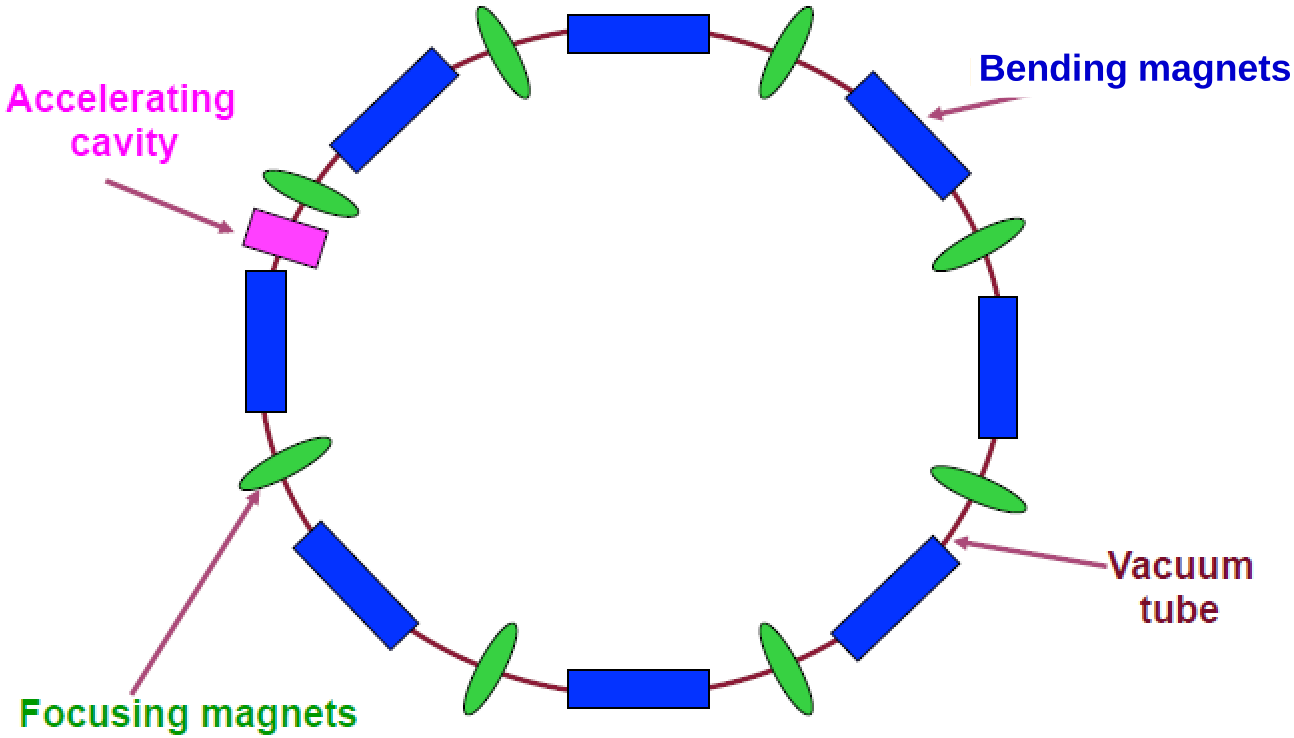
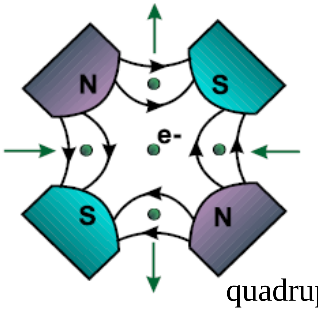
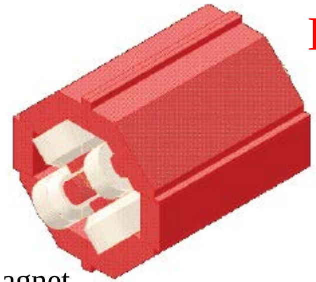
Synchrotron Ring Schematic

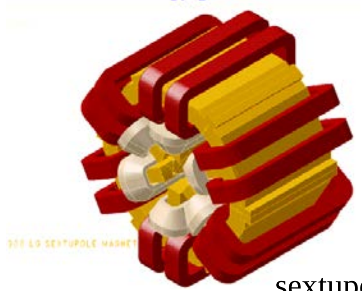




quadrupole magnet



$B \sim X$



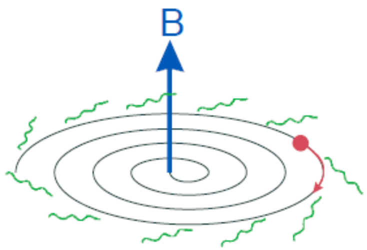
$B \sim X^2$

sextupole magnet

Synchrotrons

❖ Synchrotrons are the most widely used accelerators

- Beam of particles is constrained in a circular path by bending dipole magnets
- Accelerating cavities are placed along the ring
- Charged particles which travel in a circular orbit with relativistic speeds emit ***synchrotron radiation***



Amount of energy radiated per turn is:

$$\Delta E = \frac{e^2}{3\varepsilon_0 (m_0 c^2)^4} \frac{E^4}{\rho} = \frac{q^2 \beta^3 \gamma^4}{3\varepsilon_0 \rho}$$

electron

here $\boldsymbol{q}$ is the electric charge of a particle, $\beta = v/c, \gamma = (1-\beta^2)^{-1/2}$, and $\boldsymbol{\rho}$ is the radius of the orbit.

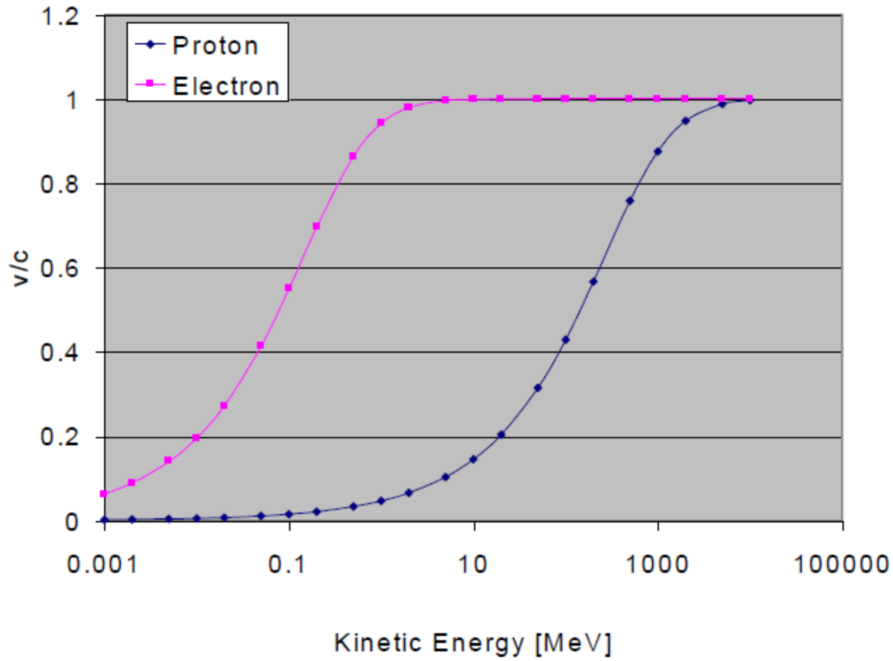
$$\left(\frac{m_p}{m_e}\right)^4 = \left(\frac{938\ MeV}{0.511\ MeV}\right)^4 = 1.1 \cdot 10^{13}$$

For $\beta \cong 1$, the energy ΔE lost per turn has a numerical value given by:

$$\Delta E(keV) = 88.5 \cdot \frac{E^4}{\rho} \quad (E\ in\ GeV, \rho\ in\ m)$$

Some numbers: For ***large electron positron collider LEP*** at 86 GeV, $\Delta E \cong 1.37\ GeV/electron$. There are about $6 \cdot 10^{12}$ electrons per beam and hence the power required to make up for this loss $\cong 20\ MW$. Power needed for RF is about 96 MW.

Proton and Electron Velocity vs. Kinetic Energy



heavy particle (***p***) become relativistic at higher energies

beam velocity: $\beta = \dfrac{\sqrt{T_{lab}{}^2 + 1863 \cdot A_1 \cdot T_{lab}}}{931.5 \cdot A_1 + T_{lab}}$

Lorentz contraction factor: $\gamma = \dfrac{931.5 \cdot A_1 + T_{lab}}{931.5 \cdot A_1}$

total energy: $E = T_{lab} + m_0 \cdot c^2$

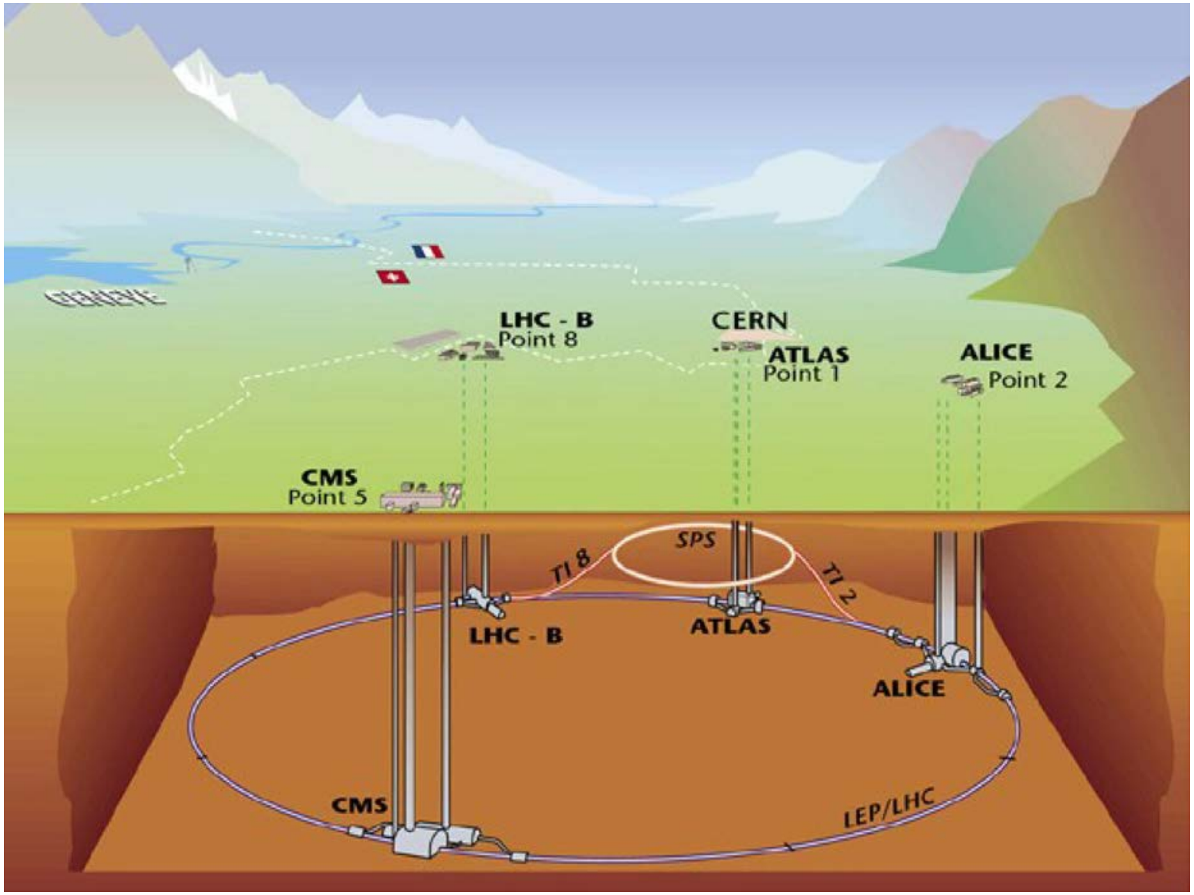
$$\beta \cdot \gamma = \frac{\sqrt{T_{lab}{}^2 + 1863 \cdot A_1 \cdot T_{lab}}}{931.5 \cdot A_1}$$

The relevant formulae are calculated if A_1, Z_1 and A_2, Z_2 are the mass number (u) and charge number of the projectile and target nucleus, respectively, and T_{lab} is the laboratory energy (MeV).

Large Electron Positron Collider LEP

⇒ For relativistic particles, $\gamma = E/mc^2$, hence energy loss grows dramatically with particle mass decreasing, being especially big for ***electrons***. ($\Delta E_{electron}/\Delta E_{proton} \approx 10^{13}$)

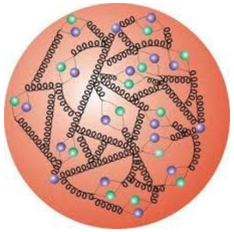
Limits on the amount of the radio-frequency power means that electron synchrotrons (***large electron positron collider LEP***, used from 1989 until 2000 at CERN) can not produce beams with energies more than ***100 GeV***.



Electron vs. Proton Machines

Electron Machine	Proton Machine
Clean – no other particle involved than e^+e^-	Messy - qq or $q\bar{q}$ interact and rest of p or $\bar{p}$ is junk.
Lower energy for same radius (synchroton radiation). LEP $e^+e^- \sim 200\ GeV$	Higher energy for same radius. LHC (pp) in LEP tunnel $\sim 14\ TeV$
Energy of e^+e^- known	Energy of qq or $q\bar{q}$ not known
Fixed energy (for a given set of operating conditions),	Range of qq or $q\bar{q}$ energies for fixed pp or $p\bar{p}$ energy.
Best for detailed study	Best for discovering new things

Hadron Collider (note, proton is a complex mixture of quarks and gluons): Crazy background due to splashed quarks and gluons connected by complex color-charge strings.



Synchrotrons

- The bending field changes with particle beam energy to maintain a constant radius:

$$\frac{1}{\rho[m]} = 0.3\frac{B[T]}{\beta \cdot E[GeV]} = 0.3\frac{B[T]}{cp[GeV]}$$

Example: for the large hadron collider LHC (ρ = 2805 [m]) and a magnetic field of the superconducting dipoles is B = 8.33 [T] (B_{iron} = 1.5 [T]) one obtains an energy of E_{max} = 7 [TeV]

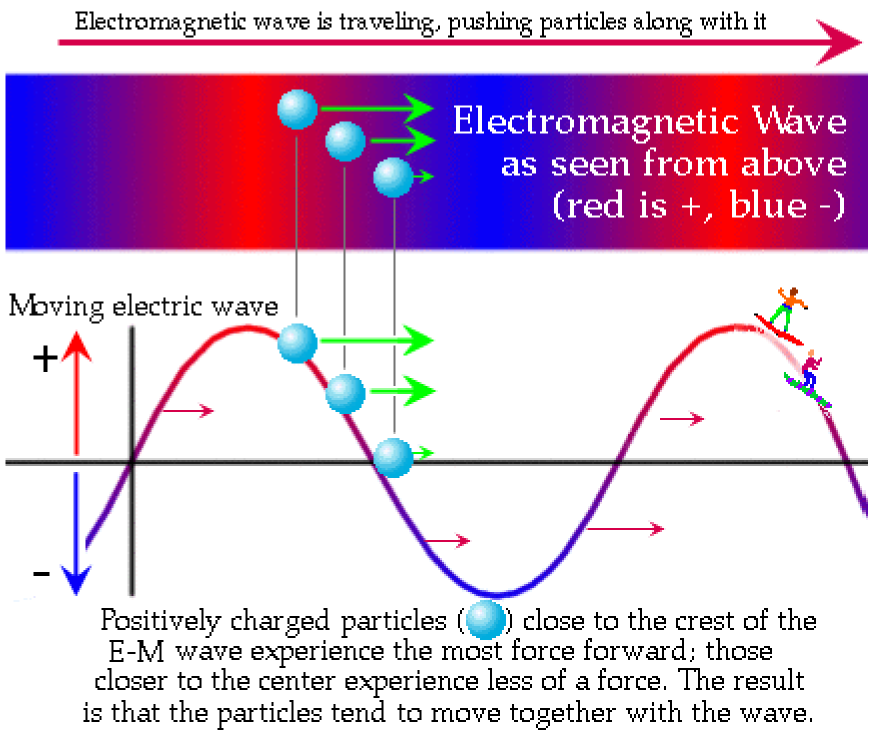
B ramps in proportion to the momentum. The revolution frequency also changes with momentum

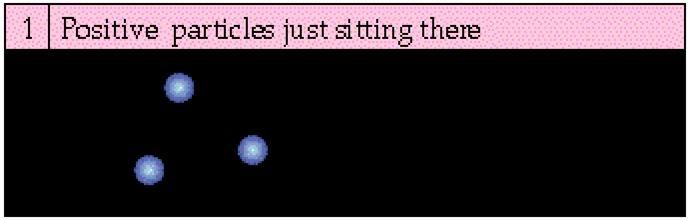
⇒ Maximal momentum is therefore limited by both the maximal available magnetic field ***B*** and the size of the ring ***ρ***.

- To keep particles well contained inside the beam pipe and to achieve the stable orbit, particles are accelerated in ***bunches***, synchronized with the radio-frequency field.
- Analogously to linacs, all particles in a bunch has to move with the circulation frequency in phase with the radio-frequency field.
- Requirement of precise synchronization, however, is not very tight: particles behind the radio-frequency phase will receive lower momentum increase, and other way around.

Synchrotrons

❖ Requirement of precise synchronization, however, is not very tight: particles behind the radio-frequency phase will receive lower momentum increase, and other way around.





⇒ Therefore all particles in a bunch stay basically on the same orbit, slightly oscillating

❖ To keep particle beams focused, quadrupole and sextuple magnets are also placed along the ring and act like optical lenses

Synchrotrons

Depending on whether beam is deposited onto a fixed target or is collided with another beam, both linear and cyclic accelerators are subdivided into two types:

- ***"fixed-target"*** machines
- ***"colliders"*** ("storage rings" in case of cyclic machines)

Much higher energies for protons comparing to electrons are achieved due to smaller losses caused by synchrotron radiation

Colliding-Beam Experiment

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

- The total energy of a projectile plus the target particle depends on the reference frame. For the production of high mass particles the relevant frame is given by the ***"center-of-mass" frame*** for which the projectile and target have equal and opposite momentum ***p***.

For simplicity let us suppose that the *projectile and target particle are the same*, or possibly particle-antiparticle (e.g. proton-proton, proton-antiproton, or electron-positron). This means that in this frame both the particles have the same energy, $\boldsymbol{E_1 = E_2 = \gamma \cdot mc^2}$ (since we are dealing with relativistic particles, this means ***kinetic plus rest energy)***.

$$s = \left(\sum_{i=1,2} E_i\right)^2 - \left(\sum_{i=1,2} p_i\right)^2 c^2$$

- In the center-of-mass frame, where the momenta are equal and opposite $\boldsymbol{p_1 = -p_2}$, the second term vanishes and we have

$$s = 4 \cdot E_1^2 = 4\gamma^2 m^2 c^4$$

i.e. ***s is the square of the total incoming energy in the center-of-mass frame*** – this is a quantity that is often used in particle physics.

$$\sqrt{s} = 2 \cdot E_1 = 2\gamma mc^2$$

1 TeV + 1 TeV = 2 TeV available cm energy

Fixed-Target Experiment

In a fixed-target experiment, a charged particle such as an electron or a proton is accelerated by an electric field and collides with a target, which can be a solid, liquid, or gas.

- The total energy of a projectile plus the target particle depends on the reference frame. For the production of high mass particles the relevant frame is given by the ***"center-of-mass" frame***.

For simplicity let us suppose that the projectile and target particle are the same, or possibly particle-antiparticle (e.g. proton-proton, proton-antiproton, or electron-positron). This means that in this frame the particles energies are $\boldsymbol{E_1 = \gamma \cdot mc^2}$ and $\boldsymbol{E_2 = mc^2}$ (since we are dealing with relativistic particles, this means ***kinetic plus rest energy***.

$$s = \left(\sum_{i=1,2} E_i\right)^2 - \left(\sum_{i=1,2} p_i\right)^2 c^2$$

For one particle we know that $E^2 - p^2c^2 = m^2c^4$ and is therefore the same in any frame of reference even though the quantities $\boldsymbol{E}$ and $\boldsymbol{p}$ will be different in the two frames. In the frame in which the target particle is at rest, its energy is $E_2 = mc^2$ and its momentum $\boldsymbol{p_2 = 0}$, so that we have

$$s = (E_1 + mc^2)^2 - p_1^2c^2 = E_1^2 + m^2c^4 + 2mc^2E_1 - p_1^2c^2 = 2m^2c^4 + 2mc^2E_1$$

$$\boxed{\sqrt{s} = \sqrt{2m^2c^4 + 2mc^2E_1} = \sqrt{2(\gamma+1)m^2c^4}}$$

1 TeV p + fixed target p = 43 GeV available cm energy

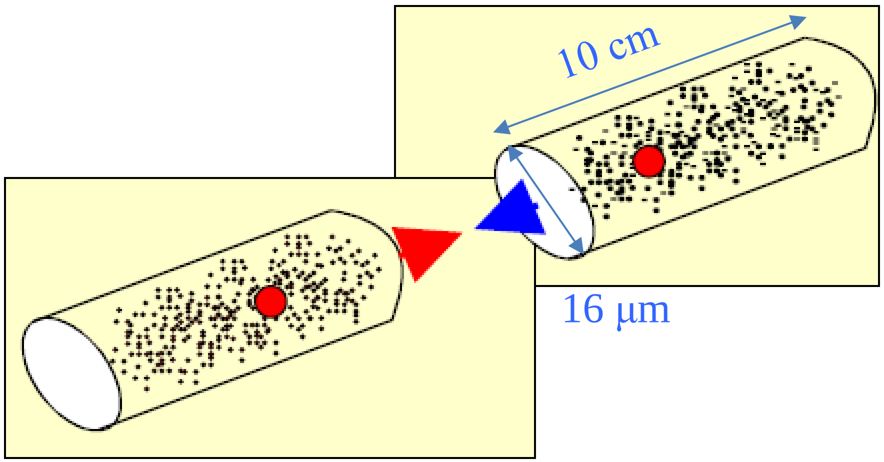
Luminosity Parameters

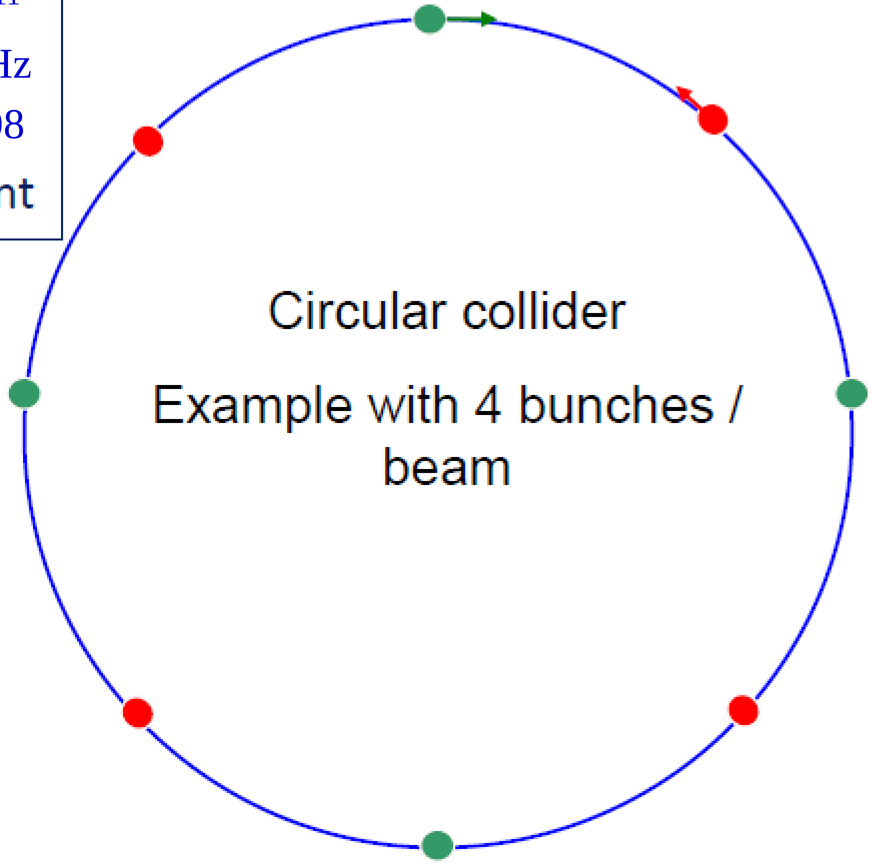
$$L = \frac{N^2 \times f_{rev} \times n_b}{4 \times \pi \times \sigma_x \times \sigma_y}$$

$10^{34}\ cm^{-2}s^{-1}$

N …	number of particles per bunch	$\sim 10^{11}$
f_{rev} …	revolution frequency	11 kHz
n_b …	number of bunches per beam	2808
$\sigma_x \times \sigma_y$	beam dimensions at interaction point	

$\sigma = 16\ \mu m$



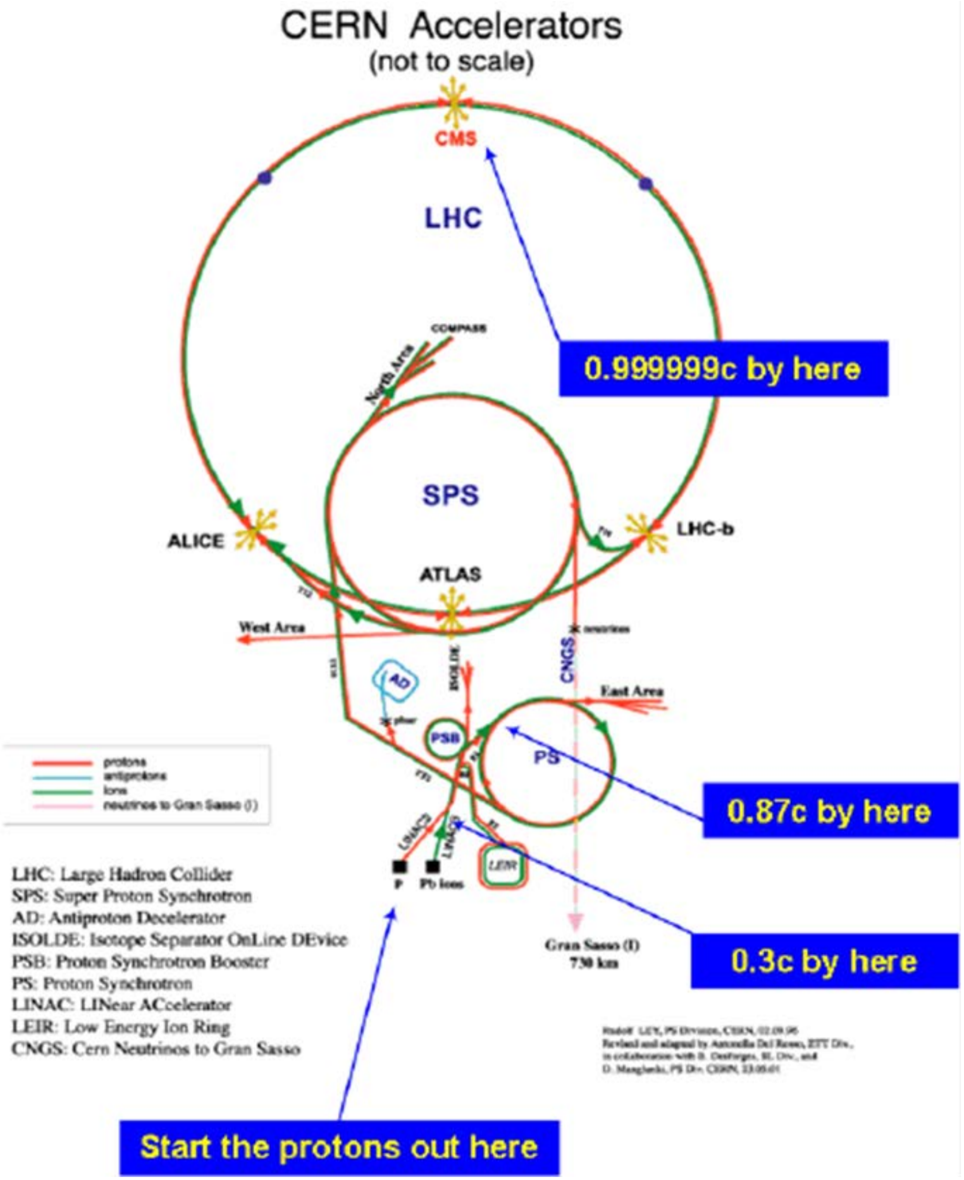


Accelerator Complex CERN

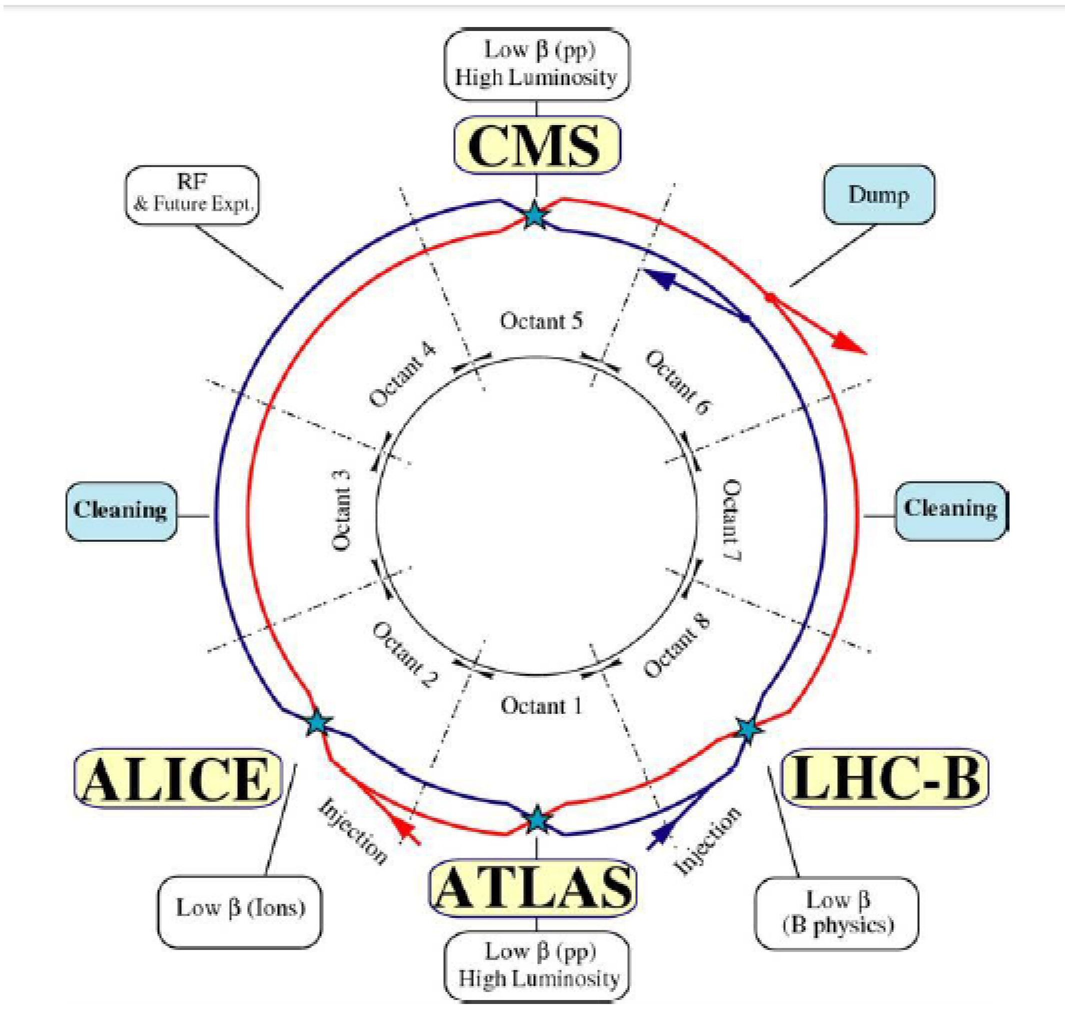
- Most modern high energy accelerators are a ***series of linear accelerators and rings***.

- Each piece is designed to accept and accelerate particles for up to a particular energy.

- Transferring a beam of particles between one piece and the next is one of the biggest challenges.



The LHC Layout



Large Hadron Collider (LHC)

LHC (p $\rightarrow\leftarrow$ p) 7(14) TeV

26.7 km circumference

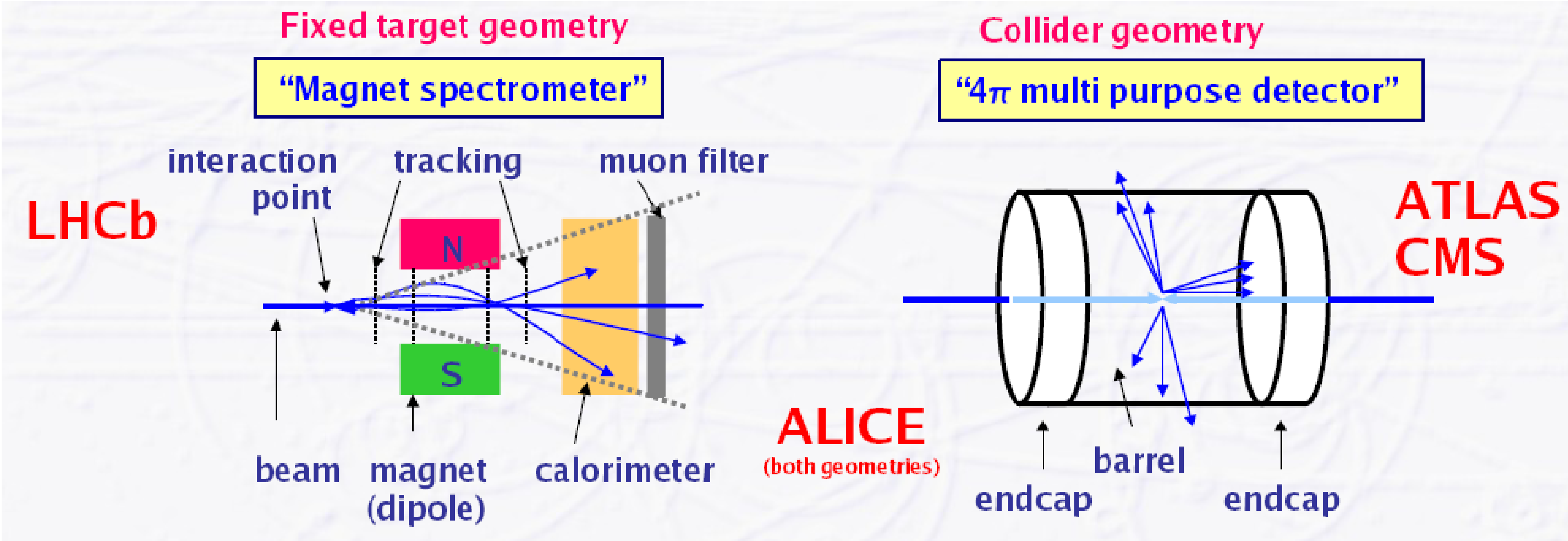
- 40000 tons of cold mass spread over 27 km
- 10000 tons of Liquid Nitrogen (at T = 80 K)
- 60 tons of Liquid Helium (cools ring to final 1.9 K)

Inside Large Hadron Collider (LHC) Tunnel

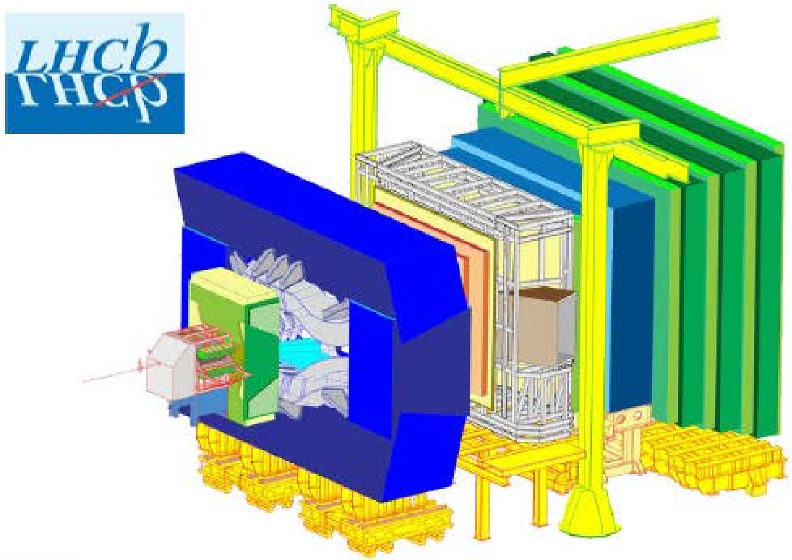
1232 superconducting magnets (14.3 m long, B = 0.5-8.33 T, 11700 Ampere)

A perfect detector should reconstruct any interaction of any type with 100% efficiency and unlimited resolution (get “4-momenta” of basic physics interaction)

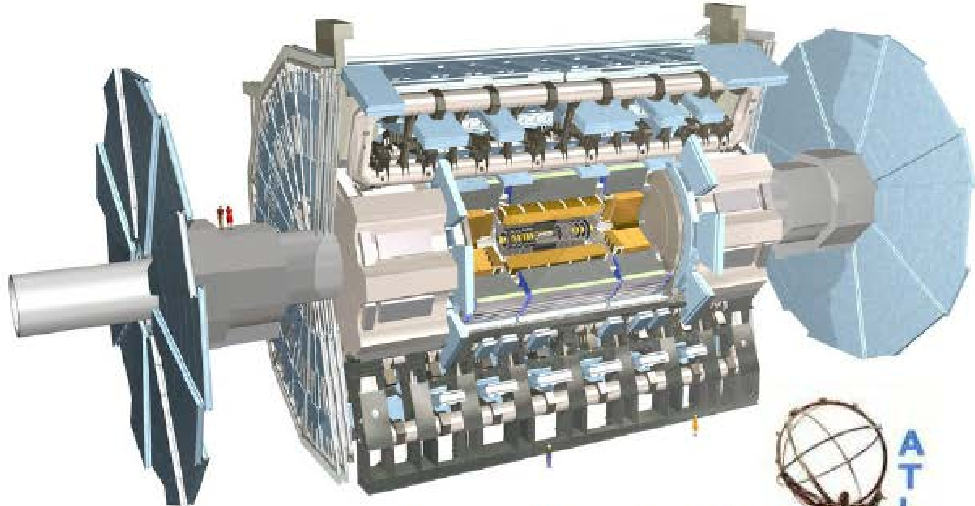
Efficiency: not all particles are detected, some leave the detector without any trace (neutrinos), some escape through not sensitive detector areas (holes, cracks for e.g. water cooling and gas pipes, electronics, mechanics)



Experiments at LHC

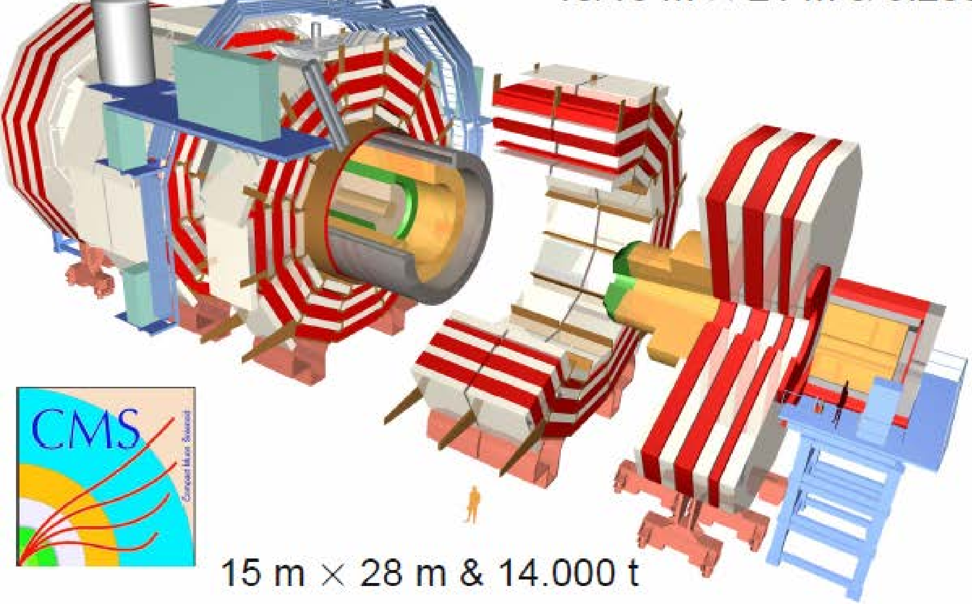


10/13 m × 21 m & 6.200 t

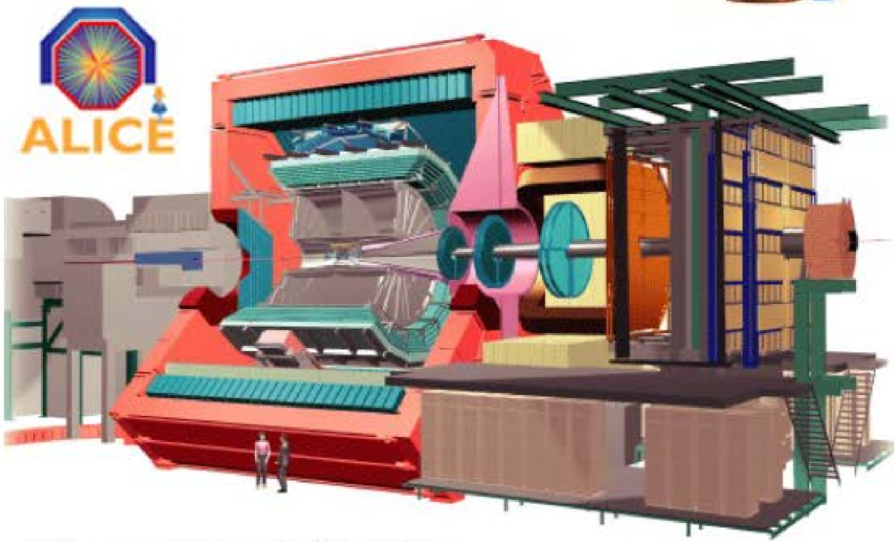


22 m × 44 m & 7.000 t

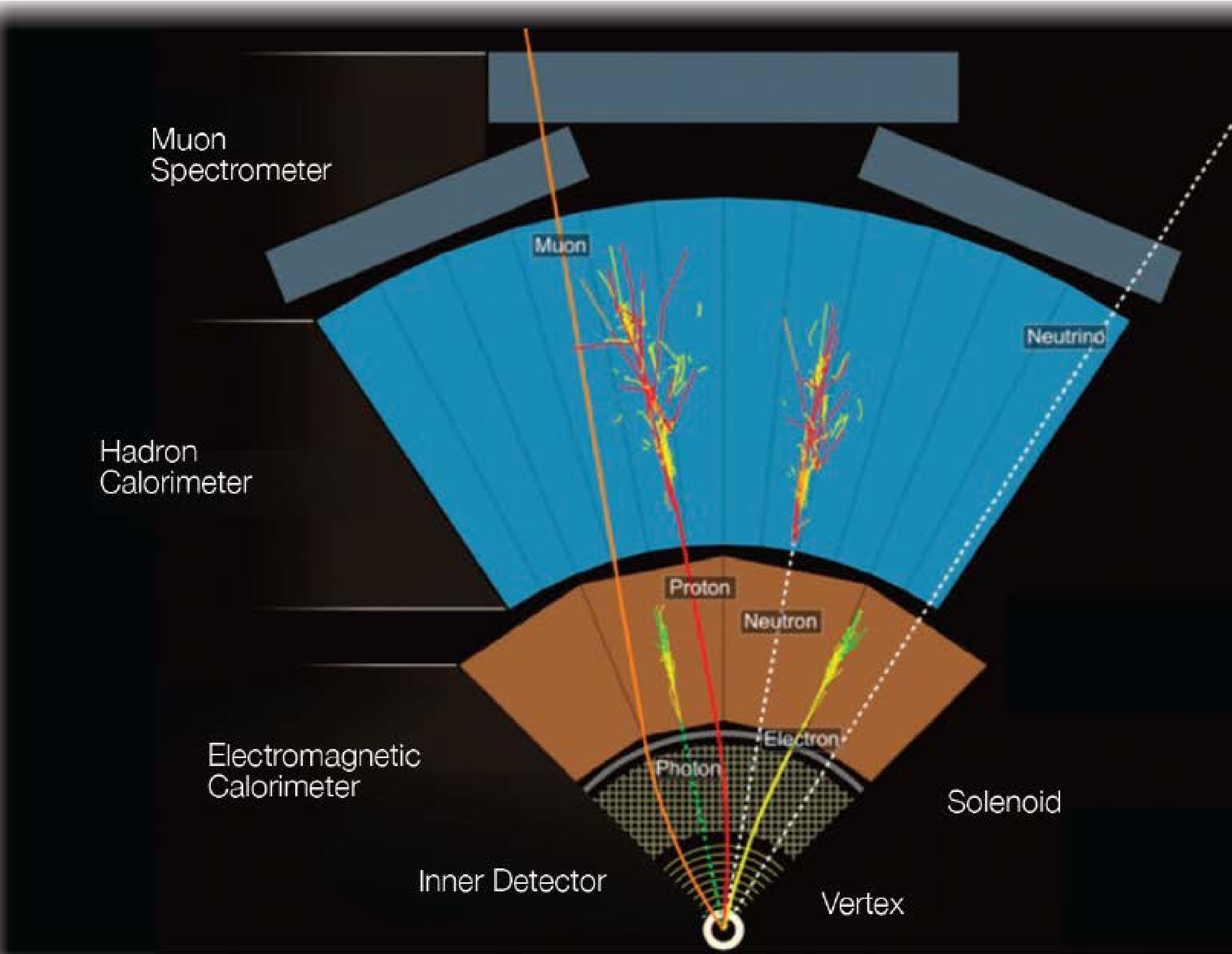
ATLAS



15 m × 28 m & 14.000 t



16 m × 25 m & 10.000 t



Toroidal magnet

Muon chambers

HCAL
Outer: scintillator
Inner: liquid Argon

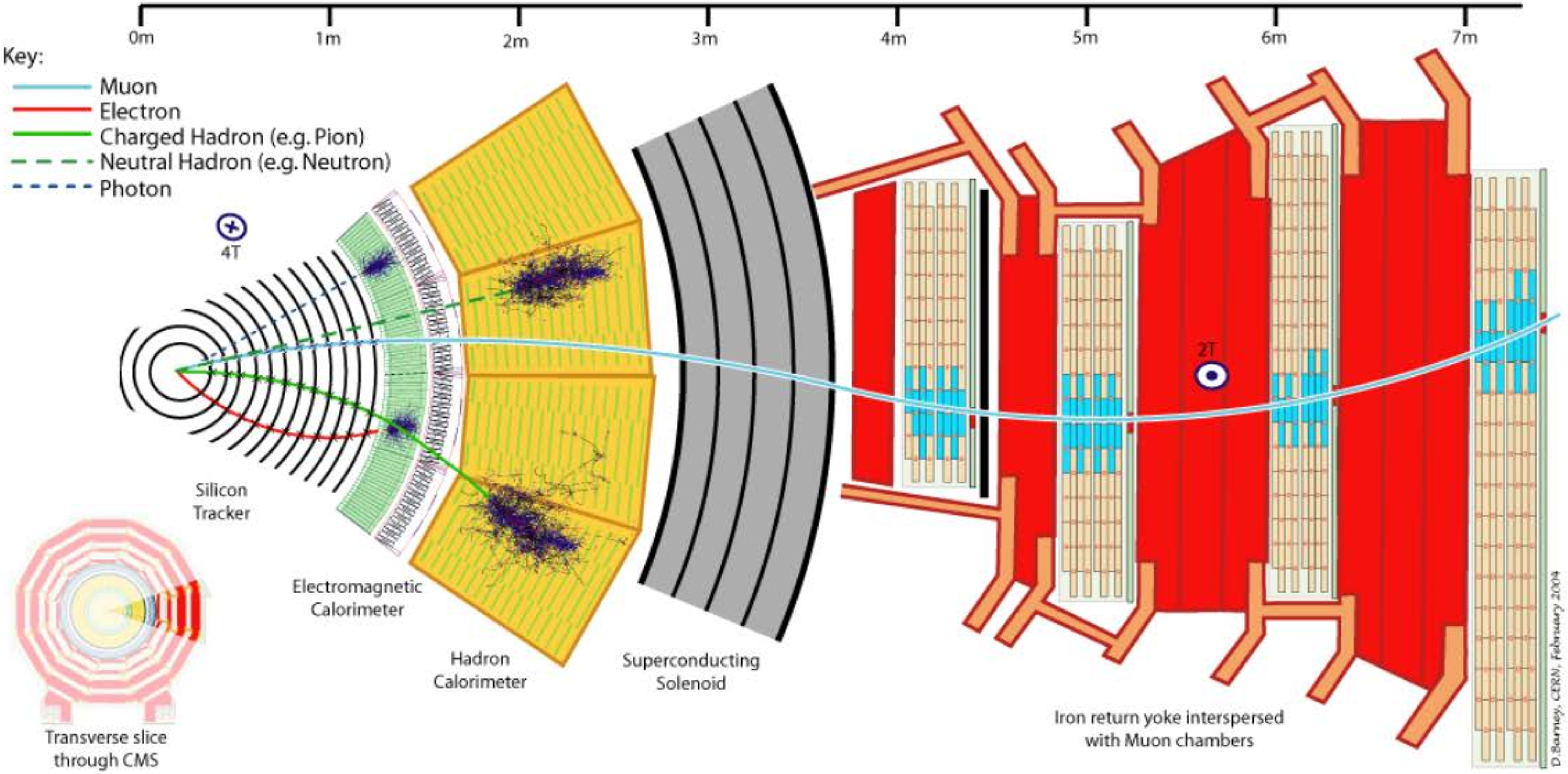
ECAL
liquid Argon

Solenoid ~2T

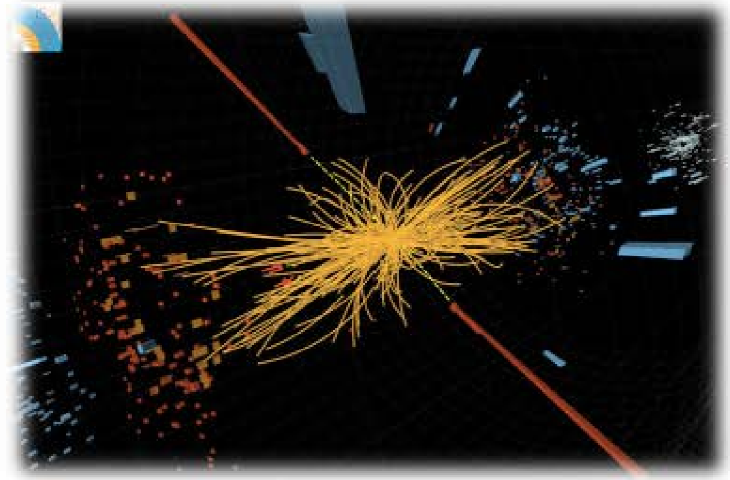
Tracking
Transion radiation
Si-Strip
Si-Pixel

Main difference to ATLAS:

- All silicon tracker
- ECAL and HCAL mostly inside solenoid magnet (~4T)
- No toroidal magnet for muon bending



Detectors are a fundamental ingredient to extract excellent physics results



Treat them with respect: them, calibrate them right, exploit them and don't abuse them

Have a lot of fun designing, building, testing, using them during your whole career …