Introduction to Particle Physics
Particle Physics describes the basic constituents of matter and their interactions. It has a deep interplay with cosmology. Modern cosmology and PP’s are complementary in our quest to answer the basic riddles in our current understanding of the Universe. There is no point in following a historical introduction in a one hour talk.
Tools

Special Relativity
Quantum Mechanics
Quantum Field Theory
General Relativity
Special units

\[ \hbar = \frac{\hbar}{2\pi} = 1 \quad c = 1 \quad k = 1 \]

1 eV = \(1.602 \times 10^{-12}\) ergs

\[1\text{ keV} = 10^3\text{ eV}\]
\[1\text{ MeV} = 10^6\text{ eV}\]
\[1\text{ GeV} = 10^9\text{ eV}\]
\[1\text{ TeV} = 10^{12}\text{ eV}\]

Everything is expressed in terms of either length or energy. Measure time in centimeters, \(x_0 = c t\). We can measure energy in grams, or mass in MeVs

The electron mass is 0.511 MeV

The proton mass is about 1 GeV

The LHC will run at 13.5 TeV

\[L \sim \frac{1}{E} \quad \quad E \sim \frac{1}{L}\]
Pythagoras with a minus sign

\[(\Delta L)^2 = (\Delta x)^2 + (\Delta y)^2\]
\[(\Delta \tau)^2 = (\Delta t)^2 - (\Delta x)^2\]

\[t' = \gamma \left(t - \frac{vx}{c^2}\right)\]
\[x' = \gamma (x - vt)\]
\[y' = y\]
\[z' = z\]

\[\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}\]

\[(E, p_x, p_y, p_y)\]

\[E^2 = p^2 + m^2\]
Einstein’s 1st equation

\[ E = mc^2 \]
Particle numbers are not conserved. Energy can be converted into particles and vice versa. This is the great difficulty with QM and Relativity. It is also the origin of the existence of antimatter.

Einstein’s 2nd equation

\[ m = \frac{E}{c^2} \]
Mechanics reminder

\[ p_N = m v \]
\[ p_E = m v \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \]
\[ E_N = \frac{m}{2} v^2 \]
\[ E_E = m c^2 \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \]

\( m \to 0, \quad v \to c \quad p = \frac{E}{c} \)

Mass (inertia) represents resistance to acceleration

Nothing to do with friction

Viscosity is resistance to velocity
Quantum mechanics

The dynamical state of a system is described by the wave function of the system, a probability amplitude, which satisfies the Schroedinger equation.

\[ i \hbar \frac{\partial}{\partial t} \Psi(r_1, r_2 \ldots, r_n, t) = \left( \sum_i \left( -\frac{1}{2m_i} \nabla_i^2 \right) + V(r_1, r_2 \ldots, r_n, t) \right) \Psi(r_1, r_2 \ldots, r_n, t) \]

The space of states is complex.

The number of particles is conserved (no particle creation).

Uncertainty relations.

Very successful description of the structure of matter in the non-relativistic limit.

\[ \Delta x \Delta p \geq \frac{\hbar}{2} \quad \Delta t \Delta E \geq \frac{\hbar}{2} \]
Quantum field theory

- Relativistic invariance
- Quantum mechanics
- Particle creation
- Infinite number of degrees of freedom
- At least one per space point
- Wave particle duality, for each field their is a particle (and its anti-particle)
- Microscopic causality

The most basic language to express the laws of nature.

The basic problem is to determine the “vacuum”, i.e. the state of minimum energy of the universe. Completely different from the “nada” in classical philosophy.
General procedure

Kinematics

Dynamics

Symmetries

Global, local

Explicit or broken

Discrete: Parity, C, T
Before chemistry
A more modern one
Each quark comes in three colours. There are three generations of quarks and leptons. All matter we see around us is made of the first generation... the last to come is H!
Two types of particles

Bosons, integer spin. Very sociable. They admit a classical description. The standard force fields are described by bosons.

Fermions half integer spin. Completely asocial. They make atoms and all matter we see around us.

What makes dark matter?

What entity is dark energy?

Why there is no antimatter?
Hadrons and nuclei are built with quarks

Hadrons come in two varieties:
Baryons
Mesons
Lowest lying baryons and mesons
Three types of interactions

Electromagnetic

Weak

Strong

All described by a similar mathematical structure, known as gauge symmetry or gauge invariance

A visual description in terms of Feynman graphs
Precise computational rules

Standard Model Interactions
(Forces Mediated by Gauge Bosons)

X is any fermion in the Standard Model.
X is electrically charged.
X is any quark.

U is a up-type quark; D is a down-type quark.
L is a lepton and \( \nu \) is the corresponding neutrino.

X is a photon or Z-boson.
X and Y are any two electroweak bosons such that charge is conserved.
Some processes...
Some more…

- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \rightarrow bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\rightarrow$ hadrons
- hadronic decays
Sometimes it can be messy...
Some interesting properties

The strong interactions are mediated by the exchange of gluons. The remarkable property is that all objects carrying colour are confined. The theory, QCD is asymptotically free, but is afflicted with infrared slavery. It happens even if quarks are massless!

This is a purely quantum phenomenon. Similar to the Meissner effect in type II superconductors. In fact, this is the origin of your mass. It is completely mind boggling.

\[ E = \sigma L \]
The Higgs mechanism, how much does it contribute to your weight?
The mass parameters obtained for the light quarks are too small to explain the masses of protons and neutrons that make up nuclei. From elementary nuclear physics we know:

\[ M(Z, A) = Z m_p + (A - Z) m_n + \Delta M(Z, A) \quad \Delta M(Z, A) << M(Z, A) \]

The largest contribution come from the fact that quarks and gluons are highly relativistic objects confined in a space of the order of a fermi. A purely quantum phenomenon due to QCD: the confinement of colour. A new scale is generated dynamically. Generated with the breaking of scale invariance. Most of the mass of nucleons come from this. Even if the mass parameters of the u,d quarks was set to zero, we would still have nucleons. What makes the study of the strong interactions hard is the fact that:

\[ \Lambda >> m_u, m_d \]

A large fraction of our mass has its origin in this quantum phenomenon of confinement. We are indeed macroscopic quantum objects! There is also a beautiful analogy with the BEH mechanism, but of a more subtle type.
An unexpected result

Is it all BEH?
Another unexpected result

The Planck chimney
Many open problems

- Flavors and families, mass and mixings
- Matter-antimatter asymmetry
- What stabilises the SM?
- Neutrino oscillations masses and mixings
- Baryogenesis, leptogenesis
- Gravity?
- Black holes?
- Dark matter and energy...
Discrete symmetries

\[ P \quad C \quad T \quad CP \quad CPT \]
Varieties of symmetries

Discrete
Continuous:
  Kinematical: space-time transformations
  Internal: global, local (change with space)

Quantum implementation:

\[ [Q_a, H] = 0, \quad Q_a |0 > = 0 \quad \text{Wigner-Weyl} \]

\[ [Q_a, H] = 0, \quad Q_a |0 > \neq 0 \quad \text{Nambu-Goldstone} \]

Every broken symmetry has associated a massless particle
Examples of both types abound in CMP and PP. It is a quantum phenomenon in the SM. The Higgs particle does not give mass. It is the Higgs vacuum. It explains the masses of W,Z and accommodates the masses of the known quarks and leptons, but does not explain them.

The interplay between local (gauge) symmetries and SSB is the theme of this conference
Thank you