PC4521 - Frontiers of Particle Physics - Lectures 1&2

There are no recommended books, as the course is too recent. Recent physics magazines / journals could provide extra information, but likely at a lower / higher level than this course.

Accelerators vs. Colliders

Fixed Target Accelerators take a beam of charged particles (normally protons or electrons), accelerates them and plows them at high energy into a target (normally solid, but it can also be liquid [e.g. H_2] or gas). The detector is after the accelerator and target due to conservation of linear momentum – the incoming particles have a lot of momentum, so there has to be a lot coming out. Vertical momentum is cancelled out post-target, as there's none coming in.

The produced particles have forward kinetic energy to match the incoming momentum. This is generally a waste of energy, and is overcome by *colliders* having two equal and opposite momenta beams (protons, electrons, etc. - anything that's charged). There is then no net momentum before the interaction, and hence none after the interaction, so is more economical. Particles produced are spewed isotropically about the interaction point, but kinetic energy is not wasted to match the momentum.

The energy of the accelerator can be calculated via

$$M_{inv}{}^2 = \left(\sum E\right)^2 - \left(\sum p\right)^2$$

The invariant mass is the energy that is actually useful – i.e. goes into the creation of new particles. For a symmetric collider, the momenta cancel, hence the CM energy is:

$$M_{CM} = 2E_{Beam}$$

Advantages of Colliders:

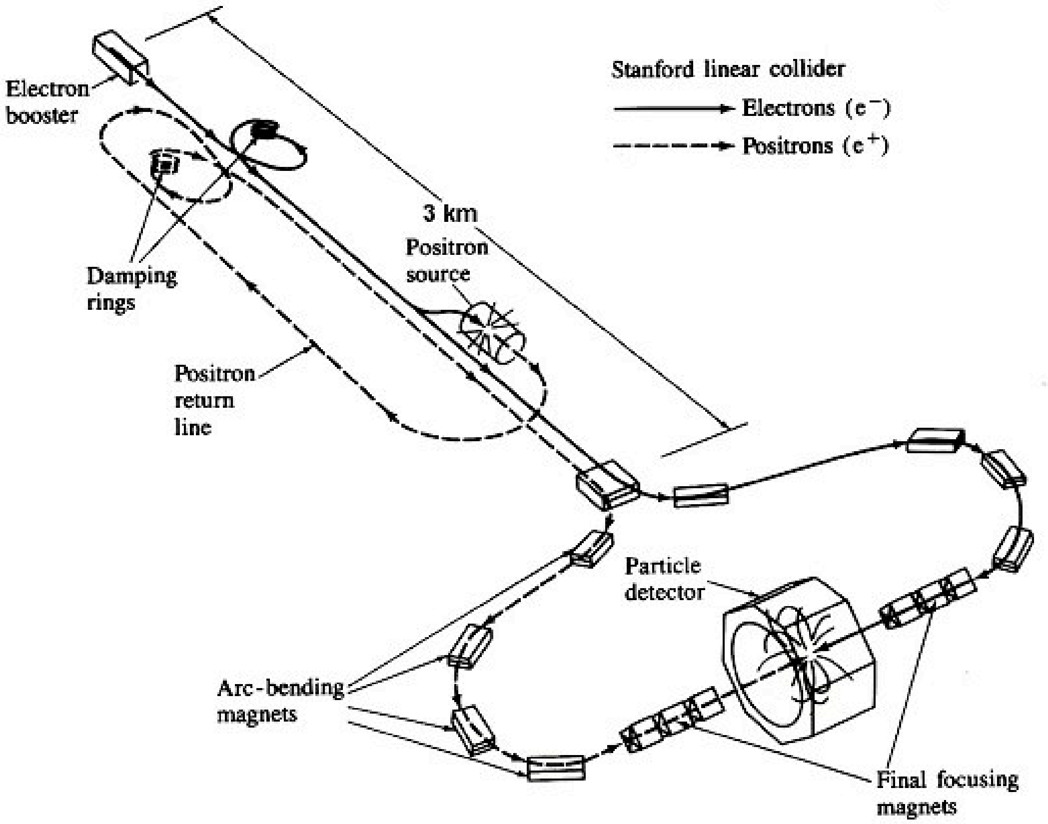
- Have higher energies in the centre of mass (CM) frame.
- Lab frame is symmetrical to the CM frame. Particles are produced uniformly in the lab, and so in principle it's easier to detect them (in accelerators, all the particles tend to be in a single high-multiplicity, collimated jet – which is more difficult to technically measure.
- $\left(e^+e^-\right)$ Can have a pre-set, adjustable CM energy. (Not as good with protons – they have constituents, which don't have precisely determined momenta. A single particle's momenta is easily known.)

Advantages of Accelerators:

- They have higher event rates – higher density targets (you're not aiming to collide two small low-density beams, you're aiming to hit a much more dense colliders with the beam)
- Can produce a collimated beam of secondary particles. Particularly useful for neutrino physics (particle → π → $\mu + \nu_\mu$) - this is having a resurgence lately, as it is now thought that they do have mass (looking for a variation in the neutrino type, "neutrino mixing". Typically putting the neutrino beam through the earth, and detecting them on the other side – possible with an accelerator but not with a collider).

This course will be focusing on colliders, not accelerators (Manchester's not involved with any accelerator projects).

Colliders come in three shapes – the standard circular synchrotron, a linac (LINear ACcelerator)- where you accelerate the particles (electrons + positrons) along a line, then swing them round to a right-angle and collide them (see picture below) – or two linacs bringing particles to a single point (i.e. facing each other).



Synchrotrons:

- LEP e^+e^- at CERN. Closed down about 5 year ago to make way for LHC
- Tevatron $\bar{p}p$ at Fermilab
- LHC pp at CERN
- HERA $e^{\pm}p$ at DESY, Hamburg

Will be focusing on the first three.

Synchrotron has a radius R. Has magnets around it to keep the charged particles in a circular orbits. It occasionally has *RF klystrons*, radio-frequency cavities that are fed with a radio frequency which is in phase with the pulses of beam particles, which feeds the particles with extra energies. (AC voltage, rising when particles are in it, falling when they're not). They have to change their frequency as the energy of the particles increases, hence why it's called a synchrotron. Particles go round many many times to gain enough energy, before they're collided in the detector.

If the opposing particles are antiparticles, then they go in opposite directions – if electrons go round one way, then the magnetic fields used will automatically be suitable for positrons going round the other way – hence you can use the same vacuum tube. If you're not using antiparticles, then you need to have two vacuum tubes.

LEP has a circumference of 27km. Particles are going at roughly the velocity of light. A typical fill is a couple of hours – hence the particles go round hundreds of millions of times. This means that it doesn't matter that the target is fairly diffuse – you can keep on sending the particles around until they hit something.

Main advantage – multiple (hundreds of millions of) collision opportunities.
Main disadvantage – they have magnets which are bending the particle trajectories, i.e. accelerating the charged particle. This leads to synchrotron radiation / (Bremsstrahlung).

Synchrotron radiation $\propto \frac{1}{(mass)^4}$, so low mass leads to a very high synchrotron rate.
Hence it is far less of an issue for machines which use protons and the like, which have a very high mass.

Energy loss / revolution:

- Electrons: $\sim \frac{10^{-4} E^4}{R}$ MeV/turn. E in GeV, R in km.
- Protons: $\sim \frac{10^{-5} E^4}{R}$ MeV/turn. E in TeV R in km.

Take the 27km CERN tunnel. LEP was e^+e^-, so $\sim 2GeV/turn$ for $100GeV$ electrons. This is about the limit for e^- synchrotrons. LHC is pp, so $\sim 5KeV/turn$ for $7TeV$ protons.

Limit for synchrotron energy loss for LEP happens at about 100GeV/beam. $\equiv 180TeV$ for protons. At the LHC, it's only 7TeV – but synchrotron energy loss is a load on the cryogenic system.

LEP has a very low magnetic field – concrete with a few layers of iron. LHC needs hugely powerful magnets, however – and the only way to generate those is if they are all superconducting magnets. Hence the whole 27km has to be supercooled. But there's 5KeV of heat coming from the beam (synchrotron radiation) – this is bad. Need to balance the heat / cooling to keep the system at the correct temperature.

LINAC has no synchrotron radiation. Most famous one is SLC at SLAC. It has rf klystrons along the beam. There's a small delay in the beams, so that electrons go down it first then positrons. The beams are then bent round, and brought together. Energy is typically 50GeV, along a 3km linac. You do get synchrotron at the curves, but you only get it once. Disadvantage is that you only have one chance at collision.

Next Big Thing: two linacs bringing two separate beams together. Has no syntrotron radiation, but there's only one chance of collision.
ILC: International Linear Collider, 2015. 500GeV electrons/positrons. Length ~ 40km
CLIC at CERN: 1.5TeV

Luminosity
Energy is important. Increase energy by:

1. Using colliders
2. RF power
3. Increase the radius of the machine
4. Use linear colliders

Need to have "high intensity" to ensure probability of particle collisions. "Intensity" of a machine is described by "Luminosity" L. Event rate $\propto$ "interaction cross-section" – a product of both the physics and the machine.
The observed event rate $R = L\sigma_{\text{int}}$, i.e. the machine luminosity times the physics cross-section.

If $\sigma_{\text{int}} = \sigma_{tot}$, then $R =$ total event rate.
If $\sigma_{\text{int}} = \sigma$ for a specific process, e.g. Higgs production, then $R =$ event rate for Higgs production.

Particles going clockwise are Particle 1, going anti-clockwise are Particle 2. The particles are constrained in bunches, length dependant on the RF structure – typically a few cm's. If n_1 and n_2 are the number of particles in colliding bunches of cross-section F $\left(cm^2\right)$, f is the revolution frequency and b is the number of bunches in the machine, then

$$L = \frac{n_1 n_2 f b}{F}$$

$$\left[L\right] = \frac{\left[no\right]\left[no\right]\left[s^{-1}\right]\left[no\right]}{\left[cm^2\right]} = \left[cm^{-2}s^{-1}\right]$$

Squeeze beams by quadrupoles, similar to how you focus a beam using lenses. There is a disadvantage to constantly be shrinking the beam – coulomb law will push them back apart – so only do the squeezing just before you collide them.