Large Hadron Collider (LHC)

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Today's Topic

1. Introduction to Large Hadron Collider (LHC)
   - How do justify the need for LHC?
   - Why hadron? Why large ?
   - Layout
2. Design of LHC
   - Important parameters of LHC
3. Key Ideas of Colliding Particles
   - Event Rate
   - Center-of-mass energy ($\sqrt{s}$)
4. Synchrotrons and Beams
   - Cyclotron Frequency
   - Betatron function $\beta(s)$
   - Emittance (ε)
   - Luminosity

Why Need An LHC?

- Probing smaller and smaller scale
  - Is necessary to understand the structure of matter and what they are made of (constituents)

$$\lambda = \frac{h}{p} \approx \frac{1.2\,[fm]}{p\,[GeV/c]}$$

De-Broglie wavelength of a proton is < 1.2 fm

For $\lambda < 10^{-3} \times 1.2\, fm \;\; p > 1$ TeV/c

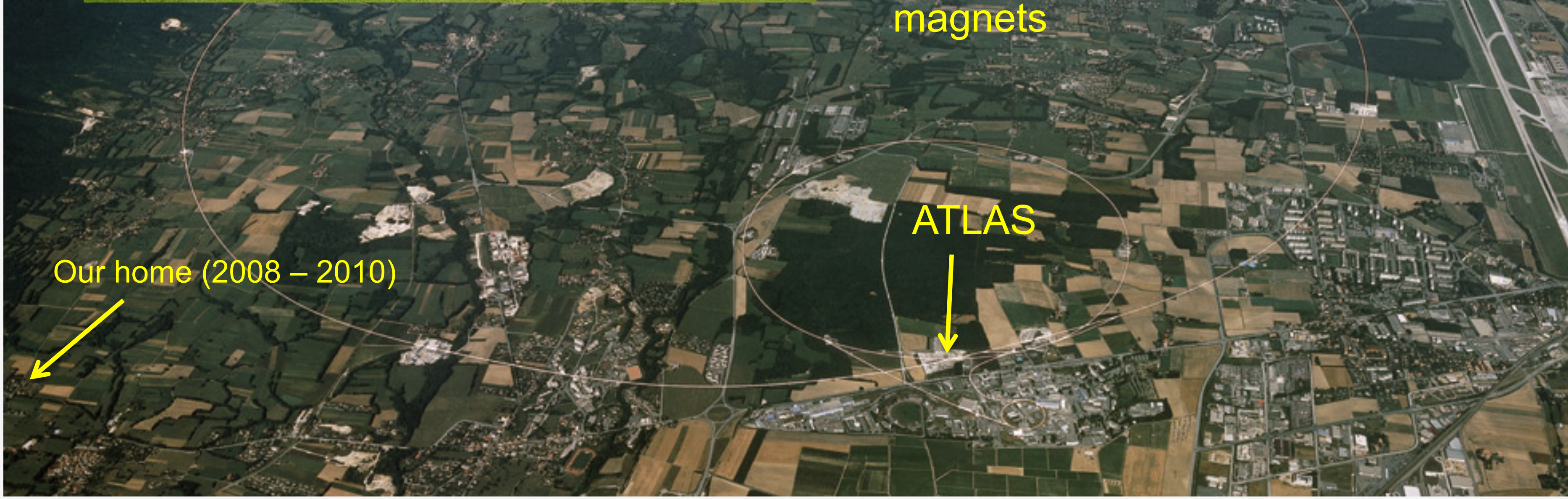
    - To probe a distance 1000 times smaller than a proton
- Search for new types of matter (or new particles)
  - Higher energies are needed to discover new particles
    - Many theories predict particles with masses > 1 TeV
    - Many of these processes are rare
      - their rate of production (cross section) is small
    - Surprising new results could be lurking. Need a probe like LHC

What’s Large About LHC ?

Hauling an ATLAS Magnet (toroid end cap)

Lake Geneva

27 km circumference
Highest energy collider ever built
Superconducting, super cooled magnets



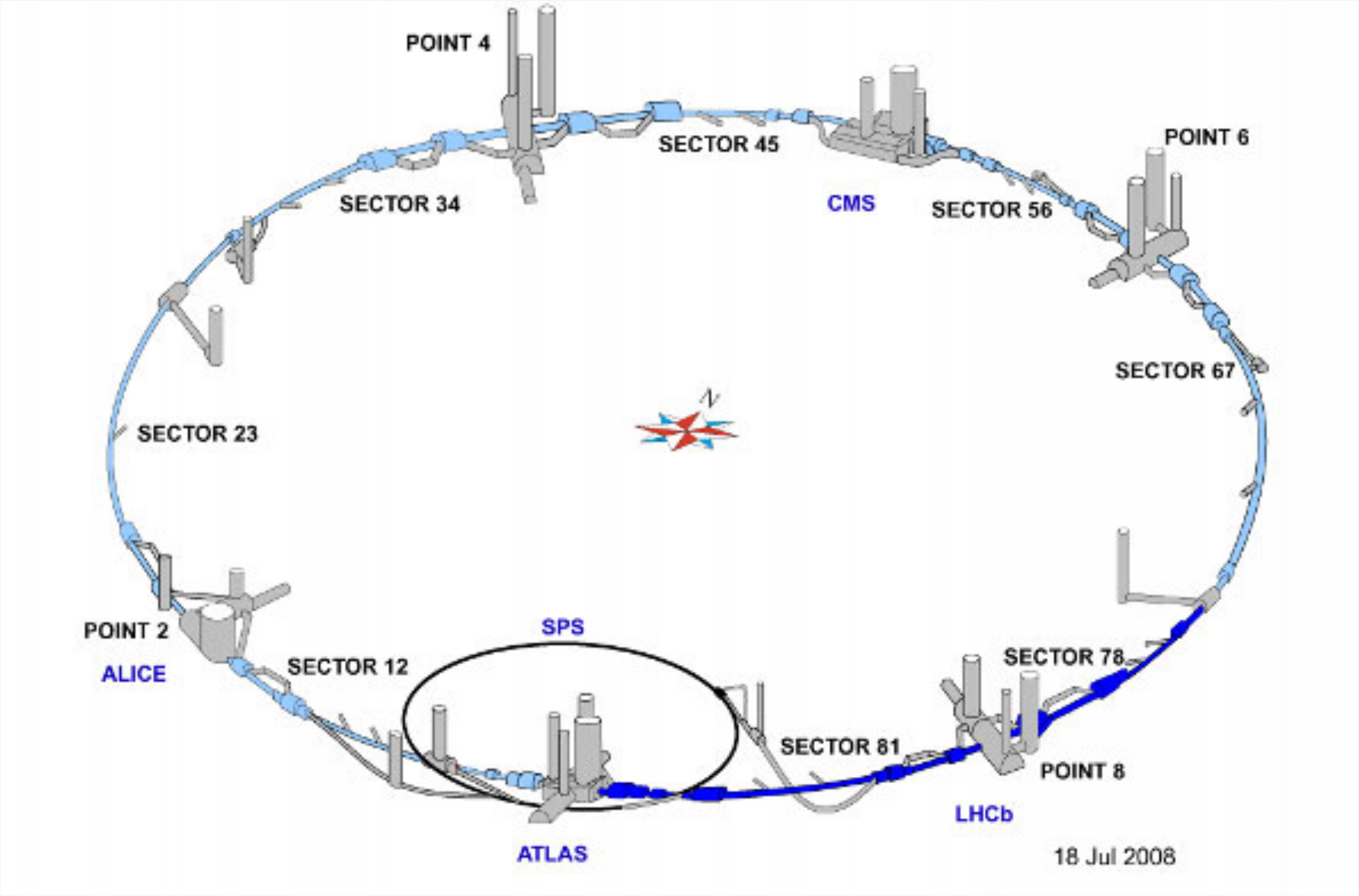
High Energy Colliders

Accelerator	Particle Type, Laboratory	Energy √s GeV	Years of operation
LEP-I	e^+e^- collider, CERN	91	1989 – 1994
LEP-II	e^+e^- collider, CERN	209	1995 – 2000
HERA-I	e^-p collider, DESY	27 + 800	1992 – 2000
HERA-II	e^-p collider, DESY	27 + 920	2002 – 2007
Tevatron, Run I	$p\bar{p}$ collider, Fermilab	1800	1987 – 1996
Tevatron Run II	$p\bar{p}$ collider, Fermilab	1960	2002 – 2011
LHC, phase I	**pp collider, CERN**	**7000**	**2010 – 2012**
LHC, phase II	**pp collider, CERN**	**14000**	**2014 – …**

HADRONS (Tevatron Run I through LHC phase II)

- Highlights:
- Phase 1: Higgs boson -- discovered July 2012
- Two year shutdown followed by Phase 2, which started in 2015

LHC Layout



- 8 crossing interaction points (IP's)
  - ATLAS, ALICE, CMS, LHCb experiments
- Accelerator sectors go in between the IP's
  - Sector 23 goes between 2 and 3, sector 34 goes between 3 and 4 etc.

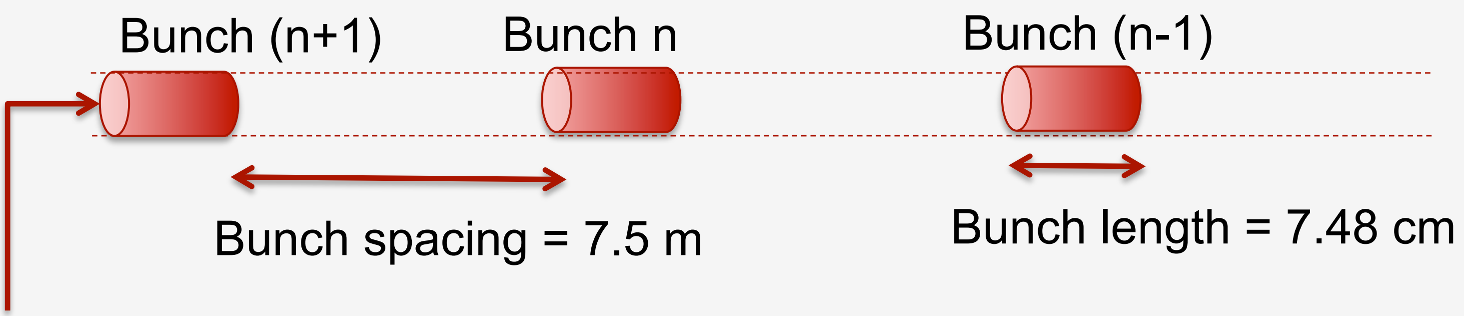
LHC Parameters

Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3ºC)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	7 TeV
Nominal energy, ions	2.76 TeV/u (*)
Peak magnetic dipole field	8.33 T
Min. distance between bunches	~7 m
Design luminosity	10^{34} cm^{-2} s^{-1}
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.1 x 10^{11}
Number of turns per second	11 245
Number of collisions per second	600 million

(*) Energy per nucleon

Proton Bunches

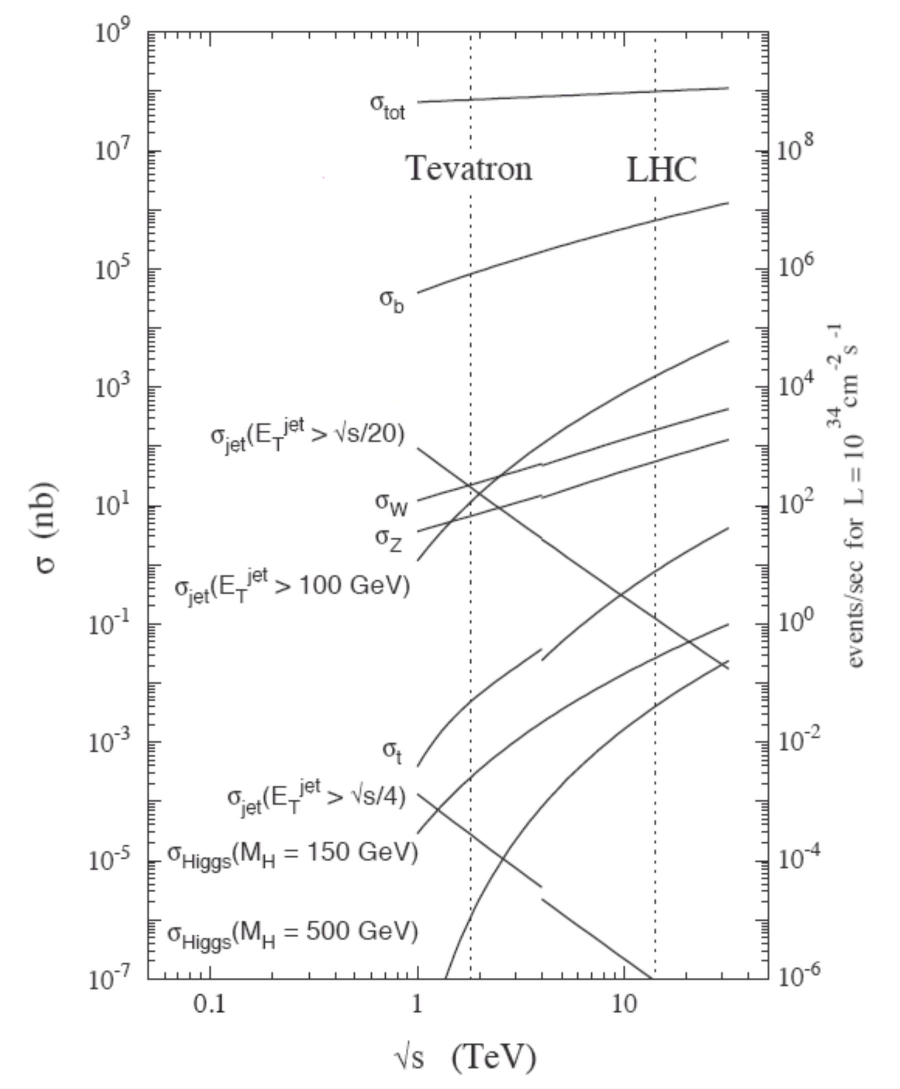
- Each beam is made up of bunches of protons
  - Each bunch is approximately a cylinder



- Effective Area (A) of a bunch
  - A = 0.2 mm far away from collision points
  - A = 16 μm at the collision or interaction point (IP)
  - Bunches get squeezed by quadrupole magnets as they approach IP
- After doing some math
  - Effective number of bunches around a 27 km ring = 2808
  - Since they are moving close to speed of light, the spacing between bunches arriving at IP is ~ 25 ns

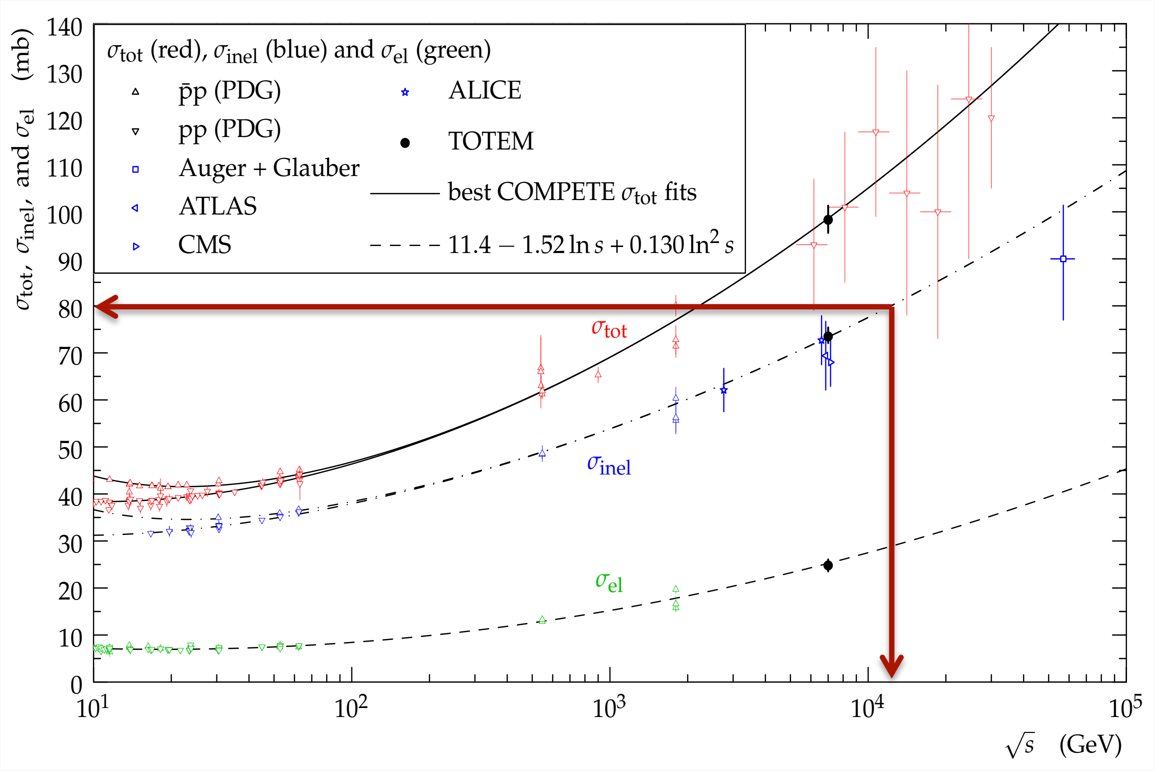
Event Rate

- Event
  - Any physical process that is allowed by nature and which obeys conservation laws (e.g., qq → Hγ)
- Cross Section (σ)
  - Probability that an event occurs (units of 1b = 10^{-24} cm^2)
  - Rare processes have small cross sections
- Luminosity = $\mathcal{L}$
  - Ability of the particle accelerator to produce the required number of interactions (cm^{-2} s^{-1})
- Event Rate
  - $\dot{n} = \mathcal{L}\sigma$



Example 1

- Find the rate of inelastic pp collisions at 14 TeV
  - L = 10^{34} cm^{-2} s^{-1}
  - $\sigma \sim 80$ mb = $80 \times 10^{-3} \times 10^{-24}$ cm^2 (at $\sqrt{s}$ = 14 TeV)
  - Event Rate = σL = $80 \times 10^{(34-3-24)}$ s^{-1} = 80×10^7/s

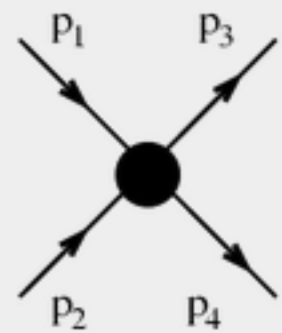


Example 2

- Find the event rate for the process qq → Zh
  - $L = 10^{34}$ cm^{-2} s^{-1}
  - $\sigma \sim 50$ fb = $50 \times 10^{-15} \times 10^{-24}$ cm^2 (at $\sqrt{s} = 14$ TeV)
  - Event Rate = $\sigma L = 50 \times 10^{(34-15-24)}$ s^{-1} = 5×10^{-4}/s
- At this rate, how long does it take to observe 100 events?
  - $t = 100/(5 \times 10^{-4}/s) \sim 55$ hours or > 2 days

Center of Mass Energy √s

$$a(p_1) + b(p_2) \longrightarrow c(p_3) + d(p_4)$$



- 2 → 2 collision (scattering)
  - p_1, p_2 are the four momenta of incoming particles (a,b)
  - p_3, p_4 are the four momenta of outgoing particles (c,d)

    - Defined as $s = (p_1 + p_2)^2 = (p_3 + p_4)^2 = 4E^2$ (Lorentz-invariant)
    - $\sqrt{s} = (E + E)$ which is the combined energy of the incoming particles as seen from the center-of-mass reference frame.
    - For LHC a=proton, b=proton, E = 7 TeV, $\sqrt{s} = 7+7 = 14$ TeV

Cyclotron Frequency

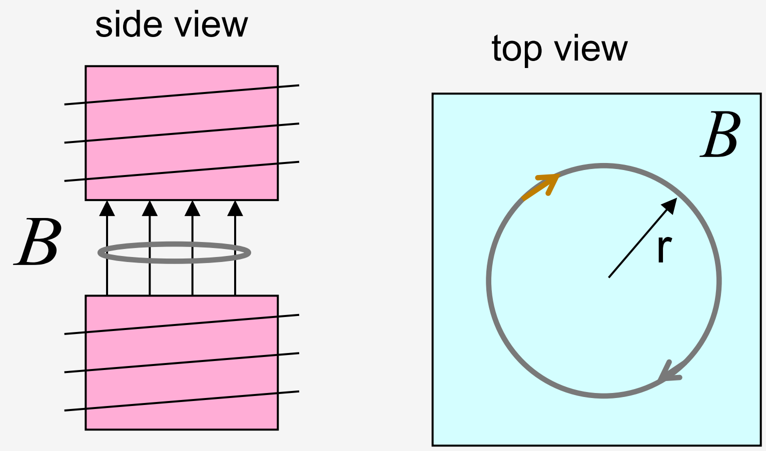
$$\vec{F}_c = \frac{mv^2}{r}$$

$$|\vec{F}_B| = |q\vec{v} \times \vec{B}| = qvB$$

$$\Rightarrow \; r = \frac{mv}{qB}$$

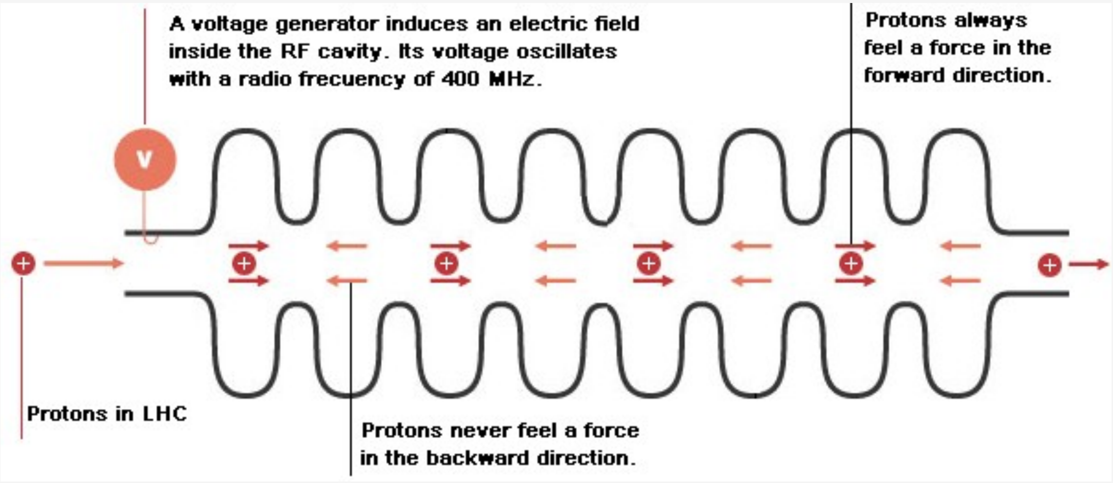
$$f_c = \frac{v}{2\pi r} = \boxed{\frac{qB}{2\pi m} = constant}$$

for a proton $\boxed{f_c = 15.2\,|B|\,MHz}$



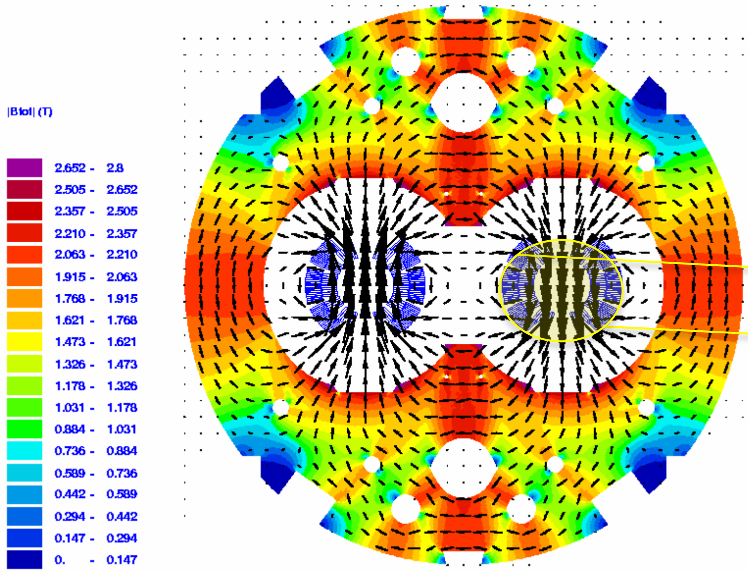
- Cyclotron
  - For small values of velocity ($\beta = v/c < 0.2$) this is a perfectly valid
- Synchrotron
  - We usually accelerate particles close to the speed of light $\beta \sim .99$
  - Relativistic correction to mass (replace m by γm_0)
  - As energy increases, f_c is no longer a constant!
    - f_c becomes smaller, *i.e.,* particles take longer to go around!

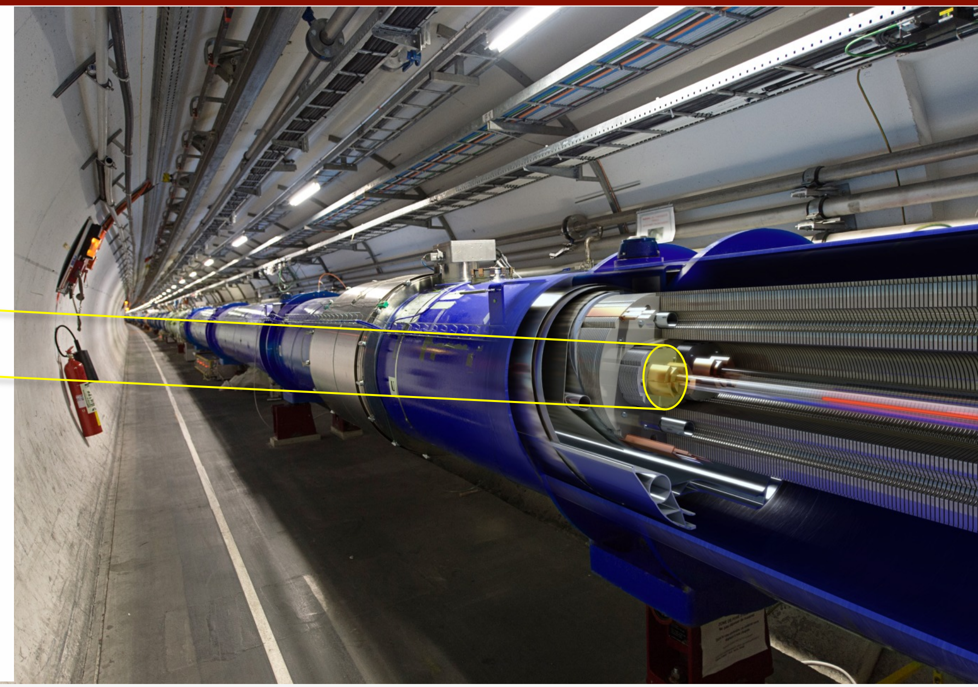
Packing a Punch

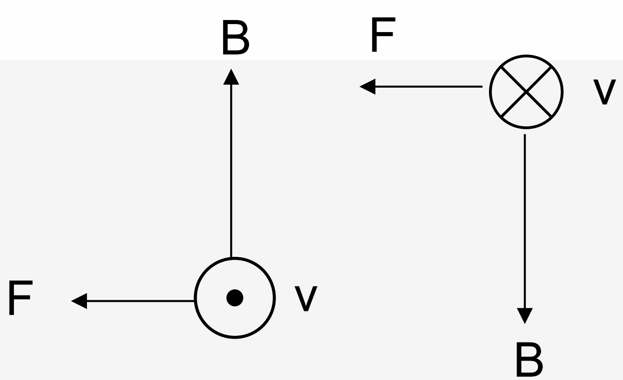


- Bunches of Protons
  - We need protons to be in a close bunch. Why?
    - in order to maximize collisions when the bunches “cross over” (*i.e.*, collide)
- Radiofrequency (RF) Cavities
  - Oscillating voltage at 400 MHz (radio frequency)
  - Help keep the protons to remain closely packed “bunches”
  - In addition, the bunches receive a “kick” in the forward direction
    - every time they pass one of these cavities they gain additional 16 MeV
    - At close to the speed of light, they complete **11245 laps in one second!**
    - To get from 0.45 TeV to 7 TeV, it takes about 37 seconds!

Bending Using Dipoles



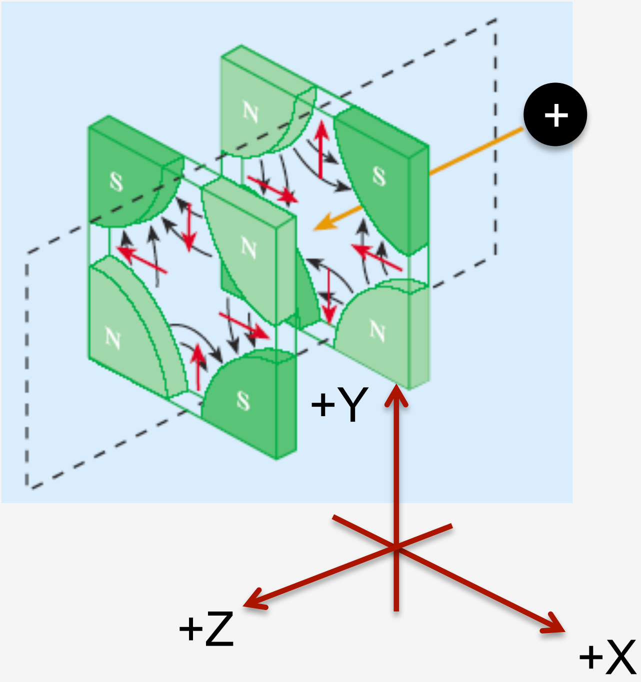


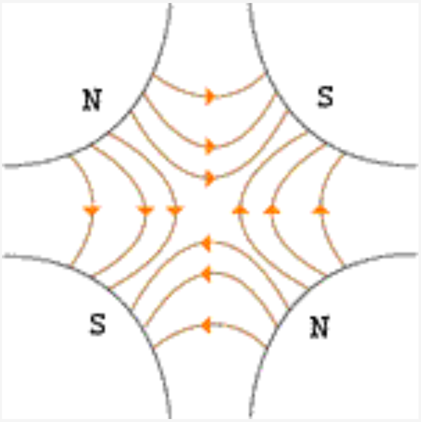


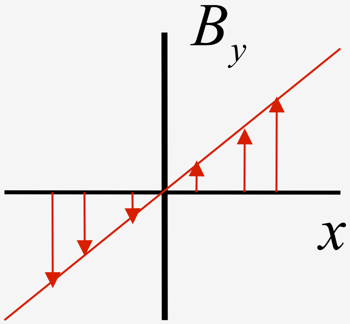
- The bending of protons occurs due to the transverse magnetic field
- The dipole magnet bends the protons and keeps them along the circular track just like a prism

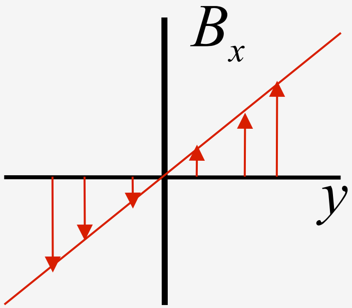
Focusing using Quadrupoles

- Imagine a bunch of protons
  - Yellow line indicates the path
  - First quadrupole magnet squeezes the bunch close together in the XY plane
  - Second quadrupole magnet does the same in YZ plane
  - This process continues to keep the bunch of protons within the vacuum tube in which they are circling around
  - LHC has a total of 858 quadrupoles

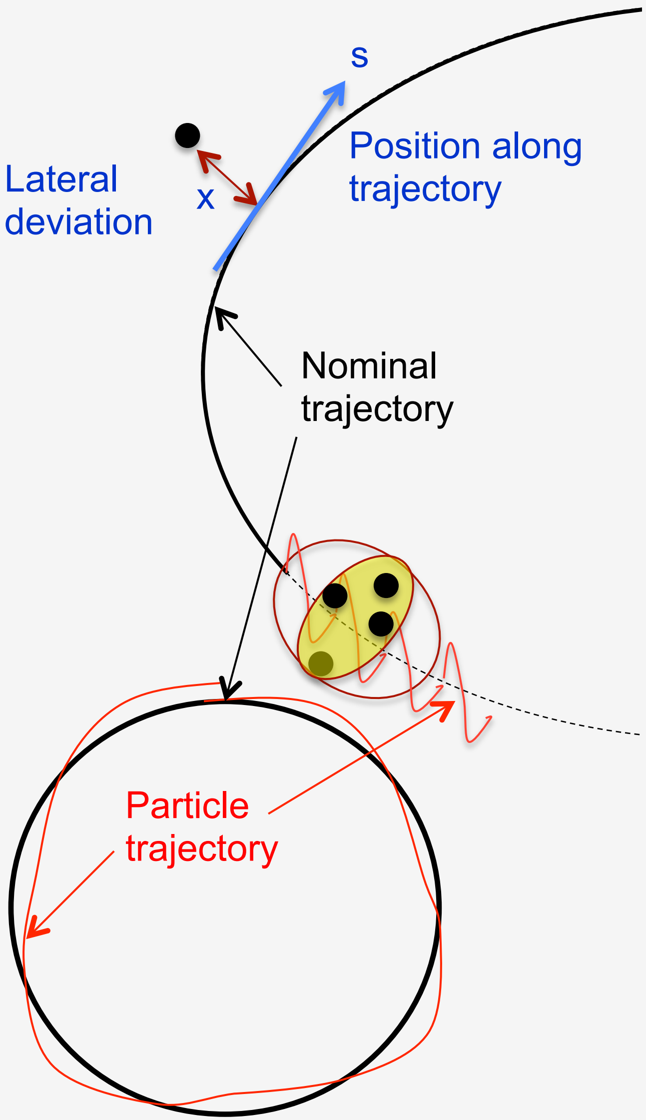








Betatron Function



- Nominal Trajectory (s)
  - Is defined by the dipoles
  - If we consider the protons in a bunch, they follow the nominal trajectory
- Lateral Deviation (x)
  - There are deviations in the XY and XZ planes from nominal
    - they oscillate around the nominal trajectory
- Beta function β(s)
  - Describes the lateral shift and gives us a "beam envelope" which would contain the protons in the bunch.

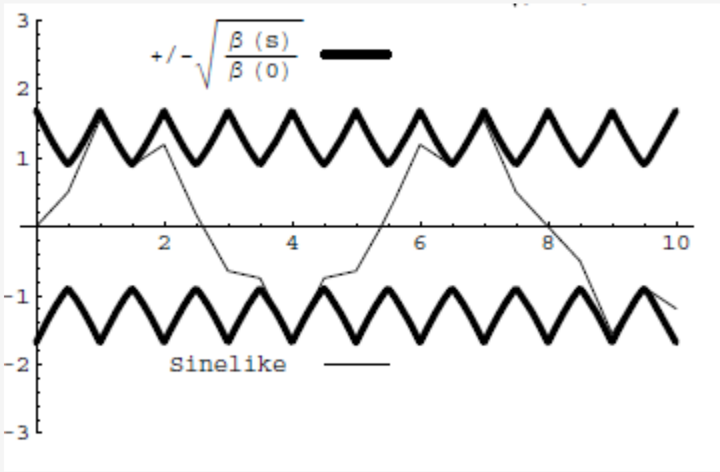
$$x(s) = A\sqrt{\beta(s)}\,\sin\left(\psi(s) + \delta\right)$$

$$\psi(s) = \oint_0^s \frac{ds}{\beta(s)}$$

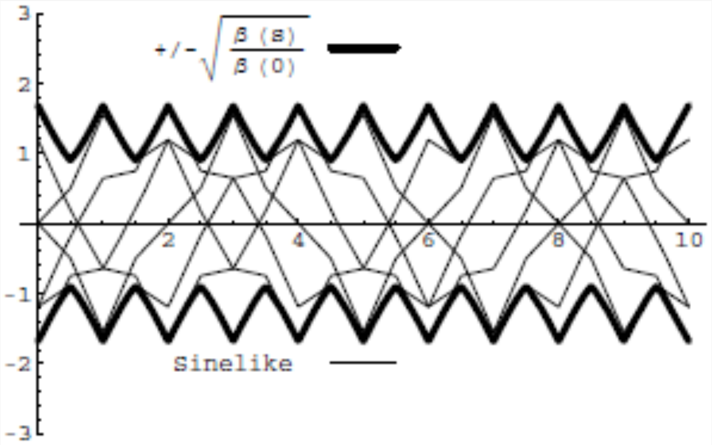
Number of oscillations for one turn => TUNE

Betatron Function

Normalized particle trajectory



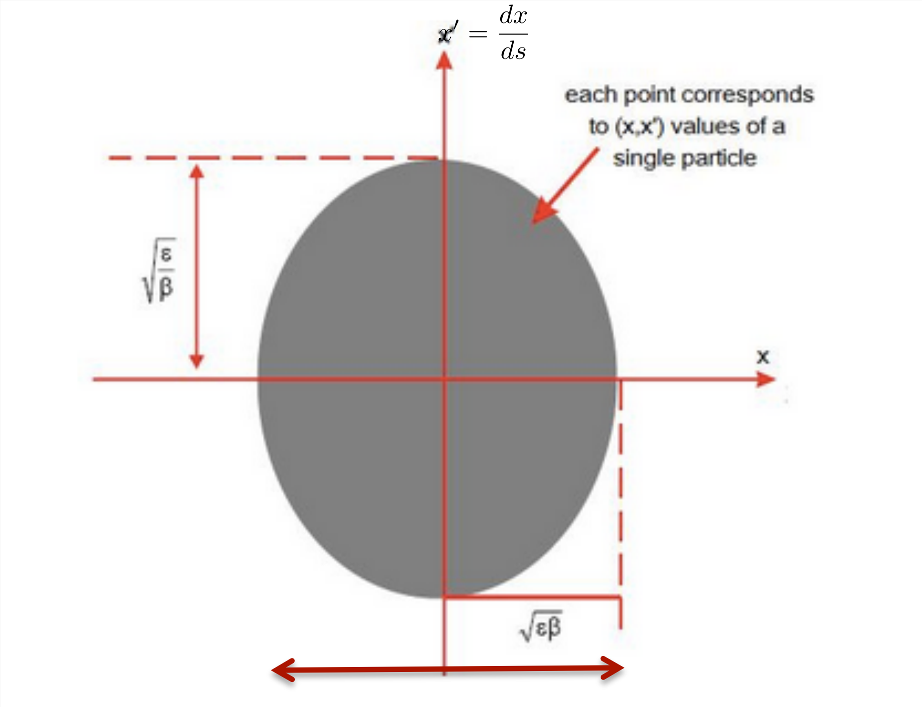
Trajectories over multiple turns



- Conceptual Understanding
  - Betatron function is the bounding envelope of the beam
    - You can think of it as the amplitude of the sine wave
    - Strong closely spaced quadrupoles lead to
      - Small β(s) , lots of wiggles
    - Weak sparsely spaced quadrupoles lead to
      - Large β(s) , fewer wiggles

Emittance

- Definition
  - x' vs x is a "phase space"
  - At any point along the trajectory, each particle can be represented by a position in this phase-space
  - The collection (ensemble) of all the protons will be inside an ellipse with a certain area. <u>This area is called "emittance"</u>
  - For a Gaussian distribution the RMS of emittance contains 39% of protons at LHC

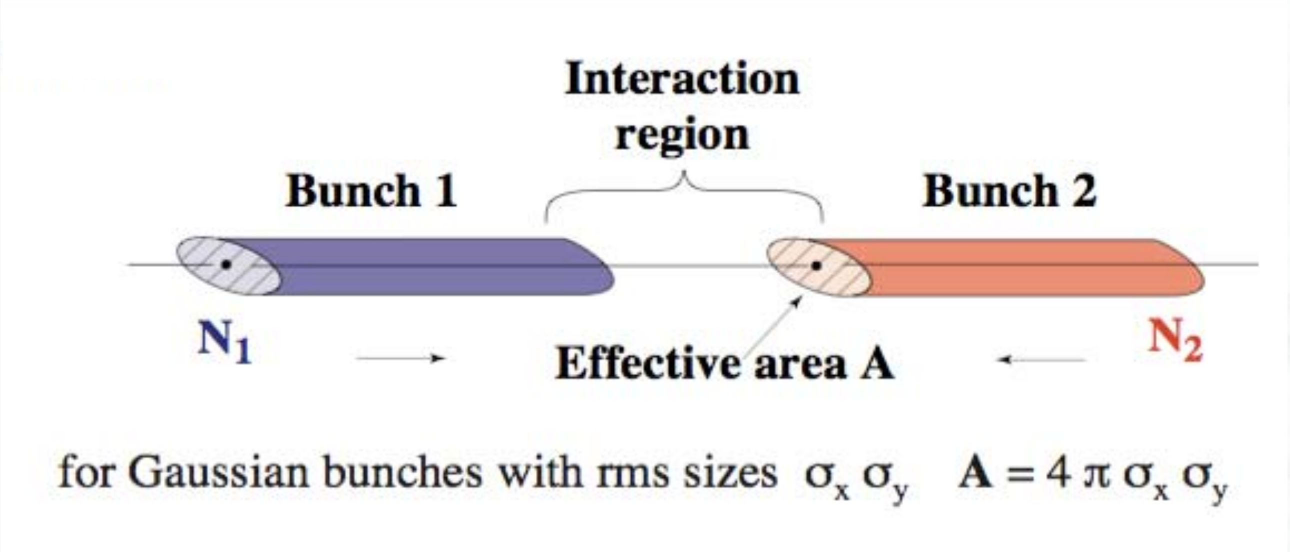


$$A = 4\pi\sigma_x\sigma_y \approx \left(2\sqrt{\epsilon\beta}\right)^2$$

$$\epsilon_{rms} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

http://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.complex_movement

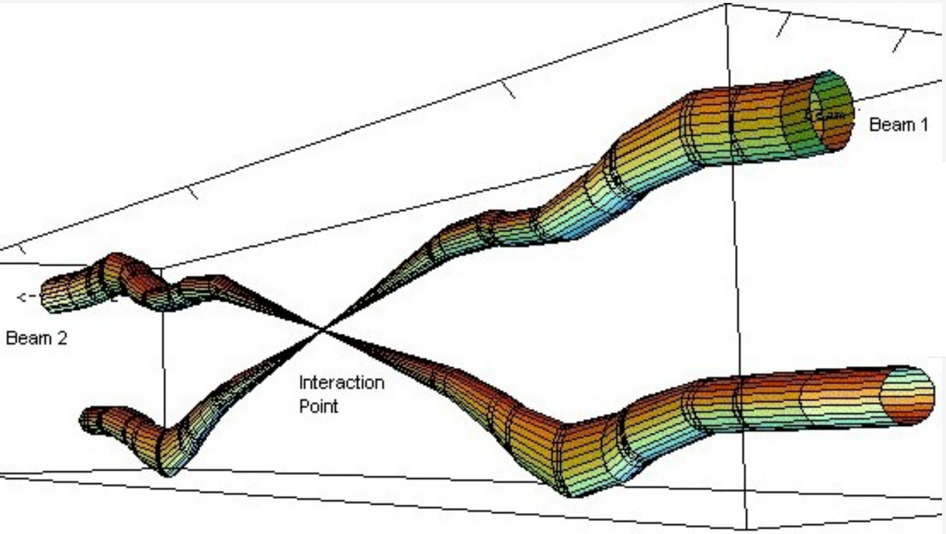
Luminosity

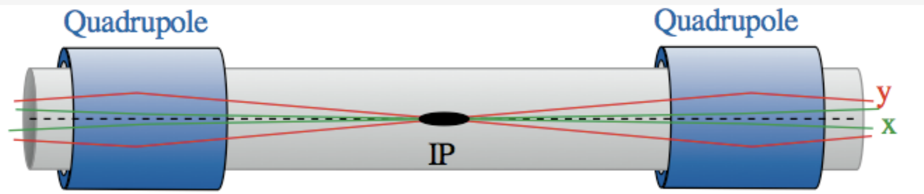


- Luminosity is a function of
  - number of protons in each bunch (N_1, N_2)
  - Effective area of collision at interaction point (A)
  - Bunch crossing frequency (f)

$$\mathcal{L} = f\frac{N_1 N_2}{A} = f\frac{N_1 N_2}{4\pi\sigma_x\sigma_y}$$

Luminosity at IP





- Accelerator physicists often express luminosity as a function of
  - Betatron function and Emittance
- The bunches are squeezed / focused at IP
  - Hourglass effect
  - Crossing angle
  - Betatron function $\beta \rightarrow \beta^*$

Increasing Luminosity

$$L = f \frac{N_b^{\,2}}{4\pi\sigma^2} R$$

- Collision frequency → f
- Particles in a bunch → $N_b^{\,2}$
- Geometrical factor: → R
  - crossing angle
  - hourglass effect
- Transverse size (RMS) → σ

$$L = f_{rev} \frac{1}{4\pi} n N_b^2 \frac{\gamma}{\beta^* \varepsilon_N} R$$

- Revolution frequency → f_{rev}
- Number of bunches → n
- Betatron function at collision point → β^*
- Normalized emittance → ε_N