**SUSY Searches at LEP**

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**Outline:**

- SUSY Framework
- LEP
- Searches:
  - Sneutrino
  - Smuon
  - Stop
  - Charginos
  - Neutralinos
- SUSY Limits

supported by BMBF
Beyond SM

SUSY

MSSM-124

MSSM-6
(e+ e-)

mSUGRA
(p p)

GMSB

MSSM
R parity violation
MSSM-6 = CMSSM

Assumptions:
GUT, no CP violation, generation-independence . . .
R parity conserved!

Parameters:

• $m_0 =$ Universal scalar mass at GUT scale
  $0 \ldots \approx 2000$ GeV

• $M_2 =$ $SU(2)$ Gaugino mass at electroweak scale
  $0 \ldots \approx 2000$ GeV

• $\mu =$ Higgs mass parameter (elw)
  $\approx -2000 \ldots \approx 2000$ GeV

• $\tan \beta =$ ratio of vacuum expectation values (elw)
  $1 \ldots \approx 50$

• $A_0 =$ Universal trilinear couplings (GUT)
  $0 \ldots \approx 2000$ GeV (sfermion mixing)

• $m_A =$ Physical mass of CP-odd Higgs
  $0 \ldots \approx 2000$ GeV (higgs masses)

Additional requirement: LSP (Lightest Susy Particle)
has no electromagnetic or strong interaction
(cosmology) $\rightarrow \tilde{\chi}, \tilde{\nu}$
**LEP 1:**
1989 - 1995
\[ \sqrt{s} \approx 91 \text{ GeV} \]
\[ L = 160 \text{ pb}^{-1} / \text{experiment} \]

Advantages:
- Xsection high
- \( Z \) (invisible) width: limits independent of decay mode

**LEP 2:**
1996 - 2000
\[ \sqrt{s} = 160 - 200 \text{ GeV} \]
\[ L = 260 \text{ pb}^{-1} / \text{experiment} \]
in 1996-1998

Advantages:
- Center of mass energy large
MSSM-6 Searches at LEP

Squarks $\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}$ and Gluinos $\tilde{g}$ are heavy → Tevatron!

**LEP:**

- **Sneutrino $\tilde{\nu}$**
  all three families mass degenerate

- **Smuon $\tilde{\mu}$**
  representative for $\tilde{e}, \tilde{\mu}, \tilde{\tau}$

- **Stop $\tilde{t}$**
  representative for $\tilde{b}, \tilde{t}$
  for heavy quarks mixing possibly large and $\tilde{t}_1$ light:

  \[
  \tilde{t}_L \quad \tilde{t}_R \quad \rightarrow \quad \tilde{t}_1 \quad \tilde{t}_2
  \]

- **Charginos $\chi^\pm_1 < \chi^\pm_2$**

- **Neutralinos $\chi^0_1 < \chi^0_2 < \chi^0_3 < \chi^0_4$**
  $\chi^0_1$ is favorite LSP candidate

**SIGNATURE:** Missing energy and momentum

Also: MSSM-Higgs searches at LEP
(see previous talks)
Sneutrino

3 families degenerate!

PRODUCTION:

Sneutrino can be stable or might DECAY:

In both cases missing energy in the final state!

Limit from invisible Z width measured at LEP I:

$$\Gamma_{\text{inv}} < 2.8 \text{ MeV} \quad 95\% \text{ CL}$$

RESULT (‘indirect’ limit):

$$m > 43 \text{ GeV} \quad 95\% \text{ CL}$$
**Smuon**

**PRODUCTION and DECAY:**

\[
\begin{array}{c}
e \to Z/\gamma \to \mu \bar{\mu} \to \mu \bar{\mu} \gamma \to \mu \bar{\mu} \tilde{\chi}^0 \tilde{\chi}^0 \to 2 \mu
\end{array}
\]

**SIGNATURE:**
Two acollinear muons

**BACKGROUNDS:**
‘two photon’: \(e^+e^-\mu^+\mu^-\)
\(W\) pairs: \(W^+W^-\)

**REMARKS:**
- Visible only if \(\Delta m = m(\tilde{\mu}) - m(\tilde{\chi}_{1}^0) > \) a few GeV.
- Righthanded sfermions are lighter than lefthanded ones!

No signal found!
Smuon Candidate (ALEPH, $\sqrt{s} = 181$ GeV)
OPAL

lightest neutralino mass (GeV)

smuon mass (GeV)

0.07 pb

0.12 pb

0.21 pb

0.28 pb

0.21 pb

0.28 pb

0.12 pb


tan\beta = 1.5

\mu < -100 \text{ GeV}

Excluded Region

for tan\beta = 1.5

for tan\beta = 35
PRODUCTION:

\[
\begin{align*}
\text{e} & \xrightarrow{Z/\gamma} \tilde{t} \\
\text{e} & \xrightarrow{Z/\gamma} \tilde{t}
\end{align*}
\]

DECAY:

\[
\begin{align*}
\tilde{t} & \xrightarrow{c} \tilde{\chi}^0 \\
\tilde{t} & \xrightarrow{b} \tilde{\chi}^+ \tilde{\nu}
\end{align*}
\]

SIGNATURE:

Two acollinear jets (+ leptons)

BACKGROUNDs:

‘two photon’: \( e^+ e^- q \bar{q} \), ‘4-fermion’: \( Z \gamma^* \ldots \)

REMARKS:

- Visible only if \( \Delta m = m(\tilde{t}) - m(\tilde{\chi}^0_1, \tilde{\nu}) > \text{a few GeV.} \)

- Mixing: \( \tilde{t}_1 = \tilde{t}_L \cos \theta_{LR} + \tilde{t}_R \sin \theta_{LR} \)
  influences mass and couplings
  For \( \cos \theta_{LR} = 0.57 \) NO coupling to \( Z \)!

No signal found!
Stop Candidate (L3, $\sqrt{s} = 183$ GeV)

Run #  673109  Event #  3053  Total Energy :  30.64 GeV
$\tilde{t}_1 \rightarrow c \, \tilde{\chi}_1^0$

Excluded by CDF

$M_{\tilde{t}_1}$ (GeV)

$M_{\tilde{\chi}_1^0}$ (GeV)

$\cos \theta_{LR} = 1.0$

$\cos \theta_{LR} = 0.57$

Excluded
Chargino

PRODUCTION:

\[ \text{e} \gamma / Z \text{e} \rightarrow \tilde{\chi}^+ \tilde{\chi}^- \]

DECAY:

\[ \tilde{\chi}^+ \rightarrow l \tilde{\nu} \]

\[ \tilde{\chi}^+ \rightarrow W^+ f \]

SIGNATURE:

lepton

jet

lepton

jet

jet

jet

BACKGROUNDS:

‘two photon’: \( e^+ e^- f \bar{f} \), ‘4-fermion’: \( W^+ W^- , Z \gamma^* \ldots \)

REMARK:

- Visible only if \( \Delta m = m(\tilde{\chi}^+) - m(\tilde{\chi}_1^0) > \text{a few GeV} \).

No signal found !
Chargino Candidate (OPAL, $\sqrt{s} = 182$ GeV)
$\sigma(\chi^+\chi^-) \text{ limit (pb)}$

$m(\chi^\pm) = 94 \text{ GeV}$

heavy sleptons assumed!
Chargino Limits for small $\Delta M$

$\Delta M^\pm$ (GeV/c$^2$)

ISR = Initial state radiation: Photon + soft particles

Long Lived = displaced vertex

or

stable particle: highly ionizing!
Neutralino

PRODUCTION:

\[ e^+ e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \text{ invisible!} \]

DECAY:

SIGNATURE:

BACKGROUNDS:

'two photon': \( e^+ e^- f \bar{f} \), '4-fermion': \( ZZ, W^+ W^- \ldots \)

REMARK:

- Visible only if \( \Delta m = m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0) > \text{a few GeV} \).

No signal found!
assuming $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + q \bar{q}$
How to obtain MSSM-6 Limits?

- **Search** and calculate experimental limits on cross sections, branching fractions...

- Calculate **excluded SUSY parameter** ($M_2, \tan \beta \ldots$) regions:
  For a given point compare MSSM cross sections etc. to the experimental limits.

- **Determine sparticle mass limits:**
  Scan through **allowed subspace** of 6-dim SUSY parameter space and calculate mass values → lower mass limit

  Note: limit in general better than from direct search in the corresponding channel!
$m_0 > 500 \text{ GeV}$

any $m_0$
MSSM-6 Limits

\[ m_0 \text{ (GeV)} \]

\[ M_2 \text{ (GeV)} \]

L3

\[ \mu = -200 \text{ GeV} \]

\[ \tan \beta = 5 \]

\[ \tan \beta = 2 \]

\[ \tan \beta = \sqrt{2} \]

\[ \text{D0 } \tan \beta = 2 \]

mSUGRA

Excluded at 95\% C.L.
MSSM-6 Mass Limits

All limits ‘unconditional’ !, CL = 95%

• Sneutrino $\tilde{\nu}$

  \[ m > 43 \text{ GeV} \]

• Neutralino $\chi_1^0$

  \[ m > 32.5 \text{ GeV} \quad (L3, \text{prelim.}) \]

• Charged Slepton $\tilde{\epsilon}_R, \tilde{\mu}_R, (\tilde{\tau}_R)$

  \[ m > 41 \text{ GeV} \]

• Chargino $\chi_1^\pm$

  \[ m > 67.7 \text{ GeV} \quad (L3, \text{prelim.}) \]

\[ m(LSP) > 32.5 \text{ GeV} \]

??? MSSM-6 parameter space fully investigated ????
Preliminary Gaugino Mass Limits

Neutralino:

\[ m(\tilde{\chi}_1^0) \geq 27.9 \text{ GeV} \]

\[ m_0 > 500 \text{ GeV} \]

\[ \tan \beta > 500 \text{ GeV} \]

Chargino \((M_2 < 2 \text{ TeV})\):

\[ \text{L3} \quad 67.7 \text{ GeV} \]

\[ \text{Opal} \quad 65.1 \text{ GeV} \]

Aleph \quad 32.3 \text{ GeV}

Delphi \quad 31.2 \text{ GeV}

L3 \quad 32.5 \text{ GeV}

Opal \quad 27.9 \text{ GeV}
Conclusions

- SUSY particles have been searched for intensively at LEP I and LEP II
- Nothing was found yet
- Limits on SUSY parameters, sparticle masses and cross sections have been set
  MSSM-6: LSP mass $> 32.5 \text{ GeV}$ (prel.)
- The hunt continues:
  2 more years of data at $\approx 200 \text{ GeV}$ . . .