Chapter 1

Lesson 1 - April 15th, 2024

Lesson delivered by Zanetti.

1.1 Introduction

The wavelength of the probe must be less than the size of what we're gonna probe. So:

$$\lambda = \frac{2\pi}{\hbar}$$

but also $\hbar k = p\frac{h}{\lambda}$ so we need high momentum to probe it better. The momentum is near E if the mass is much smaller.

Because of the Einstein relation between energy and mass, in order to excite resonances and produce particles, we need sufficient energy (threshold energy).

So we need higher and higher energies to study the particles and resonances.

1.2 Accelerators

We need particles and we need to accelerate them. The energy ΔE is increased by having the particle with charge q to go through a potential ΔV so:

$$\Delta E = q \cdot \Delta V$$

So we use very high voltages to accelerate it. The problem is that we cannot make a potential so big to do it in a single pass. We need a series of accelerating stages in order to achieve the requested energy. When passing from one stage to the next, the voltage is reversed in order to push the particle away and not back in. So the polarity changes at the right moment. This are called radiofrequency cavities and they pump in energy to accelerate the particles. Because the size of the resonators is in the order of the meter, the radiofrequency is in the order of hundreds of megahertz: $\nu \approx 100MHz$.

Now, we can either put many of these accelerating stages in a linear fashion or we can dot it in a circular fashion where the particles are recirculated through the various stages. So we have linear and circular accelerators.

Typical dimensions: in a cavity we have fields of $30MV/m$. With this $\Delta E \approx 30MeV$. So in order to arrive to $7TeV$ we would need an enormous $200km$ cavity which is of course unfeasible. So this is why we need a circular accelerator.

In order to do this we need magnets to bend the path of the particles and guide them through the accelerating stages again.

$$p[GeV] = 0.3R[m]B[T]$$

at LhC we have a radius $R = 3000m$ and the momentum $p = 7000GeV$ and the magnetic fields must be in the range of $B = 8T$ which is a lot. The LhC accelerating stage is actually just 20 meters long. All the other parts of the circle are just used to bend the path of the particles.

1.3 Main features of the colliders

It is important to know the type of particles and the so called luminosity. Typically one collides e^-, e^+, p^+, p^-, $p - p$, etc. Also, the collision doesn't really involve protons but the partons they are made of (so quarks).

An important feature is that of **luminosity**. The collisions are described in terms of probability, so we have cross sections. The theory gives us the probability for a given outcome given an input. Like we have input particles at a certain energy and we get the probability of observing the final state from the theory.

We are interested in rare processes. In order to get the chance to observe rarer and rarer events, one would want a machine capable of producing a sufficient number of events.

1.3.1 Cross section

The cross section is a surface, expressed in barns. 1 barn is $10^{-24}cm^2$. This probability must be translated into a rate of events R. This is related to the prob:

$$\boxed{R = \sigma\alpha}$$

where α is called **istantaneous luminosity** and it relates the rate R and the prob σ. The luminosity is a property of the machine itself (of the beam actually). Now, luminosity follows this formula:

$$\alpha \propto \nu \frac{nN^2}{A} \cdot f(\theta)$$

where ν is the radiofrequency, n is the particle bunches (these are group of particles that are all in phase, so that the accelerating cavities can kick them forward). N is the number of particles per bunch. So the beams must be highly focused at the interaction point where we have a transverse area A and f is a form factor. The transverse area is in the order of μm^2.

At LhC we have $n = 2800$, $N = 1.4 \cdot 10^{11}$ and $A \approx 15\mu m^2$. The luminosity is on the order of $\alpha \approx 2 \cdot 10^{34} cm^{-2} Hz$.

So this is why we need high luminosity: in this way we can compensate for the small values of the σ of the rarest processes and thus observe a decent rate for them.

1.3.2 Project about e^+, e^- - FCC

Now the e^+, e^- collider is way cleaner because these particles are much simpler since they are believed to be pointlike. So all the energy being given to the particles is given to the particles. In the case of the proton collider instead, a fraction of the energy is actually captured since the protons are bags of partons and thus the energy is split between them.

The center of mass system and the LAB system in the case of e^+, e^- coincide, which is a very nice feature. All the kinematic constrants can be used. All of this would be impossible in an hadronic machine like LhC.

So if we create, for instance, a Z-boson creation via e^+, e^- collision. And then the Z boson decays in μ and $\bar{\mu}$. On the other side there's something we don't know:

$$e^- + e^+ \to Z(\mu^+ \mu^-) + X$$

and X is fully unknown. But just by knowing the initial conditions and measuring the upper side of the events, we can infer the properties of the X unknown. We have in fact:

$$E_{tot} = 2E_b$$

and $p_{tot} = 0$. Total energy and momentum are conserved, where E_b is the energy of a single beam. At the end the total energy is $E = E_Z + E_X$ so we have $E_X = 2E_b - E_Z$, measuring the energy of the Z boson. The momentum of X is just the opposite of the measured momentum of the Z. We also know the mass since:

$$m_X^2 = E_x^2 - |\bar{p}_X|^2$$

and:

$$s = 4E_b^2$$

All of this is possible only with collisions with elementary particles.

Looking at the cross section, in this case we have that the dimension of σ is the inverse of the s Lorentz invariant (the s Mandelstam variable).

So we want both σ and s high and they contrast each other. It happens that the other dependencies of the cross section make it so there are other contributions to the σ so it's not a problem. At lower energies instead, the cross section goes down as $1/s$. So, the higher the energy, the smaller σ is. This is why the events are cleaner.

The reason why we also use hadronic machines, is that the charged particles radiates energy via synchrotron radiation. Thus they lose energy, when in circular motion as:

$$\Delta E_{lost} = \frac{4\pi}{3}\alpha^2 \frac{\gamma^4}{R}$$

and γ is the Lorentz boost. At the LEP (before LhC) this ΔE was ($R = 3km$, $E_b = 104.5GeV$). In order to compensate for this energy loss, there were radiofrequency accelerators everywhere. In fact $\Delta E/E \approx 3.3\%$. So at every turn the RF needed to provide $3-4GeV$ because of how much energy they lost. So this fixes an upper limit on the feasibility of such accelerators.

When it comes to luminosity of an $e^+.e^-$ machine, there's a problem. Antimatter is scarce. So the number of bunches will be lower (at LEP it was just 10) and $\alpha_{LEP} = 10^{32} cm^{-2} Hz$.

In the case of FCC, it will be up to 10^{34}. These are the reasons behind the hadronic machine.

In the case of hadronic machine, given the mass of the proton is much larger than that of the electron, the synchrotron radiation is not a probem.

1.4 Project with p^+, p^- - LhC

The only limitation to the energy of the protons is the magnetic fields that is bending the particles. In this case we are not colliding point-like particles but bags of particles. We have a fraction f of the probability p_a and p_b, out of all the particles inside the protons, and they collid. They occurr at energy $\hat{s}$ which is smaller than s. The momentum they carry is: $x_a p$ and $x_b p$ so they do not carry all of the momentum.

So the cross section for a given process $\sigma_{p1,p2\to X}$ is:

$$\int_{x_a}^{1} dx_a \int_{x_b}^{1} dx_b P_a(x_a) P_b(x_b) \sigma(a, b \to X)$$

these are the parton probability functions. We put everything together in order to obtain the final cross section of the process. So this $\hat{s}$ is:

$$\hat{s} = x_a x_b s << s$$

So even if we have $7TeV$, the things that collide use a much lower energy. So:

$$E = \frac{(x_a + x_b)}{2} \cdot \sqrt{s}$$

and the longitudinal momentum:

$$p_L = \frac{x_a - x_b}{2}\sqrt{s}$$

in this case the LAB and CoM systems do not coincide. The fractions x_a and x_b are not accessible, are completely stochastic so that's why it's difficult. The

LAB and CoM are thus not easily linkable with a boost because of these things that complicate everything. **We do not know the center of mass system!**

We have to exploit what we know the most: the transverse plane! In this plane we know that the momentum is exactly 0. So since the momentum is conserved, zero momentum in the transverse means transverse in the final state.

1.4.1 Transverse momentum p_t

We also talk about transverse energy E_t which is basically p_t. Then we have the angle that defines the boost that is the rapidity η:

$$\eta = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} = \frac{1}{2}\ln\frac{p+p\cos\theta}{p+p\cos\theta} \approx -\ln\tan\frac{\theta}{2}$$

This is also called pseudo-rapidity. Is the angle that defines boost along the longitudinal direction. The η is invariant. The other important quantity is ϕ. So we have: p_t, η, ϕ. Every particle is gonna be labelled by these three quantities.

So we want the detector to give us:

- Transverse momentum p_t
- Pseudorapidity η gives us the angle with respect to the longitudinal direction
- Angle ϕ

We expect physics to appear in the forward direction because of kinematical constraints. The higher the energy of the process, the more central is the interaction.

In the case of the protons, we have a higher range of processes that can be probed. We have also gluon interactions, gluon-quark, quark-quark and so on. The luminosity is also very high (order to 10^{34} and above). The events though are not clean at all.

Considering the LhC again, the luminosity for a single bunch is:

$$\alpha_b = \frac{N^2\nu}{A_T} = 10^{31}cm^{-2}Hz = 10^4 mb^{-1}Hz$$

The total cross section is in the range of $80mb$ (millibarn). So:

$$R = \alpha_b \sigma_{Inc} = 8\cdot 10^5 Hz$$

The frequency of the LhC is $10^4 Hz$. How is R higher than the machine frequency? This is because everytime the bunch collides, we have $8\cdot 10^5/8\cdot 10^4$ which is roughly 80. So we have 80 collisions of protons each time bunches interact. This is why it's so messy. We don't have just one collision, we have 80 simultaneous collisions and we only care about one of them. The others are just noise.

We have initial and final state particles. We know the colliding particles, we measure the final state particles. In between there's the interesting dynamics of the phenomenon. Knowing initial and final state, we want to know what the interesting dynamics is. That's all about it.

Since it is all dominated by quantum mechanics, a final state does not come univocally from a single initial state. So the analysis cannot be on an event by event fashion, this is because we don't know what happens istantaneously. We need to estimate distributions and here is where analysis comes in.

The events are candidate events since we do not know exactly what it is. The detectors are operated assuming that the final state particles are the standard model ones. We can interpret the data from the detector also assuming that something wierd is going on.

The standard procedure is: we interpret the data assuming that in the final state we just have standard model particles. For our work we're gonna have files, so collection of events for various particles also jets and missing energies. This is after massive data reduction on the raw data.

Typically we reduce the events to a subset that retain the number of features we're interested in. Like if we're interested in a process with 4 muons in the final state, we consider only these ones. So selecting events is done as a function to what we're interested in.

Also, we will be given montecarlo simulations of the physics in order to do comparisons with the data, to see if they somewhat correspond. We will have to try several procedures in order to enhance the signal the most over the noise. At that point we can run the analysis. Also, we need to asses statistical uncertainties (systematic will actually take years to tackle).

Chapter 2

Lesson 2 - April 24th, 2024

Lesson delivered by Zucchetta with incursions by Zanetti.

2.1 Particle processes

The processes we're interested in are the following:

- ttW: top, top, W boson
- ttZ: top, top, Z boson
- tWz: top, W and Z bosons
- tZq: top, Z boson and light quark q. A light quark can be up, down or strange.

Since we're colliding protons with protons, we're not dealing with point-like particles but with "bag" of particles that are smashed together (partons). Each of these processes is characterized by a cross section that determines how frequent it is (i.e. how probable) to observe such process. These are computed by theoretical calculations: These processes furnish the **signal**(s) but of course

Process	Cross Section
ttW	$0.60pb$
ttZ	$0.88pb$
tZq	$88fb$
tWz	$354fb$

these signals are tiny with respect to the background noise being generated by other processes that are of no interest for this analysis. This noise into which the signal is embedded is due to:

- top - antitop pair production: the cross section for this process is actually pretty big at $830pb$.

- W and Z boson processes: W-W, W-Z and Z-Z accounting for $10pb$.

The top quark, as all quarks, cannot exist alone so it fragments before it can hadronize and it goes off like this:

$$t \rightarrow Wb$$

where W is a W boson and b is a **bottom quark** (which is quite fat compared to the lighter ones). This W boson is of course unstable and it can decay in a pair of $q\bar{q}$ where q is a light quark or it can decay as a **leptonic pair**: electron and electronic neutrino, muon and muonic neutrino, tau and tauonic neutrino. These are all equiprobable.

While the $q\bar{q}$ can decay in 9 different channels given the color charge of the quarks, the leptons don't have that. We're mainly interested in the leptonic channels with electron and electronic neutrino and muon and muonic neutrino. These two account for 1/9 each of the probability of the decay of the W.

Generally calling l a lepton and ν_l the corresponding neutrino flavour, we thus consider:

$$t \rightarrow l\nu_l b$$

Now, the top quark is rarely produced alone: most of the times it is produced in pairs with the anti-top. The top-anti top pair decays in: These **final state**

Decay Channel	Probability
2l-2b	5%
1l-2q-2b	30%
4q-2b	44%

particles are those that are measured by the detector. We cannot measure quarks directly since they're too shortly lived to be measurable.

We now distinguish between two kinds of quark hadronizations:

- q hadronization: a lot of particles are produced by the hadronization process like pions, kaons, mesons. This kind of hadronization involves up, down, strange and charm quarks.
- b hadronization: this is the special case of the b (bottom) quark. The bottom quark hadronizes into a **B meson** which is a bounded state with a bottom quark and a lighter quark (so there's like the B_s meson for bottom+strange, the B_c for bottom+charm, etc). We consider $B^{\pm}$ and B^0 mesons.

The B mesons are much longer lived with respect to the quarks themselves (they can travel for up to $490\mu m$ from the interaction point, also called the **primary vertex**). Actually they travel even farther given the huge Lorentz-boost due to the high energy of the collisions. With a γ factor of almost 10 and $\beta \approx 1$, these particles can travel for half a centimeter when generated at $50GeV$.

The $B^{\pm}$ and B^0 are the ones that travel up to the **secondary vertex** where they decay. So, if we have a secondary vertex, we have a signature that something interesting happened. So **the presence of a secondary vertex in an event is the signature to look for**.

2.2 Detector geometry

The first layer of the CMS detector is the **silicon tracker** which is itself comprised of several layers: an inner tracker (a pixel detector that surrounds the interaction point) and a strip tracker (a detector that tracks the motion of the particle). The silicon tracker can only react to charged particles.

The other layers are calorimeters that measure the energy of the particles by destroying them.

The outermost layers are the muon detectors.

Finally, the detector generates a powerful magnetic field by means of superconducting magnets. The field allows to determine the sign of the charge of the charged particles since their tracks will be bent in different directions depending on their individual charges.

At the LHC, protons are collided in bunches (i.e. groups of protons). Out of these, only a fraction of them actually interact and this number is called, in HEP jargon: **pile up**. So, the higher the pile up, the more difficult the reconstruction becomes.

2.3 Jets and B-Jets

A jet is a "grouping" of multiple particles that originate from the decay of a secondary particle. A jet can be treated as a single entity so it has its own transverse momentum, energy and mass. A special type of jet is the **B-jet**.

The identification of a **B-jet** with respect to a normal jet is absolutely non trivial and it can be done only in $\approx 50\%$ of cases. A specifically purposed algorithm (a discriminator) determines the probability of a jet being a B-jet and that probability is stored in a dedicated branch inside each ROOT file.

2.4 Leptons

Leptons (electrons and muons) are easy to reconstruct. Most of them originate from decay of quarks. How to separate leptons from W decays and from b decays?

The W boson decays in $l\nu$ and typically they are **isolated**. Conversely, the leptons originating from b decays are **not isolated**. For this reason a metric known as **isolation** is defined:

$$I = \frac{\sum p_t}{p_t^l}$$

The idea is to consider, in a cone, all the particle tracks around the lepton of interest. Then, all the momentum of these particles that surround the lepton are summed and the sum is divided by the momentum of the lepton itself, p_t^l. So, if the lepton was isolated, ideally the cone would contain no other particles but the lepton, leading to an isolation of exactly 0. Of course, since background events are present, the cone will contain the tracks of other particles. So, if the lepton was an isolated one, its energy would be independent from the energy of the other particles in the cone and its isolation value would be small. On the contrary, if a lepton wasn't isolated but, for instance, it was generated by the decay of a b quark, its cone would contain a lot of secondary particles and hence its isolation value would become quite large.

Isolation variable I is thus quite useful to discriminate between events.

The particle tracks are reconstructed by an algorithm that is called **particle flow** (PF in the data).

2.5 CMS Trigger

The trigger is made of two layers: L1 and HLT. The level 1 trigger L1 operates at LHC's clock frequency of $40MHz$ and selects events in real time according to its programming (can be set to activate on several conditions depending on the physics process of interest). The data comes out of L1 at a rete of $\approx 100kHz$. This if further reduced by the HLT to $1KHz$, corresponding to a data rate of $\approx 1GB/s$.

The trigger is programmed to select events according to a specific set of rules on the various signals coming from the detector. The list of conditions is called a **menu**. Each of these conditions is sufficient, meaning that the trigger will fire if at least one of those passes and the selected event is thus written.

Inside the data files, the trigger's variables are named like "HLT" and for instance $HLT\_SingleIsoMu27$ means: the rule requires a single isolated muon of transverse momentum $> 27GeV$ for the trigger to fire. This is useful to separate the various events.

2.6 Data structure - ROOT files

Events are stored in a tree structure inside a ROOT file. Each event consists of a series of features (named branches). When an event is read, all the values in the branches at that specific event index are considered.

In order to select the various events, rules must be applied to the features in order to extract them: for instance how many leptons we want, etc.