Theoretical Particle Physics and the hunt for the next standard model

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The Standard Model

- Quarks: u, d, c, s, b, t
- Leptons: e, μ, τ, γ, ψ, h
- Forces:
  - Strong force
  - Electromagnetism
  - Weak force
  - Gravity

That’s it!
Perturbation theory fails for the weak force.

Quantum Corrections

\[ \alpha \frac{(\text{weak charge})^2(\text{energy})^2}{(\text{mass of } Z)^2} \approx \frac{E^2}{(1 \text{ TeV})^2} \]

\[ \sim \frac{E^4}{(1 \text{ TeV})^4} \]

\[ \sim \frac{E^6}{(1 \text{ TeV})^6} \]

Tiny correction at atomic energies \( E \sim 10^{-6} \text{ TeV} \) …

…but as big as leading order a LHC energies \( E \sim 1 \text{ TeV} \)

What's the problem?
Perturbation theory is restored if there is a Higgs.

\[ \frac{E^4}{(1 \text{ TeV})^4} + \frac{-E^4}{(1 \text{ TeV})^4} \approx 0.01 \]

Large correction cancels

The Higgs Boson restores our ability to calculate.

Must there be a Higgs? No.
- But then quantum field theory fails above 1 TeV
- We would need a new framework for particle physics
- Very exciting possibility!
Where is the Higgs?

Combine many observables to constrain Higgs mass

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Input value</th>
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<tbody>
<tr>
<td>( M_Z ) [GeV]</td>
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<td>( \Gamma_Z ) [GeV]</td>
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Where is the Higgs?

**Combined bound (95%)**

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Combine many observables to constrain Higgs mass.

**Recent Tevatron exclusion (160-170 GeV)**

**Combined bound (95%)**
Two experiments can find the Higgs

ATLAS

CMS

25 kilometers in diameter
The LHC is being built to find the Higgs

If there is no Higgs

The LHC will find something better

- supersymmetry
- technicolor
- extra-dimensions
- ...

Quantum Field Theory FAILS

no Higgs
(m = 1)

most exciting possibility!

The LHC is a win-win situation
Can there be *just* a Higgs?

Yes.

But we hope not.

Clues to new physics

1. Dark Matter
2. Unification
3. The Higgs is weird
4. Quantum Gravity
Can there be *just* a Higgs?

Yes.

But we *hope* not.

Clues to new physics

1. Dark Matter
2. **Unification**
3. The Higgs is *weird*
4. Quantum Gravity
When two seemingly different things turn out to be the same

Chemistry = p + e^-

Electromagnetism = Gravity

Electroweak unification

Quark model
Grand Unification

- Strong force
- Electromagnetism
- Weak force

- Explains why proton and electron have the same charge
- Coupling constants should be the same
  - \( \alpha_{\text{strong}} = 0.15 \)
  - \( \alpha_e = 0.04 \)
  - \( \alpha_{\text{weak}} = 0.02 \)

- Coupling constants are energy dependent!

unification at \( 10^{15} \text{ GeV} \)

- New force!
- New effects!

proton decay predicts:
  - Proton lifetime = \( 10^{31} \) years
  - Limit (1974) \( \sim 10^{29} \) years
  - Limit (2009) \( \sim 5 \times 10^{33} \) years

but they are energy dependent!
• What if every matter particle is unified with a force particle?

• Matter and force particles must have the same charges!

• No pairings work…
  
  hmm…
Supersymmetry

Particles and Forces

- What if every matter particle is unified with a force particle?
- Matter and force particles must have the same charges!
- No pairings work…
  hmm…
- Invent new particles!
- Superpartners must have the same mass!
  hmm…
- Supersymmetry must be broken!
Broken Supersymmetry

Standard Model: 18 particles, 30 parameters

Minimal Supersymmetry Standard Model: 40 particles, 140 parameters

“With 4 parameters I can fit an elephant, with 5 parameters I can make him wiggle his trunk”

-- Carl Friedrich Gauss
Constraints

**Tanβ** and charged Higgs mass

**smuon** and **neutralino** mass

**mSUGRA** parameterers

**gluino** and **squark** masses
Need better tests

Jets at LEP

Old Way (Brute Force)

| Q = M_Z |
| \alpha_s (M_Z) = 0.1189 |

New Way (Effective Field Theory)

MDS, T. Becher; JHEP: 0807.2477 (2008)
Need better tests

World’s best measurement of strong coupling constant:

$$\alpha_s(m_Z) = 0.1134 \pm 0.0013$$

Old value from LEP

$$\alpha_s(M_Z) = 0.1202 \pm 0.0003 \text{(stat)} \pm 0.0049 \text{(syst)}$$

New model-independent bound on the gluino

Old value: $$m_g > 5 \text{ GeV}$$

New value: $$m_g > 50 \text{ GeV}$$

Factor of 10 improvement!

Need better tests

**Photons at the LHC**

**Old Way** (Brute Force)

**New Way** (Effective Field Theory)

MDS and T. Becher, appears at 8pm
SUSY is highly constrained

Predictions
• detectable dark matter
• proton decay
• calculable Higgs mass
• B meson decays and mixings
• new sources of CP violation
• muon anomalous magnetic moment (g-2)
• flavor changing neutral currents
• collider signatures

Problems
• where are the sparticles?
• μ problem
• SUSY flavor problem
• Little hierarchy problem
• Proton decay
• CP problems
• Moduli problems
• ...

Solutions
• Gauge/Gravity/Anomaly/Gaugino mediation
• R-parity
• Hidden sectors
• NMSSM
• A terms, D terms
• ...

If supersymmetry is relevant to TeV scale physics,

Why is it hiding?
Can there be *just* a Higgs?

Yes.

But we *hope* not.

Clues to new physics

1. Dark Matter
2. Unification
3. The Higgs is *weird*
4. Quantum Gravity
The Higgs is Weird

The Higgs boson is a \textit{spinless} particle.

It \textit{naturally} wants to \textit{clump} together. It also \textit{clumps} around fermions to give them mass.

\begin{itemize}
  \item (bad)
  \item (good)
\end{itemize}

This makes it \textit{very heavy} \((10^{19} \text{ GeV})\) but it has to be light to cancel strong \(W/Z\) scattering.

This is known as the \textit{hierarchy problem}:

\begin{itemize}
  \item Why is the weak scale \((100 \text{ GeV})\) so much smaller than the Planck scale \((10^{19} \text{ GeV})\)?
  \item Why is the \textbf{Higgs so light}? \[ \text{supersymmetry:} \quad \] \[ \text{higgsino} \]
  \[ \text{fermions don't clump} \]
\end{itemize}

\[ = \text{small} \]
The Higgs is just an order parameter for electroweak symmetry breaking

Magnetization is an order parameter for spin-alignment symmetry breaking

Does a “magentization particle” exist?
No. There are electrons with spins.

What are the “electrons” for electroweak symmetry breaking?
What if the order parameter is a fermion condensate?

\[ h = \langle \bar{\psi} \psi \rangle \]

Solves the Hierarchy Problem: fermions don’t clump!

Weak scale (100 GeV) can be much smaller than Planck scale ($10^{19}$ GeV)

Weak scale is generated by pairs of virtual techniquarks and technigluons.

(We already know that the strong scale is generated by pairs of virtual quarks and gluons.)
Beautiful idea.

• But it cannot explain fermion masses.

• Huge problem with flavor-changing neutral currents
• Ruled out by precision measurements

Theories like technicolor with strong dynamics are very hard to study

Many more types that we don’t understand

Typical technicolor prediction
Other ideas

Extra dimensions
• Why not?
• Must be tiny and curled up
• Fun to think about, but not particularly well-motivated

Warped Extra dimensions
• Randall-Sundrum models
• Related to technicolor by duality
• Thousands of parameters
• Current bounds are strong
  • hard to see at the LHC

Leptoquarks

Little Higgs models
Can there be *just* a Higgs?

Yes.
But we *hope* not.

Clues to new physics

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Quantum Gravity

Recall weak boson scattering grows with energy

\[ \sim \frac{E^4}{(1 \text{ TeV})^4} \]

growth canceled by Higgs

\[ \sim -\frac{E^4}{(1 \text{ TeV})^4} \]

Graviton scattering grows with energy too

\[ \sim \frac{E^4}{(10^{19} \text{ GeV})^4} \]

what cancels the growth?

Strings?

Maybe.

Sadly, there is little chance that the LHC will tell us anything about quantum gravity… …but who knows?
Particle physics in 1930

Three particles:

- Proton ($p^+$)
- Electron ($e^-$)
- Photon ($\gamma$)

Two forces:

- Electromagnetism
- Gravity

Nuclei are made up of protons and electrons

- Neutron ($n$)

Helium

- Helium ($^4\text{He}$)
- Tritium ($^3\text{H}$)

Dirac equation (1928)

$$\left(\beta mc^2 + \sum_{k=1}^{3} \alpha_k p_k c\right) \psi(x, t) = i\hbar \frac{\partial \psi(x, t)}{\partial t}$$

- Explains spin
- Predicts positron ($e^+$)
- Klein-Nishina formula
  - Explains details of Compton scattering ($\gamma e \rightarrow \gamma e$)
  - Requires virtual positrons
- Dirac (1930): Maybe proton is the positron!
Three problems

1. Nuclear spins and magnetic moments made no sense

\[ \mu_z = \frac{e}{2m} \]

2. If \( p^+ = e^+ \), nuclei can implode

Hydrogen \( \rightarrow \) Light

3. \( \beta \) decay spectrum continuous

Three separate solutions

Needed EXPERIMENTS to find out
What will the LHC find?

- supersymmetry
- technicolor
- extra-dimensions
- ...

There is a lot we don’t understand today

1. Dark Matter
2. Unification
3. The Higgs
4. Quantum Gravity

Will we need a new principle?

Quantum Field Theory FAILS

no Higgs
($m = \infty$)
Conclusions

• The Higgs is missing

• Quantum field theory fails without a Higgs.

• The Higgs is weird

• None of our “better” ideas seem to work

• The LHC must either find the Higgs, find something else, or disprove quantum field theory

“There are more things in Heaven and in Earth than are dreamt of in our philosophy”

-- Ernest Rutherford, 1914, from Hamlet