Physics of the Large Hadron Collider

Lecture 2: New Physics at the LHC

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Outline

• Introduction: Problems with the Standard Model
• Solutions to the Hierarchy problem
  – Supersymmetry
  – Extra space dimensions
  – Little Higgs models
• Models without direct motivation: Hidden valleys, quirks
Problems with the Standard Model

1. The Hierarchy problem

- Discussed in the last lecture
- Top, W, Z and H loop corrections to Higgs boson mass quadratic in scale of new physics

\[ m_H^2 = m_{H0}^2 + \frac{3}{8\pi^2 v^2} \left( 4m_t^2 - 2m_W^2 - 4m_Z^2 - m_H^2 \right) \Lambda^2 \]

\[ \sim 100 \text{ GeV} \]

- To avoid fine-tuning, these loops must be canceled or cut off by new physics around 1 TeV

\[ M_{Pl} \sim 10^{18} \text{ GeV} \]
Problems with the Standard Model

2. Dark matter

- Only strong empirical evidence for New Physics
- Host of astronomical/cosmological observations indicate existence of non-baryonic, non-relativistic dark matter
  - Star movements in dwarf galaxies
  - Gravitational micro-lensing
  - Galaxy structure formation
  - Cosmic microwave background data favouring
    73% Dark energy – 22% Dark matter – 4.7% atoms
Problems with the Standard Model

2. Dark matter

- Most recent observation (Bradac et al):
The MACS J0025.4-1222 cluster collision

Luminous (X-ray-emitting) gas (stopped by collision)

Dark matter (deduced by gravitational lensing) (unaffected by collision)
Problems with the Standard Model

2. Dark matter

The “WIMP miracle”:

- Dark matter abundance (by equilibrium freeze-out) given by
  \[ \Omega_{\text{DM}} \propto \frac{1}{\langle \sigma_{\text{ann}} v \rangle} \propto \frac{M_{\text{DM}}^2}{\alpha_{\text{DM}}^2} \]

- Take \( M_{\text{DM}} \sim 100 \, \text{GeV} \) and \( \alpha_{\text{DM}} \sim \) weak coupling
  \( \rightarrow \) right abundance \( \Omega_{\text{DM}} h^2 \sim 0.1 \)

- Remarkable coincidence, strongly suggests that dark matter is tied to the weak scale
  - Should be possible to produce at the LHC!
There has been much excitement recently about a couple of anomalies in cosmic rays which might be attributed to Dark Matter annihilation or decay

- The ATIC excess in high-energy electron flux
- The PAMELA excess in positron/electron ratio

The interested reader is referred to the already vast literature
Problems with the Standard Model

3. Grand Unification

- For a time, it looked like the running couplings of the Standard Model gauge groups met at a scale $10^{15}$ GeV

- The idea of Grand Unification: The Standard Model $SU(3) \times SU(2) \times U(1)$ gauge group can be embedded in e.g. an $SU(5)$ or $SO(10)$ gauge symmetry, which is broken at the GUT scale
  - Running below this scale gives different values for the strong, weak and electromagnetic couplings
Problems with the Standard Model
3. Grand Unification

• However, more recently, turns out that the couplings “miss” each other (by too much to be explained only by GUT-scale thresholds)

• Can be fixed by new particles modifying the running
Classes of solutions

Model-building for New Physics has classically focused on the hierarchy problem

- Strongest argument for New Physics at the weak scale or ~1 TeV
- Dark Matter relatively recent + possible to explain by strongly coupled heavier matter (up to 100 TeV or so)
- GUT problem a matter of taste/belief (but intriguing that it is naturally solved by new particles at 1 TeV)
- Simultaneous solutions to all three problems attractive (Supersymmetry!)
Classes of solutions

Three main classes of solutions:

• **New symmetries protecting the Higgs mass**
  - Supersymmetry
  - Collectively broken global symmetries (Little Higgs)

• **Composite Higgs (Technicolor)**

• **Removing the hierarchy (new space dimensions)**
Supersymmetry

• New space-time symmetry (only possible enlargement of the Poincaré symmetry)
  – Addition of new “fermionic” symmetry operators
• Symmetry between bosons and fermions – ensures identical number of bosonic and fermionic degrees of freedom
  – All Standard Model particles have “partners” (spin-0 for fermions, spin-1/2 for gauge bosons and Higgs) with same quantum numbers and couplings
  – Two Higgs doublets, to cancel triangle anomaly and give mass to both up- and down-type fermions
### Supersymmetry

#### SM bosons:
- Gluon ↔ Gluino: $\tilde{g}$
- $W$ ↔ Wino: $\tilde{W}$
- B ↔ Bino: $\tilde{B}$
- Higgs ↔ Higgsino: $\tilde{h}$

#### SM fermions:
- Quark ↔ Squark: $\tilde{q}/\tilde{q}^*$
- Top ↔ Stop: $\tilde{t}$
- Bottom ↔ Sbottom: $\tilde{b}$
- Lepton ↔ Slepton: $\tilde{l}$

#### Mixing between charged winos and Higgsinos → Charginos
- Notation: $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$

#### Mixing between neutral wino, bino and Higgsinos → Neutralinos
- Notation: $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
Higgs mass corrections

Bosons and fermions give identical loop contributions but with different signs

→ Quadratic loop contributions exactly canceled

→ Higgs mass protected to all orders

\[ \Delta M_H^2 \sim m_t^2 - m_{\tilde{t}}^2 \]
Soft supersymmetry breaking

- No mass-degenerate superpartners seen at LEP or the Tevatron
  → Supersymmetry must be broken above weak scale

- Breaking must be in a way that preserves the cancellations of Higgs mass contributions

- Set of “soft breaking terms” allowed:
  Mass terms, scalar mixing terms and bi- and tri-linear scalar couplings
  - Minimal Supersymmetric Standard Model (MSSM) has 105 “soft” parameters (about ~20 relevant for the LHC)
SUSY breaking

• Supersymmetry breaking at the TeV scale not possible due to F-term breaking sum rule:

$$\sum m_{J=0}^2 - 2 \sum m_{J=\frac{1}{2}}^2 + 3 \sum m_{J=1}^2 = 0$$

• Solution: Assume SUSY broken in “hidden sector”, and breaking communicated to the MSSM by mediation sector.
SUSY breaking

• Natural idea for mediator: Gravity
  – Couples to all fields/sectors
  – Interactions $1/M_{Pl}$–suppressed
  – Natural in Supergravity scenarios (local/gauged SUSY)

• Minimal choice of mediation terms gives mSUGRA: 4 real parameters and 1 sign
  – 3 unified gaugino and scalar masses at GUT scale
  – Renormalization group running of masses to weak scale
  – By far most popular for experimental searches
SUSY breaking

Evolution of sparticle masses

- $M_3$
- $m_{\tilde{t}_R, \tilde{b}_L}$
- $m_{\tilde{t}_R}$
- $m_1$
- $M_2$
- $m_{\tilde{\tau}_L}$
- $m_{\tilde{\tau}_R}$
- $M_1$

Unified Higgs mass: $\sqrt{m_0^2 + \mu^2}$
Unified gaugino mass: $m_{1/2}$
Unified scalar mass: $m_0$
SUSY breaking

Mediation scenarios:

- Gravity mediation has intrinsic problems, esp. with flavor violation (flavor changing neutral currents)

- **Gauge mediation** solves these by postulating mediation by gauge couplings (flavor neutral). **Signature**: Decay of MSSM LSP to light gravitino

- **Anomaly mediation** is extreme version of gravity mediation, also without flavor violation. **Signature**: LSP is neutral wino, with long-lived chargino NLSP

- Many other scenarios with different mass spectra and (to some extent) signatures
Problems with the MSSM

- The lightest Higgs mass in supersymmetry: The SUSY relations, plus Electroweak symmetry breaking, gives

\[ m_{h_1} \lesssim m_Z \cos \beta \leq m_Z \]

at tree level – ruled out by the LEP experiment

- Avoided by loop contributions from the top-stop sector

\[
\Delta m_{h_1}^2 \sim \frac{3g^2 m_t^4}{8\pi^2 m_W^2} \left[ \ln \left( \frac{M_t^2}{m_t^2} \right) + \frac{X_t^2}{M_t^2} \right]
\]

- Can get \( m_h \) at most up to 135 GeV
Problems with the MSSM

- Electroweak symmetry breaking is dynamically generated by the soft mass parameters (in particular the stop mass).
- Therefore $W$ and $Z$ masses are directly related to the SUSY particle masses.
  - A large difference (as needed to get large lightest Higgs mass) indicates fine-tuning; About 1% needed for the MSSM.
  - Can be reduced in scenarios with extended Higgs sectors (e.g. NMSSM).
R-parity

- Naive SUSY gives proton decay and violation of baryon and lepton number
- Solved by introducing R-parity, under which SM particles are even and SUSY particles are odd
  - Lightest SUSY partner (LSP) stable
  - SUSY particles only pair-produced
- Neutral LSP (esp. zino/bino) gives excellent dark matter candidate (“the WIMP miracle”)
- R-parity violation possible if sufficiently small
SUSY signatures at the LHC

- Main production mechanism: squark/gluino pair production (since charged under QCD)
- Decay to LSP through decay chain
  - High-energy quarks from 1st decay, leptons from color singlet decays through sleptons
  - If R-parity conserved: Missing transverse energy carried away by LSP
  - Possibly charged long-lived NLSP (certain scenarios)
  - R-parity violation: LSP possibly long-lived, decays to SM particles (scalar 2-body, gaugino 3-body decays)
SUSY signatures at the LHC
Little Higgs theories

**Motivation:** New strong interactions severely constrained by precision measurements. Examples of lower limits for operators:

<table>
<thead>
<tr>
<th>Symmetry</th>
<th>Operators</th>
<th>Scale $\Lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B, L</td>
<td>$(QQQL)/\Lambda^2$</td>
<td>$10^{13}$ TeV</td>
</tr>
<tr>
<td>flavor (1,2\textsuperscript{nd} gen)</td>
<td>$(d\bar{s}d\bar{s})/\Lambda^2$</td>
<td>$10^3$ TeV</td>
</tr>
<tr>
<td>custodial SU(2)</td>
<td>$(h^\dagger D_k h)^2/\Lambda^2$</td>
<td>5 TeV</td>
</tr>
<tr>
<td>S-parameter</td>
<td>$(D^2 h^\dagger D^2 h)^2/\Lambda^2$</td>
<td>5 TeV</td>
</tr>
</tbody>
</table>

(hep-ph/0502182)

**“Little hierarchy problem”:** Tension between fine-tuning ($\Lambda < 1$ TeV) and precision ($\Lambda > 5$ TeV)
Little Higgs theories

Idea – find bosonic ("normal") symmetry to protect the Higgs mass up to 10 TeV (allowing for e.g. Technicolor at higher scales)

Let the Higgs be a pseudo-Goldstone boson

- Goldstone bosons massless remnant of spontaneously broken global symmetries
- Cf. pions in QCD – spontaneously broken chiral symmetry, mass generated by quark mass terms
- Only need protection from 1-loop contributions
Little Higgs theories

• Difficulty 1: Generate Higgs potential (mass and vacuum expectation value) without reintroducing quadratic mass corrections

• Difficulty 2: Generate gauge and fermion couplings in accordance with the Standard Model

• Must introduce (at least) two Higgs doublets and two separately broken symmetries, one of which is global and one which is gauged ("collective symmetry breaking")
Little Higgs theories

• Then, 1-loop diagrams involving only one gauge coupling do not contribute to Higgs mass

• Diagrams with two couplings give non-zero Higgs potential and can give EW symmetry breaking

\[ \phi_2 \quad g_2 \quad \phi_2 \]

\[ \phi_1 \quad g_1 \quad \phi_1 \]

EW+new gauge bosons

• Three scales:
  \[ \Lambda \sim 4\pi f \sim (4\pi)^2 M_{\text{weak}} \]

Cutoff \quad Symm. breaking
Little Higgs theories

Top quark quadratic divergence:

- Need fermionic partner $T$ to the top quark
- Global symmetries require special form for the $T$ coupling to Higgs which cancels the 1-loop top contribution to the Higgs mass:

\[
\frac{\lambda_t^2}{16\pi^2} \Lambda^2 h^\dagger h + \frac{\lambda_t^2 f^2}{16\pi^2} \left(1 - \frac{h^\dagger h}{f^2}\right) \Lambda^2 = \text{constant} + O(h^4)
\]
Phenomenology of Little Higgs

• Common for all Little Higgs theories:
  – New top quark partner(s)
  – New gauge symmetries and vector bosons

• Can add T-parity
  – Improved precision limits, get dark matter candidate
  – Need partners for all fermions, but not gluon
  – Decay chains to LTP, similar to SUSY
  – Top partner t-even, decaying to b W
    – pair produced or single produced (like top quark)
Extra space dimensions

Instead of protecting the Higgs mass – remove the hierarchy!

• If there are extra space dimensions where gravity can propagate but not SM fields, gravity would appear weak due to dilution:

\[ V(r) \sim \frac{m_1 m_2}{M_D^{n+1}} \frac{1}{R^n} \frac{1}{r} \quad (r \gg R) \implies M_{Pl}^2 \sim M_D^{2+n} R^n \]

• At distances smaller than R, gravity is modified:

\[ V(r) \sim \frac{m_1 m_2}{M_D^{n+1}} \frac{1}{r^{n+1}} \quad (r \ll R) \]
Extra space dimensions

- Size of extra dimensions with $M_D \sim 1$ TeV
  
  $n=1$ \hspace{10pt} $R=10^{11}$ m (solar system size)
  
  $n=2$ \hspace{10pt} $R=0.1$ mm
  
  $n=3$ \hspace{10pt} $R=10$ Å
  
  $n=4$ \hspace{10pt} $R=0.01$ Å

- Non-Newtonian gravity excluded down to 10 microns (arXiv:0802.2350) $\rightarrow n > 2$
Implications of large extra dimensions

Graviton Kaluza-Klein excitations due to compactified extra dimensions

- Splitting between graviton states of order $1/R^n$
- Rate of single graviton emission in process $\propto 1/M_{Pl}^2$
  
  but combined rate $\sim (\Delta E R)^n/M_{Pl}^2 \sim \Delta E^n/M_{Pl}^{2+n}$

  $\rightarrow$ Total production rate not Planck-suppressed

- Similarly, coherent exchange of tower of virtual gravitons in SM pair production not suppressed
  - modify cross sections and angular distributions

- Tevatron limits on $M_D$: 1000-800 GeV for $n=2-8$
Implications of large extra dimensions

\[ \gamma + E_T \quad \text{for } n=2, \quad M_D = 2.5 \, \text{TeV} \]

Top pair invariant mass spectrum, LHC

CMS Physics TDR

Frederix, Maltoni
arXiv:0712.2355
Randall-Sundrum

Alternative to large extra dimensions:

• Small (TeV-scale) extra dimension with strong negative curvature
  – Strength of gravity exponentially suppressed due to exponentially small wavefunction overlap with Standard Model fields
  – Weak scale again the only fundamental scale

• Setup:
  – Two 3D branes: IR brane and UV brane
  – Extra dimension orbifolded, $-\phi \rightarrow \phi, -\pi < \phi < \pi$
Randall-Sundrum

IR/TeV brane (Hidden sector)
$M_{Pl} \sim 1 \text{ TeV}$

UV/Planck brane (SM fields)
$M_{Pl} \sim 10^{15} \text{ TeV}$

$d s^2 = e^{-2k r_c \phi} \eta_{\mu \nu} d x^\mu d x^\nu - d \phi^2$

$e^{k r_c \pi} \sim 10^{15}$
Randall-Sundrum

- Kaluza-Klein graviton excitations with $\Delta M \sim \text{TeV}$
  - Weak scale, universal coupling to Standard Model particles
  - Visible as series of resonances at the LHC

Frederix, Maltoni
arXiv:0712.2355
Bulk RS models

- Possibility to allow SM particles to propagate in the extra dimension
  - Naturally gives mass hierarchies in the SM from wave function localization (next slide)
  - Kaluza-Klein excitations of Standard Model particles
  - Couple according to wave function overlap
  - KK modes localized to Higgs brane
    → Couplings to top quarks dominate for all gauge KK modes
Bulk RS models

Higgs brane

Hidden brane

Mass of fermion determined by overlap with Higgs brane, parameterized by mass parameter $c_f$

Exponential wave functions - masses randomly distributed in logarithmic chart (no large hierarchy in exponent)

Exception: Neutrinos (need see-saw mechanism)
Other ideas for New Physics

Many possibilities for New Physics not directly motivated by the hierarchy problem, but inspired by effective descriptions of GUT physics or string theory – or just that they are allowed...

- New massive vector bosons (Z', W')
- New fermion generations / vector-like quarks
- Unparticles
- Hidden valley scenarios
- Universal extra dimensions
Unparticles

- Fields in a conformal, i.e. scale-invariant, sector, would have continuous mass spectrum
- Communication between hidden sector and the SM by heavy mediator fields
- Direct production looks like production of non-integral number of invisible particles
- Virtual exchange might modify di-particle distributions through interference
- The interested reader is referred to the already large literature
Hidden valley models

- Possible that there are hidden sectors with relatively light particles, but communication with Standard Model only through heavy states (Z')

Matt Strassler
Hidden valley models

• Possible that there are hidden sectors with relatively light particles, but communication with Standard Model only through heavy states (Z')

• If there are confining forces (similar to QCD) in the hidden valley, we might get spectacular signatures
  – Production of Valley quark pairs, which radiates Valley gluons and hadronizes, giving many light Valley hadrons, which decay to SM particles
  – Large multiplicities of relatively soft SM particles, perhaps with large missing energy
Hidden valley models

- Possible that there are hidden sectors with relatively light particles, but communication with Standard Model only through heavy states ($Z'$)
- If there are confining forces (similar to QCD) in the hidden valley, we might get spectacular
Universal Extra Dimensions

- Flat extra dimensions where all Standard Model particles are allowed to propagate, naturally have a Kaluza-Klein parity, disallowing any vertex with only one KK state
- Limit on size of extra dimensions around 1 TeV
- Doesn't solve the hierarchy problem, but has a phenomenology very similar to SUSY
  - Acting as a “same-spin strawman” in studies investigating the possibility to distinguish spins of New Physics particles with missing energy signatures
Universal Extra Dimensions

- Flat extra dimensions where all Standard Model particles are allowed to propagate, naturally have a Kaluza-Klein parity, disallowing any vertex with only one KK state

\[ A^\pm = \frac{\langle \sigma(b \bar{l}) \rangle}{\langle \sigma(b \bar{l}) \rangle/\text{sum}} \]

\[ m_{\ell^\pm} \geq 350 \text{ [GeV]} \]

Alves et al. hep-ph/0605067
Summary and plan

Today I have talked about:

- Problems of the Standard Model
  - The hierarchy problem
  - Dark matter
  - Grand unification

- Solutions to the Hierarchy problem
  - Supersymmetry
  - Little Higgs theories
  - Extra space dimensions: ADD and Randall-Sundrum

- Some “unmotivated” ideas for New Physics
Summary and plan

Next lecture:
Simulation, signatures and backgrounds at the LHC
- Steps for physics simulation at the LHC, simulation tools
- Most important Standard Models backgrounds
- Simulation of QCD radiation
- New Physics signatures, in particular Supersymmetry-like signatures
Suggested reading

• Supersymmetry:

• Little Higgs theories:
Suggested reading

• Large extra dimensions

• Randall-Sundrum:
Suggested reading

• Unparticles:

• Hidden Valley models

• Universal Extra Dimensions