Aspects of Experimental High-Energy Physics

Thiago R. F. P. Tomei

SPRACE-Unesp
Outline

- Introduction to the Standard Model
- Accelerators and Detectors
- Data Reconstruction
- Data Analysis
Aspects of HEP –
Introduction to the Standard Model

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Every physicist working in HEP should have a strong knowledge of the Standard Model, its strengths and shortcomings. Of course, it is impossible to obtain such knowledge in one week. What I will try to give you in this lecture you is something akin to a treasure map.

- It shows you the way, and highlights some features.
- But it is by no means complete, and sometimes you will not understand it!

I would like to thank Prof. Novaes, Prof. Gregores, and Prof. Ponton (RIP) for their contributions to this lecture.

Finally, if you want to study the Standard Model in depth (you should!), I recommend:

- “The Standard Model and Beyond”, P. Langacker. CRC Press.
The Standard Model

- Model of electromagnetic, weak and strong interactions.
- Reproduces **extremely well** the phenomenology of all observed particles.
- Based on:
  - Experimental discoveries:
    - Positron (1932), muon (1937), strange (1953–54), charm (1974), tau (1975), …
  - Quantum Field Theory: particles are quanta of fundamental fields.
    - Quantum Mechanics + Special Relativity.
  - Invariance under transformations that belong to symmetry groups.
    - Interaction comes as result of fundamental symmetries.
- Successful predictions:
  - Existence of neutral currents that mediate the weak interactions.
  - Mass of W and Z bosons.
  - Equal numbers of leptons and quarks in isospin doublets.
  - Existence of scalar neutral boson (Higgs boson).
The Standard Model of Fundamental Particles and Interactions

### Leptons
<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass (GeV/c^2)</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>ν_e</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>e^−</td>
<td>0.511</td>
<td>-1</td>
</tr>
<tr>
<td>μ^−</td>
<td>105.695</td>
<td>-1</td>
</tr>
<tr>
<td>τ^−</td>
<td>177.63</td>
<td>-1</td>
</tr>
</tbody>
</table>

### Quarks
<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass (GeV/c^2)</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>3.34</td>
<td>+2/3</td>
</tr>
<tr>
<td>d</td>
<td>4.75</td>
<td>+1/3</td>
</tr>
<tr>
<td>c</td>
<td>1.28</td>
<td>+2/3</td>
</tr>
<tr>
<td>s</td>
<td>97.6</td>
<td>+1/3</td>
</tr>
<tr>
<td>t</td>
<td>177.6</td>
<td>+2/3</td>
</tr>
</tbody>
</table>

### Bosons
<table>
<thead>
<tr>
<th>Name</th>
<th>Mass (GeV/c^2)</th>
<th>Spin</th>
<th>Electric Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z^0</td>
<td>91.188</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>g</td>
<td>73.1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Properties of the Interactions

#### Gravitational Interaction
- Force: Mass - Mass
- Effect: Gravity

#### Weak Interaction (Electroweak)
- Effective: Quarks, Leptons
- Electrically Charged

#### Strong Interaction
- Effective: Quarks
- Color Charge

Unsolved Mysteries
- What is the Universe Accelerating? Why?
- What is a Dark Matter? Where?
- Why are there Extra Dimensions?

#### Particle Processes

- **An Electromagnetic Process**: Light (E=mc^2) absorption and emission.

- **A Nuclear Process**: Gamma ray absorption (E=mc^2) and emission.

- **A Strong Process**: Protons and neutrons in a nucleus.

- **A Weak Process**: Neutrinos.

**FIGURE**: A lepton emits a photon (light) upon absorption of a neutrino. The photon converts into an electron and a neutrino. This is a reaction between 3 (less) neutrinos.

### The Strengths of the Interactions (force constants) are given below to the strength of the electromagnetic force for two quarks separated by a specified distance.

<table>
<thead>
<tr>
<th>Property</th>
<th>Gravitational Interaction</th>
<th>Weak Interaction (Electroweak)</th>
<th>Strong Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force</td>
<td>Mass - Mass</td>
<td>Effective: Quarks, Leptons</td>
<td>Effective: Quarks</td>
</tr>
<tr>
<td>Effect</td>
<td>Gravity</td>
<td>Electrically Charged</td>
<td>Color Charge</td>
</tr>
<tr>
<td>Interaction</td>
<td></td>
<td>Quarks</td>
<td>Quarks</td>
</tr>
<tr>
<td>Strength</td>
<td></td>
<td>W^±</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Z^0</td>
<td>60</td>
</tr>
</tbody>
</table>

**Learn more at ParticleAdventure.org**

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Production Cross Section, $\sigma$ [pb]

March 2019

CMS Preliminary

7 TeV CMS measurement ($L \leq 5.0 \text{ fb}^{-1}$)
8 TeV CMS measurement ($L \leq 19.6 \text{ fb}^{-1}$)
13 TeV CMS measurement ($L \leq 137 \text{ fb}^{-1}$)
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV

All results at: http://cern.ch/go/pNj7


<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \alpha^{(S)}_{\text{had}}(m_Z)$</td>
<td>$0.02750 \pm 0.00033$ $0.02759$</td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>$91.1875 \pm 0.0021$ $91.1874$</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>$2.4952 \pm 0.0023$ $2.4959$</td>
</tr>
<tr>
<td>$\sigma^0_{\text{had}}$ [nb]</td>
<td>$41.540 \pm 0.037$ $41.478$</td>
</tr>
<tr>
<td>$R_l$</td>
<td>$20.767 \pm 0.025$ $20.742$</td>
</tr>
<tr>
<td>$A_{fb}$</td>
<td>$0.01714 \pm 0.00095$ $0.01645$</td>
</tr>
<tr>
<td>$A_l(P_t)$</td>
<td>$0.1465 \pm 0.0032$ $0.1481$</td>
</tr>
<tr>
<td>$R_b$</td>
<td>$0.21629 \pm 0.00066$ $0.21579$</td>
</tr>
<tr>
<td>$R_c$</td>
<td>$0.1721 \pm 0.0030$ $0.1723$</td>
</tr>
<tr>
<td>$A_{fb}^{0,l}$</td>
<td>$0.0992 \pm 0.0016$ $0.1038$</td>
</tr>
<tr>
<td>$A_{fb}^{0,c}$</td>
<td>$0.0707 \pm 0.0035$ $0.0742$</td>
</tr>
<tr>
<td>$A_b$</td>
<td>$0.923 \pm 0.020$ $0.935$</td>
</tr>
<tr>
<td>$A_c$</td>
<td>$0.670 \pm 0.027$ $0.668$</td>
</tr>
<tr>
<td>$A_l$(SLD)</td>
<td>$0.1513 \pm 0.0021$ $0.1481$</td>
</tr>
<tr>
<td>$\sin^2\theta_{\text{eff}}^{\text{lep}}(Q_{fb})$</td>
<td>$0.2324 \pm 0.0012$ $0.2314$</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>$80.385 \pm 0.015$ $80.377$</td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>$2.085 \pm 0.042$ $2.092$</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>$173.20 \pm 0.90$ $173.26$</td>
</tr>
</tbody>
</table>

March 2012
Quantum Field Theory (QFT)

QFT stands as our best tool for describing the fundamentals laws of nature.

- How does QFT improves our understanding of nature with respect to non-relativistic Quantum Mechanics and Classical Field Theory?
  - Dynamical degrees of freedom become operators that are functions of spacetime.
    - Quantum fields obey appropriate commutation relations.
  - Interactions of the fields are local – no “spooky action at a distance”.
  - When combined with symmetry postulates (Lorentz, gauge), it becomes a powerful tool to describe interactions.

- Quantum Theory of **Free** Fields brings:
  - Existence of indistinguishable particles.
  - Existence of antiparticles.
  - Quantum statistics.

- Quantum Theory of **Interacting** Fields also brings:
  - The appearance of processes with creation and destruction of particles.
  - The association of interactions with exchange of particles.
Consider a state describing a “particle” of mass $m$ and spin $s$ (or helicity $h$):

$$ |\vec{p}, s_z, \sigma \rangle $$

$\sigma$ stands for internal quantum numbers.

\[
\begin{align*}
\hat{P} |\vec{p}, s_z, \sigma \rangle &= \vec{p} |\vec{p}, s_z, \sigma \rangle \\
\hat{H} |\vec{p}, s_z, \sigma \rangle &= E_{\vec{p}} |\vec{p}, s_z, \sigma \rangle, \text{ with } E_{\vec{p}} = \sqrt{p^2 + m^2} \\
\hat{S}_z |\vec{p}, s_z, \sigma \rangle &= s_z |\vec{p}, s_z, \sigma \rangle, \text{ etc.}
\end{align*}
\]

Lorentz invariance requires that the Hilbert space contain all state vectors for all momenta on the “mass shell”: $p^2 = p_\mu p^\mu = m^2$.

In addition, particle types are labeled by the total spin $s$.

Classification of the irreducible representations of the 4D Lorentz group acting on the Hilbert space states.

Exactly what you know about spin from quantum mechanics.

Particles can also carry other “internal charges” (e.g. electric charge).
A single particle in the universe is described by the state:

$$|\vec{p}, s_z, \sigma\rangle = a^\dagger_{\vec{p}, s_z, \sigma} |0\rangle$$

Multi-particle states and statistics:

Bose-Einstein (bosons)

$$\left[a_{\vec{p}, s_z, \sigma}, a^\dagger_{\vec{p}', s'_{z}, \sigma'}\right] = (2\pi)^3 2E_{\vec{p}} \delta(3) (\vec{p} - \vec{p}') \delta_{s_z, s'_{z}} \delta_{\sigma, \sigma'}$$

Fermi-Dirac (fermions)

$$\left\{a_{\vec{p}, s_z, \sigma}, a^\dagger_{\vec{p}', s'_{z}, \sigma'}\right\} = (2\pi)^3 2E_{\vec{p}} \delta(3) (\vec{p} - \vec{p}') \delta_{s_z, s'_{z}} \delta_{\sigma, \sigma'}$$

whilst all other (anti-)commutators vanish.

Non-interacting particle states built by repeated application of creation operators.

Indistinguishable particles: states labeled by **occupation numbers**, i.e. how many quanta (particles) of a given momentum, z-spin, charge, etc.
Convenient to put all possible 1-particle momentum “states” together by Fourier transforming. To illustrate, we consider a spin-0 particle, and define

$$\Phi_+ (\vec{x}, t) = \int \frac{d^3 k}{(2\pi)^3} \frac{1}{2E_{\vec{k}}} a^\dagger_{\vec{k}} e^{-ik_{\mu}x^\mu} \Big|_{k_0 = E_{\vec{k}}}$$

If the particle carries a charge, the anti-particle is distinct, and we define

$$\Phi_- (\vec{x}, t) = \int \frac{d^3 k}{(2\pi)^3} \frac{1}{2E_{\vec{k}}} b^\dagger_{\vec{k}} e^{ik_{\mu}x^\mu} \Big|_{k_0 = E_{\vec{k}}}$$

One can then show from the commutation relations given earlier that the field

$$\Phi(x) \equiv \Phi_+ (\vec{x}, t) + \Phi_- (\vec{x}, t)$$

obeys \([\Phi(x), \Phi(y)\dagger] = 0\) for \((x - y)^2 < 0\) (spacelike separation). It is a causal field.
From Particles to Fields (4)

Note also that the field

$$\Phi(x) = \int \frac{d^3 k}{(2\pi)^3} \frac{1}{2E_k} \left\{ a_k e^{-ik \cdot x} + b_k^\dagger e^{ik \cdot x} \right\} \bigg|_{k_0 = E_k}$$

satisfies the Klein-Gordon equation, \((\partial_\mu \partial^\mu + m^2) \Phi(x) = 0\). The K-G equation encodes the relativistic energy-momentum equation, \(E^2 = p^2 + m^2\), when one uses the prescription for the quantum-mechanical operators:

$$\vec{p} \rightarrow -i\vec{\nabla}, \quad E \rightarrow i \frac{\partial}{\partial t}$$

Notice that it can be derived from the Lagrangian density

$$\mathcal{L} = \partial_\mu \Phi(x)^\dagger \partial^\mu \Phi(x) - m^2 \Phi(x)^\dagger \Phi(x)$$

following the usual variational principle one learns in classical mechanics:

$$\frac{\partial}{\partial \partial_\mu \Phi} \frac{\partial \mathcal{L}}{\partial \partial_\mu \Phi} - \frac{\partial \mathcal{L}}{\partial \Phi} = 0$$
Other Free Lagrangians

- The Dirac Lagrangian:
  \[ \mathcal{L} = i\overline{\psi} \gamma^\mu \partial_\mu \psi - m\overline{\psi}\psi \]
  leading to the Dirac equation for spin-1/2 particles:
  \[ i\gamma^\mu \partial_\mu \psi - m\psi = 0 \]

- The free EM Lagrangian:
  \[ \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}, \text{ where } F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \]
  leading to “Maxwell’s equations” for the free EM field:
  \[ \partial_\mu F^{\mu\nu} = 0 \]
In principle, we could choose any form for our interactions. The form of the potential in Schrödinger’s equation is arbitrary... but let’s take a closer look at electromagnetism.

The electric and magnetic fields can be described in terms of $A^\mu = (\phi, \vec{A})$

$$
\vec{E} = -\nabla \phi - \frac{\partial \vec{A}}{\partial t}; \quad \vec{B} = \nabla \times \vec{A}
$$

that are invariant under the **gauge transformation**:

$$
\phi \rightarrow \phi' = \phi - \frac{\partial \chi}{\partial t}, \quad \vec{A} \rightarrow \vec{A}' = \vec{A} + \nabla \chi
$$

At this level, this is a useful property that helps us solve EM problems in terms of the potentials. Choosing the right gauge can immensely simplify the equations for $\phi, \vec{A}$. 

Gauge Invariance in Quantum Mechanics

Let us consider the classical Hamiltonian that gives rise to the Lorentz force:

\[ H = \frac{1}{2m}(\vec{p} - q\vec{A})^2 + q\phi \]

With the usual operator prescription \((\vec{p} \rightarrow -i\vec{\nabla}, E \rightarrow i\partial_t)\) we get the Schrödinger equation for a particle in an electromagnetic field:

\[
\left[ \frac{1}{2m}(-i\vec{\nabla} - q\vec{A})^2 + q\phi \right] \psi(x, t) = i\frac{\partial\psi(x, t)}{\partial t}
\]

which can be written as:

\[
\frac{1}{2m}(-i\vec{D})^2\psi = iD_0\psi, \quad \text{with} \quad \begin{cases} 
\vec{D} = \vec{\nabla} - iq\vec{A} \\
D_0 = \frac{\partial}{\partial t} + iq\phi
\end{cases}
\]
On the other hand, if we take the free Schrödinger equation and make the substitution

\[ \vec{\nabla} \rightarrow \vec{D} = \vec{\nabla} - iq\vec{A}, \quad \frac{\partial}{\partial t} \rightarrow D_0 = \frac{\partial}{\partial t} + iq\phi \]

we arrive at the same equation.

Now, if we make the gauge transformation \((\phi, \vec{A}) \xrightarrow{G} (\phi', \vec{A}')\) does the solution of

\[ \frac{1}{2m} \left(-i\vec{D}'\right)^2 \psi' = iD_0'\psi' \]

describe the same physics?

**No!** We need to make a phase transformation on the matter field:

\[ \psi' = \exp(iq\chi) \psi \]

with the same \(\chi = \chi(x, t)\). The derivatives transform as:
\[ \mathcal{D}' \psi' = \left[ \nabla - iq(\vec{A} + \vec{\nabla} \chi) \right] \exp(iq\chi) \psi \]

\[ = \exp(iq\chi)(\vec{\nabla} \psi) + iq(\vec{\nabla} \chi) \exp(iq\chi) \psi - iq\vec{A} \exp(iq\chi) \psi - iq(\vec{\nabla} \chi) \exp(iq\chi) \psi \]

\[ = \exp(iq\chi) \mathcal{D} \psi, \]

\[ \mathcal{D}'_0 \psi' = \exp(iq\chi) \mathcal{D}_0 \psi \]

The Schrödinger equation now maintains its form, since:

\[ \frac{1}{2m}(-i \mathcal{D}')^2 \psi' = \frac{1}{2m}(-i \mathcal{D}')(-i \mathcal{D}' \psi') \]

\[ = \frac{1}{2m}(-i \mathcal{D}') \left[ -i \exp(iq\chi) \mathcal{D} \psi \right] \]

\[ = \exp(iq\chi) \frac{1}{2m}(-i \mathcal{D})^2 \psi \]

\[ = \exp(iq\chi) (i \mathcal{D}_0) \psi = i \mathcal{D}'_0 \psi' \]

whilst both fields describe the same physics since \[ |\psi|^2 = |\psi'|^2. \]
In order to make all variables invariant we should substitute

\[ \vec{\nabla} \rightarrow \vec{D}, \quad \frac{\partial}{\partial t} \rightarrow D_0 \]

and the current \( \vec{J} \sim \psi^*(\vec{\nabla}\psi) - (\vec{\nabla}\psi)^*\psi \) also becomes gauge invariant:

\[
\psi^*\left(\vec{D}'\psi'\right) = \psi^* \exp(-iq\chi) \exp(iq\chi)(\vec{D}\psi) = \psi^*(\vec{D}\psi)
\]

Could we reverse the argument?

When we demand that a theory is invariant under a space-time dependent phase transformation, can this procedure impose the specific form of the interaction with the gauge field?

In other words...
CAN SYMMETRY IMPLY DYNAMICS?
Quantum Electrodynamics (QED) – Our Best Theory

Start from the free electron Lagrangian

\[ L_e = \bar{\psi} (i \gamma_\mu \partial^\mu - m) \psi \]

Impose invariance under local phase transformation:

\[ \psi \rightarrow \psi' = \exp[i\alpha(x)]\psi \]

Introduce the photon field and the coupling via covariant derivative

\[ D_\mu = \partial_\mu + ieA_\mu \quad A_\mu \rightarrow A'_\mu = A_\mu + \frac{1}{e} \partial_\mu \alpha(x) \]

This determines the interaction term with the electron:

\[ L_{\text{int}} = -e\bar{\psi}\gamma_\mu \psi A^\mu \]

Introduce the free photon Lagrangian:

\[ L_A = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \]

and the QED Lagrangian comes out as:

\[ L_{\text{QED}} = \bar{\psi} (i \gamma_\mu \partial^\mu - m) \psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - e\bar{\psi}\gamma_\mu \psi A^\mu \]

Notice the absence of photon mass terms \( \frac{1}{2}m^2 A_\mu A^\mu \). They are forbidden for they break the gauge symmetry.
Focus on the interaction we have proposed:

\[-e \bar{\psi} \gamma^\mu \psi A_\mu = -e \bar{\psi}^A J^\mu (\gamma^\mu) A^B \psi_B A_\mu\]

This is an interaction between one photon, and two electrons. It is conveniently represented by

$$\gamma^\mu = -ie(\gamma^\mu) A^B$$

Interpretation: \(A_\mu \sim a + a^\dagger\) \(\bar{\psi} \sim b^\dagger + c\) \(\psi \sim b + c^\dagger\)

It leads to transitions like \(\gamma |a^\dagger bc |e^+ e^-\rangle\) or \(\gamma e^- |a^\dagger b^\dagger b |e^-\rangle\)

Strictly speaking, need a fourth particle to absorb momentum, but can occur as a “virtual” process.

This is of course just a simplification! In QFT, you learn how to calculate two-point correlation functions in perturbation theory, use Wick’s theorem and write Feynman diagrams!
Testing QED – Anomalous Magnetic Dipole Moment

Back to Dirac’s equation:

\[ i\hbar \frac{\partial \psi}{\partial t} = \left[ c\vec{\alpha}. \left( \vec{p} - \frac{e}{c} \vec{A} \right) + \beta mc^2 + e\phi \right] \psi \]

Get the Pauli equation for the “large component” of the spinor:

\[ i\hbar \frac{\partial \xi}{\partial t} = \left[ \frac{\vec{p}^2}{2m} - \frac{e}{2mc} (\vec{L} + 2\vec{S}) \cdot \vec{B} \right] \xi \]

where the red coefficient – interaction between the spin and the magnetic field – is called the gyromagnetic factor \( g_e \). The anomalous magnetic dipole moment \( a_e \) is defined by:

\[ a_e = \frac{g_e - 2}{2} \]

Pauli’s theory is the first-order prediction (“tree level”), \( a_e = 0 \). Dirac’s theory predicts higher-order contributions (“loops”) and a non-zero \( a_e \).
The anomalous magnetic dipole moment receives, in principle, contributions from all interactions:

\[ a_e = a_{\text{QED}} + a_{\text{EW}} + a_{\text{HAD}} + a_{\text{NEW}} \]

QED’s contribution can be written as a series in \((\alpha/n)\):

\[ a_{\text{QED}} = \sum_{n \geq 1} A_n(\ell) \left( \frac{\alpha}{\pi} \right)^n + \sum_{n \geq 2} B_n(\ell, \ell') \left( \frac{\alpha}{\pi} \right)^n \]

The dimensionless coefficients \(A_n\) are universal – they don’t depend on the lepton flavour. Some calculations:

\[
\begin{align*}
A_1 &= +0.5 \\
A_2 &= -0.328478965 \quad \text{7 diagrams, 1950(W), 1958} \\
A_3 &= +1.181241456 \quad \text{72 diagrams, 1996} \\
A_4 &= -1.91298(84) \quad \text{891 diagrams, 2003} \\
A_5 &= +7.795(336) \quad \text{12672 diagrams, 2014}
\end{align*}
\]
The 72 Feynman diagrams that contribute to $A_3$: 

![Feynman Diagrams](image-url)
To measure $a_e$, one uses a Penning trap – a magnetic trap at low temperatures. The spin flip frequency for a given magnetic field is related to $g_e$

$$
\begin{array}{ccc}
0.00119(5) & 4.2\% & 1947 \\
0.001165(11) & 1\% & 1956 \\
0.001116(40) & 3.6\% & 1958 \\
0.0011609(24) & 2100 \text{ ppm} & 1961 \\
0.001159622(27) & 23 \text{ ppm} & 1963 \\
0.001159660(300) & 258 \text{ ppm} & 1968 \\
0.0011596577(35) & 3 \text{ ppm} & 1971 \\
0.00115965241(20) & 172 \text{ ppb} & 1977 \\
0.0011596521884(43) & 4 \text{ ppb} & 1987 \\
\end{array}
$$

$\begin{align*}
  a_e^{\text{theory}} &= 0.001 \ 159 \ 652 \ 181 \ 643 \ (763) \\
  a_e^{\text{exper.}} &= 0.001 \ 159 \ 652 \ 180 \ 73 \ (28)
\end{align*}$

Agreement of nine significant digits!
1+2 gauge interactions:

- SU(3)$_C$ strong (a.k.a. QCD).
- SU(2)$_L \times$ U(1)$_Y$ electroweak (EW).
- Electroweak symmetry breaking (EWSB): weak interactions and EM are observed as separated phenomena at low energies.

Two kinds of matter particles:

- Quarks subject to all three interactions.
- Leptons subject to EW interaction only.

Gauge mediators:

- Photon ($\gamma$) for the electromagnetism.
- $W^+$, $W^-$, $Z^0$ for the weak interaction.
- Gluon (g) for the strong interactions.

Scalar field ($\phi$) / Higgs boson (H).
Basics of QCD

- Symmetry group is $SU(3)_C$
- Quarks come in three colors: R, G, B
  - They transform under the fundamental representation of $SU(3)$ – a triplet.
- The quantum of the gauge field is the gluon, and it comes in eight bicolored varieties (color + anticolor).
  - They transform under the adjoint representation of $SU(3)$ – the eight generators of $SU(3)$.
  - Since the gluons carry color themselves, they can self-interact – there are qqg, ggg and gggg vertices in the theory. Compare with the single eeγ vertex in QED.
- The theory is renormalizable!
  - When making higher-order calculations in QFT, we encounter divergences.
  - Renormalization is a collection of techniques to address those divergences.
  - Observables remain finite (renormalized); “bare” parameters in $\mathcal{L}$ are formally infinitesimal.
    - In QFT we also learn how to do it with renormalized parameters from the start.
  - A non-renormalizable theory is not amenable to standard perturbative calculations...
- A price to pay: coupling constant $\alpha_S$ depends on interaction energy scale $Q$. 
The presence of gluon self-interactions, in additions to the qqg vertex, leads to an expression for $\alpha_s(Q^2)$:

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{\alpha_s(\mu^2)}{12\pi} (33 - 2n_f) \log (Q^2/\mu^2)}$$

where $n_f$ is the number of flavours, and $\mu^2$ is the renormalization scale.

**Asymptotic freedom:** for high $Q^2$ (short distances), $\alpha_s$ becomes very small $\Rightarrow$ quarks become quasi-free.

**Confinement:** for low $Q^2$, $\alpha_s$ becomes very large $\Rightarrow$ no isolated quarks.

- Hadrons – colorless bound states. Either mesons (q$\bar{q}$) or barions (qqq).
When you calculate a process via Feynman diagrams, you assume that the initial and final states are free particles... but there are no free q’s or g’s!

- Quarks and gluons – partons – are bound inside hadrons, but in that state they are quasi-free! The **parton distribution functions** \( u^P(x) \) give the probability of having a parton of type \( u \) inside the proton.

- Final state q’s and g’s radiate / branch, and their energy gets diluted in a **parton shower**. The branchings are primarily soft and collinear – after a given point the process has to be treated non-perturbatively (high \( \alpha_S \)).

- Eventually, the whole system changes phase into a set of hadrons. Hadrons that come from a parton keep its original direction, forming a **hadronic jet**.
Basics of the Electroweak Model

- Symmetry group is $SU(2)_L \times U(1)_Y$.
- Quarks come in six flavours: $u, d, c, s, t, b$.
- Leptons come in six flavours: $e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau$.
- Left-handed particles $\psi_L$ form a weak isospin doublet, $(\uparrow, \downarrow)$. Right-handed particles $\psi_R$ are weak isospin singlets. All particles have also a hypercharge $Y$.
- The quantum of the $SU(2)_L$ gauge field are the weak bosons $W_1, W_2, W_3$; for the $U(1)_Y$ field it is the $B$ boson.
- Again, the theory is renormalizable.

... and this has nothing to do with the real particles we talked about previously! Notice that:

- The Lagrangian can't have fermion mass terms: $\bar{\psi}\psi = \bar{\psi}_R\psi_L + \bar{\psi}_L\psi_R$ has mixed symmetry.
- The $W_i, B$ bosons are massless, whilst the weak bosons are massive.
Electroweak Symmetry Breaking

Add to the Lagrangian a complex scalar field $\phi$:

$$\mathcal{L}_{\text{scalar}} = |D_\mu \phi|^2 - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2, \quad \text{with} \quad \phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

- $\phi$ is an $SU(2)_L$ doublet, with hypercharge suitably chosen.

Choose $\mu, \lambda$ such that the vacuum expectation value of $\phi$ is not zero.

The ground state of $\phi$ is now asymmetric, but the system as whole still is. The $SU(2)_L$ symmetry is broken (hidden).

Rewrite $\phi$ as:

$$\phi(x) = \exp \left[ i \frac{\sigma^i}{2} \theta^i(x) \right] \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix},$$

rewrite $\mathcal{L}$, and mass terms appear (after field rotation by angle $\theta_W$) for W and Z bosons.

- Yukawa couplings of the form $\bar{\psi} \psi \phi$ give mass to the fermions as well.
- One last field $H(x)$ remains in the theory after EWSB. Its quantum is the Higgs boson.
- Its mass is not fixed from low-energy physics.
  - Fine structure $\alpha$, Fermi’s $G_F$, Weinberg angle $\theta_W$ fix all other terms in the Lagrangian.
- Higgs properties are exquisitely dependent on its mass.
- Discovery on July 4th, 2012 by the ATLAS and CMS collab.
- All properties as expected by the SM, $m_H = 125.2 \text{GeV}$. 

![Higgs Boson Graph](image_url)
High-Energy Hadron Collisions

Full recipe for calculations

- Calculate hard matrix elements from perturbative QFT
- Embed initial state partons in protons via structure functions
- Add corrections for higher-order + non-perturbative processes to the process.

- Initial and final-state radiation
- Underlying event (i.e. "what happens to the rest of the hadron?")
- Hadronisation and decays of unstable particles
Feynman Rules

\textbf{FeynRules} is a Mathematica®-based package which addresses the implementation of particle physics models, which are given in the form of a list of fields, parameters and a Lagrangian, into high-energy physics tools.

Matrix Element Calculations

\textbf{CalcHEP} is a package for the automatic evaluation of production cross sections and decay widths in elementary particle physics at the lowest order of perturbation theory.

\textbf{MadGraph5_aMC@NLO} is a framework that aims at providing all the elements necessary for HEP phenomenology: cross-section computations, hard events generation and matching with shower codes.
Parton Shower and Hadronisation

**Herwig** is a general-purpose Monte Carlo event generator for the simulation of hard lepton-lepton, lepton-hadron and hadron-hadron collisions.

**Pythia** is a standard tool for the generation of high-energy collisions, comprising a coherent set of physics models for the evolution from a few-body hard process to a complex multihadronic final state.

### Data Formats

- **UFO**: The Universal FeynRules Output ([link](#))
- **LHE**: A standard format for Les Houches Event Files ([link](#))
- **HepMC**: an object oriented, C++ event record for High Energy Physics Monte Carlo generators and simulation ([link](#))
Enough theory for now... 

... let’s start detecting those particles!