Big Questions, L(H)C Answers

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LC/LHC Workshop, Fermilab
13 December 2002
Supersymmetry

If weak-scale SUSY exists, the next decades will be devoted to

- Discovery of superparticles
- Measurements of masses, cross sections, branching ratios, asymmetries...

WHAT COULD BE MORE BORING?!

(This is my entire career you’re talking about…)
Big Questions

How many dimensions are there?
Where are the superpartners?
Do the forces unify?
What is dark matter?

…

…and the LHC/LC interplay in answering these questions
How many dimensions are there?

- How do extra dimensions appear in 4D?
  Consider 5th dimension, a circle of radius $R$:
  \[ \Phi(x^\mu, y) = \phi(x) + \sum [\phi^n(x) \cos(ny/R) + \chi^n(x) \sin(ny/R)] \]
  Kaluza (1921), Klein (1926)

- $\phi(x)$ are SM particles; $\phi^n(x)$, $\chi^n(x)$ are KK partners with
  (a) identical spins
  (b) identical couplings
  (c) unknown masses $n/R$

- Discovering new particles with these properties is discovering extra extra dimensions
• Supersymmetry is an extra dimension theory with new coordinates $\theta_\alpha$ differing from $y$ only in that $\theta_\alpha^2 = 0$ (fermionic or intrinsically infinitesimal)

$$\Phi(x^\mu, \theta) = \phi(x) + \psi^\alpha(x) \theta_\alpha$$

• $\phi(x)$ are SM particles; $\psi^\alpha(x)$ are superpartners with
  (a) spins differing by 1/2
  (b) identical couplings
  (c) unknown masses

• Discovering new particles with these properties is discovering (fermionic) extra dimensions
• Discovery of supersymmetry is discovery of extra dimensions: heavy burden of proof

Noether’s theorem: \[ \{ P_\mu, J_i, K_i \} \rightarrow \{ P_\mu, J_i, K_i, Q_\alpha \} \]

What should we require of colliders?

• “If it quacks like a duck and walks like a duck, it is a duck.”

(Snowmass 1996)

• If it quacks like a pion and walks like a pion, it’s a muon.
• If it quacks like charm and walks like charm, it’s a tau.
• If it quacks like a chargino and walks like a chargino, it’s… a 4\textsuperscript{th} lepton?

• Particle physics is not ornithology – we can do DNA tests!
LHC

- Remarkable reach, may see all superpartners

- But this is not enough. Cf. universal extra dimensions
  
  Appelquist, Cheng, Dobrescu (2001)

Aside: this looks like disaster scenario:
  - LSP weakly interacting, stable
  - Other sparticles all nearly degenerate

Weak scale SUSY can escape all colliders

Cheng, Matchev, Schmaltz (2002)
• Remarkable precision, potential for model-independent measurements

• Spins – threshold scans,…

• Test couplings to 1% level

\[
\begin{align*}
\tilde{B} & \quad \tilde{e}^- \\
\tilde{e}^+ & \quad e^- \\
\end{align*}
\]

Feng, Murayama, Peskin, Tata (1995)

Nojiri, Fujii, Tsukamoto (1996)
Where are all the superpartners?

• What if not all superpartners are found?

• Everything we know points to some $m_{\text{SUSY}} \sim \text{few to 10 TeV}$ (e.g., flavor, CP, proton decay)

• We need to bootstrap from what we know to higher energies – LHC/LC complementarity shines here
Bootstrapping

Tree-level

- LC bounds sneutrino mass $\rightarrow$ selectron, sneutrino target for LHC
- LHC measures selectron, sneutrino mass $\rightarrow$ resolves sneutrino mass/Higgsino-ness degeneracy at LC $\rightarrow$ Higgsino target for LC
Bootstrapping

Loop-level

- Superoblique corrections “detect” arbitrarily heavy superpartners
  
  \[ Y_B \equiv \frac{g_B \tilde{e}_{R e_R}}{\sqrt{2} g'} \]
  \[ \tilde{U}_1 \equiv Y_{\tilde{B}} - 1 = \frac{11}{5} \cdot \frac{g_1^2}{16 \pi^2} \ln \frac{M_{\tilde{Q}}}{M_{\tilde{L}}} \]

- 1% level measurement of \( \tilde{U}_1 \rightarrow \) squark target for LHC

Cheng, Feng, Polonsky (1997)
Nojiri, Pierce, Yamada (1997)
Bootsstrapping

Theoretical

• LC measures $M_2 = 2M_1 \rightarrow SU(5), \ GMSB$
  $\rightarrow 7M_1$ gluino target for LHC

• LC measures $M_1 = 3.3M_2 \rightarrow AMSB$
  $\rightarrow 10M_2$ gluino target for LHC

……
Do the forces unify?

- Key motivation for SUSY: gauge coupling unification

Martin (1997)

Gaugino mass unification?

Blair, Porod, Zerwas (2002)
LHC measures mass differences, LC measures masses

What is dark matter?

• Discovery of SUSY $\rightarrow$ discovery of dark matter candidates

• Neutralino detection
  – Collider
  – Direct
  – Indirect
    • Neutrinos from Sun
    • Gamma rays galactic center
    • Positrons from halo

• Ushers in a era of particle/astroparticle complementarity, of which LHC/LC complementarity is just a small part
Neutralino freeze out: sensitive to most SUSY parameters

\[ \chi \quad \chi^+ \quad \bar{f} \quad f \quad W^- \quad W^+ \]

Relic density regions and gaugino-ness contours

Feng, Matchev, Wilczek (2000)
Dark Matter Detection

- Direct detection depends on scattering

\[ \chi \rightarrow \chi, h, H \]

\[ q \rightarrow q, \tilde{q} \]

- Indirect detection depends on annihilation or both

Feng, Matchev, Wilczek (2000)
Indirect Detection – Experiments

TABLE I. Current and planned neutrino experiments. We list also each experiment's (expected) start date, physical dimensions (or approximate effective area), muon threshold energy $E_{\mu}^{\text{thr}}$ in GeV, and 90% CL flux limits for the Earth $\Phi_{\mu}^{\text{E}}$ and Sun $\Phi_{\mu}^{\text{S}}$ in km$^{-2}$ yr$^{-1}$ for half-cone angle $\theta \approx 15^\circ$ when available.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Date</th>
<th>Dimensions</th>
<th>$E_{\mu}^{\text{thr}}$</th>
<th>$\Phi_{\mu}^{\text{E}}$</th>
<th>$\Phi_{\mu}^{\text{S}}$</th>
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<tr>
<td>Baksan [65]</td>
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<td>Kamiokande [66]</td>
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<td>Super-Kamiokande</td>
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<td>Baikal NT-96 [6]</td>
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<td>NESTOR$^8$ [72]</td>
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<td>IceCube [71]</td>
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TABLE II. Some of the current and planned $\gamma$ ray detector experiments with sensitivity to photon energies $10 \text{ GeV} \lesssim E_\gamma \lesssim 300 \text{ GeV}$. We list each experiment's (proposed) start date and expected $E_\gamma$ coverage in GeV. The energy ranges are approximate. For experiments constructed in stages, the listed threshold energies will not be realized initially. See the references for details.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Date</th>
<th>$E_\gamma$ Range</th>
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</thead>
<tbody>
<tr>
<td>EGRET [88]</td>
<td>Satellite</td>
<td>1991-2000</td>
<td>0.02–30</td>
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<tr>
<td>STACEE [89]</td>
<td>ACT array</td>
<td>1998</td>
<td>20–300</td>
</tr>
<tr>
<td>CELESTE [90]</td>
<td>ACT array</td>
<td>1998</td>
<td>20–300</td>
</tr>
<tr>
<td>ARGO-YBJ [91]</td>
<td>Air shower</td>
<td>2001</td>
<td>100–2,000</td>
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<tr>
<td>MAGIC [92]</td>
<td>ACT</td>
<td>2001</td>
<td>10–1000</td>
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<td>AGILE [93]</td>
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<td>HESS [94]</td>
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<td>AMS/$\gamma$ [95]</td>
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<td>CANGARO</td>
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<td>VERITAS [1]</td>
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<td>GLAST [98]</td>
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</tbody>
</table>

* 2 GeV for Sun

TABLE III. Recent and planned $e^+$ detector experiments. We list each experiment's (expected) start date, duration, geometrical acceptance in cm$^2$ sr, maximal $E_{e^+}$ sensitivity in GeV, and (expected) total number of $e^+$ detected per GeV at $E_{e^+} = 50$ and 100 GeV.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Date</th>
<th>Duration</th>
<th>Acceptance</th>
<th>$E_{e^+}^{\text{max}}$</th>
<th>$dN/dE$ (50)</th>
<th>$dN/dE$ (100)</th>
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<tbody>
<tr>
<td>HEAT94/95 [114]</td>
<td>Balloon</td>
<td>1994/95</td>
<td>29/26 hr</td>
<td>495</td>
<td>50</td>
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<td></td>
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<td>CAPRICE94/98 [115]</td>
<td>Balloon</td>
<td>1994/98</td>
<td>18/21 hr</td>
<td>163</td>
<td>10/30</td>
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<td></td>
</tr>
<tr>
<td>PAMELA [116]</td>
<td>Satellite</td>
<td>2002-5</td>
<td>3 yr</td>
<td>20</td>
<td>200</td>
<td>7</td>
<td>0.7</td>
</tr>
<tr>
<td>AMS-02 [117]</td>
<td>Space station</td>
<td>2003-6</td>
<td>3 yr</td>
<td>6500</td>
<td>1000</td>
<td>2300</td>
<td>250</td>
</tr>
</tbody>
</table>

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Inputs to Astrophysics

- Thermal relic density need not be the actual relic density – late decays, etc.
  - The mismatch tells us about the history of the universe between $1 \text{ MeV} < T < 10 \text{ GeV}$ or $1 \text{ s} > t > 10^{-8} \text{ s}$

- The detection rate need not be the actual detection rate
  - The mismatch tells us about halo profiles, dark matter velocity distributions

- LHC/LC parameter determinations are crucial to this program
Conclusions

• Many other big questions:
  – What about CP violation, baryogenesis?
  – Why do the SM quarks and leptons have the measured masses and mixings?
  – What is the scale of SUSY breaking?
  – What is the fundamental theory at the Planck scale?
      ……

• LHC and LC have something to say about all these

• “Supersymmetry and the Linear Collider,” Feng, Nojiri hep-ph/0210390 – comments welcome