Beyond the Standard Model

G.F. Giudice

Lecture 1

CERN Summer Student Programme 2012
The LHC is a project aiming at exploring a new energy regime.

Nobody knows exactly what will be found, but theoreticians speculate…

The goal is the exploration of small distances ($< 10^{-19}$ m) searching for new phenomena.
• The engine that drives us to build accelerators is our understanding that the key to physical laws is hidden in the microcosm.
• The same laws help us to understand the large-scale structure of the universe and its early history.
The problem of electroweak symmetry breaking
Concept of symmetry central in modern physics
invariance of physics laws under
transformation of dynamical variables

Now fundamental and familiar concept, but hard
to accept in the beginning

Ex.: Earth’s motion does not affect $c$

Lorentz tried to derive it from EM

Einstein postulates $c$ is constant (invariance
under velocity changes of observer)

Einstein simply postulates what we have deduced, with some
difficulty and not always satisfactorily, from the
fundamental equations of the electromagnetic field
All physical phenomena in the microcosm can be understood in terms of a single symmetry principle. (simply connected) spherically symmetric object

- gauge symmetry
  - space-time
  - fields
- electro-magnetism
- weak force
- strong force
- gravity
One important difference

Electromagnetism $\rightarrow$ infinite range $\rightarrow$ photon mass $=0$

Weak force $\rightarrow$ $10^{-18}$ m ($10^{-3}$ $\rho$ radius) $\rightarrow$ $W$, $Z$ massive
The problem of electroweak breaking

Transverse wave

Oscillations perpendicular to direction of motion

Longitudinal wave

Water wave

The EM wave has only 2 independent polarizations

Just an empirical fact, but a very lucky one
If 3\textsuperscript{rd} polarization existed

Scattering probability grows with $E$

Nonsense at large $E$: probability larger than 100%

In QED, 3\textsuperscript{rd} pol. does not exist $\Rightarrow$ gauge symmetry

Longitudinal polarization

Transverse polarizations

Gauge symmetry

Photon in QED

Gauge symmetry is essential to make theory free of nonsense
The “gauge trick” cannot work for massive particles

Why?

Einstein relativity: $c$ is the same in every reference frame

I can choose a frame where a massive particle is at rest

In that frame: how can I distinguish longitudinal from transverse polarizations?

We have to live with 3 pol. $\Rightarrow$ nonsense in HE scattering!
The root of the problem:

\[ \text{gauge symmetry} \iff \text{massless force carrier} \iff \text{controllable HE theory} \]

How can we reconcile $W, Z$ masses (short-range weak force) with gauge symmetry?
The Higgs mechanism is the solution!!!

Higgs field fills space with uniform distribution of EW charge

This distribution affects particle propagation

- large distances $\rightarrow$ mass
- small distances $\rightarrow$ longitudinal waves are part of the harmless Higgs field $\rightarrow$ no nonsense

Spontaneous symmetry breaking: configuration lacks the symmetry of the physical laws
The Higgs mechanism gives a new understanding of the nature of space-time
A new form of aether?
At $10^{-10}$ seconds after the Big Bang:
Space crystallized into a new form
Nature filled space because she saved energy

No difference, no matter how you move with respect to this substance
Producing the Higgs boson at the LHC
In relativistic quantum theories field $\leftrightarrow$ particle $\Rightarrow$ Higgs boson

Particle mass $\Rightarrow$ how much it is dragged by Higgs field

Coupling of Higgs to $p$ are proportional to $M_p$

$M_H$ only free parameter: it measures Higgs self-coupling

(but Higgs contributes to only 1% of my weight)
Decay Probability

\[ \begin{align*}
H &\rightarrow bb \quad 58\% \\
H &\rightarrow WW \quad 21\% \\
H &\rightarrow gg \quad 9\% \\
H &\rightarrow \tau\tau \quad 6\% \\
H &\rightarrow cc \quad 3\% \\
H &\rightarrow ZZ \quad 3\% \\
H &\rightarrow \gamma\gamma \quad 0.2\% \\
H &\rightarrow \mu\mu \quad 0.02\%
\end{align*} \]

Higgs decays in $10^{-22}$ seconds
Best Fit $M = 235 \pm 20, \epsilon = -0.05 \pm 0.10$