The Next High Energy Particle Collider

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March 6, 2014

PHAS3441 - Group 9
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3.1 Introduction

Particle colliders are particle accelerators which collide two beams charged particles (e.g. quarks, leptons and bosons) or ionic nuclei into each other or a static target. This is achieved by accelerating the particles with electromagnetic fields to kinetic energies in the regions of giga and tera electron volts (velocities in excess of 0.999c). Well known examples are the Large Hadron Collider (LHC) at CERN and the Tevatron at Fermilab.

3.2 Collision Physics

3.2.1 Lepton vs. Hadron Collisions

Leptons are elementary particles, whereas hadrons are composed of quarks bound via the strong force. Collisions involving hadrons are actually interactions of the constituent quarks and are modelled as such [**?**]. Evidently the resulting interactions of hadron-hadron will be completely different from lepton-lepton; lepton collisions tend to be considerably cleaner and simpler to analyse [**?**].

3.3 Terms

3.3.1 Linear and Circular Colliders

Colliders can be broken down into two distinct categories, Linear Accelerators (linac) and Circular (ring) Accelerators. A linac collides two bunches of particles at a fixed point in the center of a linac. After the intersubsection, the remaining particles can no longer be used since they are travelling in the wrong direction. A ring collider can have multiple collision points along the track (the LHC has four detectors) and after a collision, the uncollided particles continue on to be used again.

3.3.2 Beam Energy

Collisions are at relativistic speeds so the energy is measured in the center of mass frame.

For a fixed target, the collision energy is proportional to the root of E, whereas two beam energy is proportional to 2E and is therefore more efficient [1].

[Why is higher beam energy better?]

3.3.3 Luminosity

Luminosity is a representation of the number of events per unit time and is a measure of the colliders performance.

$$Luminosity = \frac{nN_1N_2f}{A}$$

n = number of colliding bunches. $N_{1,2}$ = num of particles in each bunch. f = frequency of collisions. A = cross subsectional area of the beam.

[Maximising the luminosity is important to...]

[Compare some luminosity.]

3.3.4 Synchrotron Radiation

When charged particles move along a curved path, they emit synchrotron radiation [why/how?]. This detracts from the kinetic energy of the particle and so can impose limits on circular colliders. The amount of energy emitted is inversely proportional to the square of the path radius and proportional to the fourth power of the velocity. Since heavier particles travel slower compared lighter particles with the same kinetic energy, this is a limiting factor for circular colliders of light particles. Accelerating an electron to the same energies as a proton in the LHC would require several orders of magnitude more energy [how much?], hence linacs, which do not lose any energy via synchrotron radiation, are often used for light particle collisions.

Synchrotron radiation is used in research as it is the brightest source of artificial X-Rays.

3.3.5 Acceleration Gradient

The acceleration gradient is measure of energy imparted on a particle beam per unit length. For a linac, the particle beam only makes one pass and so the acceleration gradient must be very large to reach the required energies. In comparison, ring colliders can accelerate the particles gradually since they may travel around millions of time before collision. This also allows ring colliders to reach energies an order of magnitude higher than linacs before synchrotron losses become prohibitive.

3.4 Systems

3.4.1 Radiofrequency Cavities

RF cavities are used to accelerate the particle beam and are typically spaced along the length of collider [2]. Electromagnetic waves are contained within the cavity and the resulting EM field transfers energy to passing charged particles. The cavities oscillate at a fixed frequency. A particle arriving at exactly the right time will not be subjected to any force, yet ones ahead or behind will be relatively pulled or pushed to match the ideal velocity. This causes particles to bunch into precise groups. On each pass the bunch will increase in energy.

Klystrons produce EM waves which are fed remotely along a metal waveguide to the RF cavities. An electron beam is bunched via the same method as a RF cavity and then meets an EM wave at a time where the wave opposes the electron's motion, causing the electrons to slow down and transfer energy to the wave. Klystrons operate with a relatively low current, but voltage in the kilovolt region.

3.4.2 Beam Control

Aside from the bunching performed by RF cavities, the particle beam needs to be narrowed in the other two planes and, in a ring collider, bent along the path. A quadrupole arrangement of magnets has two north and two south poles at 90 degrees from each other in a circle pattern and is used for focusing the beam like a lens. The field produced has a minimal potential at the center of the beam, forcing stay particles towards the bunch [**Quadrupole**]. Dipole magnets are used to bend particles around the path of a ring collider [expand].

3.4.3 Cooling

Superconductors have an electrical resistance of almost zero. This allows the bending electromagnets to produce extremely strong fields and therefore bend a higher energy particle beam.

Superconducting RF cavities can operate at a higher duty cycle, lower beam impedance (as the apertures can be made wider) and higher efficiency of the RF source (Klystron costs increase exponentially with output).

The financial savings made from the reduced power requirements during operation is approximately offset by the need to supercool the equipment [**?**].

3.4.4 Storage Rings and Injectors

Many colliders use a mixture of linacs and rings in a chain to gradually raise the particle energy before the beam reaches the collider. These are referred to as booster or injectors. For example, a ring accelerator can be used to increase the energy of leptons with a low acceleration gradient (before synchrotron losses are a consideration) and then send the bunched particles into a linac for higher energy collisions.

Storage rings hold particles at time dilating speeds, this can be useful to store, filter and bunch slow to produce and/or rapidly decaying particles (e.g. antimatter).

3.4.5 Detectors

Detectors are present at the collision point of the particles to observe their momentum, energy and mass. Typically there are several different detectors, each observing a different property.

Closest to the collision are the tracking devices, which observe the path of the particles by their interference with matter, similar to a cloud chamber. Weakly interacting particles are harder to observe. Momentum can be deduced from the deflection of the particle in a magnetic field.

Calorimeters then detect energy as particles are forced to deposit their energy into materials. Different materials are stacked in layers for strong and electromagnetic force interactions.

Velocity of particles, which combined with momentum can determine mass, [TBC - Cherenkov radiation - http://home.web.cern.ch/about/how-detector-works].

Muon detectors are the furthest out, since they need to be large to detect weakly interacting particles.

4 Review of Proposed Colliders

4.1 ILC

4.2 CLIC

4.3 TLEP

4.4 LHeC

4.5 Muon-Muon

4.6 SAPPHIRE

5 Comparison of ILC and CLIC

5.1 Introduction

Although all the colliders we reviewed have their advantages and disadvantages, we have decided to look into two in more depth: ILC and CLIC.

These colliders have a lot in common. They are both lepton colliders, meaning that they are able to produce clean collisions as the particles do not divide after the collision, and therefore lead to precise measurements. This is in contrast to hadron colliders such as the LHC, which produce collisions in which many particles are released, and are called dirty collisions. We have decided to choose lepton colliders, leading to clean collisions, as these are best to determine specific properties of particles such as top, bottom and Z quarks, as well as the Higgs boson. This also allows us to continue the momentum following the discovery of the Higgs boson, by probing it further now that we know its energy level. A lepton collider means that a specific energy range can be chosen, in contrast to colliders such as the LHC where the actual energy range of any collision is can be unknown.

They are also both linear colliders. Although circular colliders such as TLEP can generate large energies, they lose energy to synchrotron radiation, which does not occur with a linear accelerator. This problem could be solved by using a muon collider, as muons have such a small mass that any synchrotron radiation is negligible. However, any plans for muon colliders are far from complete, and the technology needed is unfeasible in the near future. They also both have high maximum energies of 1TeV and 3TeV respectively. This may not seem high in comparison to the 100TeV of the VLHC which consists of TLEP using LHC as an injector; however that project would only begin after the LHCs lifetime which is a significant amount of time for the scientific community to wait approximately 40 years.

In addition, ILC and CLIC are the most feasible, as their plans are the most finalised and viable. This is especially true in comparison to colliders such as muon colliders which are completely unfeasible so far and will be for the near future. They use technology which has either already been established or is in the final stages of testing, and they have already found sites to use. They also have plans for funding, whether they are being funded partly by governments, i.e. Japan for ILC, or will be funded by CERN, i.e. CLIC.

5.2 Cost, feasibility etc.

6 Conclusion

References

[1] C. Anastasiou, L. Baudis, and V. Chiochia. *Particle Physics Phenomenology 1, Chapter 4*. http://www.itp.phys.ethz.ch/education/hs10/ppp1/PPP1_4.pdf. Institute for Theoretical Physics, Zurich.

[2] CERN. *Radiofrequency Cavities*. URL: http://home.web.cern.ch/about/engineering/radiofrequency-cavities (visited on 09/02/2014).