The Standard Model and Beyond

Paris Sphicas
CERN & University of Athens
CERN Accelerator School
Chavannes de Bogis, February 6, 2017

■ The Standard Model of Particle Physics
  ◆ And the Higgs boson...

■ Looking for the Higgs
  ◆ A new boson at ≈ 126 GeV!
  ◆ Studying its properties

■ Is this all there is to Nature?
  ◆ Searching for New Physics; e.g. Supersymmetry?

■ Outlook
Standard Model of Particle Physics

The main ideas
Intermediate vector bosons and their masslessness
The Higgs mechanism
Nature: “forces” between particles?

- Gravity == action-at-a-distance: separated objects, in the vacuum, act on each other!
- The “charge” of gravity: mass – the substance of matter!

What about electricity and magnetism? Same as gravity; except two charges (like ones repel, opposite ones attract). But same spooky “action-at-a-distance, through the vacuum”
Nature: “forces”?!

- Maxwell and electromagnetism: the concept of a field; charges generate fields which (can) permeate all of space... Other “charges” feel this field – and thus they feel a force.
- The incredible discovery: the E/B fields can exist alone – they propagate in waves in the vacuum! Thus are radio, TV and cell-phones made possible.
There are, in total FOUR different forces in nature:
Gravity, Electromagnetism, Weak Force, Strong Force

But nuclei are held together – against the electrostatic repulsion.
So there is yet another type of force!
It must be very, very strong.

But nuclei also “break”!
Radioactivity! Neutrons become protons.
So there is yet another type of force!
And it is very, very weak.
FOUR???

What makes them different?
Are all of them “needed”? Why not just one?

The two scientific revolutions of the 20th century (Relativity and Quantum mechanics) provide (most of) the answers
20th century physics: quantum mechanics and relativity

Relativity: action can only travel at speed \( c \)
- Localization

Communication between space-time points only as long as within light-cone
- Thus: operators (that finally yield observables) are a function of \( x, t \); i.e. they are fields

Quantum Mechanics
- Discretization
  - e.g. of absorption or emission
- Wave-particle duality
  - demonstrated beyond all doubt:

Electron density waves are seen breaking around two atom-size defects on the surface of a copper crystal
Classical Mechanics: light waves

- Apparent continuity of light rays.

But: when “zooming in” on light...
“Zooming in” on light... Light “comes” in discrete units → corpuscles → particles!
Relativity Theory + Quantum mechanics: a new picture of what is a “force”

\[ L_{\text{int}} = -q \overline{\psi} \gamma^{\mu} A_{\mu} \psi \]

FORCE IS THE EXCHANGE OF PARTICLES!
Classical and Quantum picture of “force”

**Classical Field** $\mathbf{E}(\mathbf{r})$

\[
\mathbf{F} = \mathbf{E}(\mathbf{r}) \cdot Q_2 = \frac{Q_1}{r^2} \hat{r} \cdot Q_2 = \frac{Q_1 Q_2}{r^2} \hat{r}
\]

**Exchange of a virtual particle of momentum** $\mathbf{q}$:

\[
qr \approx \hbar \Rightarrow q \approx \frac{\hbar}{r} \Rightarrow \frac{dq}{ct} \approx \frac{\hbar}{ct^2} \Rightarrow \frac{dq}{dt} \approx \frac{\hbar c}{r^2}
\]
Force = exchange of particle

- The most basic process: a fermion (matter particle) emits/absorbs a boson (force particle)
Feynman diagrams (I)

- Have to draw all possibilities
  - We do not know whether X was emitted by A and absorbed by B or the opposite
  - So: X is drawn vertically [though it does not have infinite v]
Feynman diagrams (II)

- **Exchange Diagrams**
  - Particle A scatters off of particle B by exchanging intermediate particle X. If X is a photon, then the final particles C and D are the same as A and B.

![Exchange Diagram](image)

The interaction, as seen in the laboratory frame

Schematic representation of the collision in terms of a Feynman diagram.
Feynman diagrams (III)

- **Annihilation and Creation (Formation) diagrams**
  - Incoming particles A and B collide, forming an intermediate particle X, which in turn decays into particles C and D.

The interaction, as seen in the laboratory frame.

Schematic representation of the collision in terms of a Feynman diagram. Note that vertices conserve charge/momentum.
Weak interaction

Beta decay $n \rightarrow p + e^- + \bar{\nu}_e$

*Mediated by charged $W$ exchange*
Standard Model of Particle Physics

- Quantum Field theory: matter particles (spin-1/2) interact via the exchange of force particles (spin-1)

Interactions → need charges. Which should be conserved. Implies some new symmetry...
  - Internal symmetry (SU(3) x SU(2) x U(1)) → massless bosons
FAQ: how to make a universe

**Strong**: Gluons (8)
- Quarks
- Mesons
- Baryons
- Nuclei

**Electromagnetic**: Photon
- Atoms
- Light
- Chemistry
- Electronics

**Gravitational**: Graviton ?
- Solar system
- Galaxies
- Black holes

**Weak**: Bosons (W,Z)
- Neutron decay
- Beta radioactivity
- Neutrino interactions
- Burning of the sun
Except... We got a basic issue wrong.

Because the range of the weak force is very small.

Which means the carrier must be massive.

Very massive!

Mathematical Interlude
Quantum mechanics and Relativity

- Classical Energy \( \Rightarrow \) Schrödinger’s equation:
  \[
  E = \frac{p^2}{2m} + V(\vec{r}) \quad \Rightarrow \quad -\frac{\hbar^2}{2m} \nabla^2 \psi + V(\vec{r})\psi = i\hbar \frac{\partial \psi}{\partial t}
  \]

- Klein-Gordon equation:
  \[
  E^2 = p^2 c^2 + m_0^2 c^4 \quad \Rightarrow \quad -\hbar^2 \frac{\partial^2}{\partial t^2} \phi = -\hbar^2 c^2 \nabla^2 \phi + m^2 c^4 \phi
  \]

- Static potential (forgetting time dependence)
  \[
  \nabla^2 V(r) = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial V}{\partial r} \right) = \frac{m^2 c^2}{\hbar^2} V(r)
  \]
  \[
  U(r) = \frac{g}{4\pi r} e^{-r/R}, \quad R = \frac{\hbar}{mc}
  \]
What IS mass?

Newton: mass is the property of a particle – the one that makes it resist changes in its motion.

A particle travelling in empty space continues travelling in a straight line (“forever”)
Quantum Vacuum: anything but “empty”
The full quantum vacuum...
Brout-Englert-Higgs mechanism

- Generate masses for the fundamental particles (some of the bosons of the EWK interaction AND the fermions that make up matter)
  - $M(\gamma)=0; \ M(W)=80 \text{ GeV}/c^2; \ M(Z)=90 \text{ GeV}/c^2$

- BUT: this has to take place starting from an overall symmetric “universe” in which there is “no difference” in the way the photon and the W/Z appear
  - We cannot add mass terms by hand (due to the original symmetry “gauge invariance”)
  - How can we end up with an asymmetric world [in which $M(W)\neq M(\gamma)$] when the laws are symmetric?
Potential with two minima

- “Law of nature”: potential. 
  \[ V(x) \rightarrow \text{Lagrangian} \rightarrow \text{eqns of motion} \]
  Can be Left-Right symmetric while equilibrium state is not

- Ball chooses one of the two minima → Left-Right symmetry is “broken”

Laws: LR symmetric; but low-energy world need not be!
BEH mechanism in words

- There is a new field – which is different from ALL others: it has no spin at all (so, not a matter field, and not a boson that transmits a force)

- It’s everywhere – filling up all space. It’s in the vacuum – and interacts with anything that travels in the “vacuum”.

- Thus: point particles, travel in a “sea” made by the Higgs Field. They meet resistance... Inertia... Mass.

- Quantum Mechanics: particle (a boson) corresponding to the field. The Higgs boson.
The Higgs Mechanism: mathematics

- With two independent (complex) fields (4 DoFs)
- Two “motions” in the potential
  - One on the plane; “massless” mode that is lost (once a direction is chosen). Each degree of freedom appears as additional degree of freedom of a gauge boson
    - Extra polarization state
    - The boson becomes massive!
  - One up/down on potential; massive
    - Higgs boson; for which we know everything, except one parameter: its mass!

Thus were the W/Z masses born in theory; and discovered (at the right value) @ CERN in 1984.
In 1983, the $W$ and $Z$ particles were discovered at CERN (UA1 and UA2)
- 1984 Nobel Prize to Simon van der Meer and Carlo Rubbia

**Sneak preview:** at that point, the Higgs boson became the last important missing piece of SM!
The Standard Model up until 2012

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
<th>( \frac{O_{\text{meas}} - O_{\text{fit}}}{\sigma_{\text{meas}}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \alpha_{\text{had}}^{(5)}(m_Z) )</td>
<td>0.02758 ± 0.00035</td>
<td>0.02768</td>
</tr>
<tr>
<td>( m_Z ) [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>91.1874</td>
</tr>
<tr>
<td>( \Gamma_Z ) [GeV]</td>
<td>2.4952 ± 0.0023</td>
<td>2.4959</td>
</tr>
<tr>
<td>( \sigma_{\text{had}}^0 ) [nb]</td>
<td>41.540 ± 0.037</td>
<td>41.474</td>
</tr>
<tr>
<td>( R_l )</td>
<td>20.767 ± 0.025</td>
<td>20.742</td>
</tr>
<tr>
<td>( A_{l,0}^{(5)} )</td>
<td>0.01714 ± 0.00005</td>
<td>0.01742</td>
</tr>
<tr>
<td>( A_l(P_{\tau}) )</td>
<td>0.1465 ± 0.0006</td>
<td>0.1481</td>
</tr>
<tr>
<td>( R_b )</td>
<td>0.2162 ± 0.0010</td>
<td>0.2168</td>
</tr>
<tr>
<td>( R_c )</td>
<td>0.542 ± 0.0010</td>
<td>0.546</td>
</tr>
<tr>
<td>( A_{l,0}^{(5)}(W) )</td>
<td>0.0742 ± 0.0007</td>
<td>0.0742</td>
</tr>
<tr>
<td>( A_{l,0}^{(5)}(b) )</td>
<td>0.935 ± 0.0007</td>
<td>0.935</td>
</tr>
<tr>
<td>( A_{l,0}^{(5)}(c) )</td>
<td>0.668 ± 0.0007</td>
<td>0.668</td>
</tr>
<tr>
<td>( A_{l,0}^{(5)}(SLL,B) )</td>
<td>0.1481 ± 0.00005</td>
<td>0.1481</td>
</tr>
<tr>
<td>( \sin^2 \theta_{\text{eff}} )</td>
<td>0.2324 ± 0.0012</td>
<td>0.2314</td>
</tr>
<tr>
<td>( m_W ) [GeV]</td>
<td>80.399 ± 0.023</td>
<td>80.379</td>
</tr>
<tr>
<td>( \Gamma_W ) [GeV]</td>
<td>2.085 ± 0.042</td>
<td>2.092</td>
</tr>
<tr>
<td>( m_t ) [GeV]</td>
<td>173.3 ± 1.1</td>
<td>173.4</td>
</tr>
</tbody>
</table>

Confirmed to better than 1% precision by 100's of precision measurements

only missing piece: Higgs

July 2010

P. Sphicas
The Standard Model and Beyond

CERN Accelerator School
Feb 06, 2016
Standard Model of Particle Physics
LHC($t_0+\Delta t=2.5\text{yrs}$):

Foundations established
a “tour de force” of SM measurements

and, of course,
the hunt for the Higgs boson…
The problem: the background

a famous physicist
The LHC: signals much smaller than “bkg”

- General event properties
- Heavy flavor physics
- Standard Model physics
  - QCD jets
  - EWK physics
  - Top quark
- Higgs physics
- Searches for SUSY
- Searches for ‘exotica’
Jets

- To probe the hard scatter:
  - The hard scatter: jet $P_T$ and $\eta$, dijet correlations, dijet mass, …

$M_{jj} = 4.04 \text{ TeV}$

$P_{T1} = 1850 \text{ GeV}$, $\eta = 0.32$

$P_{T2} = 1840 \text{ GeV}$, $\eta = -0.53$
W/Z at 7 TeV: (still) clean & beautiful

**Z → electron + positron**

CMS Experiment at LHC, CERN
Run 133877, Event 28405693
Lumi section: 387
Sat Apr 24 2010, 14:00:54 CEST

Electrons $p_T = 34.0, 31.9$ GeV/c
Inv. mass = 91.2 GeV/c$^2$

**W → electron + neutrino**

ATLAS Experiment
W-ev candidate in 7 TeV collisions
$p_T(e+) = 34$ GeV
$\eta(e+) = -0.42$
$E^{miss}_T = 26$ GeV
$M_T = 57$ GeV
Standard Model Measurements

June 2016

CMS Preliminary

Production Cross Section, $\sigma [pb]$

- $7$ TeV CMS measurement ($L \leq 5.0$ fb$^{-1}$)
- $8$ TeV CMS measurement ($L \leq 19.6$ fb$^{-1}$)
- $13$ TeV CMS measurement ($L \leq 2.7$ fb$^{-1}$)
- Theory prediction
- CMS $95\%$CL limit

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

CMS 95\%CL limit (7 TeV) $\leq 7$ TeV CMS measurement ($L$)
CMS 95\%CL limit (8 TeV) $\leq 19.6$ fb$^{-1}$ CMS measurement ($L$)
CMS 95\%CL limit (13 TeV) $\leq 2.7$ fb$^{-1}$ CMS measurement ($L$)

P. Sphicas
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What about the Higgs boson?

Some “signatures”
H → γγ candidate
$p_T(\mu) = 36, 48, 26, 72 \text{ GeV}; \ m_{12} = 86.3 \text{ GeV}, \ m_{34} = 31.6 \text{ GeV}$

15 reconstructed vertices

$H \rightarrow ZZ \rightarrow 4\mu$ candidate with $m_{4\mu} = 125.1 \text{ GeV}$
$\mu^+ (Z_1) \ p_T : 43 \text{ GeV}$

$e^- (Z_2) \ p_T : 10 \text{ GeV}$

$e^+ (Z_2) \ p_T : 21 \text{ GeV}$

$\mathbf{8 \text{ TeV DATA}}$

$\mathbf{4\text{-lepton Mass : 126.9 \text{ GeV}}}$

$m^- (Z_1) \ p_T : 24 \text{ GeV}$

$H \rightarrow ZZ \rightarrow \mu \mu ee \text{ candidate with } m_{4\mu} = 125.1 \text{ GeV}$

CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115
Are these events “significant”?

Discovery of a new boson
Mass peaks: $H(\gamma) \rightarrow \gamma \gamma$ & $H(\gamma) \rightarrow ZZ \rightarrow 4\text{leptons}$

Despite the low branching fraction to the final state, the mass resolution of these two channels enables the siting of a “peak”. The ZZ peak has a Z calibration as well(!)
Putting it all together...
And thus was born, on July 4th 2012, “a new boson with mass ~126 GeV”: it decayed to two bosons (two $\gamma$; two $Z$; two $W$)

It is not spin-1: it decays to two photons (Landau-Yang theorem)

It is either spin-0 or spin-2 (could also be higher spin, but this is really disfavored)
Couplings to particles

\[ \lambda_f = \frac{m_f}{v} \]

\[ g_V = 2 \frac{m_V^2}{v} \]
H→ZZ→4leptons: angular analysis

Matrix Element Likelihood Analysis:
uses kinematic inputs for signal to background discrimination
\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}

\[
MELA = \left[ 1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})} \right]^{-1}
\]
Scalar or pseudoscalar? Spin 2 or 0?

- Test angular distributions under both the $0^+$ and $0^-$ hypotheses
- Test angular distributions under both the $2^+$ and $0^+$ hypotheses

\[ CL_s\left(\frac{0^-}{0^+}\right) = 0.16\%, \quad CL_s\left(\frac{2^+}{0^+}\right) = 1.5\% \]
So is this it?

In a world of an SM Higgs, is there any room for new physics?
Learning from history

- With the discovery of the Higgs boson, the Standard Model (SM) is now complete
  - The SM provides a remarkably accurate description of experiments with and without high-energy accelerators.

- With the physics of the very small [thought to be] understood at energy scales of at least 100 GeV, the situation is reminiscent of previous times in history when our knowledge of nature was deemed to be “complete”.

Lord Kelvin (1900):
There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.
Dark matter

Probably the biggest mystery in nature (as we speak)
New type of matter?
New forces?
New dimensions?

Dark (invisible) matter!

Gasesous Matter

Dark Matter
The magic of the Higgs boson mass

- Quantum Mechanics: ultimate destructor of small numbers (in nature) not protected by some symmetry (thus “law”)
- Higgs boson: the ultimate example.

\[ m^2(p^2) = m_o^2 + p \phi^2 \]

- If no new physics up to Planck scale, then \( \Lambda \sim 10^{19} \) GeV
- \( m^2 = 1234567890123456789012345675432189012 - 1234567890123456789012345675432173136 = 15876 \) GeV

- Two possible explanations for this:
  (a) The A word
  (b) New Physics

P.A.M Dirac
The A word: anthropic [aka “accident”]*

- Extreme fine-tuning (ETF) of parameters: no problem!
  - $10^{-43}$s: inflation ceases, GUT breaks
  - $10^{-35}$s: EWK force splits
  - $10^{-10}$s: protons and neutrons form
  - $10^2$ s: Helium nuclei form
  - 300kyears: atoms form; transparent univ.
  - 1Gyrs: galaxies form
  - 13Gyrs: humankind debates naturalness

- Of the $10^{500}$ possible ways of making a universe, we live in the one that has this cancellation – so as to ensure that we end up with a “livable” universe as we know it.
The NP word(s): this is no accident

- **Strong dependence of Physics(Λ_{EWK}) on Physics(Λ_{PL})?**
  - It’s like saying that to describe the Hydrogen atom one needs to know about the quarks inside the proton (not true!)

- **No way. There must be some physics that cancels these huge corrections. A straightforward way:**
SUSY (super-symmetry) premise: for every particle in the SM, there is a super-partner with spin-$\frac{1}{2}$ difference

Before proceeding, need to explain:
- Why we have not observed spin–0 electrons (or muons...) up to now [simple: spartners are heavy; not produced thus far...]
- Lack of other new phenomena, e.g. why proton does not decay
SUSY is a broken symmetry!

SUSY partners do not have the same mass as their Standard Model counterparts.

- Though they are the same in (essentially) every other aspect.

Make/keep the mass split at ~TeV and nature’s choice of the Higgs boson mass is... “natural”
A super(b) symmetry!

Higgs (mass) is natural ?!

Grand Unifier?

Dark Matter candidate

With SUSY

Without SUSY
SUSY? What it could look [looks?] like

\[
\begin{align*}
MHT &= 693 \text{ GeV} \\
HT &= 1132 \text{ GeV} \\
M_{\text{eff}} &= MHT + HT = 1.83 \text{ TeV}
\end{align*}
\]
Constrained MSSM: Highly Constrained...

MSUGRA/CMSSM: \( \tan(\beta) = 30, A_0 = -2m_0, \mu > 0 \)

**ATLAS**

\( s = 8 \text{ TeV}, \ L = 20 \text{ fb}^{-1} \)

All limits at 95\% CL.

- Expected (\( \pm 1 \sigma_{\text{exp}} \))
- Observed (\( \pm 1 \sigma_{\text{theory}} \))

- (0+1)-lepton combination
- 0-lepton + 7-10 jets + \( E_T^{\text{miss}} \)
- 0/1-lepton + 3 b-jets + \( E_T^{\text{miss}} \)
- Taus + jets + \( E_T^{\text{miss}} \)
- SS/3L + jets + \( E_T^{\text{miss}} \)
- 1-lepton (hard) + 7 jets + \( E_T^{\text{miss}} \)
Supersymmetry

- The LHC has placed very severe constraints on Supersymmetry
  - In fact, the more “constrained” models of SUSY are now almost excluded
  - So, is it dead? [it seems the press loves to declare this…]

- There is a lot of room still left. But if SUSY is the answer to the “naturalness” problem, then there must exist light colored particles
  - Leading hypothesis: a relatively light (~TeV) top squark (partner of the top quark)
  - Second-to-leading: compressed spectra
SUSY: searching for the top squark

\[ \tilde{b}/\tilde{t} \rightarrow \tilde{g} \tilde{\chi}_1^0 \]

\[ \tilde{t}\tilde{t} \text{ production, } \tilde{t}\rightarrow b f f' / \tilde{t}\rightarrow c \tilde{\chi}_1^0 / \tilde{t}\rightarrow W b \tilde{\chi}_1^0 / \tilde{t}\rightarrow t \tilde{\chi}_1^0 \] Status: ICHEP 2016

ATLAS Preliminary
- \( \tilde{t}\rightarrow t \tilde{\chi}_1^0 \)
- \( \tilde{t}\rightarrow t \tilde{\chi}_1^0 \)
- \( \tilde{t}\rightarrow W b \tilde{\chi}_1^0 \)
- \( \tilde{t}\rightarrow c \tilde{\chi}_1^0 \)

\( t\overline{s}=13 \text{ TeV, 10 L 13.2 fb}^{-1} \) [CONF-2016-077]
\( t\overline{t}L 13.2 \text{ fb}^{-1} \) [CONF-2016-050]
\( \overline{t}L 13.3 \text{ fb}^{-1} \) [CONF-2016-076]
\( \overline{t}\overline{s} \text{ 3.2 fb}^{-1} [1604.0777] \)

Run 1 [1506.08616]

Observed limits

CMS Preliminary
- SUS-2014, 0-1 lep (H_t), 12.9 fb^{-1}
- SUS-2015, 0-1 lep (M_{12}), 12.9 fb^{-1}
- SUS-2016, 0-1 lep (M_{12}), 12.9 fb^{-1}
- SUS-2016, 1-1 lep (M_{12}), 12.9 fb^{-1}
- SUS-2017, 1-1 lep (M_{12}), 12.9 fb^{-1}
- SUS-2017, 1-2 lep (SS), 12.9 fb^{-1}
- SUS-2018, 1-3 lep, 12.9 fb^{-1}
- SUS-2018, 0-1 lep (top tag), 12.9 fb^{-1}
- SUS-2018, 1-1 lep (H_{12}^\text{miss}), 2.3 fb^{-1}

Expected

- Observed

ICHEP 2016

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A dizzying exclusion map

Looked for a lot of possible new things

Nothing has turned up yet

Still looking intensively
The LHC at 13 TeV vs 8 TeV

ratios of LHC parton luminosities: 13 TeV / 8 TeV

- $gg$
- $\Sigma qq$
- $qg$

MSTW2008NLO

2 TeV

3 TeV
Outlook
(LHC at 13-14 TeV & at very high luminosity)
&
Summary
Summary

- The Standard Model of particle physics is actually much more: it’s the Standard Theory of particle physics
  - An elegant description of “interactions”, based on Quantum Field Theory (special relativity and quantum mechanics)
  - One tricky issue: symmetry breaking. Needed a truly new mechanism – BEH? There should be a left-over boson
    - For decades: missing element – the Higgs boson

- A new boson with mass 125 GeV has been found
  - We are probing its properties. It IS a Higgs boson! Is it the SM Higgs boson? Need to study it in more detail.

- Even if this turns out to be the very Higgs boson of the Standard Model, there are huge reasons to believe that new physics is within reach;
  - A gigantic amount of work on searches for SUSY, extra dimensions, etc…; Null so far, but, the best has yet to come!