Standard Model Brief Introduction & the LHCb Event Display

Standard Model Introduction

Here, we give some background material on the Standard Model, to help understand the LHCb event display to help the user understand a bit better what is being shown.

It is first worthwhile to give a brief introduction to our current theory of matter, called the Standard Model. The Standard Model (SM) contains the following ingredients:

1) Particles:
    a. 6 Quarks: up, down, strange, charm, bottom and top (u, d, s, c, b, t).
    b. 6 Leptons: 3 charged: e^-, μ^-, τ^- ; and 3 neutral partners: ν_e, ν_μ, and $\nu_{\tau.}$
2) Forces:
    a. Elecrtromagnetic force: responsible for essentially all of chemistry, including normal forces, friction, etc.
    b. Strong force: responsible for quarks binding as well as the strong nuclear force.
    c. Weak force: responsible for decay of many unstable particles.
3) Higgs boson: responsible for giving mass to the particles.

Gravity is extremely weak, much weaker than the SM forces, and is not discussed further. Each of the SM particles has a corresponding antiparticle. Antiparticles are frequently represented with a "bar" over the particle. For example, an anti-up quark is symbolized as $\overline{u}$, or an anti-bottom quark as $\overline{b}$. The Higgs boson is theorized to be the reason the quarks and leptons have the masses that they do, and it was just discovered at the Large Hadron Collider at CERN in Geneva Switzerland. Believe it or not, the discovery was just announced on July 4, 2012, after searching for it in particle physics experiments for over 50 years! Truly amazing!

We find in nature that neither quarks nor antiquarks are observed as free particles, rather the strong force binds them up into either (1) three quark combinations, called baryons, or (2) quark-antiquark combinations, called mesons. Because quarks interact most strongly via the strong force, we refer to either mesons or baryons as "hadrons", where "hadro" comes from the Greek, signifying "strong". You are certainly familiar with two well-known baryons, the proton and neutron, each of which are composed of up and down quarks, as shown in Fig. 1. However, as there are 6 quarks, this combination is not unique, and in fact there are many more possible 3-quark combinations. For example, baryons containing bottom quarks, as shown in
Fig 1 (right) are produced and studied by the LHCb experiment.

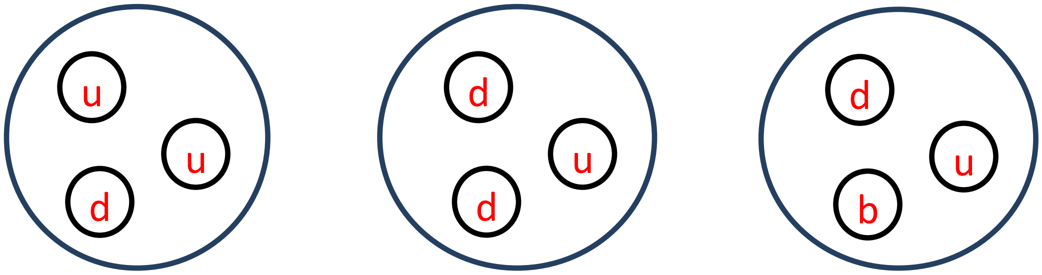

Figure 1: Quark contents of the proton (left), neutron (middle) and Λ_b baryon (right).

You might ask at this point: “Why don’t we see these ‘baryons’ that contain b-quarks”? The reason is that most particles in nature are unstable, and disintegrate into lighter particles. Those lighter particles themselves may also be unstable, and decay as well to even lighter particles. The decay processes continue until only stable particles remain. While this may seem peculiar, you already probably know that Uranium is unstable. The nucleus undergoes radioactive decay, and in many cases, eventually reaches the stable Lead-209 nucleus, which is stable. In particle physics, there are far more unstable particles than stable ones. The only truly stable particles we know of are the proton, the electron and the three neutrinos (and their anti-particles). While the neutron is also stable when in the confines of a stable atom, when by itself, it decays with an average time of about 15 minutes.

There are many examples of mesons as well. Just pair any quark, with any antiquark, and you have yourself a valid meson. One small exception should be noted. The top quark is very, very heavy (about as heavy as a Gold atom!), and it decays so rapidly ($\sim 10^{-23}$ sec), that it doesn’t even have a chance to latch onto other quarks or antiquarks to form a hadron. So, when you try to form either a meson or baryon, leave the top quark off! Examples of mesons are shown in Fig. 2.

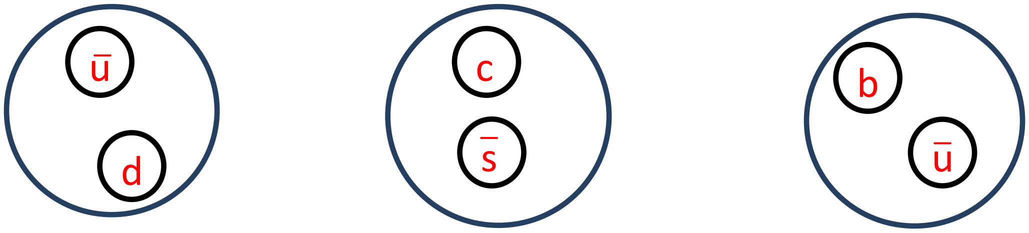

Figure 2: Examples of mesons formed from quark-antiquark pairs. Shown are [left] π^- ($\bar{u}d$), [middle] $D_s^+(c\bar{s})$, and [right] B^- $(b\bar{u})$.

Over the past 50 years or so, many of the baryons and mesons that have come to be expected from the quark model have in fact been discovered. Some have regular Arabic letter names, such as D^+ ($c\bar{d}$), B^- ($b\bar{u}$), or K^0($\bar{s}$d), whereas others have been given Greek letter names, such as Λ_b (bud), or ϕ($s\bar{s}$). There are many such particles, and it can be overwhelming. The main point to understand is that there are mesons and baryons, and almost all of them do decay with some characteristic time.

In particle physics experiments, such as LHCb, particles are produced in violent collisions. The particles emerge at very high energies, and are moving at nearly the speed of light. Two of the charged particles (kaons and pions) have a relatively long lifetime are detectable by detectors placed even several meters away. These mesons are the π^+ ($u\bar{d}$), the π^- ($\bar{u}d$), the K^+ ($\bar{s}u$), and the K^- ($s\bar{u}$). They have lifetimes of about 10^{-8} sec. This may seem like a very small number (and it is), but consider that these particles are moving at nearly the speed of light. You might guess that the average π or K will then travel a distance $d \approx (3\text{x}10^8\text{ m/s})(10^{-8}\text{ s}) \approx 3$ m. Remember, however, that these particles are moving incredibly fast, and time passes more slowly for things moving near the speed of light., in accordance with Special Relativity As a result, this particle can “live” much longer than the naïve expectation, and the increase can easily be a factor of 100 times larger! The peculiarities of Special Relativity, such as time dilation, are extremely interesting in their own right. Unfortunately, we shall not detour onto a detailed discussion of Special Relativity.

In the LHCb experiment, we are interested in a wide variety of decays of particles containing B mesons. The LHC collides protons into protons at very high energy. In actuality, the LHC accelerator contains about 2000 “bunches” of protons circulating in opposite directions within the 25 km circumference. Each ones of these “bunches” contains about 100 billion protons each! Every 25 ns, a bunch going clockwise encounters a counter-clockwise rotating bunch right in the center of the LHCb detector. You might guess that there would be many proton-proton (*pp*) collisions, but in fact the bunches are spread out over about 20 cm along the beam direction and about 0.1 mm in the perpendicular directions. Because protons are so small (~10^{-15} m), the chance for a head on collision is actually pretty low. In the end, we only typically get on average about two independent proton-proton collisions per crossing. But the challenge at the LHC, is that this happens every 25 ns ! During the time that it takes you to count to 1 second, That is, if you just count to 1 sec, roughly 80 million proton-proton collisions will have just occurred. Our (daunting) task at the LHC is to acquire enough information about each event, and to figure out if it should be saved to permanent storage (disk) or discarded, and to do all of this at 40 MHz. Once it is discarded, it is gone for good. In practice, LHCb saves about 0.02% of all collisions, namely the ones we view as potentially the most interesting. Said another way, we have to sift through about 40 million events every second, and we keep only about 2000, and we do this every second, 24 hours a day! Such a task requires very sophisticated detectors, high speed networks and a massive computing infrastructure. The result is data samples that are measured not in MegaBytes, not in GigaBytes, not in TeraBytes, but 10’s of PetaBytes per year.

Once the events that are deemed interesting are written to disk, they are analyzed by scientists, in the hope that some of these decays could help solve some of the deepest puzzles in Elementary Particle Physics. Some of these puzzles are:

- Why do we live in a Universe that is composed of all matter and almost no antimatter?
- Why do particles have the masses that they do?
- Why are there 3 families of quarks? Why not 4 or 5 or infinite?
- What is the dark matter in the Universe? Is it a new fundamental particle?
- Plus many other deep questions about the Universe we live in.

It turns out that certain b-hadron decays are expected to be very sensitive to *New Physics*. We refer to "New Physics" as any phenomena that cannot be explained by the Standard Model. The hope is that by studying many different b-hadron decays, some of them might be influenced by this New Physics in a fairly dramatic way, and we will see significant deviations from expectations of the Standard Model. If such a significant deviation is observed, it could be signaling the presence of New Physics in the decays of particles containing b-quarks.

The Event Display

The event display will show a cartoon of simulated events from the LHCb experiment at the Large Hadron Collider (LHC). When you launch the event display, it will first ask you:

- "*Which type of event would you like to look at*"?

  There are currently 6 *b*-hadron decays that can be viewed. They are:

$$1 - B^0 \to D^- \pi^+, \quad \text{with } D^- \to K^+ \pi^- \pi^-$$

$$2 - B^0 \to D^- \pi^+ \pi^- \pi^+, \quad \text{with } D^- \to K^+ \pi^- \pi^-$$

$$3 - \Lambda_b \to \Lambda_c^+ K^- \pi^+ \pi^-, \quad \text{with } \Lambda_c^+ \to p K^- \pi^+$$

$$4 - B_s^0 \to D_s^+ D_s^-, \quad \text{with } D_s^+ \to K^+ K^- \pi^+, D_s^- \to K^- K^+ \pi^-$$

$$5 - B_s^0 \to D^0 \overline{D^0}, \quad \text{with } D^0 \to K^- \pi^+, \overline{D^0} \to K^+ \pi^-$$

$$6 - B^- \to D^0 D_s^-, \quad \text{with } D^0 \to K^- \pi^+, D_s^- \to K^- K^+ \pi^-$$

$$- -$$

$$0 - \text{randomly choose among the processes 1-6}$$

Feel free to choose any particular one, or choose 0, if you'd like them randomly mixed. Perhaps try one or two single event types, and then try to randomize.

Then you will be asked:

- "*How many animations do you wish to see?*"
  Enter as many as you'd like to view by eye.

Answering these questions, you will need to double-click on the center screen to advance to an event, and do this again after each animation is complete. You will see two bunches of protons approaching each other in the center screen. Of course this is greatly over-simplified, as each bunch in the LHC really contains about 10^{11} protons, and moves at nearly the speed of light around the LHC. Anyhow, it gives you an idea. When the bunches cross through each other, there is a small probability of a head-on collision between any pair of approaching protons; on average we get only a few (average of about 2) such head-on collisions every 25 ns. In actuality, *b*-hadrons are produced in only about 1/200 such collisions. Because these are events simulated by a computer program to mimic the real data, each event is guaranteed to have a b-hadron!

As the event develops you will see b-hadrons produced, traveling a small, but finite distance of ~1 cm or so, and then decaying into other particles. It decays into other particles which may themselves be unstable and decay. The solid lines show particles that are detectable with our detectors, whereas dashed ones represent short-lived bottom and charm-hadrons, whose presence are inferred by measuring all of their decay products. The center animation shows a view looking at the collision from the side, and in the top left is a view looking at the collision in the plane transverse to the beam directions. In the lower left will be a legend that identifies the particle types in the decay.

As you scan the events by eye, the program will also fill histograms, one event at a time, showing the distribution of four quantities related to the b-hadron. The quantities are:

- **Mass:** This is the invariant mass of the *b*-hadron, taking into account the measured energies and momenta of all the decay products. It is NOT the sum of the masses of the decay products though.
- **Energy:** This is the total energy of the b-hadron in GeV (in Giga-eV, or 10^9 eV).
- **Decay time:** This is the so-called proper time of the decay, expressed in units of pico-seconds (10^{-12} sec). It is the time that the unstable b-hadron existed, measured as if you were riding on top of the b-hadron. Thus in your frame of reference it looks like the b-hadron is at rest! Note that the low end is depleted in events due to the selection requirements made in identifying these events.
- **Distance:** This is the distance (in mm) measured in the frame of the laboratory (as shown in the display). Again the deficit at small distances is due to the b-hadron selection process.

After you reach the end of the animations you requested, the program will automatically begin filling histograms (top right) of the above four quantities without showing any more event displays.

It is interesting to see how just a few events accumulate into statistical distributions. It is these types of statistical distributions that are analyzed by scientists.

In the “Mass” distribution, you will see a prominent peak (or possibly several peaks, if you chose to randomly sample all the event types). These mass peaks correspond to the physical masses of the b-hadrons in this sample. Can you figure out which peaks correspond to which particles?

The energy distribution gives the energy of each reconstructed decay. The decay time shows the decay time of all reconstructed candidates; and distance shows how far the b-hadrons travelled before they decayed.

You’ll notice that in the decay time, and decay distance, there is a deficit of events near zero. This occurs because our main tool at distinguishing the b-hadron decays is that their decay products typically do not point back to the associated proton-proton collision. This is important, because in these high energy collisions, there are many particles emerging from the *pp* collision, and just taking them all would lead to an enormous number of possible combinations. Thus we often select only particles that do not point back to ANY pp collision in the event! As a result, we see much fewer events that decay close to the *pp* collision.

Analyzing the proper time distribution?

- As the decay of unstable particle follow a radioactive decay law, they should obey the relation

$$N = N_0 e^{-t/\tau}$$

$$\rightarrow \quad \ell n(N) = \ell n(N_0) - \left(\frac{1}{\tau}\right) t$$

So, ℓn(N) vs t is a line, with slope = -1/τ and intercept $\ell n(N_0)$

- To do the fit, bring the cursor to the left of the vertical axis until you get a “+” symbol, then right-click and choose “Fit Panel”. When the Fit Panel pops up, select “expo” in the function drop-down menu. Near the bottom, there are sliders where you can select the desired fit range. The one one the left can be used to set the lower time limit, and the one on the right sets the upper time limit. After doing this, click on the “Fit” button.

- To see the results of the fit, go back to the original ROOT window.

- Compute 1/slope. What is the lifetime of the b-hadron? Also note that value of the error. What is the percent error on the slope determination? Since the same percent error applies to the lifetime determination (1/slope), what is the lifetime uncertainty?

Particles you may encounter in the event display:

Particle	**Quark Content**	**Mass (MeV/c^2)**	**Lifetime**
"Stable" Hadrons (directly detectable in particle physics detectors)			
π^+	$u\bar{d}$	139.6	26 *ns*
π^-	$\bar{u}d$	139.6	26 *ns*
K^+	$u\bar{s}$	493.7	12 *ns*
K^-	$\bar{u}s$	493.7	12 *ns*
p	uud	938.3	$> 2.1x10^{29}$ *yrs*
$\bar{p}$	$\overline{uu}\bar{d}$	938.3	$> 2.1x10^{29}$ *yrs*
Charm Particles (they all contain a charm quark)			
D^0	$c\bar{u}$	1865	410 *fs*
$\overline{D^0}$	$\bar{c}u$	1865	410 *fs*
D^+	$c\bar{d}$	1869	1040 *fs*
D^-	$\bar{c}d$	1869	1040 *fs*
D_s^+	$c\bar{s}$	1968	500 *fs*
D_s^-	$\bar{c}s$	1968	500 *fs*
Λ_c^+	cud	2286	200 *fs*
$\bar{\Lambda}_c^-$	$\overline{cu}\bar{d}$	2286	200 *fs*
b - hadrons (they all contain a bottom quark)			
B^0	$\bar{b}d$	5280	1520 *fs*
$\overline{B^0}$	$b\bar{d}$	5280	1520 *fs*
B^+	$\bar{b}u$	5280	1640 *fs*
B^-	$b\bar{u}$	5280	1640 *fs*
B_s^0	$\bar{b}s$	5367	1466 *fs*
$\overline{B_s^0}$	$b\bar{s}$	5367	1466 *fs*
Λ_b^0	bud	5620	1425 *fs*
$\bar{\Lambda}_b^0$	$\bar{b}\bar{u}\bar{d}$	5620	1425 *fs*

Some questions to ponder:

- Can you find out what the quark content of the various mesons and baryons are?
- Why are the mass peaks not sharp spikes, since each particle has a unique mass?
- Why do you think the various b-hadrons have somewhat different masses?
- Some of the events do not lie in the “mass peaks”… What are those events?
- Why does the decay time distribution not peak at some average value, but rather appear to follow more of an exponential behavior (ignoring the deficit of events at short lifetime, for which the reason is given above).
- Given the lifetime distribution, how far might you expect a typical b-hadron to travel, assuming it’s moving at about the speed of light. Does this agree with the values shown in the “decay distance” plot? If not, why might this be the case?

Additional questions on the reading or the event display

- Why does there need to be so many protons in a “bunch” in order to get a reasonable rate of collsions?
- Why are the protons collided at such high energy?
- Using $E=\gamma mc^2$, where $\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$, determine the velocity of a proton with energy E= 7 TeV.
- Why is the chance of a proton-proton collision relatively low?
  - Protons themselves are mostly empty space. The soft collisions are much more probable, since the quarks are flying around within the proton. If you take a large room as the size of a proton, the quarks would be no bigger than a raisin. They are at least 1000 times smaller than the proton, so most of the proton is empty space! Most of the mass of the proton is within the stored energy of the fields. A proton has a mass ~900 MeV and the quarks have a mass of ~3 MeV.
- Why is the mass of the b-hadron not equal to the sum of the masses of the particles it decays into?
- What are the hadrons discussed in the reading? What are their quark constituents? Can you come up with other valid hadrons, and classify them as either baryons or mesons?
- Do meson or baryon lifetimes depend on the types of quarks inside?
- Why would scientists be looking for “new physics”?
- What does the “Entries” entry on each graph correspond to? What about the mean and RMS? (Referring to event simulation simulation)
- If collisions at the LHC happen every 25 ns, how many collisions occur in 1 minute?
- What does the slope of the log(N) versus time represent (on the event display)?
- Does the slope of the curve depend on the time range over which you perform the fit?
- What happens to the slope if you include the events at small time in your fit? Do you thin that biases your results?
- What is the difference between mesons and baryons?
- Come up with 3 valid baryons and/or mesons and determine their charges. Is it possible to have a meson with total charge of +2 or -2? What about a baryon with total charge +2 or -2?
- Why don’t all the particle tracks from a collision point back exactly to the vertex from which they presumably came?
- How does the simulation differ from reality? (What are some of the limitations of the simulation?)

- Why do the beams cross at an angle? (They have to get back to separate beam pipes, and so there is no chance of interaction outside of the interaction region).
- Compare and contrast some aspect of the LHCb experiment with either the CMS or ATLAS experiments?
- Why does LHCb look down the pipe, whereas others surround the pipe?
- Write down on of the possible decay processes, and then write the corresponding quark content for each particle just below. Are there more quarks after the decay or before? How can that be? Is number of quarks a “conserved” quantity? How can that be?
- When we discovered that there were things called atoms, why didn’t we just stop?
- At 40 MHz, how many events occur every day?
- How does the slope of the ln(N) vs time compare for the different b-hadron types? Are they the same, very different, very similar?
- Compare and contrast baryons and mesons. How are they similar? How are they different?

Resources/Links

- The particle adventure: http://www.particleadventure.org/
- Tables of particle properties: http://pdglive.lbl.gov/listings1.brl
- The LHCb Experiment: http://lhcb-public.web.cern.ch/lhcb-public/
- SU’s Outreach page: http://hepoutreach.syr.edu/
- Bottle to Bang:http://cdsweb/cern.ch/record/1125472/
- LHC Status: http://lhc.web.cern.ch/lhc/
- LHC Statistics: https://lhc-statistics.web/cern/ch/LHC-Statistics/

Sidenotes/extras:

[1] How does one compute the "mass" of the b-meson, given that you measure the momentum and energy of the particles it decays into?

According to relativity, the total energy of a particle X, is E_X, is given by:

$$E_X^2 = p_X^2 c^2 + m_X^2 c^4 \qquad [1]$$

where p_X is its total momentum, m_X is its rest mass (its mass when its velocity is zero), and c is the speed of light (i.e., $3\text{x}10^8$ m/s). The "beauty" about this relationship is that it works in any reference frame from which you measure the energy and momentum. That is, you could measure (E_X,p_X) in the lab, or you can measure it running alongside particle X, where it appears then to be at rest to you. **The relationship will hold in ANY reference frame**.

One can invert this relation, to express the rest mass of X in terms of E and p, as:

$$m_X = \frac{1}{c^2}\sqrt{E_X^2 - p_X^2 c^2} \qquad [2]$$

This mass, m_X, you compute using the energy E_X , and the momentum, p_X, will be the same in any reference frame is thus called a "relativistic invariant", or just "invariant" for short. What has that done for us? Well, recall here, E is the total energy and p is the total momentum. Suppose a particle X decays to A, B and C, namely 0→A+B+C. Then, due to energy and momentum conservation, it must be the case that:

$$\begin{aligned} E_X &= E_A + E_B + E_C \\ \vec{p}_X &= \vec{p}_A + \vec{p}_B + \vec{p}_C \end{aligned} \qquad [3]$$

That is, the energy and momentum after the decay are equal to the values before the decay. We can the substitute [3] into [2], to get:

$$m_X = \frac{1}{c^2}\sqrt{(E_A + E_B + E_C)^2 - \left(\vec{p}_A + \vec{p}_B + \vec{p}_C\right)^2 c^2}$$

And there you have it. If you measure the particles that X decays into, you can compute the rest mass of X. Since this is the mass in a frame where its velocity is zero, this is its "true" mass, absent of any relativistic effects.

Typically for each of the decay products (A, B, C) that you measure directly in the detector, you get the energy by combining its measured momentum with the mass. The masses of these directly detected particles are determined using specialized detectors (within the main detector) capable of distinguishing π, K, p, e, and μ from one another. Once you determine the particle type, you know its mass, and can then use, for example: $E_A^2 = p_A^2 c^2 + m_A^2 c^4$

Are there any interesting statistics regarding the LHC?

Absolutely!

1. The LHC is the largest machine in the world!
2. The LHC is (by far) the largest refrigeration unit in the world, and keeps the machine at a temperature lower than what you would encounter in outer space!
3. The LHC has the fastest (human accelerated) protons in the world!
4. The beam pipe of the LHC is kept at a pressure lower than that found on the moon!
5. The collisions at the LHC produce the highest human-generated energy densities in the world!
6. The LHC has the biggest and most sophisticated detectors ever constructed!
7. The LHC uses the biggest computing system in the world to analyze the enormous data stream that it generates!
8. The LHC will run for at least 2 decades, yet it was constructed to study events that occur on a time scale as short as 10^{-23} seconds!