Physics Beyond the Standard Model: Questions for the LHC

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The LHC: 7 TeV protons (7 times more powerful than the Tevatron!), 17 miles long, few G$
Particle Collider is a Giant Microscope!

- **Optics**: diffraction limit, $\Delta_{\text{min}} \approx \lambda$
- **Quantum mechanics**: particles $\leftrightarrow$ waves,
  
  $$\lambda \approx \frac{\hbar}{p}$$

- **Higher energies $\leftrightarrow$ shorter distances:**
  - **Nucleus**: $\Delta \sim 10^{-13} \text{ cm} \leftrightarrow$ proton mass $M_p c^2 \sim 1 \text{ GeV}$
  - **Colliders so far**: $E \sim 100 \text{ GeV} \leftrightarrow \Delta \sim 10^{-15} \text{ cm}$
  - **LHC**: $E \sim 1000 \text{ GeV} \sim 1 \text{ TeV} \leftrightarrow \Delta \sim 10^{-16} \text{ cm}$

  \[ \text{parton } E \sim 1/10 \text{ proton } E \]
Particle Colliders Can Create New Particles!

- All naturally occurring matter consists of particles of just a few types: protons, neutrons, electrons, photons, neutrinos.
- All other known particles are highly unstable (lifetimes \( \ll 1 \) sec) don’t occur naturally (but did in Early Universe!)
- In Special Relativity, energy and momentum are conserved, but mass is not: energy-mass transfer is possible! \( E = mc^2 \)
- So, a collision of 2 relativistic protons can result in particles with \( m \gg m_p \), “made out of” their kinetic energy.
- Example: top quark \( m \approx 170 \text{ GeV} \approx 170m_p \)
- LHC: produce particles up to \( m \approx 5 \text{ TeV} \approx 5000m_p \)
- Study properties of new particles to uncover new laws of nature, and new insights into the meaning of the old laws.
All our knowledge about subatomic physics is summarized in the **Standard Model** - arguably the most successful Physics theory ever!

### Standard Model of

**FUNDAMENTAL PARTICLES AND INTERACTIONS**

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is not included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

#### FERMIIONS

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c^2</th>
<th>Electric Charge</th>
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<tbody>
<tr>
<td>u electron</td>
<td>1.4 x 10^-3</td>
<td>1/3</td>
</tr>
<tr>
<td>d electron</td>
<td>1.3 x 10^-3</td>
<td>2/3</td>
</tr>
<tr>
<td>s electron</td>
<td>1.3 x 10^-3</td>
<td>0</td>
</tr>
<tr>
<td>c electron</td>
<td>1.3 x 10^-3</td>
<td>2/3</td>
</tr>
<tr>
<td>t electron</td>
<td>1.3 x 10^-3</td>
<td>0</td>
</tr>
<tr>
<td>b electron</td>
<td>1.5 x 10^-3</td>
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#### QUARKS

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<tr>
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<td>1.3 x 10^-3</td>
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<tr>
<td>s quark</td>
<td>1.3 x 10^-3</td>
<td>0</td>
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<tr>
<td>c quark</td>
<td>1.3 x 10^-3</td>
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<tr>
<td>t quark</td>
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</tr>
<tr>
<td>b quark</td>
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#### BOSONS

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<th>Name</th>
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<td>Z^0</td>
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<td>W^+</td>
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<td>1</td>
</tr>
<tr>
<td>W^-</td>
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<td>-1</td>
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**PROPERTIES OF THE INTERACTIONS**

<table>
<thead>
<tr>
<th>Property</th>
<th>Interaction</th>
<th>Gravitational</th>
<th>Weak</th>
<th>Electromagnetic</th>
<th>Fundamental</th>
<th>Strong</th>
<th>Residual</th>
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<tbody>
<tr>
<td></td>
<td>Particles mediating:</td>
<td>W^+</td>
<td>W^-</td>
<td>Z^0</td>
<td>γ</td>
<td>Gluons</td>
<td>Mesons</td>
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<tr>
<td></td>
<td>Strength relative to electron:</td>
<td>for two quarks at:</td>
<td>3 x 10^-13 m</td>
<td>3 x 10^-13 m</td>
<td>3 x 10^-13 m</td>
<td>3 x 10^-13 m</td>
<td>3 x 10^-13 m</td>
</tr>
<tr>
<td></td>
<td>for two protons in nucleus</td>
<td>10^-7</td>
<td>10^-4</td>
<td>10^-3</td>
<td>10^-2</td>
<td>10^-1</td>
<td>10^-0</td>
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### Baryons qqq and Antibaryons q̄q̄q

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Quark</th>
<th>Electric Charge</th>
<th>Mass GeV/c^2</th>
<th>Spin</th>
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<tr>
<td>p</td>
<td>proton</td>
<td>uud</td>
<td>1/2</td>
<td>938.98</td>
<td>1/2</td>
</tr>
<tr>
<td>n</td>
<td>neutron</td>
<td>udd</td>
<td>-1</td>
<td>939.57</td>
<td>0.55</td>
</tr>
<tr>
<td>Λ</td>
<td>lambda</td>
<td>udds</td>
<td>0</td>
<td>1160</td>
<td>2/3</td>
</tr>
<tr>
<td>Σ</td>
<td>sigma</td>
<td>uudd</td>
<td>0</td>
<td>1540</td>
<td>5/3</td>
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<tr>
<td>Ψ</td>
<td>psi</td>
<td>uudd</td>
<td>0</td>
<td>3097</td>
<td>0</td>
</tr>
</tbody>
</table>

### Matter and Antimatter

For each particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (e.g., –e = electron’s antiparticle, the antielectron or positron). Particle and antiparticle have identical mass and spin but opposite charge. Some particles neutral and hence have no electric charge, e.g., μ, e, and τ, but not K^- = 0). These are their own antiparticles.

### Figures

These diagrams are an artist’s conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons in the gluon field, and red lines the quark paths.

### The Particle Adventure

Visit the award-winning website The Particle Adventure at http://ParticleAdventure.org

This chart has been made possible by the generous support of: U.S. Department of Energy, U.S. National Science Foundation, Lawrence Berkeley National Laboratory, Stanford Linear Accelerator Center, Fermi National Accelerator Laboratory, and The Particle Adventure. The Particle Adventure is a non-profit organization of teachers, physicists, and educators. Send mail to: CPEM, MS 50-338, Lawrence Berkeley National Laboratory, Berkeley, CA 94720. Information on drafts, test materials, hardcopy classroom activities, and workshops, see http://CPEMweb.org.

[from: particleadventure.org]
Predictive Power of the Standard Model

• The Standard Model is not just a list of particles and a classification - it is a theory that makes detailed, precise quantitative predictions!

• Consider a head-on collision of a 100 GeV electron and a 100 GeV antielectron ("positron"). Possible outcomes:

\[ e^+ e^-, \mu^+ \mu^-, \tau^+ \tau^-, p\bar{p}, W^+ W^-, e^+ e^+ e^- e^-, \ldots \]

• Quantum mechanics: there is no way to know for sure which outcome will occur in a given collision, but the SM predicts probabilities ("cross sections") of each outcome, plus details like directions of the produced particles, etc.

• Works spectacularly well! (some predictions experimentally verified to 0.1% accuracy)
Feynman Diagrams

Example: **Coulomb repulsion** between electrons, due to a photon exchange

```
et_\to_ e_ \quad \gamma \quad e_\to_ e
```

“Feynman Rules”: diagram $\rightarrow$ mathematical expression for the cross section
Before the SM: QED and Weak

• The success story of the 1950's: Quantum Electrodynamics
  • Unified description of electricity and magnetism
  • Consistent with special relativity and quantum mechanics
  • Non-trivial predictions confirmed by experiment (e.g. Lamb shift, anomalous magnetic moment, ...)

• The nightmare of the 1950's: Weak Interactions
  • Not described by QED
  • Phenomenological model (Fermi model) with little predictive power
  • Inconsistent with QM at high energies (not probed then)
Problem with the Fermi Model

- **Experiment**: accelerate electrons and protons to high energies and **collide** them!

- **Weak interactions**: inverse beta decay, \( e^- + p \rightarrow n + \nu \)

\[
\sigma \sim G_F^2 E_{c.m.}^2
\]

\[
G_F = 1.166 \times 10^{-5} \text{ GeV}^{-2}
\]

- **Unitarity** bound (quantum mechanics): \( \sigma < \frac{\pi}{E_{c.m.}^2} \)

- **Violate unitarity** predict **probability > 1**!

- **Unitarity** bound violated at \( E_{c.m.} \approx 300 \text{ GeV} \)

- **Fermi-model description** **MUST** break down at or below this scale!
Fixing the Fermi Model

- EM interactions (QED): elastic scattering, \( e + p \rightarrow e + p \)

\[
\sigma \sim \frac{\alpha}{E_{c.m.}^2}
\]

\[
\alpha = \frac{e^2}{4\pi} \approx \frac{1}{137}
\]

- Idea: “Massive Vector Boson” for weak interactions

\[
\sigma \sim G_F^2 E_{c.m.}^2, \quad E_{c.m.} \ll M_W
\]

\[
\sigma \sim \frac{\alpha_w}{E_{c.m.}^2}, \quad E_{c.m.} \gg M_W
\]

- Successes of the Fermi model are preserved

- Unitarity problem is avoided if \( M_W < 300 \text{ GeV} \)

- MVBs (W and Z) discovered at CERN in 1983, with masses slightly below 100 GeV
Electroweak Unification

- MVB model predicts: EM and weak interactions have similar structure at high energies

In fact, EM and Weak forces become equally strong at energies above \( \sim 100 \text{ GeV} \)
(or distances below \( 10^{-15} \text{ cm} \) )

Weak force is short-range, with range about \( 10^{-15} \text{ cm} \)

\[
V_{\text{weak}} \propto \frac{e^{-r/r_0}}{r}
\]

\[
r_0 \sim M_W^{-1}
\]
Symmetry Breaking in Superconductors

• Analogy: recall **Meissner effect** in superconductors

• Magnetic flux exclusion → finite-range EM field → massive photon

• Cooper pair condensate spontaneously breaks the gauge symmetry of QED

• Result: consistent quantum theory with a massive photon!
Universe is a Weak Superconductor

• Generalize: the weak force is described by a theory with spontaneously broken gauge symmetry

• Assume that some condensate is permeating the Universe we live inside a “weak superconductor”!

• The condensate breaks the gauge symmetry of the weak interactions but not the EM short-range weak force, long-range EM

• The success of the Standard Model is an indirect proof of the existence of the condensate!
Questions About EWSB

- This raises **two fundamental questions:**
  - What is the condensate made of?
  - What makes it condense?

- So far, no **experimental** answers to these questions - not enough energy

- We’re like a very-low-energy experimentalist inside a superconductor:
  - Sees that EM is short-range -- guesses that there must be a condensate
  - Cannot break up Cooper pairs -- does not know that electrons exist!
EWSB in the Standard Model

- The Standard Model explanation of the condensate: Higgs phenomenon
- Postulate a new particle - the Higgs boson - of spin 0
- Higgs bosons feel the weak force but are not electrically charged
- At high temperatures (above $\sim 100 \text{ GeV} \sim 10^{15} \text{ K}$), both EM and weak force are long-range
- At “low” temperatures, Higgs bosons form a condensate, weak force becomes short-range, EM force unaffected
ElectroWeak Phase Transition

- The phase transition happened at
  
  \[ kT \sim 100 - 1000 \ \text{GeV}, \quad T \sim 10^{15} \ \text{K} \]

(or, about \(10^{-10} \ \text{sec}\) after the Big Bang)

\[ V(H) \]

\[ T > T_c \]

\[ V(H) \]

\[ T < T_c \]

\[ V(T=0) = -\mu^2 H^2 + \lambda H^4 \]
Is the Higgs Really There?

• There is no direct experimental evidence for the existence of the Higgs

• LEP II experiment @ CERN (1997-2000):

\[ E_{cm} < M_Z + M_H \]

• No observation

• Lower bound on Higgs mass: \( M_H > 114 \text{ GeV} \)

• Properties of W and Z bosons would be slightly modified by virtual effects involving Higgs, consistent with experiment for \( M(H) < 200 \text{ GeV} \) (but other explanations possible!)
Higgs and Precision EW Data

- Standard Model with a light Higgs provides a good fit to all data, indirect determination of H mass:

\[ M_H < 186 \text{ GeV} \quad (95\% \text{ c.l.}) \]
Higgs at the LHC

- The LHC will discover the SM Higgs if it’s there.
- Modified Higgs may take longer, but no good examples of “undiscoverability”
- Expect more new physics beyond the Higgs!
Radiative Corrections

• Quantum mechanics allows for energy non-conservation for short periods of time: $\Delta E \Delta t \sim \hbar$

• A particle-antiparticle pair may spontaneously appear from the vacuum, and then disappear after $\Delta t < 1/M$

• The vacuum is full of such “virtual” pairs!

• The virtual pairs can interact with particles: this is described by Feynman diagrams with loops (”radiative corrections”)

\[ \sim \]

• Computing radiative corrections involves integration over the lifetime of the virtual pair, in principle down to $t=0$ (or equivalently energy up to infinity)
Beyond the SM

- Computing radiative corrections in most quantum field theories (including the SM) involves integrals which **diverge** at high virtual energies.

- Mathematically, this can be dealt with by **renormalization**.

- Physically, divergences mean that we’re applying the theory in a regime where it is **no longer valid**!

Expect a deeper layer of structure beneath the SM!
Running Couplings

- If an electric field is present, virtual pairs (e.g. e+e-) act as dipoles - orient themselves to reduce (screen) the field!

- EM force becomes **stronger** at shorter distances faster than 1/r (less screening) - violation of Coulomb’s law

- Distance- (or energy-) dependant electric charge, or “running” fine-structure constant (e.g. \( \alpha(M_Z) = \frac{1}{128} \), not \( \frac{1}{137} \))

- All other SM parameters (coupling constants, masses) also run

[Hera: running of \( \alpha_s(\mu) \)]

[Example: running of the QCD coupling constant measured at HERA]
Running Higgs Mass I

- Imagine that a new Fundamental Theory replaces the SM at some high energy scale $\Lambda \gg 100$ GeV cutting off the divergences of the SM

- The Fundamental Theory determines the “bare” values of the SM parameters at the scale $\Lambda$

- Bare values + running $\rightarrow$ experimentally observed values at $E<100$ GeV

- For all SM parameters, running is weak (logarithmic)

  $\alpha(\mu) = \alpha(\Lambda) + \frac{\alpha^2}{4\pi} \log \left( \frac{\Lambda}{\mu} \right)$

- Exception: the Higgs mass runs very fast (“instability”)

  $m^2(\mu) \approx m^2(\Lambda) - \frac{3\lambda_t^2}{16\pi^2} (\Lambda^2 - \mu^2)$
Correct description of the Weak force requires

\[ m^2(\mu = 100 \text{ GeV}) \approx (100 \text{ GeV})^2 \]

Unless there is a finely tuned cancellation between the bare and the running contributions, this implies

\[ \Lambda \sim 4\pi m \sim 1 \text{ TeV} \]

Divergences in the Higgs sector must be cut off around the TeV scale - new physics is within reach at the LHC!

Divergence cancellation requirement + precision electroweak data guide theorists in guessing what the new physics might be, but there is no unique answer.

\[ \Lambda \sim 4\pi m \sim 1 \text{ TeV} \]
Guess 1: Supersymmetry?

- Example: the largest contribution to the Higgs mass running comes from virtual top-antitop pairs ("top loops")

- If 2 new particles, "stops", just like top but spin-0 (instead of 1/2) are added, this contribution is canceled out completely:

- It is possible to cancel all Higgs mass instabilities if the SM spectrum is doubled in this way

- A theory constructed in this way possesses a new boson-fermion exchange symmetry, a.k.a. supersymmetry
SUSY as an Extra (Fermionic) Dimension

- **Grassmann** (anticommuting) numbers:
  \[ \theta : \{\theta_1, \theta_2\} = 0 \implies \theta^2 = 0 \]
  cf normal numbers: \[ x : [x, y] = 0 \]

- In quantum field theory, fields of **fermions** (e.g. electrons) are Grassmann-valued - **Pauli exclusion principle** built in!

- Imagine a space with 1 or more \( G \)-valued coordinates, in addition to the usual 4: **superspace**

- “**Superfield**” lives in this superspace: \( \Phi(x^\mu, \theta) \)

- Taylor expand to obtain usual 4D fields: \( \Phi(x^\mu, \theta) = \phi(x) + \theta \psi(x) \)

- Supersymmetry is the generalization of **Poincare group** (rotations, translations, boosts) to this new superspace
“Minimal” Supersymmetry

- SUSY not symmetry of nature \(\rightarrow\) must be broken
- Superpartner masses at the TeV scale \(\rightarrow\) loops cut off at TeV, instability avoided, but superpartners invisible so far
- Introduce a discrete R-parity to avoid rapid proton decay: all SM particles are even, their superpartners are odd
- “Minimal” supersymmetric SM (MSSM): superpartner for each SM d.o.f., most general “soft” SUSY-breaking terms \((\sim 100!\))

<table>
<thead>
<tr>
<th>Names</th>
<th>Spin</th>
<th>(P_R)</th>
<th>Gauge Eigenstates</th>
<th>Mass Eigenstates</th>
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<td>+1</td>
<td>(H_0^0) (H_0^0) (H_d^0) (H_{d'}^0)</td>
<td>(h^0) (H^0) (A^0) (H^\pm)</td>
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<tr>
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<tr>
<td>sleptons</td>
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<td>(same)</td>
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</tr>
<tr>
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<td>(\tilde{\tau}_L) (\tilde{\tau}<em>R) (\tilde{\nu}</em>\tau)</td>
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<td>(\tilde{N}_1) (\tilde{N}_2) (\tilde{N}_3) (\tilde{N}_4)</td>
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<td>(W^\pm) (H_u^0) (H_d^0)</td>
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<td>(\tilde{G})</td>
<td>(same)</td>
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</tbody>
</table>

Table 7.1: The undiscovered particles in the Minimal Supersymmetric Standard Model (with sfermion mixing for the first two families assumed to be negligible).
All SM states R-even, superpartners R-odd \(\rightarrow\) superparticles need to be pair-produced, lightest superpartner (LSP) stable

Typically, superparticles decay promptly to SM + LSP

Strong limits on colored/charged relics in the universe prefer neutral LSP (also a WIMP dark matter candidate!)

Neutral LSP escapes the detector \(\rightarrow\) apparent momentum non-conservation, or “missing transverse energy” (MET)

**SM:** MET from neutrinos, especially \( Z \rightarrow \nu \bar{\nu} \)

“Reality”: MET from detector malfunctioning, jet energy mismeasurements, etc.
MSSM: Golden Region


- Making detailed predictions of the MSSM signatures is hard: ~100 unknown parameters

- Common approach: assume relations among the parameters motivated by specific theoretical models of SUSY breaking

- Idea: try to use existing data to get some hints about what the MSSM parameters might be!

- The most intriguing piece of data is the Higgs mass bound from LEP2: $M(H) > 114$ GeV

- Tree-level MSSM prediction: $M_{\text{tree}}(H) < M_Z = 91.2$ GeV

- Loop corrections must be large to reconcile the two

- Same loop corrections contribute to the Higgs mass instability tension! (a few-% fine-tuning required)
Golden Region: LHC Signature

- Tension minimized if the two stops have large mass difference (200-300 GeV) and mixing angle is large

- Characteristic signature: decay $\tilde{t}_2 \rightarrow \tilde{t}_1 Z$

- At the LHC, see events with $b$-jets, $Z$'s, and MET

- Not easy but should be observable with $\sim 100 \text{ fb}^{-1}$

Guess 2: Little Higgs?

- In Little Higgs models, Higgs mass instability is canceled by particles of the same spin: e.g. spin-1/2 “heavy top”

- Cancellations are a consequence of the symmetry structure of the theory (see next page)

- It is **NOT** possible to cancel Higgs mass instabilities beyond one-loop in this way ➔ theory may be valid only up to ~10 TeV scale

- Above 10 TeV, more new physics is required! (e.g. SUSY?)
  
  [e.g. Csaki, Heinonen, MP, Spethmann, arXiv:0804.0622]

- However that new physics has no effect at the LHC - beyond this talk
Little Higgs as an Extra Dimension

• Suppose that space-time has an extra **spatial** dimension

• If a gauge (vector) field lives in this 5D space, it appears to a 4D observer as **2 fields**: spin-1 and spin-0

\[ A_M(x) = (A_\mu(x), A_5(x)) \]

• This spin-0 field can play the role of the **Higgs**

• **No instability** for the vector field masses (e.g. photon) due to gauge symmetry

• A **timely merger** with the vector saves the Higgs from the instability

• Extra dimension has to be compact, 5D fields appear as **Kaluza-Klein excitations** of SM particles

• Little Higgs partners are **level-1 KK excitations**
Kaluza-Klein Particles from Extra Dimensions

- Suppose that space-time has an extra spatial dimension, which is circular, with radius $R$.

- Free field can be decomposed into momentum eigenstates (waves): $\phi \sim e^{i(p \cdot x + p_5 y)}$.

- Periodicity → momentum quantization: $p_5 (2\pi R) = 2\pi n \Rightarrow p_5 = \frac{n}{R}$.

- Fourier expansion = Kaluza-Klein decomposition:
  $$\phi(x, y) \sim \sum_{n=0}^{\infty} \phi^n(x) e^{iny/R}$$

- Each KK mode behaves like a 4D particle, with mass $M_n = \frac{n}{R}$.

- SM fields can be fundamentally 5D, if $\frac{1}{R} > 500$ GeV.
• Early LH models (2002-04) had difficulties satisfying precision electroweak constraints
• A discrete T-parity (a la R-parity of the MSSM) helps solve this problem [Cheng, Low, 2004]
• “Littlest Higgs with T-Parity” (LHT) gives acceptable fits to precision electroweak observables without fine-tuning

![Graph showing measurements vs. fits with m(H) = 115 GeV.](image)

<10% tuning

| Measurement | Fit | \(|O_{\text{meas}} - O_{\text{fit}}|/O_{\text{meas}}\) |
|-------------|-----|-------------------------------------|
| \(\Delta a_\mu^{\text{ew}}(m_Z)\) | 0.02758 ± 0.00035 | 0.02767 |
| \(m_Z\) [GeV] | 91.1875 ± 0.0021 | 91.1874 |
| \(\Gamma_Z\) [GeV] | 2.4952 ± 0.0023 | 2.4959 |
| \(\sigma_{\text{had}}\) [nb] | 41.540 ± 0.037 | 41.478 |
| \(R_b\) | 0.01714 ± 0.00095 | 0.01642 |
| \(A_b^{(P)}\) | 0.1465 ± 0.0032 | 0.1480 |
| \(R_c\) | 0.21629 ± 0.00066 | 0.21579 |
| \(\sigma_{\text{coll}}\) [nb] | 0.0992 ± 0.0016 | 0.1037 |
| \(A_b^{(C)}\) | 0.0070 ± 0.0035 | 0.0742 |
| \(A_t\) | 0.923 ± 0.020 | 0.935 |
| \(A_t\) | 0.670 ± 0.027 | 0.668 |
| \(A_t^{(SLD)}\) | 0.1513 ± 0.0021 | 0.1480 |
| \(\sin^2\theta_{\text{eff}}\) | 0.2324 ± 0.0012 | 0.2314 |
| \(m_W\) [GeV] | 80.404 ± 0.030 | 80.377 |
| \(\Gamma_W\) [GeV] | 2.115 ± 0.058 | 2.092 |
| \(m_t\) [GeV] | 172.7 ± 2.9 | 173.3 |

LHT Collider Phenomenology

- T-odd partner for each SM particle - e.g. “T-quarks”, “T-leptons”, etc. [though some may be absent, e.g. T-gluon!]

- The Lightest T-Odd Particle (LTP) is stable, typically the neutral, spin-1 “heavy photon” - WIMP DM candidate

- Hadron collider signature: T-quark pair-production, decays to LTP+jets $\rightarrow$ MET signature, just like in SUSY

LHT or SUSY: Discrimination?

- MET + jets/leptons signature common to the MSSM and LHT (dictated by the parity, R or T).

- Model discrimination requires careful analysis of properties (e.g. angular distributions) of the observed events

- Example 1: distinguishing gluino (spin-1/2) from T-gluon (spin-1)

\[ \tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0 \]

\[ G^1 \rightarrow q\bar{q}B^1 \]

Squark or T-quark?

- Example 2: distinguishing squark (spin-0) from T-quark (spin-1/2)
- Both decay to quark+invisible particle
- Study distributions of quarks (jets)
- Jets from T-quark tend to be at larger angle to the beam, due to angular momentum conservation

[Hallenbeck, MP, Thom, Spethmann, Vaughan, to appear]
Guess 3: Extra Dimensions

- In string theory, all divergent integrals cut off at $M_S$; Higgs and other particles turn into finite-size strings!

- If $M_S \sim 1$ TeV, there is no hierarchy problem! But $M_S \sim M_{Pl}$

- ADD model: SM on a 4D brane inside higher-D space, with extra dimensions compactified with
  \[ R \sim M_{Pl}^{-1} \left( \frac{M_{Pl,4}}{M_{Pl}} \right)^{2/n} \gg M_{Pl}^{-1} \]

- At $E < M_{Pl}$, missing energy signature due to graviton emission into the extra dimensions

Black Holes at the LHC?

- If two partons collide at super-plankian energies \( E \gg M_{P1} \), a black hole must form.
- NY Times: BH production at the LHC is dangerous?
- Given existing constraints on \( M_{P1} \), it seems pretty unlikely that the LHC will probe the region \( E \gg M_{P1} \) [Meade, Randall, 0708:3017]
- BHs decay too quickly (\( \tau \sim 10^{-26} \text{ s} \)) to do damage.
- In any (weakly coupled) string theory, Regge excitations of SM particles lie below Planck scale:
  \[
  M_n = \sqrt{n}M_S, \quad M_S < M_{P1}
  \]
- Reggeons appear as s-channel resonances in SM scattering processes: Easy to see, more realistic target than BHs [Cullen, MP, Peskin, hep-ph/0001166, PRD62:055012]
“Warped” Extra Dimensions

[Randall, Sundrum, 1999]

Higgs on a “brane”

Slice of AdS$_5$

\[ ds^2 = e^{-2k|y|} (dx)^2 + r^2 dy^2 \]

5th dimension

(5D gauge and fermion fields)

[see Raman Sundrum’s colloquium in 2 weeks]
Guess 4: No Higgs at all

- No fundamental spin-0 field $\rightarrow$ no instability!
- Weak Condensate may be an intrinsically strong-coupling phenomenon, no Higgs boson required (e.g. QCD)
  \[ \sigma \sim \frac{\alpha_w}{M_W^2} \]
- Unitarity bound violated at $E_{\text{c.m.}} \sim 1.8$ TeV
- Something has to happen at or below that scale!
- This experiment will in effect be performed, for the first time, at the LHC!
The “Higgsless” Approach

[Csaki, Grojean, Terning, Murayama, Pilo, ‘03-04]

4D Condensate on a “brane”

5th dimension (5D gauge and fermion fields)

Note: going to 5D allows to solve long-standing problems of Higgsless (technicolor):
Large precision electroweak corrections and fermion mass generation
Example: Unitarity in $W_L^\pm Z_L \rightarrow W_L^\pm Z_L$ Scattering

SM sans Higgs:

\[ M \propto E^2 \]

SM:

\[ M \propto E^0 ! \]

Higgsless:

\[ M \propto E^0 ! \]
WZ Elastic Scattering Cross Section in 5 Models


- The LHC will be able to discover the resonances in the WZ channel predicted by the Higgsless model.
- Mass and width of resonances discriminate between the 5D Higgsless and “old-fashioned” 4D technicolor models.
Thermal Dark Matter

• **Dark matter** (non-luminous, non-baryonic, non-relativistic matter) well-established by a variety of independent astro observations, ~20% of the universe

• None of the SM particles can be dark matter

• Assume **new particle**, in thermal equilibrium with the cosmic plasma in the early universe

• **Measured** DM density $\rightarrow$ interaction cross section $\sigma_{\text{DM-SM}}$

\[ \sigma \approx 1 \text{ pb} \sim \frac{\alpha}{(\text{TeV})^2} \]

**Independent** hint for new physics at the TeV scale!

[figure: Birkedal, Matchev, MP, hep-ph/0403004]
• The required annihilation cross section is \textit{exactly} in the right range to be produced by weak-scale physics:
\[ 1 \text{ pb} \approx \frac{\alpha}{\pi} (100 \text{ GeV})^{-2} \]

• \textbf{Hypothesis}: dark matter consist of stable, weakly interacting particles with mass\~\textit{weak} scale

• Massive Weakly Interacting Particles - \textbf{WIMPs}!

• Many \textbf{candidates} in theories of electroweak symmetry breaking - SUSY, Extra Dimensions, ...

• \textbf{Example}: the heavy photon LTP of the Littlest Higgs with T Parity
Little Higgs Dark Matter

Contours of constant $B^1$ relic density in the LHT model

Little Higgs Dark Matter: Indirect Signature


- Heavy photons accumulate in galactic halo, can pair-annihilate into W/Z bosons
- Energetic gamma rays (~10-100 GeV) are produced in the subsequent decays of the W/Zs
- GLAST telescope is searching for such anomalous high-energy gammas - should see a signal if this model is correct!

GLAST
The Gamma Ray Large Area Space Telescope
Dark Matter Production at Colliders

• Weak-scale WIMP annihilation cross section into SM states implies weak-scale WIMP pair-production cross section in SM collisions at sufficiently high energies

• WIMPs escape the detector - “missing energy”

• Predict photon+missing energy rates in a model-independent fashion - difficult at the LHC, but should be observable at the next $e^+e^-$ collider (ILC)

• LHC may produce DM particles in decays of other new particles (see discussion of SUSY, LHT signatures)
EW Phase Transition

- The phase transition happened at
  
  \[ kT \sim 100 - 1000 \text{ GeV}, \quad T \sim 10^{15} \text{ K} \]

(or, about \(10^{-10} \text{ sec}\) after the Big Bang)

\[ V(T=0) = -\mu^2 H^2 + \lambda H^4 \]
First-Order EW Phase Transition?

First-order transition involves strong deviations from thermal equilibrium - necessary condition for baryogenesis!
EW Phase Transition and the LHC

Theories with strong first-order phase transition generically predict large deviations of the Higgs cubic coupling from its SM value

Exp. prospects: 23% for a 140-GeV Higgs at a 500-GeV ILC (Snowmass 01), 20-30% for 160-180 GeV Higgs at SLHC, 8-25% for 150-200 GeV Higgs at 200 TeV VLHC
Summary

• Central question for the LHC is the mechanism of electroweak symmetry breaking

• SM explanation - the Higgs mechanism - will be definitively tested

• The Higgs requires more new physics for theoretical consistency, at the scale accessible to the LHC

• Many candidates for new physics: SUSY, Little Higgs, TeV Strings, and others; LHC will test these ideas

• If no Higgs at all, definite signatures in W/Z scattering

• Dark matter particle may be produced and studied

• LHC data may also provide info about the EW phase transition in the early universe (e.g. 1-st order?)
Backup Slides
Is the Higgs Really There?

- Indirect effect of the Higgs: radiative corrections

\[ Z \leftrightarrow H \leftrightarrow Z \]

- Small corrections to the mass, width, decay branching ratios, etc. of the W and Z bosons

- Very precise experimental studies of these properties (~0.1% precision) give sensitivity to the radiative corrections

- Large number of observables, both at high energies (LEP, SLC/SLD, Tevatron) and low energies (atomic parity violation, Möller Scattering)
Standard Model with a light Higgs provides a good fit to all data, indirect determination of $H$ mass:

$M_H < 186$ GeV (95% c.l.)
The Standard Model (1960-70s)

- **Unified** description of weak and electromagnetic interactions in a single theory
- Small number of **input parameters** (just 3 in the electroweak sector)
- Numerous **predictions**, confirmed by experiment at the level of $\sim 0.1\%$

[Nobel prize 1979: Glashow, Salam, Weinberg]
16 different elementary particles have been observed in collider experiments: 12 “matter particles” and 4 “force particles”

Matter particles are further divided into leptons and quarks.

There are 6 leptons and 6 quarks: 3 “generations”, 2 leptons and 2 quarks in each.

Particles in each row (e.g. u, c and t quarks) are identical except for their masses: t is heavier than c, which is heavier than u.

(The Periodic Table - just like Chemistry, but much simpler and way cooler!)
Fixing the Problem with MVBs

• The Standard Model’s solution to this problem is the Higgs boson!

\[ \sigma \sim \frac{\alpha_w}{E^2_{c.m.}}, \quad E_{c.m.} \gg M_h \]

• If the Higgs boson exists and ..., unitarity is never violated - SM is a consistent quantum theory!

\[ M_h < 1 \text{ TeV} \]