Linear Collider Capabilities for Supersymmetry in Dark Matter Allowed Regions of the mSUGRA Model

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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 the Tevatron

• prospects for mSUGRA at the CERN LHC

• prospects for mSUGRA at a linear \( e^+e^- \) collider

• parameter determination in the HB/FP region

• indirect DM detection

• LC connection to leptogenesis

• 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: $K = \Sigma_i \hat{S}_i \hat{S}_i + \hat{h}^\dagger \hat{h}$
- 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
  - $m_0$, $m_{1/2}$, $A_0$, $\tan \beta$, $\text{sign}(\mu)$

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 $BF(b \rightarrow s\gamma)$ HB, Brhlik, Castano, Tata
    * $BF(b \rightarrow s\gamma) = (3.25 \pm 0.54) \times 10^{-4}$ (incl. 12% theory)
  - calculate SUSY contribution to $(g - 2)_\mu$ HB, Balazs Ferrandis, Tata
    * $\Delta a_\mu = (24.1 \pm 14.0) \times 10^{-10}$ (Narison $e^+e^-$)

- 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, $b \rightarrow s\gamma, (g - 2)_\mu$)
$\chi^2$ for $\mu < 0$:

- **green**: low $\chi^2/dof$
- **yellow**: medium $\chi^2/dof$
- **red**: high $\chi^2/dof$
\( \chi^2 \) for \( \mu > 0 \):

- **green**: low \( \chi^2 / dof \)
- **yellow**: medium \( \chi^2 / dof \)
- **red**: high \( \chi^2 / dof \)
\( \chi^2 \) for \( \mu > 0 \) and large tan\( \beta \):

- **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$^{-1}$

$mSugra$ with $\tan\beta = 10$, $A_0 = 0$, $\mu > 0$

\[ m_{\mu/2} \text{ (GeV)} \]

\[ m_0 \text{ (GeV)} \]
Sparticle masses/ cross sections in the HB/FP region:

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

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

- In HB/FP, $\mu \to 0$

![Graphs showing distributions](image-url)
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$^{-1}$

**mSugra with tan$\beta = 45$, $A_0 = 0$, $\mu < 0$**

- $\text{B} \cdot \sigma (Z_1 Z_2) = 2 \text{ fb (LC500)}$
- $m(\tau_1) = 250 \text{ GeV}$
- $m(H^+) + m(Z^0) = 500 \text{ GeV}$
- $m(A^0) + m(h^0) = 500 \text{ GeV}$
- $m(H^+) = 250 \text{ GeV}$
- $\sqrt{s} = 500 \text{ GeV}$
- $\sqrt{s} = 1 \text{ TeV}$
- $\text{Far HB/FP cuts}$

**l$^+$l$^-$ cuts**

- Standard $W^+ W^-$ cuts
Reach of linear $e^+e^-$ collider:

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

$m$Sugra 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$^{-1}$

![Graph of mSugra with tanb = 10, A_0 = 0, $\mu > 0$]
Compare all colliders with WMAP allowed region:

- LC reach for $\sqrt{s} = 0.5$ and 1 TeV, 100 fb$^{-1}$
Compare all colliders with WMAP allowed region:

- LC reach for $\sqrt{s} = 0.5$ and 1 TeV, 100 fb$^{-1}$
Compare all colliders with WMAP allowed region:

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

![Graph showing mSugra with tan$\beta = 52$, $A_0 = 0$, $\mu > 0$]
Determination of fundamental parameters:

- $m(jj)$ vs. $E(jj)$
Determination of fundamental parameters:

- $E(jj)$ bins

![Graphs showing distribution of events vs. $E(jj)$ for different masses.](image_url)
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 $\sigma(\tilde{W}_1^+\tilde{W}_1^-)$
Probing neutralino resonance annihilation via indirect detection of DM

- **Indirect detection via:**
  - $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow X \rightarrow \nu$ in core of earth or sun
  - $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow X \rightarrow \gamma$ in galactic core or halo
  - $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow X \rightarrow e^+$ in halo
  - $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow X \rightarrow \bar{p}$ in halo
  - see e.g. DarkSUSY by Gondolo, Edsjo, Ullio, Bergstrom, Schelke and Baltz

- in stau co-annihilation region, *no* indirect signals

- in HB/FP region, large annihilation cross section, *and* large $\tilde{\chi}_1^0 p$ cross section: *all* signals may be observable (see Feng, Matchev, Wilczek)

- in $A$ funnel, $\sigma(\tilde{\chi}_1^0 p)$ small, so neutrino signal absent, but large $\sigma(\tilde{\chi}_1^0 \tilde{\chi}_1^0)$ cross section gives large rates for $\gamma$, $e^+$, $\bar{p}$ signals

Leptogenesis and the LC

- 1. Neutrinos have mass
- 2. Most elegant way to arrange $m_\nu$: see-saw (GRS, Y)
- 3. Add gauge singlet $\hat{N}^c$ chiral superfield to MSSM, one for each generation
- 4. superpotential
  \[ -\hat{f} \equiv f_\nu e_{ij} \tilde{L}^i \tilde{H}_u^j \hat{N}^c + \frac{1}{2} M_N \hat{N}^c \hat{N}^c \]
- 5. soft terms
  \[ -\mathcal{L}_{\text{soft}} \ni -m^2_{\nu R} |\tilde{\nu}_R|^2 + \left[ A_\nu f_\nu e_{ij} \tilde{L}^i \tilde{H}_u^j \tilde{\nu}_R^\dagger + \frac{1}{2} B_\nu M_N \tilde{\nu}_R^2 + \text{h.c.} \right] \]
- 6. In $SO(10)$, $f_{\nu_R} = f_t$ at $Q = M_{\text{GUT}}$ so $f_\nu$ big
- 7. $f_\nu$ contributes to RGE running of 3rd gen. sleptons:
  \[
  \Delta_R = m^2_{e_R} - m^2_{\tau_R}, \\
  \Delta_L = m^2_{\tilde{e}_L} - m^2_{\tilde{\tau}_L}, \\
  \frac{d}{dt} (2\Delta_L - \Delta_R) = \frac{4}{16\pi^2} f_\nu^2 X_\nu
  \]

- RGEs: see HB, Diaz, Quintana and Tata, JHEP0004, 016 (2000)

- precision measurement of 1st and 3rd gen. slepton masses to $\sim 3\%$ will show influence of $f_\nu$ and $M_N$; important parameters for leptogenesis scenario!

- for details, see HB, Balazs, Mizukoshi, Tata; PRD63, 055011 (2001).
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