Neutralino Dark Matter and the Linear Collider

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OUTLINE

• mSUGRA model
• Constraints on mSUGRA
  – LEP2
  – relic density: WMAP
  – $b \rightarrow s\gamma$
  – $(g - 2)_{\mu}$
  – $\chi^2$ determination; favored regions of parameter space
• prospects for mSUGRA at a linear $e^+e^-$ collider
• compare LC reach to that of Tevatron and LHC
• parameter determination in the HB/FP region
• non-universal SUGRA model
• favored regions of NU SUGRA parameter space
• prospects for colliders: light 1st/2nd gen. sleptons
• conclusions
Constructing the mSUGRA model

- Begin with Lagrangian of locally supersymmetric gauge theory
- Specify matter and Higgs superfields of MSSM
- Specify SM gauge symmetry
- Specify Kahler function $G = K + \log |f|^2$:
  - superpotential $f = f_{MSSM} + f_{hidden}$
  - flat Kahler metric: $K = \Sigma_i \hat{S}_i^\dagger \hat{S}_i + \hat{h}^\dagger \hat{h}$
- Specify simple gauge kinetic function: $f_{AB} = \delta_{AB} f(\hat{h})$
- Arrange for SUSY breaking in hidden sector
- Calculate supergravity induced soft SUSY breaking terms
- Limit as $M_{Pl} \rightarrow \infty$ with $m_{3/2}$ fixed: global SUSY renormalizable gauge theory with TeV scale soft breaking terms valid at high scale e.g. $M_{GUT}$
- weak scale model constructed via RGE evolution; EW symmetry broken radiatively
- mSUGRA model parameter space
  - $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$, $sign(\mu)$

Chamseddine, Arnowitt and Nath; Barbieri, Ferrara and Savoy; Hall, Lykken and Weinberg; ···
Constraints on mSUGRA model

- Generate SUSY spectrum in mSUGRA parameter space
  - Calculate $\Omega_{\tilde{Z}_1} h^2$ HB, Balazs, Belyaev
    * use Gondolo, Gelmini, Edsjo + CompHEP: Isared program
    * WMAP: $\Omega_{CDM} h^2 = 0.1126 \pm 0.0090$
  - calculate $BF(b \to s\gamma)$ HB, Brhlik, Castano, Tata
    * $BF(b \to s\gamma) = (3.25 \pm 0.54) \times 10^{-4}$ (incl. 12% theory)
  - calculate SUSY contribution to $(g-2)_\mu$ HB, Balazs Ferrandis, Tata
    * $\Delta a_\mu = (31.7 \pm 9.5) \times 10^{-10}$ (Hagiwara et al. $e^+e^-$; new E821 results)

- from these three, calculate $\chi^2$, plot in mSUGRA parameter space HB, Balazs
  - see also Ellis, Olive, Santoso and Spanos

- allowed DM regions
  - stau co-annihilation (Ellis et al.)
  - HB/FP (Chan, Chattopadyay, Nath; Feng, Matchev, Moroi)
  - $A$-annihilation funnel (Drees, Nojiri; HB, Brhlik)
  - “bulk” region at low $m_0, m_{1/2}$ disfavored (LEP2, $b \to s\gamma, (g-2)_\mu$)
\( \chi^2 \) for \( \mu > 0 \):

- **green**: low \( \chi^2 / \text{dof} \)
- **yellow**: medium \( \chi^2 / \text{dof} \)
- **red**: high \( \chi^2 / \text{dof} \)
Reach of linear $e^+e^-$ collider:

- LC reach for $\sqrt{s} = 0.5$ and 1 TeV, 100 fb$^{-1}$
Sparticle masses/ cross sections in the HB/FP region:

- In HB/FP, $\mu \to 0$
- $m_{1/2} = 225$ GeV
Sparticle masses/ cross sections in the HB/FP region:

- $m_{1/2} = 900 \text{ GeV}$
Distributions for case study in HB/FP region

- In HB/FP, $\mu \to 0$
Reach of linear $e^+e^-$ collider:

- LC reach for $\sqrt{s} = 0.5$ and 1 TeV, 100 fb$^{-1}$

$mSugra$ with $\tan\beta = 30$, $A_0 = 0$, $\mu > 0$
Reach of linear $e^+ e^-$ collider:

- LC reach for $\sqrt{s} = 0.5$ and 1 TeV, 100 fb$^{-1}$
Reach of linear $e^+e^-$ collider:

- LC reach for $\sqrt{s} = 0.5$ and 1 TeV, 100 fb$^{-1}$

$mSugra$ with $\tan\beta = 52$, $A_0 = 0$, $\mu > 0$
Compare all colliders with WMAP allowed region:

- LC reach for $\sqrt{s} = 0.5$ and 1 TeV, 100 fb$^{-1}$
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Determination of fundamental parameters:

- $m(jj)$ vs. $E(jj)$

![Graph showing $m(jj)$ vs. $E(jj)$ and distinguishing between Signal and Background data points.](#)
Determination of fundamental parameters:

- $E(jj)$ bins

![Graphs showing the distribution of events for different $m_{jj}$ values: $m_{jj}=8 \pm 2$ GeV, $m_{jj}=12 \pm 2$ GeV, $m_{jj}=16 \pm 2$ GeV, and $m_{jj}=20 \pm 2$ GeV.](image)
Determination of fundamental parameters:

- $m_{\tilde{Z}_1}$ vs. $m_{\tilde{W}_1}$
Determination of fundamental parameters:

- determine \( \mu \), \( M_2 \), \( \tan \beta \) from \( m_{\tilde{W}_1} \), \( m_{\tilde{Z}_1} \) and \( \sigma(\tilde{W}_1^+\tilde{W}_1^-) \)
Motivation for non-universal SUGRA model

- In general SUGRA models, Kähler metric not flat
- Even if it is a tree level, universality destroyed by rad. corrections

Motivation from experiment

- $BF(b \to s\gamma)$ prefers $m_{\tilde{t}_1} \gtrsim 1$ TeV
- $(g - 2)_{\mu}$ prefers relatively light 2nd ge. sleptons
- must all be consistent with WMAP $\Omega_{\tilde{Z}_1} h^2$

Enlarge parameter space:

- $m_0(1), m_0(3), m_H, m_{1/2}, A_0, \tan \beta, \text{sign}(\mu)$
- we take $m_0(1) \simeq m_0(2)$ to satisfy FCNC constraints
- take $m_H \simeq m_0(3)$ (gives best fit)
- (model realized in Allanach et al. model with twisted moduli sector)
Constraint from $\Delta m_K^*$:

- prefer $m_{\tilde{q}}(1) \approx m_{\tilde{q}}(2)$
Constraint from $\Delta m_B$:

- allow $m_{\tilde{q}}(1) \simeq m_{\tilde{q}}(2) \neq m_{\tilde{q}}(3)$
Soft term evolution:

- gives $m_{\tilde{q}}(1) \simeq m_{\tilde{q}}(3)$
- also $m_{\tilde{e}} \simeq m_{\tilde{\mu}} \ll m_{\tilde{\tau}}$

\[ m_{\tilde{q}}(1,2) = 100\text{GeV}, \quad m_{\tilde{q}}(3) = 1400\text{GeV}, \quad m_{1/2} = 550\text{GeV}, \quad A_0 = 0, \quad \tan \beta = 30, \quad \mu > 0, \quad m_t = 175\text{GeV} \]
$\chi^2$ for NU SUGRA:

- **green**: low $\chi^2/\text{dof}$
- **yellow**: medium $\chi^2/\text{dof}$
- **red**: high $\chi^2/\text{dof}$
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<tr>
<th>parameter</th>
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<td>$BF(b \rightarrow s\gamma)$</td>
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<tr>
<td>$\Delta a_\mu$</td>
<td>$35.1 \times 10^{-10}$</td>
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Masses and parameters in GeV units for
$m_0(3)$, $m_{1/2}$, $A_0$, $\tan \beta$, $\text{sign}(\mu) = 1500$ GeV, 450 GeV, 0, 30, +1 in the NMH SUGRA model. We also take $m_H = m_0(3)$ and $m_0(1) = 100$ GeV. The spectrum is obtained using ISAJET v7.69.
Conclusions

- Constraints on mSUGRA (esp. WMAP)
  - “bulk” region dis-favored
  - stau co-annihilation strip
  - HB/FP region at large $m_0$
  - $A$-annihilation funnel

- reach of 0.5-1 TeV LC
  - see stau co-ann. region for $\tan \beta \lesssim 30$
  - see HB/FP region beyond LHC capability!
  - see part of $A$-annihilation funnel (LHC can see $\sim$ all)

- determination of $\mu$, $M_2$ possible in (lower) HB/FP region

- non-universal SUGRA motivated by $BF(b \to s\gamma)$, $(g - 2)_\mu$

- generically gives light sleptons; accessible to LC!