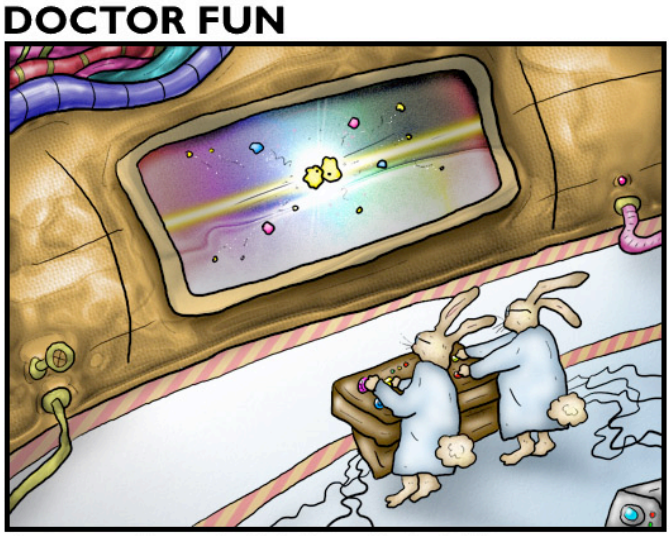
Subatomic Physics:

Particle Physics

Lecture 4: The Large Hadron Collider and other accelerators

November 13th 2009



Bunny researchers at the High Energy Candy Collider generate exotic short-lived isotopes of Peeponium.

- Previous colliders
- Accelerating techniques: linacs, cyclotrons and synchrotrons
- Synchrotron Radiation
- The LHC
- LHC energy and luminosity

Particle Acceleration

Long-lived charged particles can be accelerated to high momenta using electromagnetic fields.

- e^+, e^-, p, $\bar{p}$, $\mu^\pm$(?) and **Au, Pb & Cu nuclei** have been accelerated so far…

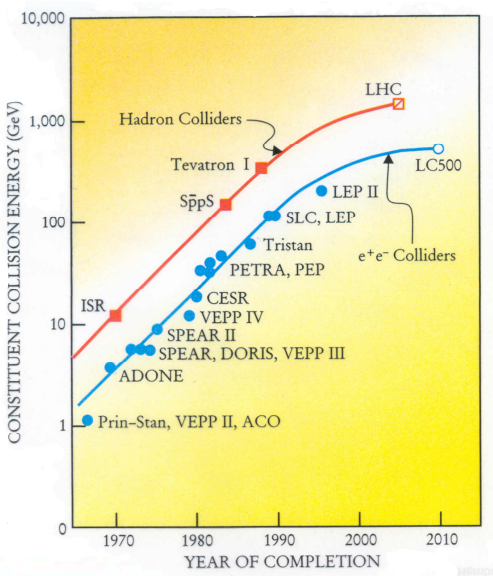
Why accelerate particles?

- High beam energies ⇒ high E_{CM} ⇒ more energy to create new particles
- Higher energies probe shorter physics at shorter distances
- De-Broglie wavelength: $\dfrac{\lambda}{2\pi} = \dfrac{\hbar c}{pc} \approx \dfrac{197\ \mathrm{MeV\ fm}}{p\ [\mathrm{MeV}/c]}$
- *e.g.* **20 GeV/c** probes a distance of **0.01 fm**.

An accelerator complex uses a variety of particle acceleration techniques to reach the final energy.

A brief history of colliders

- Colliders have driven particle physics forward over the last 40 years.
- This required synergy of
  - hadron - hadron colliders
  - lepton - hadron colliders &
  - lepton - lepton colliders
- Experiments at colliders discovered W-boson, Z-boson, gluon, tau-lepton, charm, bottom and top-quarks.
- Colliders provided full verification of the Standard Model.

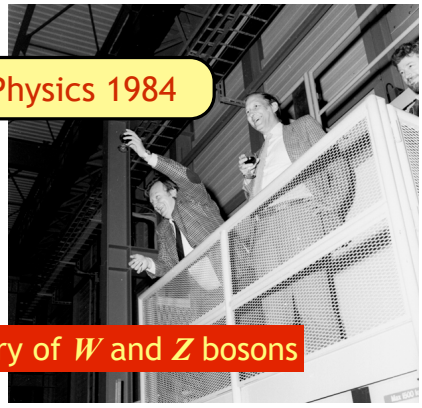


$S\bar{p}pS$ at CERN & HERA at DESY

$S\bar{p}pS$: Proton anti-Proton collider at CERN.

- Ran from 1981 to 1984.
- Centre of Mass energy: **400 GeV**
- 6.9 km in circumference
- Two experiments: UA1 and UA2
  - Accelerator now used to accelerate protons for LHC

Nobel Prize for Physics 1984



Highlight: discovery of W and Z bosons

HERA = Hadron Electron Ring Accelerator

- world's only electron - proton collider
- $E(e^-) = 30$ GeV, $E(p) = 820$ GeV
- 6.3 km in circumference
- ran 1992 - 2007
- Three experiments:
  - Two general purpose experiments: ZEUS, H1
  - One specialised experiment for bottom quark-physics experiment: HERA-*b*

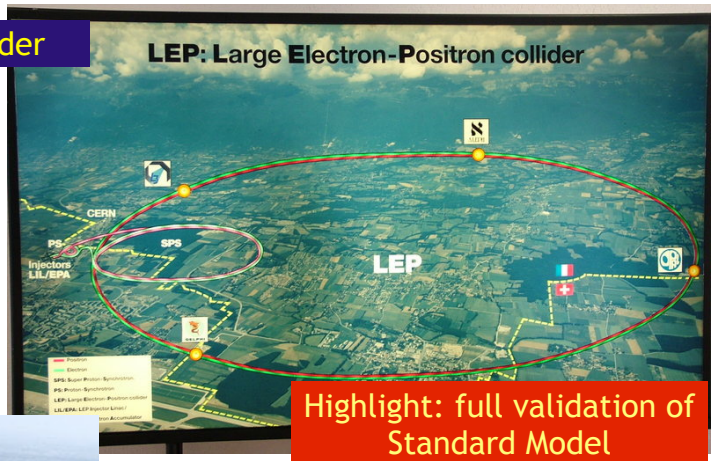
Highlight: detailed measurement of proton structure

LEP at CERN & Tevatron at Fermilab

LEP = Large Electron Positron Collider

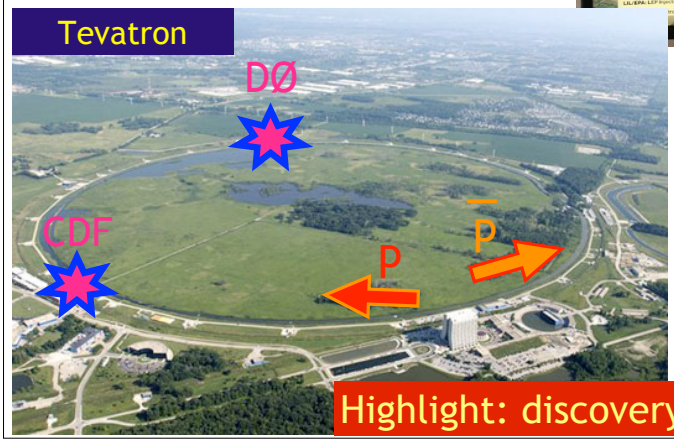
- The world's highest energy e^+e^- collider: $\sqrt{s} = 89$ to 206 GeV
  - 27 km circumference.
  - Ran from 1989 to 2000
  - Four collision points: Aleph, Delphi, L3, Opal

LEP tunnel now used for LHC



Highlight: full validation of Standard Model

Tevatron



- **Proton anti-proton collider**

Run 1: 1987 - 1995

- E_{CM} = 1.80 TeV

Run 2: 2000 - 2008

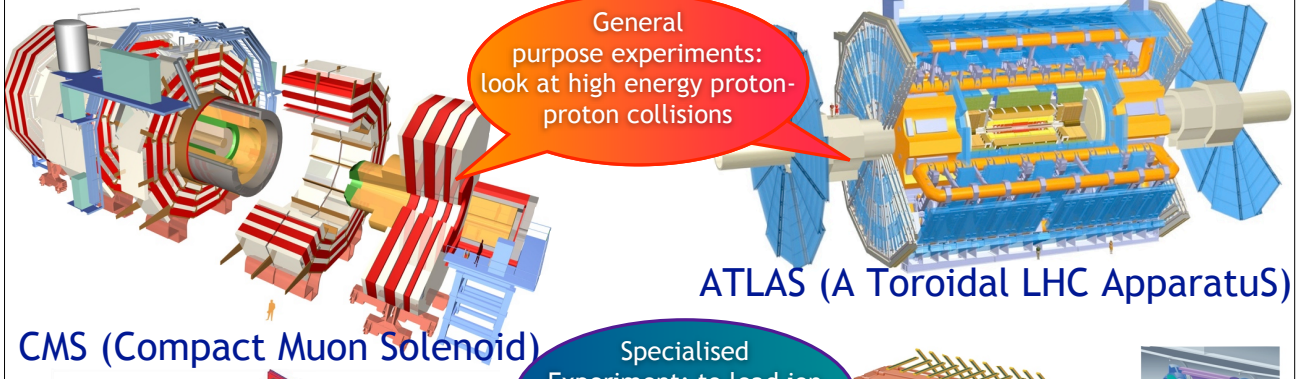
- E_{CM} = 1.96 TeV
- ~40% increase in interesting cross

Highlight: discovery of top quark

LHC Experiments

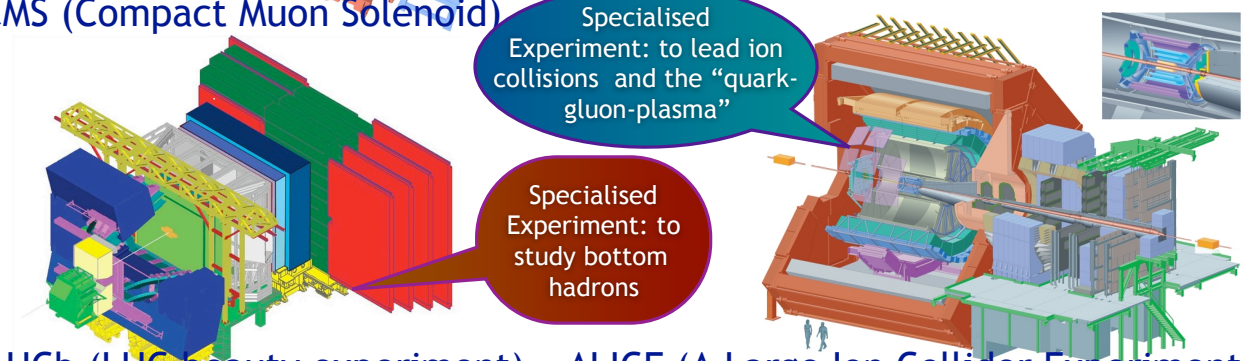
There are four points in the LHC where the beams collide.

Each of the four collision points hosts an experiment:



CMS (Compact Muon Solenoid)

ATLAS (A Toroidal LHC ApparatuS)

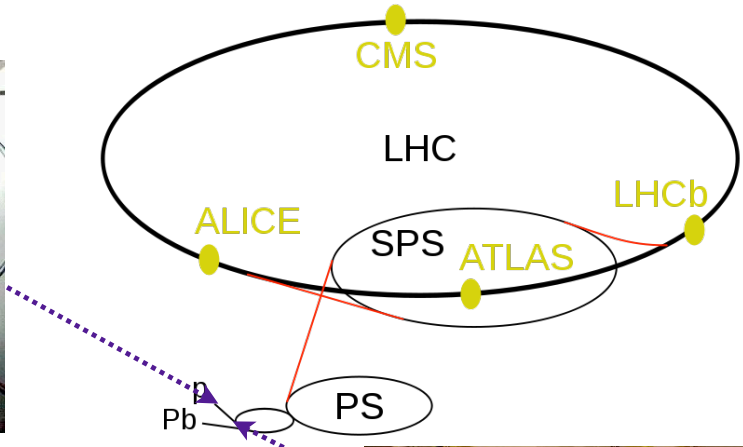


LHCb (LHC beauty experiment)

ALICE (A Large Ion Collider Experiment)

The CERN Chain of Accelerators

- Various accelerators and acceleration techniques are used to accelerate protons to 7 TeV



Proton source: bottle of hydrogen. (0.2ng /day)

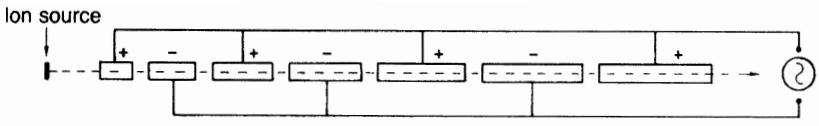
Hydrogen gas is fed into **duoplasmatron** source: which ionises the gas.

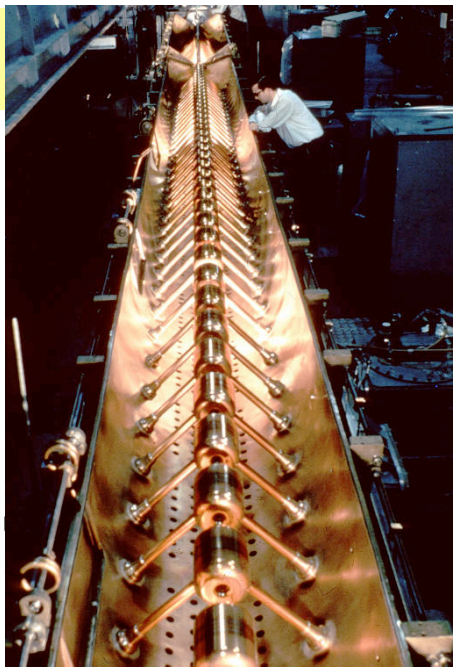
Output proton KE ~ 100keV

Next step "Linac 2" accelerates protons to 50 MeV

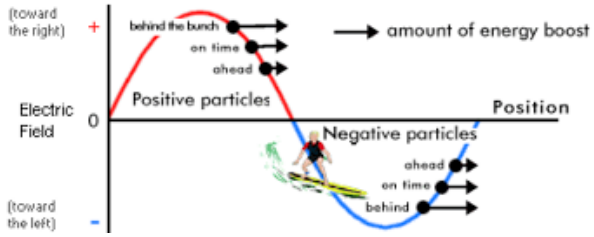
Linacs

- Next step is Linac2 (**lin**ear **ac**celerator)
- Charged particles in vacuum tubes accelerated by very high frequency alternating current "Radio Frequency" (RF)
- RF frequencies typically a few 100 MHz
- Field strengths – few MV/m requires specialised power sources: "klystrons"



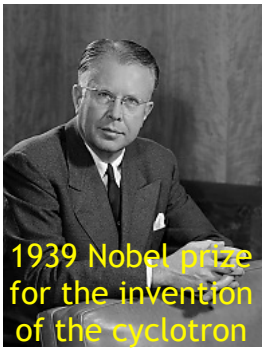


- The tubes act as Faraday cages: when the particles are in the tubes they feel no force
- Outside of the tubes they feel the potential difference between successive tubes, they accelerate forward
- Alternating current ensures that the difference always has the correct sign for acceleration.

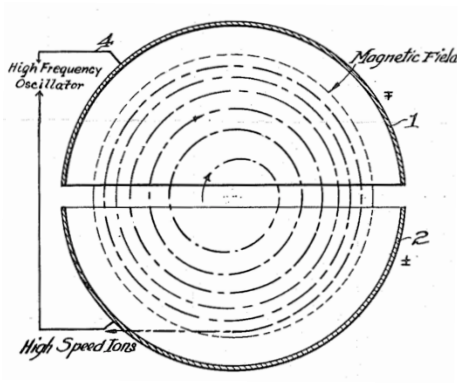


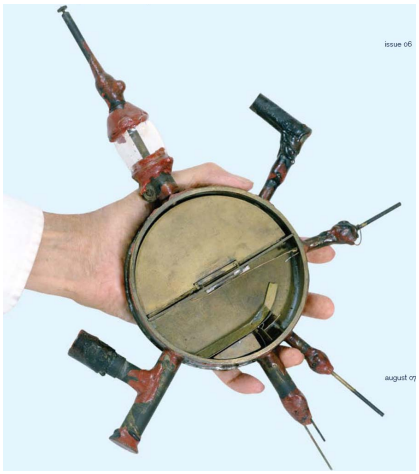
Cyclotrons and Synchrotrons

- The Cyclotron - invented by Ernest Lawerence
- Two D-shaped electrodes - perpendicular magnetic field
  - Constant frequency AC current applied to each electrode
  - Can to accelerate particles to ~10 MeV
  - At higher energies relativistic effects take over, circular path cannot be maintained need...



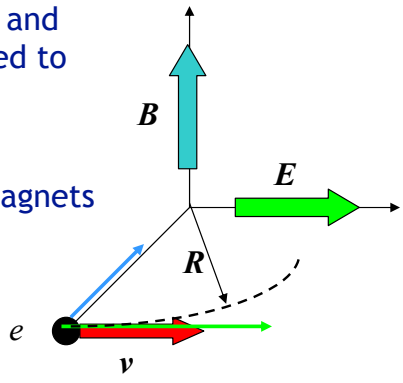
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$



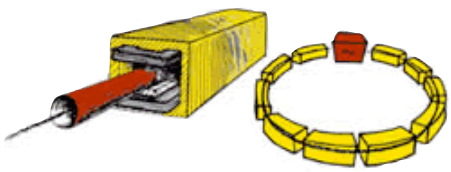


Synchrotrons

- Synchrotron accelerators use variable B-field strength and radio frequency E-field, synchronised with particle speed to accelerate charged particles to relativistic energies.



- Series of dipole (bending) and quadrapole (focussing) magnets



$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

- Beams have a constant radius in a synchrotron.
- In a circular accelerator $|\vec{p}| = q|\vec{B}|R$

$$p[\mathrm{GeV}/c] \approx 0.3\, B[\mathrm{T}]\, R[\mathrm{m}]$$

B: magnetic field strength

R: radius of curvature

⇒ For high momentum beams need high field and/or large radius

- Synchrotrons can be used as storage rings and colliders.

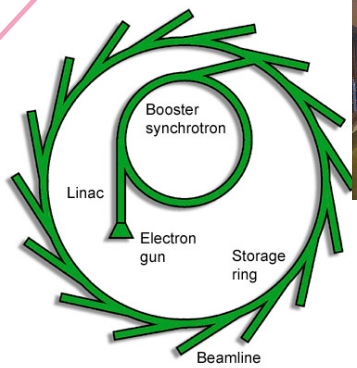
Synchrotron Radiation

- In a synchrotron the accelerated charged particles emit photons: **synchrotron radiation.**

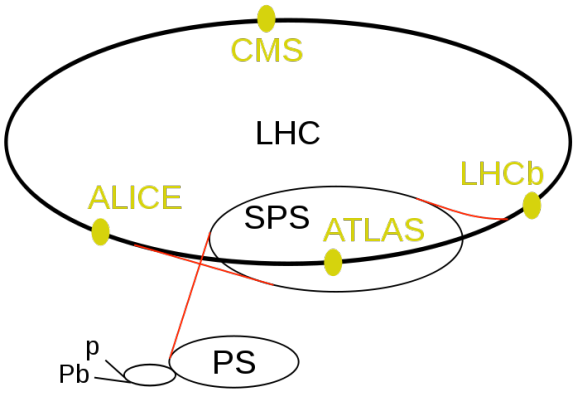
- The energy lost every turn depends of the energy and mass of the particle ($\gamma = E/m$) and the radius of the orbit, ρ:

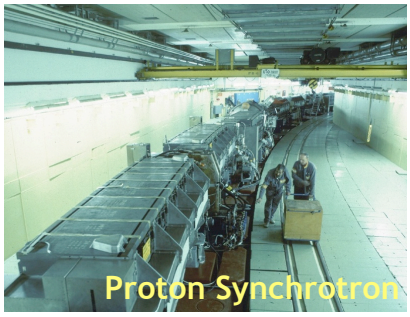
$$\Delta E = \frac{q^2 \beta^3 \gamma^4}{3\epsilon_0 \rho}$$

- Synchrotrons are used as high-energy photon sources
- In a storage ring, the energy lost due to synchrotron radiation must be returned to the beam to keep the collision energy constant.



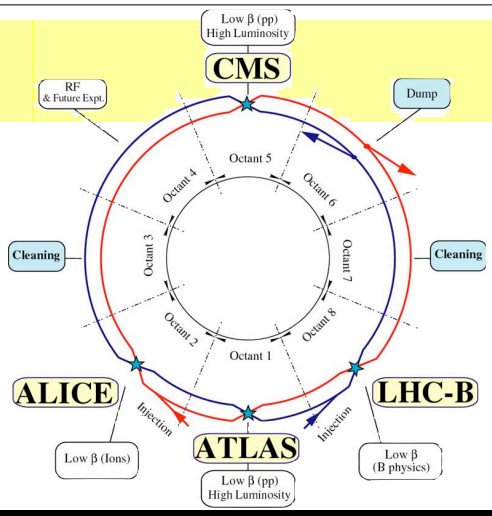
Synchrotrons in LHC Chain



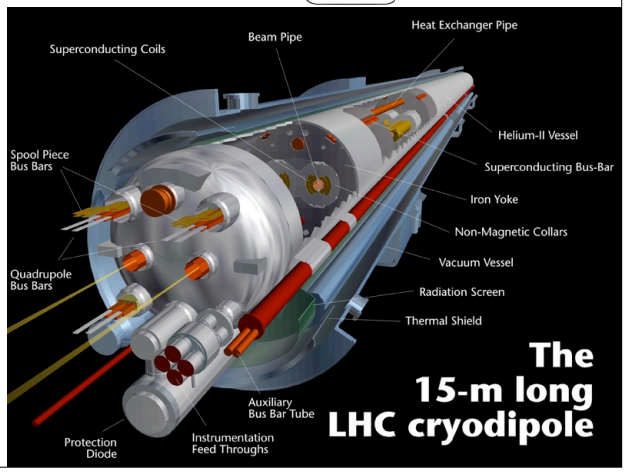


- Three synchrotrons pre-LHC:
  - **PS Booster:** accelerates proton from 50 MeV to 1.4 GeV
  - **Proton Synchrotron (PS):** accelerates protons from 1.4 GeV to 25 GeV
  - **Super Proton Synchroton (SPS):** accelerates protons from 25 GeV to 450 GeV
- **Protons are then transferred from SPS are transferred to LHC - also a synchrotron.**

The LHC Synchrotron



- LHC circumference is 27 km.
- LHC accelerates proton from **450 GeV** to **7 TeV** over ~20 minutes.
- ***B*-field** varies from **1.18 T** to **8.33 T**.
- Once at 7 TeV the beams are steered to collide at the four collision points.
- The accelerator chain is used once every 10 - 15 hours to create and accelerate enough protons to fill LHC. The two protons orbits are filled successively.
  - Main accelerating structure are 1232 15 m dipole magnets.
  - Magnets operate at 1.9K
  - Peak field in magnet coil 8.76T



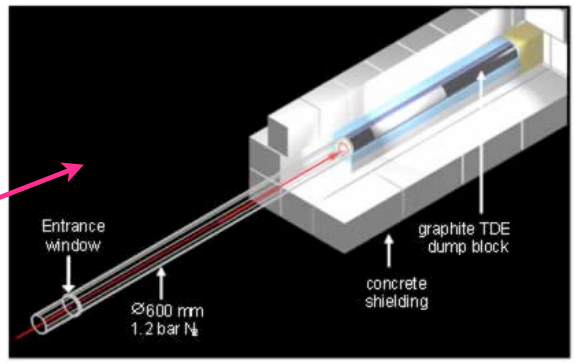
LHC Energy

- The beam is not continuous stream of protons: protons will be grouped into 2808 bunches, 25 ns apart, in each direction.
- Each bunch consists of up to ~1.15×10^{11} protons, ~1 cm long and ~1 mm across.

$$E_{\text{beam}} = N_p\, n_b\, \gamma\, m_p\, c^2$$

γ = Relativistic factor
N_p = Number of protons per bunch
n_b = Number of bunches

- With 1.15×10^{11} protons per bunch and 2808 bunches: $E_{\text{beam}} = 362$ MJ.
- This is equivalent to 120 elephants charging 120 elephants at full attack speed.
- Each individual proton-proton collision has an energy of 14 TeV: equivalent to two mosquitos flying into each other, **but in a very small area!**
- At the end of the 10-15 hour collision period, the beams are dumped into a dedicated beam dump: water-cooled graphite and steel surrounded by lots of concrete.



LHC Luminosity

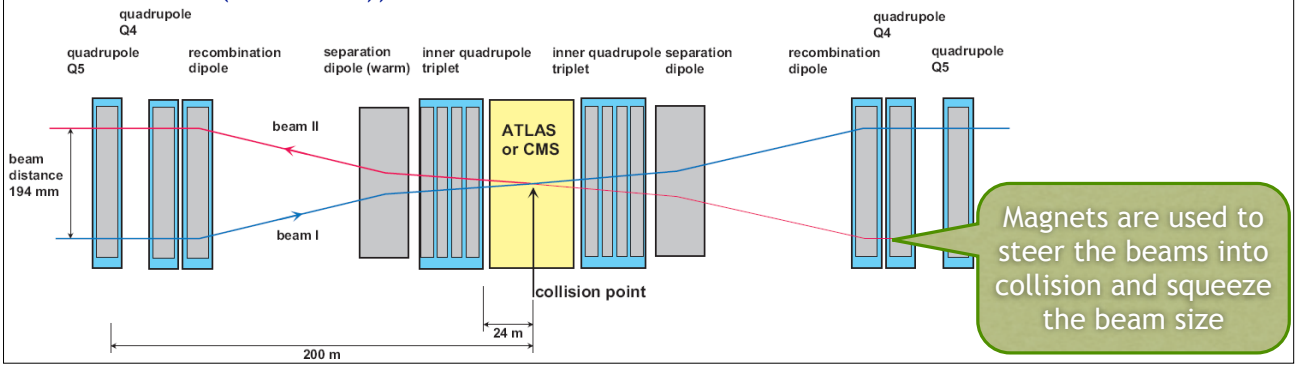
$$N(\text{interactions}) = \sigma \int \mathcal{L}\,\mathrm{d}t$$

- For a given process (eg creating a Higgs boson), σ is fixed for a given E_{CM}.
- To maximise number of events: maximise instantaneous luminosity, $\mathcal{L}$, and run for as long as possible.

$$\mathcal{L} = \frac{N_p^2\, n_\mathrm{b}\, f_\mathrm{rev}}{A}$$

f = Revolution frequency
A = Effective area of collision
γ = Relativistic factor n_b = Number of bunches
N_p = Number of protons per bunch

- At the collision point bunches are squeezed to 16 μm across to maximise luminosity.
- Design $\mathcal{L}$ for LHC is $10^{34}\ \mathrm{cm^{-2}\ s^{-1}}$: $O(100\ \mathrm{fb^{-1}})$ per year (100 times more intense than Tevatron (next best))



Summary

- We accelerate particles to obtain more E_{CM} in order to produce new, as yet, undiscovered particles.

- Long-lived charged particles may be accelerated in a magnetic field.
- An accelerator complex uses a system of **Linacs** and **Synchrotrons** to accelerate particles to the desired energy.
- Synchrotrons can also be used to store energetic particles.
- Synchrotron radiation: energy loss due to photon emission
  - ➡ energy need to be added back to beam at a collider
  - ➡ can be exploited produce high frequency gamma rays

- The LHC is a proton - proton synchrotron accelerator.
- Superconducting magnets operating at 1.9 K are used to accelerate the protons to 7 TeV.
- LHC is used to store the protons beams, and bring them into collision at four points - where the four experiments are located.
- LHC will be the world's highest energy accelerator and highest luminosity collider.