Particles, Strings and Cosmology 2025

Instrumentation

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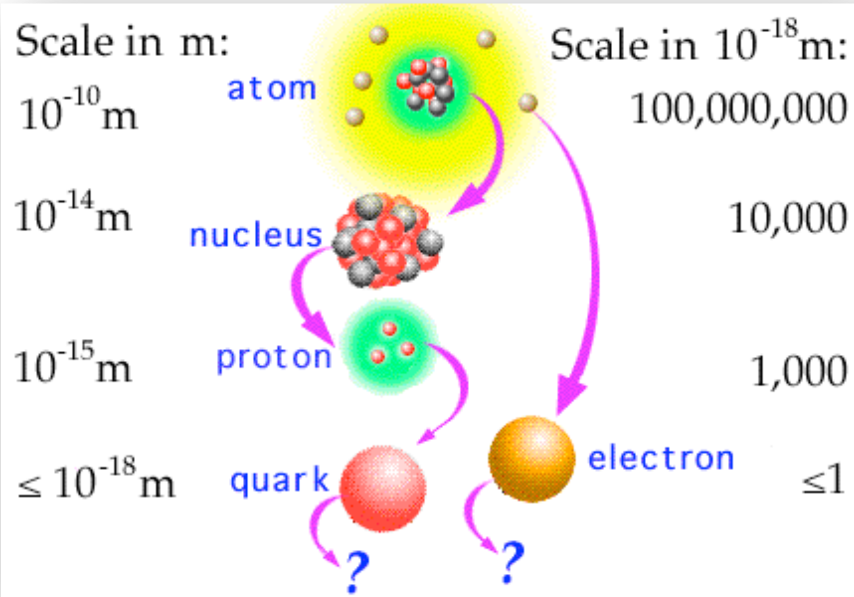
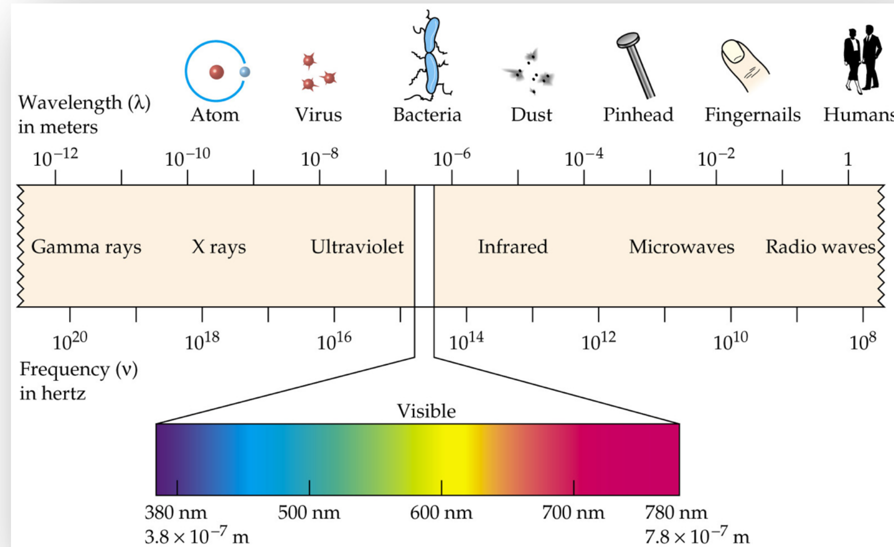
DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

DESY.

Particles accelerators

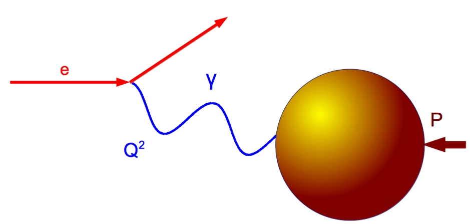




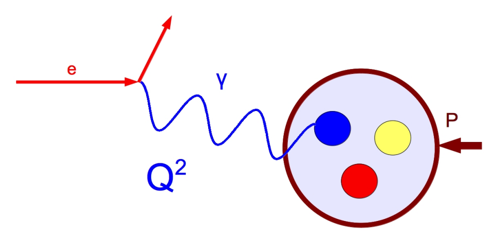
d ~ hc/Q ~ 197 MeV fm/Q

To see distances of the order of 10^{-18} m, values of Q around ~100 GeV are needed -> particle accelerators (or cosmic rays)

Now: LHC, $\sqrt{s}$= 13 TeV

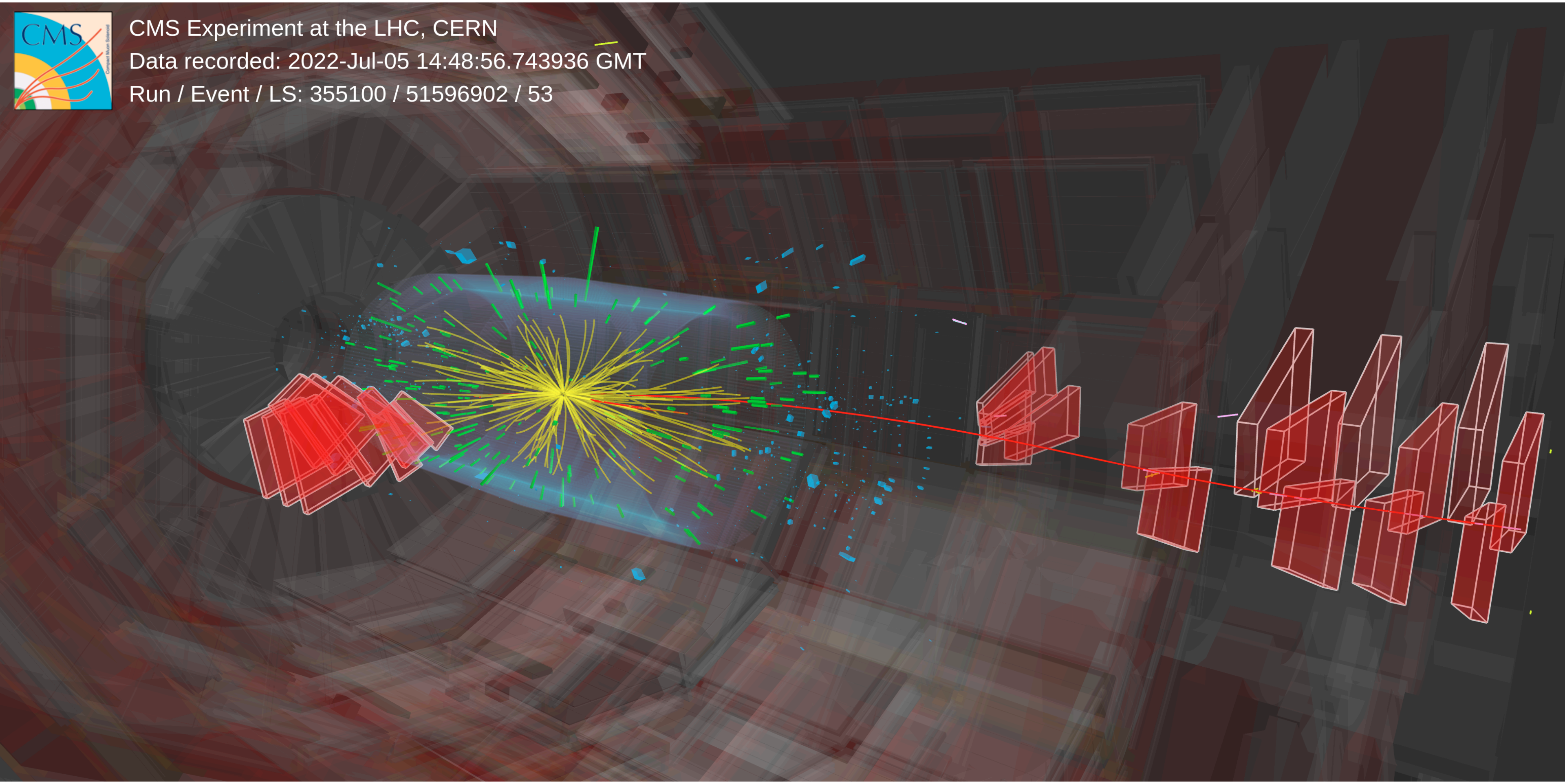


~MeV



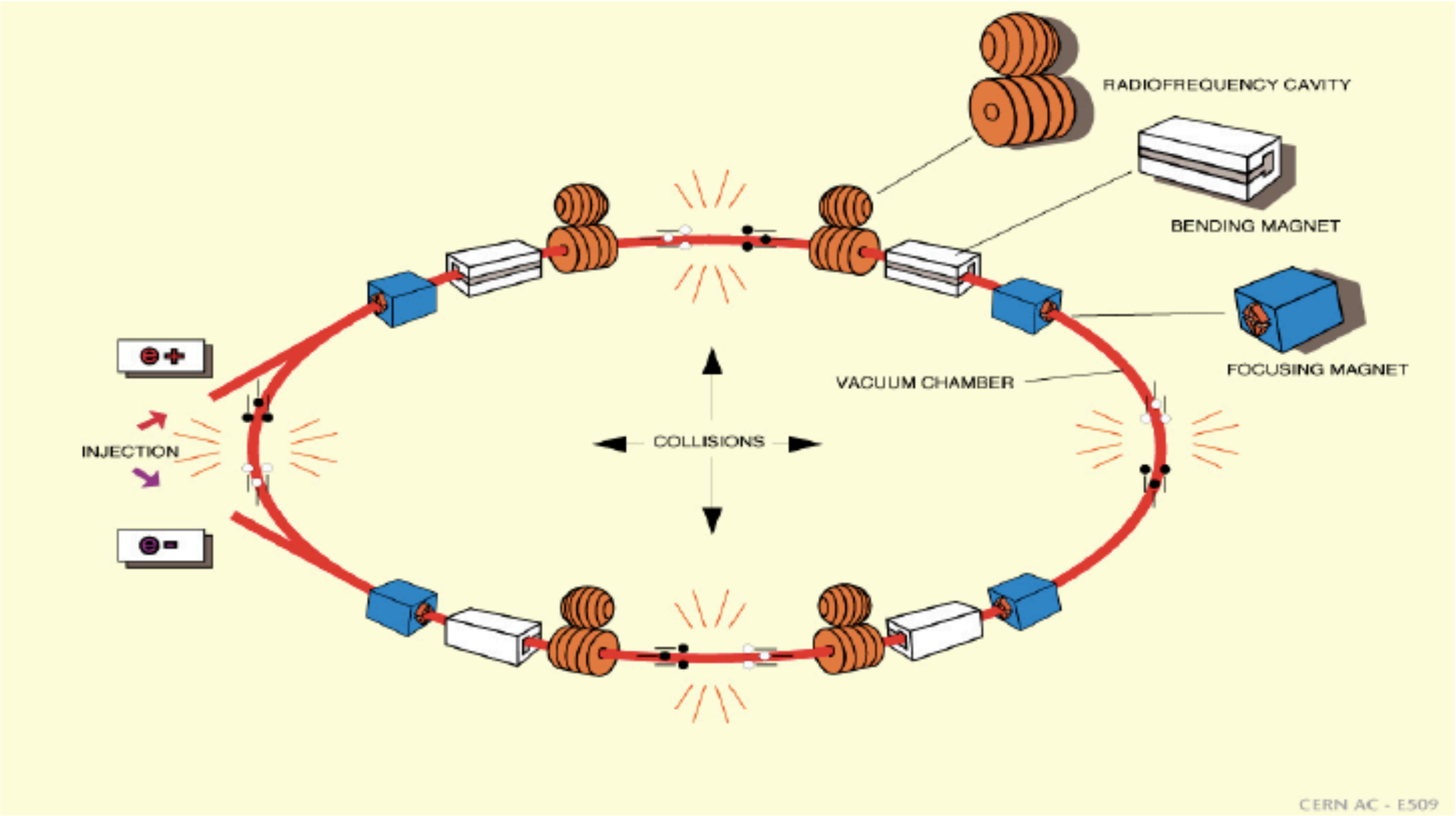
~GeV

LHC at 13.6 TeV



Start of LHC at 13.6 TeV, the highest c.m. energy ever, 5th July 2022
One of the first events in the CMS detector

Accelerators



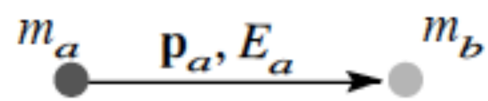
Accelerators

Accelerators have two important parameters:

- the center-of-mass energy $\sqrt{s}$, i.e. reach for new particle searches, higher cross sections etc.
- the instantaneous luminosity, i.e. search for rare processes, precision measurements etc.

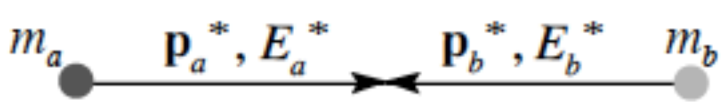
c.m. energy in fixed target:

$$s = (E_a + m_b)^2 - p_a^2 = m_a^2 + m_b^2 + 2m_b E_a$$



c.m. energy in a collider:

$$s = (E_a + E_b)^2 - (\mathbf{p}_a + \mathbf{p}_b)^2 \longrightarrow s \approx (2E^*)^2$$



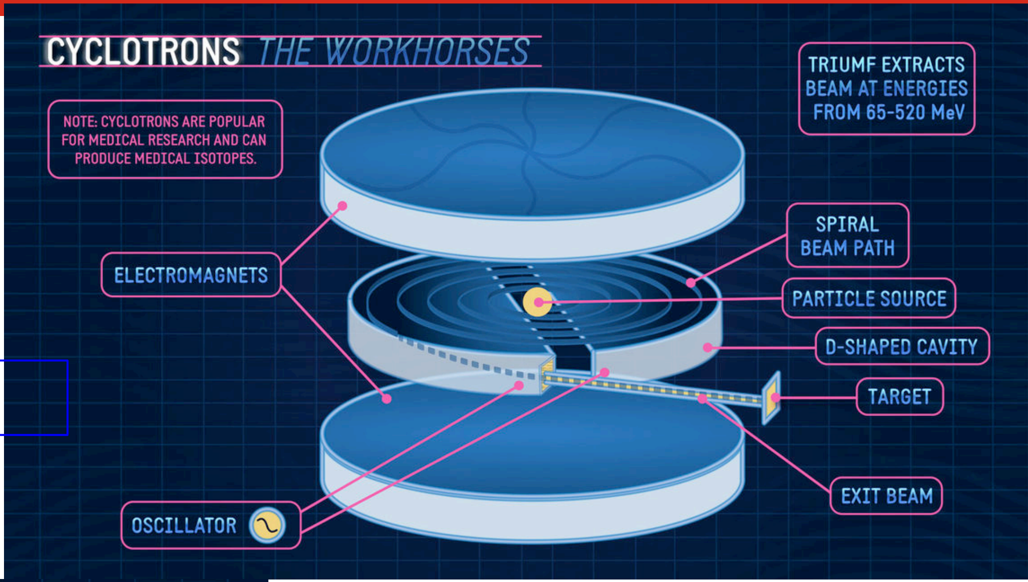
Font: Bettini, symmetry;

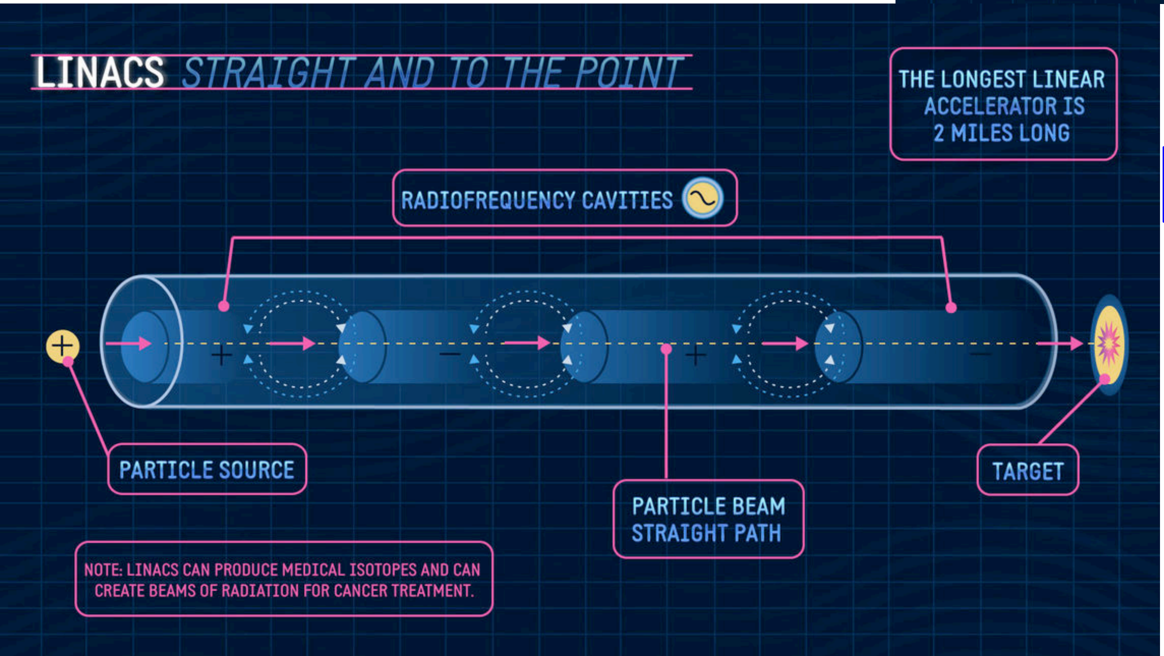
Accelerators

Formula that we will use a lot:

$$p[GeV] = 0.3B[T]\rho[m]$$

Cyclotrons



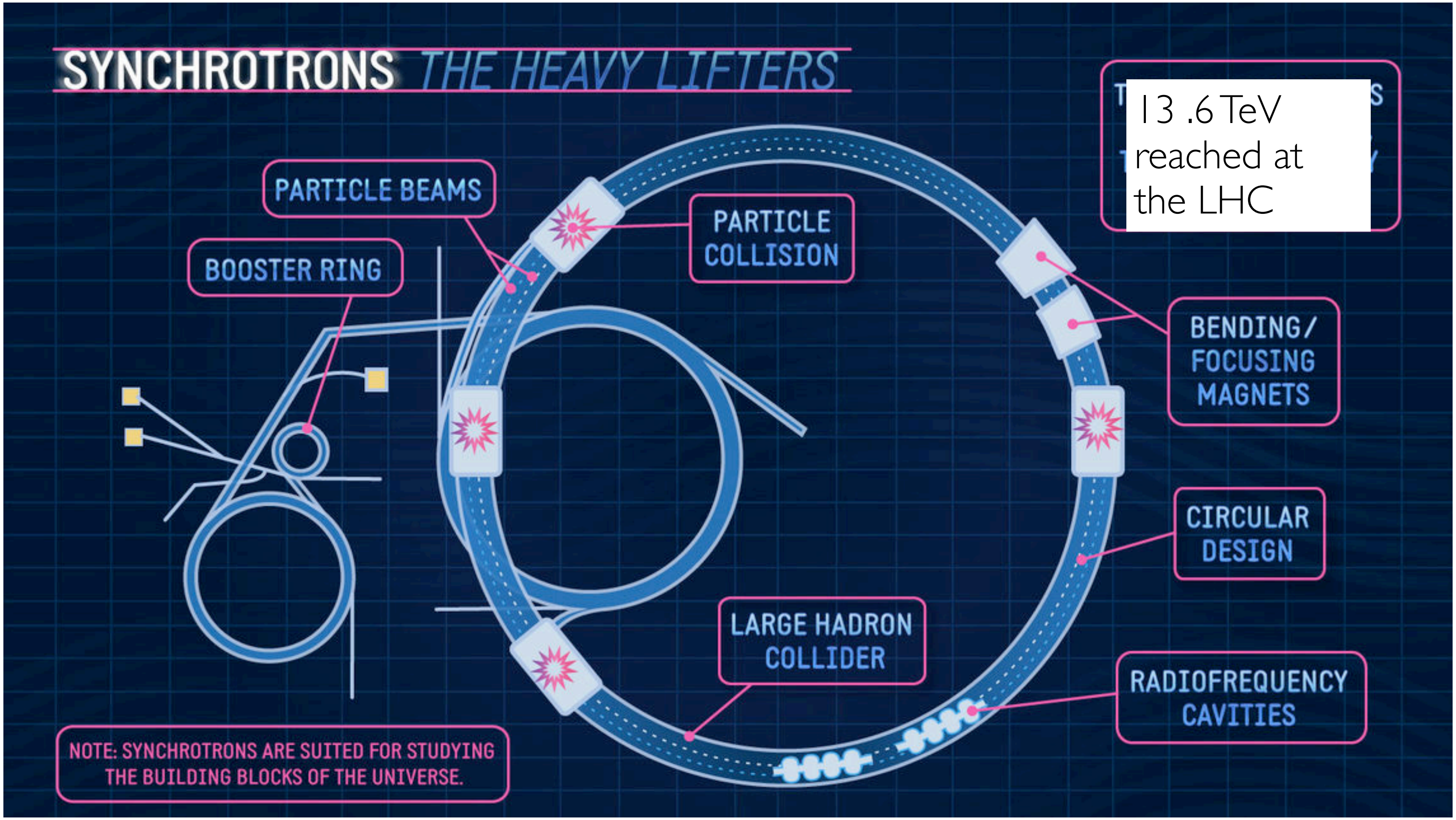


Linacs

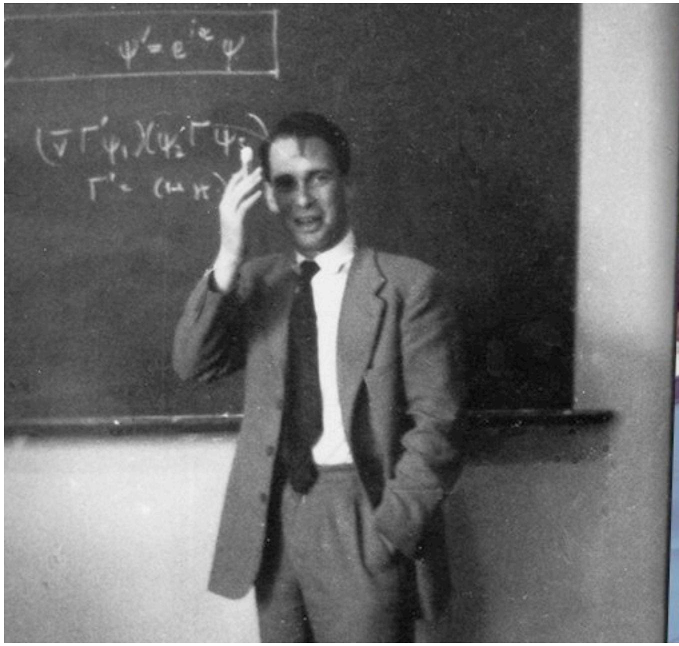
Accelerators

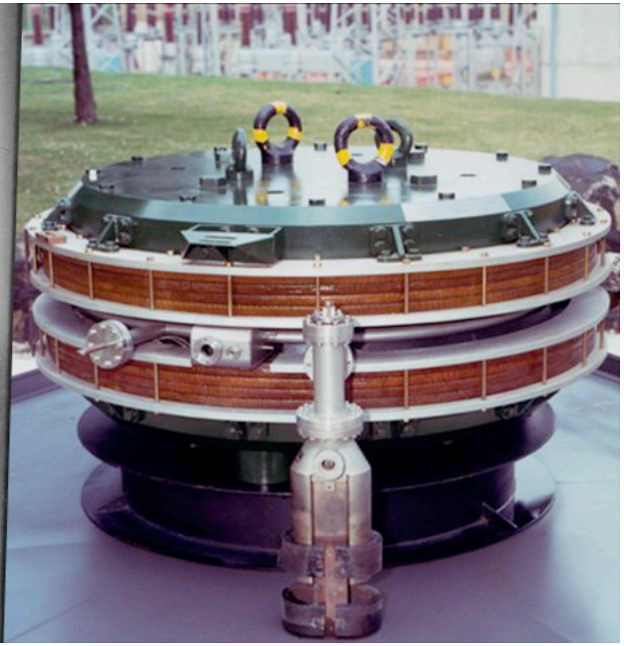
Synchrotrons: Bρ=p/e; At fixed radius, B is proportional to

$\propto$ *particle beam momentum, B increases synchronous with Energy*

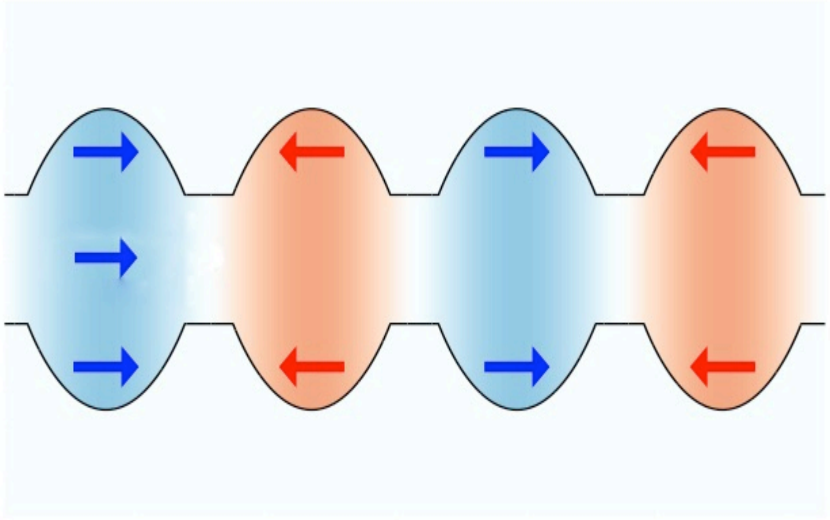


Ada and Bruno Touschek

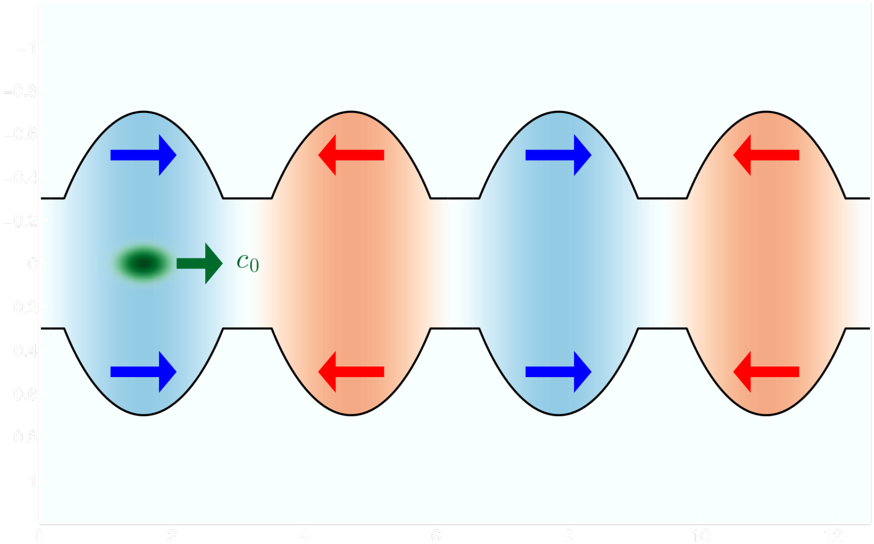




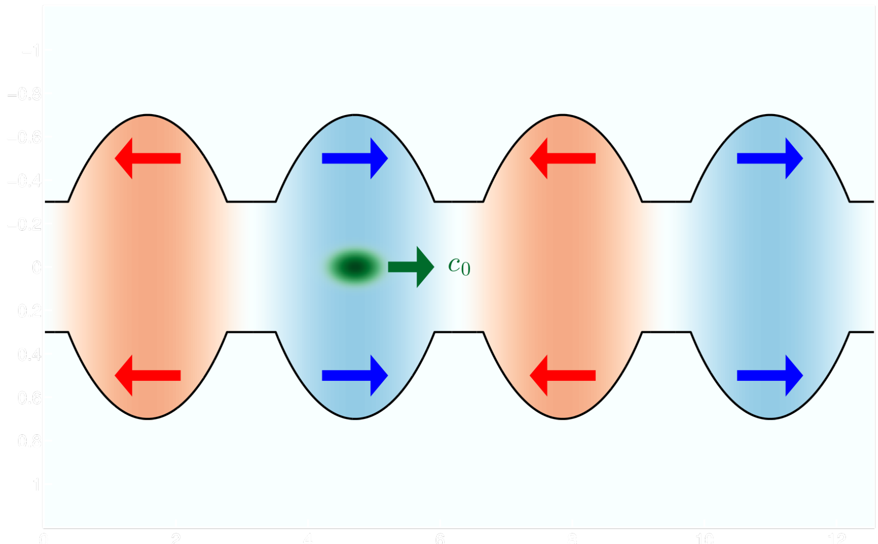
RF cavities



RF cavities

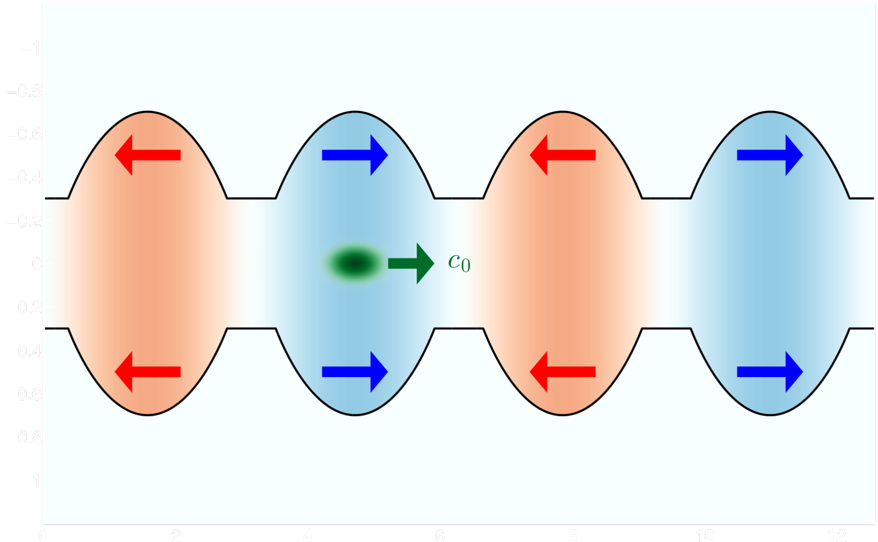


RF cavities

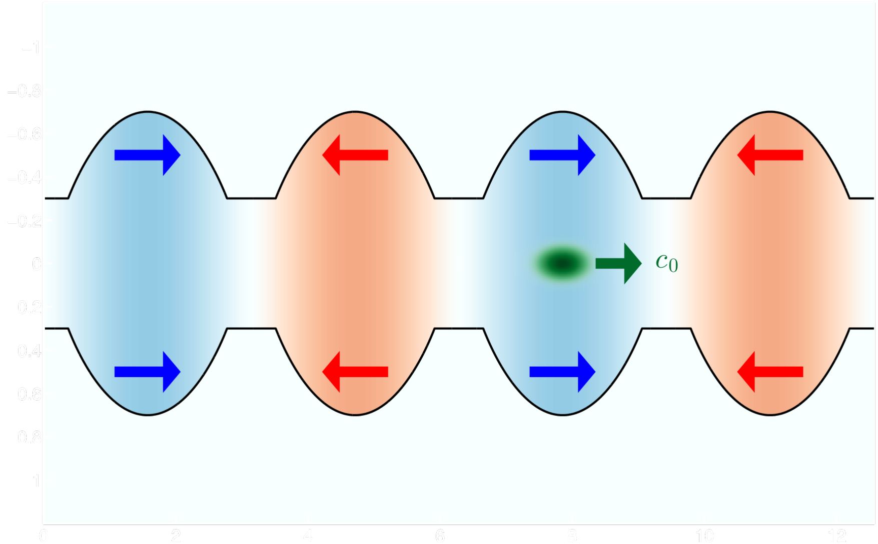


Particles are accelerated in bunches in order to synchronise their arrival with the phase of the Radiofrequency cavities.

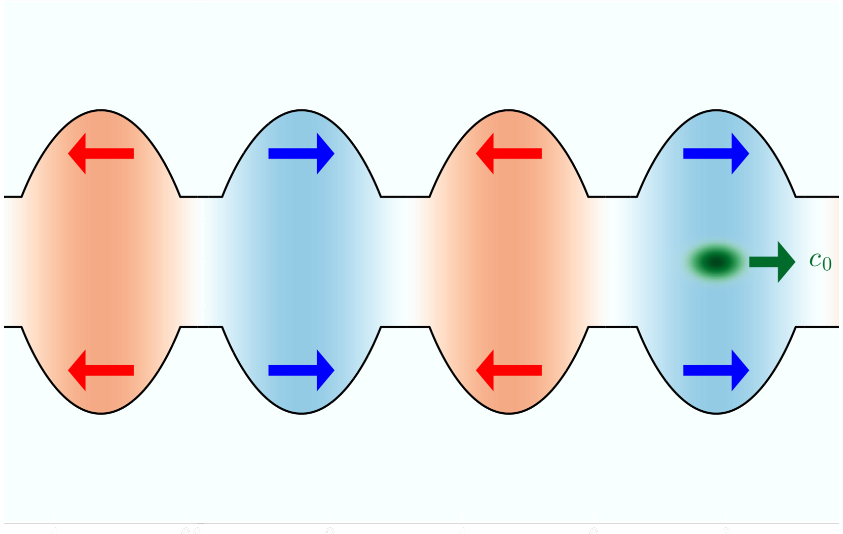
RF cavities



RF cavities



RF cavities

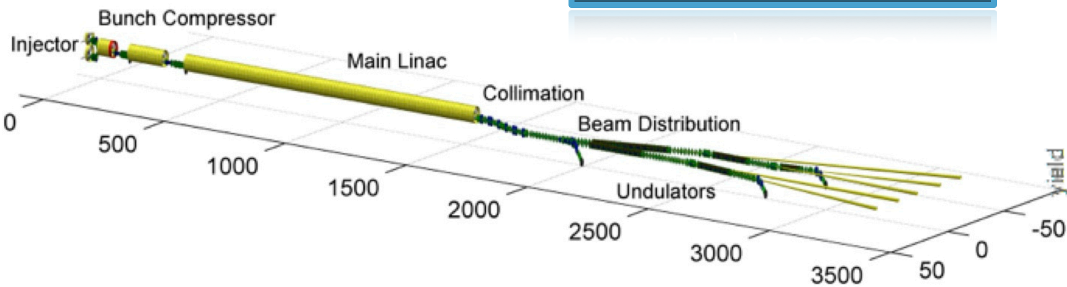


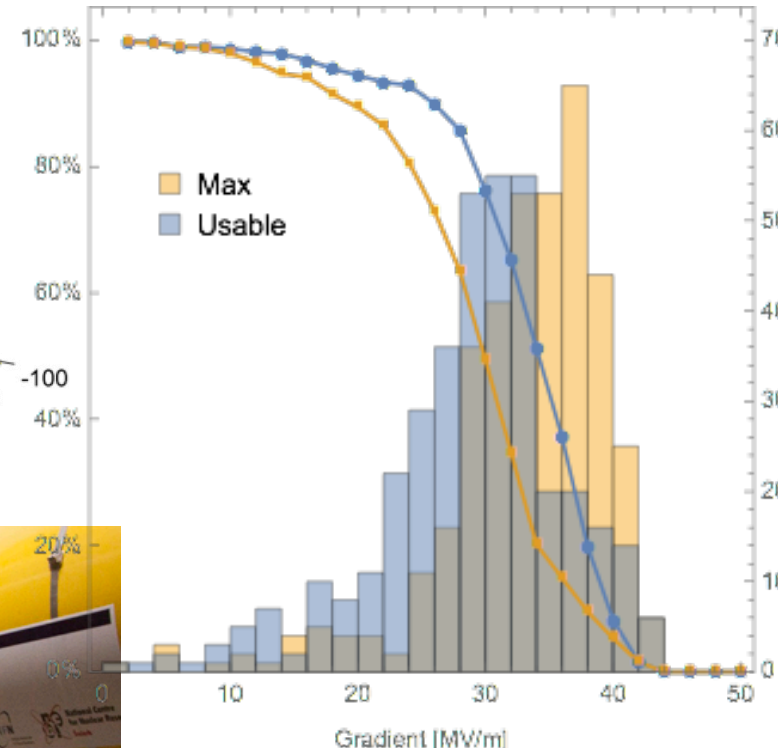
from Brian Foster

RF cavities

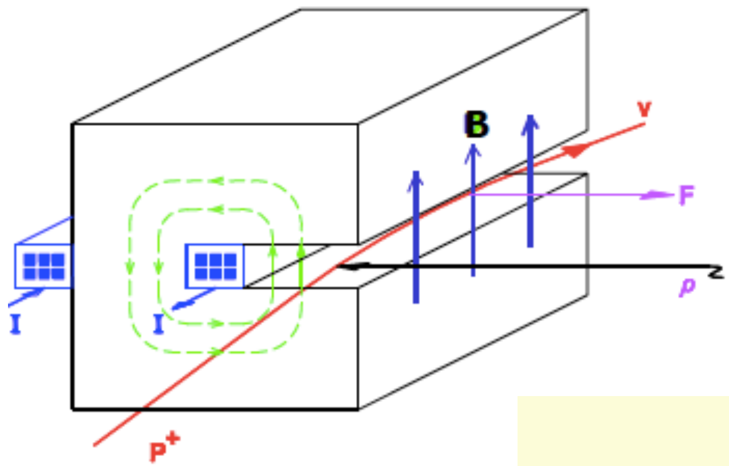
In superconducting RF cavities an electron can be accelerated up to ~25MV/m.
Here at the XFEL, in Hamburg

EuXFEL, 17.5 GeV





Dipole magnets

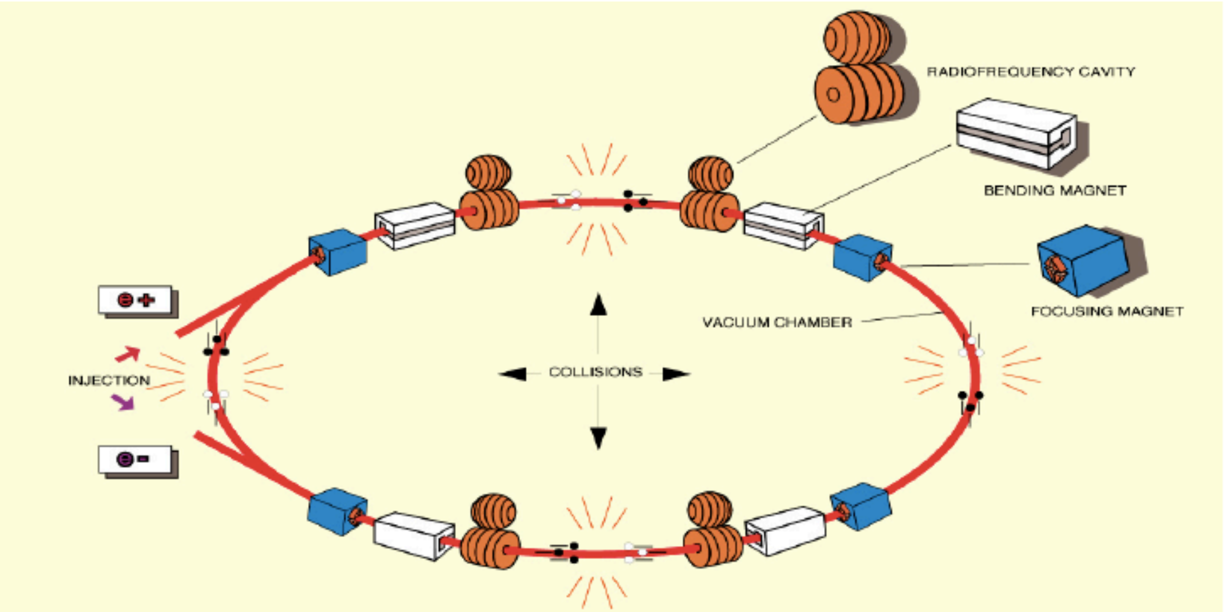


Charged particles are bent in the ring using dipole magnets

$$p[GeV] = 0.3B[T]\rho[m]$$

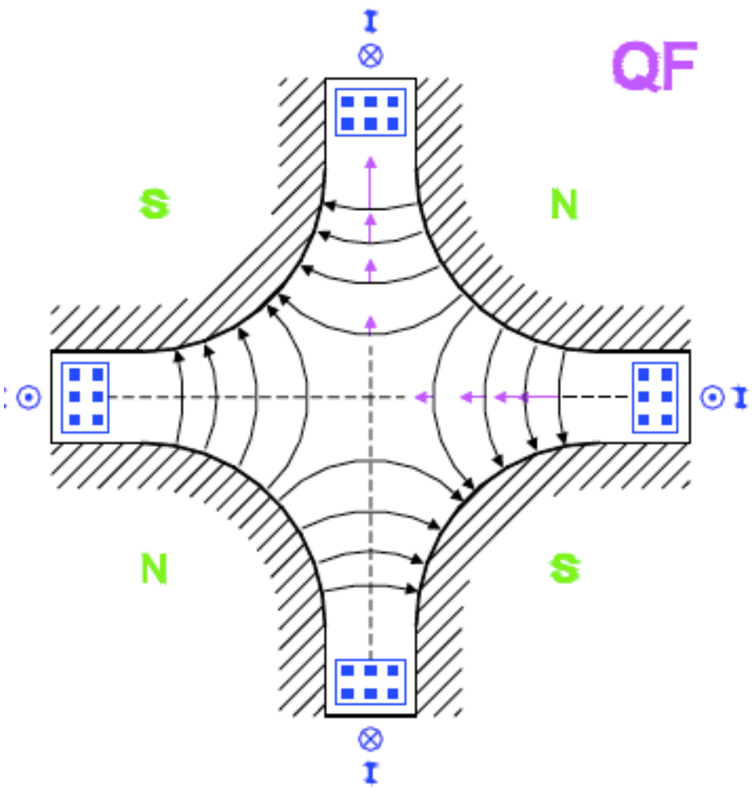
A rough scheme of a collider

In a synchroton the B field changes linearly while the p increases linearly, as rho is constant, until the maximum energy is reached.



Font for following figures: CERN Lectures Brandt

Quadrupole magnets

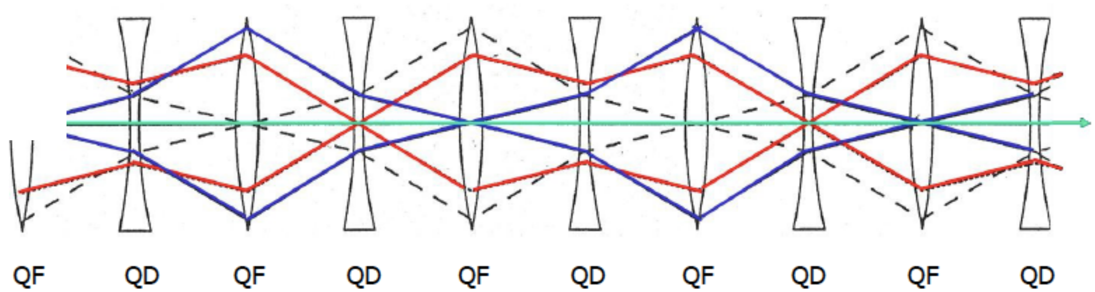


Quadrupole magnets are used to focus the beam. A particle beam passing through a quadrupole magnet is focussed in one of the two planes (but unfortunately defocussed in the other plane):

$F_X = -g.x$

$F_Y = g.y$

Alternating focussing and defocussing magnets has the net effect of focussing the beam (FODO cell).

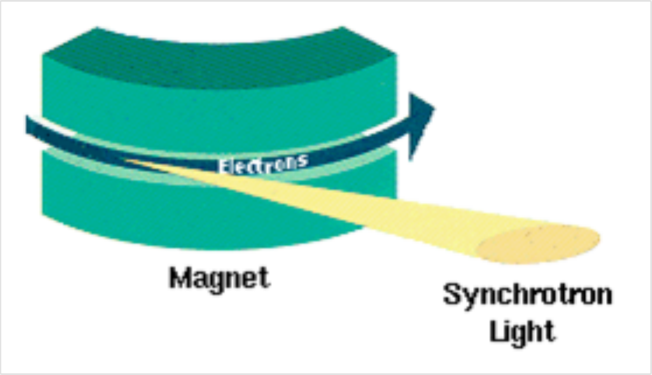


Type of collider

- Linear versus circular:

Particles bending in a magnetic field emit synchroton radiation:

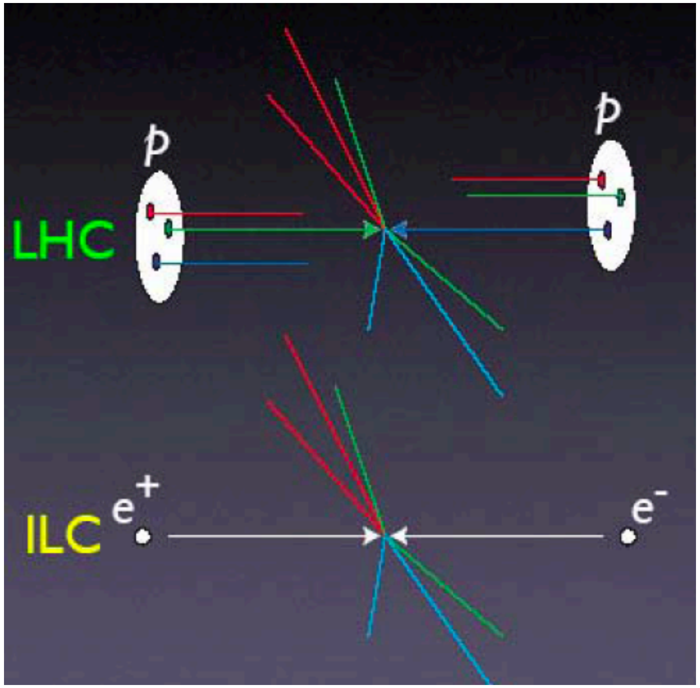
Energy loss~ $\gamma^4/\rho = (E/m)^4/\rho$
$(m_e/m_p)^{-4} = 10^{13}$
so that at the ~TeV energy only protons are possible for present radius ρ



- electrons vs protons

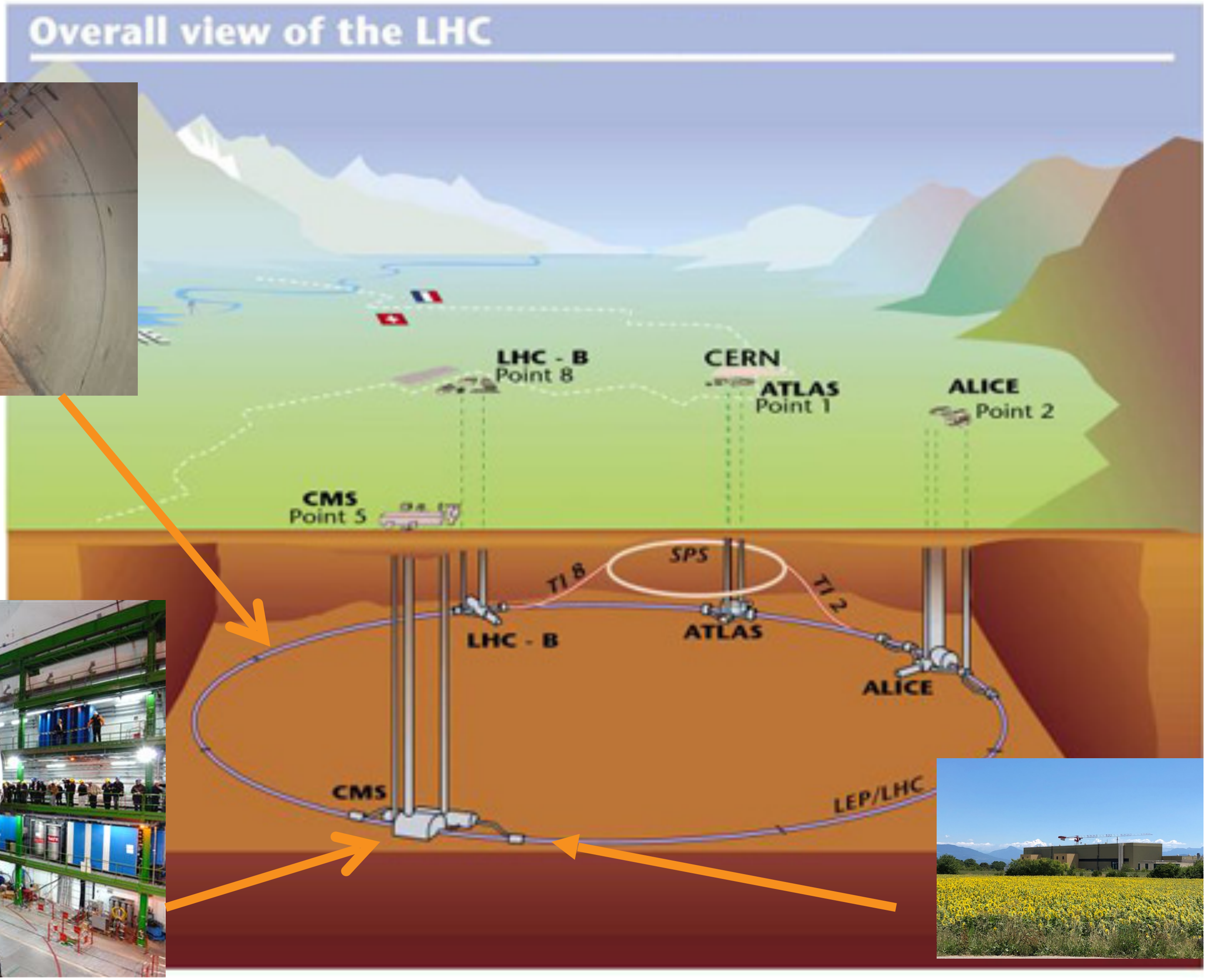
In pp the elementary collision is between partons, and not elementary particles, the final state is not completely reconstructed, energy balance only in the transverse direction

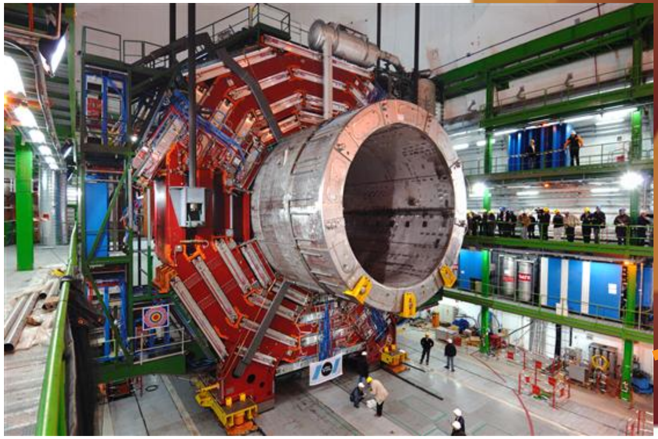
- Background due to underlying hadron interactions is much higher



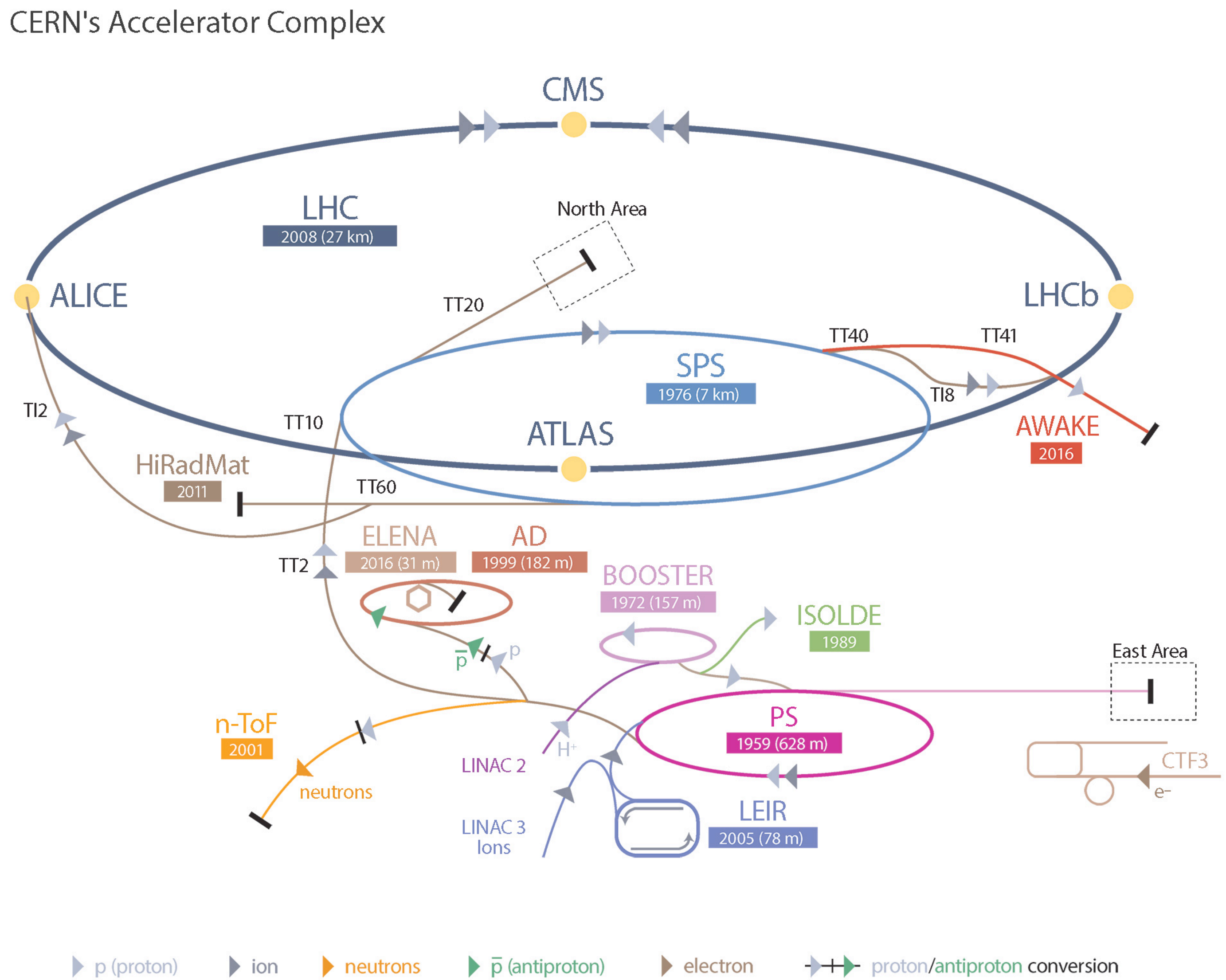
SuperKEKB in Japan

The Large Hadron Collider





CERN accelerator complex

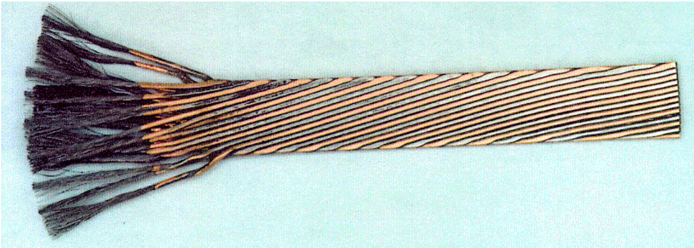


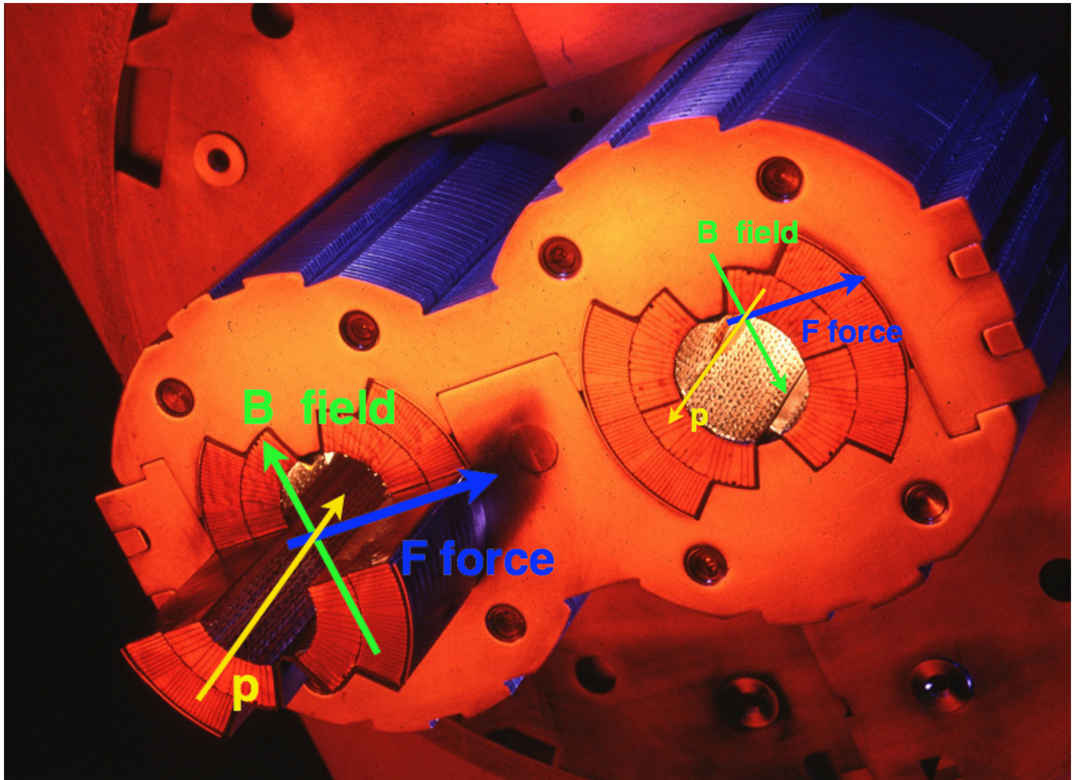
https://videos.cern.ch/record/1458950

LHC numbers

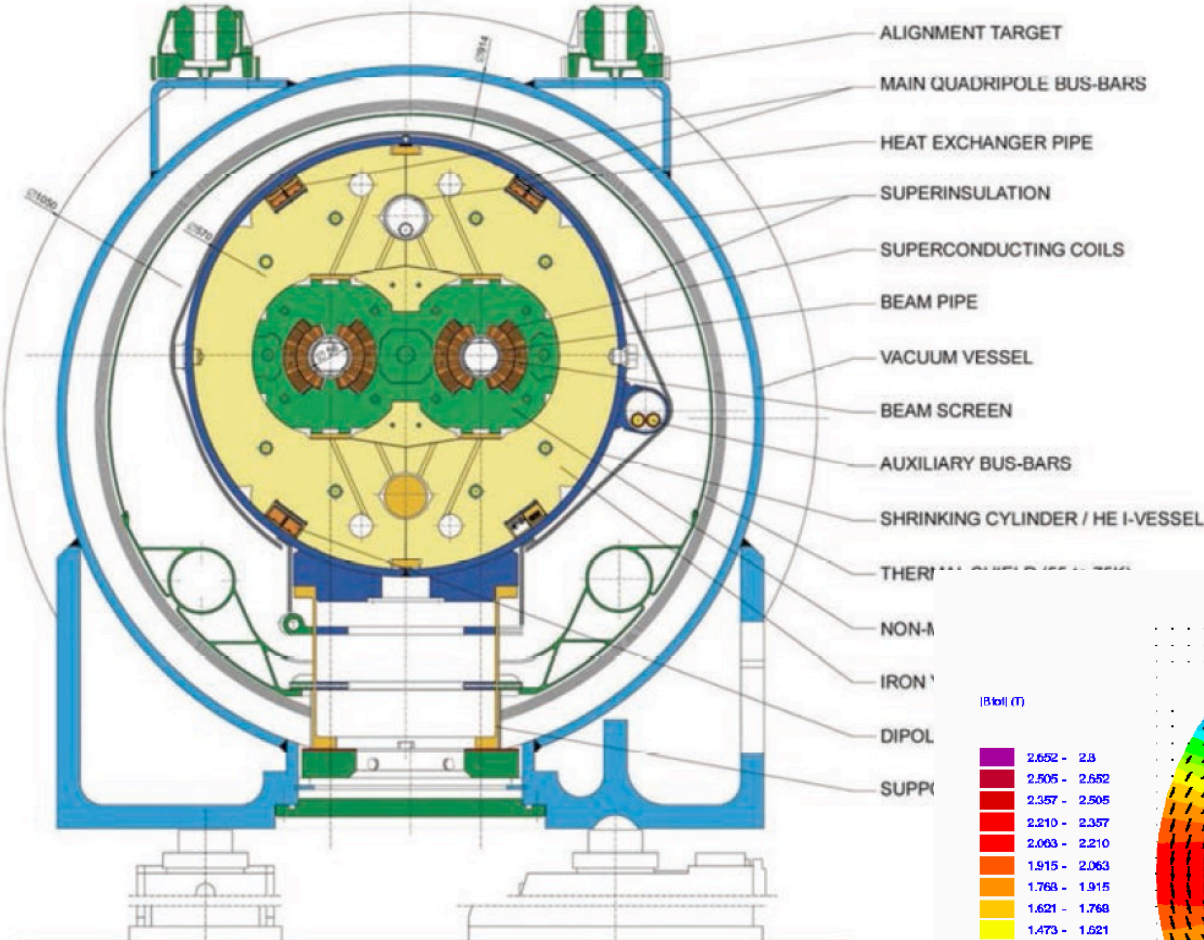
- 1232 dipoles with B=8.4 T at 1.9K
- 33000 tons of cryogenic liquid
- superconducting cavities at 5MV/m, 400 MHz, 4.5 K
- beam current 0.5A
- 2808 (max) bunches, 1.11X 10^{11} protons/bx, 25 nsec bunch crossing (~7.5m)
- Energy in one beam: 293 MJ (now) Like a train of 400t at 150 km/h
- Energy stored in magnets: 11 GJ, 11850 A
- transverse beam size in x-y ~ 15micron
- Vacuum 10^{-10}-10^{-11} mbar

7000 km of Ni-Ti cables



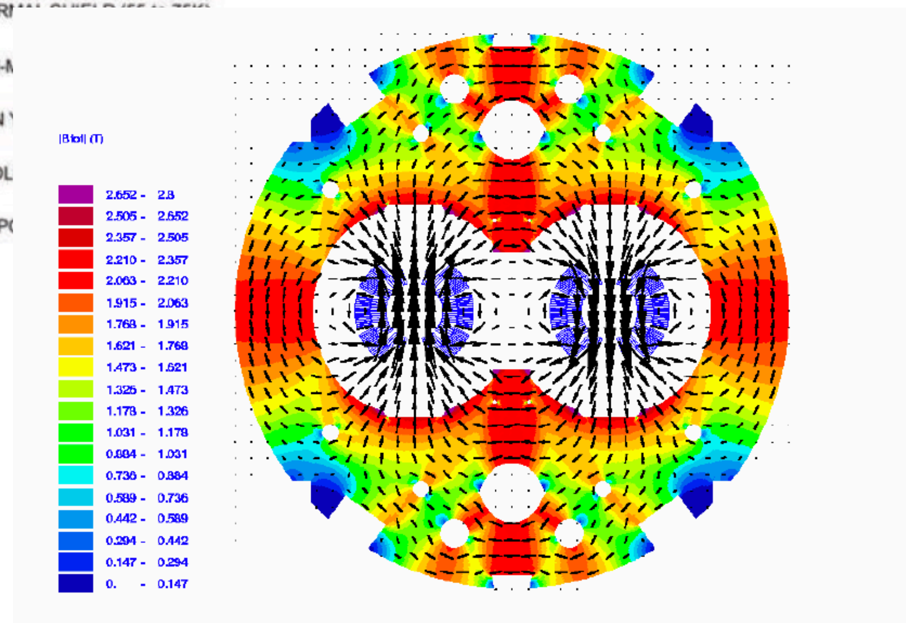


LHC dipole



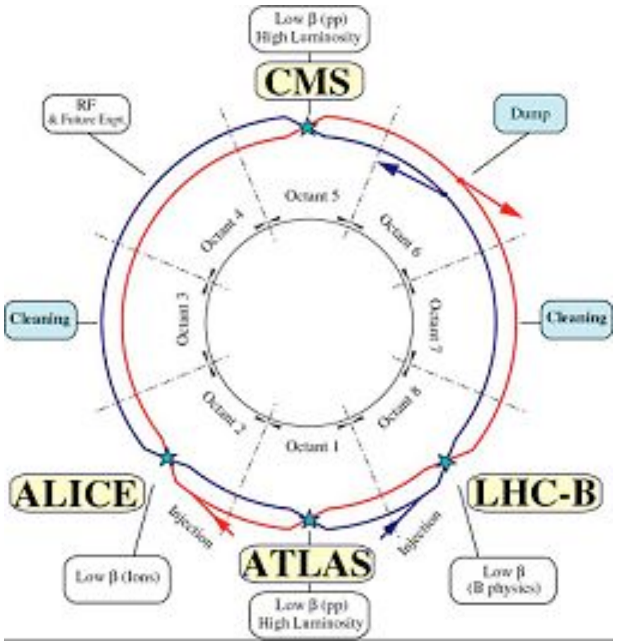
Cross section of LHC dipole magnet

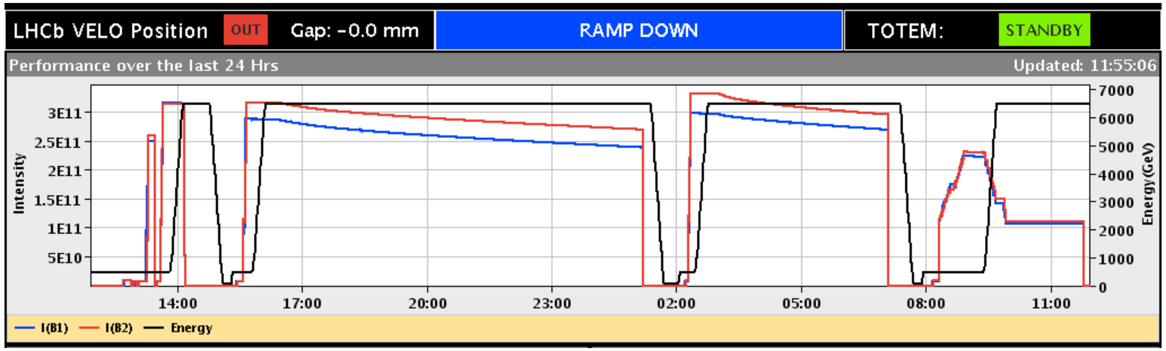
Dipole magnetic flux



Font: Talk of L. Evans

LHC layout





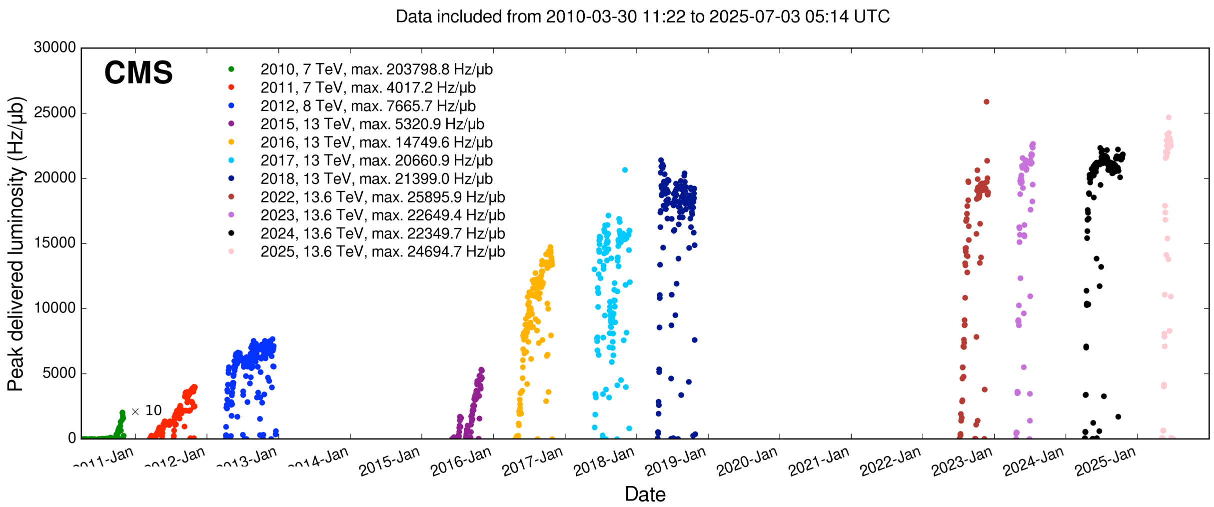
Movie for public with nice videos:
https://www.youtube.com/watch?v=328pw5Taeg0
https://www.youtube.com/watch?v=pQhbhpU9Wrg

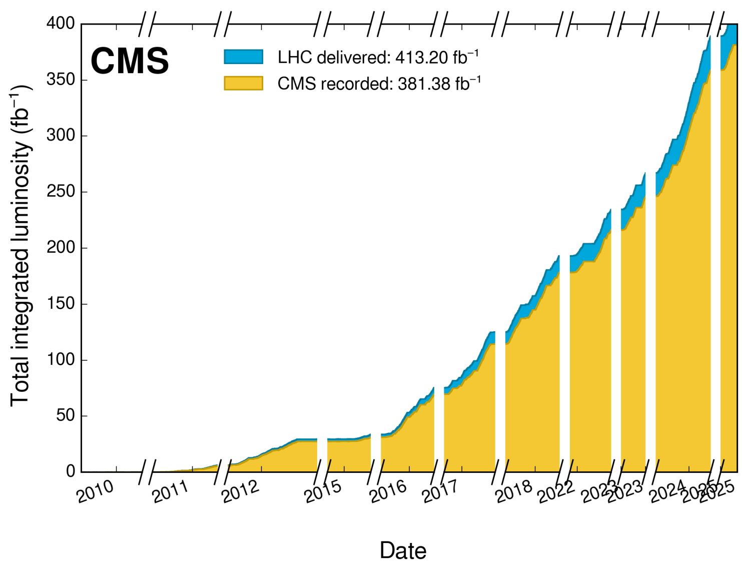
Normalized emittance: 2.2 um, beta*=30 cm, max designed L= 2.0 X 10^{34} cm^2 sec^{-1}

https://op-webtools.web.cern.ch/vistar/vistars.php?usr=LHC3

Luminosity at the LHC

>~ 2.0 X 10^{34} $cm^{-2}sec^{-1}$





remember:

$$L_{inst} = f\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

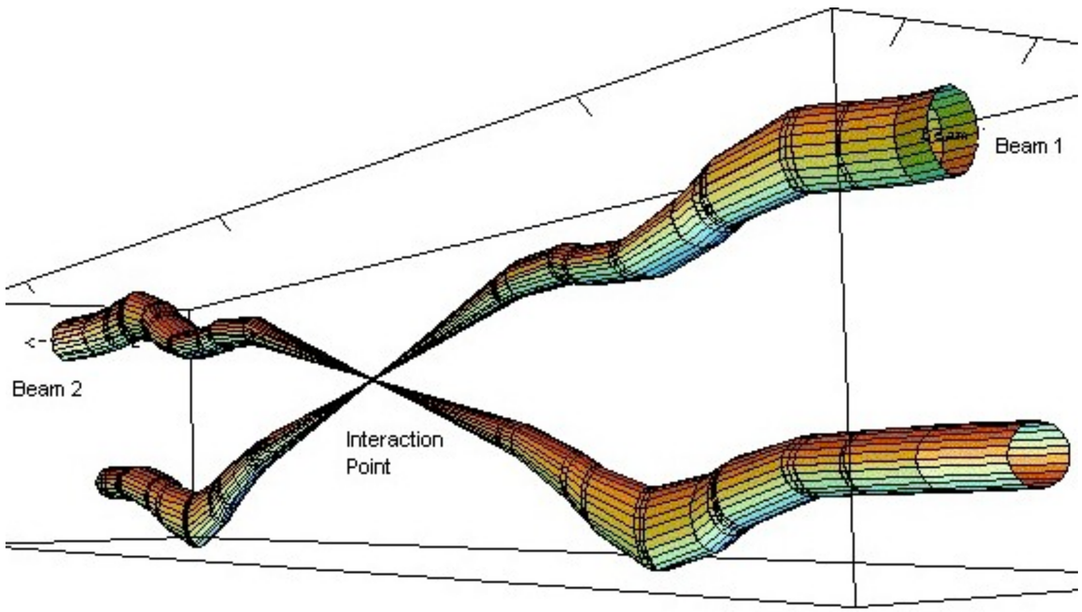
$$L_{int} = \int L_{inst}dt$$

$$N_{events} = \sigma \times L_{int}$$

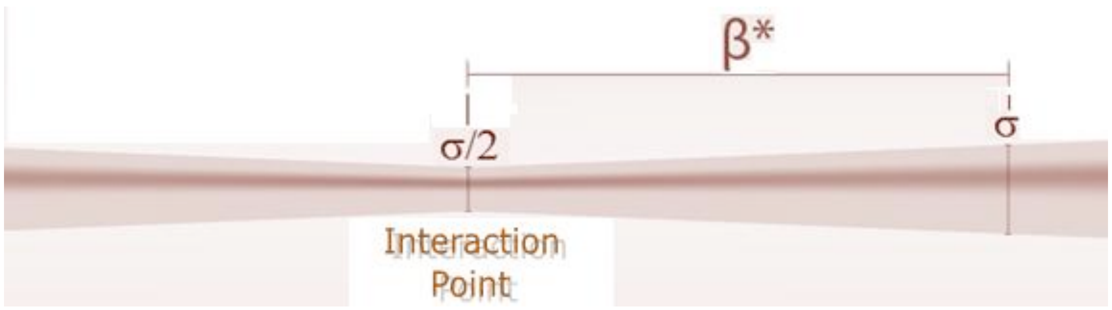
https://cmslumi.web.cern.ch/cmslumi/publicplots/int_lumi_animated_4x_pp_run2.gif

Beam emittance

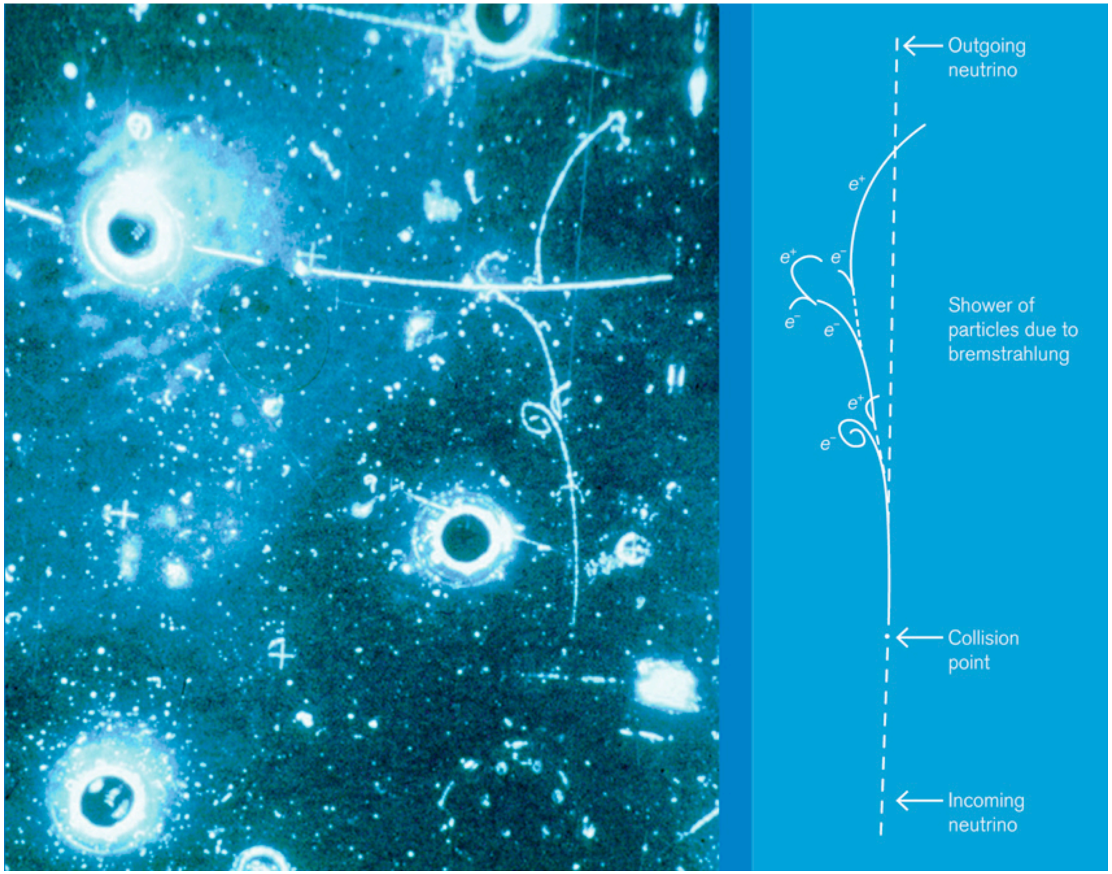
The beams are „squeezed" at the interaction point, in order to have narrow beams and high luminosity.



β^* is the distance from the focus point where the beam width is 2 times the one at the focus. Now ~ 30-40 cm at the LHC.



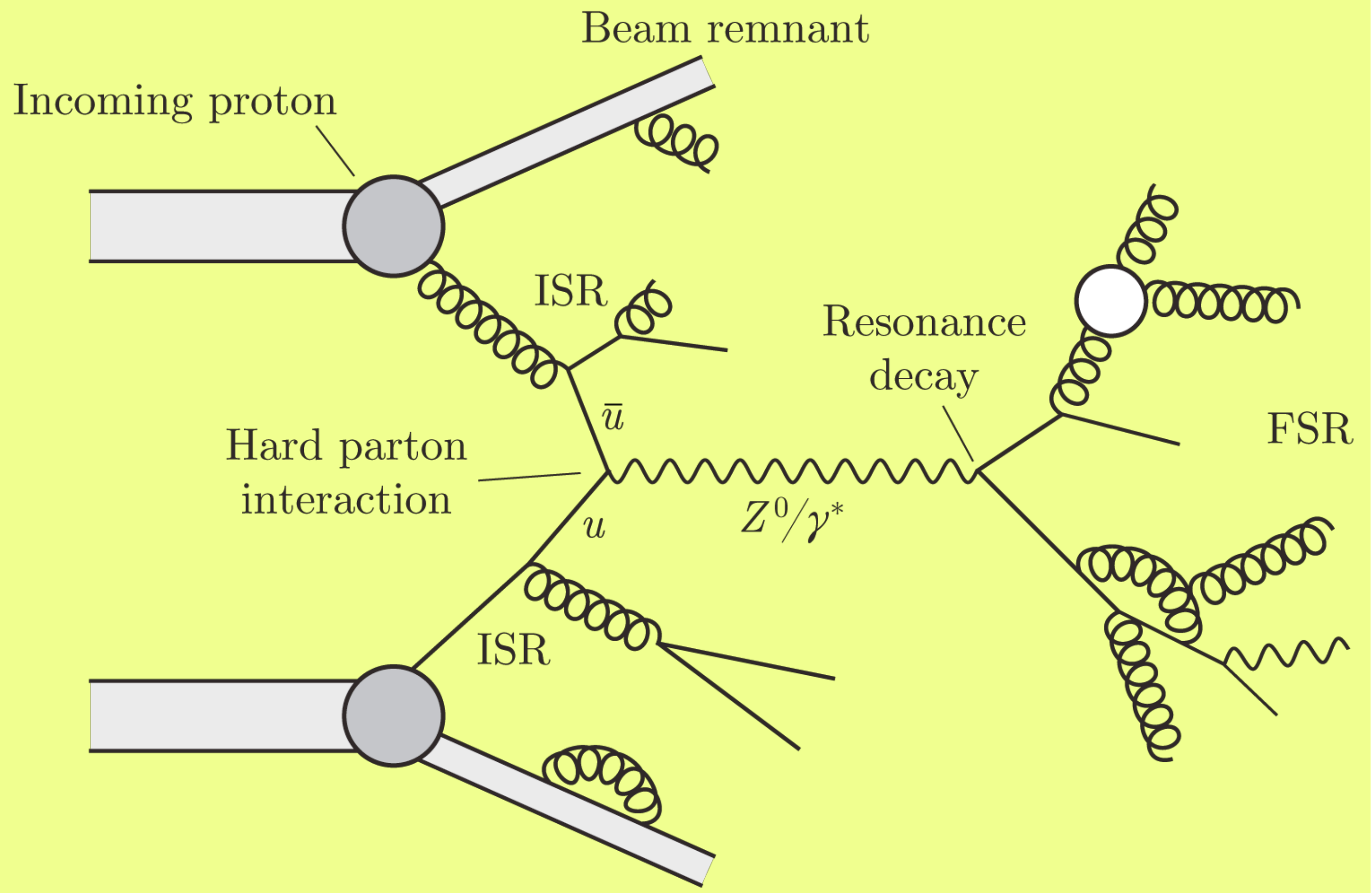
Particle Detectors



- When a high-energy particle or a photon passes through matter, it looses energy interacting with the material. This energy gives a signal in the medium, which is collected by an ADC or digitized etc. as a „number“ which gives an information of the E,p, charge or v of the particle.
- The segmentation of the detector allows to reconstruct the position (x,y,z, or R, ϕ, ϑ)
- Particle ID is possible through combination of different layers or special detectors
- At the end we want to measure 4-momenta for candidate particles

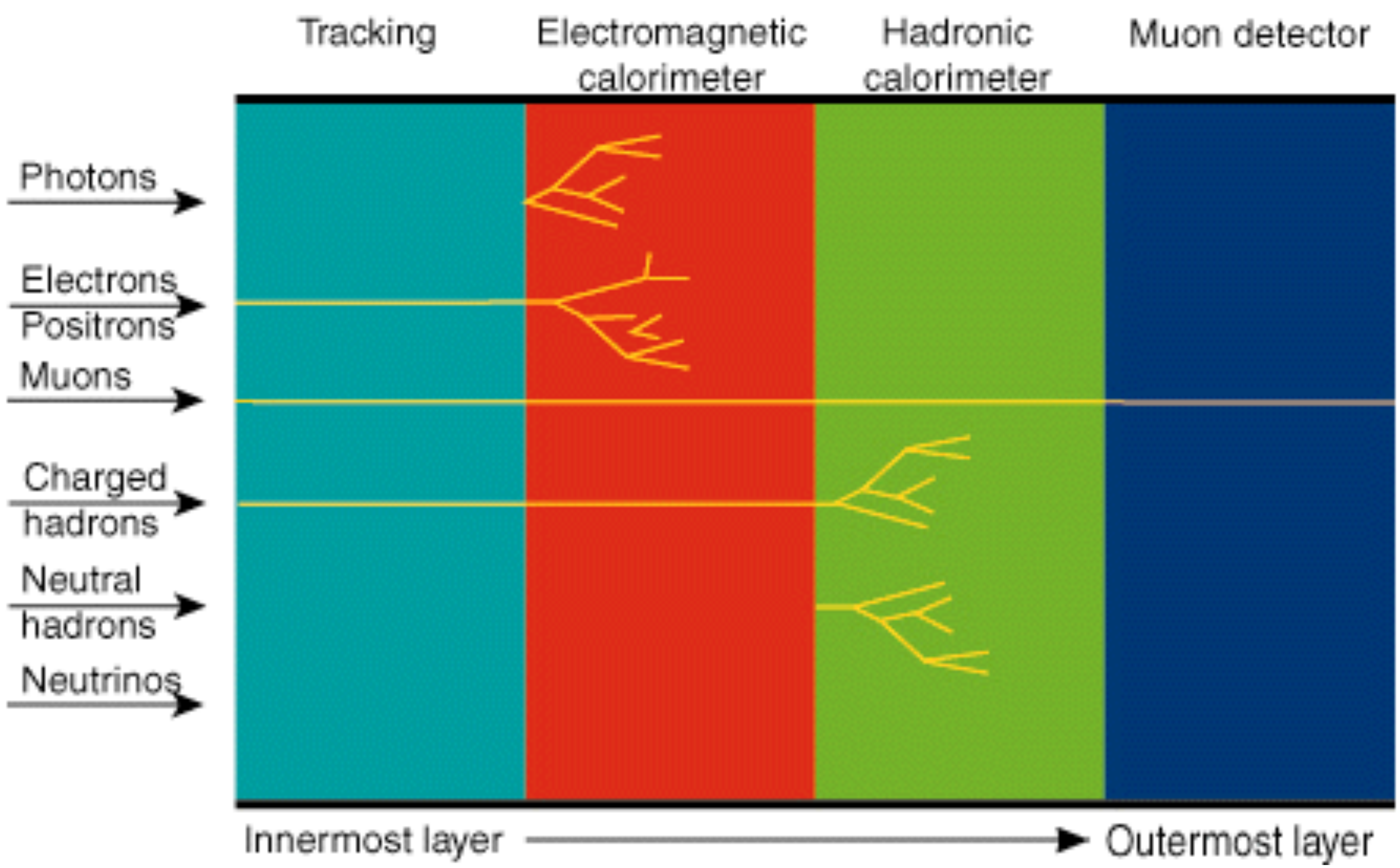
Font for this part: PdG, Bettini, Wermes,..

Example: a pp interaction

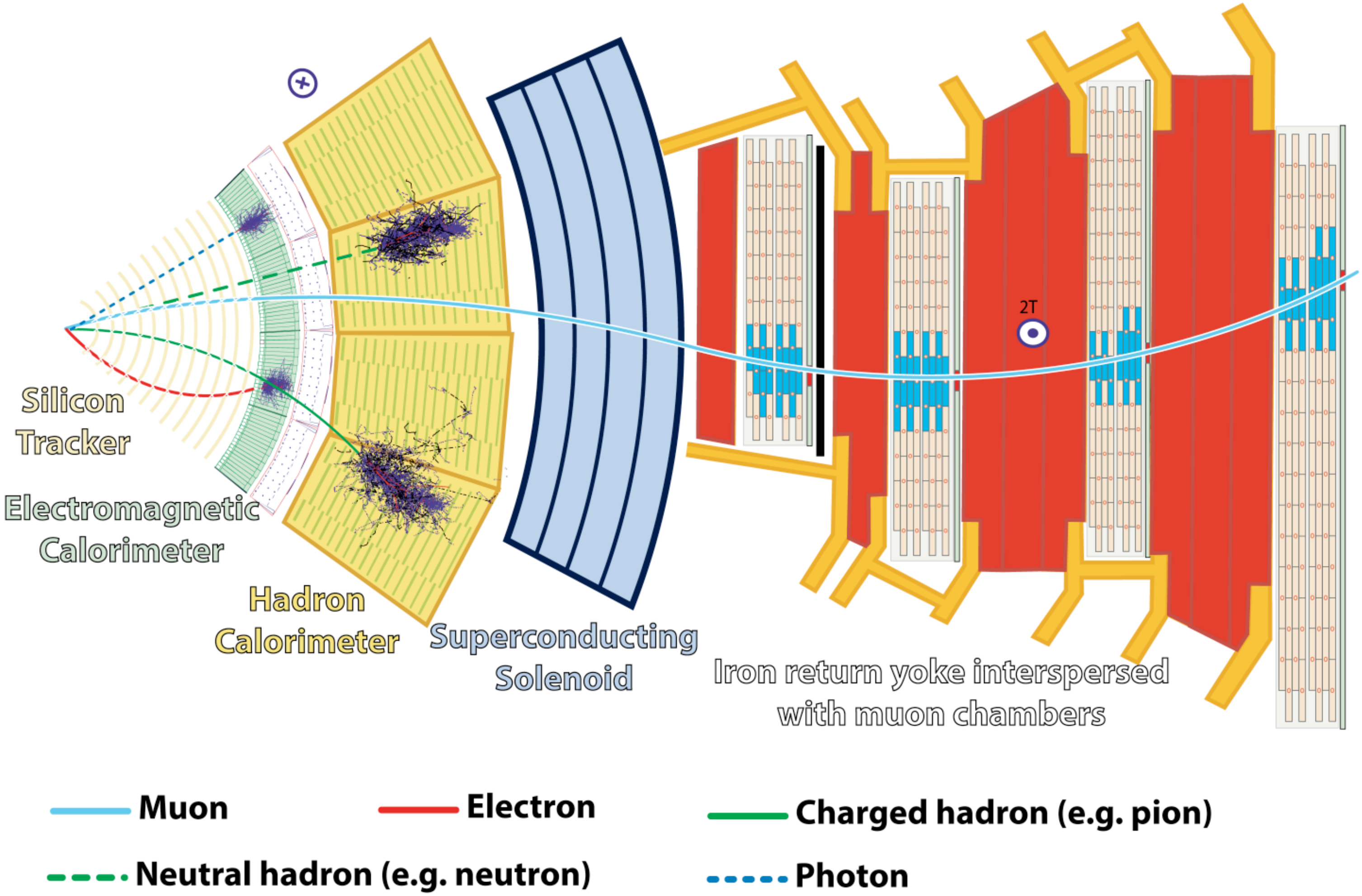


Rate of collisions at the LHC: 40 MHz (every 25 nsec)
Rate of events written to tape~ 1K Hz; event size ~ few Mb

Layers in a detector

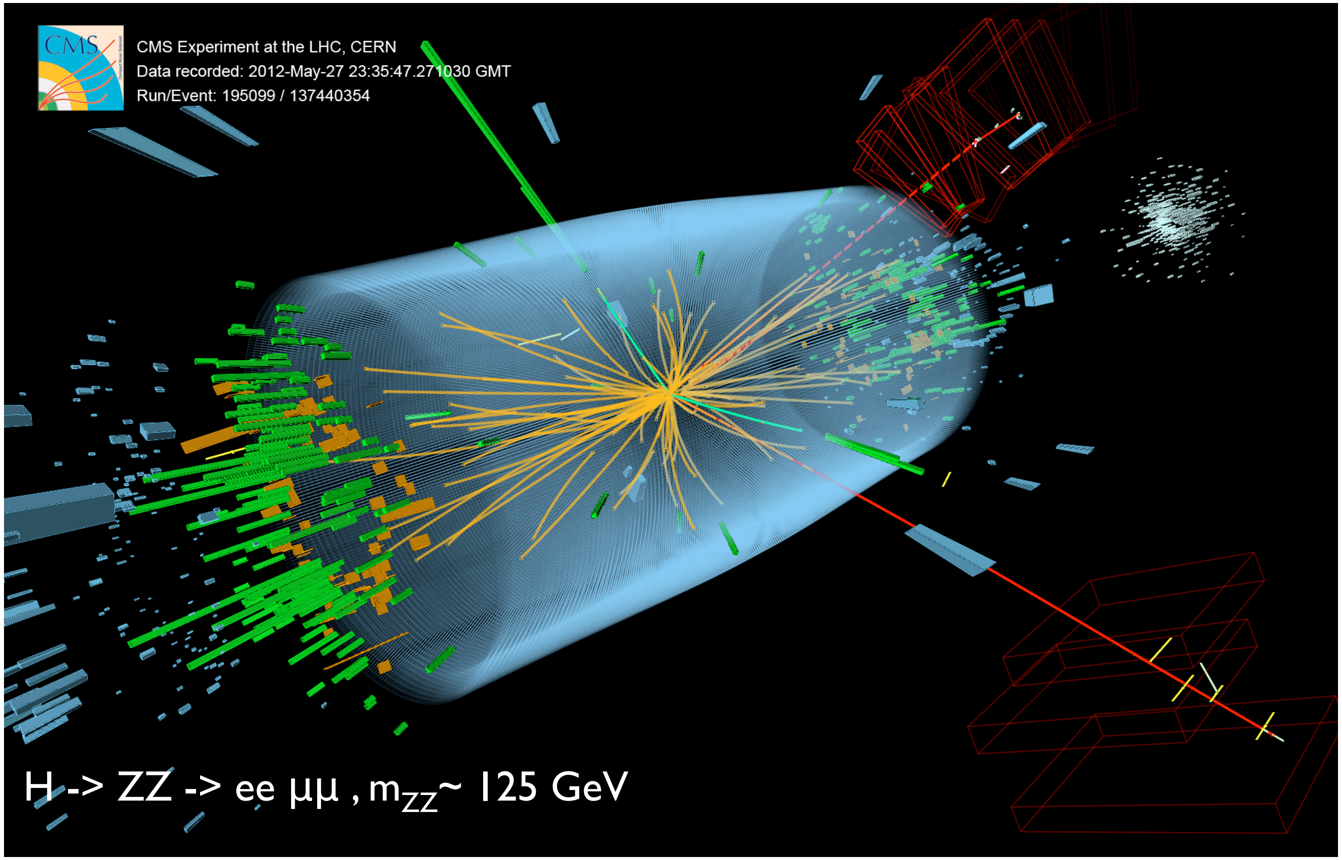


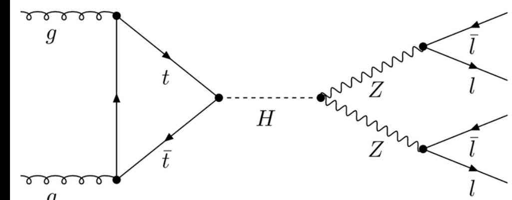
Example: the CMS detector



How do I reconstruct neutrinos?

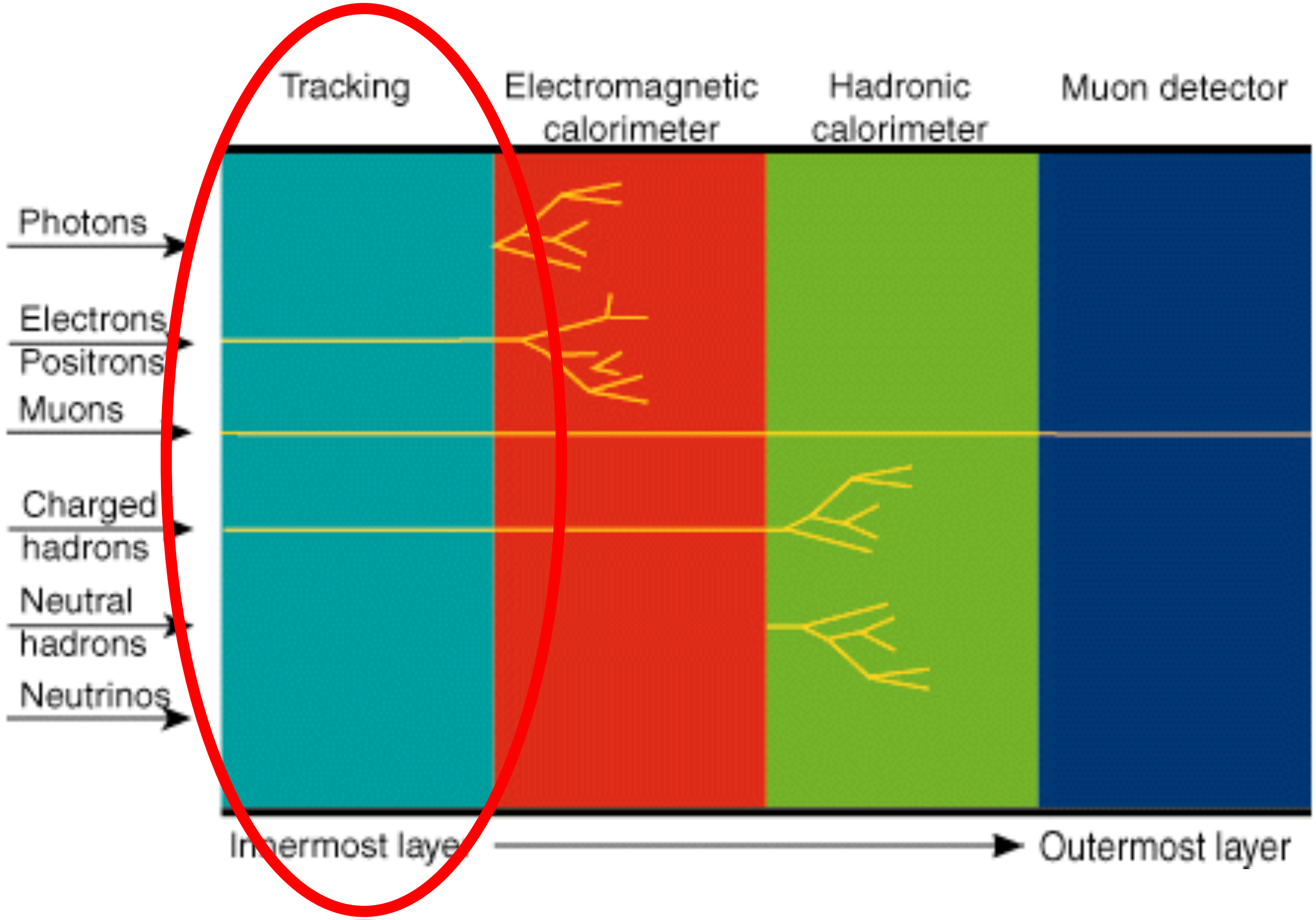
Example: an event in CMS





Is this a Higgs candidate?
How do I claim the discovery of a new particle?

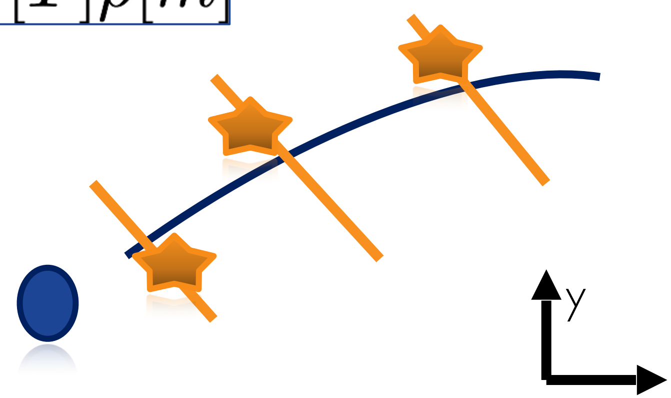
Tracking layers



Tracking

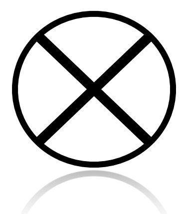
Charged particles interact with the material in the Tracker layers (see next slide) giving hits, and the trajectory can be reconstructed.
The curvature in the transverse plane gives the momentum of the particle and its charge.

$$\boxed{p[GeV] = 0.3B[T]\rho[m]}$$



Interaction point

Track reconstruction for a charged particle from the hits in the individual layers, as seen in the transverse plane to the beam

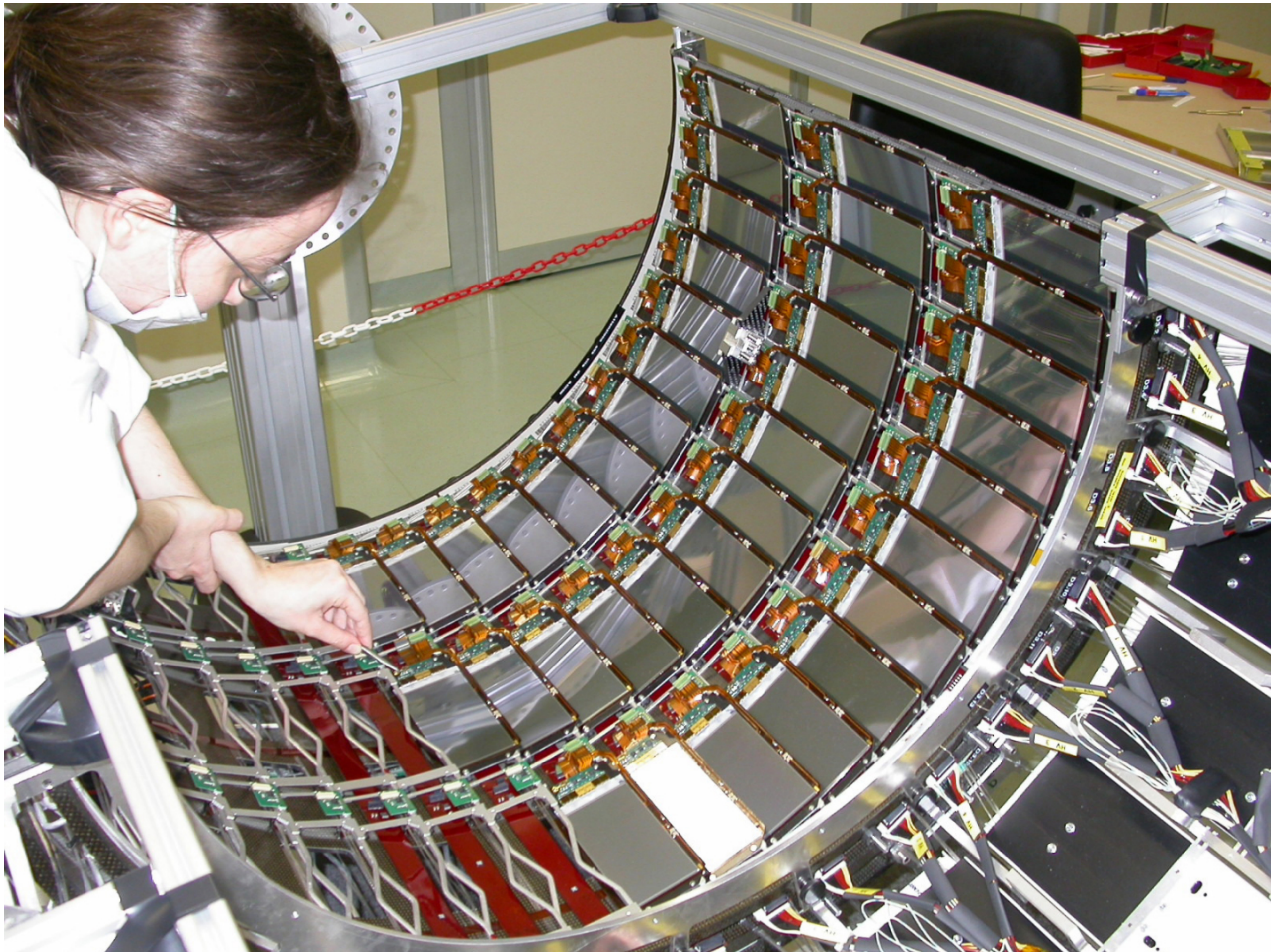


Tracker immersed in a strong magnetic field 3.8 T at CMS, along z

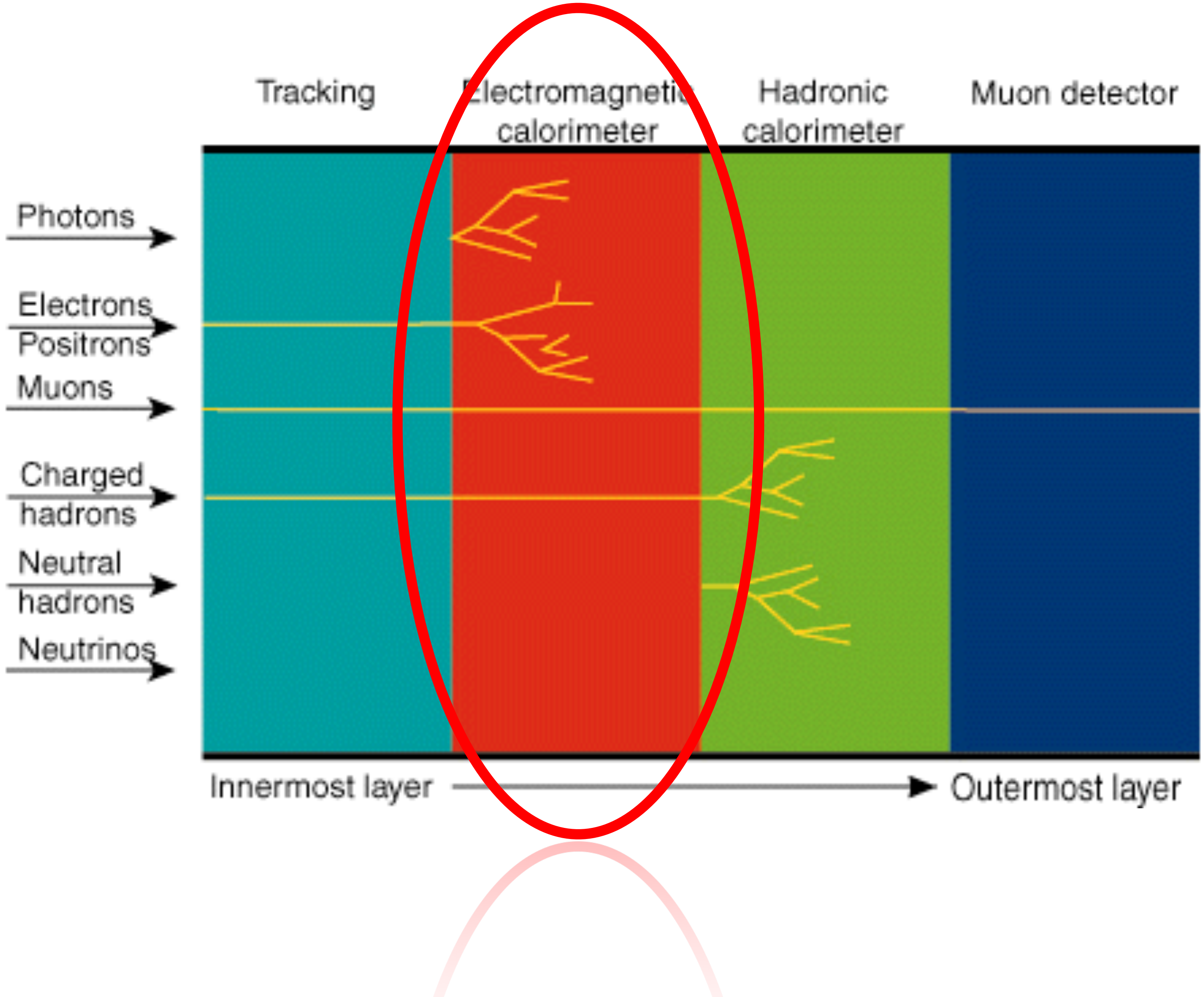
Particle which do not interact in the Tracker are neutral particles.

Tracking detectors

Nowadays most Tracker devices (at least in pp collisions) are made of semiconductor silicon sensors, thanks to their radiation hardness and granularity.

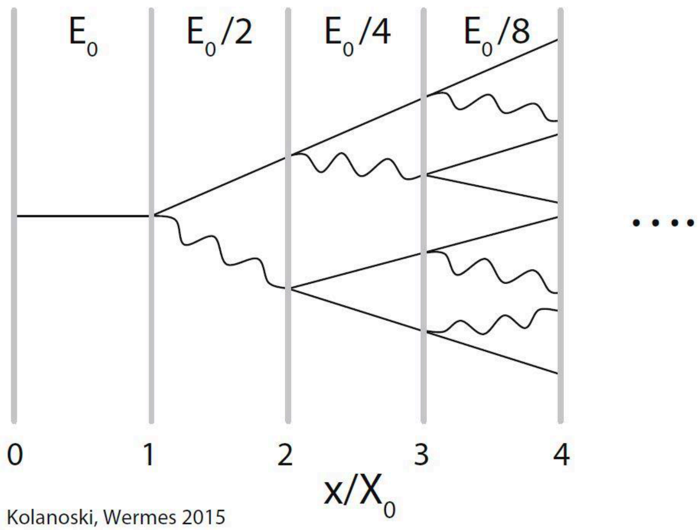


Layers in a detector



Electron/Photon shower

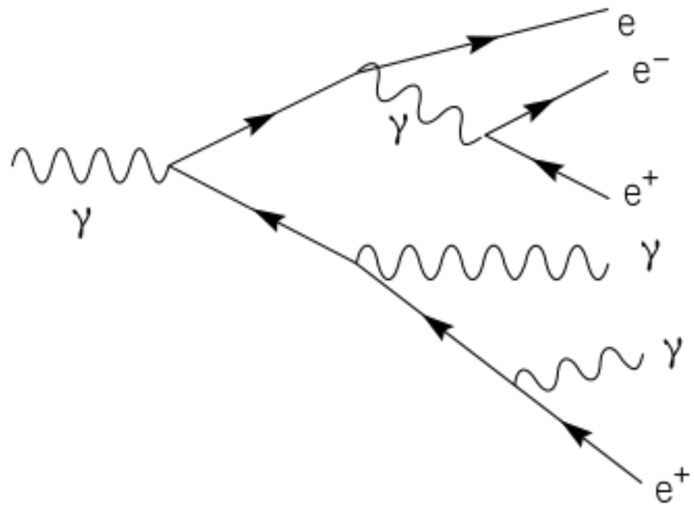
Electron shower



$$-dE/E = dx/X_0$$

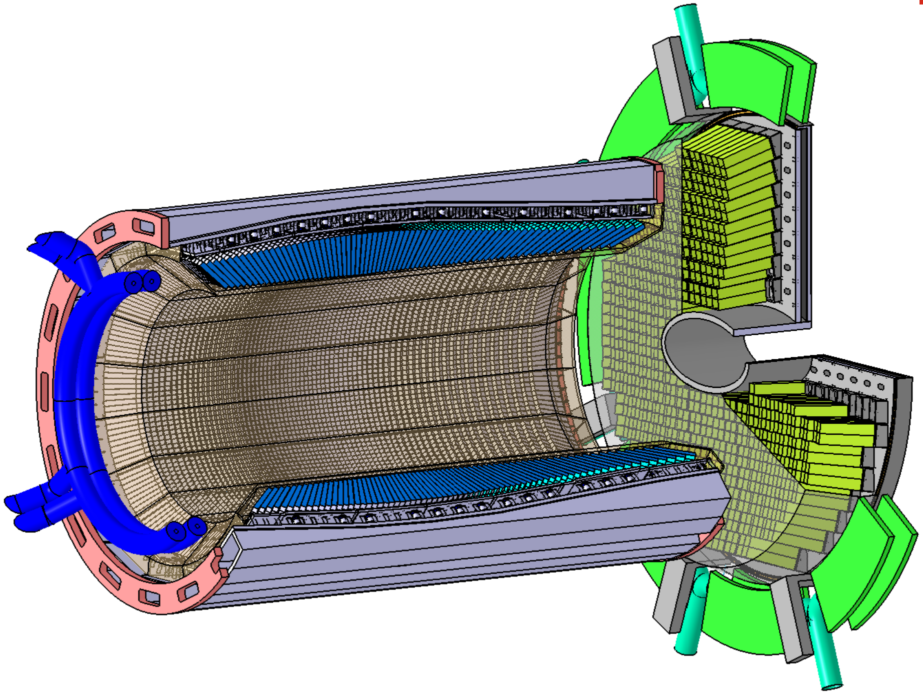
- The quantity X_0 is called radiation length and after 1 X_0 the impinging energy is reduced by 1/e. After ~ 20-22 X_0 basically all the electron/photon energy is absorbed.

Photon shower

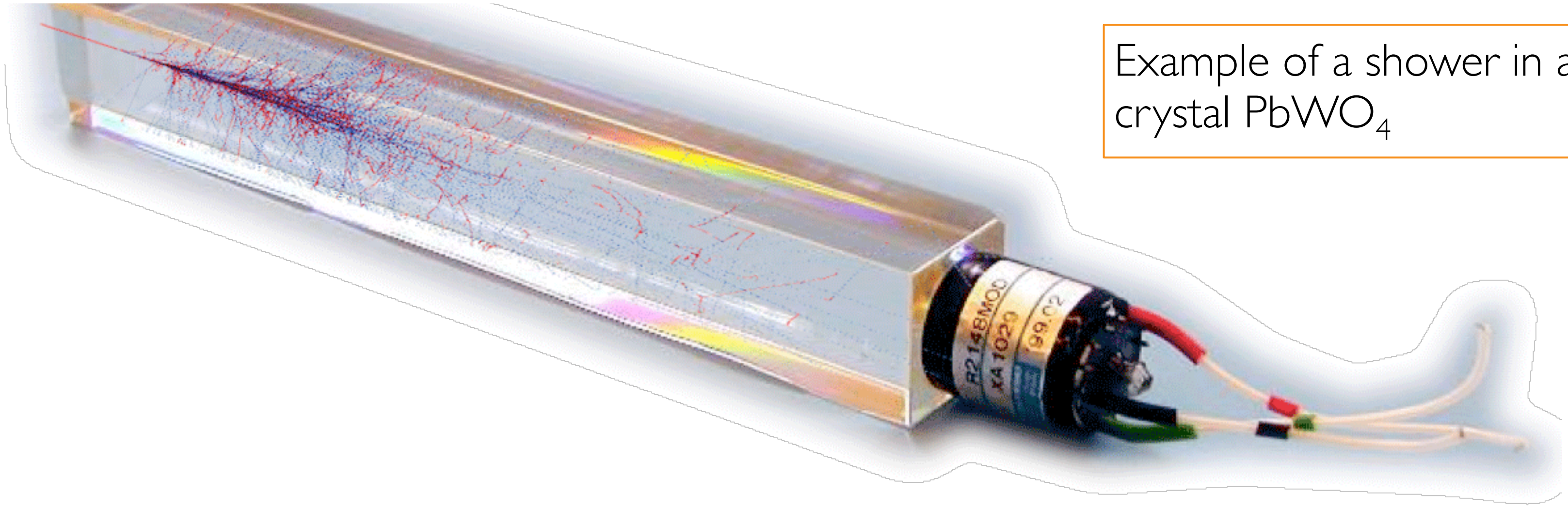


Photon are absorbed in a similar way with an absorbtion length~ 9/7 X_0

Example of shower in CMS

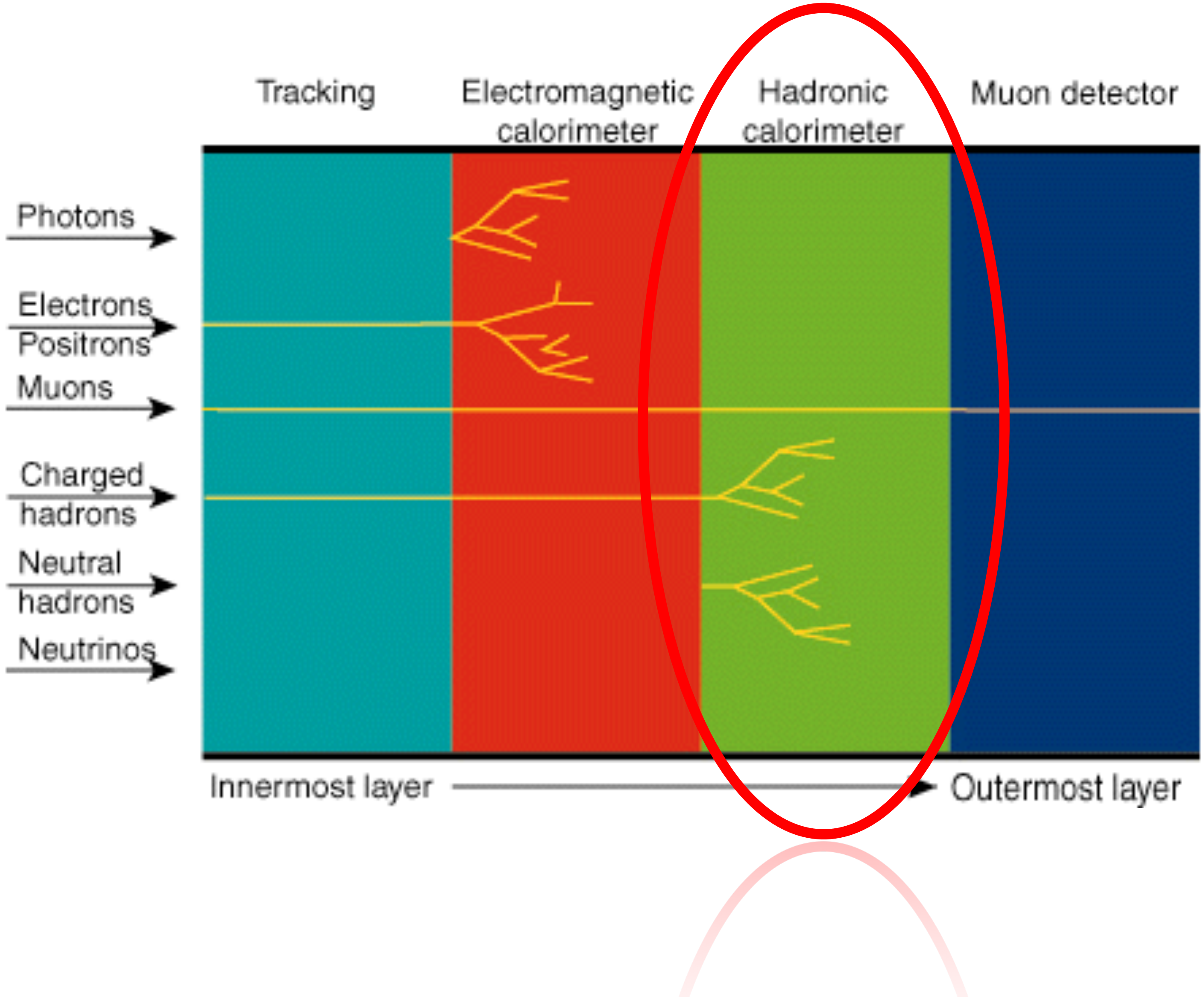


- The CMS Ecal is a so- called homogenous type of calorimeter, i.e. the absorption medium is also the detection medium, in this case scintillating crystals.
- It has ~24 X_0 in order to contain the shower
- The shower transversal width, called the Moliere radius, is typically narrow (~ 2cm at CMS)



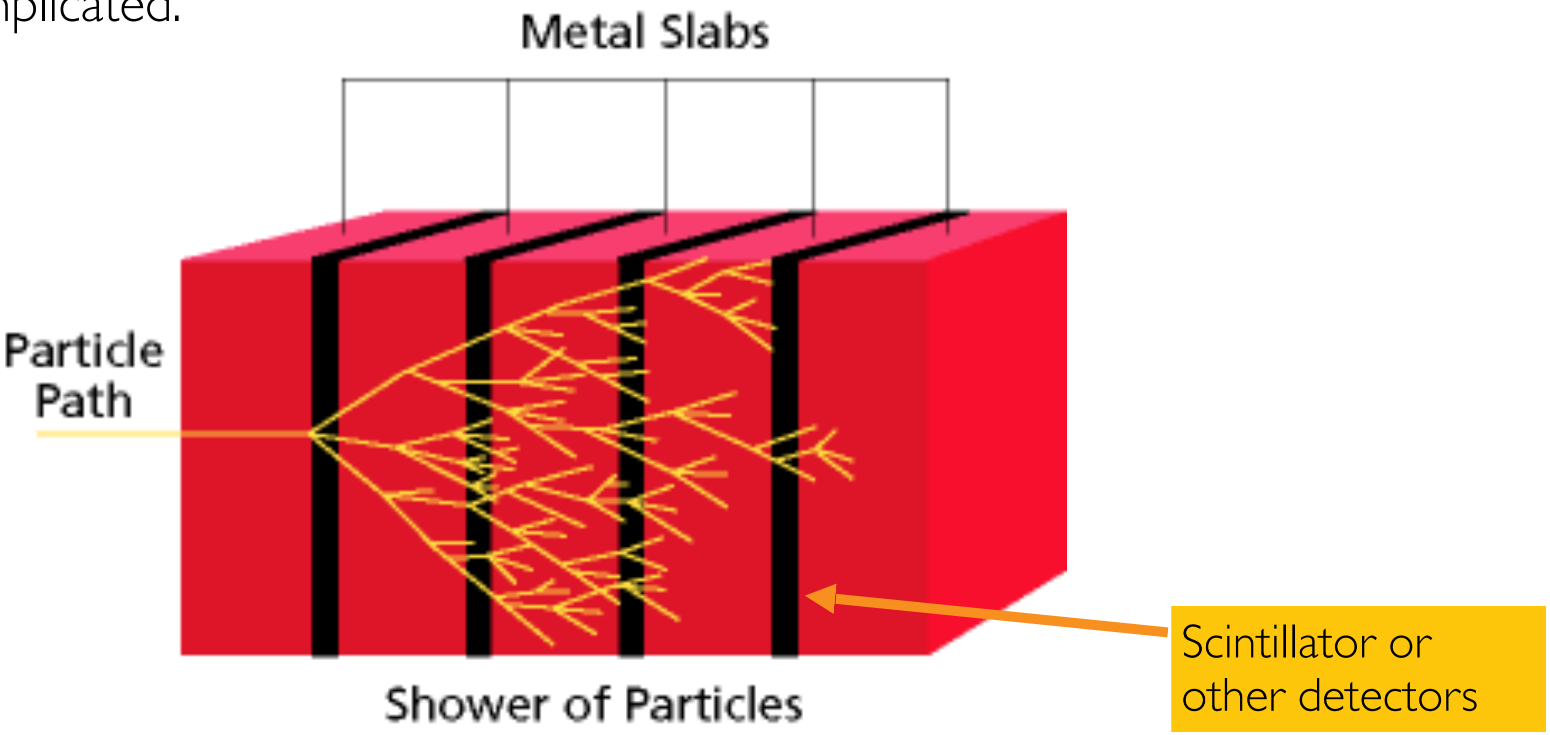
Example of a shower in a CMS crystal $PbWO_4$

Layers in a detector



Hadronic calorimeters

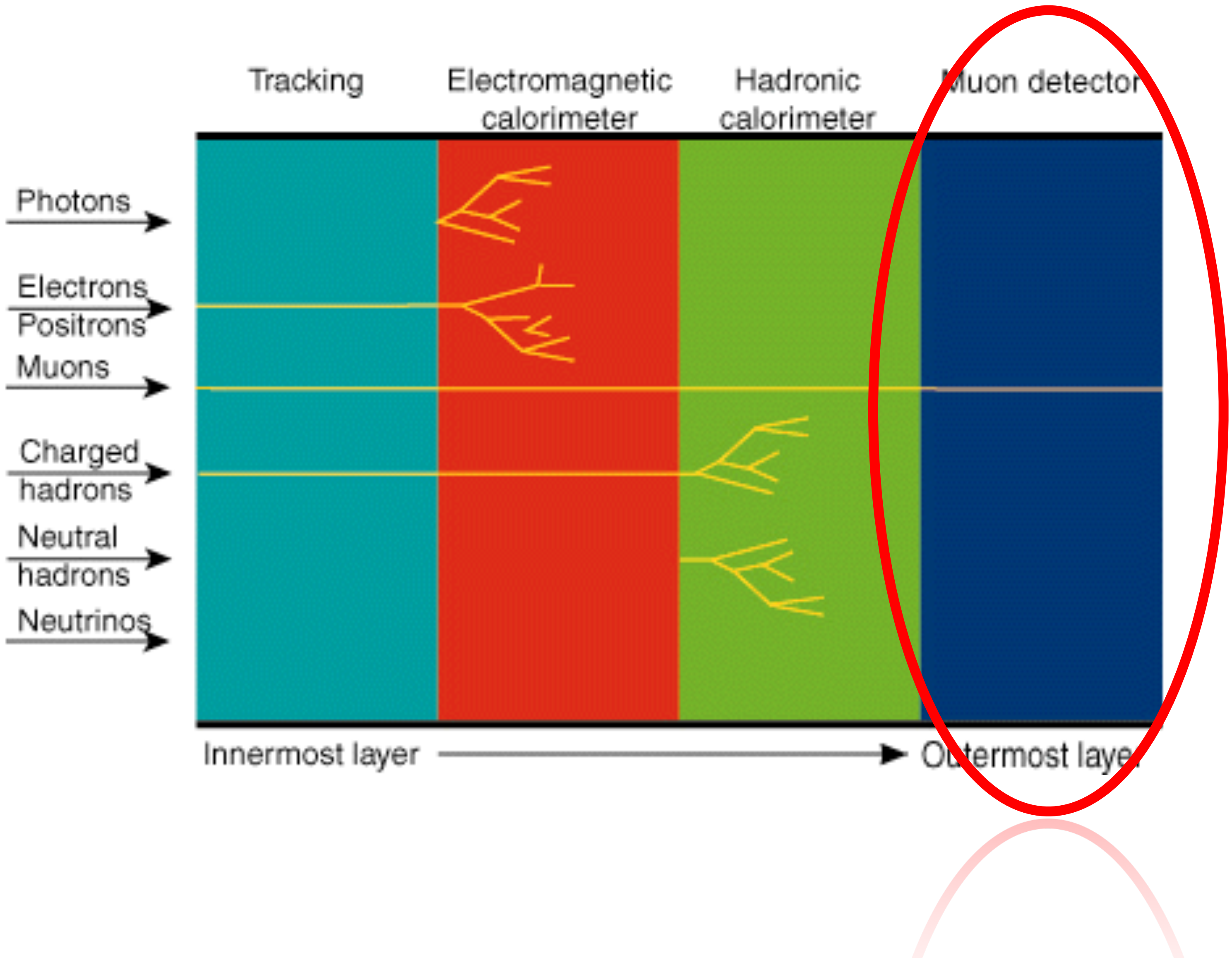
High-energy hadrons interact with the nuclei and the shower here is longer, wider and more complicated.



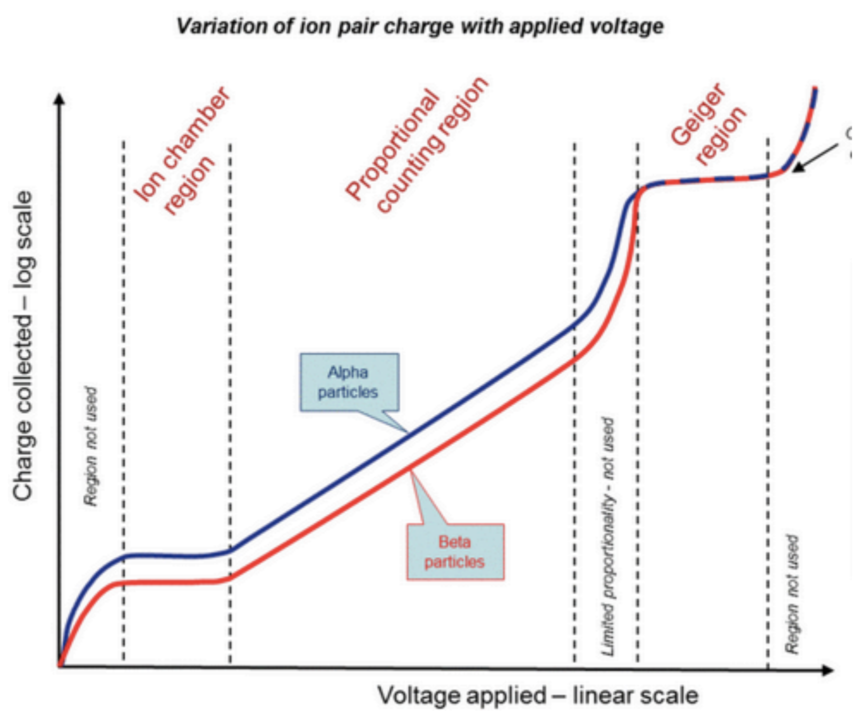
- Interaction length λ: Distance over which a neutron beam is attenuated by 1/e
- Usual calorimeters are ~5-10 λ in depth and are „sampling“ calorimeters, with absorber layers alternated to detection layers, i.e. scintillators, Si layers, etc., in order to absorb the whole shower

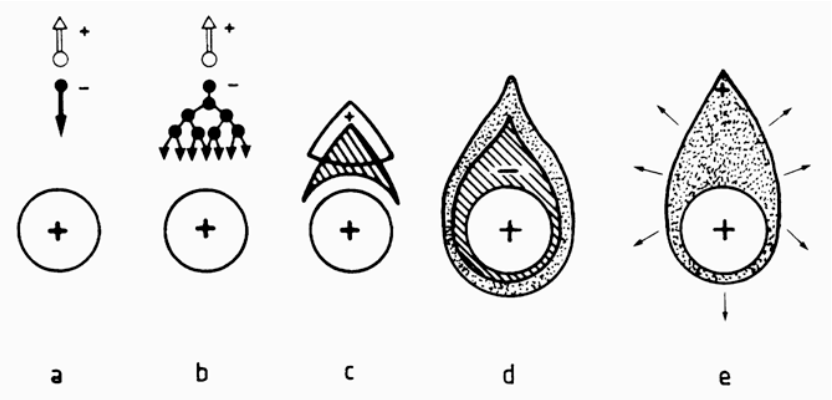
Font: Quantum Diaries

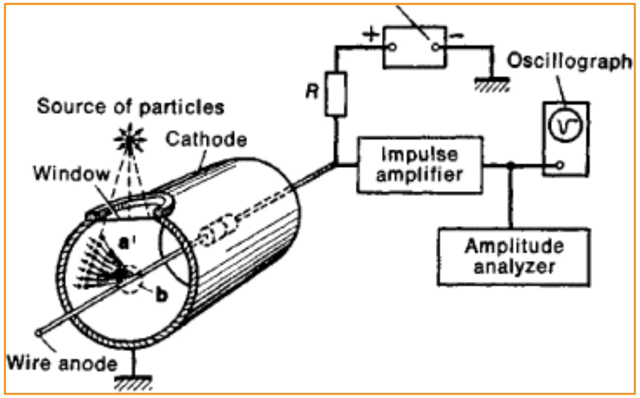
Layers in a detector



Ionization chambers





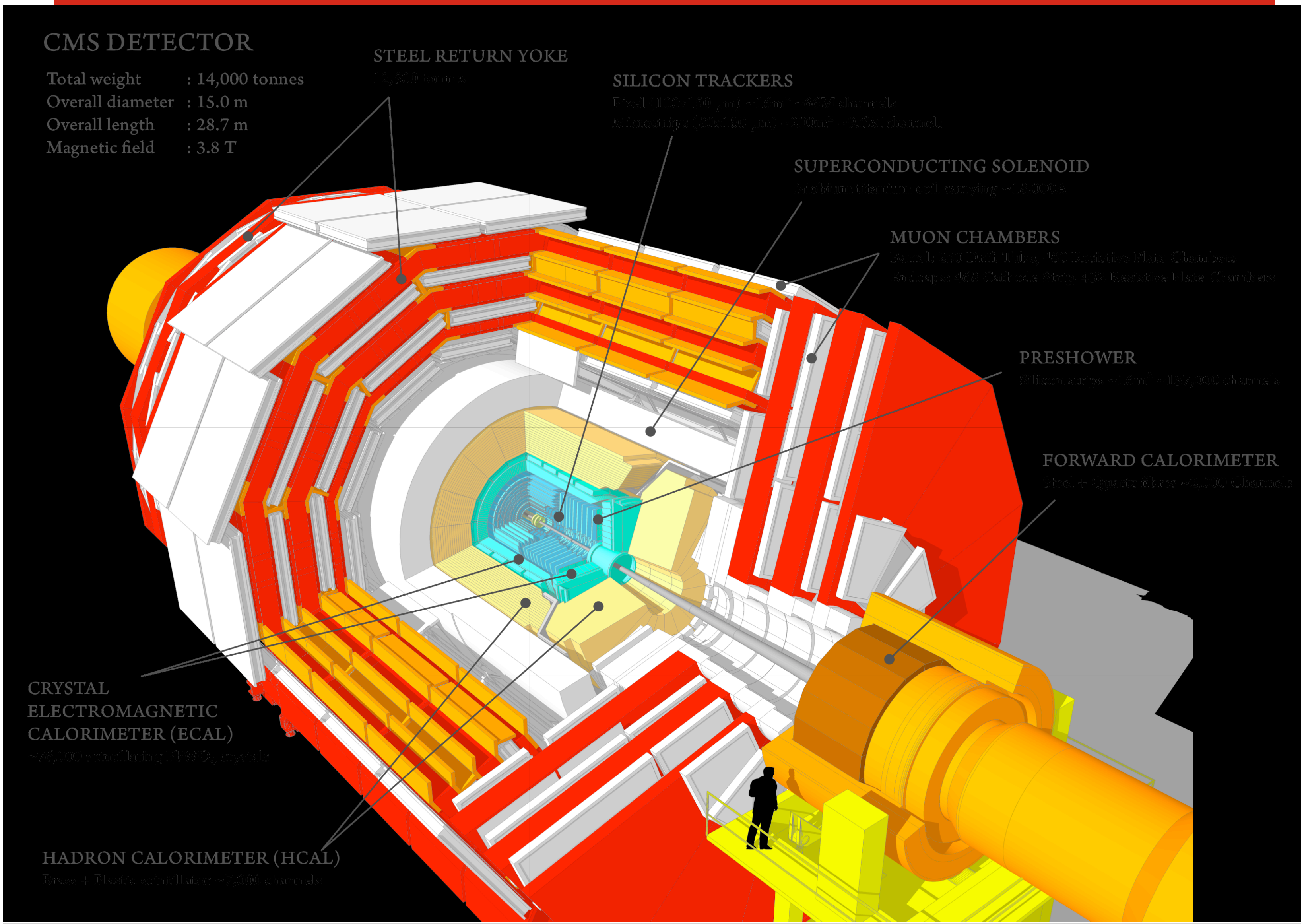


Electrons produced in the ionization drift to the anode wire and because of the high voltage applied there is an amplification of the primary ionization. For a certain voltage this amplification is proportional, in Geiger mode there is a breakdown.

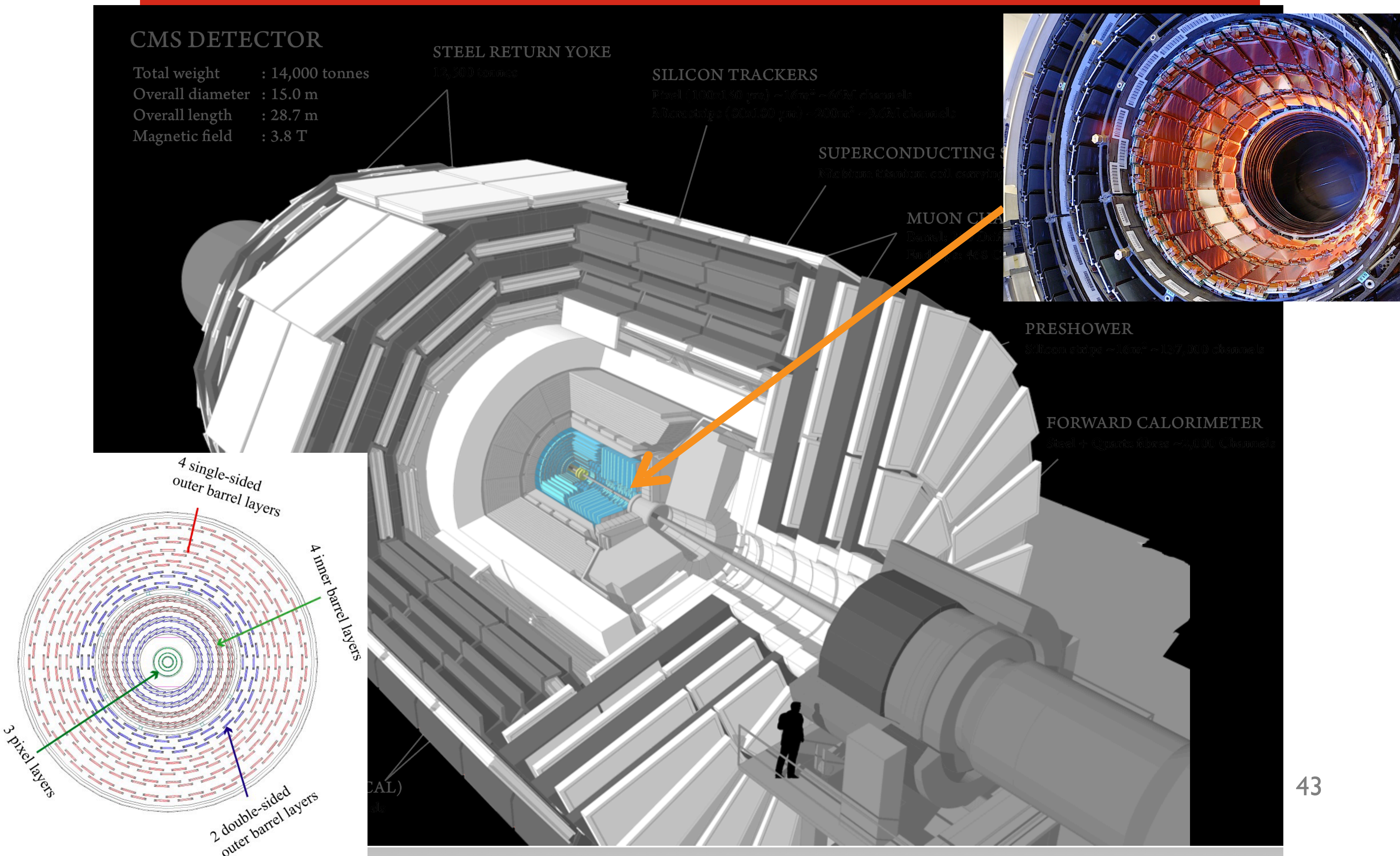
Font: Wikipedia, Charpak (Nobel 1992), Soviet Encyclopedia

Have you ever used a Geiger?

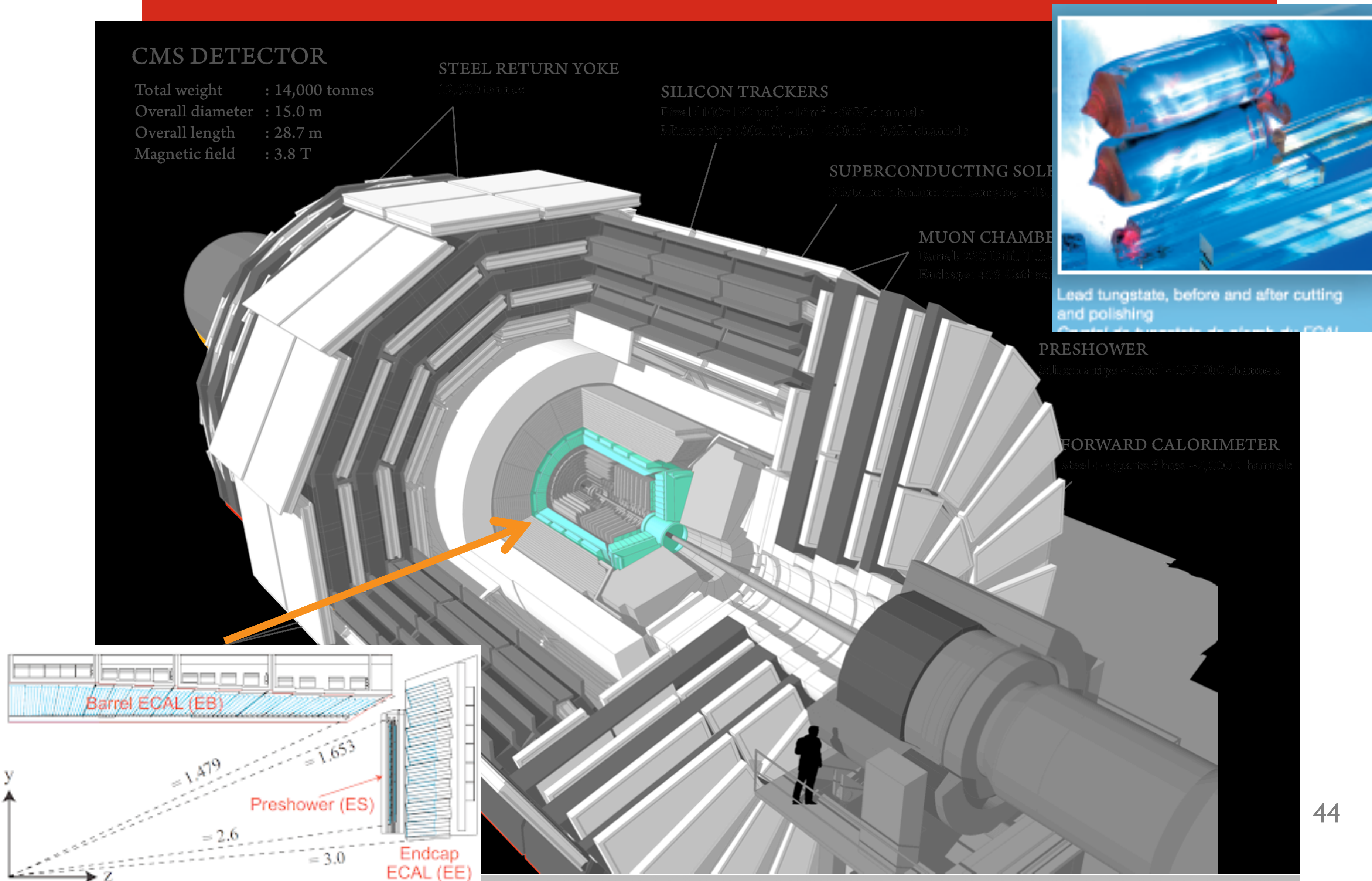
Summary: the CMS detector



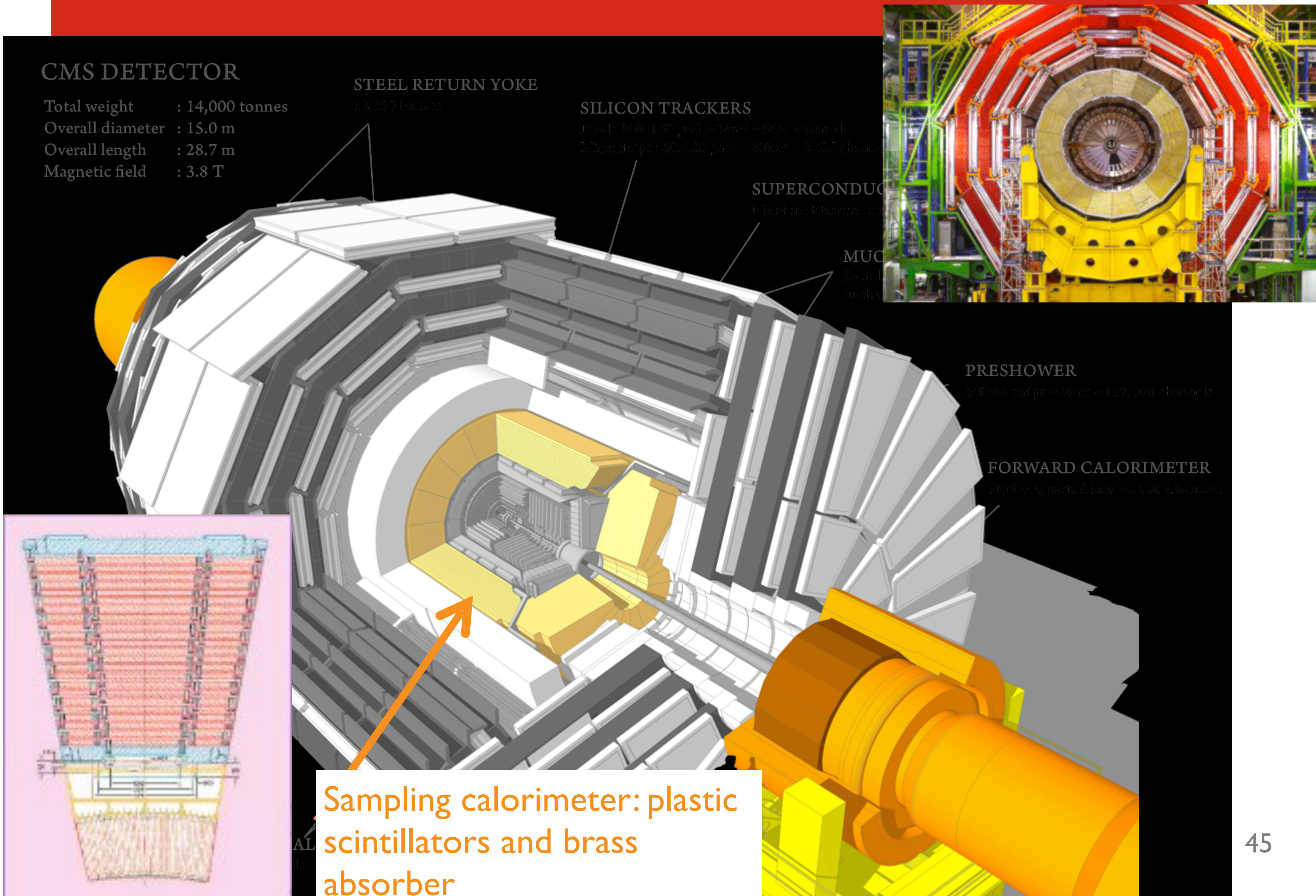
The CMS detector



The CMS detector

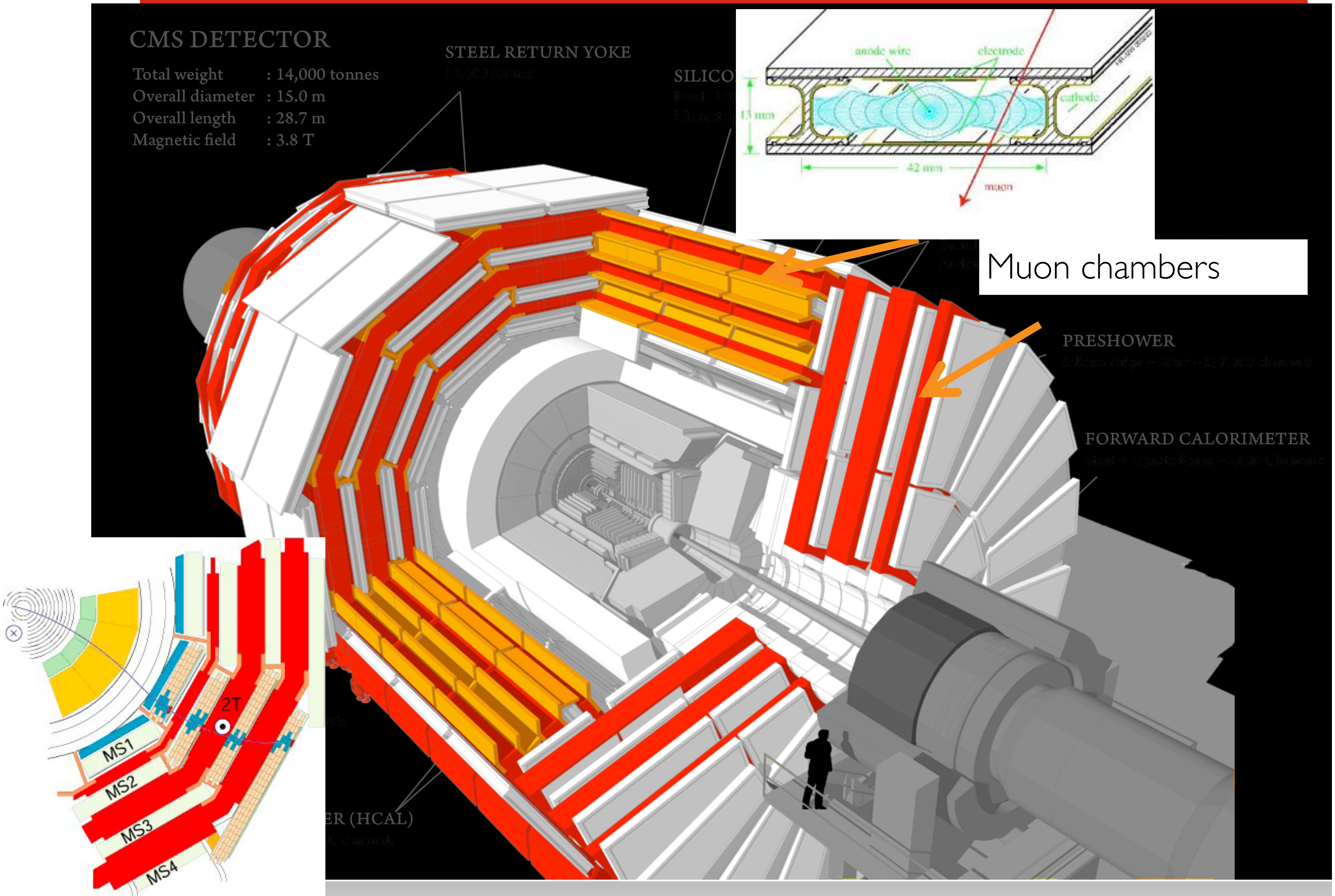


The CMS detector



Sampling calorimeter: plastic scintillators and brass absorber

The CMS detector

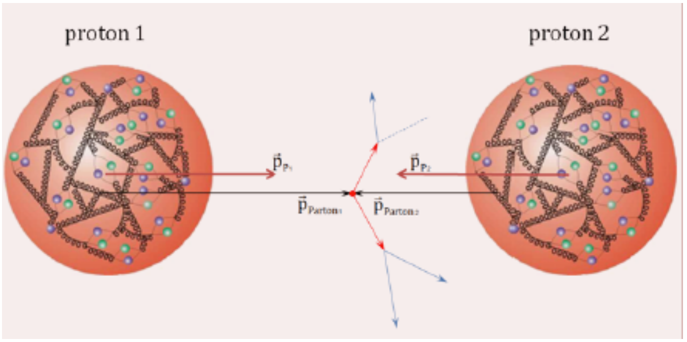


Backup

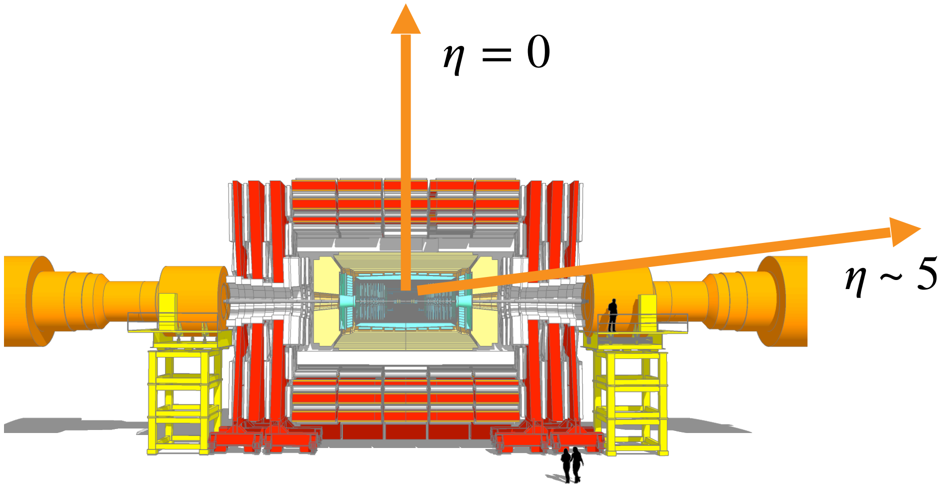
Coordinates

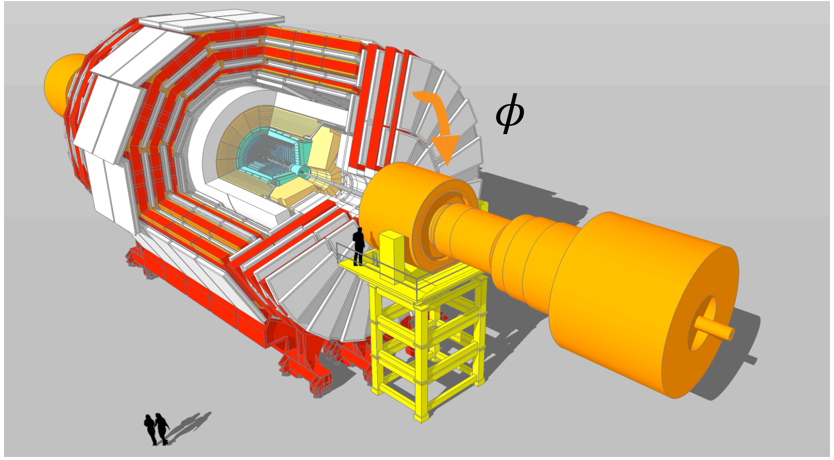
At hadron colliders we tend to use other coordinates, due to the boost along the z-direction

$$\boxed{(E, p_x, p_y, p_z) \to (E, p_\mathrm{T}, \eta, \phi)}$$



z coordinate is by convention along the beam direction





Coordinates

The following quantities are used very often:

- The transverse momentum

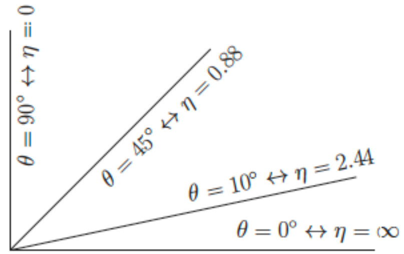
$$\boxed{p_T = \sqrt{p_x^2 + p_y^2}}$$

- The rapidity. It has the properties that differences in rapidities are invariant under a Lorentz boost in the z-direction (-> Exercise)

$$\boxed{y = \frac{1}{2}\log\frac{E + p_z}{E - p_z}}$$

- For the ultra-relativistic limit in which E~p, this simplifies in the pseudo-rapidity, which is used instead of the polar angle

$$\boxed{\eta = -\log\left(\tan\frac{\theta}{2}\right)}$$



Example: collider

$(E_1, 0, 0, p_z^1)$ $\qquad$ $(E_2, 0, 0, p_z^2)$ $\qquad$ z

Electron-positron colliding with the same energy, i.e. 45 GeV like at LEP

$$s = (p_1 + p_2)^2 = p_1^2 + p_2^2 + 2(p_1 \cdot p_2)$$
$$s = m_e^2 + m_e^2 + 2(E_1 \cdot E_2 - \vec{p_1} \cdot \vec{p_2})$$
$$s \simeq 2(E_1 \cdot E_2 - (E_1 \cdot (-E_2)) \simeq 4E_1 \cdot E_2$$

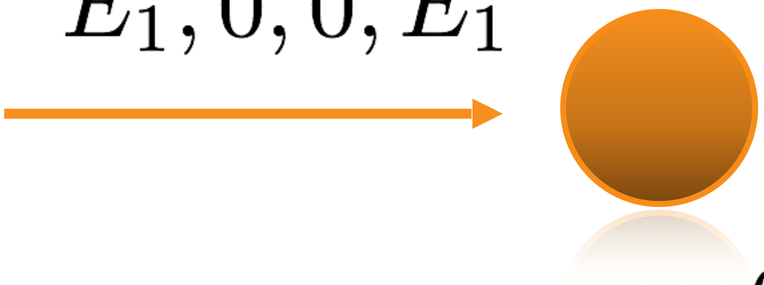
Where I have neglected the electron masses and where p_2 has the component Z in the direction –z ~ $-E_2$.

$$\boxed{\sqrt{s} = 2 \cdot E_{beam}}$$

For equal beam energies:
The c.m. energy of a collider grows linearly with the beam energy

Example: fixed target

$$E_1, 0, 0, E_1$$



$$m_2, 0, 0, 0$$

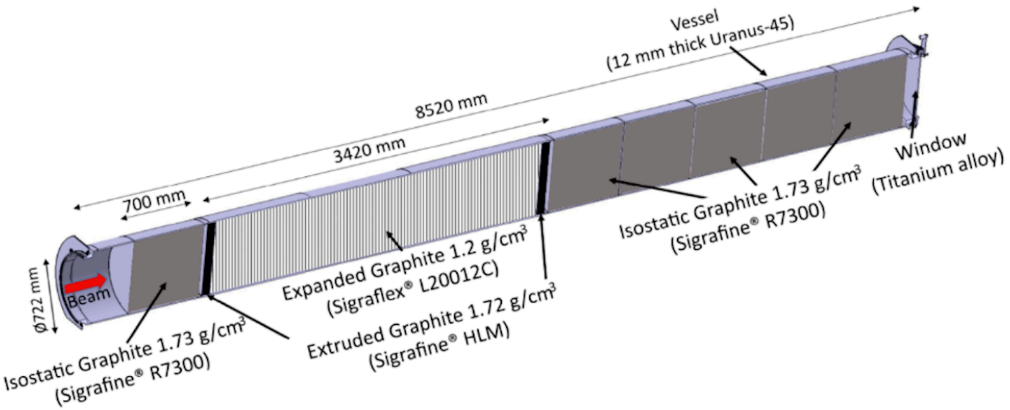
$$s = (p_1 + p_2)^2 = m_1^2 + m_2^2 + 2E_1 \cdot m_2$$
$$\sqrt{s} = \sqrt{2E_1 \cdot m_2}$$

In fixed target the c.m. energy increases only with the sqrt of the beam energy. To double the c.m. energy, I need 4X beam energy, not very efficient.

Is there an advantage anyway? Why do I want higher c.m. energy usually?

Backup: LHC beam dump

What are the current LHC beam dumps made of?



(Image: CERN)

The LHC's external beam dumps comprise a graphite dump measuring 8.5 metres in length and 722 mm in diameter, contained in a 12-mm-thick 318LN stainless-steel-alloy tube. In total, each dump weighs 6.2 tonnes.

Each beam dump is made of several graphite blocks of varying density: high-density isostatic graphite; a stack of 1700 2-mm-thick low-density expanded graphite discs; and two extruded graphite discs (the black bands), which hold the low-density graphite stack together.

Font: CERN Bulletin