- HW level? Interest?
- Problem 4 D: Try it!
- No lecture on Thursday

Particle Physics Detectors Lecture 9

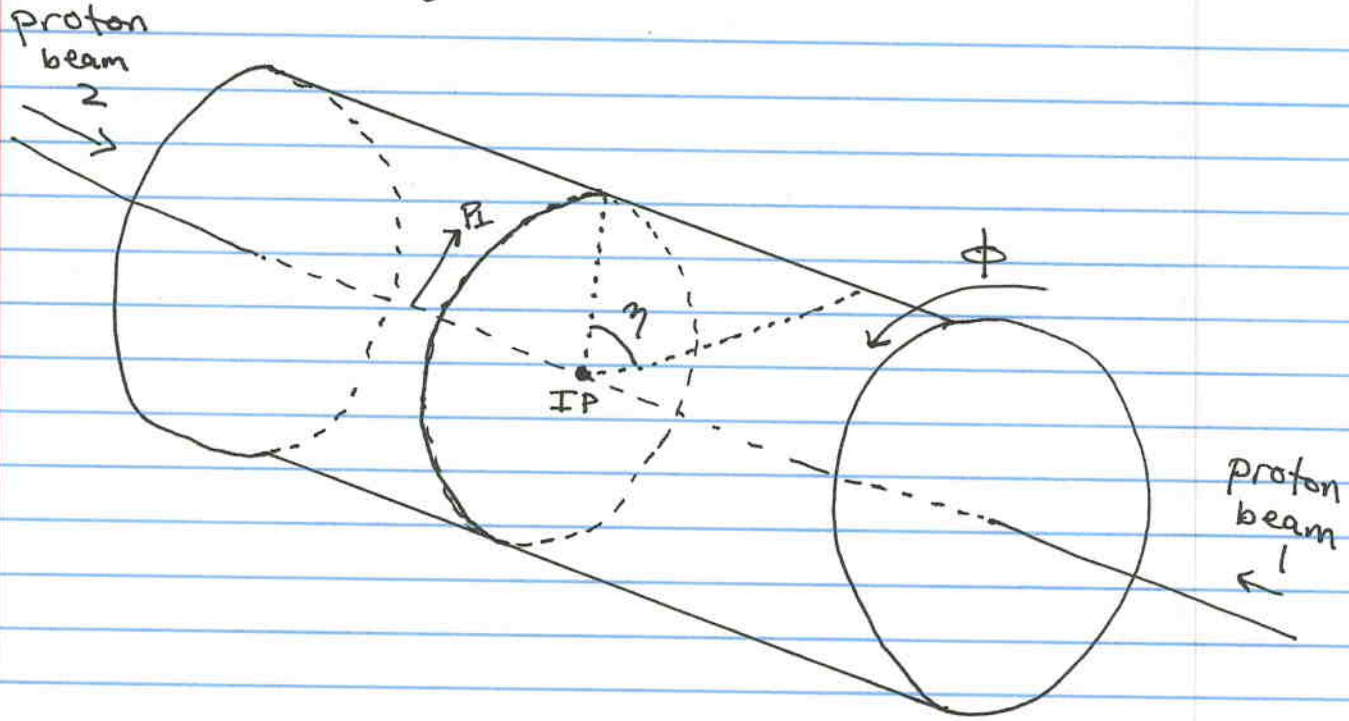
In this shortened week (remember: no lecture on Thursday, February 23!) we'll spend today's lecture discussing particle physics detectors and experiments. After today, we will have a sufficient foundation necessary to study the strong and weak forces, which we begin next week.

The first thing we should do in any particle physics experiment is determine what it is we want to measure. A central goal of particle physics is the measurement of particle properties, like their mass, electric charge, spin, etc. When we measure these properties, then we know how particles will interact with other particles, what forces they are sensitive to, etc. It turns out that measuring mass directly is hard to do (and hard to define what that means), but we can determine mass if we measure the energy and momentum of a particle. The mass is then:

$m^2 = E^2 - \vec{p}^{\,2}$, and note that momentum

is a vector; we need to measure all 3 components somehow. Measuring charge is a bit tricky as well; we can't rub amber with lamb's wool and see how a particle moves easily! (Okay, that's a bit unrealistic :.)
To discuss these and other issues regarding particle physics detection, I want to couch it in the introduction and discussion of one of the experiments at the LHC. We'll discuss ATLAS (the textbook discusses CMS a bit) but the general properties and techniques are widely applicable and used.

For this lecture, I will draw a schematic version of the ATLAS detector, and we will fill in parts as we define them. Both the ATLAS + CMS detectors are cylinders, with the colliding proton beams along the axis of the cylinder:

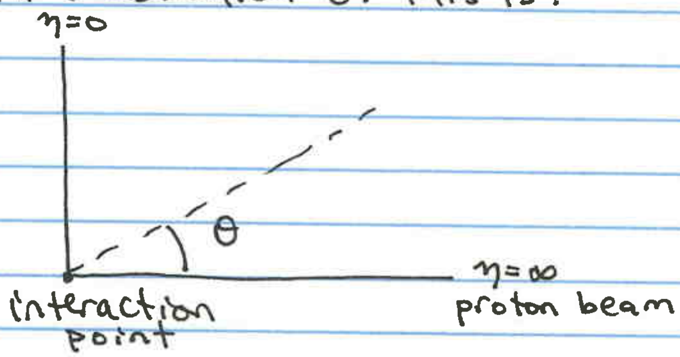


The center of the cylinder is where the proton beams collide, which is called the collision point or <u>interaction point</u>. (I've denoted it as IP on the figure.) As the ATLAS experiment is a cylinder, we should use cylindrical coordinates to orient ourselves and express vectors. The cylindrical coordinates we use are azimuthal angle ϕ, pseudorapidity η, and transverse momentum $p_\perp$.

The azimuthal angle ϕ is just the angle about the proton beams, as illustrated in the figure. In cylindrical coordinates, we also need a "z" coordinate that specifies the distance <u>along</u> the proton beams, away from the interaction point. At the LHC, this is measured as the pseudorapidity η, which is defined with respect to the polar angle as measured with respect to the proton beam. The pseudorapidity η is

$$\eta = -\ln \tan\frac{\theta}{2}, \text{ where the polar angle is } \theta.$$

An illustration of this is:



Pseudorapidity η is 0 for "central" collisions, directly perpendicular to the beam at the interaction point. It is $\pm\infty$ along the proton beams where the polar angle is 0 or π. What makes pseudorapidity useful is that it is true rapidity for massless particles.

Recall from HW#2 that the rapidity y is defined as

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}, \text{ where the } z\text{-axis coincides with}$$

the proton beams. For Lorentz boosts along the proton beam direction, the rapidity just transforms additively. That is, differences of rapidity are invariant to Lorentz boosts along the z-direction. (This is very important!)

For a massless particle, energy is equal to the magnitude of momentum: $E = |\vec{p}|$.

and so the polar angle is: $\cos\theta = \frac{p_z}{E}$

Plugging this into the expression for rapidity, we have

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta} = -\ln\left(\frac{1-\cos\theta}{1+\cos\theta}\right)^{1/2} = -\ln\tan\frac{\theta}{2} = \eta$$

In general, however, rapidity and pseudorapidity do not coincide.

Okay, that is η & ϕ, what about $p_\perp$? Transverse momentum, or $p_\perp$, is just the effective radial coordinate on the experiment. $p_\perp$ is the magnitude of particle momentum that is transverse to the proton beam, as illustrated in the drawing of ATLAS. Like (pseudo) rapidity, $p_\perp$ has a nice property at hadron colliders like the LHC. The initial momentum of the protons (and their constituent quarks and gluons) is along the z axis of the experiment. Therefore, the initial transverse momentum vector is 0, and so is the final transverse momentum vector. That transverse momentum is conserved and easy to measure at collider experiments like ATLAS is a very useful and important property.

With the z-coordinate along the proton beam, the $p_\perp$ is:

$$p_\perp = \sqrt{p_x^2 + p_y^2}$$

, for x- and y-components of momentum. Any massless four-vector can be expressed in $(\eta, \phi, p_\perp)$ coordinates as:

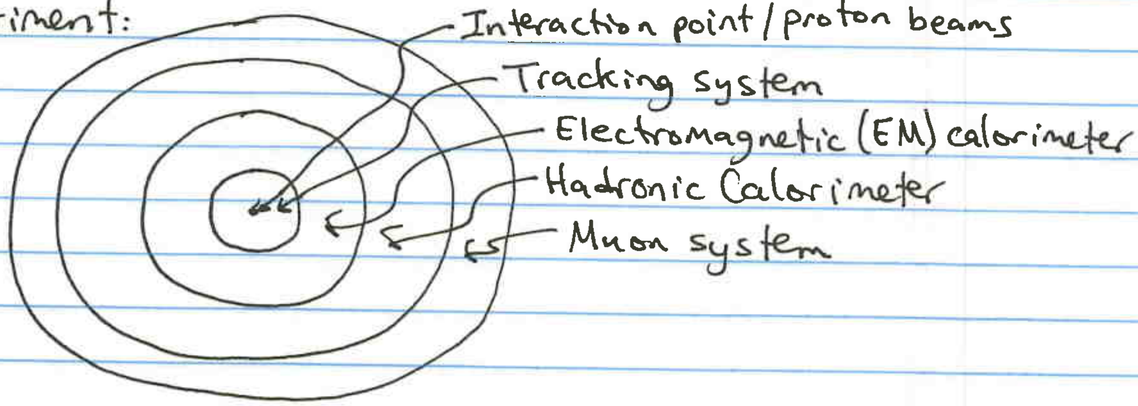
$$p = p_\perp\left(\cosh\eta, \cos\phi, \sin\phi, \sinh\eta\right)$$

A massive four-vector is similar, we just need to include the mass appropriately:

$$p = \left(\sqrt{p_\perp^2 + m^2}\cosh\eta,\ p_\perp\cos\phi,\ p_\perp\sin\phi,\ \sqrt{p_\perp^2+m^2}\sinh\eta \right)$$

The quantity $m_T^2 = p_\perp^2 + m^2$ is called the transverse mass and is invariant to boosts along the z-direction.

Okay, now we know how to specify vectors on the ATLAS experiment; let's go on to how to measure particle properties. Here's a head-on view of the ATLAS experiment:



Like an onion, the ATLAS experiment consists of many layers, each of which measure particular properties or are sensitive to particular particles. At the center is the interaction point, and the proton beams go into and out of the page/board.

Immediately outside of the beam region is the tracking system. The tracking system consists of millions of individual channels that respond when a charged particle hits one. These channels consist of silicon or gas that can ionize when a high energy particle with charge passes through. This ionization is recorded at numerous points along the trajectory of the charged particle and traces out a "track" of the charged particle. For this reason, charged particles are often called "tracks" at the LHC experiments.

While this is neat, it isn't necessarily useful by itself, just observing the tracks of particles. What makes the tracker especially useful is that in the tracking region, there is a solenoidal magnet that bends charged particles. The solenoidal field points along the z-direction (parallel to the proton beam) and so chargedparticles' trajectories are affected by the magnitude of the particle's charge and its transverse momentum (perpendicular to the field). So the tracking system is sensitive to both charge and momentum of particles! Let's see how this works.

As is shown in Example 12.11 of Griffiths's E+M textbook, the radius of curvature of a charge with transverse momentum $p_\perp$ in a field with strength B is

$$R = \frac{p_\perp}{QB}, \text{ where } Q \text{ is the charge of the particle.}$$

As written, this is in SI units (meters, Coulombs, Tesla), so not so useful directly for particle physics. Converting to units where R is meters, B is Tesla, $p_\perp$ is GeV and Q is the charge in units of the electron charge, 1.6×10^{-19} Coulombs, we have

$$R \cong 3\,\frac{p_\perp}{QB}$$

That is, for a 1 GeV electron in the 2T magnetic field of the ATLAS tracker, the radius of curvature is about 1.5 meters.

So, by the radius of curvature, we can measure the magnitude of transverse momentum and by the right hand rule, can measure the sign of the charge of the particle.

How is this measured, though? The tracking system consists of many layers of materiel away from the interaction point. As the charged particle passes through, it hits these layers:

where the crosses are hits,

Curvature can be determined by a minimum of 3 hits, though the tracking system at ATLAS has many 10s of layers (~30). Importantly, it is the curvature, not the radius of curvature that is more easily measured. The curvature is just the inverse of the radius of curvature, which is inversely proportional to transverse momentum. Note that the uncertainty on the curvature is

$$\Delta \frac{1}{R} \propto \Delta \frac{1}{p_\perp} = \frac{\Delta p_\perp}{p_\perp^2}$$

That is, the uncertainty on the measurement of momentum in this way increases with increasing $p_\perp$:

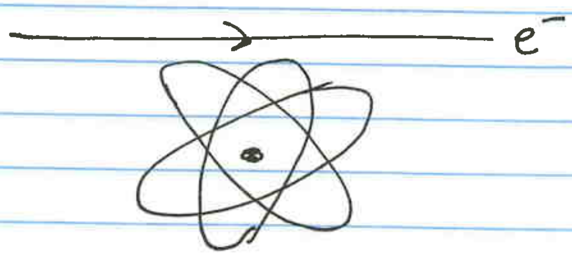
$$\Delta p_\perp \sim p_\perp^2 \left(\Delta \frac{1}{R}\right)$$

Therefore, it is increasingly challenging to measere $p_\perp$ in the tracking system at high $p_\perp$.

This is somewhat okay, though, because of the next parts of the detector. The EM and hadronic calorimeters have the same basic function, but are designed to be sensitive to different types of particles. As calorimeters, these parts of the experiment are designed to stop particles and have them dump all of their energy into individual cells of the calorimeters called "towers". These towers are finely segmented in ϕ and η, and can therefore be used to determine momenta of particles, assuming the particles are massless.

As their names suggest, the EM and hadronic calorimeters are sensitive to EM and hadronic radiation, respectively. In particular, the EM calorimeter stops electrons and photons; low mass particles that interact via electromagnetism. The most important ways that the EM calorimeter stops is through ionization radiation and bremmstralung (literally "breaking radiation" in German).

The textbook goes through a detailed derivation of the theory of ionizing radiative energy losses, so I won't discuss it much here. High energy charged particles, like electrons, can lose energy by passing close to the charged electron cloud of an atom:



The energy loss per unit length or dE/dx via ionizing radiation was first calculated by Hans Bethe in the 1930s. He found:

$$\frac{dE}{dx} = -4\pi\alpha^2 Q^2 \frac{nZ}{m_e v^2}\left[\ln\frac{2\gamma^2 m_e v^2}{\hbar\omega} - \frac{v^2}{c^2}\right]$$

Here, α is the fine structure constant which is a measure of the strength of electromagnetism:

$$\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c}$$, Q is the charge of the high-energy particle in units of e, n is the number density of atoms in the materiel, Z is the atomic number, V is the velocity of the particle, m_e is the mass of the electron, and ω is a characteristic energy (frequency) difference between states in the atom.

This formula says that more energy is lost if the material is denser (n increases) or if there are more electrons (Z increases). Also, not surprisingly, the rate at which energy is lost increases with v through the logarithmic factor: Faster particles ~~lose~~ lose energy more quickly than slower particles (relativistically).

Bremmstralung, on the other hand, is the process by which an electron emits a photon, which decreases its energy. In a similar way, a photon can split into an electron-positron pair, and decrease energy. We might express these processes with the Feynman diagrams:

and

While Bremmstralung can be calculated by considering the collinear emission of a photon off of an electron, I will just quote the result here. The rate of energy loss per unit length via Bremmstralung is

$$\frac{dE}{dx} \simeq -\frac{E}{X_0}$$ where X_0 is called the radiation length.

The radiation length X_0 for an electron to lose energy is a function of the materiel through which the electron is moving, just like ionization radiation. A radiation length is the distance over which the electron loses a fraction e (=2.71828...) of its energy. Typical radiation lengths are of order centimeters, and your calorimeter should be many radiation lengths thick to capture all the energy of the electron.

At ATLAS, the EM calorimeter consists of lead plates immersed in liquid argon. The liquid argon ionizes, and the energies of low energy particles can be measured efficiently. The lead plates have strong stopping power for more energetic particles; lead has one of the shortest radiation lengths (about 5 mm!). Together, they form the EM calorimeter and stop (nearly) all electrons and photons created in collision.

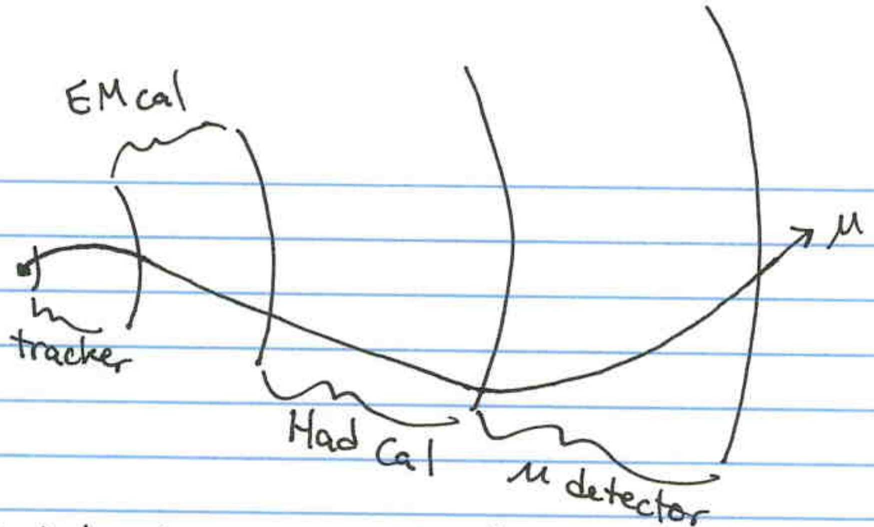
The hadronic calorimeter acts much in the same way as the EM calorimeter; however, it must stop particles with a much higher mass than electrons. Hadrons, like pions, interact most strongly with atomic nuclei, and not atomic electrons. As such, their interactions are more complicated to understand but the same basic principles are at work. Hadrons pass through a material and ~~[illegible]~~ lose energy by inelastic collisions with atomic nuclei. The rate of collisions, just like bremmstralung, can be characterized by a nuclear interaction length, λ_I. Over one λ_I, a high-energy hadron loses a fraction e of its energy to interactions with nuclei. Iron is one of the materials with the smallest λ_I; in ATLAS, the hadronic calorimeter consists mostly of iron.

The nuclear interaction length of iron is about 16 cm and the hadronic calorimeter is about 11 λ_I in depth. This captures almost all of the energy of hadrons produced in proton collisions.

So, we've captured almost all radiation that could be created in collisions! There are a couple of particles (that exist for a long enough time) that I haven't mentioned:

1) Muons. Muons are like electrons, but are 200 times heavier, and so lose much less energy in ionization and bremmstralung. (For the same force, muons are accelerated less than electrons.) The technique at the LHC to measure their energy is to first give up hope that we can stop them in a calorimeter.

At both ATLAS and CMS, outside of the hadronic calorimeter, there is a muon detection system. At ATLAS, it consists of detectors for tracking in a high toroidal magnetic field (and where ATLAS gets its name). Muons are therefore observed in the inner tracking system and the outer muon tracker, and this redundancy enables high precision measurements of muon momentum. At ATLAS, the toroidal magnetic field is arranged so that muons bend the opposite direction as in the inner tracker. That is, the trajectory of a muon would look something like:



I tried to draw the muon traveling straight through the calorimeters (where there is 0 magnetic field).

2) The other particles I haven't mentioned are neutrinos. Like photons, neutrinos are neutral and have (very, very) small mass, and so one might think that they would/could stop in a calorimeter. However, neutrinos interact incredibly weakly with matter, and so the vast majority of the time, pass right through the detector without so much as a "hello". Indeed, in collider physics, we assume that neutrinos do not interact with the detector.

However, this does not mean that they are "invisible." We can see the effects and existence of neutrinos indirectly. Recall I said long ago that momentum transverse to the proton beam is 0. Well, if you measure a non-zero net $p_\perp$ in the detector, then a neutrino (or a few of them) must have taken the missing momentum away!

There are methods to directly observe neutrinos, and we'll talk about that near the end of the semester.

Finally, just briefly a word on the extent of the ATLAS and CMS detectors. They are ~~often~~ referred to as "4π hermetic" detectors because (as best as possible) they capture all radiation from proton collision throughout 4π steradians of a sphere.

This task is impossible, because, at last, the beams must come in somewhere, cables have to go somewhere, etc. However, the coverage is otherwise exceptional. The tracking systems ~~ex~~ extends out to $\eta = 2.5$, which is only about an angle of $10°$ above the proton beam. The calorimetry extends further, it goes out to about $\eta = 5$, which is less than one degree above the proton beam!

We can look at event displays and attempt to understand what is going on.