The Quest for the Higgs Boson

Matthew Strassler
Rutgers University
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What Does It All Mean?

• This is an astounding accomplishment!

• It is important to see it in proper perspective
  – Represents the end of a 50 year quest
  – Just a part of a century-long and still continuing saga

• The meaning and implications of the discovery aren’t known yet

• But they will be big in the long term –
  – we just don’t know precisely in what way
Nature as We Currently Know It

• A Quantum Mechanical World

• Quantum Fields in Presumably Quantum Spacetime
  – Electromagnetic Field, Electron Field,…

• Waves in Fields are made from Quanta (“Particles”)
  – Photons, Electrons,…

• The Universe
  – Expanding at an accelerating rate [Dark “Energy”]
  – Most of the matter is of one or more unknown types [Dark Matter]
Gravity
(graviton [?])

Standard Model

Strong Nuclear (gluons)

Electromagnetic (photon)

Weak Nuclear (W,Z)

Higgs

Quarks:
- Top/Bottom
- Charm/Strange
- Up/Down

Charged Leptons:
- Tau
- Muon
- Electron

Neutrinos:
- Neutrino 3
- Neutrino 2
- Neutrino 1

Other Sectors of Particles (?)

Dark “Energy”
Cosmological “constant”

Unstable Cousins of Dark Matter?

Dark Matter (?)
Gravity (graviton [?])

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  - Cosmological “constant”

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- Dark Matter (?)

Ordinary Matter

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Gravity (graviton [?])

Standard Model

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Electromagnetic (photon)

Weak Nuclear (W,Z)

Higgs

Strong Nuclear (gluons)

Electro-magnetic (photon)

Weak Nuclear (W,Z)

Higgs

Other Sectors of Particles (?)

Unstable Cousins of Dark Matter?

Dark Matter (?)

Dark “Energy” Cosmological “constant”

Stellar Fusion Supernovas

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Four Known Forces (“Interactions”) of Nature

All known processes in nature can be classified as one of four types

• **Electromagnetic interaction** (atomic structure)

• **Strong nuclear interaction** (nuclear structure, protons/neutrons)

• **Weak nuclear interaction** (radioactivity, supernovas)

• **Gravitational interaction** (galaxies, stars, planetary systems,…)

NEW #5! Higgs Interaction…
The “Scales” of the Forces of Nature

Some important distance scales in nature

- **Atomic scale** (atom radius $10^{-10}$ m, electron mass $10^{-12}$ m)
  - Energy eV – MeV [1900-1940]

- **Strong nuclear interaction scale** (proton size $10^{-15}$ m)
  - Energy GeV [1930-1980]

- **Weak nuclear interaction scale** (Higgs mechanism $10^{-18}$ m)
  - Energy TeV [1930-present]

- **Gravitational interaction scale** (quantum space-time $10^{-33}$ m)
  - Energy $10^{27}$ eV = $10^{15}$ TeV [2210?!?]

Convert distance $d$ to energy $E$

$$d = \frac{\hbar c}{E}$$

LHC: first time in 40 years we reach a new physical scale
Understanding the Electro-Weak Interaction

Two Long-Range Forces:
- “Weak Isospin” and “Hypercharge”
  - Four massless photon-like spin-1 bosons
  - Many massless fermions
    - electrons, muons, quarks, neutrinos

“Higgs Mechanism”

• Rearranges the forces
  - Short-Range Weak Nuclear Force
    • Massive $W^+$ $W^-$ $Z$ bosons
  - Long-Range Electromagnetic Force
    • Massless photon

• Gives masses to fermions
Understanding the Electro-Weak Interaction

Two Long-Range Forces:

- “Weak Isospin” and “Hypercharge”
- Four massless photon-like spin-1 bosons
- Many massless fermions: electrons, muons, quarks, neutrinos

“Higgs Mechanism”

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    - Massless photon
- Gives masses to fermions

Prediction of Higgs Mechanism:

New physics required at or below the LHC energy scale

But in what form? Higgs particle(s)? New forces? …

$W^+ W^- Z$

$\gamma$

$t$, $b$, $c$, $s$, $\mu$, $u$, $d$, $e$, $\nu_1$, $\nu_2$, $\nu_3$
**Quarks:**
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- Up/Down

**Leptons:**
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- Muon
- Electron

**Neutrinos:**
- Neutrino 3
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**Standard Model**

**SM-minus-Higgs not consistent.**

Scattering of W bosons violates unitarity; new forces or particles needed.

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Quarks:
- Top/Bottom
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- Neutrino 2
- Neutrino 3

Strong Nuclear (gluons)

Electromagnetic (photon)

Weak Nuclear (W,Z)

Higgs

The simplest repair:
- one Higgs field
- one Higgs particle

Higgs particle must be lighter than 1 TeV

SM-minus-Higgs not consistent.

Scattering of W bosons violates unitarity; new forces or particles needed.
### Periodic Table of the Elements

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**Lanthanide Series**

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Top 175,000
Quarks:
  Bottom 4500
  Charm 1500
  Strange 150
Down 8
Up 4

Higgs?

Weak Nuclear (W,Z) 80,000

Charged Leptons:
  Tau 1780
  Muon 105
  Electron 0.5

Neutrinos:
  Neutrino 3,2,1 <10^-6

Strong Nuclear (gluons)

Electromagnetic (photon)

Masses in MeV
M = 10^6 eV = electron-volt
Proton mass = 938 MeV
1 GeV = 1000 MeV
1 TeV = 1000 GeV

M = 10^6 eV = electron-volt
Standard Model

Quarks:
- Top 175,000
- Bottom 4500
- Charm 1500
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- Down 8
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Leptons:
- Electron 0.5
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Neutrinos:
- Neutrino 3,2,1 <10^{-6}

Strong Nuclear (gluons)

Weak Nuclear (W,Z) 80,000

Higgs ?

Masses in MeV
- $M = 10^6$ eV = electron-volt

Proton mass = 938 MeV
- 1 GeV = 1000 MeV
- 1 TeV = 1000 GeV

Puzzle #1: Why masses show this pattern? FLAVOR PROBLEM
### Standard Model

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**Weak Nuclear (W,Z)**

- Mass: 80,000 MeV

**Strong Nuclear (gluons)**

**Electromagnetic (photon)**

**Higgs**

- Mass: 125,500 MeV

**Puzzle #1: Why masses show this pattern?**

**FLAVOR PROBLEM**

**Masses in MeV**

- $M = 10^6$ eV = electron-volt

**Proton mass = 938 MeV**

- $1$ GeV = $1000$ MeV

- $1$ TeV = $1000$ GeV
**Standard Model**

**Quarks:**
- Top 175,000
- Bottom 4500
- Charm 1500
- Strange 150
- Down 8
- Up 4

**Leptons:**
- Tau 1780
- Muon 105
- Electron 0.5

**Neutrinos:**
- Neutrino 3, 2, 1 <10^{-6}

**Weak Nuclear (W,Z)**
- 80,000

**Higgs**
- 125,500

**Strong Nuclear (gluons)**

**Electromagnetic (photon)**

**Puzzle #1:**
Why masses show this pattern?
FLAVOR PROBLEM

**Puzzle #0:**
Why masses at all?
MASS PROBLEM (Higgs)
Why Masses at All? Fermions

• In quantum mechanics class, we put the electron mass $m$ in by hand

$$[p^2/2m + V(x)] \Phi(x) = E \Phi(x)$$

It's not something to explain, we just take it for granted.

• In quantum field theory, it was initially the same

$$\bar{\Psi}(i\not\partial + m) \Psi = 0$$

• But then a problem arose: the Weak Nuclear Force violates parity (1957)
Fermion Mass vs. Weak Nuclear Force

- For massless spin-$\frac{1}{2}$ particle, helicity is conserved
  - All observers agree on what a particle’s helicity is
- For spin-$\frac{1}{2}$ particle with mass, helicity isn’t a good quantum number
  - Different observers disagree
    
    Mass relates positive and negative helicity particles

- But weak nuclear force violates “parity” [invariance under mirror]
  - Converts neutrinos to electrons and back again
  - Always create neutrinos with negative helicity
  - Electrons of negative and positive helicity behave differently

- Can’t simply write $\bar{\Psi}( i \not{\partial} + m) \Psi = 0$ and combine it with the weak force
The Higgs Mechanism

Question:

How can the W and Z particles become massive?
How can electrons and other fermions become massive?

Answer: Higgs Mechanism

• Invented a number of times in quick succession 1963-64
  – Condensed matter (non-relativistic) first – Anderson
  – Within a year, relativistic version, largely independent
    • Higgs; Englert & Brout; Guralnik, Hagen, Kibble
    • Goldstone?
The Higgs Mechanism

- \( (d^2/dt^2 - c^2 \nabla^2) \Phi = 0 \)

Spin-0 ("scalar") fields \( \Phi(x,y,z,t) \)

Classical eq of motion is wave eq.

- Each wave mode \( e^{i\omega t - ikx} \) acts as independent oscillator

\[ \omega^2 - k^2 c^2 = 0 \]

Quantize: De Broglie: \( E = \hbar \omega, \ p = \hbar k \)

\[ \implies \text{spin-0 particles with} \quad E^2 - p^2 c^2 = 0 \quad \text{MASSLESS} \]
The Higgs Mechanism

- \( \frac{d^2}{dt^2} - c^2 \nabla^2 \Phi = - \left( \frac{m^2 c^4}{\hbar^2} \right) \Phi \)

- Each wave mode \( e^{i\omega t - ikx} \) acts as independent oscillator
  \[ \omega^2 - k^2 c^2 = \frac{m^2 c^4}{\hbar^2} \]

Quantize: De Broglie: \( E = \hbar \omega, \ p = \hbar k \)

\( \implies \) spin-0 particles with \( E^2 - p^2 c^2 = m^2 c^4 \) MASSIVE
The Higgs Mechanism

- \( \left( \frac{d^2}{dt^2} - c^2 \nabla^2 \right) \Phi = - \left( \frac{m^2 c^4}{\hbar^2} \right) \Phi \)
- \( \left( \frac{d^2}{dt^2} - c^2 \nabla^2 \right) A = 0 \)

Also for electromagnetic waves:

- Each wave mode \( e^{i\omega t - ikx} \) acts as independent oscillator

\[ \omega^2 - k^2 c^2 = 0 \]

Quantize: De Broglie: \( E = \hbar \omega \), \( p = \hbar k \)

\[ \Rightarrow \text{spin-0 particles with} \quad E^2 - p^2 c^2 = m^2 c^4 \quad \text{MASSIVE} \]

\[ \Rightarrow \text{spin-1 particles with} \quad E^2 - p^2 c^2 = 0 \quad \text{MASSLESS} \]
The Higgs Mechanism

- \( (d^2/dt^2 - c^2 \nabla^2) \Phi = - \left( \frac{m^2 c^4}{\hbar^2} \right) \Phi + igA \cdot \nabla \Phi + g^2 A^2 \Phi \)
- \( (d^2/dt^2 - c^2 \nabla^2) A = - g^2 \Phi^{*} \Phi A + ig\Phi^{*} \nabla \Phi - ig\Phi \nabla \Phi^{*} \)

- Nonlinear coupled wave equations

\[ \rightarrow \text{spin-0 particles with } \quad E^2 - p^2 c^2 = m^2 c^4 \quad \text{MASSIVE} \]
\[ \rightarrow \text{spin-1 particles with } \quad E^2 - p^2 c^2 = 0 \quad \text{MASSLESS} \]

Couple the two fields together (coupling strength \( g \))
The Higgs Mechanism

- \( (d^2/dt^2 - c^2 \nabla^2) \Phi = - (m^2 c^4 / \hbar^2) \Phi + igA \cdot \nabla \Phi + g^2 A^2 \Phi + \ldots \)
- \( (d^2/dt^2 - c^2 \nabla^2) A = - g^2 \Phi^* \Phi A + ig \Phi^* \nabla \Phi - ig \Phi \nabla \Phi^* \)

- Nonlinear coupled wave equations
- Add potential \( V(\Phi) \),
  
  minimum at \( \Phi = v \)

\[ \Rightarrow \text{spin-0 particles with} \quad E^2 - p^2 c^2 = m^2 c^4 \]
\[ \Rightarrow \text{spin-1 particles with} \quad E^2 - p^2 c^2 = 0 \]

Let \( <0|\Phi|0> = v \) nonzero
Write \( \Phi = v + \delta \Phi \)

Let \( V_{\text{Higgs}} = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \)
The Higgs Mechanism

- \( \frac{d^2}{dt^2} - c^2 \nabla^2 \) \( \Phi = - (m^2 \frac{c^4}{\hbar^2}) \Phi + igA \cdot \nabla \Phi + g^2 A^2 \Phi + \ldots \)
- \( \frac{d^2}{dt^2} - c^2 \nabla^2 \) \( A = - g^2 \nu^2 A + ig \Phi^* \nabla \Phi - ig \Phi \nabla \Phi^* + \ldots \)

Let \( < 0 | \Phi | 0 > = \nu \) nonzero
Write \( \Phi = \nu + \delta \Phi \)

The expectation value for \( \Phi \) generates mass for \( A \)

\[ \rightarrow \text{spin-0 particles with } E^2 - p^2 c^2 = m^2 c^4 \]
\[ \rightarrow \text{spin-1 particles with } E^2 - p^2 c^2 = g^2 \nu^2 \hbar^2 \]
The Higgs Mechanism

- \( (d^2/dt^2 - c^2 \nabla^2) \Phi = - (m^2 \, c^4 / \hbar^2) \Phi + igA \cdot \nabla \Phi + g^2 A^2 \Phi + \ldots \)
- \( (d^2/dt^2 - c^2 \nabla^2) A = - g^2 \, v^2 A + ig\Phi^* \nabla \Phi - ig\Phi \nabla \Phi^* + \ldots \)

Let \( <0|\Phi|0> = v \) nonzero
Write \( \Phi = v + \delta\Phi \)

- The expectation value for \( \Phi \) generates mass for \( A \)!!

Superconductor: \( \Phi \) Cooper pair density
- Photon massive
- Electric screening; Meissner effect

Particle Physics: \( \Phi \mapsto H \) “Higgs Field”
- \( <H> = v = 246 \text{ GeV} \)
- \( W^+, W^-, Z \) massive (80,91 GeV) [photon massless]
- Fermions couple to \( H \mapsto \) they also become massive
- Standard Model: \( \delta H \) is a massive scalar field: the Higgs boson
The Higgs Mechanism

- Spin-zero field $H$ gets expectation value $v = 246 \text{ GeV}$
- $W$, $Z$ bosons get mass of order $v$ (photon remains massless)
- Standard model fermions get mass less than or of order $v$
- Quantum of waves oscillating around $v$ is the Higgs particle
Saga of a Century!! And Not Over Yet

• 1897 – Electron discovered, mass measured, source of mass unknown
• 1905-20 – Massless photon suggested; discovered 1924
• 1957 – Discovery that weak nuclear force is mirror-asymmetric!
• 1964 – Higgs Field papers (Higgs, Brout & Englert, and Guralnik, Kibble & Hagen)
• 1967 – Weinberg (and Salam) theory of weak nuclear force, based on crucial work by Glashow, using Higgs Field to give masses for the then-known particles

• Mid-1970s – Serious consideration of how to make/discover Higgs Particle
• 1980s–90s – proposal of the U.S. SSC, European Large Hadron Collider (LHC)
• 1990s–2000s– searches elsewhere for simplest Higgs: 0 – 115, 140 – 170 GeV
• 2012 LHC data reveals new particle consistent with Higgs at about 125 GeV

Proton mass = 0.938 GeV
The Large Hadron Collider

The Design:
• Underground tunnel
• Store bunches of high-energy protons going in opposite directions
• Accelerate, steer, focus bunches using electric and magnetic fields
• Adjust until collision location, rate matches requirements

In proton-proton collisions, hope to produce
• Higgs particles, at a bare minimum
• Other new and unexpected particles or phenomena, if they are there
gluon gluon $\rightarrow$ Higgs $\rightarrow$ photon photon
gluon gluon $\rightarrow$ Higgs $\rightarrow$ photon photon
gluon gluon $\Rightarrow$ Higgs $\Rightarrow$ photon photon
gluon gluon $\rightarrow$ Higgs $\rightarrow$ photon photon
Proton + Proton $\rightarrow$ Higgs? $\rightarrow$ Two photons

Number of Collisions with Two Photons
vs. Invariant Mass of the Two Photons
July 4, 2012

Proton + Proton $\rightarrow$ Higgs? $\rightarrow$ Two “lepton pairs”

“lepton pair” = electron + positron or muon + anti-muon

Number of Collisions with Four Leptons vs. Invariant Mass of the Four Leptons
So Much We Still Don’t Know

• Is this a Higgs particle? (probably, in my view)
• Could this be anything else? (yes, but similarity to a Higgs will then be accidental)
  – Know more by November and March
  – Then not much for a while
    • 2013-2014 LHC shutdown, some continuing data analysis

• SM or not SM: One Higgs field or several, each with its own type of Higgs particle?

• SM or not SM: An elementary field, or made from other elementary fields
  – Higgs particle elementary like electron? Or composite like proton?

• Is it possible the Higgs field has no particle at all? (It was; but data apparently says no!)
SM now a consistent set of equations.

Is that it, for LHC?!

Standard Model

**Gravity**
(graviton [?])

**Other Sectors of Particles (??)**

**Dark “Energy”**
Cosmological “constant”

**Unstable Cousins of Dark Matter?**

**Dark Matter (?)**

**Strong Nuclear (gluons)**

**Electro-magnetic (photon)**

**Weak Nuclear (W,Z)**

**Higgs**

**Quarks:**
Top/Bottom
Charm/Strange
Up/Down

**Charged Leptons:**
Tau
Muon
Electron

**Neutrinos:**
Neutrino 3
Neutrino 2
Neutrino 1

**Matthew Strassler  Rutgers University**
Maybe –  
But at a very high price:  

THE HIERARCHY  
“PROBLEM”
The Hierarchy Paradox

- **Quantum Harmonic Oscillator**: Zero Point Energy $E_0 = \frac{1}{2} \hbar \omega$

- **Quantum Field**: Infinite # of Coupled Oscillators per Unit Vol.
  - Zero-Point Energy Density $E_0 / \text{Vol} \rightarrow \text{Infinity}$

Is this infinite constant a problem?

- Probably not infinite
- Spacetime probably changes at Gravitational scale, $E_0 / \text{Vol}$ not infinite
  - Probably $E_0 / \text{Vol} = 10^{15} \text{ TeV} / (10^{-34} \text{ m})^3$ [still huge]
The Hierarchy Paradox

- **Quantum Harmonic Oscillator**: Zero Point Energy $E_0 = \frac{1}{2} \hbar \omega$

- **Quantum Field**: Infinite # of Coupled Oscillators per Unit Vol.
  - Zero-Point Energy Density $E_0 / \text{Vol} \rightarrow \infty$ $10^{15} \text{ TeV} / (10^{-34} \text{ m})^3$

Is this huge constant a problem?
  - Not if you ignore gravity…
    - Gravity $\Rightarrow$ *This is a Huge Cosmological Constant*
    - *By rights this should destabilize cosmos – ??!??*

But wait – **it isn’t even constant**! Even without gravity, must pay attention!
  - For each field, value of $\omega$ depends on mass of the field
  - Masses of many fields depend on value of Higgs field $<H> = v$

- $E_0$ is really $E_0(H)$
  - **Big Quantum Correction to Higgs Potential $V(H)$ from $E_0/\text{Vol}$**
Classical $V(H)$

$\langle H \rangle = v = 246 \text{ GeV} = 10^{-15} \, m_{\text{Planck}}c^2$

Quantum $V(H) \sim E_0(H)/\text{Vol}$

$\langle H \rangle = v \sim m_{\text{Planck}}c^2$
Classical $V(H)$

$\langle H \rangle = \nu = 246 \text{ GeV} = 10^{-15} m_{\text{Planck}} c^2$

Quantum $V(H) \sim \frac{E_0(H)}{\text{Vol}}$

$\langle H \rangle = \nu = 0$
The Hierarchy Problem:
How is it that $v / m_{\text{Planck}} c^2 \sim 10^{-15}$ instead of $= 0$ or $\sim 1$?
Light and Lonely Higgs Is “Unnatural”

• In either case:
  – The Higgs boson should have an enormous mass
  – The energy scale of the weak nuclear force should be huge or zero

• Unnatural for there to be an observable Higgs boson, by this argument

• But we need one for the SM to make theoretical sense
  • And there’s something like one in the data
    – So either the SM is incomplete, or the hierarchy argument is wrong

• Light spin-0 particle, with nothing additional to explain its presence, would fly in face of our understanding of quantum field theory
  – Such “Naturalness” arguments have worked throughout particle physics and condensed matter physics in the past
  – Failure here would be jaw-droppingly mysterious
    • “SM is simplest repair” – but also most radical of all
The Standard Model + Gravity + Dark Stuff

If what we have at LHC is just the SM, leaves many deep unsolved problems:

- **#10^{15}** – **Hierarchy Problem:** Why is $v$ nonzero but very small?
  - Why spin-zero particle with nothing new near its mass scale?
- **#0** – **Mass Problem:** Why is there mass at all? – *Apparently solved.*
- **#1** – **Flavor Problem:** Why the wacky pattern of masses? Of decays?
  - Why is top quark so heavy?
- **#2** – **CP Problem:** CP symmetry violated in weak nuclear force, but not strong nuclear force (even though latter seems natural)

- And more --
  - **#3** – Why are there three generations of particles in SM?
  - **#4** – Why are there four types of forces in SM?
  - **#X** – What is dark matter?
  - **#10^{120}** – C.C. Problem: Why is universe accelerating, but very slowly?
  - **#ω** – Why is quantum mechanics the world’s way of being?
Gravity (graviton [?])

Quarks:
- Top/Bottom
- Charm/Strange
- Up/Down

Charged Leptons:
- Tau
- Muon
- Electron

Neutrinos:
- Neutrino 3
- Neutrino 2
- Neutrino 1

Standard Model

Other Sectors of Particles (???)

Heavy Particles, More Higgs Fields, New Forces, ???

Electromagnetic (photon)

Weak Nuclear (W, Z)

Higgs

SM a consistent set of equations.
But it suffers an horrible-looking hierarchy problem

Dark “Energy”
Cosmological “constant”

Unstable Cousins of Dark Matter?

Dark Matter (?)
Popular Potential Solutions?

The Hierarchy Problem:
How is it that \( \frac{v}{m_{\text{Planck}} c^2} \sim 10^{-15} \) instead of \( = 0 \) or \( \sim 1 \)?

- Higgs field is a composite field held together by new forces at the TeV scale
  - *Calculation of zero point energy is wrong above that point*

- Supersymmetry:
  - “Superpartner” particles for every known particle near TeV scale
  - *Cancel the zero-point energy of fermions and bosons of similar mass*

- Gravity, Extra Dimensions at TeV scale, not \( 10^{15} \) TeV
  - *Planck scale, spacetime, etc. are not what we think*

These and others predict new particles/forces/phenomena that LHC can find *(sooner or later)*
Searching for Signs

• Dozens of different search strategies in use
  – Still looking mostly for relatively high rate, easily-detected processes
  – Testing SM predictions for the Higgs particle itself in detail

• So far? Nothing.
  – Big breakdown in quantum field theory unlikely
  – Many (but not all) composite-Higgs scenarios excluded
  – Otherwise still ambiguous
    • Disfavors many versions of supersymmetry (others remain)
    • Disfavors some classes of extra dimension models (others remain)
    • Some sensitivity to some types of hidden sectors (many remain)

• But still in early stages of LHC!
  less than few % of total data collected
  many types of data analysis strategies not tried yet
Gravity (graviton [?])

Other Sectors of Particles (?)

Standard Model

Strong Nuclear (gluons)

Electromagnetic (photon)

Weak Nuclear (W,Z)

Higgs

Quarks:
Top/Bottom
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Charged Leptons:
Tau
Muon
Electron

Neutrinos:
Neutrino 3
Neutrino 2
Neutrino 1

SM a consistent set of equations.

Is that it, for now?!

Maybe. But extraordinary if true.

Dark “Energy”
Cosmological “constant”

Unstable Cousins of Dark Matter?

Dark Matter (?)

Matthew Strassler  Rutgers University
Is it the SM (for now), or Isn’t it?

• Theoretically: SM or not SM is night vs. day
  – Not SM at LHC? then great puzzles of SM – especially the hierarchy problem – may be on the verge of solution.
  – Only SM at LHC? Hierarchy problem unsolved; a lightweight lonesome elementary scalar particle… And all the other puzzles to remain unsolved for now as well. Very deep mysteries.

• Experimentally: SM or not SM may be night vs. deep twilight.
  – Plenty of non-SM theories may differ from SM by
    • Subtle effects on the Higgs particle’s properties of order 10%
    • Hard-to-discover new particles
  – Thus all possible information must be squeezed from LHC’s data
    • Can prove SM is false; can’t prove it true!
      – Maybe just need a bit more precision…?
Goals of Next Phase of LHC

2012 at 8 TeV per collision; 2015-2018 or later at 13-14 TeV per collision

• Precision measurements of the new particle
  – Is it really a Higgs particle?
  – Do all of its properties agree perfectly with the predictions of the SM?
    • Spin, Parity
    • Production rates
    • Decay rates
    • Any exotic properties?

• Continued search for non-SM particles, forces, phenomena
• Precision tests of many other SM predictions

• Aim to determine as far as possible: SM or not SM
The Higgs Era Has *(probably)* Begun

- A new particle has been discovered at the Large Hadron Collider
  - Consistent with some type of Higgs particle
  - Consistent so far with the simplest type, that of the Standard Model

- The Standard Model has numerous profound puzzles; is it really right?
  - The Higgs field gives mass to most Standard Model particles
    - Explains how particles can have mass at all
    - But we have no idea what sets the precise values of the masses
  - And then there’s the huge Hierarchy Problem
    - Why is weak scale neither zero nor at Planck scale?
    - How/why is a lightweight spin-0 particle like Higgs reasonable?

- Solutions to Hierarchy Problem all give discoverable particles at LHC
  - No sign of them yet, but it is still early days at the LHC

- So stay tuned as we test the Standard Model from all sides