Introduction to Quantum Field Theory - II (Theory of Scalar Fields)
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Module - 6
Lecture - 16
High Energy Physics Experiments

So, we have come quite far in our course on Quantum Field Theory and now I want to start a description of high energy experiments and how to make contact with them. So, let us quickly summarise what we have learnt so far.

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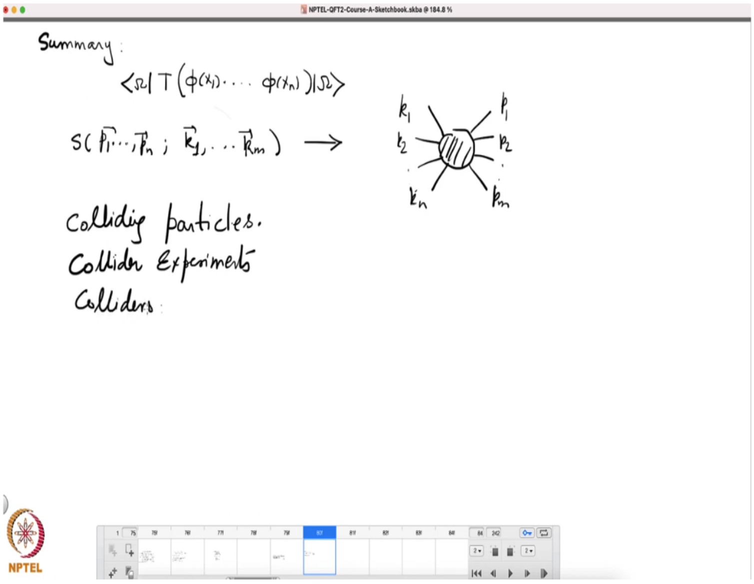

Summary:

$\langle\Omega| T(\phi(x_1)\cdots\phi(x_n))|\Omega\rangle$

$S(\vec{p}_1\cdots,\vec{p}_n;\ \vec{k}_1,\cdots\vec{k}_m) \longrightarrow$

Colliding particles.

Collider Experiments

Colliders:

Summary: It is very brief summary. So, in course 1, we learnt how to calculate the abstract quantities which we call Green's function and we learnt how to write down expressions for them in perturbation theory. So, we have learnt how to obtain these objects. And then in this course, we have seen that the S matrix elements which we denoted by S p 1 to p n, these labels refer to out states and k 1 to k m in state, these momentum labels refer to in states.

This we saw that we can write it as, we saw that this is proportional to amputated Green's function. Apart from some factors of 2 pi's and some factors of z, this is basically this object where the legs have been amputated, and there are no external corrections like this here. That is what we meant by amputated Green's functions. This is what we have learnt. And now, what we want to learn is how to make some contact with experiments given that we have learnt how to calculate these objects.

So, that is the goal, and before I tell you that, let us first look at few experiments that have already been carried out and are in progress. So, I am listing a few of them. So, one of the very famous experiments was, it is not one experiment, it is a set of experiments, and typically, these experiments in high energy physics are basically colliding particles. So, that is what we do. I will tell you why we do so, but first let me give some details.

So, a typical high energy physics experiment would involve that you create a bunch of particles in a very controlled manner, meaning that you know what their initial momenta are and you let them collide. And once they collide, then you look at the whatever you get in the final state after the collision. So, these experiments are usually called collider experiments. And these facilities where such experiments are done are called colliders, because they collide particles.

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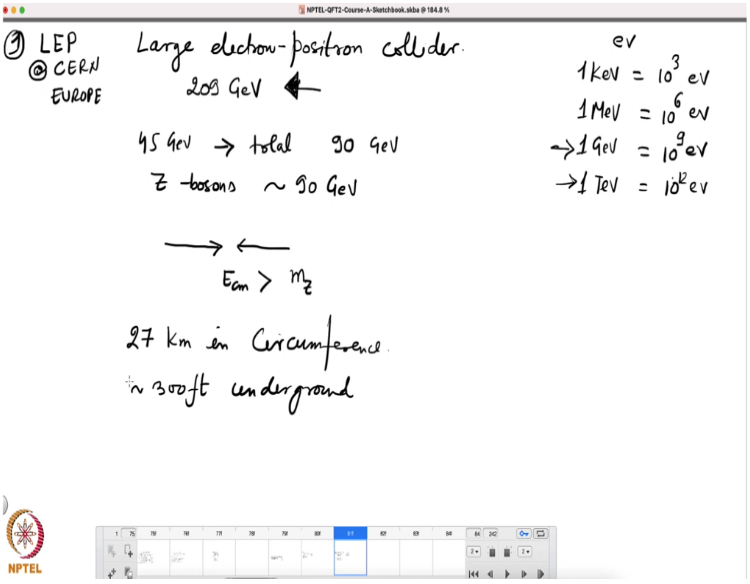

① LEP

@ CERN

EUROPE

Large electron-positron collider.

209 GeV ←

45 GeV → total 90 GeV

Z-bosons ~ 90 GeV

$\longrightarrow \longleftarrow$

$E_{cm} > m_Z$

27 km in Circumference

~ 300ft underground

eV

1 keV = 10^3 eV

1 MeV = 10^6 eV

→ 1 GeV = 10^9 eV

→ 1 TeV = 10^{12} eV

So, one such very important collider is LEP, which is large electron positron collider. And as the name says, it is colliding electrons and positrons. So, this facility is at CERN; was at CERN actually, it is not there anymore; was at CERN in Europe. And the energy, the maximum energy that reached in this collisions was 209 GeV. Let me also tell you what this unit is. So, you know electron volt already; that is unit of energy.

Then you have 1 kiloelectron volt which is 1000 electron volts. Then 1 mega-electron volt which is 1000 times more than this or 10 to the 6 electron volts or 1 million electron volts. And then you have 1 giga-electron volt which is again 10, a factor of 1000. And then 1 TeV which is 10 to the 12 electron volt. So, you see that you are here, 209 GeV. So, you are in this, somewhere between these two. This is for LEP.

And in the beginning of this collider, they were colliding electrons and positrons, each of which had energy equal to 45 GeV. So, total would be 90 GeV. And the reason that why we had this energy in this machine was because the Z bosons; these are particles, also fundamental particles; they also have mass around 90 GeV.

So, thing is that if you have an electron and a positron colliding and then the total energy is 90 GeV or more or let us say higher than the Z boson mass; if the centre of mass energy is greater than Z boson mass; let me call it m z; then you can produce these particles, because the minimum energy that you need to create a Z boson mass, a Z boson particle would be equal to the mass of that particle.

If you provide just that much energy, then you produce these Z bosons at rest, and if you have additional energy, then that energy would go into giving momentum to the Z boson mass and also producing some other particles; and that is why this initially the electron positron collider, the LEP had energy around 90 GeV; it started with 90 GeV. Also these facilities are quite big.

So, this one was in a tunnel which was 27 kilometres in circumference and roughly 300 feet underground. To get a sense of this number, recall that these days the height of roof of our apartment is around 9 feet, so, let us say it is approximately 10 feet; then this is 30 times of that, meaning you are looking at the height which is equivalent to that of a building which is 30 storeys high, which will have 30 storeys.

So, that much deep you have to go in the ground, and that is where it is. It is at that depth where the LEP tunnel is located. And then this also passes through both Switzerland and France; it passed through. So, that is the electron positron collider, and for Lepton colliders, this is the collider where the maximum energy was ever achieved. Later colliders which have higher energies than this are not Lepton colliders but they are Hadron colliders which I will tell you in a moment. Another collider which played a lot of role in development of high energy physics is Tevatron, and this was at Fermilab in United States.

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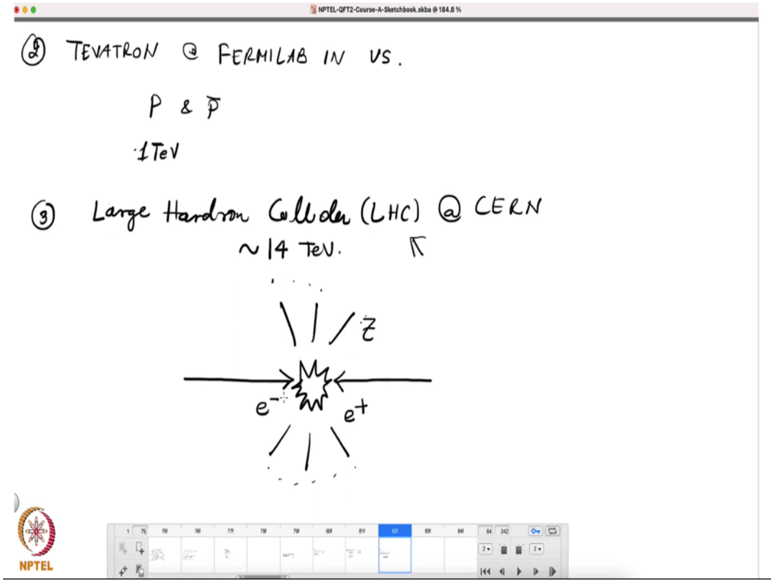

② TEVATRON @ FERMILAB IN US.

P & $\bar{P}$

1 TeV

③ Large Hadron Collider (LHC) @ CERN

~ 14 TeV.

And this machine collided protons and antiprotons. And this machine was a second highest energy collider which was ever built, and the centre of mass energy was up to 1 TeV tera-electron volt. And then we have presently Large Hadron Collider, LHC; Large Hadron Collider, LHC, and this is at again CERN in Europe, and it is in the same tunnel in which LEP was, and the energy is currently almost equal to 14 TeV.

And also remind you that Higgs was discovered in LHC. So, what do these experiments do? So, as I said, they collide particles. So, typical high energy physics experiment will go like this. Let us look at the example of LEP. So, here you will have an electron which will be coming with high energy. As I said in the beginning, they were a 45 GeV. And then you have another particle which is positron coming towards the electron, again with 45 GeV, and then they collide, they interact, and they will produce lots of things.

Now remember, we are going to produce not just electrons and positrons in the final state. See, typically when you; let us say you have 2 bricks, you collide them, the fragments that you get, they are also of the same thing, they are also parts of the brick, you have not produced coal out of this collision; but here when we are doing these experiments, it is possible that you collide this electron and positron and they both disappear and they give you let us say a Z boson and together with a bunch of other particles.

So, the initial state and final state could have very different particle composition. So, it is also possible that you collide electron and positron and in the final state also you have electron and positron; that is of course a possibility; but you will also find final states with other particles and this is happening because of interactions; but in this course, we are going to look only at one field which is phi and it is self-interacting.

So, in our case, the initial particles, the particles which come in the initial state which are colliding, they are also phi particles, meaning particles which correspond to field phi. And what you produce in the final state also correspond to the same variety of particles, but the particle numbers could be different in the initial state and the final state. You might collide 2 particles and produce 20 particles in the final state.

So, then what do you measure in these experiments? This is what we write. We collide these particles and we produce some things, but what is that we measure and why do we measure whatever we measure? So, here is what we measure.

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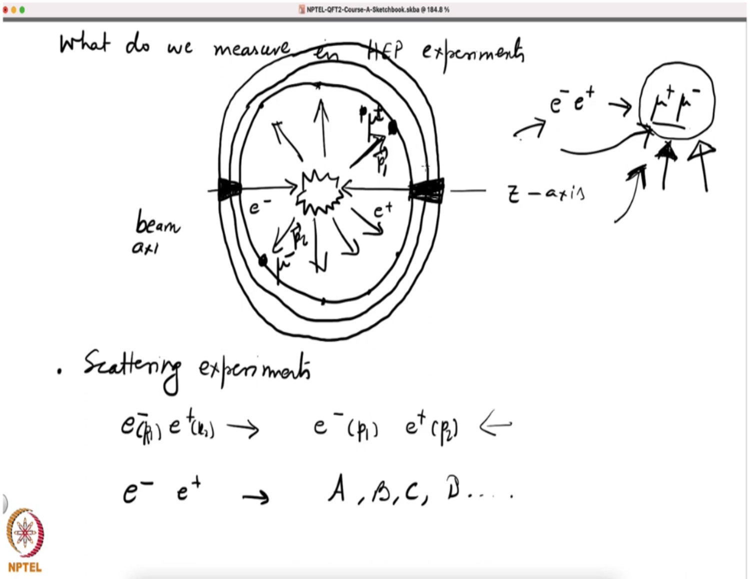

What do we measure in HEP experiments

- Scattering experiments

$$e^-(k_1)\, e^+(k_1) \rightarrow e^-(p_1)\, e^+(p_2) \leftarrow$$

$$e^- e^+ \rightarrow A, B, C, D \ldots$$

What do we measure in these experiments, in HEP experiments? So, let me draw first a setup. Again I will look at the example of LEP. So, you have electron and positron coming towards each other, and let us call this axis as z-axis. So, here some collision will happen. When they are reasonably close, they will feel their interactions and then some final state will be produced.

It will produce many things; it will produce whatever it can produce, which includes leptons and also hadrons. So, this is also called beam axis. It is beam because it is not just 1 electron colliding against another positron, but it has a bunch of electrons moving along this direction and it has a bunch of positrons. So, you have a beam basically of electron and a beam of electron and positron which is colliding.

So, what you do is, you place detectors all around. So, this is a sphere, not a circle. So, you have placed; so, think of this as, think of this as a sphere. So, these detectors will typically detect the energy deposits which these particles hitting the detectors make. And one can also determine the momenta of these particles which are hitting the detectors. So, you know where the particles have hit at what angle and also you know the momentum.

And also you would usually have many layers of detectors because some particles will get detected at the first layer and maybe the first layer of detectors is not going to detect some another set of particles. So, you will have another layer and maybe more depending on what all particles you want to detect, and it is still possible that you do not detect some of the particles and they completely escape all these detectors like neutrinos will not get detected by this, because they do not get stopped by these detectors at all.

So, that is the setup. Now let us look at an event in which after this collision you have a muon, a mu minus and mu plus. Muon is another particle which is just like an electron but it has a higher mass; and mu plus, anti-muon is its anti-particle. So, suppose in this experiment, in one particular collision you get this, e + e - going to mu plus mu minus. That is an event that is happening in this process.

So, you might ask the following question. If I were to collide millions and millions of, let us say 1 million times electrons and positrons how many times I am going to get a mu plus mu minus pair where mu plus is going in, has a momentum let us say p 1 and mu minus has momentum p 2? Or if you want, we can say that it has a momentum, centre momentum p 1 and we allow for some spread in some range around this and similarly for this.

So, we could ask how many such events are produced in these collisions. Or equivalently, if you are asking only for one collision, then you could ask what is the probability that this collision produces a mu plus mu minus pair where mu plus carries a momentum p 1 and mu minus which is muon carries momentum p 2? So, these are the questions which we typically ask.

Now, you might ask why you asked such questions that, what is the probability of producing this final state configuration in this collision. And the reason why we are interested in such questions that so and so particle is produced with so and so momentum is because this probability of producing this final state is influenced or it is determined by the kind of interactions that are present.

If the interaction between electron and positron were to be changed, then these probabilities would also change. Whatever probability you have given the universe we have right now, whatever interactions these particles experience, given that, you can calculate and measure what is the probability of producing a particular final state. Now, if you were to change the nature of interaction between electron and positron, then these outcomes will also become different.

And not only these outcomes become different, but it is also possible that certain outcomes are not even allowed once you change the nature of interactions. So, measuring these quantities, these objects; I will give you more precisely what I mean by these quantities; but measuring these probabilities also tell you about the kind of interactions that these particles are undergoing. So, it goes both ways knowing what kind of interactions we have.

We can predict what kind of outcomes we will get with what probabilities; and other way around, having found the outcomes in the experiment, one could also infer the kind of interactions that the interacting particles are experiencing, and of course, the final state particles, what they are experiencing. So, there is a lot of information that is to be gained by doing such collision experiments and looking at the final states.

So, I have hopefully given you an idea of the reason behind designing such experiments. Now, let me tell you that typically all these experiments are called scattering experiments. So, when you scatter an electron and a positron, they may deflect in different directions. So, let us say you started with momentum p 1 or let us say k 1 and k 2 and you produced particles with momentum p 1 and p 2.

Now the initial state and final state has same set of particles, so, they are moving in different directions and this is what you usually call scattering; but even when they produce many different particles, whatever these particles be, so forth, even then, we call this as a scattering experiment. Though it is different from this variety, but the generic term that is used is scattering.

Now, before I start looking at scattering and try to figure out how to answer questions regarding probabilities of certain outcomes, let me first look at the structure of the S matrix and then we will go on to more detailed study of scattering.

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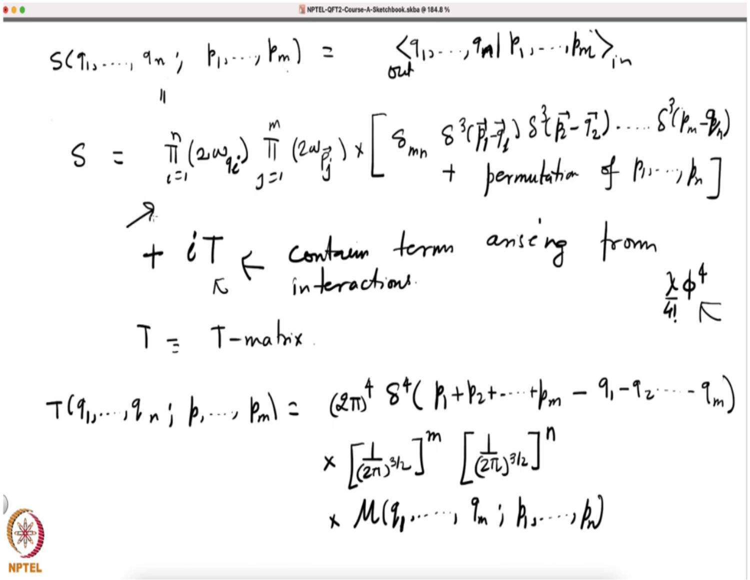

$$S(q_1, \ldots, q_n ;\ p_1, \ldots, p_m) = {}_{\text{out}}\langle q_1, \ldots, q_n | p_1, \ldots, p_m \rangle_{\text{in}}$$

$$\parallel$$

$$S = \prod_{i=1}^{n} (2\omega_{q_i}) \prod_{j=1}^{m} (2\omega_{\vec{p}_j}) \times \Big[\delta_{mn}\, \delta^3(\vec{p}_1 - \vec{q}_1)\, \delta^3(\vec{p}_2 - \vec{q}_2) \ldots\ldots \delta^3(p_m - q_n) + \text{permutation of } p_1, \ldots, p_n \Big]$$

$$+\ iT \leftarrow \text{contain terms arising from interactions}$$

$$\frac{\lambda}{4!}\phi^4$$

$$T \equiv T\text{-matrix}$$

$$T(q_1, \ldots, q_n ;\ p_1, \ldots, p_m) = (2\pi)^4\, \delta^4(p_1 + p_2 + \cdots + p_m - q_1 - q_2 \cdots - q_m) \times \left[\frac{1}{(2\pi)^{3/2}}\right]^m \left[\frac{1}{(2\pi)^{3/2}}\right]^n \times \mathcal{M}(q_1, \ldots, q_m ;\ p_1, \ldots, p_n)$$

So, let us look at the S matrix which we have seen, which is basically the inner product of instate and outstate. Does not matter whatever I write here, remember that this was; now remember, we are doing a perturbation theory where we have a parameter lambda which appears in the Lagrangian. Now, to the lowest order, the result will be that of a free theory. By lowest order, you would mean that if you were to put lambda equal to 0, whatever you get is the result of free theory.

So, we know that already; we have seen that in free theory. So, I am just going to write S now; I am writing this object. In free theory, you get the following. These are coming from the normalisation of the states. This is n and this is m. And then we will have delta m n, because when you are looking at free theory, m and n has to be the same. So, whatever particles you have in the initial state, the same number of particles you should have in the final state, and this is how the initial state and final state momentum are related.

The initial state and final state momenta are the same. That is what these delta functions ensure and plus permutations of p 1 to p n. That is what you would expect in free theory and that is why this would be the lowest order term in interacting theory as well. And then of course, you will have other terms that will arise due to the interactions and let me call them generically as i times T.

So, T contains terms that arise due to from interaction; T is called the T matrix. This is the really non-trivial part; the first part is trivial. This is what carries information about the scattering and let me write down the general structure of T. So, T of q's and p's will have the following form. You remember that when we analysed S matrix, we saw that we will always have total energy momentum conservation and it was always come accompanied by these factors 2 pi to the 4 delta 4, and you have initial state which is p 1, the momenta in the initial state, and that should equal to the sum of momenta in the final state.

This is the overall energy momentum conservation. And then we had also seen these factors of 1 over 2 pi 3 halves appearing. So, they also appear; and it is not important that I keep these factors but it is useful to keep them. And then, so, this is a general structure of T. You have this delta function and some constants hanging around, and then the real content is in a function which I define to be M. So, this expression is basically defining M.

So, T, how do you get T? You get T by subtracting from S this free theory part. So, that is what is T. And then T, I further write as M; so, this defines M; and all you have done is you have pulled out certain factors that you know are going to appear. So, that is the definition of M, and this is the object that you would like to calculate from the theory and then make connection with our question of what is the probability of producing a particular final state in a collision.

Now, notice that when you are doing scattering; see, I should carefully construct in state and out state, but still you can see from here that when you are doing a scattering, this non-trivial contribution which is coming due to interaction, this T contains lambda. So, it has factors of lambda and where lambda is the; this lambda I am talking about, lambda phi to the 4, this lambda.

And lambda is the parameter in which you are doing perturbation theory, so, you treat lambda to be small, which means that these contributions coming from here, they are small. In the first term, there is no lambda, it is just this factor; and the second term has powers of lambda, so, it is a term which is suppressed; it is of higher order in perturbation theory. So, most of the time, when you are scattering particles, they will behave as if they are free particles.

So, they will not just see each other; they will just continue along their paths and reach the detector; but because of this presence, once in a while, they will get deflected and reach the detector at different angles or even produce new particles moving in different directions. But in our case, all the particles will be of the same variety but you might have, you begin with 2 particles in the initial state; you collide 2 particles, 2 phi particles and you get may be 4 particles or 10 particles in the final state; but majority of the collisions will be governed, will be controlled by this, so, they will be just reaching the detector without any deflection.

So, now what is going to happen is that, one thing is that you have lot of energy that you have pumped in, in these electrons and positrons. So, they are very energetic. Second, you have lot of intensity, because, it is not just one electron that you are firing at a positron, but you have a huge number of electrons that are being fired and similarly huge number of protons that are being fired per second; and all of them actually a big fraction of them are going to just reach the detector on the other side.

And similarly for positrons, they are going to reach to the detector on the other side and that is because of this first term. And if they reach, they are in large numbers with large energy; they are just going to burn the detector. So, this part is just going to get damaged. So, once you have damaged it, you have to replace it or just leave it like that because it does not do anything, or you simply do not put any detectors there to begin with; that will be a much smarter thing to do.

So, to play you do not put anything along the beam axis because that is going to burn anyway. It is just like your skin receiving sunlight. The skin can receive sunlight; it can feel the temperature; but if you are to put a lens and have lot of light now getting concentrated at one place, then the detector, your skin, it just burns up because it cannot handle that many of photons with that energy arriving on your skin. That is the same structure here.

So, now we understand the set up. We also understand the question that we want to ask and also the reason behind why we want to ask such questions. Now we have to precisely formulate mathematically what is that object and how to determine it using quantum field theory. So, that is our next task.