Focus Point Phenomenology

“LCC2” Benchmark studies

Linear Collider Cosmology Connection

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Chris Jones
Dan Riley
Jim Alexander

theorists

On the job market - postdoc.
On the job market - faculty.

graduate
students.
Focus Point Benchmark LCC-2

SUSY

mSUGRA

m\(_{1/2}\) m\(_0\) A \(\tan\beta\) \(\mu\)

CONTRAINTS - EW & WMAP

\[ m_0 = 3280 \quad m_{1/2} = 300 \]
\[ A = 0 \quad \tan\beta = 10 \]
\[ \text{sgn}(\mu) = + \quad (m_\tau = 175) \]

Howard Baer et al 2004
JHEP02(2004)007
Cosmological Connections

ILC Experiment

$\sigma_L, \sigma_R, \frac{d\Gamma}{dM}, \frac{d\Gamma}{dE}, ...$

$m_+, m_0, \zeta = (v_+^2 - a_+^2)/(v_+^2 + a_+^2), v_0^2 + a_0^2, ...$

$M_1, M_2, A, \tan \beta, \mu, ...$

$\Omega_{cdm} h^2$

WMAP, Planck, ...
Detector Benchmarking

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<tr>
<th>Process and Final states</th>
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</thead>
<tbody>
<tr>
<td>$ee \rightarrow Z^0 h^0 \rightarrow \ell^+\ell^- X$</td>
<td>0.35</td>
<td>$M_{recsol}$, $\sigma_{ZH}$, $BR_{zb}$</td>
<td>$\sigma_{ZH} = 2.5%$, $\delta BR_{zb} = 1%$</td>
<td>T</td>
<td>(1)</td>
</tr>
<tr>
<td>$ee \rightarrow Z^0 h^0 \rightarrow b\bar{b}/c\bar{c}/\tau\tau$</td>
<td>0.35</td>
<td>Jet flavour</td>
<td>$\Delta m_{ZH} = 40$ MeV, $\delta (\sigma_{ZH} \times BR_{WW^*}) = 5%$</td>
<td>V</td>
<td>(2)</td>
</tr>
<tr>
<td>$ee \rightarrow Z^0 h^0/\mu^+\mu^- h^0 \rightarrow WW^*$</td>
<td>1.0</td>
<td></td>
<td>$\delta (\sigma_{ZH} \times BR_{WW^*}) = 5%$</td>
<td>C</td>
<td>(3)</td>
</tr>
<tr>
<td>$ee \rightarrow Z^0 h^0/\mu^+\mu^- h^0 \rightarrow \gamma \gamma$</td>
<td>1.0</td>
<td></td>
<td>$\delta (\sigma_{ZH} \times BR_{WW^*}) = 5%$</td>
<td>C</td>
<td>(4)</td>
</tr>
<tr>
<td>$ee \rightarrow Z^0 h^0, h^0 \nu \bar{\nu}, h^0 \rightarrow \mu^+\mu^-$</td>
<td>1.0</td>
<td></td>
<td>$5\sigma$ Evidence for $m_h = 120$ GeV</td>
<td>T</td>
<td>(5)</td>
</tr>
<tr>
<td>$ee \rightarrow Z^0 h^0, h^0 \nu \bar{\nu}, h^0 \rightarrow invisible$</td>
<td>0.5/1.0</td>
<td></td>
<td>$\delta (\sigma_{ZH} \times BR_{bb}) = 1%$</td>
<td>C</td>
<td>(6)</td>
</tr>
<tr>
<td>$ee \rightarrow h^0 \nu \bar{\nu}$</td>
<td>0.5</td>
<td>$\sigma_{bb}, M_{bb}$</td>
<td>$\delta (\sigma_{ZH} \times BR_{bb}) = 1%$</td>
<td>C</td>
<td>(7)</td>
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<tr>
<td>$ee \rightarrow h^0 \nu \bar{\nu}$</td>
<td>0.5</td>
<td>$\sigma_{bb}, M_{bb}$</td>
<td>$\delta (\sigma_{ZH} \times BR_{bb}) = 1%$</td>
<td>C</td>
<td>(8)</td>
</tr>
<tr>
<td>$ee \rightarrow Z^0 h^0/\mu^+\mu^- h^0 \rightarrow invisible$</td>
<td>0.5/1.0</td>
<td>$\sigma_{ZH}, \sigma_{bb}, M_{bb}$</td>
<td>$\delta (\sigma_{ZH} \times BR_{bb}) = 1%$</td>
<td>C</td>
<td>(9)</td>
</tr>
</tbody>
</table>

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<tbody>
<tr>
<td>$SSB$ $ee \rightarrow W^+W^-$</td>
<td>0.5</td>
<td>$\Delta \kappa$, $\lambda_i = 2 \cdot 10^{-4}$</td>
<td></td>
<td>V</td>
<td>(10)</td>
</tr>
<tr>
<td>$SSB$ $ee \rightarrow W^+W^-\nu\bar{\nu}/Z^0Z^0\nu\bar{\nu}$</td>
<td>1.0</td>
<td>$\sigma$</td>
<td>$\sigma_{st}, \lambda_3 = 3$ TeV</td>
<td>C</td>
<td>(11)</td>
</tr>
</tbody>
</table>

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<tbody>
<tr>
<td>$SUSY$ $ee \rightarrow \tilde{e}_R^+ \tilde{e}_R^- (Point 1)$</td>
<td>0.5</td>
<td>$F_\sigma$</td>
<td>$\delta m_{\tilde{e}_R^+} = 50$ MeV</td>
<td>T</td>
<td>(12)</td>
</tr>
<tr>
<td>$SUSY$ $ee \rightarrow \tilde{\tau}_1^+ \tilde{\tau}_1^- (Point 1)$</td>
<td>0.5</td>
<td>$E_{\tau}, E_{2\tau}, E_{3\tau}$</td>
<td>$\delta (m_{\tilde{\tau}<em>1} - m</em>{\tilde{\tau}_2}) = 200$ MeV</td>
<td>T</td>
<td>(13)</td>
</tr>
<tr>
<td>$SUSY$ $ee \rightarrow \tilde{t}_1 \tilde{t}_1 (Point 1)$</td>
<td>1.0</td>
<td>$\tau_1, \tau_2$</td>
<td>$\delta m_{\tilde{t}_1} = 2$ GeV</td>
<td>C</td>
<td>(14)</td>
</tr>
</tbody>
</table>

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<tbody>
<tr>
<td>$-CDM$ $ee \rightarrow \tilde{\tau}_1^+ \tilde{\tau}_1^- (Point 2)$</td>
<td>0.5</td>
<td>$M_{jj}$ in $jjZ$, $M_{le}$ in $jjZ\ell\ell H$</td>
<td>$\delta (m_{\tilde{\tau}<em>1} - m</em>{\tilde{\tau}_2}) = 500$ MeV</td>
<td>C</td>
<td>(15)</td>
</tr>
<tr>
<td>$-CDM$ $ee \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0, \chi_1^+ \chi_1^- (Point 2)$</td>
<td>0.5</td>
<td>$\delta m_{\chi_1}$, $\delta m_{\chi^2}$</td>
<td>$\Delta m_{\chi_1} = 1$ GeV</td>
<td>F</td>
<td>(16)</td>
</tr>
<tr>
<td>$-CDM$ $ee \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0, \chi_1^+ \chi_1^- (Point 5)$</td>
<td>0.5</td>
<td>$\delta m_{\chi_1}$, $\delta m_{\chi^2}$</td>
<td>$\Delta m_{\chi_1} = 1$ GeV</td>
<td>C</td>
<td>(17)</td>
</tr>
<tr>
<td>$-CDM$ $ee \rightarrow H^0 A^0 \rightarrow b\bar{b}b\bar{b}$ (Point 4)</td>
<td>1.0</td>
<td>Mass constrained $M_{bb}$</td>
<td>$\delta m_{A^0} = 2$ GeV</td>
<td>C</td>
<td>(18)</td>
</tr>
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<tr>
<td>$-alternative$ $ee \rightarrow \tilde{\tau}_1^+ \tilde{\tau}_1^- (Point 6)$</td>
<td>0.5</td>
<td>Heavy stable particle</td>
<td>$\delta m_{\tilde{\tau}_1}$</td>
<td>T</td>
<td>(19)</td>
</tr>
<tr>
<td>$-alternative$ $ee \rightarrow \gamma + \gamma (Point 7)$</td>
<td>0.5</td>
<td>Non-pointing $\gamma$</td>
<td>$\delta \gamma = 10%$</td>
<td>C</td>
<td>(20)</td>
</tr>
<tr>
<td>$-alternative$ $ee \rightarrow \chi_1^+ \chi_1^- + \nu_{e,\mu,\tau} (Point 8)$</td>
<td>0.5</td>
<td>Soft $\pi^\pm$ above $\gamma \gamma$ bkgd</td>
<td>$5\sigma$ Evidence for $\Delta m = 0.2 - 2$ GeV</td>
<td>F</td>
<td>(21)</td>
</tr>
</tbody>
</table>

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<th>Notes</th>
</tr>
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<tr>
<td>Precision SM $ee \rightarrow tt \rightarrow 6 jets$</td>
<td>1.0</td>
<td></td>
<td></td>
<td>V</td>
<td>(22)</td>
</tr>
<tr>
<td>Precision SM $ee \rightarrow f\bar{f} (f = e, \mu, \tau; b, c)$</td>
<td>1.0</td>
<td>$\sigma_{ff}, A_F, A_L$</td>
<td>$5\sigma$ Sensitivity for $(g - 2)/2 \leq 10^{-3}$</td>
<td>V</td>
<td>(23)</td>
</tr>
<tr>
<td>New Physics $ee \rightarrow \gamma \gamma$ (ADD)</td>
<td>1.0</td>
<td></td>
<td>$5\sigma$ Sensitivity to $M(Z_{LR}) = 7$ TeV</td>
<td>C</td>
<td>(24)</td>
</tr>
<tr>
<td>New Physics $ee \rightarrow K K \rightarrow f\bar{f}$ (RS)</td>
<td>1.0</td>
<td>$\sigma(\gamma + \ell\ell)$</td>
<td>$5\sigma$ Sensitivity</td>
<td>T</td>
<td>(25)</td>
</tr>
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</tr>
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<tbody>
<tr>
<td>Energy/Lumi Meas. $ee \rightarrow e e_{rec}$</td>
<td>0.3/1.0</td>
<td></td>
<td></td>
<td>T</td>
<td>(26)</td>
</tr>
<tr>
<td>Energy/Lumi Meas. $ee \rightarrow Z^0\gamma$</td>
<td>0.5/1.0</td>
<td></td>
<td></td>
<td>T</td>
<td>(27)</td>
</tr>
</tbody>
</table>
**Point 2:** neutralinos & charginos are relatively isolated --> simplifies things

Since the scalars are heavy in this scenario, they decouple.

As a result, neutralino and chargino production and decay mechanisms are rather simple, with usually only one contributing amplitude.
Focus Point Spectrum

Scalars

Neutralinos & charginos

mass

300 GeV

$\chi_2^0$ $\chi_2^+$

$\chi_4^0$

200 GeV

$\chi_3^0$ $\chi_1^+$

$\chi_2^0$

100 GeV

$\chi_1^0$

Labels are Backwards!

Spectrum computed by ISAJET

p6/31
Production and Decay

Cross sections computed by ISAJET

Single channel decay mechanism is a feature of this benchmark point.

Labels are Backwards!
Studies Presented at LCWS-05

\[ e^+ e^- \rightarrow \chi_2^0 \chi_3^0 \]

- Richard Gray
  - hep-ex/0507008
- Andreas Birkedal
  - hep-ph/0507214
Studies Presented at LCWS-05

$e^+e^- \rightarrow \chi_2^0\chi_3^0$

- **Talks:**
  - Richard Gray
    - hep-ex/0507008
  - Andreas Birkedal
    - hep-ph/0507214

- **Results (500fb$^{-1}$):**
  \[
  \begin{align*}
  m(\chi_3^0) - m(\chi_1^0) &= 82.3 \pm 0.2 \\
  m(\chi_2^0) - m(\chi_1^0) &= 58.8 \pm 0.3 \\
  m(\chi_1^0) &= 108.3 \pm 1.0 \\
  \frac{\varepsilon_2\varepsilon_3}{\varepsilon_1} &= + - \quad (13\sigma)
  \end{align*}
  \]
Mode du jour: $e^+e^- \rightarrow \chi_1^+\chi_1^-$

But:
- much larger cross section
- lepton sign tags chargino (maybe useful later?)
Production

\[ e^+ e^- \rightarrow \chi_1^+ \chi_1^- \]

Note that possible t-channel term is suppressed in this benchmark point (large sneutrino mass):

[Diagram showing the production process and the interference term]

\[ R = \frac{\sigma(e^+ e^- \rightarrow \chi^+ \chi^-)}{\sigma(e^+ e^- \rightarrow \mu^+ \mu^-)} \]

\[ \sim \frac{1}{t - M_{\tilde{\nu}}^2} \]
Production:  

*The $\chi_1^+\chi_1^- (Z^0, \gamma)$ vertex*

\[ \sigma = \frac{ig}{2\cos\theta_W} \gamma^\mu [O_{11}^L(1-\gamma_5) + O_{11}^R(1+\gamma_5)] \]

- **Yield:** $\sigma$
- **$M_2, \mu, \tan\beta$**

(a) for photon coupling, $R=L$
(b) for $Z^0$ coupling $R \neq L$, but in this case $(R-L)/(R+L) \sim -0.09$. $A_{fb}$ is small.
(C) $\chi^+$--wino and higgsino components couple differently; results in significant beam polarization dependence.
Decay: The $\chi_1^+ \chi_1^0 W^{*+}$ vertex

Kinematic distributions
$d\Gamma/dM, d\Gamma/dE$

\[
\frac{ig}{2} \left[ O_{11}^L (1-\gamma_5) + O_{11}^R (1+\gamma_5) \right]
\]

$M_1, M_2, \mu, \tan\beta$

For future study:
If the $\chi^+$ is polarized, $d\Gamma/d\cos\theta^*$ could be interesting. (Use lepton tag to separate $\chi^+, \chi^-$, measure $d\Gamma/dE$.)

$(R-L)/(R+L) \sim -0.06$
Couplings are hard. Spectroscopy is easier.

Mass determinations can be done at LHC - albeit with limited resolution.

Unfolding couplings and mixings is unique to ILC. But not too hopeful in this particular case.

Labels are Backwards!
Kinematics of the hadronic system

\[ \chi_1^+ \rightarrow W^+ \chi_1^0 \]

For given \( M \), just 2-body decay:

\[ E^* = \frac{M^2 + m_+^2 - m_0^2}{2m_+} \]

\[ P^* = \sqrt{E^*^2 - M^2} \]

\[ \cos \theta^* = \pm 1 \]

Mass: \( M \)
Energy: \( E \)

Dalitz plot (almost)

\[ \gamma = \sqrt{s}/2m_+ \]

\[ M = m_+ - m_0 \]
Andreas Birkedal calculated: (generic for $F \rightarrow ff' F'$)

$$\frac{d\Gamma}{dM} \sim \frac{MP^*}{m_+^2(M^2 - m_W^2)^2} \times \left[ m_0^4 + m_+^4 + M^2m_+^2 - 2M^4 + m_0^2(M^2 - 2m_+^2) - 6\zeta M^2 m_0 m_+ \right]$$

Note: $\zeta$ is asymmetry in vector & axial-vector couplings at $\chi^+ W^{*+} \chi^0$ vertex:

$$\zeta \equiv \frac{\nu_+^2 - a_+^2}{\nu_+^2 + a_+^2}$$

- Dependence:
  - Strong: $m_+ - m_0$
  - Medium: $\zeta$
  - Weak: $m_+ + m_0$

Fit yields $m_+ - m_0$ and $\zeta$ ....and they are strongly (+) correlated
Example: toy expts fitting to $d\Gamma/dM$

Generate ~500 toy expts, fit to formula.

Sample fit

Shape includes resolution smearing

\( \zeta \) versus \( m_+ - m_0 \)
Thus for a given $M$, $d\Gamma/dE$ measures the angular distribution $d\Gamma/d\cos\theta^*$. 

This distribution depends on $m_+$, $m_0$,... as well as $R_+, L_+$ couplings and degree of $\chi^+$ polarization...
If \( d\Gamma/\cos\theta^* \) is symmetric, then \( <\cos\theta^*> = 0 \).
- We can ensure symmetry of \( d\Gamma/\cos\theta^* \) by ignoring opposite-side-lepton sign -- so we do not distinguish \( \chi^+, \chi^- \)
- Alternatively, \( d\Gamma/\cos\theta^* \) may be flat (eg if \( \chi^+ \) is unpolarized... which it basically is, it turns out).

Assuming \( <\cos\theta^*> = 0 \), we find:

\[
\langle E \rangle = \langle \gamma \rangle E^* = a + bM^2
\]

\[
a = \frac{\sqrt{s}}{4} \left(1 - \left(\frac{m_0}{m_+}\right)^2\right)
\]

\[
b = \frac{\sqrt{s}}{4m_+^2}
\]

Mainly sensitive to the ratio \( m_+/m_0 \)

Note: in ISAJET \( d\Gamma/\cos\theta^* = \text{flat} \).
Simultaneous fit for $d\Gamma/dM$ & $d\Gamma/dE$

$d\Gamma/dM$ fit: $m_+ - m_0$

$d\Gamma/dE$ fit: $m_+ / m_0$
Simulation Details

ISAJET 7.69 → stdhep

LCDROOT: FASTMC (SDMar01) → root → SUEZ

Lumi = 500 fb⁻¹:
- 250 fb⁻¹ e⁻ pol = +95%
- 250 fb⁻¹ e⁻ pol = -95%

Note: “95%” means \( \frac{R - L}{R + L} = 0.90 \)

Analysis (to be described):
- reconstruction eff = 36%
- \( W^* \) branching ratios = 15%

Signal yield = (500 fb⁻¹) \( \times \) (940 fb) \( \times \) (0.36 × 0.15) = 12000 evts
- 1500 evts

Backgrounds: \( WW, ZZ, tt \) + generic (1 ab⁻¹ from Tim Barklow)
Signal Selection

$E > 300 \text{ GeV}$

$N > 10$ (no jet finding)

Lepton ID

30deg isolation cone

$E > 15 \text{ GeV}$

costh = 0.90
Background Suppression

$e^{-}e^{+}$

$M < 70$ GeV

$W^{+}W^{-}$

$P_{T} > 15$ GeV

$e\gamma$
Signal and Backgrounds

dΓ/dM, 500 fb⁻¹

Cuts kill this region

Kinematic endpoint at M = m⁺ - m₀ = 51.7 GeV
Detector Resolution Matters!

Analysis “A”

(oops - colors mean different things in these two plots!)

Analysis “B”

\[
\frac{\sigma_E}{E} \sim \frac{0.15}{\sqrt{E}}
\]

\[
\frac{\sigma_E}{E} \sim \frac{0.8}{\sqrt{E}}
\]
Yields, $\sigma_L$, $\sigma_R$

Counting events in FASTMC with Analysis “B”

<table>
<thead>
<tr>
<th>Source (Signal $\chi_1^+ \chi_1^- \rightarrow e^\pm jj(g)$)</th>
<th>left-pol.</th>
<th>right-pol.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUSY backgrounds (including $\chi_1^+ \chi_1^-$ to other modes)</td>
<td>1751</td>
<td>480</td>
</tr>
<tr>
<td>Standard Model backgrounds</td>
<td>3170</td>
<td>1209</td>
</tr>
<tr>
<td>Cross-section measurement</td>
<td>940 ± 10 fb</td>
<td>119 ± 4.3 fb</td>
</tr>
</tbody>
</table>

~1% on total cross section (or $\sigma_L$);
~4% on $\sigma_R$.

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = 0.78 \pm 0.01$$

Note: this polarization asymmetry is due to lopsided chargino content. $e^-_R e^+_L$ only couples to (small) higgsino component of chargino. Thus the cross section measurement alone probes mixing.
Simultaneous fit for $d\Gamma/dM$ & $d\Gamma/dE$

Explore further with toy MC -- flexible, fast

- 250 toy experiments
- generate 10k events in each expt:
  - $d\Gamma/dM$ - Andreas' formula: $\zeta=0.86$
  - $d\Gamma/dE$ flat
- $E,M$ smeared by $\sigma_E=30%/\sqrt{E}$ --> optimal PFA
- Restrict fit to $M>25\text{GeV}$:
  - ISAJET/FASTMC:
    - low mass range is sculpted
    - not understood yet.
    - main impact on fit is reduced statistics (64%)
- Fit includes resolution smearing
  - Sensitive - get it right!!
- No brem/beam-strahlung for now.
- No background for now.
Simultaneous fit for $d\Gamma/dM$ & $d\Gamma/dE$

250 toy experiments: 10K evts, $\sigma_E = 30%/\sqrt{E}$

$m_+ = 158.5 \pm 0.8$

(generated value: 159.4)

$m_0 = 107.1 \pm 0.6$

(generated value: 107.7)
Simultaneous fit for $d\Gamma/dM$ & $d\Gamma/dE$

250 toy experiments: 10K evts, $\sigma_E=30%/\sqrt{E}$
Mass Sensitivity vs Detector Resolution

Dependence on “jet” energy resolution is somewhat mild…

CAVEATS!
1. No bkg included. Bkgs will raise the floor and the slope.
2. Toy Monte Carlo...
3. Preliminary!

<table>
<thead>
<tr>
<th>Res</th>
<th>mchg</th>
<th>mlsp</th>
<th>mdiff</th>
<th>zeta</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>+-0.66</td>
<td>+-0.56</td>
<td>+-0.19</td>
<td>+-0.020</td>
</tr>
<tr>
<td>30%</td>
<td>+-0.8</td>
<td>+-0.6</td>
<td>+-0.25</td>
<td>+-0.025</td>
</tr>
<tr>
<td>60%</td>
<td>+-1.3</td>
<td>+-0.9</td>
<td>+-0.47</td>
<td>+-0.039</td>
</tr>
</tbody>
</table>
Other things to pursue…

• Lepton spectrum (other side of event) also contains useful kinematic info. Use it!

• Threshold production: mass, spin; fully polarized.

• Beam polarization, $A_{LR}$, $A_{LRFB}$,…

• Neutralino production needs to be revisited: purely Z0 produced; richer content. R,L couplings?? Threshold production?

• Detector benchmarking.