Chargino and Neutralino Searches at LEP

Beyond the Standard Searches

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DESY

Outline

- MSSM Particle Spectrum
- Chargino/Neutralino Production at LEP
- Chargino/Neutralino Decays
- Supersymmetry Breaking
- Experimental Results
 - SUGRA
 - GMSB
 - AMSB
- Summary

MSSM Particle Spectrum

SM particle	SUSY particle	
	weak eigenstates	mass eigenstates
ν_L	$\tilde{\nu}_L$	$\tilde{\nu}_L$
$\ell_{L,R}^\pm$	$\tilde{\ell}_{L,R}^\pm$	$\tilde{\ell}_{1,2}^\pm$
$q_{L,R}$	$\tilde{q}_{L,R}$	$\tilde{q}_{1,2}$
g	$\tilde{g}$	$\tilde{g}$
h, H, A	$\tilde{h}, \tilde{H}$	$\left. \begin{array}{c} \\ \\ \end{array} \right\} \tilde{\chi}_j^0$
γ	$\tilde{\gamma}$	
Z^0	$\tilde{Z}^0$	
$H^\pm$	$\tilde{H}^\pm$	$\left. \begin{array}{c} \\ \end{array} \right\} \tilde{\chi}_i^\pm$
$W^\pm$	$\tilde{W}^\pm$	
G	$\tilde{G}$	$\tilde{G}$

Interlude: R -Parity

- as a result of $(B - L)$ invariance, MSSM comes along with a multiplicative R -parity invariance

$$R = (-1)^{3(B-L)+2S} \Rightarrow \begin{cases} 1 \text{ SM particles} \\ -1 \text{ SUSY particles} \end{cases}$$

- consequences:

- supersymmetric particles must be produced in pairs
- the lightest supersymmetric particle (LSP) is
 - absolutely stable
 - terminates the decay chain of every SUSY particle
 - almost certainly electrically and color neutral

(unless otherwise mentioned R -parity conservation is assumed)

$\tilde{\chi}^\pm$ and $\tilde{\chi}^0$ Production at LEP

● Chargino Production

● Neutralino Production

$\tilde{\chi}^{\pm}$ and $\tilde{\chi}^0$ Decays (Examples)

● Chargino Decays

● Neutralino Decays

SUSY Signatures

signature	example	scenario
jets + $\cancel{E}$	$\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow q\bar{q}'q''\bar{q}''' \tilde{\chi}_1^0 \tilde{\chi}_1^0$	SUGRA
jets + leptons + $\cancel{E}$	$\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow q\bar{q}'\ell^+\ell^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$	SUGRA
leptons + $\cancel{E}$	$\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \ell^+\ell^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$	SUGRA
γ + $\cancel{E}$	$\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \gamma \tilde{\chi}_1^0 \tilde{\chi}_1^0$	SUGRA
low momentum pions + $\cancel{E}$	$\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow (n\pi) \tilde{\chi}_1^0 \tilde{\chi}_1^0 \ (n = 1, 2, 3)$	AMSB, SUGRA
$\gamma\gamma$ + $\cancel{E}$	$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma\gamma \tilde{G}\tilde{G}$	GMSB
$\tau^+\tau^-$ + $\cancel{E}$	$\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tau^+\tau^-\nu_\tau\bar{\nu}_\tau \tilde{G}\tilde{G}$	GMSB
stable, heavy, charged particles kinked tracks secondary vertices	long-lived charginos	all
...	...	...

Supersymmetry Breaking

Hidden Sector
SUSY Breaking

- assume SUSY is realized in nature
- SM particles and SUSY particles are not mass-degenerate
- SUSY is not an exact symmetry of nature
- SUSY must be broken

?

Observable Sector
MSSM

general parameterization leads to more than 100 new parameters

(m)SUGRA

Hidden Sector
SUSY Breaking

- gauge couplings unify at ultra-high energy scale M_X
- SUSY breaking defined at M_X arises due to **gravitational interaction**
- SUGRA-inspired Constrained MSSM (CMSSM) defined by 6 parameters
 - m_0 common scalar mass at M_P
 - M_2 $SU(2)$ gaugino mass parameter at M_{EW}
 - $\tan \beta$ v_2/v_1 VEV ratio of two Higgs doublets
 - μ mixing parameter of Higgs doublet fields
 - A_0 trilinear sfermion/Higgs coupling
 - m_A pseudoscalar Higgs mass at M_{EW}
- LSP: $\tilde{\chi}_1^0$ ($\tilde{\nu}$)

gravitational
interaction

Observable Sector
MSSM

SUGRA: Decay Topologies

chargino channel: $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow f \bar{f}' f'' \bar{f}''' \tilde{\chi}_1^0 \tilde{\chi}_1^0$

final states	BR [%]	topology
$q\bar{q}' q\bar{q}'$	46	jets+ $\cancel{E}$
$q\bar{q}' \ell^- \bar{\nu}$	44	jets + lepton + $\cancel{E}$
$\ell^+ \nu \ell^- \bar{\nu}$	11	leptons + $\cancel{E}$

neutralino channel: $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow f \bar{f}' \tilde{\chi}_1^0 \tilde{\chi}_1^0$

final states	BR [%]	topology
$q\bar{q}' q\bar{q}'$	70	jets+ $\cancel{E}$
$q\bar{q}' \ell^- \bar{\nu}$	10	leptons + $\cancel{E}$
	20	invisible

Cross-section Limits $\tilde{\chi}^0$

$$\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow Z^{0(*)} \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

- OPAL 95% C.L. upper σ limit at $\sqrt{s} = 208$ GeV
- assuming 100% Z^0 BRs
- region $M_{\tilde{\chi}_2^0} + M_{\tilde{\chi}_1^0} < M_{Z^0}$ is not considered
- exclusion to kinematic limit for $\Delta M^0 = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} > 10$ GeV
- $M_{\tilde{\chi}_1^0} > 44.9$ GeV
- $M_{\tilde{\chi}_2^0} > 79.6$ GeV
(any m_0 , $\tan \beta = 1.5$)

Cross-section Limits $\tilde{\chi}_1^\pm$

$$\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow f \bar{f}' f'' \bar{f}''' \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

- L3 95% C.L. upper σ limit at $\sqrt{s} = 208 \text{ GeV}$
 - assuming 100% $W^\pm$ BRs
 - exclusion to kinematic limit for $\Delta M^\pm = M_{\tilde{\chi}_1^\pm} - M_{\tilde{\chi}_1^0} > 3 \text{ GeV}$
- small $\Delta M^\pm$ region ←

Interlude: Small $\Delta M^\pm$ Searches

- small $\Delta M^\pm$ implications
 - trigger:
 - Large $\Delta M^\pm$: no problem
 - Small $\Delta M^\pm$: only little detector activity
 - background:
 - Large $\Delta M^\pm$: 4-fermion ($\sigma \sim 20\text{pb}$)
 - Small $\Delta M^\pm$: 2-photon ($\sigma \sim \mathcal{O}(\text{nb})$)
- solution:
 - use hard ISR photons in order to
 - increase the trigger efficiency
 - reduce the two-photon background
- tradeoff:
 - small signal efficiency ($\epsilon \sim \mathcal{O}(1\%)$)

(for more details see talk by S. Paiano)

Small $\Delta M^\pm$ Topology

Signal

● $\sigma_{\text{LEP}} \sim \mathcal{O}(\text{pb})$

Two-Photon-Event

$$e^+e^- \rightarrow e^+e^-\gamma^{(*)}\gamma^{(*)} \rightarrow e^+e^-X$$

● $\sigma_{\text{LEP}} \sim \mathcal{O}(\text{nb})$

Small $\Delta M^\pm$ and ISR

- require ISR-Photon with $E_T > \sqrt{s} \frac{\sin \theta_D}{1 + \sin \theta_D}$
(θ_D : minimal accessible polar angle)

- signal and background events become distinguishable:
 - reject event if beam electron is detected

The Very Small $\Delta M^\pm$ Region

- for decreasing $\Delta M^\pm$ lifetime effects become important

- depending on expected lifetime search for:

- secondary vertices
- impact parameters
- stable, heavy, charged particles (dE/dx)

$\tilde{\chi}_1^\pm$ quasi-stable

- OPAL 95% C.L. upper σ limit at $\sqrt{s} = 206.3$ GeV

- $M_{\tilde{\chi}_1^\pm} > 102$ GeV
(for $\tau_{\tilde{\chi}_1^\pm} > 1\mu s$)

Mass Limits $\tilde{\chi}_1^\pm$

$$\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow X \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

- Aleph 95% C.L. excluded $M_{\tilde{\chi}_1^\pm}$ region
($\sqrt{s} = 189\text{-}209\text{ GeV}$)
- $M_{\tilde{\chi}_1^\pm} > 89\text{ GeV}$
($m_0 > 500\text{ GeV}$)
- many analyses not shown
- mass limits translate into limits on
 - μ
 - M_2
 - $\tan \beta$
 - ...

(for more details see talk by B. Tellili)

GMSB

- poor man's GMSB construction kit
 - hidden sector with broken SUSY
 - messenger sector: particles with $SU(3) \times SU(2) \times U(1)$ quantum numbers
 - observable sector with MSSM
- free parameters
 - Λ universal mass scale of SUSY particles
 - N number of messenger pairs
 - M_m messenger mass scale
 - $\tan \beta$ VEV ratio of two Higgs doublets
 - $\text{sign}(\mu)$ sign of Higgs mixing parameter fields
 - $\sqrt{F}$ SUSY breaking scale
- implications
 - LSP: gravitino $\tilde{G}$, ($M_{\tilde{G}} \sim \text{eV} - \text{keV}$)
 - NLSP determines topology

Hidden Sector
SUSY Breaking

direct
coupling

Messenger Sector

virtual
exchange

Observable Sector
MSSM

GMSB: NLSP and Signal Topologie

scenario	sparticle production	final state (+ $\tilde{G}\tilde{G}$)
neutralino NLSP	$\tilde{\chi}_1^0 \tilde{\chi}_1^0$	$\gamma\gamma$
	$\tilde{\ell}_R \tilde{\ell}_R$	$\gamma\gamma \ell\ell$
	$\tilde{\chi}_1^+ \tilde{\chi}_1^-$	$\gamma\gamma W^{+(*)} W^{-(*)}$
	$\tilde{\chi}_1^0 \tilde{\chi}_2^0$	$\gamma\gamma Z^{0(*)}$
slepton co-NLSP ($M_{\tilde{\ell}_R} < \min[M_{\tilde{\chi}_1^0}, M_{\tilde{\tau}_1} + M_\tau]$)	$\tilde{\chi}_1^0 \tilde{\chi}_1^0$	$\ell\ell' \ell\ell'$
	$\tilde{\ell}_R \tilde{\ell}_R$	$\ell\ell$
stau NLSP	$\tilde{\chi}_1^+ \tilde{\chi}_1^-$	$\tau\nu_\tau \tau\bar{\nu}_\tau$
	$\tilde{\ell}_R \tilde{\ell}_R$	$\tau\tau \ell\ell \tau\tau$
	$\tilde{\tau}_1 \tilde{\tau}_1$	$\tau\tau$
neutralino-stau co-NLSP ($ M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} < M_\tau$)	$\tilde{\chi}_1^0 \tilde{\chi}_1^0$	$\gamma\gamma$
	$\tilde{\tau}_1 \tilde{\tau}_1$	$\tau\tau$

GMSB: The NLSP Lifetime

- NLSP lifetime depends on gravitino mass ($M_{\tilde{G}} \propto (\sqrt{F})^2$):

$$c\tau_{NLSP} \simeq \frac{1}{100} \left(\frac{\sqrt{F}}{100\text{TeV}} \right)^4 \left(\frac{M_{NLSP}}{100\text{GeV}} \right)^{-5} \text{cm}$$

- $c\tau_{NLSP} = \mathcal{O}(1\mu\text{m})\text{-}\mathcal{O}(10\text{m}) \Leftrightarrow 30\text{ TeV} < \sqrt{F} < 1800\text{ TeV}$
- each final state may have one out of three possible topologies:
 - prompt decays
 - decays within the detector but separated from primary vertex
 - decays outside of the detector
- only a few examples of analyses can be shown ...

A Selection of GMSB Scenarios

- Minimal Gauge Mediated SUSY Breaking Scenario
 - constraints on slepton and gaugino masses
 - $\tilde{\chi}_1^0$ is NLSP
channel: $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma\gamma \tilde{G}\tilde{G}$
signature: $\gamma\gamma + \cancel{E}$
 - $\tilde{\tau}_1$ is NLSP
channel: $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow \tau^+ \tau^- \nu_\tau \bar{\nu}_\tau \tilde{G}\tilde{G}$
signature: $\tau^+ \tau^- + \cancel{E}$
- Extended Gauge Mediated SUSY Breaking Scenario
 - no severe constraints on slepton and gaugino masses
 - search for classic SUSY signatures (+ photons)
 - $\tilde{\chi}_1^0$ is NLSP
channel: $e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0 \rightarrow Z^{(*)} \gamma\gamma \tilde{G}\tilde{G}$
signature: $f \bar{f} \gamma\gamma + \cancel{E}$

GMSB: $\gamma\gamma + \cancel{E}$

● $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma\gamma \tilde{G}\tilde{G}$

● main background $e^+e^- \rightarrow \nu\bar{\nu}\gamma\gamma(\gamma)$

● Aleph analysis:

- after two-photon selection 93 candidates remain while 88 events expected
- cuts are optimized using the 'Minimal Gauge Mediated SUSY Breaking Model'
(e.g. $\min(E_1^\gamma, E_2^\gamma) > 37 \text{ GeV}$)
- $\tilde{\chi}_1^0$ mass limits $\Rightarrow$

GMSB: $\gamma\gamma + \cancel{E}$, Mass Limits

- $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \gamma\gamma \tilde{G}\tilde{G}$
- cross-section $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ depends strongly on $M_{\tilde{e}_R^\pm}$
- 'CDF region' corresponding to $q\bar{q} \rightarrow \tilde{e}_R \tilde{e}_R \rightarrow ee \tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow ee \gamma\gamma \tilde{G}\tilde{G}$
- mass limits calculated for $\tilde{\chi}_1^0$ lifetime smaller than 3 ns
- Aleph lower mass limit:
 $M_{\tilde{\chi}_1^0} \geq 99 \text{ GeV at 95\% C.L.}$
($\sqrt{s} = 189\text{-}208 \text{ GeV}$)

GMSB: $\gamma\gamma + \cancel{E}$, More Limits

L3, assuming prompt decays

DELPHI preliminary, $\sqrt{s} = 192 - 209\text{ GeV}$

GMSB: $\tau^+\tau^- + \cancel{E}$

- sensitive to $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tau^+\tau^-\nu_\tau\bar{\nu}_\tau\tilde{G}\tilde{G}$
- search strategy depends on NLSP ($\tilde{\tau}_1$) lifetime (DELPHI approach):
 - $M_{\tilde{G}} \lesssim 1\text{eV}$
 $\tilde{\chi}_1^\pm$ decays at vertex $\Rightarrow$ apply 'standard' SUGRA search
 - $1\text{eV} \lesssim M_{\tilde{G}} \lesssim 1000\text{eV}$
 $\tilde{\chi}_1^\pm$ has intermediate mean decay length
 - $1000\text{eV} < M_{\tilde{G}}$
 $\tilde{\chi}_1^\pm$ is quasi-stable $\Rightarrow$ apply search for stable, heavy, charged particles

GMSB: $\tau^+\tau^- + \cancel{E}$, Mass Limits

DELPHI, published, $\sqrt{s} = 183 - 202 \text{ GeV}$

all $M_{\tilde{G}}$

$M_{\tilde{G}} > 100 \text{ eV}$

$M_{\tilde{G}} > 1000 \text{ eV}$

$M_{\tilde{\chi}_1^\pm}$ limit at 95% C.L.

($\Delta M > 0.3 \text{ GeV}$)

95.2 GeV

96.8 GeV

99.0 GeV

GMSB: $f\bar{f}\gamma\gamma+\cancel{E}$

- sensitive to

$$e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^0 \rightarrow Z^{0(*)}\gamma\gamma\tilde{G}\tilde{G}$$
- OPAL procedure:
 - low- and high multiplicity selection
 - $\Delta M^0 = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$ dependent selection
 - consider nonzero $\tilde{\chi}_1^0$ lifetime
 - two-photon selection
 - one-photon selection
 - zero-photon selection (SUGRA)

GMSB: $f\bar{f}\gamma\gamma+E$, Cross-section Limit

$$e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0 \rightarrow Z^{0(*)} \gamma \gamma \tilde{G} \tilde{G}$$

- limits at 95% C.L. for $e^+e^- \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0$ at $\sqrt{s} = 206.1 \text{ GeV}$
- assuming $\tilde{\chi}_2^0 \rightarrow Z^{0(*)} \tilde{\chi}_1^0$ decays
- followed by prompt $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$ decay

AMSB

Hidden Sector
SUSY Breaking

- anomalous mediated SUSY breaking:
SUSY particle masses are generated at loops
 - gaugino masses at one loop
 - scalar masses at two loops
- free parameters
 - m_0 common scalar mass
 - $m_{3/2}$ gravitino mass
 - $\tan \beta$ VEV ratio of two Higgs doublets
 - $\text{sign}(\mu)$ sign of Higgs mixing parameter
- LSP: $\tilde{\chi}_1^0$

Observable Sector
MSSM
(masses via loops)

AMSB: Implications

- $\tilde{\chi}_1^0$ is LSP
 - small mass splitting $\Delta M^\pm \sim 1$ GeV between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$
 - $e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow (n\pi) \tilde{\chi}_1^0 \tilde{\chi}_1^0$
 - typical signature: $\cancel{E}$ + little detector activity
 - use ISR Method
 - no mass limits available yet
 - but analyses are underway
 - still help needed from theory community
 - cross-sections
 - branching ratios
 - ...
- lack of software that can do the calculations and produce measurable quantities

AMSB: Small $\Delta M^\pm$ Candidate

ALEPH, $\sqrt{s} = 195.4$ GeV, $E_\gamma \approx 21$ GeV, $M_{\tilde{\chi}_1^\pm} < 84$ GeV

Prospects

- most results are preliminary
- more general results are expected for the next months
- LEP combinations will complete the searches
- Y2k data:
 - 220 pb⁻¹ per experiment with $\sqrt{s} \geq 200.0$ GeV
 - 9 pb⁻¹ per experiment with $\sqrt{s} \geq 207.5$ GeV

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Summary

- Aleph, Delphi, L3, OPAL considered a huge variety of SUSY scenarios respectively search channels
(R -parity violating scenarios not even mentioned)
- $\tilde{\chi}_1^\pm$ excluded at 95% C.L. in almost full kinematically accessible region at LEP2
- still unexcluded parameter space
- final analyses will be more general
- LEP combined analyses will be base and benchmark for the following years