Searches For New Physics

Gustaaaf Brooijmans

Meeting of the Division of Particles and Fields of the American Physical Society
University of California, Riverside
2004
I apologize

Too Much To Talk About

• I'd like to cover
  – Direct searches, indirect searches and future prospects

• Sounds simple enough, but looking at the parallel session agendas...
  – 31 talks in “Direct Searches”
  – 10 talks in “Muon g-2, LFV, EDMs”
  – 9 talks in “LHC-LC Comparison”
  – 43 talks in non-top “Heavy Flavor Physics”
The Standard Model in Words

- Matter is built of spin ½ particles that interact by exchanging 3 different kinds of spin 1 particles corresponding to 3 different (gauge) interactions.
- There are 3 generations of matter particles.
- The 4 different matter particles in each generation carry different combinations of (quantified) charges characterizing their couplings to the interaction bosons.
- The matter fermions and the weak bosons have “mass.”
- Gravitation is presumably mediated by spin 2 gravitons.
- (There appear to be 3 macroscopic space dimensions.)
Many Fundamental Questions

- What exactly is (weak iso)spin? Or color? Or electric charge? Why are they quantified?
- Are there only 3 generations? If so, why?
- Why is there no matter that doesn't interact weakly?
- What is mass?
- How does all of this reconcile with gravitation? How many space-time dimensions are there really?
- Is “our universe” the unique solution?
The One We Think We May Have a Handle On: Mass

- The addition of a naïve $M^2WW$ mass term to generate the gauge boson masses (luckily) not only breaks gauge invariance, but also destroys renormalizability of the Standard Model
  - At high energy ($\sqrt{s} \sim 1.7$ TeV), $W_L W_L$ scattering violates unitarity

- An elegant solution is provided by the Higgs mechanism: the “Standard Model Higgs” generates both boson and fermion masses, and “restores” unitarity (if $m_H < \sim 1$ TeV).
**Standard Model Higgs Mass**

- Yellow shaded: excluded by LEP2 direct search ($m_H > 114.4$ GeV @ 95% CL).
- Curve: $m_H$ inferred from precision measurements, very sensitive to $m_{top}$, $m_W$ (best fit value shifted up ~18 GeV with 4 GeV increase in $m_{top}$ – DØ, Nature 429: 638, 2004)
Prospects for SM Higgs Discovery

- Tevatron Higgs sensitivity study redone in 2003 with better knowledge of detector performance, 1999 results confirmed

- Detection through production of WH or ZH, leptonic W/Z decay and H decay to $b\bar{b}$

8 fb$^{-1}$ by early '08
SM Higgs at the LHC

- If there is a Higgs with “Standard Model properties”, discovery at LHC is “certain”

- Measurement of properties:

Duehrssen et al., hep-ph/0407190

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The LHC is Real!

Real Magnets in Tunnel!

Atlas Cavern

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Studying The Higgs at a LC

- **Couplings:**
  - b: <1 - 10% for $m_H = 115-200$ GeV
  - c, tau: 12% for $m_H < 160$ GeV
  - t: through $t\bar{t}H$ production (10-20%, as LHC) for $m_H < 350$ GeV
  - W: 2 – 0.5% for $m_H = 115-200$ GeV
  - photon: 5 – 25% for $m_H = 115-200$ GeV
  - Z: 1% at $m_H = 200$ GeV

- **Spin:**
  - (Angular distributions in) decays
  - Production cross-section

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Dawson & Oreglia
hep-ph/0403015

Dova, Garcia-Abia and Lohmann
hep-ph/0302113
Higgs Drawbacks

- Higgs by itself is very unsatisfactory:
  - Why are the Yukawa couplings what they are?
  - What is the link to gravity?
  - Why exactly is $(\mu)^2$ negative?

- Higgs mechanism introduces new problems (or benefits):
  - Higgs mass is “naturally” the next energy scale, so if we have a “Standard Model Higgs”, that's about 200 GeV

- Two approaches:
  - Fix by addition (SUSY, ... at ~ 200 GeV – 1 TeV)
  - Fix by subtraction (forget about Higgs)
Low Scale Supersymmetry

- For each boson/fermion, there is an associated fermion/boson
  - All quantum numbers (except spin), and all couplings are the same, masses appear to be different
  - Then, what is spin?
- Fermionic and bosonic loop corrections to the Higgs mass cancel each other, so Higgs mass is \( \sim \)SUSY mass scale
- Requires 2 Higgs doublets, get 5 physical Higgses
Minimal Supersymmetric SM

- Minimally constrained means 105 parameters (superpartner masses, mixing angles,...)

These analyses assume LSP is the lightest neutralino, process BR

- LEP, D0 limits on stop and sneutrino mass assuming stop $\rightarrow b\ l$ sneutrino
- CDF limits on gluino and sbottom mass assuming gluino $\rightarrow$ sbottom bottom

![Graph showing LEP, D0 limits on stop and sneutrino mass](image1)
![Graph showing CDF limits on gluino and sbottom mass](image2)
SUSY Breaking

- Sparticle masses are different from particle masses, so SUSY must be broken
- Various breaking models, with different phenomenological signatures

Explain Electroweak Symmetry Breaking! (Mass!)

Barger et al., hep-ph/0003154
SUpGrAyvity

- SUSY breaking is transmitted from a hidden sector through gravity – this reduces the number of free parameters to 5 (in mSUGRA)

**LEP combined lower bound on neutralino mass in SUGRA-like model**

(LEPSUSYWG/04-07.1)

<table>
<thead>
<tr>
<th>m(χ^0_1) (GeV/c^2)</th>
<th>σ × BR(3l) [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤ 1 TeV/c^2</td>
<td>2.2</td>
</tr>
<tr>
<td>m_{top} = 178 GeV/c^2</td>
<td>2.0</td>
</tr>
<tr>
<td>m_{h} = 175 GeV/c^2</td>
<td>1.8</td>
</tr>
</tbody>
</table>

**D0 bound on associated chargino-neutralino production in mSUGRA**

(Trileptons: “Golden” channel at Tevatron)

147-249 pb

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Gauge Mediated Susy Breaking

- SUSY breaking messengers participate in SM gauge interactions, LSP is a very light gravitino so phenomenology is driven by NLSP

LEP combined slepton and bino NLSP


Example: N=2, medium M, $\mu > 0$, short lifetime

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D0 bino NLSP

**Run II Preliminary**

$N_L = 1$

$M_L = 2 \Lambda$

$\tan \beta = 5$

$\mu > 0$

185 pb$^{-1}$

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"The" CDF Run 1 Event
Always at least one of 5 physical Higgses observable

- At large $m_A$, distinguishing SUSY from SM based on Higgs alone is difficult, but in that region, other SUSY signatures are usually present
SUSY at the LHC - Sparticles

- Plethora of signatures
  - Jets + missing ET
  - Trileptons
  - ...

- Detect cascade decays of heavier particles, with LSP escaping -> use endpoints of kinematic distributions to determine masses

Atlas Physics TDR, 10 fb⁻¹
SUSY Measurements

• If there is low-scale SUSY, it will be discovered at the LHC, then move to measurement phase
  – Verify it is SUSY (measure couplings and quantum numbers)
  – Measure pattern of sparticle masses, deduce the pattern of SUSY breaking

• How much of this will be accessible at the LHC and, later, LC depends on the sparticle masses themselves
LHC vs LC

- LC obviously gives better precision (ingoing longitudinal momentum is known)

<table>
<thead>
<tr>
<th>LHC: llq mass (squark decay)</th>
<th>LC: lepton spectrum (slepton decay)</th>
</tr>
</thead>
</table>

Allanach et al., hep-ph/0403133

At LC, can also perform threshold scans
Comparison For Snowmass Pt 1a

- LC clearly improves mass determination
- But SPS point 1a is very good for the LC (masses are \( \sim \)low):

\[
\begin{array}{|c|c|c|c|c|}
\hline
& \text{Mass, ideal} & \text{“LHC”} & \text{“LC”} & \text{“LHC+LC”} \\
\hline
\tilde{\chi}_1^{\pm} & 179.7 & - & 0.55 & 0.55 \\
\tilde{\chi}_2^0 & 382.3 & - & 3.0 & 3.0 \\
\tilde{\chi}_1^0 & 97.2 & 4.8 & 0.05 & 0.05 \\
\tilde{\chi}_2^0 & 180.7 & 4.7 & 1.2 & 0.08 \\
\tilde{\chi}_3^0 & 364.7 & - & 3.5 & 3.5 \\
\tilde{\chi}_4^0 & 381.9 & 5.1 & 3.5 & 2.23 \\
\tilde{\epsilon}_R & 143.9 & 4.8 & 0.05 & 0.05 \\
\tilde{\epsilon}_L & 207.1 & 5.0 & 0.2 & 0.2 \\
\tilde{\nu}_e & 191.3 & - & 1.2 & 1.2 \\
\tilde{\mu}_R & 143.9 & 4.8 & 0.2 & 0.2 \\
\tilde{\mu}_L & 207.1 & 5.0 & 0.5 & 0.5 \\
\tilde{\nu}_\mu & 191.3 & - & - & - \\
\tilde{\tau}_1 & 134.8 & 5.8 & 0.3 & 0.3 \\
\tilde{\tau}_2 & 210.7 & - & 1.1 & 1.1 \\
\tilde{\nu}_\tau & 190.4 & - & - & - \\
\tilde{q}_R & 547.6 & 7-12 & - & 5-11 \\
\tilde{q}_L & 570.6 & 8.7 & - & 4.9 \\
\tilde{t}_1 & 399.5 & 2.0 & - & - \\
\tilde{t}_2 & 586.3 & - & - & - \\
\tilde{b}_1 & 515.1 & 7.5 & - & 5.7 \\
\tilde{b}_2 & 547.1 & 7.9 & - & 6.2 \\
\tilde{g} & 604.0 & 8.0 & - & 6.5 \\
\hline
\end{array}
\]

\( \text{in GeV} \)

\[ H^\pm, A^0, H^0, \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\tau}_2^0, \tilde{\nu}_\tau, \tilde{\nu}_e, \tilde{\epsilon}_L, \tilde{\epsilon}_R, \tilde{\nu}_\tau, \tilde{\nu}_e \]

Allanach et al., hep-ph/0403133

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Combined mSUGRA Reach

- Red: theoretically not accessible
- Yellow: LEP 2 excluded
- Green: preferred region from WMAP dark matter measurement
- Note area accessible to LC but not LHC

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SUSY, Rare Decays and Precision Measurements

- Rare decays are processes in which the tree-level SM process is forbidden (for example because it is a FCNC)
  - At 1 loop level often still involve a weak process
  - These often provide a relatively background-free means of probing physics at the 1 or 2 loop level
- Other processes are measured with stunning precision, and theoretical precision is just as impressive
- In many cases, these drive limits on new couplings (like R-Parity Violation in SUSY)
At the Tevatron...

- Tevatron is a copious source of $B_s$, search for decays to muons
  - In the SM $\text{BR} = 3.8 \times 10^{-9}$ (Buchalla & Buras, NPB400 (1993) 225)
  - Could be up to 3 orders of magnitude higher in SUSY:

```
\begin{align*}
\text{b} & \rightarrow t W^+ W^- \rightarrow \mu^+ \mu^- \\
\text{s} & \rightarrow t W^- W^- \rightarrow \mu^+ \mu^- \\
\text{b} & \rightarrow t H^+ \rightarrow \mu^+ \\
\text{s} & \rightarrow t H^- \rightarrow \mu^- \\
(\text{This one is present in all 2HDM models...})
\end{align*}
```

New Limits from D0 and CDF (240 and 171 pb$^{-1}$), combined by M. Herndon: $\text{BR} < 2.7 \times 10^{-7} @ 90\% \text{ CL}$
Or at SLAC (and KEK) ...

- BABAR searches for $B_d \rightarrow l^+l^-$ decays in
  $\sim 120 \text{ fb}^{-1}$ of on- and off-resonance:
  (BABAR, hep-ex/0408096)
  
  - $\text{BR}(B_d \rightarrow ee) < 6.1 \times 10^{-8}$ (SM: $1.9 \times 10^{-15}$)
  - $\text{BR}(B_d \rightarrow \mu\mu) < 8.3 \times 10^{-8}$ (SM: $8.0 \times 10^{-11}$)
  - $\text{BR}(B_d \rightarrow e\mu) < 18 \times 10^{-8}$ (SM: 0)

- Allows them to put limits on MSSM parameters using
  Bobeth et al., PRD 66, 074021 (2002)
  
  - e.g. $M_H > 138 \text{ GeV} @ 90\% \text{ CL}$ for $\tan(\beta) = 60$
Or at Brookhaven...

• New result from E949:
  
  – $\text{BR} (K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.47 \pm 1.30 \times 10^{-10}$
    
    (E949, hep-ex/0403036)
  
  – Current SM estimate: $\text{BR}^{\text{SM}} = 8.18 \pm 1.22 \times 10^{-11}$
    
    (Deandrea et al., hep-ph/0407216)
  
  – SUSY contribution without R-Parity violation is maximum 50% of SM (with current bounds), but use to set limits on some RPV couplings which are the most stringent to date (same authors)
Muon g-2

• Motivation:

– Difficult, but well-understood experiment, done to a precision of 0.5 ppm (!), sensitive to 2-loop corrections – potential to see effects from heavy new particles

– Theoretical value well known (0.7 ppm!), although some variation in calculations, and always 2 results, depending on input to hadronic vacuum polarization. (In one of those, issue with uncertainties due to isospin breaking effects)
• Current situation:
  – Discrepancy is 2-3 sigma

• This discrepancy is larger than the effect of weak interactions by 30%! (de Troconiz & Yndurain hep-ph/0402285)

• Can be used to put strong constraints on new physics that contributes in other direction

Heinemeyer et al., hep-ph/0405255
Maybe There is No Low Scale SUSY

- Quite a few alternatives have been explored, most address hierarchy problem first and foremost:
  - Technicolor
  - Extra space dimensions
  - Complex group-theoretical constructions

- Others argue fine-tuning may be part of nature:
  - “Split” SUSY (Arkani-Hamed & Dimopoulos, hep-th/0405159)
Technicolor Searches

- QCD-inspired, strongly coupled theory
  - Hierarchy explained as a confinement phenomenon
  - No fundamental scalars
- Strong coupling makes it difficult to satisfy constraints from precision data, now have *topcolor-assisted walking technicolor*
- Also makes predictions difficult
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Large Extra Dimensions

• In original Arkani-Hamed, Dimopoulos & Dvali (ADD) scenario, SM particles are confined to a 3-brane, with gravity propagating in more dimensions

• Hierarchy problem solved by bringing down Planck scale (only “appears” high in 3D)

• Two main types of signatures:
  – Interference from KK graviton excitations in SM processes
    • Look at high energy/mass, and angular behavior
  – On-shell KK graviton excitation production
    • Missing energy (graviton goes back to non-SM dimensions)
• D0 search in dielectron (Drell-Yan) and diphoton events

Leads to Most Stringent Limits to Date on Fundamental Planck Scale: 

\[ M_S > 1.43 \text{ TeV} @ 95\% \text{ CL} \]  

(GRW Convention)

LHC reach is up to 9 TeV (depending on number of dimensions)  

Atlas & CMS hep-ex/0310020
Resonances

• Many of the non-SUSY models predict resonances:
  
  – “Warped” extra dimensions (Randall-Sundrum and variations)
    
    • Graviton resonances
    • Gauge boson KK excitations
  
  – Little Higgs and other models with extended group structures
    
    • $Z'$, $W'$ bosons with various coupling strengths

• Experimentally, one analysis gets reinterpreted multiple ways...
Randall Sundrum Gravitons

- Masses correspond to zeros of Bessel function (ratio $k/M_{Pl}$ changes cross-section and width of resonances)
- Search in all dilepton and diphoton channels

![Graph showing search bounds and cross-sections](image)

DØ Run II Preliminary

200 pb$^{-1}$

Davoudiasl et al., PRD63 075004, 2001

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Extra Gauge Bosons

- **CDF search in ditaus**

  - In some models, dominant coupling is to 3\(^{rd}\) generation
Note: Moller Scattering (E158) should be competitive
Distinguishing Gravitons from Z'

• Exploit the fact that the graviton is spin 2:

• But if parameters conspire, distinction may not be possible until LC (see for example Rizzo, hep-ph/0109179)

• If graviton, still need LC to distinguish between models using lineshape (Rizzo, hep-ph/0110202)

Allanach et al., JHEP 0009:019, 2000

1.5 TeV Graviton, 100 fb⁻¹ at LHC
Z' At Future Colliders

- Mass reach at LHC reaches 5 TeV at high luminosity if model parameters cooperate.
- If accessible at LC, use FB asymmetries to determine model.

Azuelos et al., hep-ph/0402037

BR reaches max at 4%
Split SUSY

- Recent model which doesn't attempt to address EWK fine-tuning problem (Arkani-Hamed & Dimopoulos, hep-th/0405159)
  - Fermion partners are ultraheavy (SUSY scale)
  - Gauginos are light (use chiral symmetry), so still have trileptons
  - Still have gauge coupling unification
  - Still have light Higgs (although mass can now go up to 150 GeV)
  - Get long-lived gluino
New Model...

... but long-lived gluino phenomenology gives signatures similar to

- GMSB (long lived strongly interacting NLSP)
- LED (monojet + missing ET due to escaping neutral gluino-hadrons instead of gravitons)
New Physics in Lepton Flavor Violation

- The generational structure of the SM fermions clearly suggests a link between the generations
  - LFV is therefore to be expected at some scale
  - And it's seen in the neutrino sector!

- Experimentally, LFV muon decays or conversions yield a very sensitive probe to high scale physics:

<table>
<thead>
<tr>
<th>Process</th>
<th>Leading experiment</th>
<th>BR reach</th>
<th>Future experiment</th>
<th>BR reach</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>PRIME (2008)</td>
<td>$\sim 10^{-18}$ [7]</td>
</tr>
</tbody>
</table>

- No signal yet, but ratios can be used to distinguish between processes:

  Maybury & Murakami, hep-ph/0401170, also see talk by V. Cirigliano
**Proton Decay**

- Quark-lepton unification leads to proton decay
  - Non-observation already imposes stringent constraints on models
  - Current limit is lifetime $> 10^{31-33}$ years depending on decay mode
- Next generation detector should reach sensitivity $\sim 10^{35}$ years
- Expect $\sim 10^{36}$ years from GCU (see talk by D. Bourilkov)
Isolated Leptons at HERA

- Select W candidates in HERA data:
  - Isolated lepton
  - Missing Transverse Energy

- Total event count in reasonable agreement with SM, but if look at recoil $p_T$, apparent excess in H1 data

- ZEUS excess in tau channel only

<table>
<thead>
<tr>
<th></th>
<th>$P_T^X &gt; 25$ GeV</th>
<th>$P_T^X &gt; 40$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H1 Data</td>
<td>SM</td>
</tr>
<tr>
<td>electron</td>
<td>5</td>
<td>1.8 ± 0.3</td>
</tr>
<tr>
<td>muon</td>
<td>6</td>
<td>1.7 ± 0.3</td>
</tr>
<tr>
<td>combined</td>
<td>11</td>
<td>3.4 ± 0.6</td>
</tr>
<tr>
<td>electron</td>
<td>2</td>
<td>2.9$^{+0.6}_{-0.3}$</td>
</tr>
<tr>
<td>muon</td>
<td>5</td>
<td>2.8 ± 0.2</td>
</tr>
<tr>
<td>combined</td>
<td>7</td>
<td>5.7 ± 0.6</td>
</tr>
</tbody>
</table>

$120 \text{ pb}^{-1}$
• Is this a signal? Are the two experiments compatible?
  
  - H1 electron+muon is a 2.8 sigma effect
  - Carli et al., MPLA 19, 1881, 2004 investigated compatibility under different scenarios: anomalous W, top or tau production

• HERA Run II, H1 result only:
  
  - 7 e events, 4.1 expected
  - 1 muon, 1 expected
  - 3 with $p_T > 25$ GeV, 1.5 exp
Magnetic Monopole(s)

- Existence of even a single magnetic monopole would explain electric charge quantization (Dirac, 1931), no prediction for mass

- In GUTs, magnetic monopoles exist, with mass $m > 10^{16}$ GeV

- Since magnetic charge is conserved, they are stable
Multilepton Events at HERA

- H1 observed 3 dielectron events in HERA-RUNI with $M_{ee} > 100$ GeV, no new events are observed. The expected number is 0.44
- ZEUS does not see any excess
Model-Independent Searches

- In channels where backgrounds are sufficiently small and/or understood, can pursue model-independent searches
  - Typically counting experiments above pre-fixed thresholds
- Of course, these a-priori analyses do not exploit all information (shapes of distributions,...)
The Fundamental Questions

• Understanding EWSB explains mass

• If there is Grand Unification, understanding its breaking will tell us about electric charge, color and spin
  – Both direct (low scale) and indirect (high scale)data critical

• Manifestations of extra dimensions would lead to better understanding of space-time

• Hopefully, information about GUT breaking or extra dimensions will help understand why there are 3 generations
Conclusions

• Nothing convincing yet
  – (And beware of effects at the edge of sensitivity)

• Things would need to conspire to avoid detection at the LHC, LC (with sufficient c.o.m energy) needed for measurements

• Only SUSY deals with the hierarchy problem, gauge coupling unification and EWSB, but it comes at (IMHO) a significant price

• Most of the really fundamental questions are going to remain unanswered for a while longer
No-Lose at the LHC?

- Suppose there is no Higgs, no resonances are seen, nothing
- Study $V_L V_L$ scattering to find what “saves” unitarity
- Start from effective chiral lagrangian

Heavy and Broad Scalar Resonance

Haywood et al., hep-ph/0003275