Particle Physics

Columbia Science Honors Program

Week 10: LHC and Experiments

April 8th, 2017

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Course Policies

- Attendance:
  - Up to four excused absences

    (two with notes from parent/guardian)
  - Send notifications of all absences to shpattendance@columbia.edu
- Valid excuses:
  - Illness, family emergency, tests or athletic/academic competitions, mass transit breakdowns
- Invalid excuses:
  - Sleeping in, missing the train
- I will take attendance during class.
- Please no cell phones.
- Ask questions :)

Lecture Materials

- https://twiki.nevis.columbia.edu/twiki/bin/view/Main/ScienceHonorsProgram

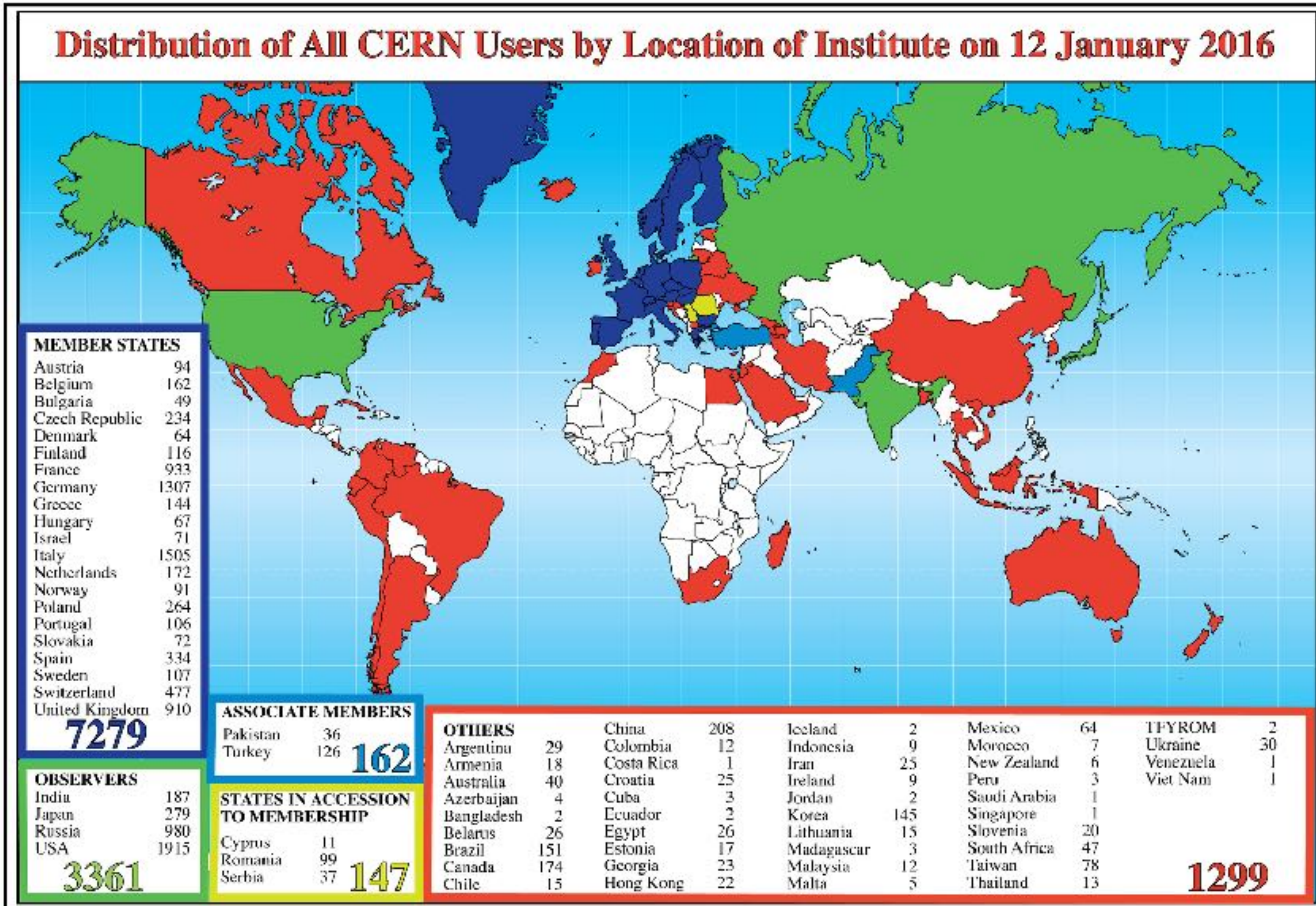
Schedule

1. ~~Introduction~~
2. ~~History of Particle Physics~~
3. ~~Special Relativity~~
4. ~~Quantum Mechanics~~
5. ~~Experimental Methods~~
6. ~~The Standard Model - Overview~~
7. ~~The Standard Model - Limitations~~
8. ~~Neutrino Theory~~
9. ~~Neutrino Experiment~~
10. LHC and Experiments
11. The Higgs Boson and Beyond
12. Particle Cosmology

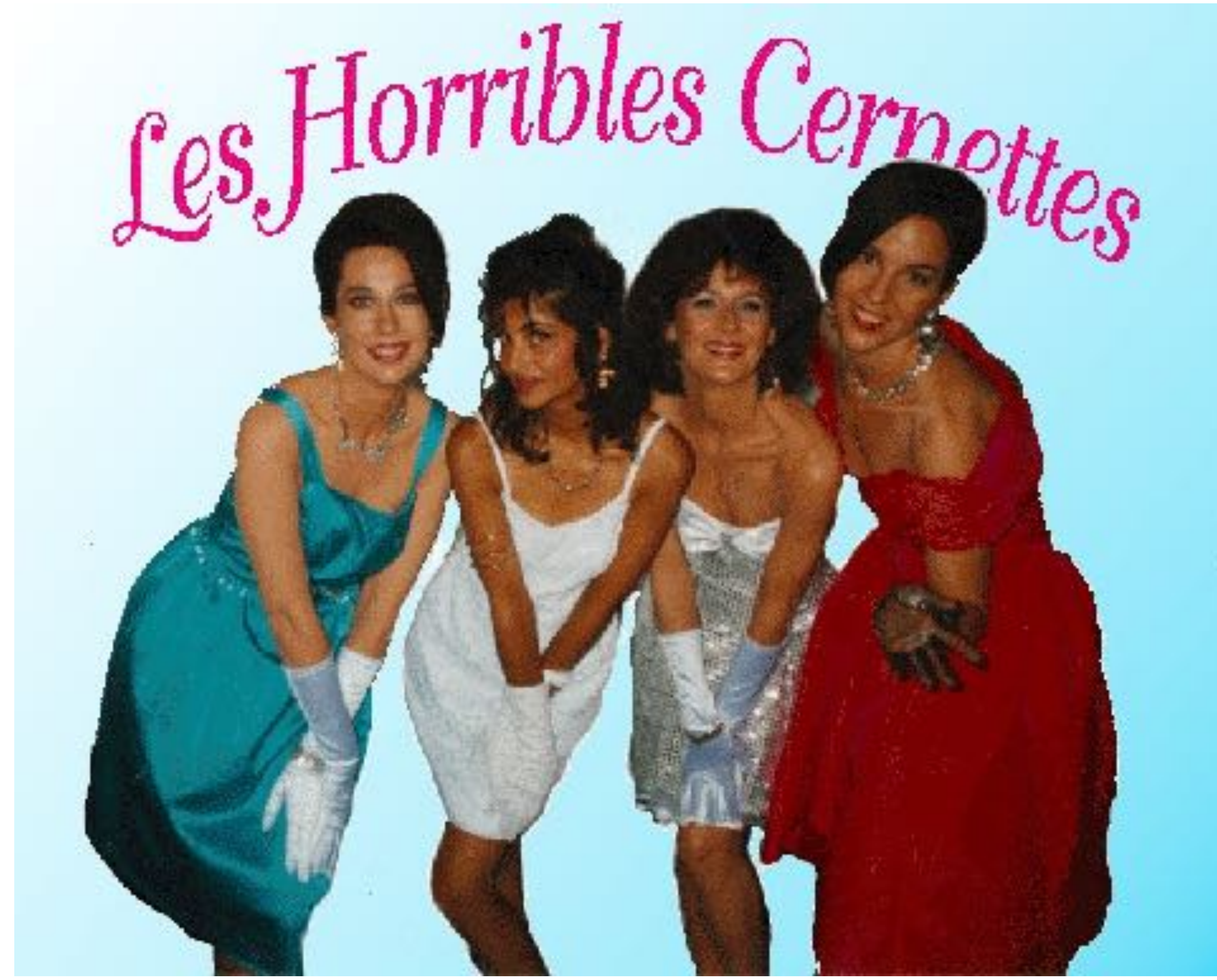
LHC and Experiments


Jörg Wenninger

CERN: European Organization for Nuclear Research



CERN: European Organization for Nuclear Research

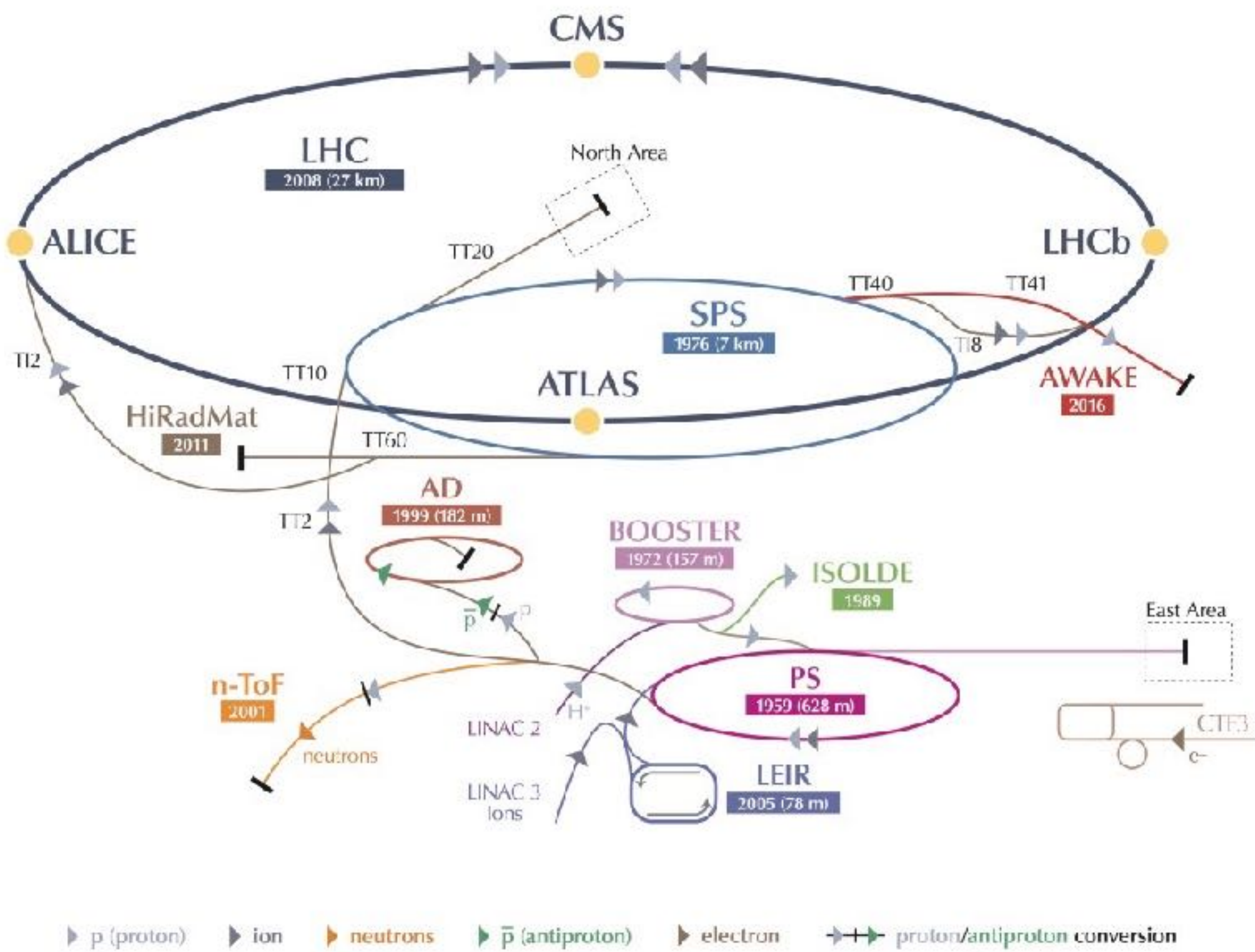


Founded in 1954. Currently operates a network of six accelerators.

A few of the scientific and computing achievements:

- Neutral currents in Gargamelle bubble chamber
- W/Z bosons in UA1 and UA2 experiments
- The World Wide Web!

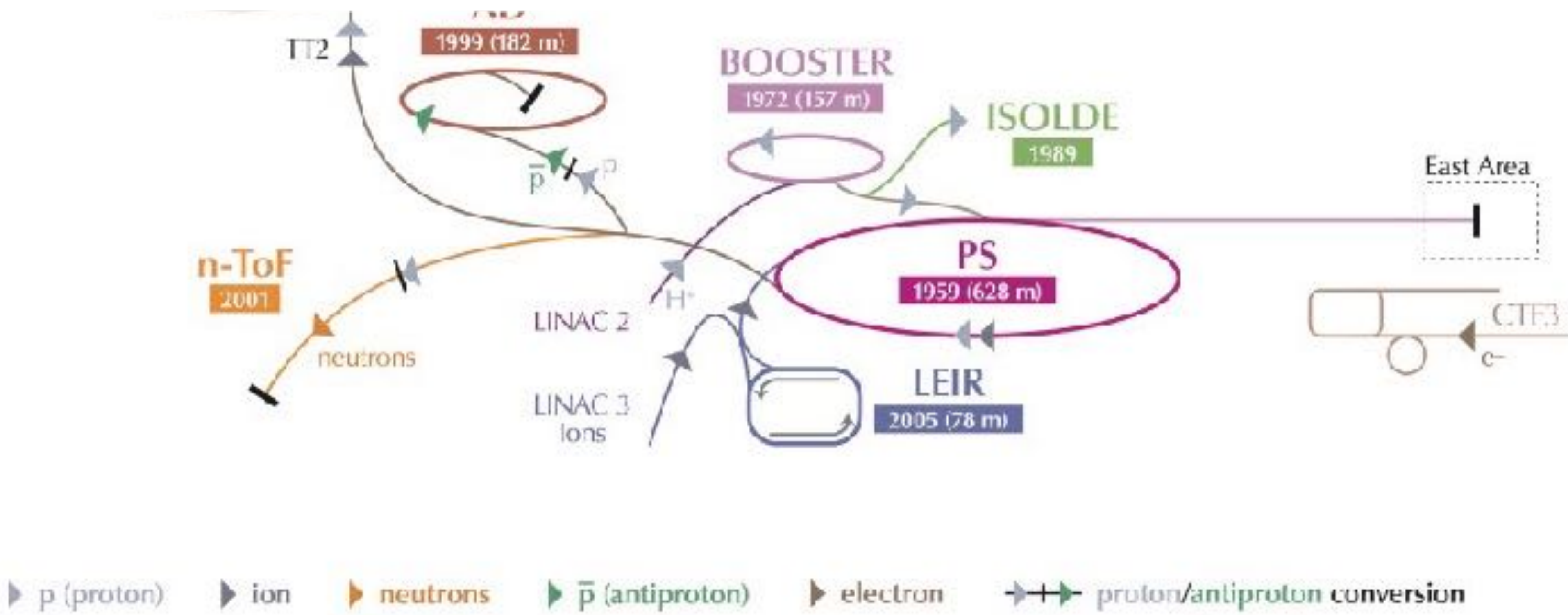
CERN's accelerator complex



CERN's accelerator complex

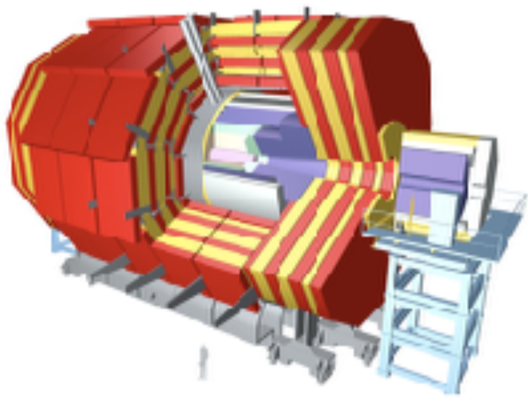
Kinetic energy of a proton (K)	Speed (%c)	Accelerator
50 MeV	31.4	Linac 2
1.4 GeV	91.6	PS Booster
25 GeV	99.93	PS
450 GeV	99.9998	SPS
7 TeV	99.9999991	LHC

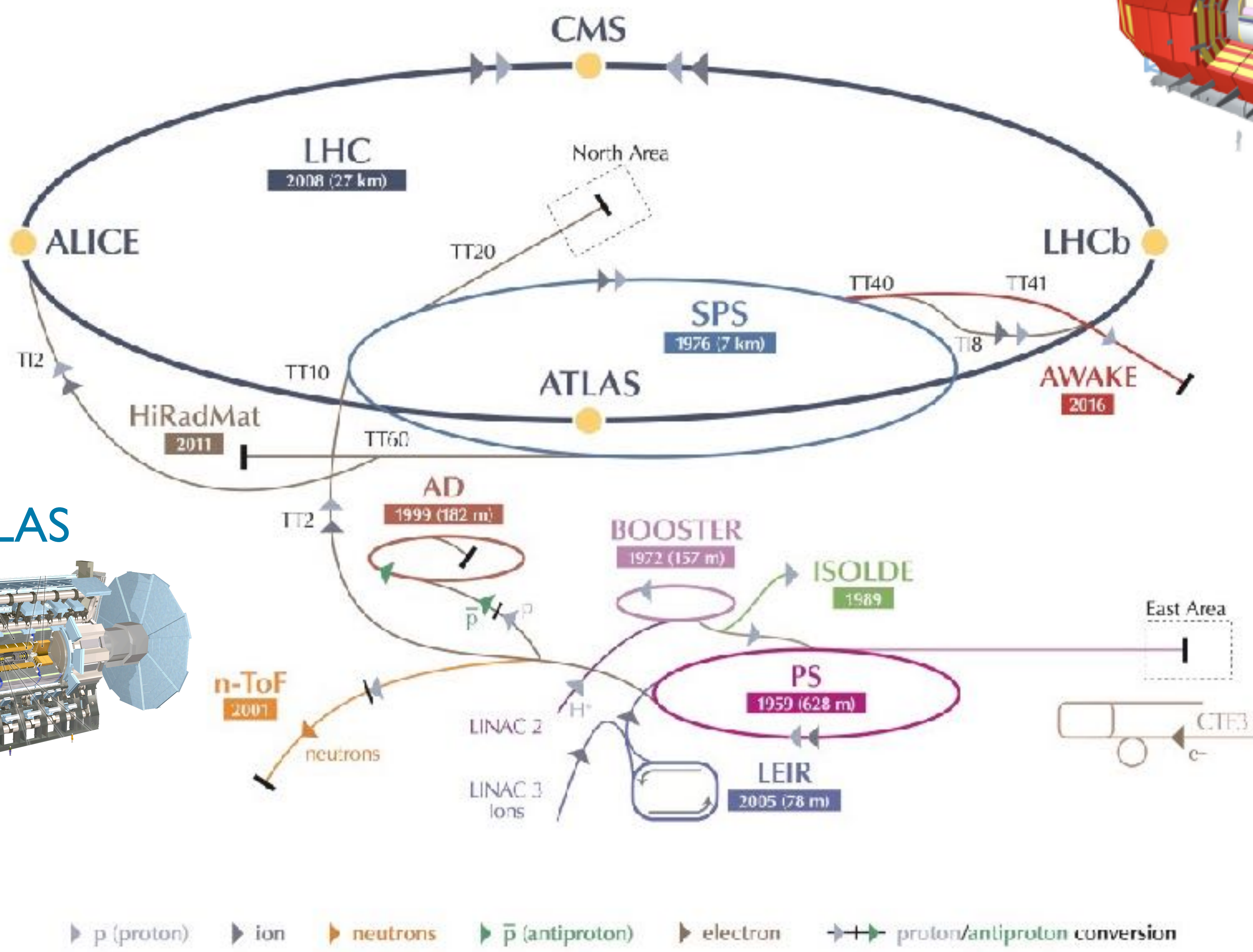
Relationship between kinetic energy and speed of a proton in the CERN machines. The rest mass of the proton is 0.938 GeV/c^2



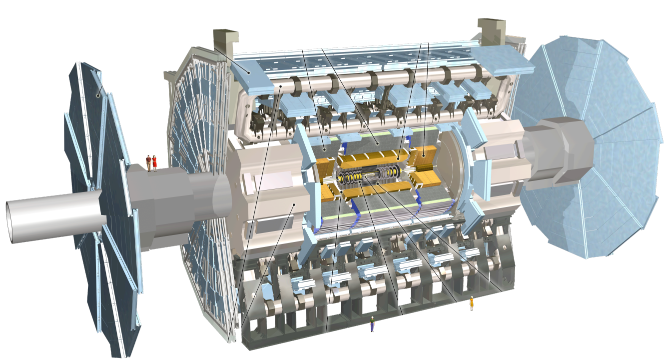
The Large Hadron Collider

CMS

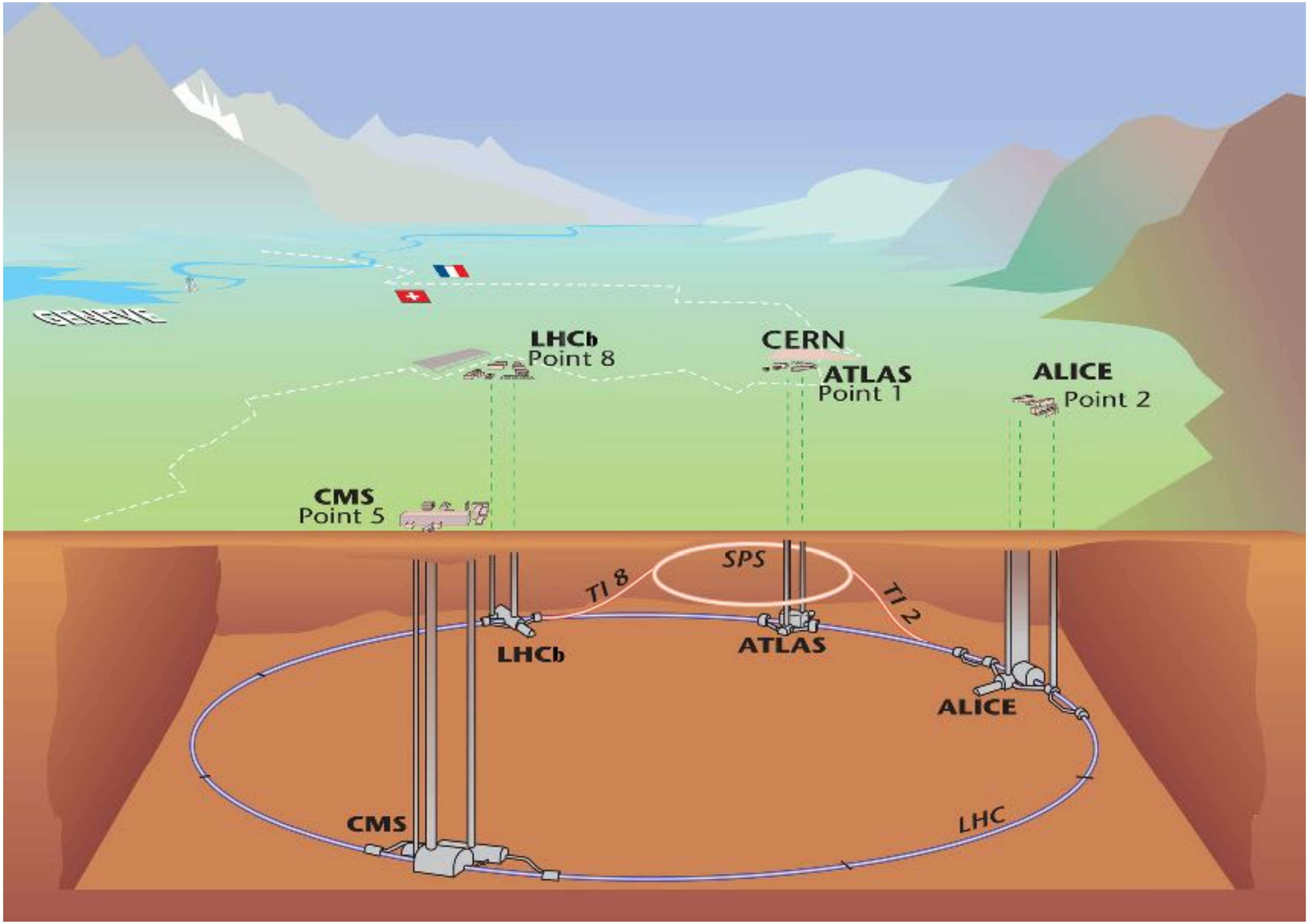




ATLAS

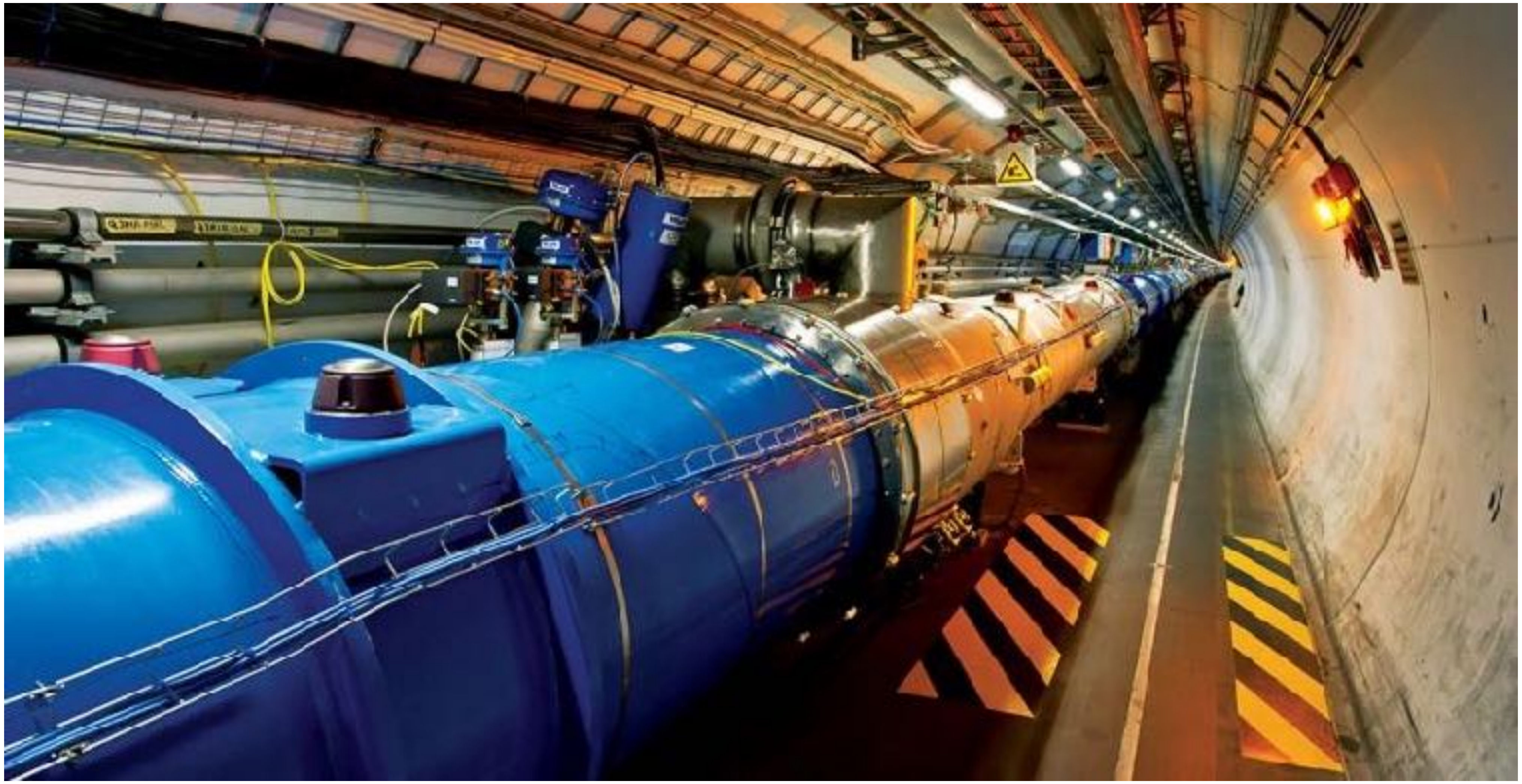


The **L**arge **H**adron **C**ollider



The **L**arge **H**adron **C**ollider

- The LHC is the world's largest and most powerful particle accelerator.
- It consists of a 27 km ring of superconducting magnets and radio-frequency cavities to boost the energy of particles along the way.



The **L**arge **H**adron **C**ollider

- The LHC accelerates and collides two beams of protons.
- The proton beams can be accelerated to energies of up to 7 TeV, translating into a collision energy of:

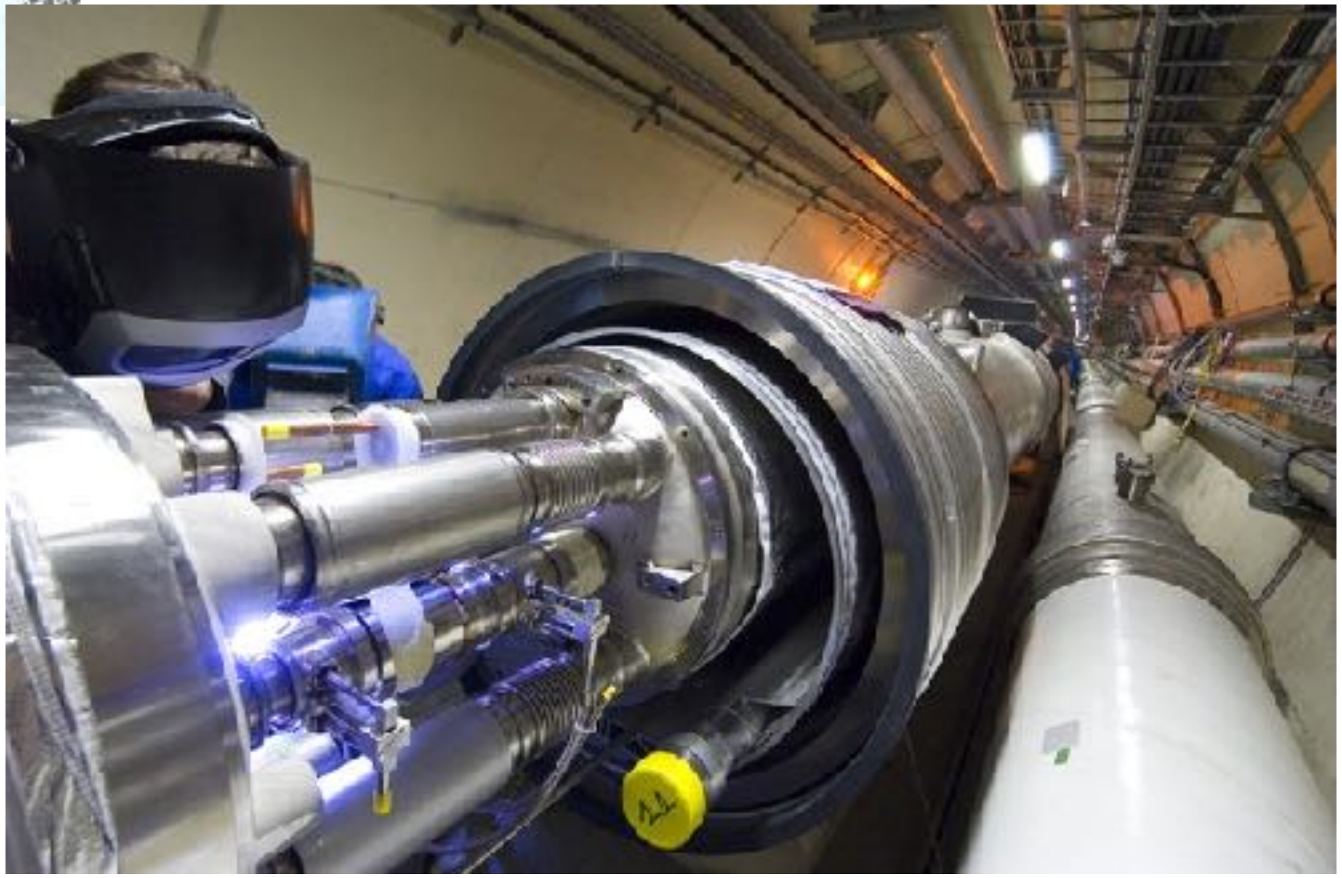
$$\sqrt{s} = 14 \text{ TeV}$$

- Compare with other accelerators:
  - LEP: electrons + positrons
  - Tevatron: protons + anti-protons

- Note: in addition to protons, the LHC can also accelerate and collide lead ions, up to an average centre-of-mass energy of pairs of colliding nucleons of ~ 5 TeV.

The Large Hadron Collider

- The already existing tunnel had been built for LEP (electron-positron accelerator).



- The first LHC magnet was lowered into the tunnel in March, 2005.
- The first beams were injected in August, 2008.

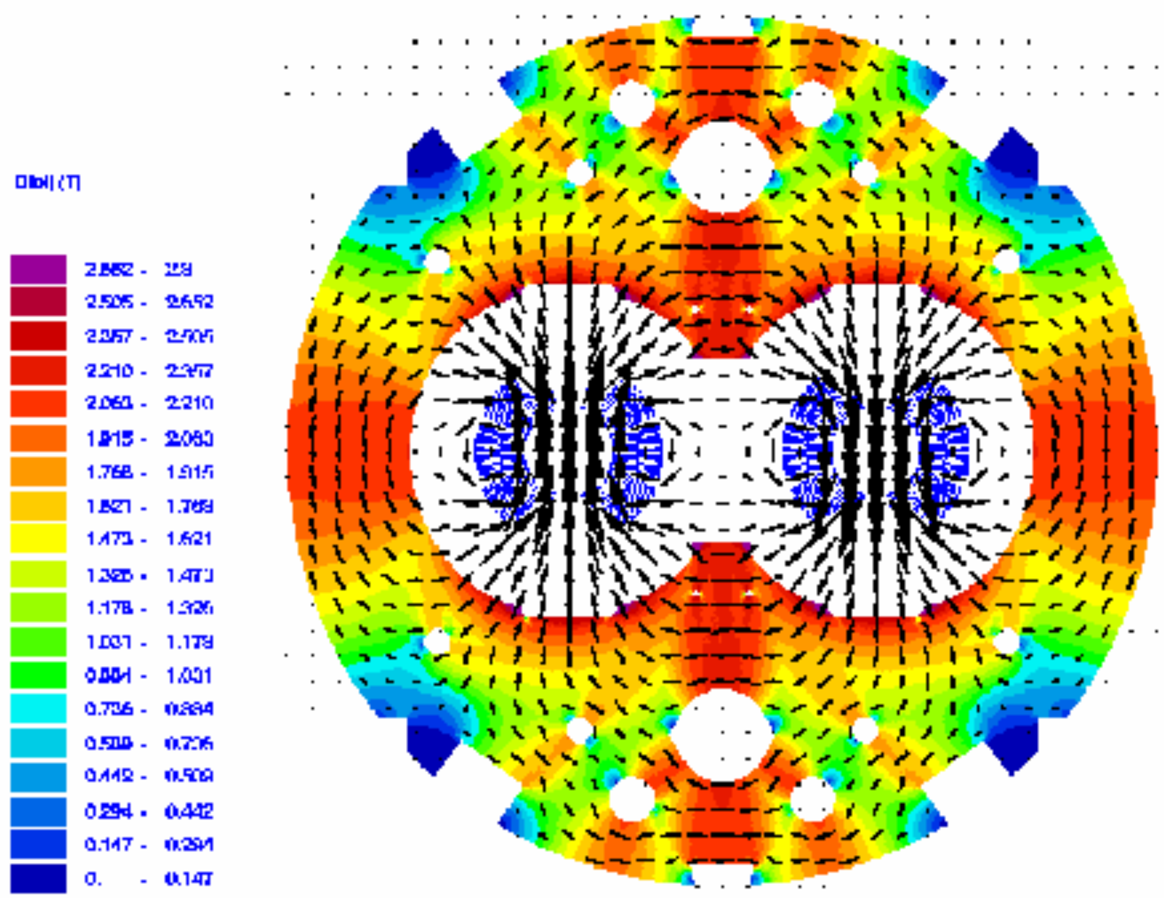
The Large Hadron Collider

- Rocky start…
- A faulty electrical connection caused a violent release of helium into the tunnel.

- The LHC resumed operation on November, 2009 by successfully circulating two beams.

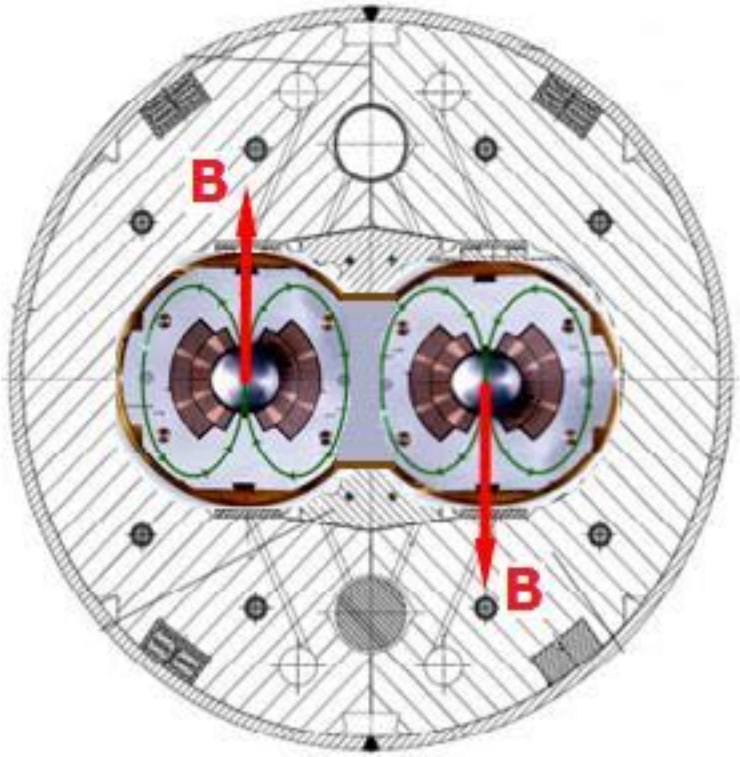
Magnet system

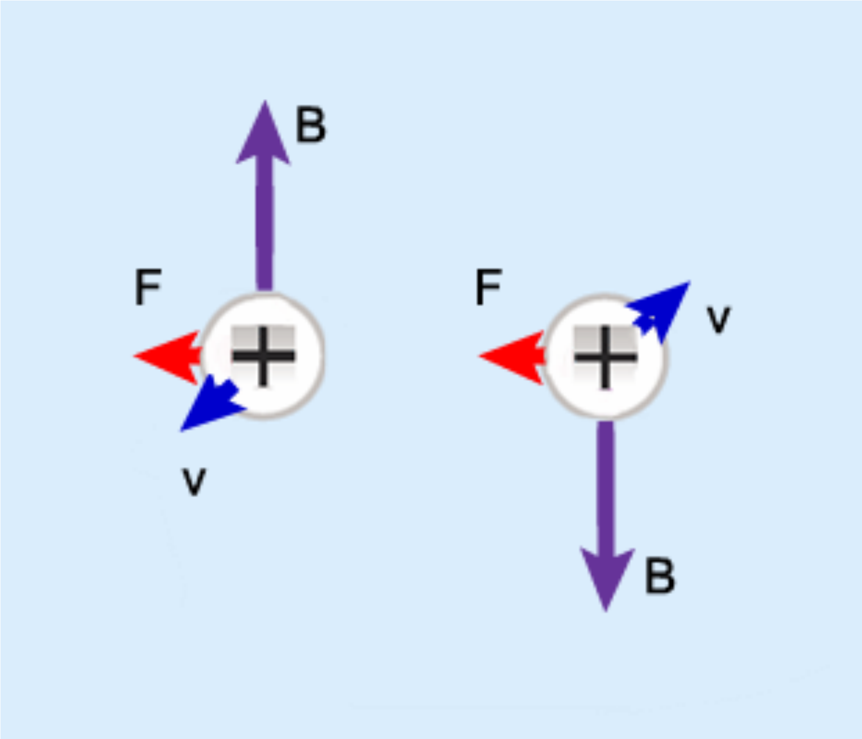
- Superconducting magnets are used to bend the path of charged particles.
- A total of 1232 dipole magnets and 506 quadrupole magnets are used, to steer and focus the beam.
- Liquid helium is used to cool the magnets to a temperature of −271.3°C.

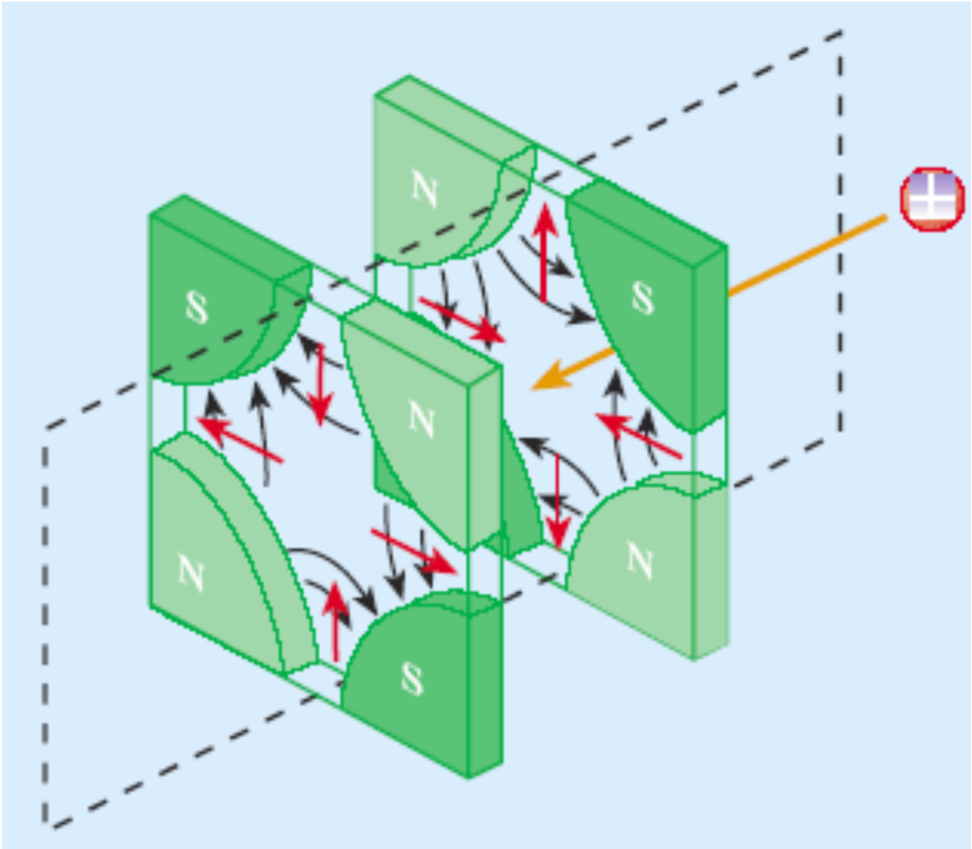


- The dipole magnets create a homogeneous field inside the beam pipe and keep the charged particles in their curved trajectory.
  - Magnetic field of 8.3 Tesla!
- The quadrupoles shape the beam in the transverse directions to its movement, focusing it.

Magnet system



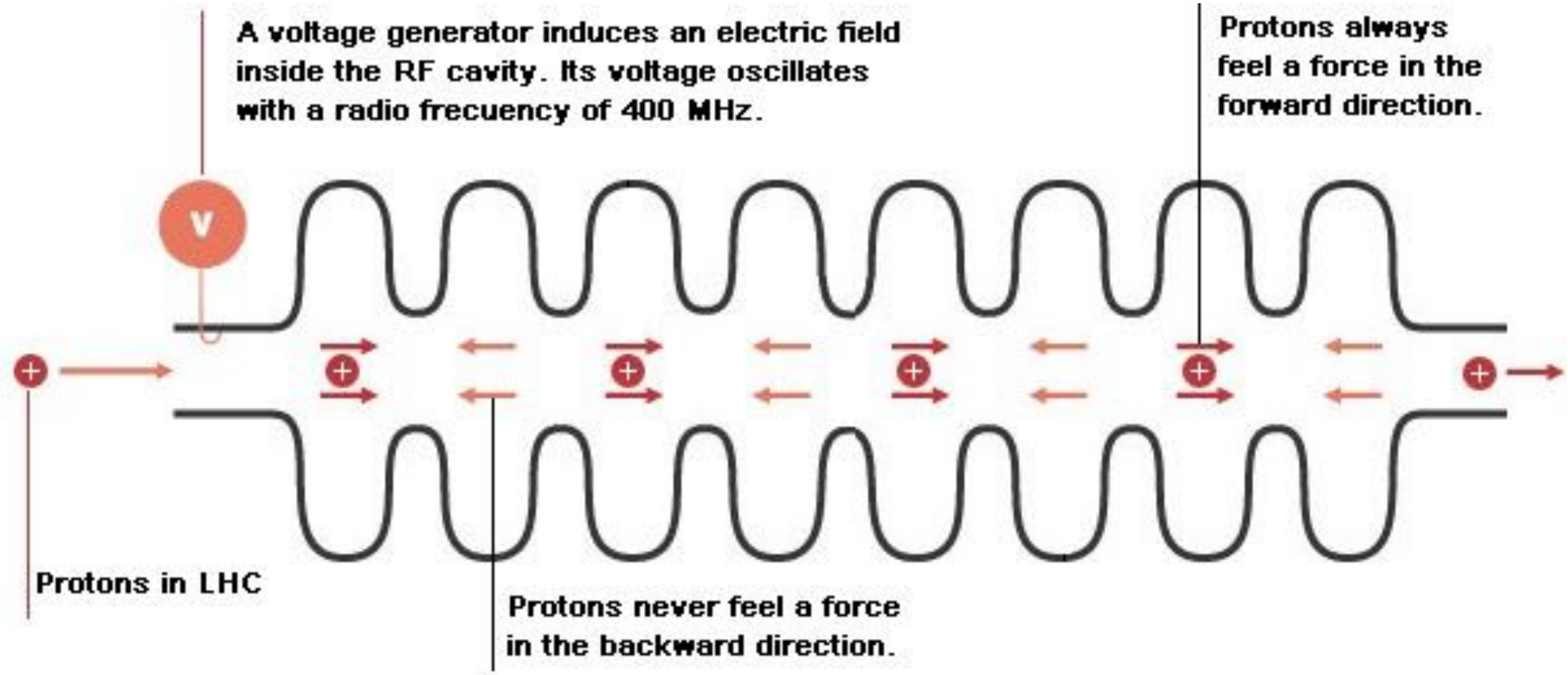




- Focusing the beam means keeping the protons tightly bunched together, maximizing the number of collisions in the interaction point.
- Note: there would be serious damage to the accelerator if an uncontrolled quench or beam dump were to occur.

Radio-frequency cavities

- The RF cavities are used to keep the protons tightly bunched together and ensure high luminosity at the interaction points.
- They are also responsible for delivering radio-frequency power to the beam, accelerating it to its nominal energy.



Radio-frequency cavities

- The LHC has 8 RF cavities per beam, each delivering 2 MV, at 400 MHz.
- The cavities operate at 4.5 K!

- Each proton circulating around the LHC is affected for:

$$2 \times 8 \text{ MV} = 16 \text{ M}$$

- So, it receives an extra energy of 16 MeV.
- Since every proton goes around the LHC 11245 times per second, the total energy per second is:

$$(16 \text{ MeV/lap}) \times (11245 \text{ laps/s}) = 1.8 \cdot 10^5 \text{ MeV/s} = 0.18 \text{ TeV/s}$$

- The protons enter the LHC with 0.45 TeV, so the amount of energy that cavities have to provide is:

$$7\text{-}0.45 = 6.55 \text{ TeV}$$

- Therefore, the amount of time it takes to accelerate the beam to full energy is:

$$6.55 \ / \ 0.18 = 36.5 \text{ s}$$

- In reality, it takes about 20 minutes, given that protons are not fully affected by the total voltage of the cavity.

Low temperatures

- The superconducting electromagnets are built from coils of superconducting cable.
- Superconducting materials operate at very low temperatures: ~ 2 K (-271℃).
  - Colder than outer space.
- To cool and keep the magnets at this temperature, much of the LHC is connected to a distribution system of **superfluid helium**.
- 120 tons of helium must flow and be cooled permanently, in order to drive the heat away.

- The LHC tunnel contains two rings: the LHC itself, with the beam pipe, magnets and RF cavities, and the "cyrogenic ring" which is responsible for keeping the magnets at 1.8 K.

Vacuum

- As the LHC accelerates and circulates protons and heavy ions around its rings, it is **crucial** that the space inside the beam pipes and around the interaction points is as **empty** as possible!
- Otherwise, collisions with gas molecules would limit the energy and rate of proton-proton collisions.

- **Ultrahigh vacuum:** the pressure in the beam pipe is ~10^{-7} Pa. Close to the interaction points, it is lower than 10^{-9} Pa.
- As a result, the contribution from proton-gas collisions at the experiments' interaction points is extremely small!

lhc-closer.es

Luminosity

- The luminosity (L) is a crucial parameter defining the performance of an accelerator.
  - It measures the number of collisions that can be produced in a detector, in a given unit of area and time.
- At the LHC, we want to maximize the luminosity:
  - The bigger the value of L, the bigger the number of collisions.

$$N_{\mathrm{events/s}} = \mathrm{luminosity} \cdot \mathrm{cross\text{-}section} = L \cdot \sigma_{event}$$

- Integrating over time, one can define the integrated luminosity, i.e., a measurement of the total number of collisions, or the collected data size:

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

The **L**arge **H**adron **C**ollider

- Since it resumed operations in 2009, the LHC has been performing extremely well.

- Two long runs of high quality proton-proton data for physics analysis:
  - **Run 1** (2010-2012) @ 7, 8 TeV
    - ATLAS and CMS collected approximately ~20 fb^{-1} of 8 TeV data.
  - **Run 2** (2015-2018) @ 13 TeV
    - So far, ATLAS and CMS have collected already ~30 fb^{-1}!

- The design luminosity was first reached in June 2016: 10^{34} $cm^{-2}s^{-1}$.
- This value has in the meantime been improved to about 40% above the design value!

The **L**arge **H**adron **C**ollider

In numbers we can all understand…

- Each proton beam is accelerated to an energy of up to 7 TeV:

$$7 \text{ TeV} = 7 \cdot 10^{12} \text{ eV} \cdot 1.6 \cdot 10^{-19} \text{ J/eV} = 1.12 \cdot 10^{-6} \text{ J}$$

- An insect of 60 mg flying at 20 cm/s has a kinetic energy of:

$$E_k = \frac{1}{2} m \cdot v^2 \leftrightarrow E_k = \frac{1}{2} 6 \cdot 10^{-5} \cdot 0.2^2 \sim 7 \text{ TeV}$$

- Each proton bunch contains an energy of:

$$7 \text{ TeV/proton} \cdot 1.15 \cdot 10^{11} \text{ protons/bunch} \sim 1.29 \cdot 10^5 \text{ J/bunch}$$

- A motorbike of 150 kg traveling at 150 km/h:

$$E_k = \frac{1}{2} \cdot 150 \cdot 41.7^2 \sim 1.29 \cdot 10^5 \text{ J}$$

- The energy stored by a beam:

$$1.29 \cdot 10^5 \text{J/bunch} \times 2808 \text{ bunches} \sim 360 \text{ MJ}$$

which is equivalent to 77.4 kg of TNT.

So… Why did we build the LHC?

- One of the main questions troubling physicists until very recently was related to the mechanism of mass generation.
  - How are the W and Z bosons massive?
- The idea of a Higgs mechanism and an associated Higgs boson was suggested in the 1960s.
- By the 1980s, physicists had started searching for the Higgs boson and to that end (and others), several generations of experiments contributed, including:
  - LEP @ CERN
  - Tevatron @ Fermilab

While the physics opportunities are vast, searching for the Higgs boson was certainly one of the most important motivations for building the LHC.

Then, in 2012…

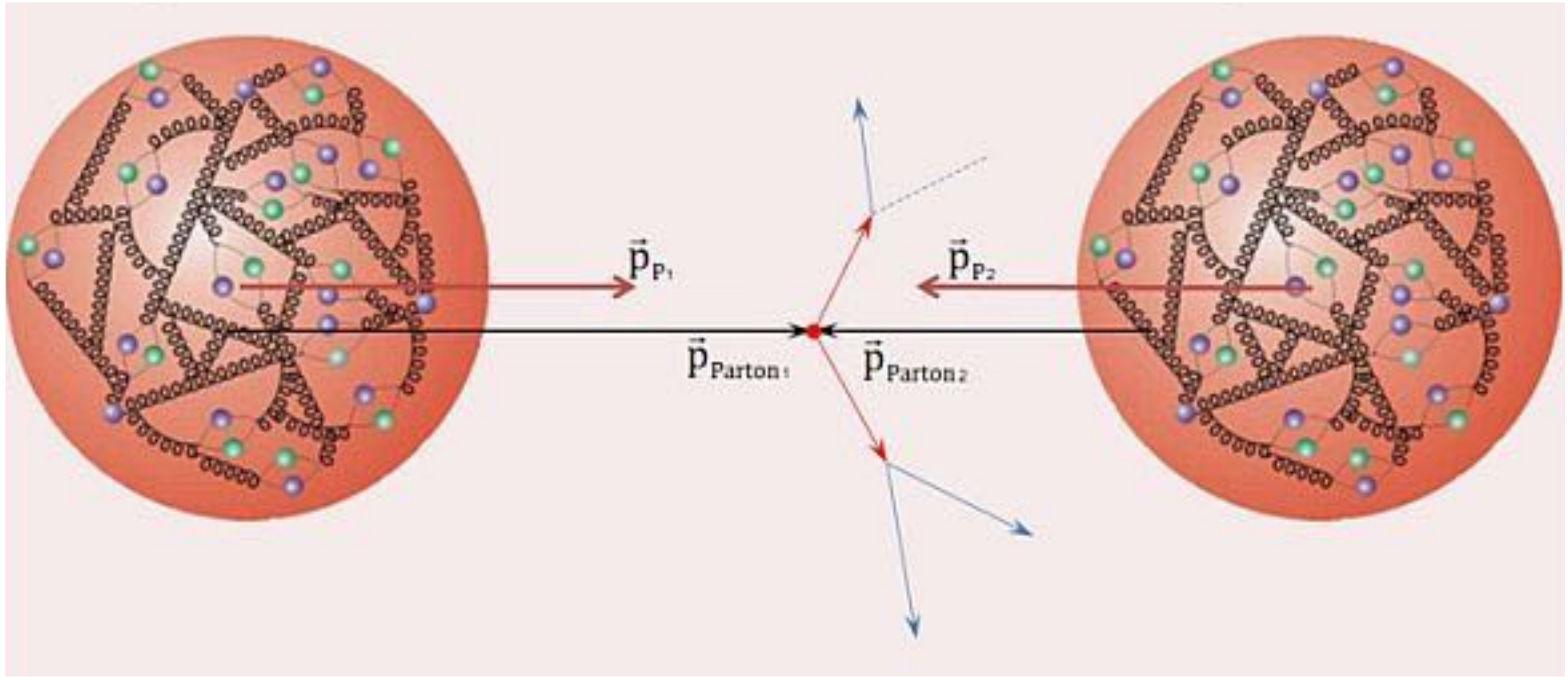
More on the next lecture!

Proton-proton collisions

Proton-proton collisions

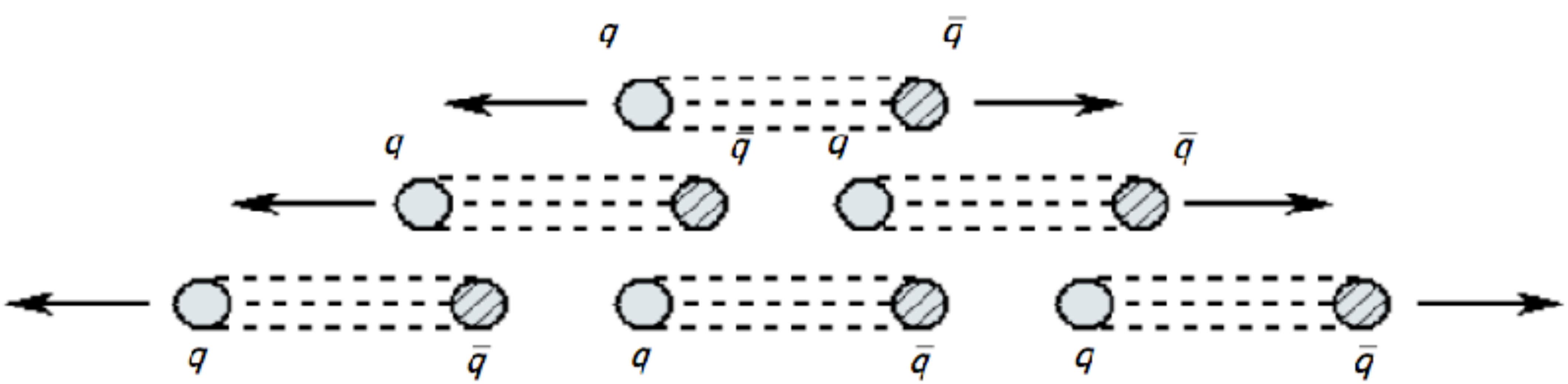
- Quantum Chromodynamics theory is expressed in terms of quarks and gluons (partons).
  - We are colliding composite objects!
- At the LHC energies, quarks and gluons collide and the actual collision energy is a fraction of the total:

$$\sqrt{\hat{s}} << \sqrt{s} = E_{\mathrm{cm}} = 2E_p$$



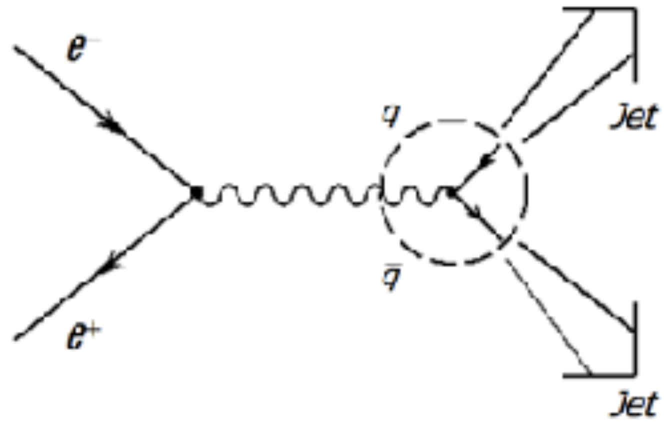
Color lines and hadron production

- Why you can't get free quarks:
  - Suppose we have a meson and we try to pull it apart. The potential energy in the quark-antiquark color field starts to increase.
  - Eventually, the energy in the gluon field gets big enough that the gluons can pair-produce another quark-antiquark pair.
    - The new quarks pair up with the original quarks to form mesons, and thus our four quarks remain confined in colorless states.
  - Experimentally, we see two particles!

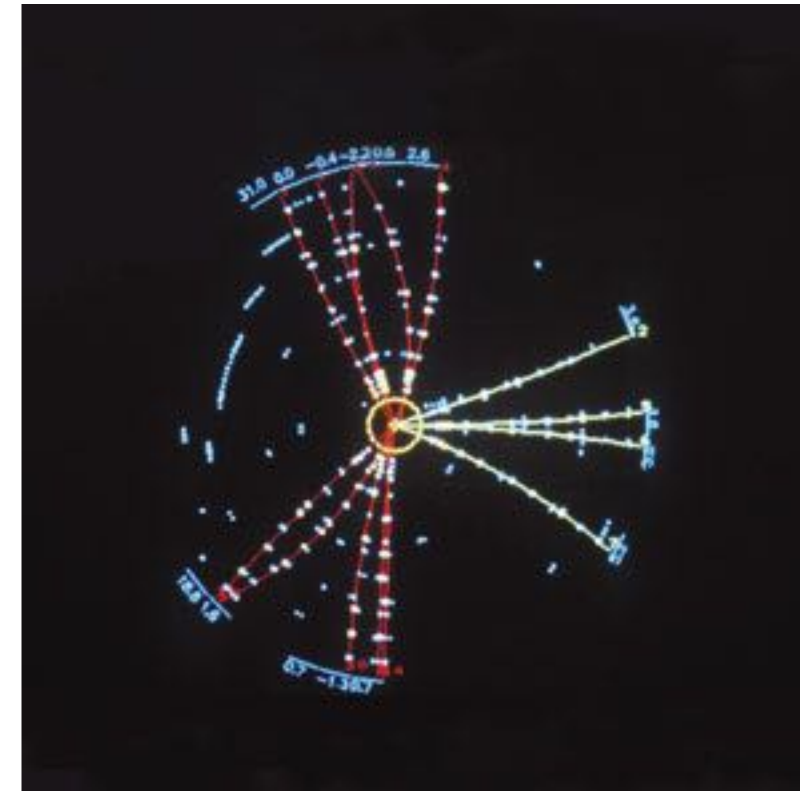


Recall

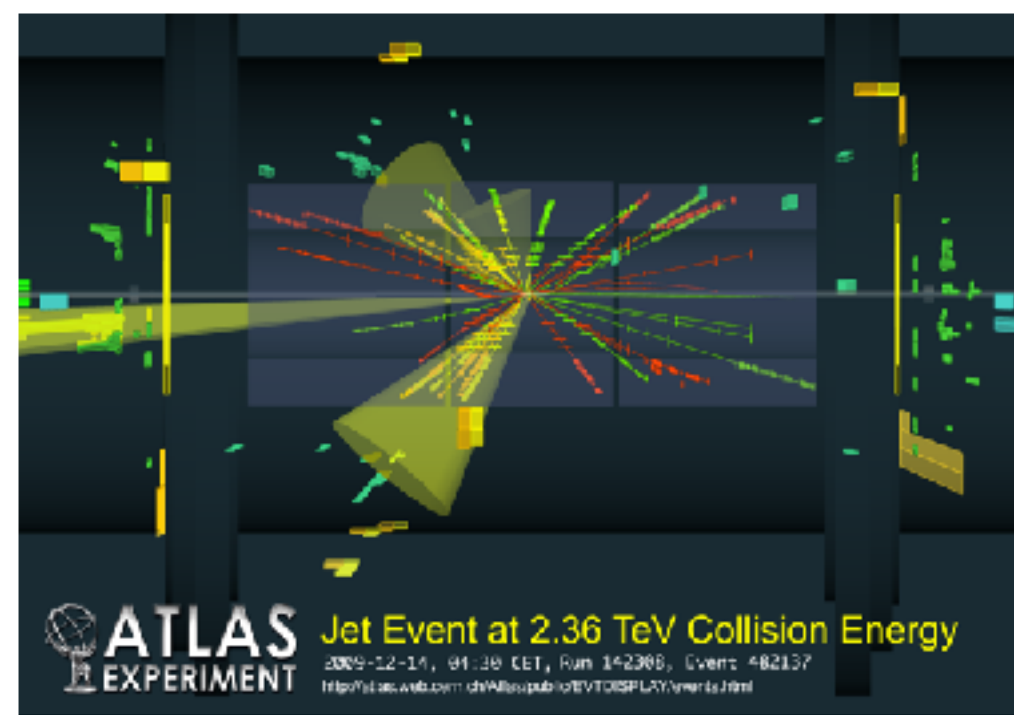
Hadronic jets



- The process just described is observed experimentally in the form of hadron jets.
- In a collider experiment, two particles annihilate and form a quark-antiquark pair.
- As the quarks move apart, the color lines of force are stretched until the potential energy can create another quark-antiquark pair.
- This process continues until the quarks' kinetic energy have totally degraded into cluster of quarks and gluons with zero net color.
- The experimentalist then detects several "jets" of hadrons, but never sees free quarks or gluons.



Jet formation at TASSO detector at PETRA



What we see in the detector:

- **Stable particles**, which are directly seen:

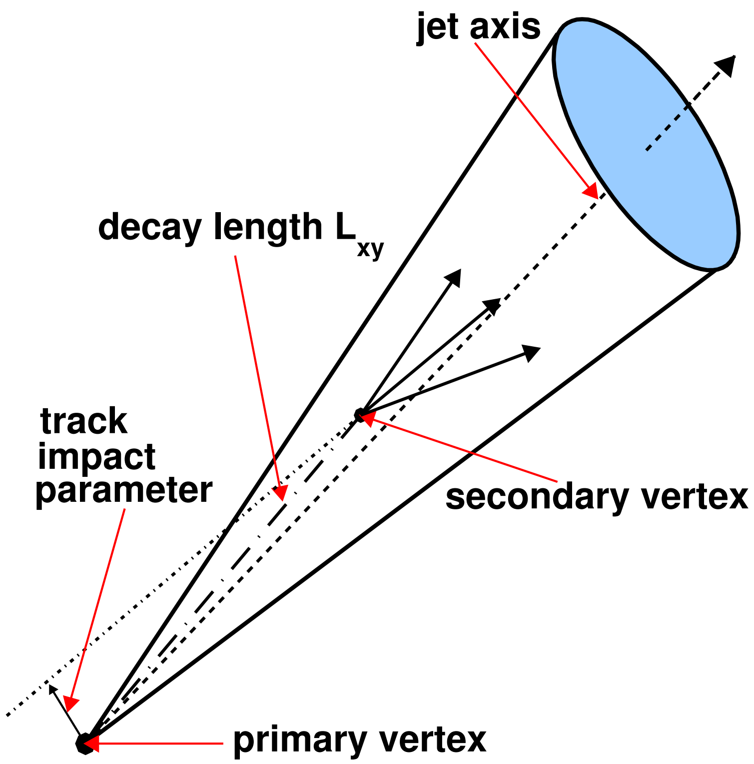
$$p, \bar{p}, e^{\pm}, \gamma$$

- **Quasi-stable particles**, with a long lifetime are also directly seen:

$$n, \Lambda, \mu^{\pm}, \pi^{\pm}, K_L^0, K^{\pm}, \ldots$$

- Particles with a short lifetime may be indicated by a **secondary vertex**:

$$B^0, B^{\pm}, D^0, D^{\pm}, \tau^{\pm}, \ldots$$



What we see in the detector:

- **Short-lived particles** that can only be reconstructed by their decay products:

$$\pi^0, \rho^0, \rho^\pm, ..., Z, W^\pm, t, H$$

- **Invisible particles**: we don't see them, but we can infer their presence

$$\nu, \tilde{\chi}^0, G_{KK}, ...$$

What we see in the detector:

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$$\nu, \tilde{\chi}^0, G_{KK}, \ldots$$

? ?

Recall

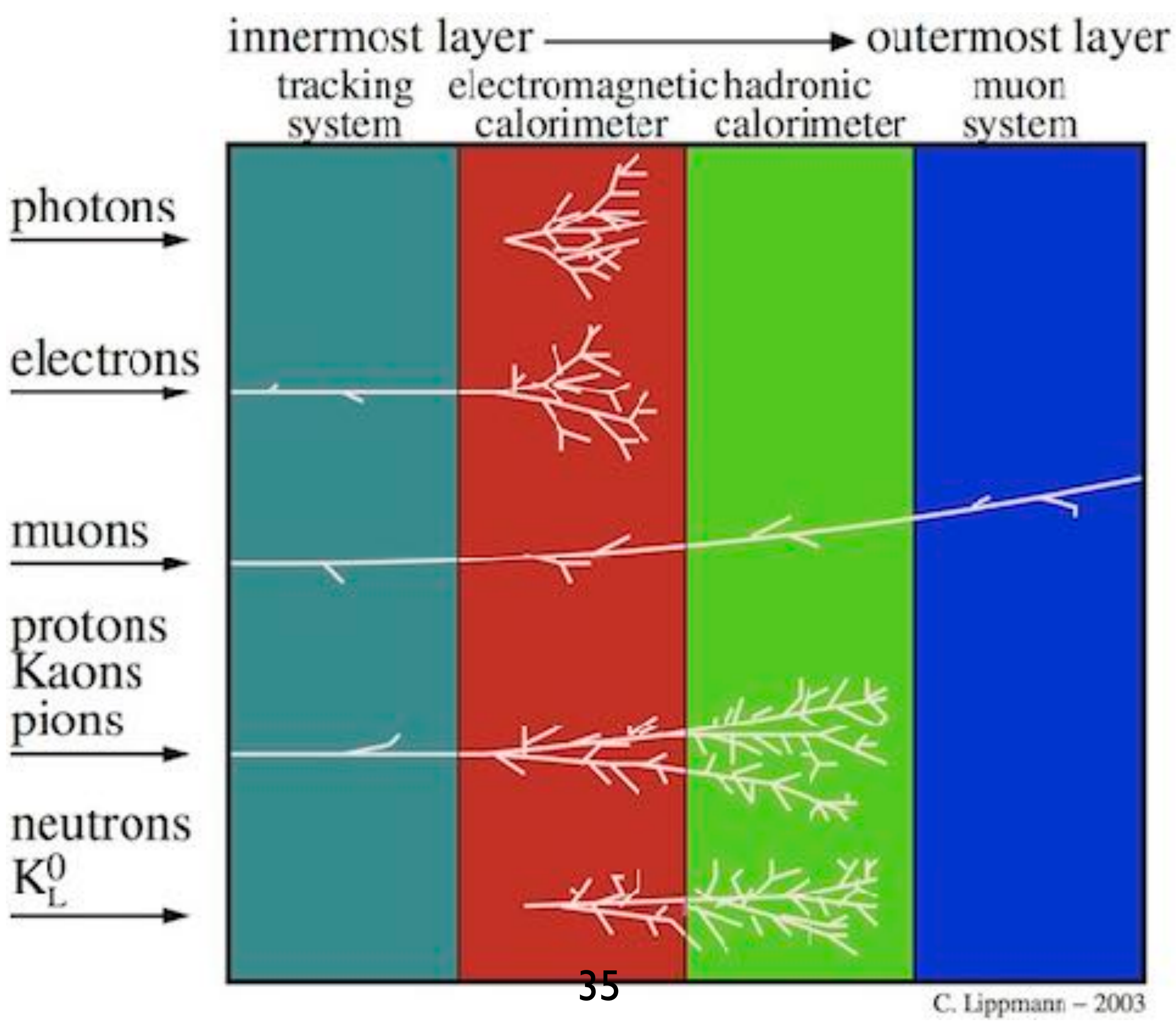
Particle interactions in the detector

Tracking system: detector that records the paths of charged particles

EM calorimeter: particles interacting via EM force create EM showers and deposit their energy

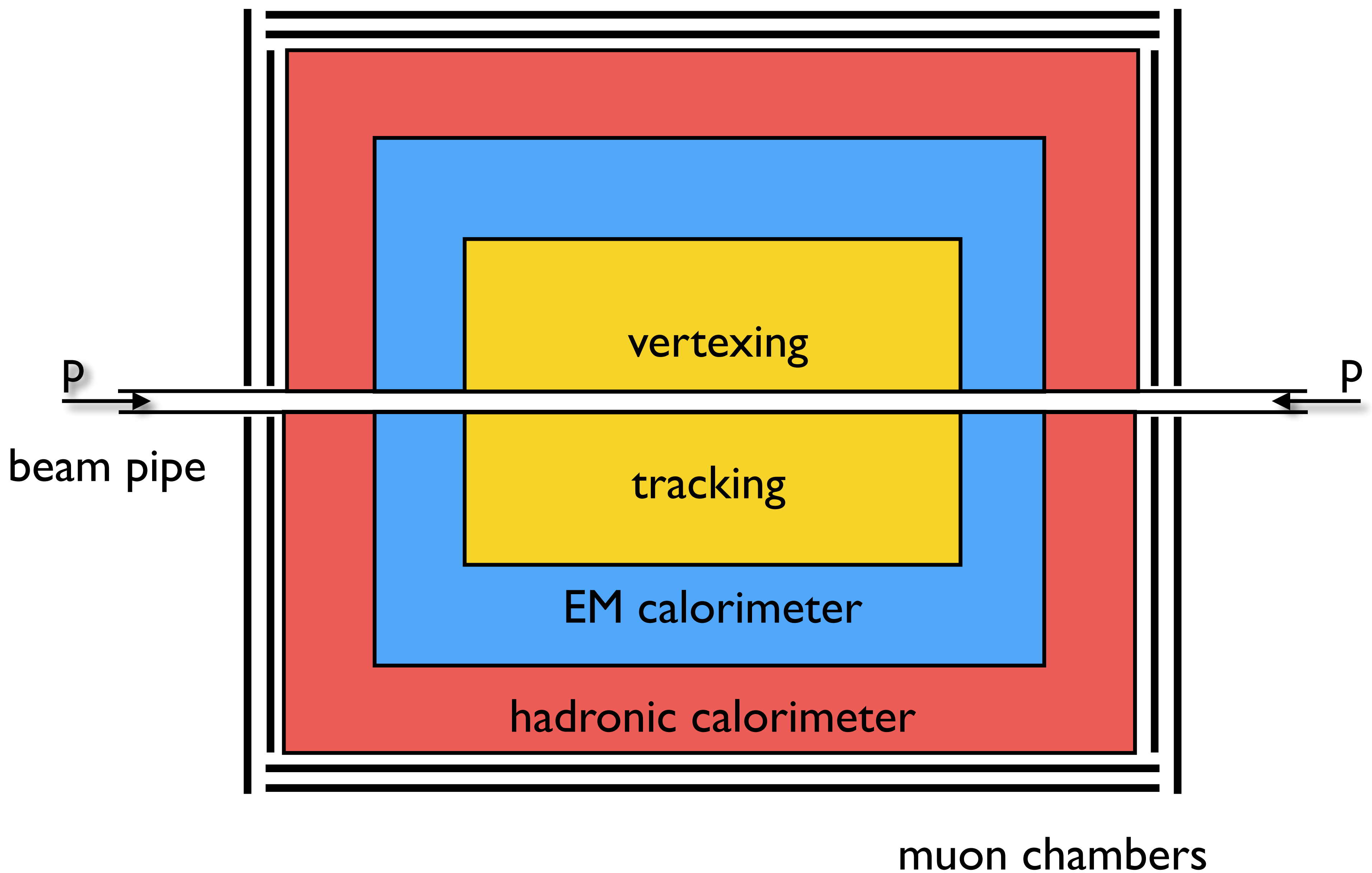
Hadronic calorimeter: to measure the energy of hadronic showers

Muon system: to record the trajectory of muons



Recall

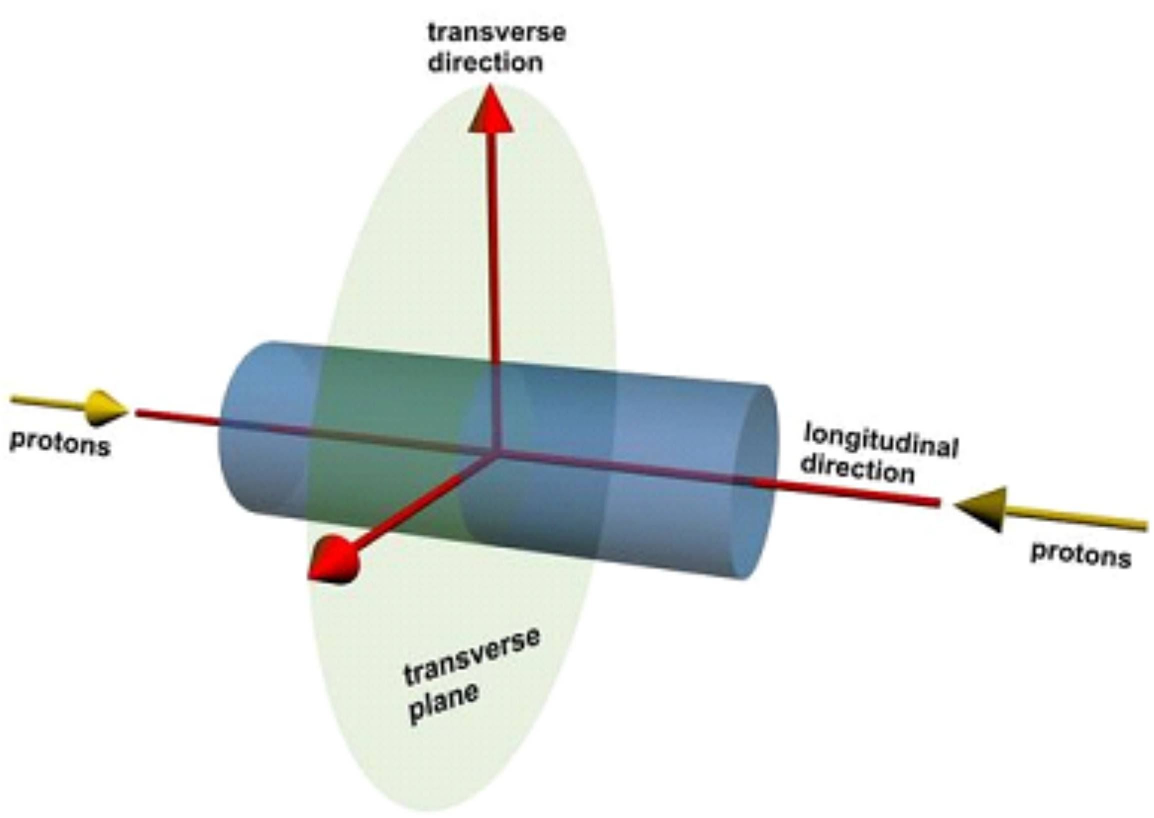
Basic concept of a general purpose detector

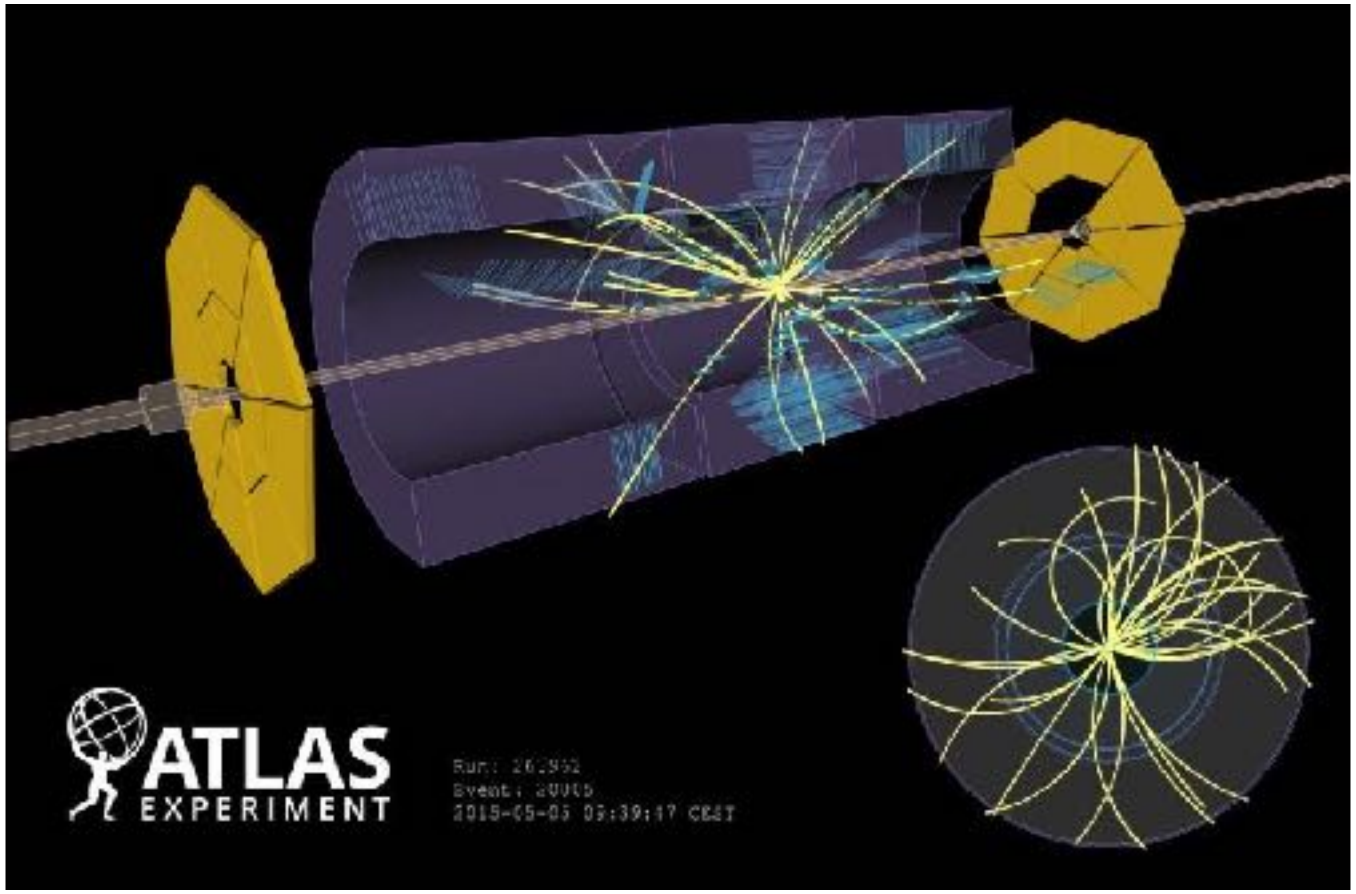


The kinematics of proton-proton collisions

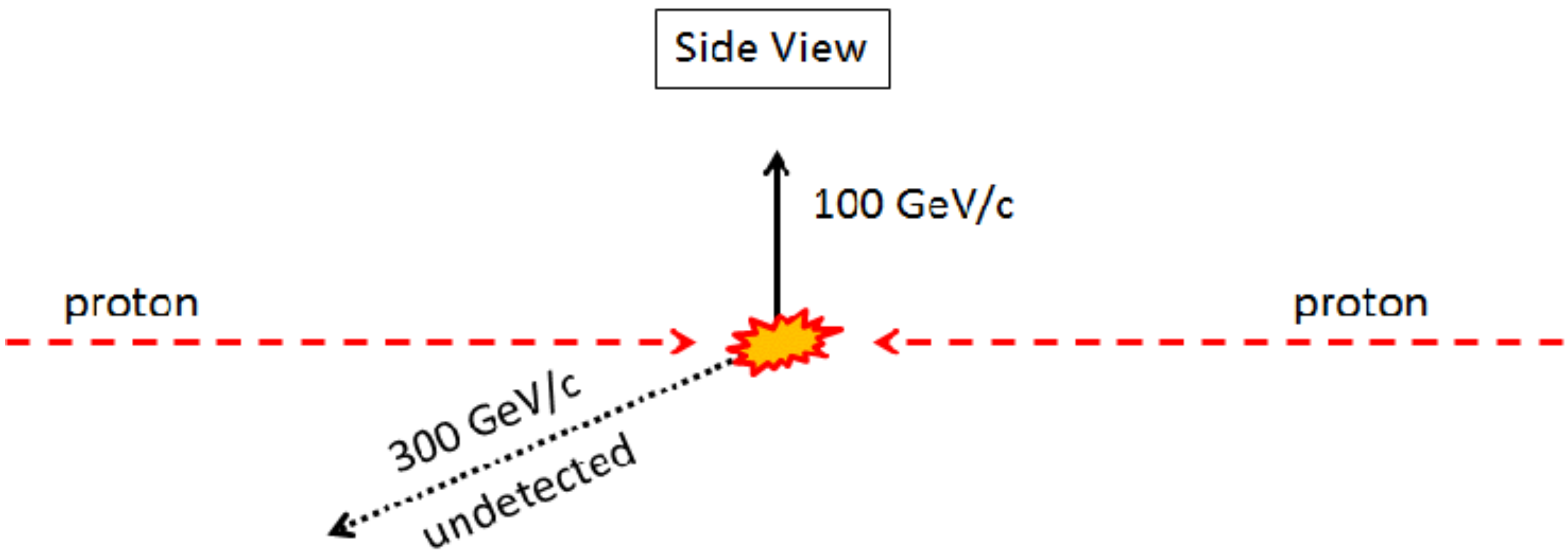
- We don't know the **longitudinal** momentum of the initial partons that collide: we can't apply a conservation law on the beam direction.

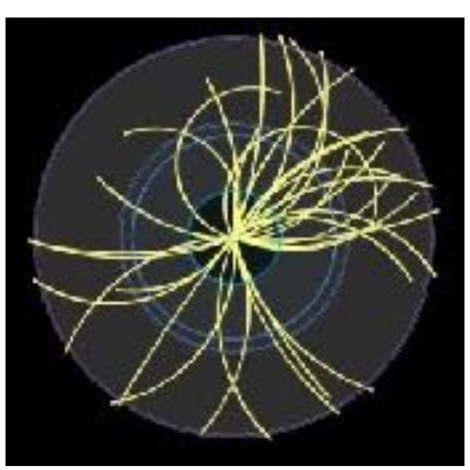
- Instead, what is conserved are the quantities in the **transverse** plane
  - The transverse momentum/energy is zero before the collision.

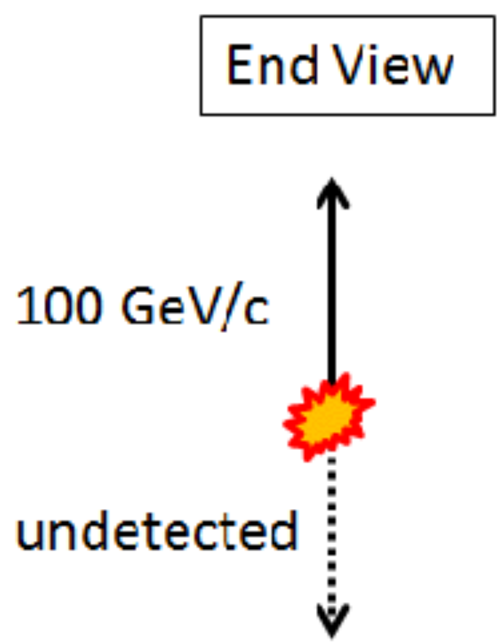




The kinematics of proton-proton collisions





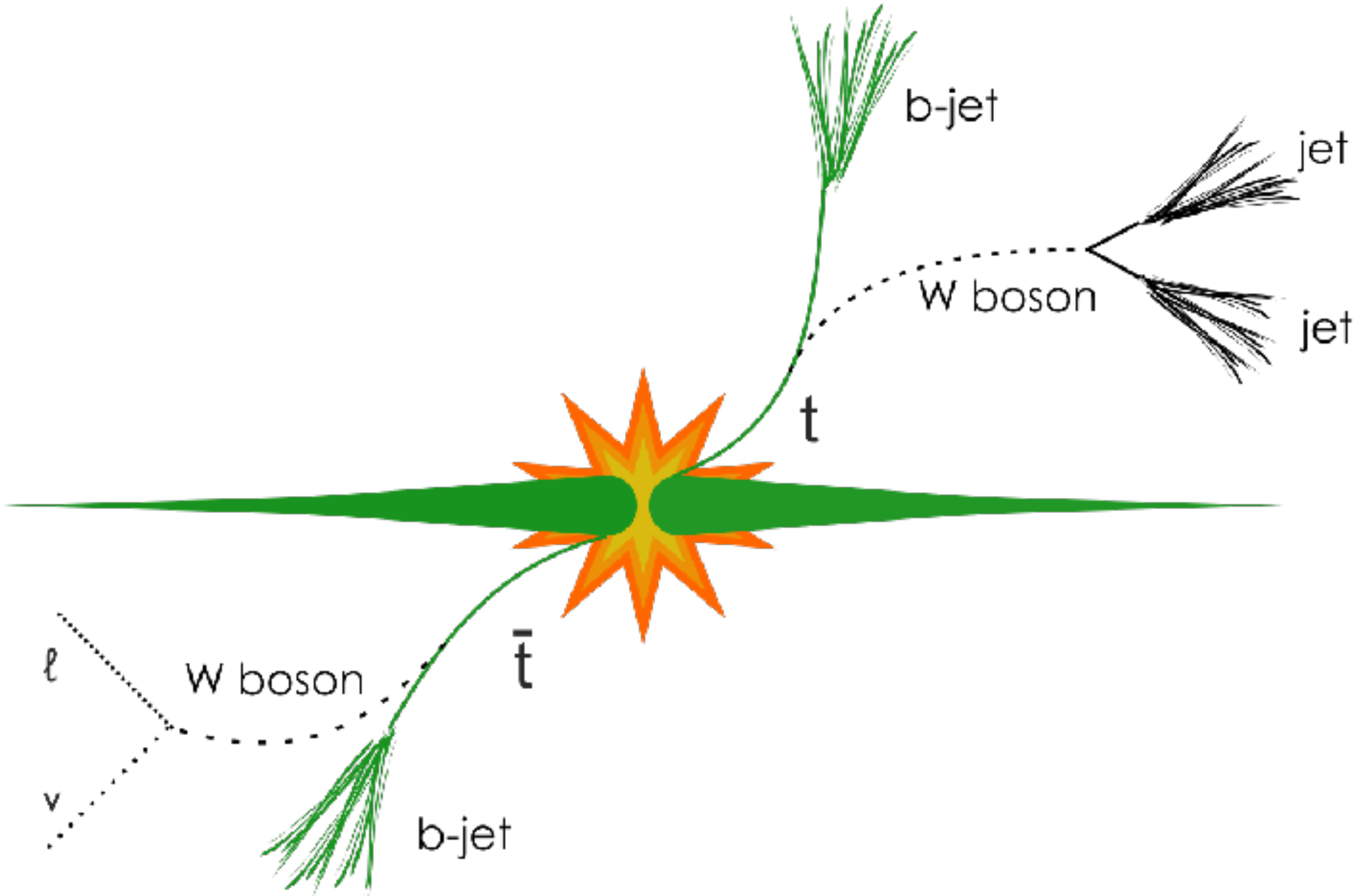


Visible Transverse `Energy' = 100 GeV

Missing Transverse `Energy' = 100 GeV

M. Strassler 2012

A top-pair event



- There are millions of top quarks produced each year of running at the LHC!

LHC experiments

- The LHC covers a broad physics program (not just the Higgs!):
  - **ATLAS** and **CMS** are general purpose experiments:
    - QCD, rare hadron decays, Standard Model precision measurements, searches for new physics, …
  - Other experiments have a dedicated physics program:
    - **LHCb**: B-decays and CP violation
    - **ALICE**: heavy ion physics