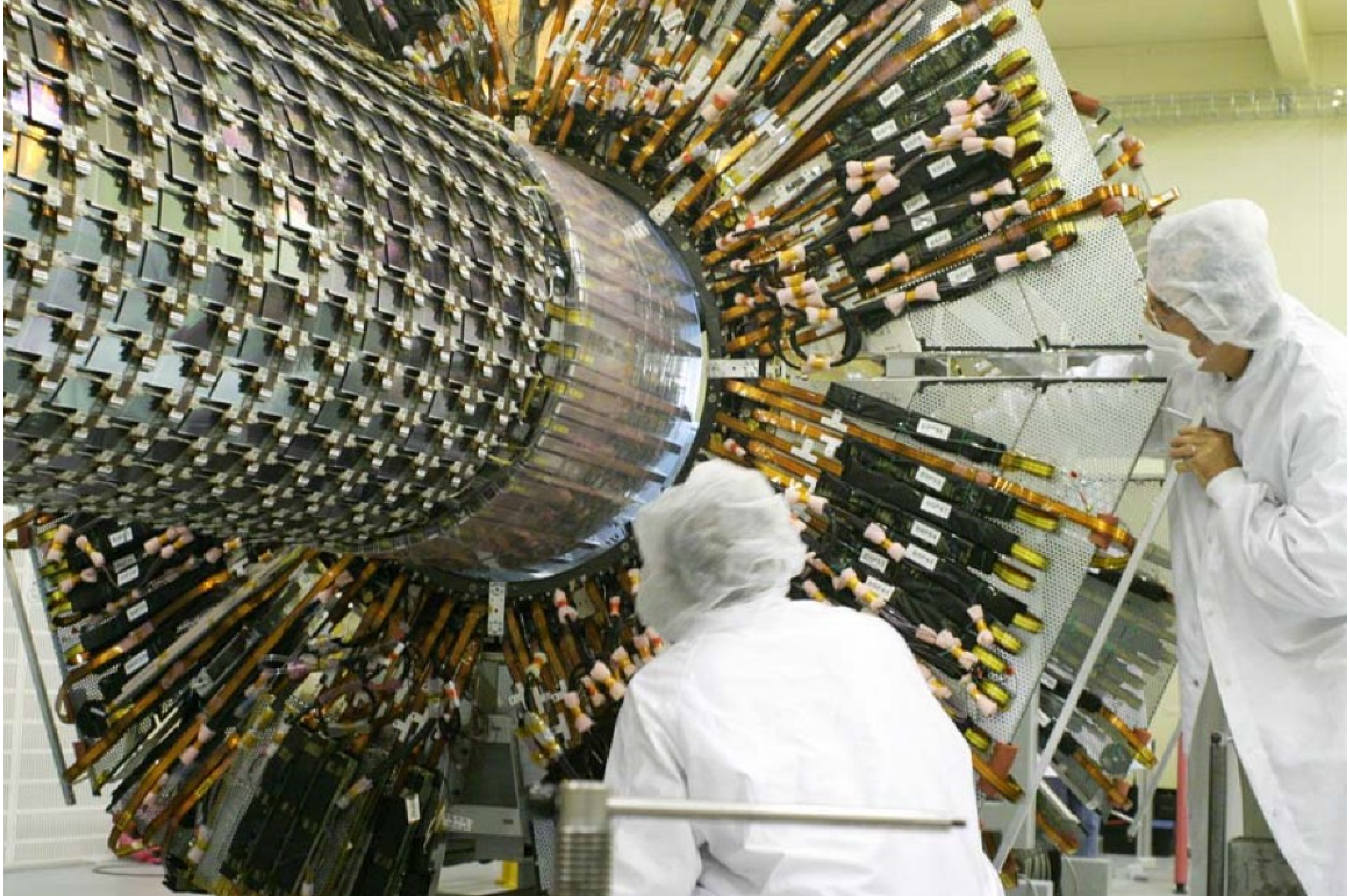


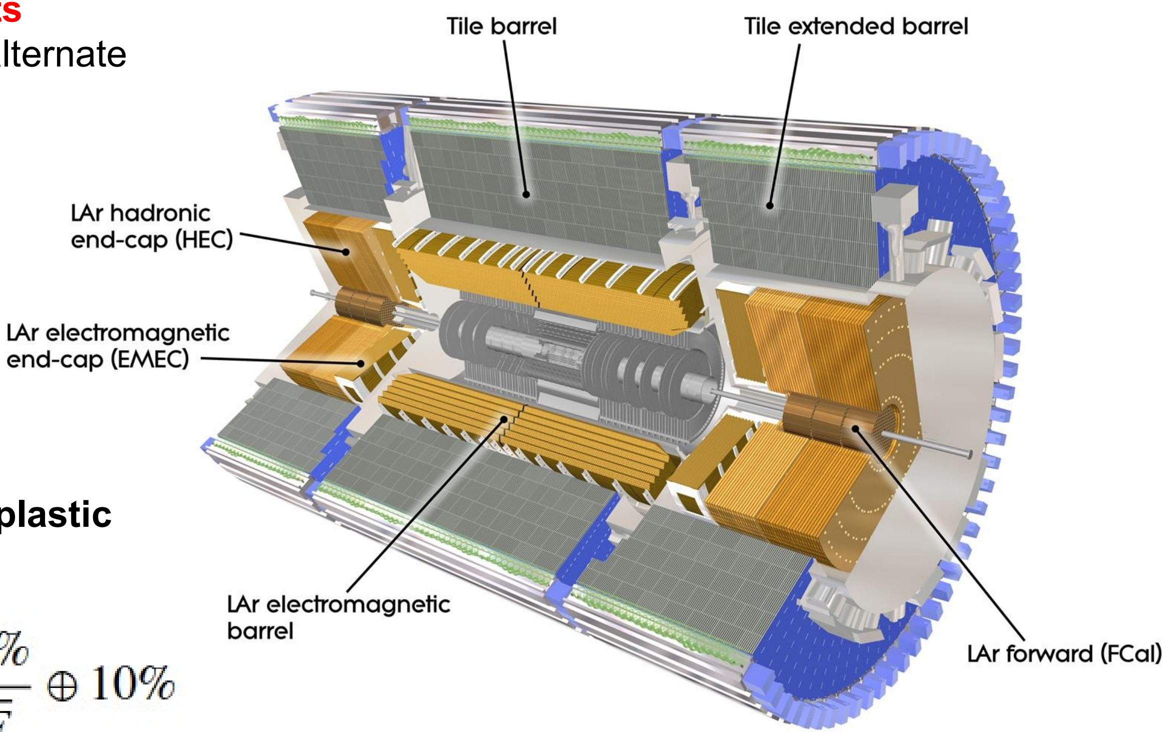
Calorimeter system

- 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**

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

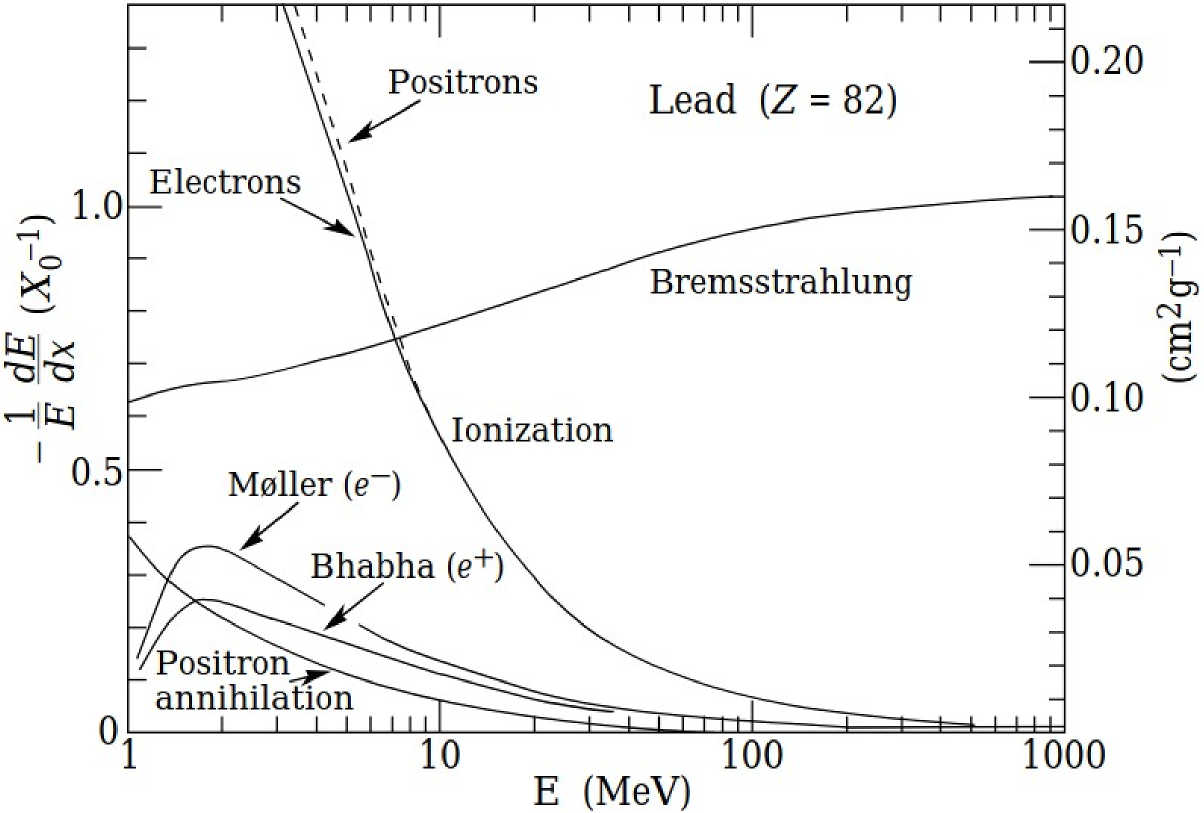


Calorimetry

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

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

Z = Atomic number of absorber
A = Atomic mass of absorber



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

Calorimetry

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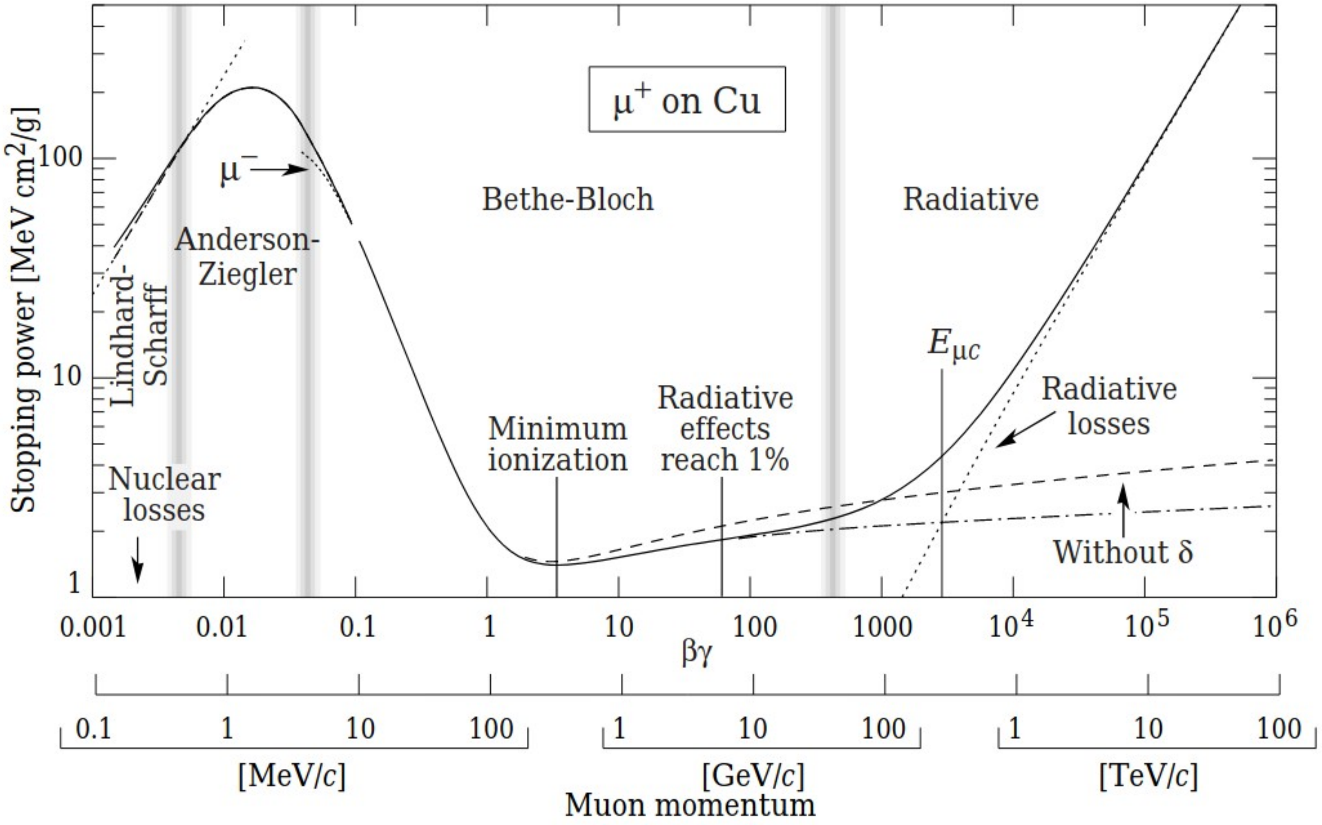

Calorimetry

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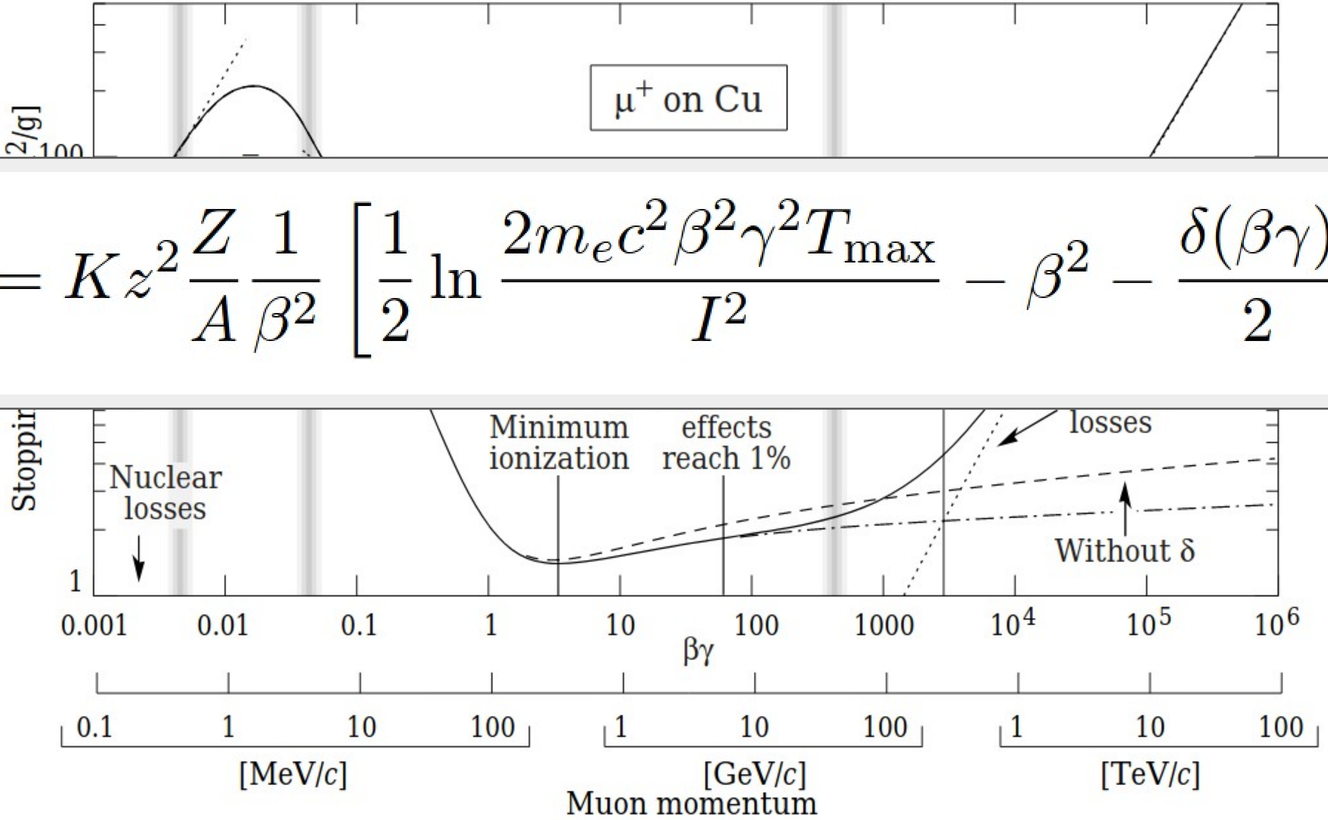
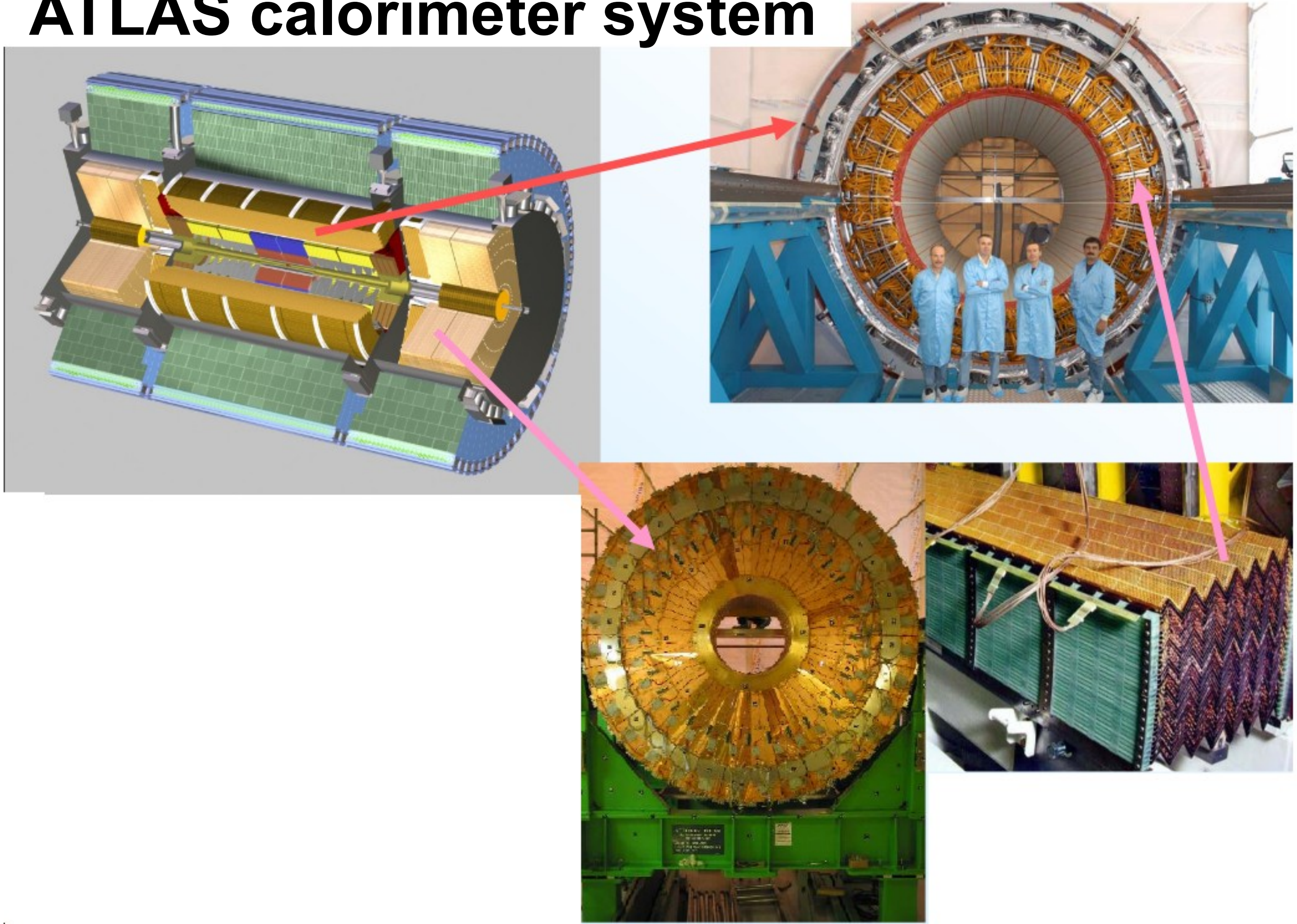


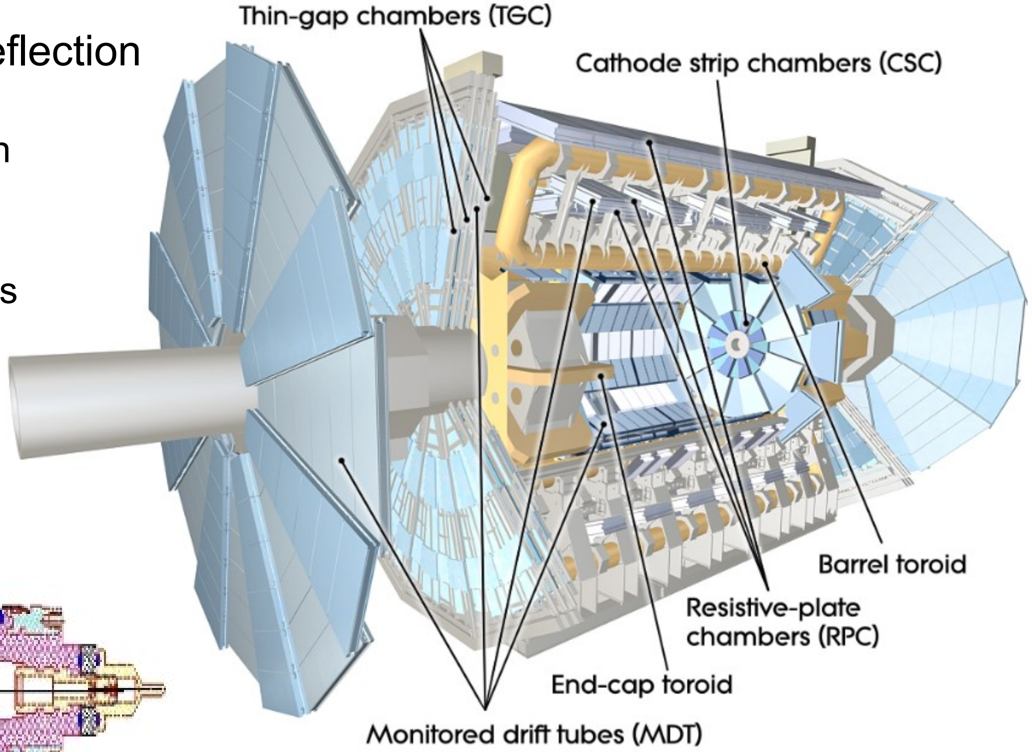
$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

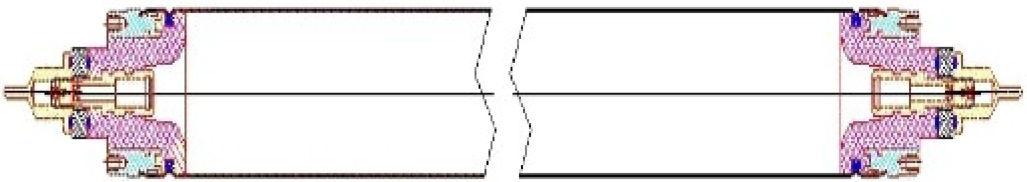
ATLAS calorimeter system



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 pT between 10GeV - 1TeV
  - Spatial resolution of 30 μm

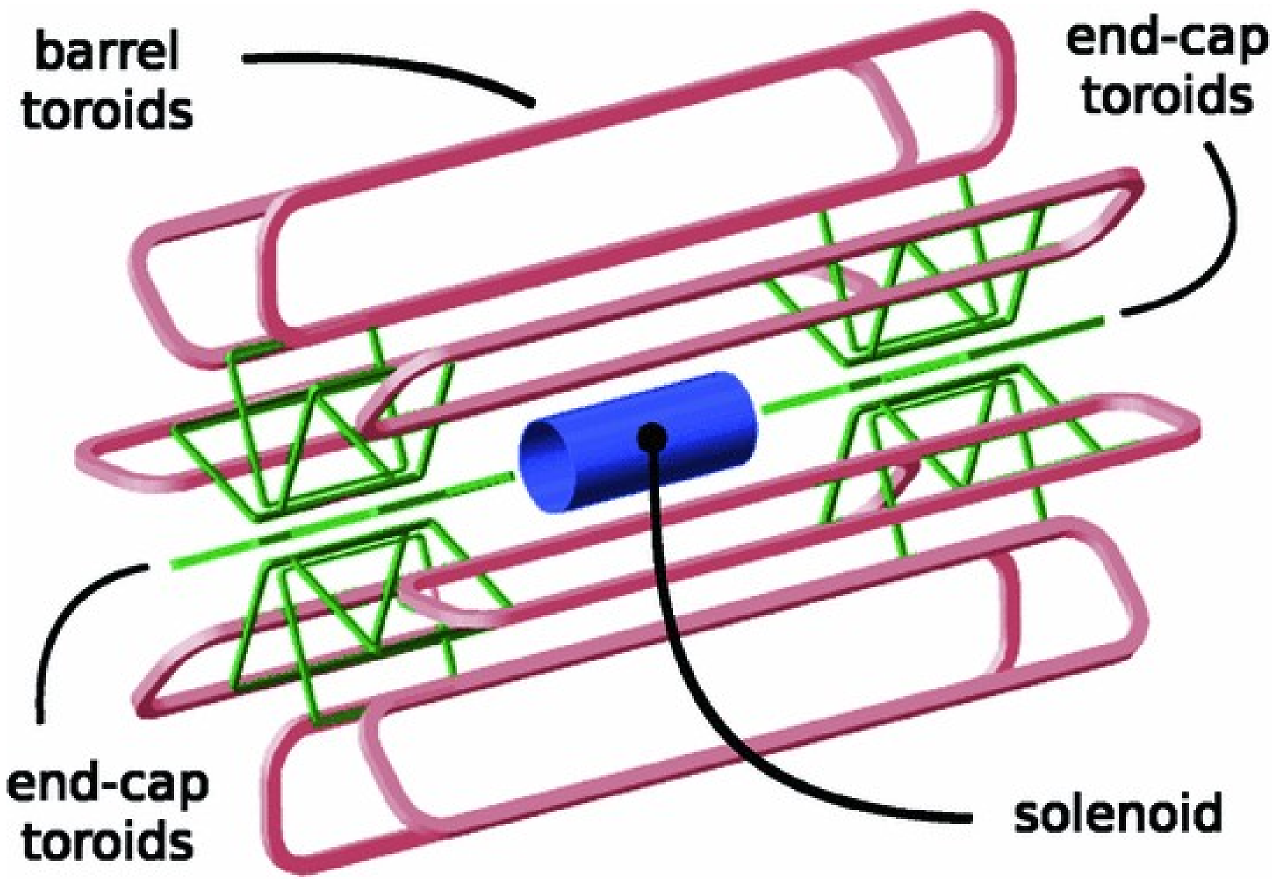




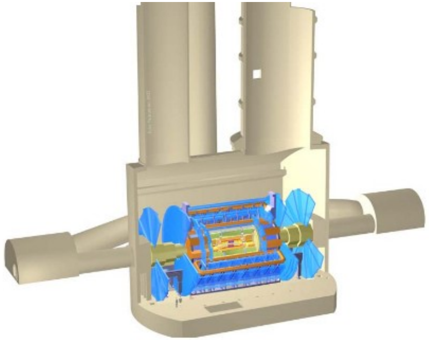
Construction of muon chambers

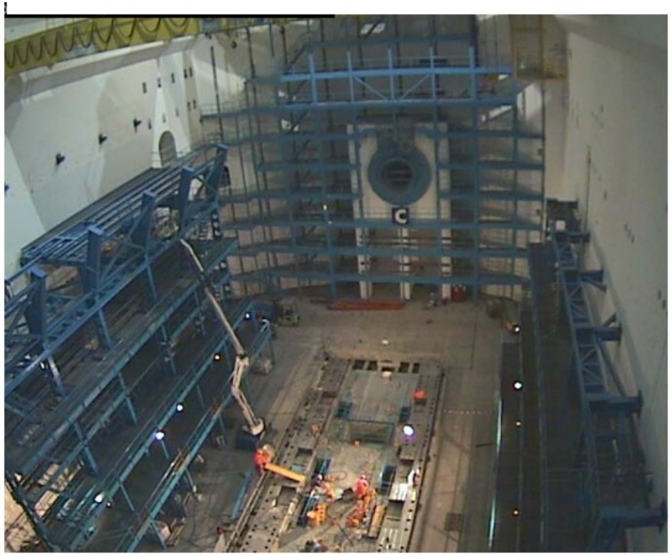
Magnet system

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



Construction



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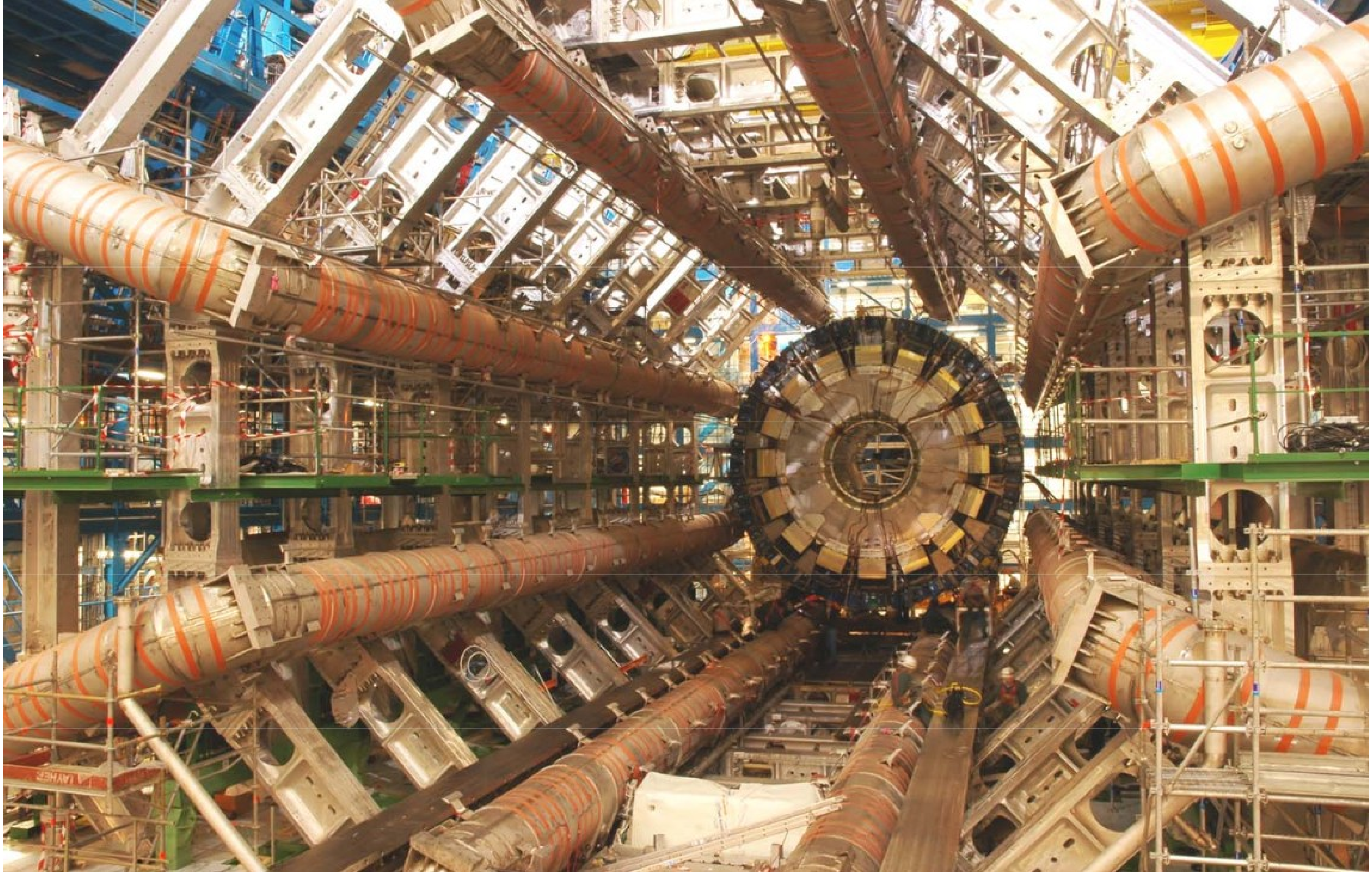
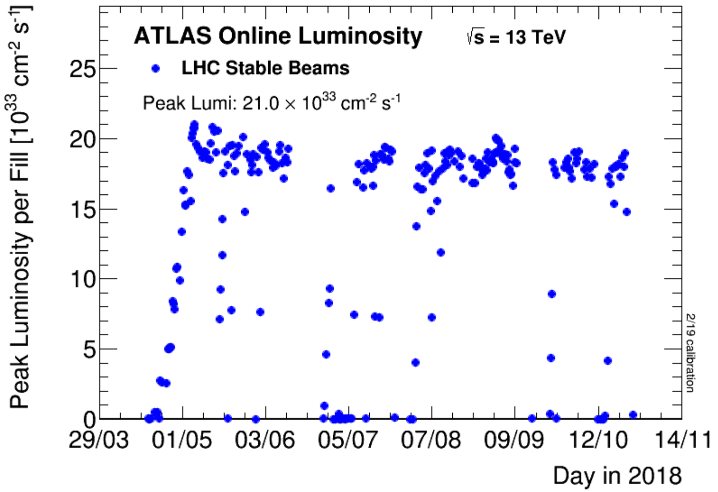
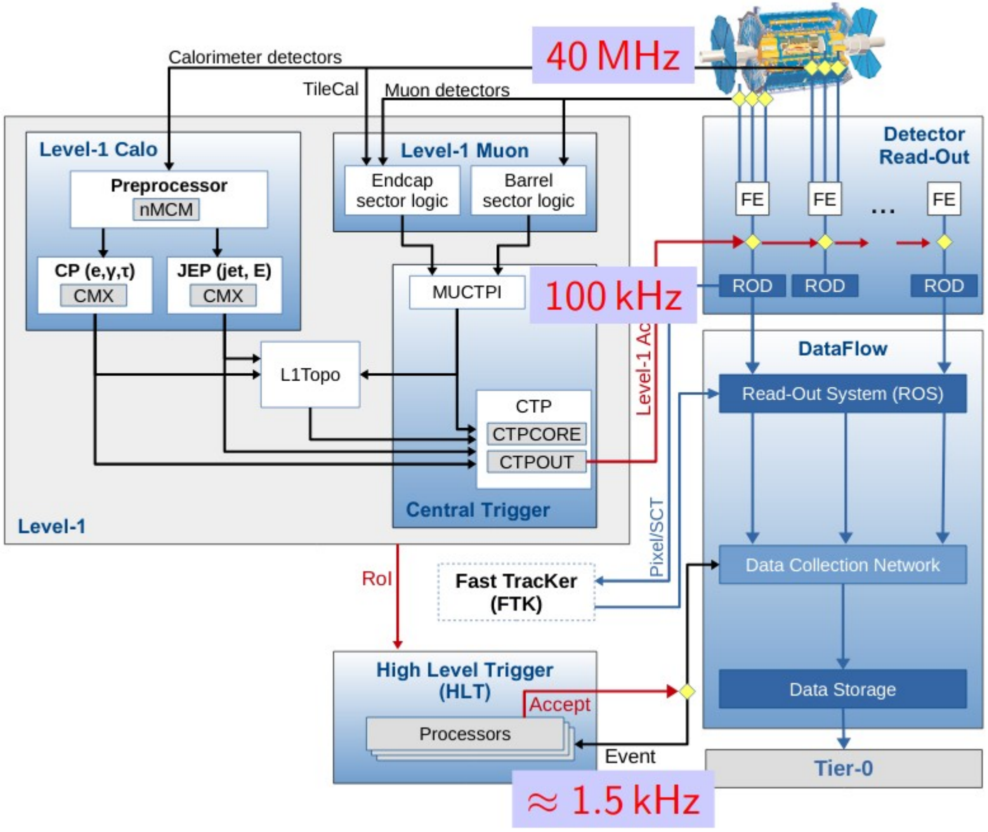


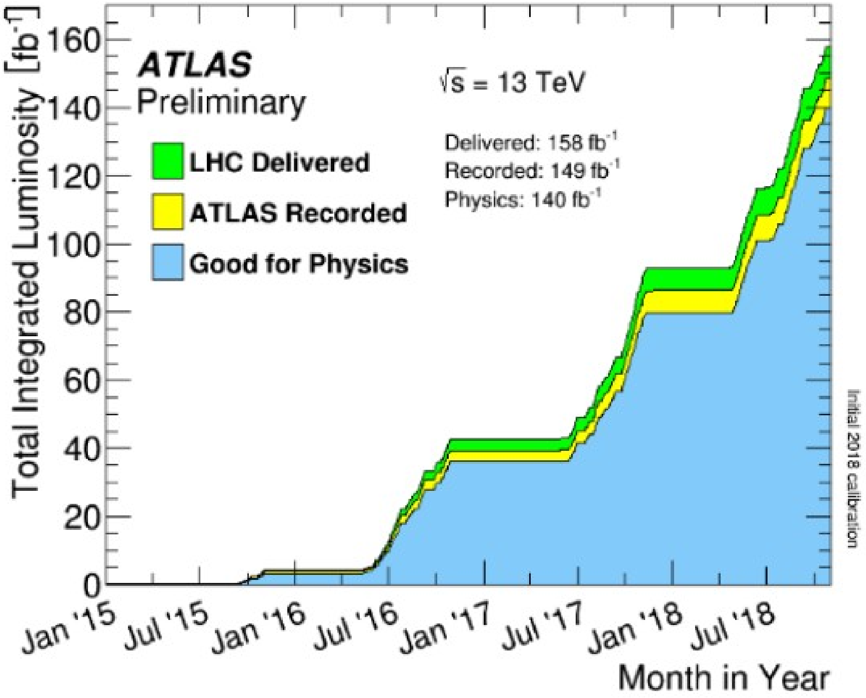
Trigger system

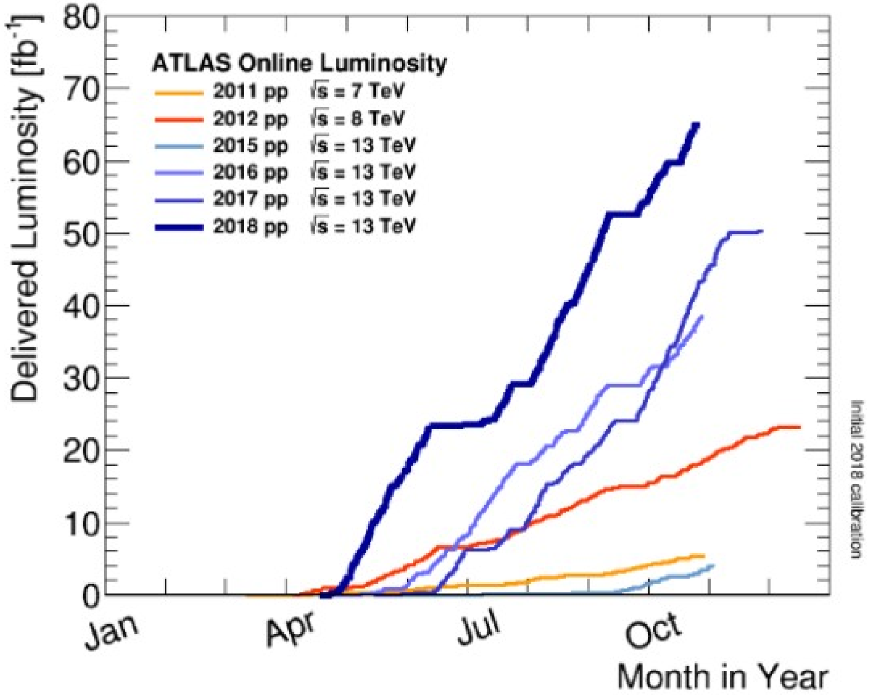
- **Trigger system filters out potentially interesting events**
  - Reduces the data to a more manageable amount





Data taking

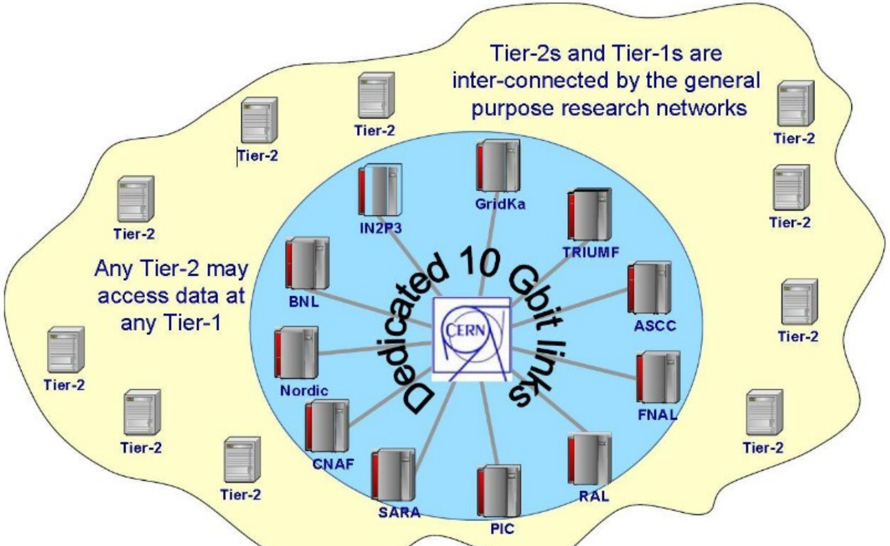




$$N = L \cdot \sigma$$

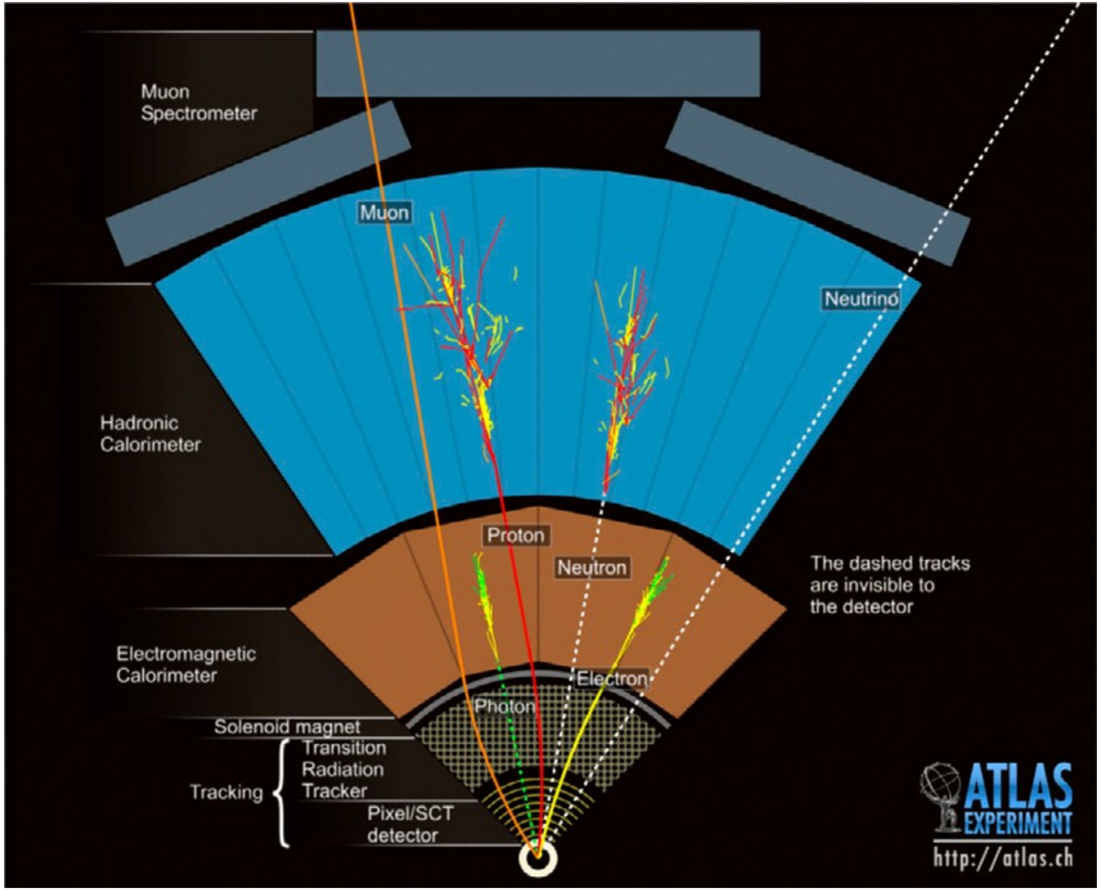
Grid computing

- 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

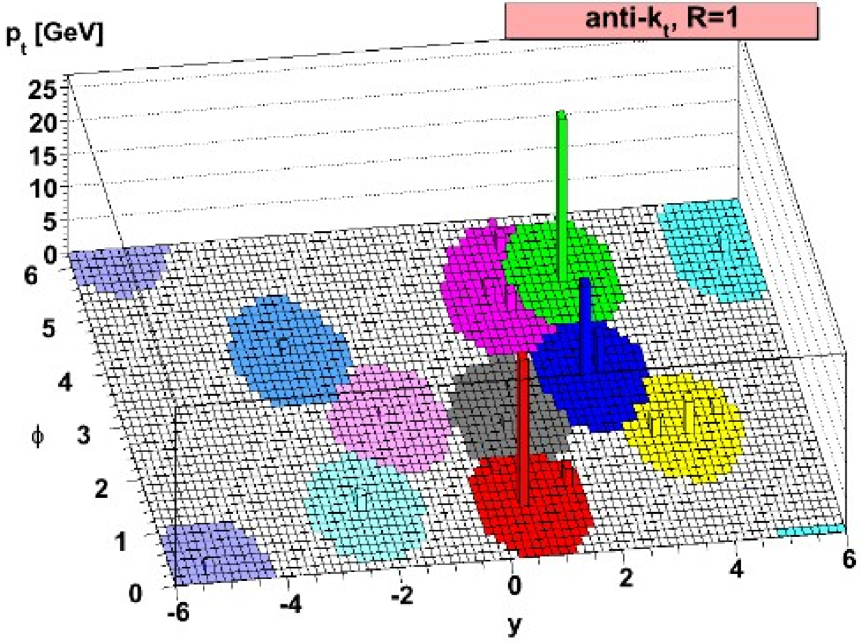


Jets

- **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 preferrably use so called **sequential clustering algorithms**
- Application: Calculate for all pairs of particles i an 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_{ij} is clustered if $d_{ij} < d_{iB}$, for $d_{iB} < d_{ij}$ object i is called a jet

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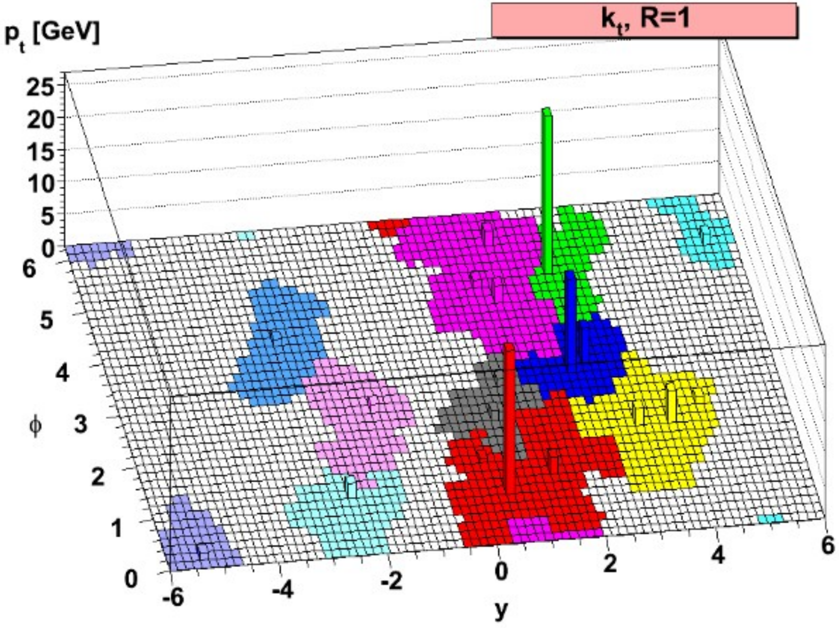

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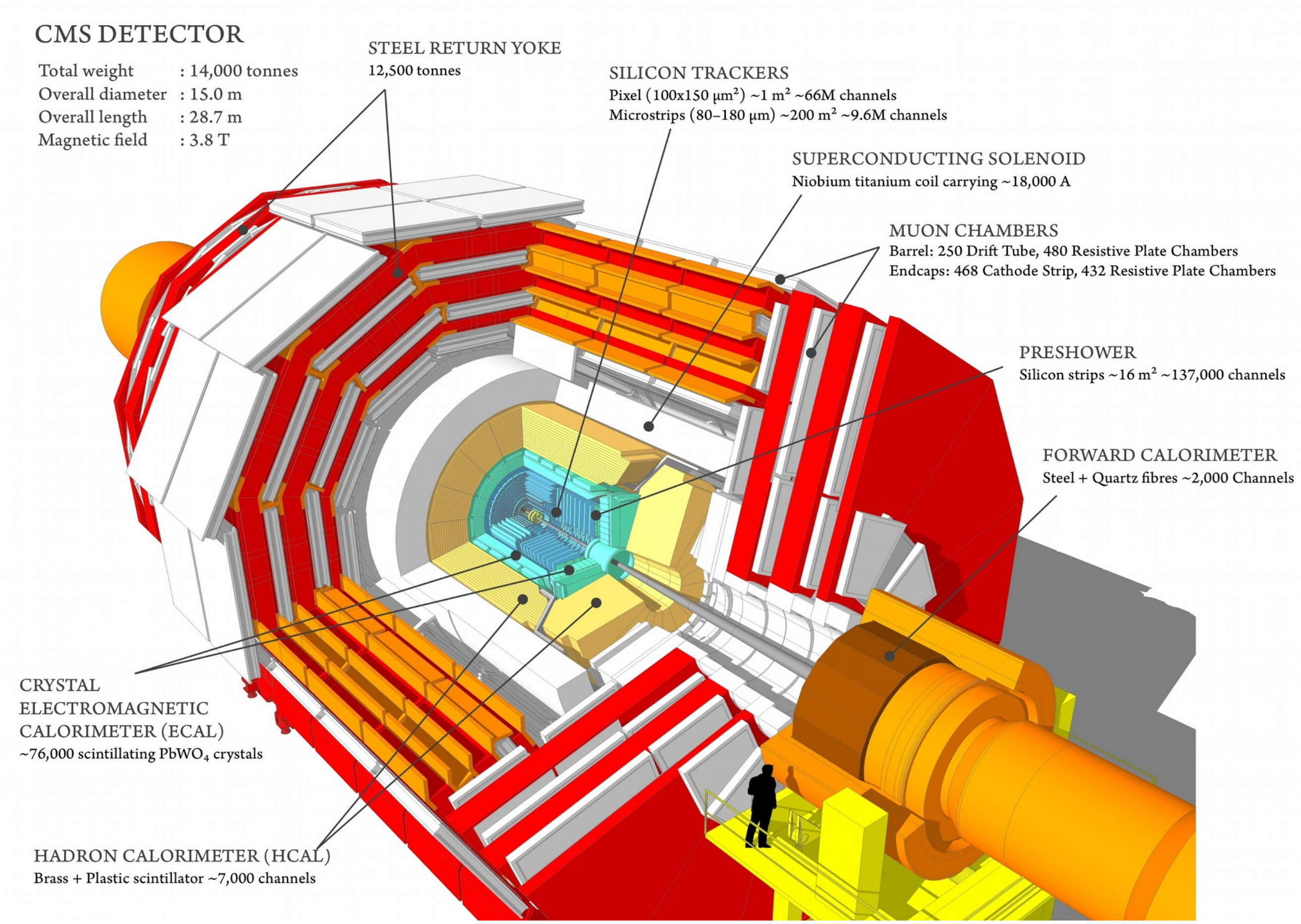
The CMS Detector



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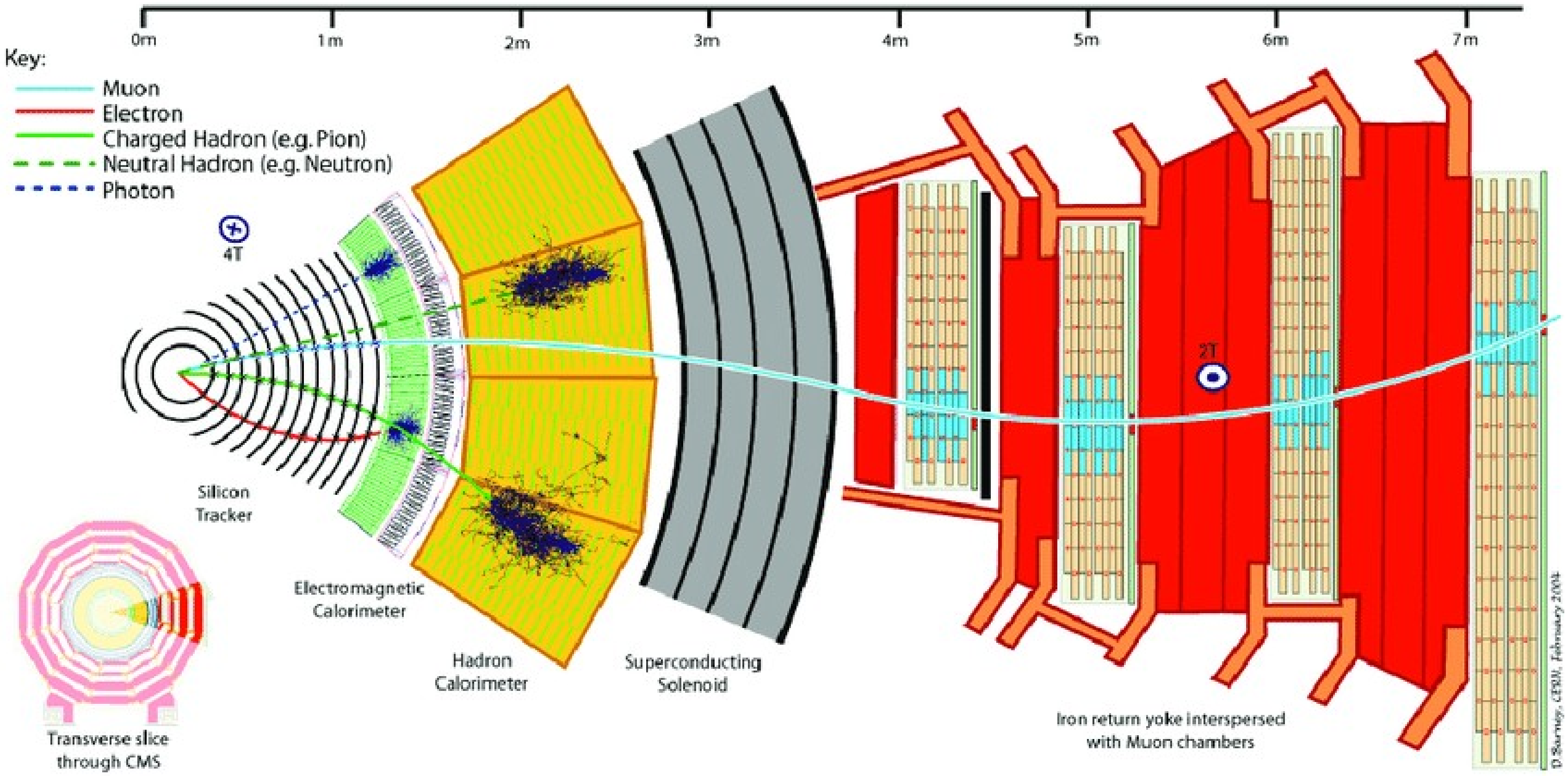

The LHCb Detector