ISP220, spring 2019: Final Exam; 20 pts

Quarks, Spacetime, and the Big Bang

Friday, May 03, 2019

The Story

By now you've played with Feynman Diagrams a bit. Their practical use comes in trying to predict how particular reactions will make themselves known in a real detector. In this project, you'll work in teams of four to fill out a set of reactions all the way to what would actually be measured. I'll show you some examples of what I mean and then you're on your own to try it for yourselves.

In a separate packet the 5 reactions for which your group is responsible will be handed out on Friday during the final. The primary project is worth 4 points for each reaction and each carries extra credit work of...4 points for each. Yes. The extra credit is worth as much as the actual exam itself. You're welcome. The workflow for each is as follows:

1. I'll provide you with the complete chain in a formula language.
2. I'll provide you with the primary production diagram.
3. (2 points) You complete the diagram that will result in the original formula.
4. (2 points) You fill a table of the final state particles.
5. (2 points) (extra credit) Draw a space-diagram of the reaction.
6. (2 points) (extra credit) Sketch how the reaction would look in a diagram of a generic colliding beam detector.

There are two new things that we need to understand in order to complete this project and the rest of this document explains them.

1. **Unstable Particle Decays** We've not emphasized this, but the only particles that would make it into a final state are two leptons (electrons and muons), two messenger particles (photons and gluons), and some quarks (up quark, down quark, and bottom quark). All of the other particles we've discussed (W and Z bosons, Higgs Bosons, and top quarks) are unstable and will themselves decay into the stable particles long before they would reach any particle detector. We'll explain how to deal with that below.

2. **Particles in Detectors** I've alluded to this before and you've seen projections of particles depositing energy in our ATLAS detector when viewed from the beam's-eye-projection. I'll create a toy detector cartoon that you can use for each reaction in the extra credit portion.

Note: Here you and I will be relaxed about particle-antiparticle designation and the arrows on the lines. I'll include them when they are useful, but you'll not have to. So for you, $\bar{e}$ can be written by you as plain old e. Also, even though parts of ATLAS are inside of designer magnetic fields, I'll not ask you to correlate charged particles' bending trajectories. For this project, it's the thought that counts.

Also, the only quark that I'll refer to specifically by name will be the top and bottom quarks. All of the others I'll lump under the generic symbol q. You'll see.

1 Particle Decays

Let's enumerate the unstable particles and unpack their diagrams and symbols.

1.1 W boson decay

The W boson decays into two different quarks (about 70% of the time) or a lepton and a neutrino (about 30% of the time). The decay diagram is exactly like its Primitive Diagram, suitably rotated and attached to the overall diagram as necessary. We'd write the decay as $W \to q + q'$ or $W \to e + \nu_e$ or $W \to \mu + \nu$. Remember that the W boson's job is to connect the upper and lower particles in those doublets that I showed in class. Because it changes electrical charge, it changes the quark "flavor." More specifically

$$\begin{pmatrix} u \\ d \end{pmatrix} \text{ or for this project: } \begin{pmatrix} q \\ q' \end{pmatrix}$$

So the $W \to q+q'$ stands for $W \to u+\bar{d}$ or $W \to d+\bar{u}$ depending on whether the W is positive or negative. (Again, we're not going to care here.) Here are the diagrams:

Figure 1:

1.2 Z boson decay

The Z boson decays into same-quark pairs (quark antiquark) or same-lepton pairs (lepton antilepton), such as $Z \to q + \bar{q}$. So representative decays of the Z boson are $Z \to u + \bar{u}$ or $Z \to \mu + \bar{\mu}$. Again, we'll represent all light quarks as just q. Here are the diagrams:

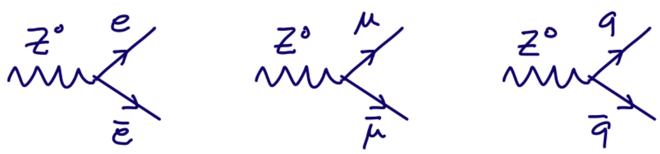


Figure 2:

1.3 Higgs boson decay

We'll represent the Higgs boson with the symbol h. Its most straightforward decays are: $h \to b + \bar{b}$, $h \to W^* + W$, $h \to Z^* + Z$[1] Here are the diagrams: It also decays indirectly to $h \to \gamma + \gamma$ as in Fig. 4, which is rare. In fact, in spite of the fact that this decay doesn't happen very often, it was one of the "discovery channels" in our announcement in 2012 because this final state is almost completely free of being mimicked by non-Higgs processes. When we saw it, we knew it.

[1]These two decays are slightly nuanced. The Higgs boson mass is smaller than that of two W's or two Z's so one of the final state bosons are "off-shell" (that's the "*") and are not real particles, but virtual ones that nonetheless decay into the standard W and Z final states. So we'll ignore that also.

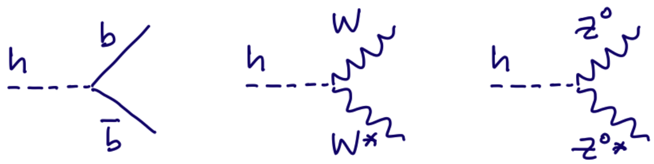


Figure 3:

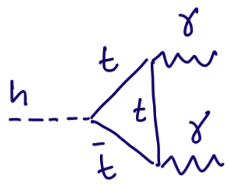


Figure 4:

1.4 Top quark decay

The top quark is special because of its enormous mass of 172 times that of a proton. Its decay is essentially into one particular state: $t \rightarrow W + b$. The W will then of course decay in one of its many ways so that top quark final states are varied. The diagram for top quark decay is in Fig. 5.

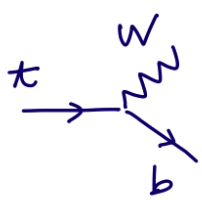


Figure 5:

2 Detectors: For Extra Credit

You might want to look at Lesson 6, *Collisions*, in particular the section on collisions at the LHC. Here's the URL: https://tinyurl.com/y9mvtz8e Identifying what particles are what in our detectors makes use of the dramatically different ways electrons and gamma rays interact in matter and how both are very different from how muons interact in matter. Here's a brief introduction.

2.1 Particles In Matter

We'll consider three kinds of particles and their effects. Figure 6 illustrates the first two kinds.

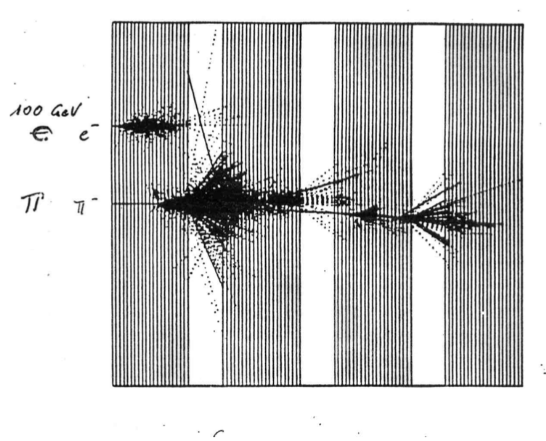


Figure 6:

1. **Electrons and Gamma Rays** We've already seen that particles ionize matter—kick out electrons which can be collected and measured as a current (remember Madame Curie and Ernest Rutherford)—and can leave tracks in material that is not too dense. If an electron goes through a denser material it will also kick out electrons, thousands of them, and because they are so light they will quickly radiate photons which will in turn create electron-positron pairs...which in turn will then knock out more electrons. The result of this is the development of what's called an "**electromagnetic shower**" of thousands of particles. If the material is instrumented, then slices of readout of these showers can lead to an image of this shower which can be readily identified as and electron or photon —because if a photon enters the same sort of material, the same shower occurs. The top image in Fig. 6 shows a high energy electron entering such a material and the tight shower is the clue. So: **Electrons and photons create tight, short electromagnetic showers in instrumented detector material.**

2. **Strongly Interacting Particles** If a proton or neutron (or pion or kaon...or any particle made of quarks) enters such a material, the interaction is not so much with the atomic electrons, but with the nuclei of the material. This interaction also produces self-sustaining particle production in a columnated image, but it's much bigger and "shaggier"...spread out and ragged. Were a quark or a gluon to enter such a material, the same sort of thing would occur. These less-tightly generated multi-particle events are called hadronic "**jets**" and a typical jet produced by a high energy pion entering the same detector as the electron is shown in the bottom of Fig. 6. Notice that it takes longer for a hadronic jet to start...much longer...than the electron which gets down to business right away. So: **For us, up, down, charm, strange, and bottom quarks and gluons create ragged, late hadronic jets in instrumented detector material.**

3. **Muons** Muons are heavy electrons and it is that mass that causes muons to radiate much less...in fact they happily go through Iron without interacting at all, except to leave ionization evidence of their passage—no showers. Figure 7 shows an event from a detector we built at Fermilab in the 1980's to catch neutrinos. A neutrino (invisibly) enters and interacts from the left and interacts in the detector material creating an event of mostly hadronic jets plus a muon. The muon continues on through the back of the detector and enters a large collection of iron magnets (the orange and purple rectangles) which are magnetized in order to bend specifically such muons. The circles highlight hits in detectors between the iron slabs and detect the passage of the muon before it enters the next slab of magnetized iron and so on. You can see that it's not straight and that curve allows us to determine the muon's momentum. So: **Muons create sparse, single tracks in instrumented detector material.**

2.2 How To Build A Particle Detector

These different characteristics of particles in matter can be exploited to build a layered detector with materials specifically designed to register the presence of each. Figure 8 (left) shows a cartoon of a wedge of a detector that's layered in a now-standard way.

The right picture is meant to represent a montage of the consequence of different particle beams aimed at this wedge as indicated by the generic red

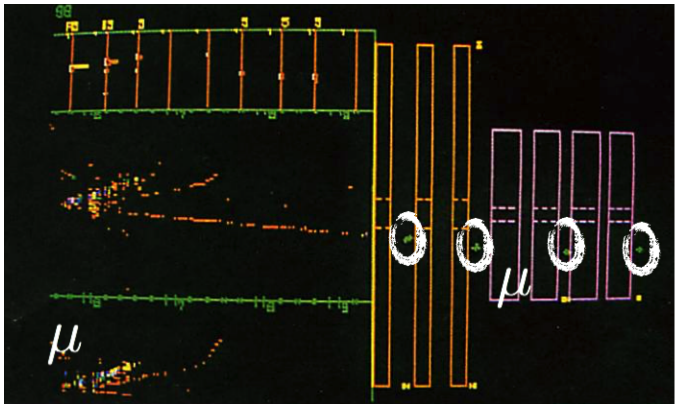


Figure 7:

arrow. The first material that a particle encounters is a tracking detector (T) which has very little mass (and hence no showering and no jets) and simply indicates where a *charged* particle went as small hits. The second layer material (EM) consists of atoms with an especially large number of atomic electrons and enhances the likelihood that if an electron or a gamma ray hits it that an electromagnetic shower will start. Such a detector is deep enough to completely absorb (and register) all of the energy that the original electron or gamma ray possessed. The third layer (H) is a dense material with very heavy nuclei and will be most likely to eventually initiate a hadron jet. It too completely absorbs all of the energy of any hadronic jet. Finally, the outer layer (M) is meant to represent a muon detector...just hits. Typically there is a magnetic field surrounding the tracker and muon detectors and while I'll show bending for examples of charged particles, you'll not have to worry about that.

Overlaid are what various particles could look like as the incident (red arrow) beam:

- e is an electron, which leaves a track in the tracking chamber (the line) and then an electromagnetic shower in the first layer. You can see that the negative electron track curves as it passes through the tracker.
- γ is a photon which behaves identically to the electron in EM, but is neutral and so it leaves no track (no line!) in the tracker and of course doesn't bend.
- q, g are quarks and gluons which initiate many charged and neutral

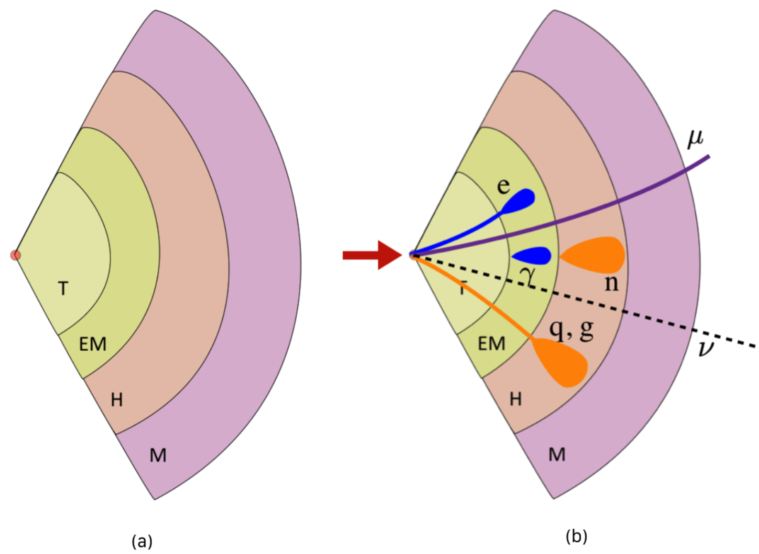


Figure 8:

tracks. For our purposes we'll pretend that any quark or gluon-initiated tracks are protons so you see them leaving tracks in the tracker (and EM) (the line) and then depositing all of their energy in the H layer. Also, it bends in the opposite direction from the electron.

- n is a neutron, for fun...it would behave like a proton, except it would not leave a track anywhere since it's neutral. We'll not have any neutrons in our events.
- μ is a muon which goes all the way through the detector and out the back of M leaving tracking evidence (the line) all the way. I've drawn it as if it's negative, but it could be positive as well.
- Oh. The elusive guy: ν, a neutrino. Neutrinos will not interact in any of the detector layers...but it will carry away momentum and so when there's a momentum imbalance, our computers are trained to indicate the direction of that missing momentum and we then likely assign the source of that to an escaping neutrino. The dashed line indicates an after-the-fact calculation of the (invisible) trajectory of a neutrino.

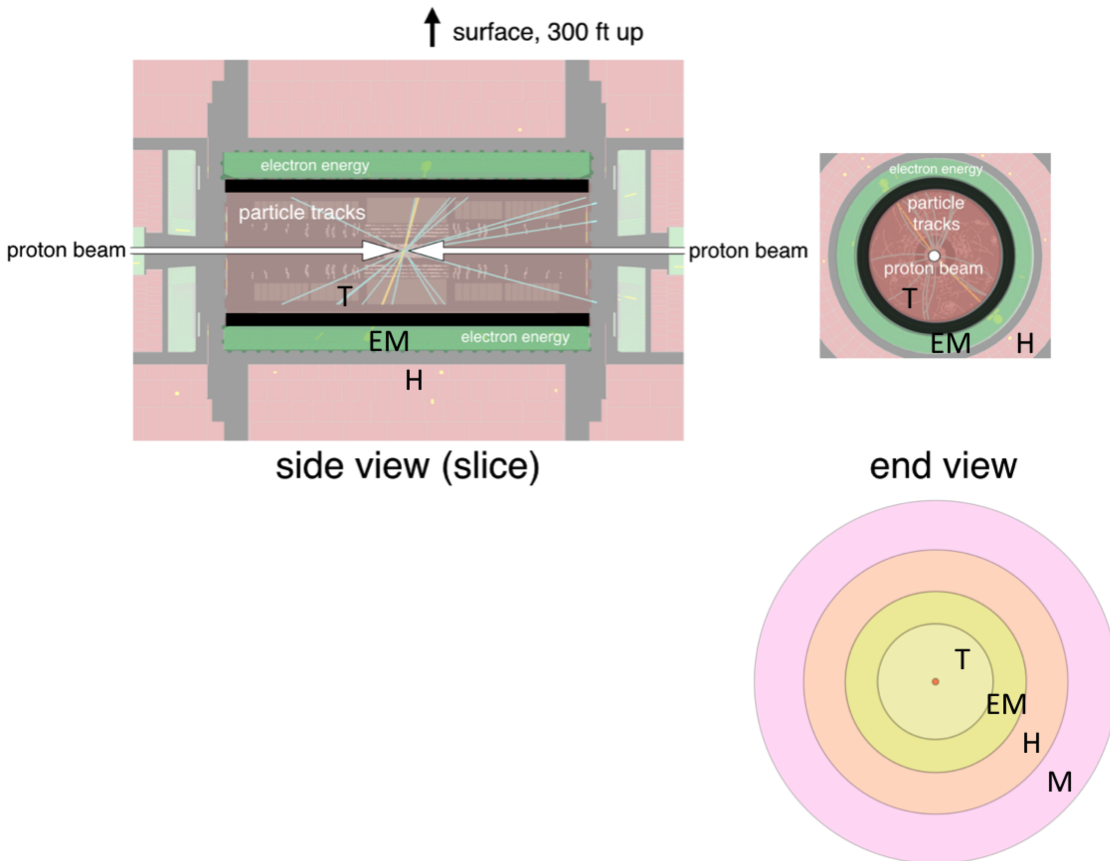


Figure 9:

2.3 A Collider Detector Cartoon

So these individual shapes and tracks are the pieces you'll use to create the effects of your reactions. However, the wedge is just an explanatory tool. Figure 9 is from Lesson 6 that shows how we'll use these to predict collider experiment final states. The top left shows the side view of our ATLAS detector. The protons from the right (France) collide with the protons from the left (Switzerland) at the center of the detector. The top right picture is looking at the detector from the end with the beams going into (and out of) the "paper." Just below that is the cartoon detector that we'll use.

Look at the two images in the top half of Fig. 10. The top image (a) is a collision in ATLAS that creates two electrons in the final state and nothing else. We know that because they are back-to-back in both the side and end views and so conserve momentum. The lower image (b) is of a collision in ATLAS in which there are two jets that also are back to back and balance momentum. The lower half of Fig. 10 shows our cartoon end view with the (c) electromagnetic shower drawn in (like you would do) on the left corresponding to the top collision and the lower right (d) is the sketch of the second top event as you'd draw it. Below them are the formulae that represent the reaction and under them, representative Feynman Diagrams that would produce those final states.

3 Examples

I'll do two examples exactly as you'll see them at the exam. For each you'll receive the full reaction and enough of the production diagram for you to be able to fill in the rest. Then you'll fill in the table of the final state particles. And then, if you want the extra credit, you'll create the space diagram and the detector diagram.

In these, I'll put in black what I would provide for these and in red what you'd respond with. They are Example 1 and Example 2 in Figures 11 and 12.

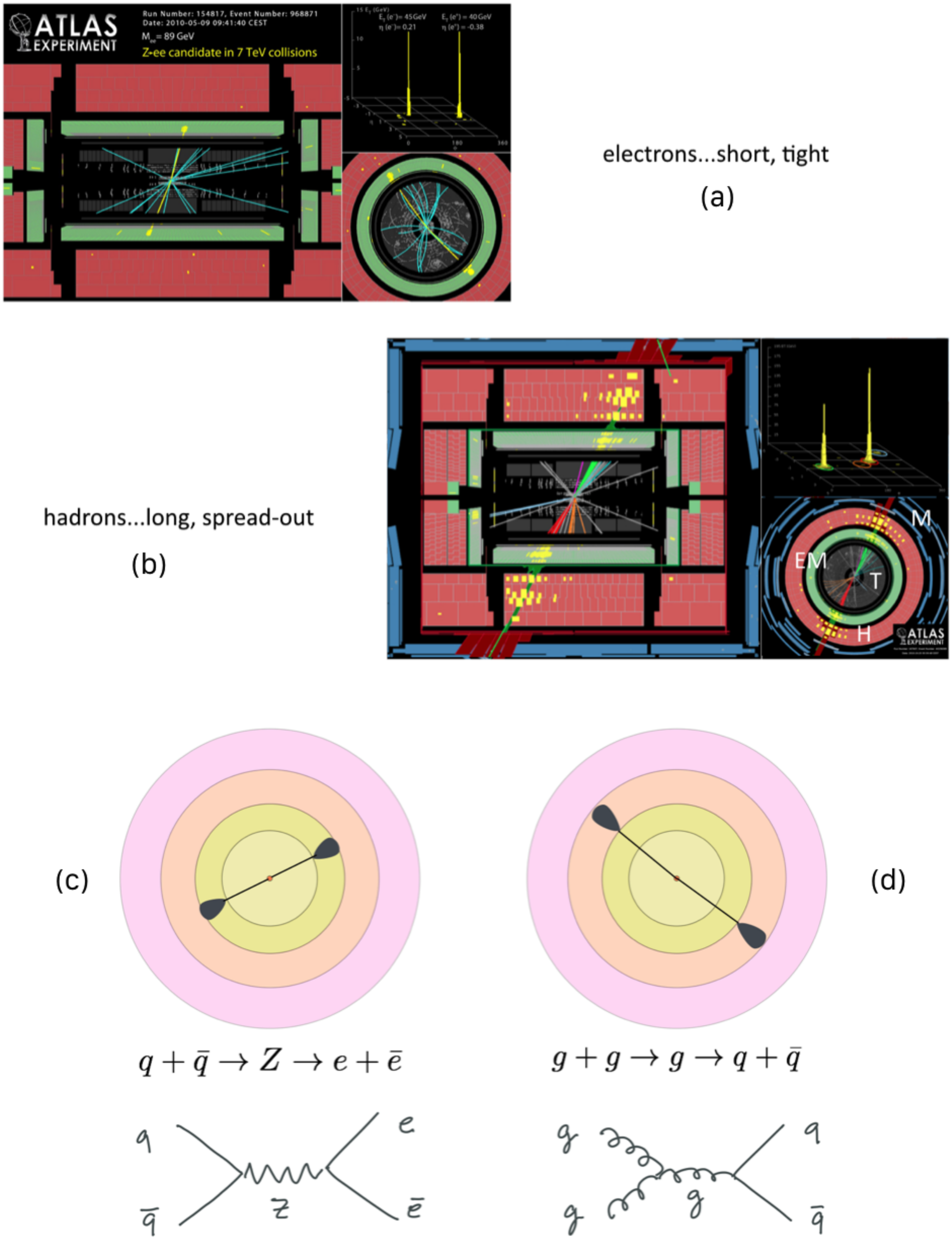

ATLAS EXPERIMENT
Run Number: 154817, Event Number: 968871
Date: 2010-05-09 09:41:40 CEST
Z→ee candidate in 7 TeV collisions
electrons...short, tight
(a)
hadrons...long, spread-out
(b)
M
EM
T
H
(c)
(d)
$q + \bar{q} \to Z \to e + \bar{e}$
$g + g \to g \to q + \bar{q}$

Figure 10:

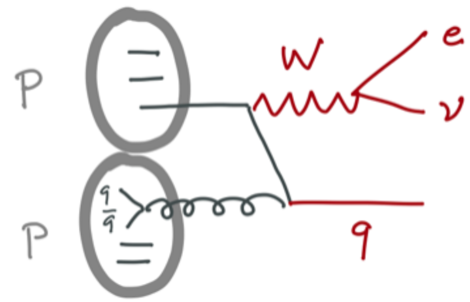
Number: Example 1

Title: Drell-Yan production of W bosons with one jet, with the W decaying into an electron

Reaction: $q + g \to q \to W + q \to e + \nu$

points

Feynman Diagram:



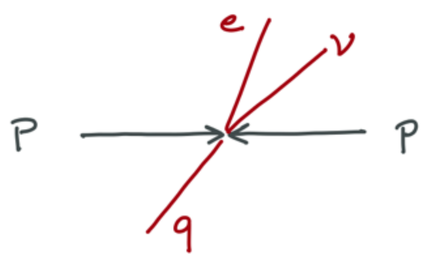
/2

Final State:

e	γ	μ	jet	missing momentum
1	0	0	1	1

/2

Space Diagram:



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Detector Image:

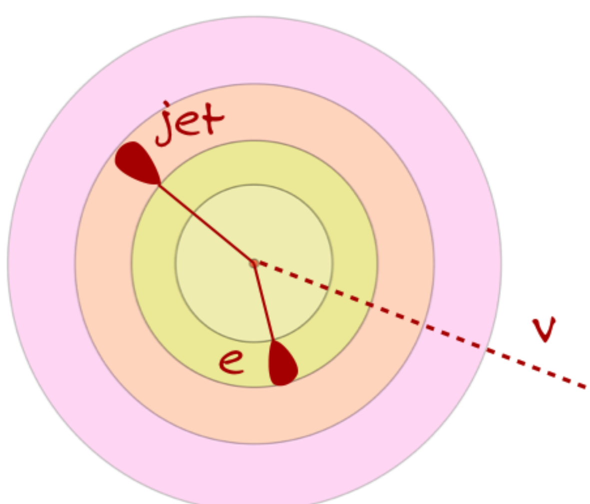

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Figure 11:

Number: Example 2

Title: Top quark pair production into dilepton mu-e final states

Reaction:

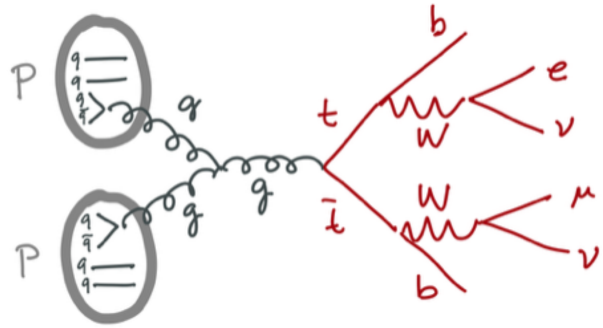
$$g + g \to g \to t + \bar{t}$$

$\bar{t} \hookrightarrow W + b$, $W \hookrightarrow e + \nu$

$t \hookrightarrow W + b$, $W \hookrightarrow \mu + \nu$

points

Feynman Diagram:



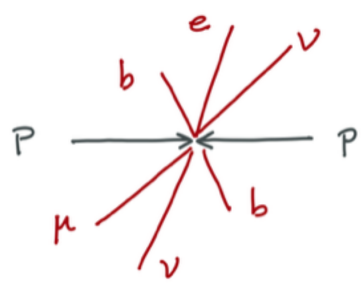
/2

Final State:

e	γ	μ	jet	missing momentum
1	0	1	2	2

/2

Space Diagram:



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Detector Image:

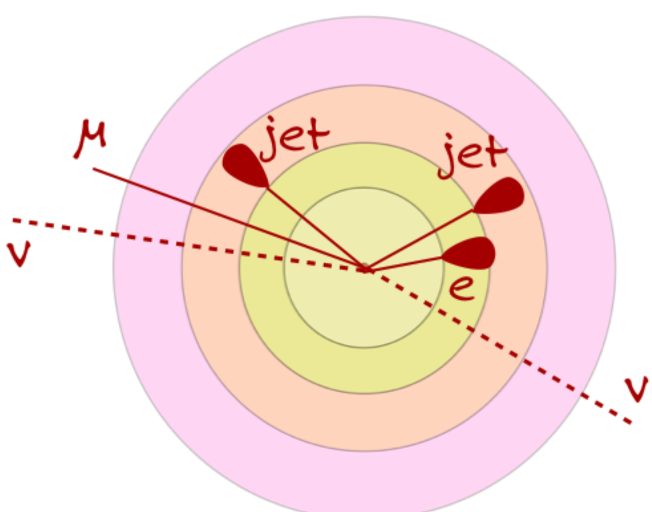

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Figure 12: