• The Standard Model
• The Plot
• Collecting Evidence
• A Suspect
  • SUSY (very little on that today)
• A Simple Observation
• Parity
• Extra Dimensions
The Standard Model in Words

- Matter is built of spin 1/2 particles that interact by exchanging 3 different kinds of spin 1 particles corresponding to 3 different (gauge) interactions.
- The matter fermions and the weak bosons have “mass”.
- There appear to be 3 generations of matter particles.
- The 4 different matter particles in each generation carry different combinations of quantized charges characterizing their couplings to the interaction bosons.
- Gravitation is presumably mediated by spin 2 gravitons.
- Gravitation is extremely weak for typical particle masses.
- There appear to be 3 macroscopic dimensions.
About the Standard Model

- It’s a theory of interactions:
  - Properties of interaction bosons in terms of couplings, propagations, masses are linked:
    - Measuring a few allows us to predict the rest, then measure and compare with expectation
  - Properties of fermions are inputs

- It’s remarkably successful:
  - Predictions verified to be correct at sometimes incredible levels of precision
  - After ~30 years, still no serious cracks

- But no information about the nature of particles
Many Fundamental Questions

• What exactly is spin? Or color? Or electric charge? Why are they quantified?
• Are there only 3 generations? If so, why?
• Why are there no neutral, colored fermions?
• What is mass? Why are particles so light?
• Is there a link between particle and nucleon masses?
• How does all of this reconcile with gravitation? How many space time dimensions are there really?
• …
The Plot
Vector Boson Scattering

- There is in fact one known problem with the standard model:
  - If we collide W’s and Z’s (not so easy...), the scattering cross-section grows with the center of mass energy, and gets out of control at about 1.7 TeV
- This is similar to “low” energy neutrino scattering:
  - If $q^2 << (M_W)^2$, looks like a “contact interaction”, and cross-section grows with center of mass energy
  - But when $q^2 \approx (M_W)^2$, W-boson propagation becomes visible, and “cures” this problem
One way to solve the VBS problem, is to introduce a massive, spinless particle (of mass < ~1 TeV)

- Couplings to W and Z are fixed, quantum numbers are known...
- .... to be those of the vacuum
- Its mass is unknown, and its couplings to the fermions are unknown.... well, maybe
  - Fermions can acquire mass by coupling to this Higgs boson, so their couplings could be proportional to their masses. This is called the “standard model Higgs”
Precision Measurements

- If so, we can say something about the standard model Higgs mass
- If the fermions get their mass from the Higgs, we know all couplings and can infer the Higgs mass from precision measurements
- Result is very sensitive to measured top quark, W boson masses
  - Really wants a “light” Higgs boson
Higgs Drawbacks

- In principle, with the addition of a Higgs boson around 150 GeV particle physics could be “complete”
  - Like Mendeleev’s table for chemistry

- But by itself, the Higgs is very unsatisfactory:
  - Why are the couplings to the fermions what they are?
    - Dumb luck (aka landscape)?
  - What is the link to gravity?
  - Why does the Higgs break the symmetry?
  - Why are there 3....?
The Plot Thickens
Higgs Mass

- Higgs, in fact, also acquires mass from coupling to W’s, fermions, and itself!
- These “mass terms” are quadratically divergent
- Drive mass to limit of validity of the theory
- So we expect the Higgs mass to be close to the scale where new physics comes in....
Collecting Evidence
DØ at the Tevatron

- Tevatron: 1.96 TeV center of mass proton-antiproton collider
  - Run I in early 90’s led to the discovery of the top quark
  - Run II since 2001 has led to lots of interesting results, but no Higgs seen yet
  - Main focus is the Higgs search now
ATLAS and the LHC

- 14 TeV proton - proton
- Start operations in 2008
  - Compared to Tevatron:
    - Production cross-sections increase by 1-2 orders of magnitude for ~100 GeV objects
    - 100x luminosity
  - Superior detectors
LHC Schedule

Sector 5-6: cooldown ongoing

Sector 4-5: thermal instability prevented ramping to more than 8.5 kA (12 kA needed for 7 TeV)
A Suspect
Supersymmetry

- Symmetry between bosons and fermions: for each boson/fermion, there is an associated fermion/boson

- Fermionic and bosonic loop corrections to the Higgs mass cancel each other: Higgs mass is naturally at the “electroweak scale” provided SUSY partners exist at that mass

- String theory wants SUSY, but not necessarily at the electroweak scale
Good SUSY, Bad SUSY

- SUSY has a number of attractive features
  - “Explanation” for low Higgs mass, and EWSB
  - Gauge coupling unification
  - Dark matter candidate (but R-parity is ad hoc)
  - No new interactions

- But answering those questions comes at a large cost
  - Many new particles, with masses and mixing angles
  - Need to explain why SUSY mass scale is so low (or high)
  - Do away with the mystery of spin?
A Simple Observation
Inside a generation, the more a fermion interacts, the heavier it is

(Of course, we don’t know that the $\tau$-$\nu_\tau$ lepton generation doesn’t really match up with the d-u quark generation)

Pattern suggests fermion masses might be related to a more complex mechanism

Indirect relation to interactions?

Higgs may then only be relevant for VV scattering, relaxing mass constraints
Spin & Mass

- Problem with mass is that it allows a particle to change helicity
  - And, of course, since parity is maximally violated in weak interactions, this “breaks the symmetry”
  - Deeper understanding of spin as useful to making progress as a Higgs observation

→ Scenario of restoration of parity might lead to understanding of fermion masses
  - No necessarily strict left-right...
Parity
Parity Restoration: Signals

- Primary signals are (right-handed) $W'$, $Z'$

- Dilepton resonances offer clean signals, well-understood backgrounds
  - At LHC, some concern about extrapolation of calibration from $Z$ to very high energies

- Electron/muon resolution improves/degrades with $p_T$

- $tt$ decays visible (maybe)

- $\nu_R$ is presumably heavy, $W'$ may only decay to quarks
  - If $\nu_R$ lighter than $W'/Z'$, $\nu_R$ decays become important

- Note: many kinds of $Z'$ - recent review by Langacker
Z’ Production and Decay

- Production from u, d quarks is dominant at LHC
- Couplings vary by model
- E.g. for LR symmetric models, $\kappa = g_R/g_L$ drives production cross-section (convolute with PDFs) and branching ratios
- Decays somewhat similar to Z (but almost no BR to light neutrinos, decays to top open up), plot assumes $\nu_R$ heavier

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T. Rizzo, hep-ph/0610104

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ATL-PHYS-PUB-2005-010
Z’ → ee

- Most promising channel:
  - At Z’ masses, energy resolution dominated by constant term
    - 10 GeV for 1.5 TeV electron
    - Could measure width!
  - Extend Tevatron reach as soon as understand data
    - Backgrounds very low!
  - Study currently being updated with best full simulation

- SSM Z’, ~100 fb⁻¹
- SSM Z’, ~1 fb⁻¹
Z’ → μμ: Early Potential

- CMS 1 TeV Z_{η} study
  - Narrower than SSM (7 vs 31 GeV), but dominated by detector anyway
  - Cross-section 2-3 times smaller than SSM
  - Note: statistics scaled down, so fluctuations “not to scale”

CMS TDR
“Early Alignment”
100 pb^{-1}

New ATLAS Result Soon
Z’ → μμ Reach

- 5σ discovery reach
- Systematics don’t change these results much
- 2-3 TeV with 1 fb⁻¹
- 3-4 TeV with 10 fb⁻¹
- Again, assumes no “exotic” decays
- Discovery reach about 700 GeV below 95% CL limit at highest masses
“Look Elsewhere” Effect

- If search is done by counting experiment in a shifting mass window, need to factor in “look elsewhere” effect
  - CDF does this

- Global fit to the DY spectrum is a better approach
  - Shape analysis more sensitive
  - No look elsewhere problem if single global fit
Spin Determination

- Look at angle between lepton and beam direction
- Spin 1 particles tend to emit leptons closer to beam
- Plot is potentially optimistic: sensitivity is in the forward region where lepton identification is not nearly as efficient or pure
Model Determination

- Angular distribution gives excellent handle on $g_V$, $g_A$ for various fermions
- Charm may be possible
- This will come after an initial determination of branching ratios (obviously)
- Complementary information in determining nature of resonance
Z'/W' → jj

- In the dijet channel, the backgrounds are obviously much larger

- But not necessarily unmanageable: DØ published a Run 1 search for resonances in the dijet channel

(PRD Rapid Comm. {69}, 111101 (2004))
If $\nu_R$ is light, lepton and jets collimated → leptons embedded in merged jets

- If $\nu_R$ is lighter than $m(Z')/2$, decay channel opens up
- $\nu_R$ subsequently decays to $lW_R^*$ (assuming $W_R$ is heavier than $\nu_R$), leading to signature with two leptons and 4 jets
- Or other combinations if $m(\nu_R') < m(\nu_R)$, for example more leptons
- Since $\nu_R$ is majorana, can get same-sign leptons!
$Z' \rightarrow \nu_R \bar{\nu}_R (2)$

- Backgrounds include $t\bar{t}$, $ZZ$, ... + jets, but also $W_R$!

Reconstruction of $\nu_R$ (ejj) and $Z'$ (eejjjj) masses

Discovery Potential

$\text{ATLAS, } L_{\text{int}} = 300 \text{ fb}^{-1}$

$\text{m}(Z') \leq 2\text{m}(N_e)$

$\text{m}(N_e) = \text{m}(N_\mu) = \text{m}(N_\tau)$

2 isolated electrons + 4 jets

2 jets with EM activity
W’ Production

- W’ production rate not very dependent on couplings
- But interference with W important (and not in experimental studies)!
- Key in identifying W’ coupling helicity in fact
  (T. Rizzo, hep-ph/0704.0235)
- (This plot is for e+MET transverse mass, which may not be a signature)
\[ W' \rightarrow \mu \nu_R \]

- **SSM W’**
  - “Standard” \( M_T \) plot
- **Discovery reach \( \sim 4.5 \) TeV with 10 fb\(^{-1}\)**
- **Similar reach with electrons**
  - Note very different resolution effects in electrons vs muons
- **Decay does not necessarily exist!**
**W’ → tb**

- ATLAS fast simulation study
  - Use of very high $p_T$ b-tagging
    - B meson decays *outside* first pixel layer!
    - High $p_T$ top (more later)
  - Overall, could already make a (BR) statement very early on

**Note:** This is for $W_H$ from Little Higgs

ATL-PHYS-PUB-2006-003

30 fb$^{-1}$
• Require at least one of the $W$, $Z$ to decay leptonically to suppress backgrounds

• Then use mass constraints to improve S/B further

• Cleanest channel is obviously when both decay leptonically (but BR only 1.4%)

• LR model study by ATLAS

• (Also a technicolor signature, probably at lower mass)
If allow one boson to decay hadronically, higher BR (4.6/15%) but higher backgrounds

Hadronically decaying boson has large boost, so jets are merged → rely on jet mass

W/Z + jets background not well known
Exotic Quarks

- In most cases, existence of a Z’ requires existence of new fermions to cancel anomalies
- Exotic leptons or quarks
- Quarks could be pair-produced, then decay
  - D → Zd, D → Wu
  - Then require one or both W/Z to decay leptonically
Extra Dimensions
Extra Dimensions

A promising approach to quantum gravity consists in adding extra space dimensions: string theory.

Additional space dimensions are hidden, presumably because they are compactified.

Radius of compactification usually assumed to be at the scale of gravity, i.e. $10^{18}$ GeV.

In the late 90’s people realized they may be much larger.
“ADD”

- Original “large extra dimension” scenario (developed by Arkani-Hamed, Dimopoulos and Dvali):
  - Standard model fields are confined to a 3+1 dimensional subspace (“brane”)
  - Gravity propagates in all dimensions
  - Gravity appears weak on the brane because only felt when graviton “goes through”

Drawing by K. Loureiro
ADD Signatures

- Edges of extra dimensions identified
  - Boundary conditions
  - Momentum along extra dimension is quantified
- Looks like mass to us
- Very small separations $\rightarrow$ looks like continuum
- Called Kaluza-Klein tower

- Coupling to single graviton very weak, but there are *lots* of them!
- Large phase space $\rightarrow$ observable cross-section
  - Impacts all processes (graviton couples to energy-momentum)
Consider processes that involve the bulk (i.e. gravitons)

- Translational invariance is broken
  - Momentum is not conserved ...
  - ... because graviton disappears in bulk right away

- Look for $p p \rightarrow$ jet + nothing (i.e. $E_T$), or deviations in high mass/angular behavior in standard model processes

- Graviton has spin 2!

- Limit size of ED at $\sim 1$ TeV
Warped Extra Dimensions

• “Simple” Randall-Sundrum model:
  • SM confined to a brane, and gravity propagating in an extra dimension
  • As opposed to the original ADD scenario, the metric in the extra dimension is “warped” by a factor $\exp(-2kr_c\phi)$
  • (Requires 2 branes)
Hierarchies

Physics on a curved gravitational background:

- Scales depend on position along extra dimensions

  - UV brane scale is $M_{Pl} = 2 \times 10^{18}$ GeV
  - IR brane scale is $M_{Pl} e^{-kL} \sim 1$ TeV if $kL \sim 30$
  - If were to localize Higgs on IR brane, naturally get EW scale $\sim 1$ TeV (from geometry!)
Flavor

- Interesting variation has fermions located along the extra dimension
  - Fermion masses generated by geometry
  - Heavier fermions are closer to IR brane, and gauge boson excitations as well
    - Gauge boson excitations expected to have masses in the 3-4 TeV range (bounds from precision measurements)
  - Flavor changing determined by overlap of fermion “wave function” in the ED
    - Nice suppression of FCNC etc.
Gauge Boson Excitations

- Excitations of the gauge bosons are very promising channels for discovery
- Couplings to light fermions are small
  - Small production cross-sections
- Large coupling to top, $W_L$, $Z_L$
  - Look for $t\bar{t}$, $WW$, $ZZ$
    resonances (that can be wide)

B. Lillie et al., JHEP 0709:074, 2007
New Experimental Phenomenology

- Possibility to produce heavy resonances decaying to top quarks, W and Z bosons
  - Heavy objects with momentum $>>$ mass
    - Decay products collimated
  - For leptonic W/Z decays, not a big issue since we measure isolated tracks very well
  - But hadronic decays lead to jets, which are intrinsically wide
Top Quark Decays

- Simulated decays:
  - $dR = \sqrt{(\Delta \eta^2 + \Delta \phi^2)}$
  - Typical jet radius $\sim 0.5$
  - LHC calorimeters have granularity $0.1 \times 0.1$ or better
- For top $p_T > \sim 200$ GeV
  - $dR$ (qq from W) $< 2 R_{jet}$
  - $dR$ (bW) $< 2 R_{jet}$
  - (No isolated lepton!)

![Graph 1: dR b-W vs top pT](image1)

![Graph 2: dR qq (from W) vs top pT](image2)
Jet Structure

- Decay hadrons reconstructed as a single jet
  - But even if it looks like a single jet, it originates from a massive particle decaying to 2/3 hard partons, not one
  - If I measured each of the partons in the jet perfectly, I would be able to:
    - Reconstruct the “originator’s” invariant mass
    - Reconstruct the direct daughter partons
- But
  - quarks hadronize -> cross-talk
  - my detector can’t resolve all individual hadrons
“YSplitter”

- kT jet algorithm is much better suited to understand jet substructure than cone:
  - Cone maximizes energy in an $\eta \times \phi$ cone
  - kT is a “nearest neighbor” clusterer

$$y_2 = \min \left( E_a^2, E_b^2 \right) \cdot \theta_{ab}^2 / p_T^{2(jet)}$$

$$Y \text{ scale } = \sqrt{p_T^{2(jet)} \cdot y_2}$$

- Can use the kT algorithm on jet constituents and get the y-scale at which one switches from 1 $\rightarrow$ 2 ($\rightarrow$ 3 etc.) jets
  - scale is related to mass of the decaying particle
Applied to high $p_T$ WW scattering:

- $k_T$ jet algorithm, with $R = 0.5$
- Cuts applied: $p_T(jet) > 300$ GeV,

What about top?
Z' → tt

ATLAS Preliminary

M(Z') = 2 TeV
M(Z') = 3 TeV

Jet pT (GeV)

Jet Mass (GeV)

Number of Jets

YScale 1-2 (GeV)

YScale 2-3 (GeV)

YScale 3-4 (GeV)
- All distributions drop off exponentially, as expected
- Look at correlations to separate signal & background
Correlations

- In principle, multivariate tool is the best choice
  - But then want to optimize for a particular signal
- Here, chose to take a more conservative approach:
  - 2-D cuts, get good S/B over large top “monojet” $p_T$ range
Example Cuts

- Cuts in:
  - jet mass vs $p_T$
  - YScale 1-2 vs YScale 2-3
  - YScale 2-3 vs YScale 3-4
  - YScale 1-2 vs jet mass
  - YScale 2-3 vs jet mass
  - YScale 3-4 vs jet mass
- Optimized “by eye”
**Result**

![Efficiency Curve](image)

### Efficiencies

<table>
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<th>Jet $p_T$ (GeV)</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>1000</th>
<th>1100</th>
<th>1200</th>
<th>1300</th>
<th>1400</th>
<th>1500</th>
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<tr>
<td>Top Samples (%)</td>
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<td>19</td>
<td>32</td>
<td>37</td>
<td>47</td>
<td>45</td>
<td>56</td>
<td>64</td>
<td>63</td>
<td>68</td>
<td>74</td>
</tr>
<tr>
<td>Background Samples (%)</td>
<td>0.1</td>
<td>0.5</td>
<td>1.3</td>
<td>2.5</td>
<td>4.2</td>
<td>4.7</td>
<td>7.1</td>
<td>7.4</td>
<td>9.8</td>
<td>12.8</td>
<td>10.2</td>
</tr>
</tbody>
</table>
So Much More....

- Many other interesting models/signatures
  - Technicolor
  - UED, 6DSM
  - Heavy top/bottom partners with charge 5/3, 2/3, -1/3
- Some interesting studies made at Les Houches
  - Proceedings out soon
- Of course, with real data it’s all a lot harder
Conclusions

- We have strong reason to believe something is on the horizon
  - Hopefully something more interesting than a Higgs boson
- Many possibilities beyond the Higgs
  - With SUSY we may not gain much knowledge
  - Other models may tell us more about the origin of particle properties
- But be patient... it’s probably not right around the corner (of course, the c.o.m. increase at LHC is spectacular)