Beyond the Standard Model

CERN summer student lectures 2017

Lecture 1/4

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What is physics beyond the Standard Model?

?  

I don’t know. Nobody knows  
If it were known, it would be part of the SM!  
You won’t learn during these lectures what BSM is.  
(maybe) You’ll learn what BSM could be.  
“Looking and not finding is different than not looking”  
We’ll study the limitations/defaults of the SM as a guide towards BSM.  
We want to learn from our failures
The SM and... the LHC data so far rules the world!

(and we, HEP practitioners, are all entitled for some royalties!)

The SM and the LHC data so far rules the world!

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The SM and the LHC data so far rules the world!
The SM and... the rest of the Universe is not enough

- neutrino masses
- matter-antimatter asymmetry
- Dark Matter
- Dark Energy
- Quantum gravity

[and we all have to return our royalties!]
Outline

☐ Monday
  ○ General introduction
  ○ Higgs physics as a door to BSM

☐ Tuesday
  ○ Naturalness
  ○ Supersymmetry
  ○ Grand unification, proton decay

☐ Wednesday
  ○ Composite Higgs
  ○ Extra dimensions
  ○ Effective field theory

☐ Thursday
  ○ Cosmological relaxation
  ○ Quantum gravity
Ask questions

Your work, as students, is to question all what you are listening during the lectures...
Recommended Readings

- **popular account**
  - “The Zeptospace odyssey” by Gian-Francesco Giudice [CERN library link]

- **fun physics**
  - “Order-of-magnitude physics” by S. Mahajan, S. Phinney and P. Goldreich [available for free online]

- **technical accounts**
  - “Journeys beyond the Standard Model” by P. Ramond [CERN library link]
  - Many lecture notes, e.g. TASI (@Inspire: “t TASI”)
Classical/Quantum EM & Antimatter

an electron makes an electric field which carries an energy

$$\Delta E_{\text{Coulomb}}(r) = \frac{1}{4\pi \varepsilon_0} \frac{e^2}{r}$$

and interacts back to the electron and contributes to its mass

$$\delta m c^2 = \Delta E$$

$$\delta m < m_e \quad \Rightarrow \quad r > r_e \equiv \frac{e^2}{4\pi \varepsilon_0 m_e c^2} \sim 10^{-13} \text{ m} \quad \text{i.e.} \quad E < \frac{\hbar c}{r_e} \sim 5 \text{ MeV}$$

At shortest distances or larger energies, classical EM breaks down

new states \(\Delta E = -\frac{1}{4\pi \varepsilon_0} \frac{e^2}{r} \) \(\Rightarrow\) [Diagram]

\(\delta m < 0.1 m_e \quad \Rightarrow \quad E < 10^{21} \text{ GeV} \)

Christophe Grojean

BSM

CERN, July 2017
The Standard Model: Matter

How many quarks and leptons?

Three Generations of Matter (Fermions) spin \( \frac{1}{2} \)

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>Charge</td>
<td>Name</td>
</tr>
<tr>
<td>( \frac{2}{3} )</td>
<td>2.4 MeV</td>
<td>( \frac{2}{3} ) u up</td>
</tr>
<tr>
<td>( -\frac{1}{3} )</td>
<td>4.8 MeV</td>
<td>( -\frac{1}{3} ) d down</td>
</tr>
<tr>
<td>( \frac{1}{3} )</td>
<td>104 MeV</td>
<td>( \frac{1}{3} ) c charm</td>
</tr>
</tbody>
</table>

Leptons:

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>Name</td>
<td></td>
</tr>
<tr>
<td>( 0 )</td>
<td>( \nu_e ) electron neutrino</td>
<td>0.511 MeV</td>
</tr>
<tr>
<td>( -1 )</td>
<td>( \nu_\mu ) muon neutrino</td>
<td>1.057 MeV</td>
</tr>
<tr>
<td>( -1 )</td>
<td>( \nu_\tau ) tau neutrino</td>
<td>1.777 GeV</td>
</tr>
</tbody>
</table>
The Standard Model: Matter

How many quarks and leptons?

6+6=12?

6x3+6=24?

6x3x2+3x2+3=45?

it is an accident that eL ≠ eR for QED

it is an accident that eL ≠ eR for QED

SM is a chiral theory: eL ≠ eR

shouldn't we count different color states?

Three Generations of Matter (Fermions) spin ½

6x3x2+6x2=48?

are there νR?

are they part of the SM?
The Standard Model: Matter

How many quarks and leptons?

Is the SM theoretically consistent?

$SM = \text{theory based on (chiral) gauge symmetries}$

a symmetry is consistent with QM

iff the “sum” of the charges of the different fermions vanishes

$$Q = T_L^3 - Y$$

<table>
<thead>
<tr>
<th>Particles</th>
<th>$SU(3)_C$</th>
<th>$SU(2)_L$</th>
<th>$U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L^i_L$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N^i = (\nu^i, \tilde{\nu}^i)$</td>
<td>1</td>
<td>2</td>
<td>1/2</td>
</tr>
<tr>
<td>$E^i = (\tilde{e}_L, \tilde{\nu}^i)$</td>
<td>1</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>$Q^i_L$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$U^i_L = (u^i_L, \tilde{u}^i_L)$</td>
<td>3</td>
<td>2</td>
<td>-1/6</td>
</tr>
<tr>
<td>$D^i_L = (d^i_L, \tilde{d}^i_L)$</td>
<td>3</td>
<td>2</td>
<td>-1/6</td>
</tr>
<tr>
<td>$U^i_R = (CP(u^i_R), CP(\tilde{u}^i_R))$</td>
<td>3</td>
<td>1</td>
<td>2/3</td>
</tr>
<tr>
<td>$D^i_R = (CP(d^i_R), CP(\tilde{d}^i_R))$</td>
<td>3</td>
<td>1</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

Exercise 1: within the SM, check that
(1) $\text{Tr}_L Y - \text{Tr}_R Y = 0$
(2) $\text{Tr}_L Y^3 - \text{Tr}_R Y^3 = 0$

note that this was a priori no-guarantee to find a solution
to this system of non-linear equations.

It works because EM is a vector-like theory

Exercise 2: Within the SM, the anomaly cancelation fixes the relative electric charges of the leptons and quarks. Show that with the addition of a right-handed neutrino, this ratio of electric charges is free. Still the cancelation of the anomaly imposes that the proton is electrically neutral.
The Standard Model: Interactions

- **U(1)γ** electromagnetic interactions
  - Photon $\gamma$
  - Bosons $W^\pm, Z^0$

- **SU(2)L** weak interactions
  - Bosons $W^\pm, Z^0$

- **SU(3)c** strong interactions
  - Gluons $g^a$

\begin{align*}
\text{light atoms} & \left\{ \begin{array}{l}
\beta \text{ decay} \\
\alpha \text{ decay}
\end{array} \right. \\
& \left\{ \begin{array}{l}
n \xrightarrow{W^\pm} p + e^- + \bar{\nu}_e \\
e^+ + e^- \xrightarrow{Z^0} D_{(cs)}^+ + D_{(cs)}^-
\end{array} \right. \\
& 238_{92}U \rightarrow 234_{90}Th + 4_{2}He \\
\end{align*}

**strength**
The Standard Model

the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions $SU(3)_c \times SU(2)_L \times U(1)_Y$

![Image of a bubble chamber event](image)

[Fig. 14: First $\nu_\mu e^-$ elastic scattering event observed by the Gargamelle Collaboration [10] at CERN. Muon neutrinos enter the Freon (CF$_3$Br) bubble chamber from the right. A recoiling electron appears near the center of the image and travels toward the left, initiating a shower of curling branches.]

By analogy with the calculation of the $W$-boson total width (2.43), we easily compute that:

$$\Gamma(Z \rightarrow \bar{\nu}_\nu \bar{\nu}_\nu) = G F M_Z^2 \sqrt{2}$$

$$\Gamma(Z \rightarrow e^- + e^-) = \Gamma(Z \rightarrow \bar{\nu}_\nu \bar{\nu}_\nu) \left[L^2 e + R^2 e/3\right]$$

(2.47)

The neutral weak current mediates a reaction that did not arise in the $V-A$ theory, $\nu_\mu e \rightarrow \nu_\mu e$, which proceeds entirely by $Z$-boson exchange:

$$\nu_\mu e^- \rightarrow \nu_\mu e^-$$

This was, in fact, the reaction in which the first evidence for the weak neutral current was seen by the Gargamelle Collaboration in 1973 [10] (see Figure 14).

To exercise your calculational muscles, please do Problem 3. It's an easy exercise to compute all the cross sections for neutrino-electron elastic scattering.

Show that:

$$\sigma(\nu_\mu e^- \rightarrow \nu_\mu e^-) = G^2 F^2 m_e E_\nu^2 \pi \left[L^2 e + R^2 e/3\right]$$

$$\sigma(\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-) = G^2 F^2 m_e E_\nu^2 \pi \left[L^2 e/3 + R^2 e\right]$$

$$\sigma(\nu_e e^- \rightarrow \nu_e e^-) = G^2 F^2 m_e E_\nu^2 \pi \left[(L e + 2)^2/3 + R^2 e\right]$$

$$\sigma(\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-) = G^2 F^2 m_e E_\nu^2 \pi \left[(L e + 2)^2/3 + R^2 e\right]$$

(2.48)
Gauge Theory as a Dynamical Principle

the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$\text{e}^+\text{e}^- \rightarrow W^+W^-$$

![Graph showing LEP data with different curves indicating various interactions involving W and Z bosons and neutrinos.](attachment:lepgraph.png)
The Standard Model and the Mass Problem

the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

\[ SU(3)_C \times SU(2)_L \times U(1)_Y \]

the masses of the quarks, leptons and gauge bosons don't obey the full gauge invariance

\[ \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \text{ is a doublet of } SU(2)_L \text{ but } m_{\nu_e} \ll m_e \]

\[ \Delta A_\mu = \partial_\mu \epsilon^a + gf^{abc} A_\mu^b \epsilon^c \]

spontaneous breaking of gauge symmetry
Electroweak Unification

High energy ($\sim 100$ GeV)

This room is full of photons but no $W/Z$

The symmetry between $W$, $Z$ and $\gamma$ is broken at large distances

EM forces $\approx$ long ranges

Weak forces $\approx$ short range

$\gamma < 6 \times 10^{-17}$ eV

$m_{W^\pm} = 80.425 \pm 0.038$ GeV

$m_{Z^0} = 91.1876 \pm 0.0021$ GeV
The longitudinal polarization of massive W, Z

A massless particle is never at rest: always possible to distinguish (and eliminate!) the longitudinal polarization.

The longitudinal polarization is physical for a massive spin-1 particle.

Symmetry breaking: new phase with more degrees of freedom.

\[ \epsilon_\parallel = \left( \frac{|\vec{p}|}{M}, \frac{E_\parallel}{M} \right) \]

Polarization vector grows with the energy.

(pictures: courtesy of G. Giudice)
The longitudinal polarization of massive W, Z

A massless particle is never at rest; always possible to distinguish (and eliminate!) the longitudinal polarization.

\[ \epsilon = \left( \frac{p}{M}, \frac{E}{M} \frac{p}{|p|} \right) \]

Polarization vector grows with the energy.

Symmetry breaking: new phase with more degrees of freedom.

\[ 3 = 2 + 1 \]

Guralnik et al '64

The longitudinal polarization is physical for a massive spin-1 particle.

(pictures: courtesy of G. Giudice)
Indeed a massive spin 1 particle has 3 physical polarizations:

\[ A_\mu = \epsilon_\mu \, e^{\imath k_\mu x^\mu} \]

\[ \epsilon^\mu \epsilon_\mu = -1 \quad k^\mu \epsilon_\mu = 0 \]

- 2 transverse:
  \[ \epsilon^\mu_1 = (0, 1, 0, 0) \]
  \[ \epsilon^\mu_2 = (0, 0, 1, 0) \]

- 1 longitudinal:
  \[ \epsilon^\mu_\parallel = \left( \frac{k}{M}, 0, 0, \frac{E}{M} \right) \approx \frac{k^\mu}{M} + \mathcal{O} \left( \frac{E}{M} \right) \]

( in the R-ξ gauge, the time-like polarization \( \epsilon^\mu \epsilon_\mu = 1 \quad k^\mu \epsilon_\mu = M \) is arbitrarily massive and decouple )

in the particle rest-frame, no distinction between L and T polarizations
in a frame where the particle carries a lot of kinetic energy, the L polarization “dominates”
The BEH mechanism: "$V_L=$Goldstone bosons"

At high energy, the physics of the gauge bosons becomes simple.

\[ \Gamma(t \to b W_L) = \frac{g^2}{64\pi} \frac{m_t^2}{m_W^2} \frac{(m_t^2 - m_W^2)^2}{m_t^3} \]

\[ \Gamma(t \to b W_T) = \frac{g^2}{64\pi} \frac{2(m_t^2 - m_W^2)^2}{m_t^3} \]

- at threshold ($m_t \sim m_W$)
  democratic decay
- at high energy ($m_t \gg m_W$)
  $W_L$ dominates the decay

At high energy, the dominant degrees of freedom are $W_L$
The BEH mechanism: “$V_L=$Goldstone bosons”

At high energy, the physics of the gauge bosons becomes simple

~~ why you should be stunned by this result: ~~

we expect: $\Gamma \sim g^2 m_{\text{mother}}$

instead $\Gamma \propto m_{\text{mother}}^3$ means $g \propto m$

very efficient way to suck up energy from the mother particle

$\tau \ll \tau_{\text{naive}}$

In other words, LEP established a simple description of the electroweak sector for $E \gg m_W$.

This description is valid for $m_W \ll E \ll 4\pi v = \frac{8\pi m_W}{g}$

The goal of the LHC was/is to understand what comes next.
Call for extra degrees of freedom

--- NO LOSE THEOREM ---

Bad high-energy behavior for
the scattering of the longitudinal
polarizations

\[ A = \epsilon_\mu^\nu(k)\epsilon_\nu^\lambda(l)g^2(2\eta_{\mu\rho}\eta_{\nu\sigma} - \eta_{\mu\nu}\eta_{\rho\sigma} - \eta_{\mu\sigma}\eta_{\nu\rho})\epsilon_\rho^\rho(p)\epsilon_\sigma^\sigma(q) \]

\[ A = g^2 \frac{E^4}{4M_W^4} \]

violations of perturbative unitarity around \( E \sim M/\sqrt{g} \) (actually \( M/g \))

Extra degrees of freedom are needed to have a good description
of the W and Z masses at higher energies

numerically: \( E \sim 3 \text{ TeV} \) \( \square \) the LHC was sure to discover something!
What is the SM Higgs?
A single scalar degree of freedom that couples to the mass of the particles

\[ \mathcal{L}_{\text{EWSB}} = m_W^2 W_\mu^+ W_\mu^- \left(1 + 2a \frac{h}{v} + b \frac{h^2}{v^2}\right) - m_\psi \bar{\psi}_L \psi_R \left(1 + c \frac{h}{v}\right) \]

'\(a\)', '\(b\)' and '\(c\)' are arbitrary free couplings

\[ A = \frac{1}{v^2} \left(s - \frac{a^2 s^2}{s - m_h^2}\right) \]

growth cancelled for \(a = 1\)
restoration of perturbative unitarity
What is the SM Higgs?

The Higgs boson unitarizes the $W$ scattering (if its mass is below $\sim 1$ TeV)

$$A = g^2 \left( \frac{E}{M_W} \right)^2$$

$$A = -g^2 \left( \frac{E}{M_W} \right)^2$$

$$A = g^2 \left( \frac{M_H}{2M_W} \right)^2$$

Lee, Quigg, Thacker ’77
What is the Higgs the name of?

A single scalar degree of freedom that couples to the mass of the particles

\[ \mathcal{L}_{\text{EWSB}} = m_W^2 W^+_\mu W^+_{\mu} \left( 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} \right) - m_\psi \bar{\psi}_L \psi_R \left( 1 + c \frac{h}{v} \right) \]

'a', 'b' and 'c' are arbitrary free couplings

For a=1: perturbative unitarity in elastic channels \( WW \to WW \)

For \( b = a^2 \): perturbative unitarity in inelastic channels \( WW \to hh \)

Cornwall, Levin, Tiktopoulos ’73

Contino, Grojean, Moretti, Piccinini, Rattazzi ’10
What is the Higgs the name of?
A single scalar degree of freedom that couples to the mass of the particles

$$\mathcal{L}_{\text{EWSB}} = m_W^2 W_\mu^+ W^+\mu \left(1 + 2a \frac{h}{v} + b \frac{h^2}{v^2}\right) - m_\psi \bar{\psi}_L \psi_R \left(1 + c \frac{h}{v}\right)$$

'a', 'b' and 'c' are arbitrary free couplings

For a=1: perturbative unitarity in elastic channels $WW \to WW$

For $b = a^2$: perturbative unitarity in inelastic channels $WW \to hh$

For $ac=1$: perturbative unitarity in inelastic $WW \to \psi \psi$

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10
**What is the Higgs the name of?**

A single scalar degree of freedom that couples to the mass of the particles

\[ \mathcal{L}_{EWSB} = m_W^2 W^+_\mu W^-_\mu \left( 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} \right) - m_\psi \bar{\psi}_L \psi_R \left( 1 + c \frac{h}{v} \right) \]

'\(a\)', '\(b\)' and '\(c\)' are arbitrary free couplings

For \(a=1\): perturbative unitarity in elastic channels \(WW \rightarrow WW\)

For \(b = a^2\): perturbative unitarity in inelastic channels \(WW \rightarrow hh\)

For \(ac=1\): perturbative unitarity in inelastic \(\psi \psi\)

Cornwall, Levin, Tiktopoulos ’73

Contino, Grojean, Moretti, Piccinini, Rattazzi ’10

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**Higgs couplings are proportional to the masses of the particles**

\[ \lambda_\psi \propto \frac{m_\psi}{v}, \quad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2} \]
Higgs boson at the LHC

producing a Higgs boson is a rare phenomenon since its interactions with particles are proportional to masses and ordinary matter is made of light elementary particles

NB: the proton is not an elementary particle, its mass doesn’t measure its interaction with the Higgs substance

From electrons

\[
\begin{array}{c}
\text{e} \\
\downarrow \\
\text{h} \\
\text{e}
\end{array}
\]

probability \( \sim 10^{-11} \)

From top quarks

\[
\begin{array}{c}
\text{\( \uparrow \)} \\
\downarrow \\
\text{h} \\
\text{\( \uparrow \)}
\end{array}
\]

probability \( \sim 1 \)

but no top quark at our disposal
Higgs boson at the LHC

Difficult task
Homer Simpson's principle of life:

If something's hard to do, is it worth doing?
Higgs boson at the LHC

Proton 2
\( p_2 \)

Proton 1
\( p_1 \)

\( f_b(x_2, Q^2) \)

\( f_a(x_1, Q^2) \)

\( g \)

\( g \)

\( W/Z \)

\( W/Z \)
Higgs boson at the LHC
Higgs boson at the LHC
Higgs boson at the LHC

$\sigma \sim 10 \text{ pb} \Leftrightarrow 10^5 \text{ events for } L=10 \text{ fb}^{-1}$

The LHC has produced $10^5$ Higgs bosons out of $10^{16}$ pp collisions
The production of a Higgs is wiped out by QCD background only 1 out of 100 billions events are “interesting” (for comparison, Shakespeare’s 43 works contain only 884,429 words in total) furthermore many of the background events furiously look like signal events
SM Higgs @ LHC

The production of a Higgs is wiped out by QCD background

only 1 out of 100 billions events are “interesting”
(for comparison, Shakespeare’s 43 works contain only 884,429 words in total)

furthermore many of the background events furiously look like signal events

... like finding the paper you are looking for in (10^8 copies of) John Ellis’ office
Higgs@LHC: a paradoxical triumph

The Higgs is related to some of the deepest problems of HEP

\[ \mathcal{L}_{\text{Higgs}} = V_0 - \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + (y_{ij} \bar{\psi}_L \psi_R H + h.c.) \]

vacuum energy

hierarchy problem

triviality/stability

mass and mixing

flavour & CP

\[ V_0 \approx (2 \times 10^{-3} \text{ eV})^4 \ll M_{\text{Pl}}^4 \]

\( m_H \approx 100 \text{ GeV} \ll M_{\text{Pl}} \)

~~ Higgs interactions ~~

gauge symmetry is the organizing principle for interactions in the gauge sector

not in the Higgs sector \( \Rightarrow \) many free parameters!

but they obey 3 basic structures

(1) proportionality: \( g_{hff} \propto m_f \)  \( g_{hVV} \propto m_V^2 \)

\( \Rightarrow \) test for extended Higgs sectors

(2) factor of proportionality: \( g_{hff}/m_f = \sqrt{2}/v \)

\( \Rightarrow \) test for extended Higgs sectors

\( \Rightarrow \) test for Higgs compositeness

(3) flavor alignment: \( g_{hf_i f_j} \propto \delta_{ij} \)

\( \Rightarrow \) test for flavor models, origin of fermion masses
Higgs couplings = door to BSM

heavy new physics induce deformation of the Higgs couplings
(in the same way to W exchange mediate muon decay and β decay)

\[ \frac{\delta g}{g} \sim \frac{g_* v^2}{\Lambda^2_{\text{BSM}}} \sim \left( \frac{g_*}{0.3} \right)^2 \left( \frac{1 \text{ TeV}}{\Lambda} \right)^2 0.5\% \]

Higgs coupling precision measurements are an indirect way to probe heavy (strongly coupled) new physics that cannot be observed directly