Search for new particles at LEP2

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DESY, 8-9 April 2003
12 years of excellent e+e- data

$E_{cm}$ 91-209 GeV, $\sim$1000 pb$^{-1}$/Exp

<table>
<thead>
<tr>
<th>Year</th>
<th>Lum/Exp (pb$^{-1}$)</th>
<th>$E_{cm}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>89-95</td>
<td>175</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td></td>
<td>130-136</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>161-172</td>
</tr>
<tr>
<td>1995</td>
<td></td>
<td>183</td>
</tr>
<tr>
<td>1996</td>
<td>22</td>
<td>189</td>
</tr>
<tr>
<td>1997</td>
<td>55</td>
<td>192-202</td>
</tr>
<tr>
<td>1998</td>
<td>160</td>
<td>204-209</td>
</tr>
<tr>
<td>1999</td>
<td>230</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>220</td>
<td></td>
</tr>
</tbody>
</table>

**LEP2:** $E_{cm}$ 161-209 GeV
Lum $\sim$2700 pb$^{-1}$
Last data in 2000, analyses being finalised now...

**LEP Working Groups:**

- Fruitful collaboration between experiments:
- Combined results
LEP Physics

- SM tests to ~0.1%
- $m_{\text{top}}$ indirect estimation
- $m_{\text{Higgs}}$ indirect limits

$N_\nu = 2.9841 \pm 0.0088$

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**Summer 2002**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Pull $\Delta_{\text{meas}} - \Delta_{\text{fit}}/\sigma_{\text{meas}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m^{(S)}_{\text{had}}(m_Z)$</td>
<td>$0.02761 \pm 0.00036$</td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>$91.1875 \pm 0.0021$</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>$2.4952 \pm 0.0023$</td>
</tr>
<tr>
<td>$\sigma_{\text{had}}^{(S)}$ [nb]</td>
<td>$41.540 \pm 0.037$</td>
</tr>
<tr>
<td>$R_\tau$</td>
<td>$20.767 \pm 0.025$</td>
</tr>
<tr>
<td>$A_{\text{fb}}$</td>
<td>$0.01714 \pm 0.00095$</td>
</tr>
<tr>
<td>$A_{l}(P_{\ell})$</td>
<td>$0.1465 \pm 0.0032$</td>
</tr>
<tr>
<td>$R_b$</td>
<td>$0.21644 \pm 0.00065$</td>
</tr>
<tr>
<td>$R_c$</td>
<td>$0.1718 \pm 0.0031$</td>
</tr>
<tr>
<td>$A_{\text{fb}}^{0,b}$</td>
<td>$0.0995 \pm 0.0017$</td>
</tr>
<tr>
<td>$A_{\text{fb}}^{0,c}$</td>
<td>$0.0713 \pm 0.0036$</td>
</tr>
<tr>
<td>$A_{\ell}$</td>
<td>$0.922 \pm 0.020$</td>
</tr>
<tr>
<td>$A_{\ell}$</td>
<td>$0.670 \pm 0.026$</td>
</tr>
<tr>
<td>$A_{\ell}(\text{SLD})$</td>
<td>$0.1513 \pm 0.0021$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{\ell}(Q_{\ell})$</td>
<td>$0.2324 \pm 0.0012$</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>$80.449 \pm 0.034$</td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>$2.136 \pm 0.069$</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>$174.3 \pm 5.1$</td>
</tr>
<tr>
<td>$\sin^2 \theta_W(vN)$</td>
<td>$0.2277 \pm 0.0016$</td>
</tr>
<tr>
<td>$Q_{\ell}(\text{Cs})$</td>
<td>$-72.18 \pm 0.46$</td>
</tr>
</tbody>
</table>
LEP Physics – Indirect limits

Precision measurements at LEP give a hint on what is (or not!) beyond...

**Indirect limits on the Higgs mass** from fits to EW data (LEP + SLD)

- $M_H > 114.4$ GeV/c$^2$ @ 95% CL

A light Higgs is favoured... and partly excluded by direct searches

**Indirect limits on new physics scale $\Lambda$** from $e^+e^- \rightarrow l^+l^-$ cross-sections

- Dependence on type of coupling

$\Lambda = $ New physics scale in the Contact Interactions effective Lagrangian

Exclusion depends on type of coupling
Searches at LEP – why?

SM: still very successful, but...

• EW symmetry breaking
  => we need the Higgs

• Fine tuning / Mass hierarchy problem
  $M_{Planck} >> M_{EW}, M_H \sim M_{EW}$ but $\delta M^2_H \sim M^2_{Planck}$

• Flavour pattern => 3 families?

• Many free parameters
  • Quantum numbers of particles?
  • Mass values?

• Unification?
• Gravity?

$\Lambda$ should be:
• Large enough to explain decoupling of new physics
• Close enough to EW scale to address hierarchy problem

Around the corner?
γ, W^±, Z, H

Extended fermion sector

• A fourth family?
• Exotic?
• Composite?

SUSY

{\tilde{\chi}, \tilde{q}, \tilde{\nu}, \tilde{\ell}, h, A, H, H^\pm}

Technicolor
Extra dimensions

Searches at LEP – what?

• SUSY
  - SUGRA
  - GMSB
  - AMSB (RPV)
  - Technicolor
  - Extra dimensions

LQ
L
q^*_L
\nu^*_L
\ell^*_L

\gamma, W^\pm, Z
H
Searches at LEP – how?

Clean e^+e^- environment => excellent conditions for new physics searches

- Increasing $E_{cm}$ → Threshold channels
- Luminosity → Sensitivity
- Phase-space and cross-section…?

Many and exhaustive searches

- Direct / indirect
- New particles / new interactions

... Trying to look everywhere!

Model independent (topologies)

Systematic exploration of model(s)

Some “golden” topologies:
- Acoplanar jets and leptons, 4 jets, photons only
Search at LEP – how?

Clean e+e- environment... Still some background!
- Well understood (ISR, ...)
- well modeled by MC simulation

- “γγ”: affects low visible energy channels
- 4-fermions: sometimes irreducible

Radiative return to the Z

Open triggers => wide coverage of channels
Sensitivity ~ fraction of pb
Mass reach ~ $\sqrt{s}/2$
Outline

Non-SUSY
• Motivation
• $4^{th}$ family leptons
• Excited/exotic leptons

SUSY
• Motivation
• Exotic – GMSB, AMSB
• SUGRA
• CMSSM
• (RPV)

No signal in any of the channels...

... Many searches not covered:
All Higgs (many extended/exotic scenarios), Technicolor, FCNC, Extra-dims....

Thank you!
To the LEP accelerator team and many many people in the 4 LEP collaborations!!
Complicating the fermionic sector...

- Fermion flavour pattern and Interactions group not justified in the SM
  - Additional families?
  - Fermions with different SU(2)x(U1) quantum numbers?
  - Additional bosons?

  ... May arise in gauge unification theories or extended EW models

- Are we at the fundamental level?
  - Excited states
  - Particles with L and B

  => Composite models

Powerful limits exist: LEP1 (Z total and invisible width, direct searches)
  - Low energy $\mu \rightarrow e\gamma$, g-2, ...
  - ...
4\textsuperscript{th} family leptons

Observable production cross-sections

Decay through mixing with light lepton

$L^0 L^0 \rightarrow W W l l$

Mass limits (GeV/c\(^2\))

<table>
<thead>
<tr>
<th></th>
<th>$L^0 \rightarrow eW$</th>
<th>$L^0 \rightarrow \mu W$</th>
<th>$L^0 \rightarrow \tau W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dirac</td>
<td>101.3</td>
<td>101.5</td>
<td>90.3</td>
</tr>
<tr>
<td>Majorana</td>
<td>89.5</td>
<td>90.7</td>
<td>80.5</td>
</tr>
</tbody>
</table>

... Considerably extending LEP1 limits
4th family leptons L± search

L± → W W ν ν

Mass limits (GeV/c²) L3

<table>
<thead>
<tr>
<th>L±→νW</th>
<th>L±→L0W (Δm&gt;15)</th>
<th>L± stable</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.8</td>
<td>101.5</td>
<td>90.3</td>
</tr>
</tbody>
</table>

Comparable limits for exotic fermions (Vector, Mirror)

Long lived

Chain decays ...

Comparative limits for exotic fermions (Vector, Mirror)
Excited leptons

Substructure in the fermionic sector => Excited states

\[ \ell^*, \nu^* \rightleftharpoons \ell, \nu, \gamma, Z, W \]

Effective model

\[ \mathcal{L}_{\text{eff}} = \frac{1}{2\Lambda} \cdot \bar{\ell}^* \cdot \sigma^{\mu\nu} \left[ g \cdot f \frac{\tau}{2} W_{\mu\nu} + g' \cdot f' \frac{Y}{2} B_{\mu\nu} \right] \ell^* + \text{h.c.} \]

e.g. Boudjema, Djouadi, Kneur Z.Phys.C57 (1993)
Hagiwara, Zeppenfeld, Komamiya Z.Phys.C29 (1985)

\( \Lambda \) compositeness scale
\( f, f' \) weight factors

We assume \( |f| = |f'| \)

Mass and coupling of the excited lepton:

\[ \frac{f}{\Lambda} = \sqrt{2} \cdot \lambda / m_{\ell^*} \]
Excited leptons

Single production

\[ e^+ \rightarrow Z, \gamma, l^* \]
\[ e^- \rightarrow l, e^* \]
\[ e \rightarrow e, \gamma \]

1/$\Lambda$ suppression but sensitive up to $E_{cm}$

Pair production

\[ e^+ \rightarrow Z, \gamma, l^* \]
\[ e^- \rightarrow l, e^* \]
\[ e \rightarrow e, \gamma \]

Decay:

\[ \ell^*, \nu^* \rightarrow \ell, \nu, Z, W \]

Indirect mode

\[ e^+ \rightarrow e^*, \gamma \]
\[ e^- \rightarrow e^- \]

All BR matter... Many topologies

\[ \ell\ell, \gamma, jj\ell, jj, ll, jj\ell\ell, \ldots \]

Graphs:

- Charged L: $f=f$
  - $L^* \rightarrow L\gamma$
  - $L^* \rightarrow LW$
  - $L^* \rightarrow LZ$

- Charged L: $f=-f$

$BR$ vs. $M_{L^*}$ (GeV/c$^2$)
Excited leptons

Pair production

Single production: direct + indirect

Excited electron ($f = f'$)

Mass limits (GeV/c$^2$)

<table>
<thead>
<tr>
<th></th>
<th>$e^*$</th>
<th>$\mu^*$</th>
<th>$\tau^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f = f'$</td>
<td>103.1</td>
<td>103.2</td>
<td>102.7</td>
</tr>
<tr>
<td>$f = -f'$</td>
<td>102.0</td>
<td>102.0</td>
<td>102.0</td>
</tr>
</tbody>
</table>
Outline

Non-SUSY
• Motivation
• 4th family leptons
• Excited/exotic leptons

SUSY
• Motivation
• Exotic – GMSB, AMSB
• SUGRA
• CMSSM
• (RpV)

No signal in any of the channels...

... Many searches not covered:
All Higgs (many extended/exotic scenarios), Technicolor, FCNC, Extra-dims....
SUSY – why, what, how?

Why ?
Hierarchy problem  Grand unification  Connection to gravity
Light Higgs  Possible dark matter candidate

What ?

Sparticles = SUSY partners of SM particles

\((s\pm 1/2)\)
(MSSM)

fermions
\{ e  \mu  \tau  \\
\nu_e  \nu_\mu  \nu_\tau \\
u  c  t  \\
d  s  b \}

leptons
neutrinos

quarks

\(W^\pm, H^\pm, \gamma, Z^0, h^0, H^0, A^0\)

g_i

bosons

\(\chi^0, \chi^\pm\)

sleptons
neutralinos

sneutrinos

\(\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau\)

squarks

\(\tilde{u}, \tilde{c}, \tilde{t}\)

\(\tilde{d}, \tilde{s}, \tilde{b}\)

bosons

\(\tilde{\chi}^0, \tilde{\chi}^\pm\)

charginos
neutralinos

\(\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0\)

fermions

Many parameters...

- \(M_1, M_2, M_3\) Gaugino masses
- \(m_f\) Sfermion masses
- \(\tan \beta, \mu, m_A\) Higgs(ino) mass/mixing
- \(A_\tau, A_b, A_t\)

SM + 105
(+45 RPV)
SUSY – how?

How?

\[ R_p = (-1)^{3B-L+2S} \]

SUSY is a broken symmetry => SUSY Mechanism?

R-parity conservation:

Pair production of Sparticles

\[ \tilde{p} \rightarrow p \rightarrow e^+ e^- \]

Decay to stable (neutral) LSP

\[ \tilde{p} \rightarrow p \rightarrow \text{LSP} \]

\[ \Delta M = m_{\tilde{p}} - m_{\text{LSP}} \]

\[ \Delta M = 0 \]

Low \( \Delta M \) “\( \gamma\gamma \)” background (high \( \sigma \))

High \( \Delta M \) 4-fermion (irreducible)

E\text{beam}_{\text{low}} \Delta M \]

Decay chains to NLSP: several \( \Delta M \) involved
SUSY – how?

Mechanism of SUSY breaking has deep implications on phenomenology

- **Hidden SUSY**
  - Gravity mediated
  - LSP: frequently $\tilde{\chi}_1^0$

- **SUGRA**
  - Gravity mediated
  - LSP: $\tilde{\chi}_1^0$

- **GMSB**
  - Gauge mediated
  - LSP: $\tilde{G}$ ($m \ll \text{GeV}$)

- **Other**
  - e.g. **AMSB**
  - LSP: $\tilde{\chi}_1^0$, $\tilde{\nu}$, $\tilde{G}$

Signatures & dominant channels depend on specific scenario considered

Increased predictability, but still large number of free parameters
GMSB: Hiden SUSY \rightarrow \text{Gauge forces} \rightarrow \text{Visible sector}

\[ 10^3 < \sqrt{F} < 10^{10} \text{ GeV} \Rightarrow \text{Light } \tilde{G} \text{ (LSP) (order 1 KeV/c}^2, \text{ or less)} \]

- No severe FCNC (Gauge forces flavour blind)
- No dark matter candidate

\[ \tilde{G} \text{ couples weakly with all particles } \Rightarrow \text{only NLSP decays directly into } \tilde{G} \]

Gravitino mass and Nature of NLSP determine phenomenology

\[ \tau_{\text{NLSP}} \propto \frac{m_G^2}{m_{\text{NLSP}}^5} \]

\[ \Rightarrow \text{Lifetime signature} \]

\[ \tilde{\chi}_1^0 \rightarrow \gamma \tilde{G} \quad \text{or} \quad \ell \rightarrow \ell \tilde{G} \]

\[ \Rightarrow \text{Additional photons/leptons in the final state} \]
GMSB – lifetime signature

\[ e^+ e^- \rightarrow \tilde{\ell}^+ \tilde{\ell}^- \rightarrow \ell^- \tilde{G} \rightarrow \ell^+ \tilde{G} \]

\[ m_{\tilde{G}} \leq \text{few eV/c}^2 \]

Large impact parameter

\[ m_{\tilde{G}} \approx \text{eV/c}^2 - \text{0.1KeV/c}^2 \]

Acoplanar leptons

\[ \beta_{\text{yc}} = 0.005m \]

\[ \beta_{\text{yc}} = 0.20m \]

\[ \beta_{\text{yc}} = 2.0m \]

ADLO Prelim \( \sqrt{s} = 189-209 \text{ GeV} \)

Kinked tracks

\[ m_{\tilde{G}} \geq \text{few KeV/c}^2 \]

Stable charged particles
GMSB – Constraints on parameters

Few parameters to define the minimal model:

\( \sqrt{F} \): scale of SUSY breaking
\( M \): messengers mass scale
\( N \): number of messenger generations
\( \tan(\beta) \)
\( \text{sign}(\mu) \)
\( \Lambda \approx F/M \): effective SUSY breaking scale

![Graph showing the relationship between \( N \) and \( \Lambda \)](image)
AMSB:

- Rescaling anomalies in supergravity lagrangian => soft mass parameters in visible sector
- Additional non-anomaly contributions to avoid tachyonic sleptons
- Could solve SUSY FCNC problem

Rather characteristic phenomenology:

LSP: $\tilde{\chi}^0_1, \tilde{\nu}$ or $\tilde{\tau}$

Heavy squarks

Light Higgs

$M_1 : M_2 : M_3 \gg 2.8 : 1 : -8$

$\tilde{\chi}^0_1$ and $\tilde{\chi}^\pm_1$

Nearly mass degenerate and gaugino-like
Small $\Delta M$ Chargino search

$\Delta M = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$

Low $\Delta M$ => large $\gamma\gamma$ background
- Low visible energy
- Low transverse momentum
- Very high cross-section

$\Rightarrow$ ISR tag!

Signal cross-section still OK

$\bar{\nu}$ mass dependence!
AMSB – Constraints on parameters

Four parameters to define minimal model: $m_{3/2}$, $\tan\beta$, $m_0$, $\text{sign}(\mu)$

- LEP1 constraints (Z width)
- SM Higgs search
  $M_H > 114.4$ GeV/c$^2$ @ 95% CL
- Invisible Higgs search
- Small $\Delta M$ chargino search
- Search for $\tilde{\chi}^\pm \rightarrow \tilde{\nu} \, l^\pm$

AMSB scan with Isajet 7.63

$1 < m_{3/2} < 50$ TeV/c$^2$
$0 < m_0 < 1$ TeV/c$^2$
$1.5 < \tan\beta < 45$

$m(\tilde{\chi}_1) > 68$ GeV/c$^2$

$m(\tilde{\nu}) > 98$ GeV/c$^2$
SUGRA: Hiden SUSY  Gravity  Visible sector

- LSP dark matter candidate
- Possible FCNC problems

Explored at LEP in an exhaustive way

Searches for
- Charginos - Sleptons
- Neutralinos - Squarks

1) Searches conducted in “model-independent” way:
   - Minimal set of assumptions
   - Interpretations in terms of involved masses/cross-sections

“Baseline” search + “difficult cases/corners”

2) Common interpretations in terms of model parameters
   => Manageable number of free parameters
   => Specific scenarios

⇒⇒ “LEP-CMSSM”
⇒⇒ mSUGRA
MSSM => SUGRA => CMSSM => mSUGRA

- Minimal particle/field content (MSSM)
- Soft SUSY breaking
- R parity conservation $R_p = (-1)^{3B-L+2S}$
- Gravity mediated SUSY breaking
- Neutralino LSP
- Assumptions on BR's
- Gaugino mass unification $m_{1/2}$
- Assumptions on sfermion masses
- Assumptions on trilinear couplings
- Sfermion mass unification $m_0$
- Scalar mass unification
- Unification of trilinear couplings $A_0$
- EW breaking scale

e.g. $\text{BR}(\tilde{p} \rightarrow p \text{LSP}) = 1$

$M_1 = \frac{5}{3} \tan^2 \theta_w M_2 \approx 0.5 M_2$

e.g. Heavy sfermions

e.g. No mixing

"LEP-CMSSM"

$m_0, m_{1/2}, A_\tau, A_b, A_t, \tan \beta, \mu$

mSUGRA

$m_0, m_{1/2}, A_0, \tan \beta, \text{sign}(\mu)$
Chargino searches

Main direct SUSY detection channel in large region of parameter space

$\tilde{\chi}^\pm_1 \rightarrow \tilde{\chi}^0_1 W^* \rightarrow \tilde{\chi}^0_1 jj, \tilde{\chi}^0_1 \ell\nu$

- Leptonic BR enhanced if sleptons are light
- cascades $\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 \gamma$

=> Large cross-sections

Negative interference. Is there a light sneutrino?
Chargino searches
Exclusion nearly up to kinematic limit

Cross-section limits

If sleptons are light
• Cross-sections may be suppressed
• Undetectable final states may arise

M > 103.5 GeV
high $\Delta M$, gaugino region
$m_{\tilde{\nu}} > 300$ GeV/c$^2$

M > 92.4 GeV

ADLO Higgsino
$\tan\beta = 2$ $\mu = -200$ GeV
$\sqrt{s} > 206.5$ GeV
Slepton searches

Smuons
Almost model-independent

Selectrons
t-channel => cross-section very model-dependent

Staus
Mixing: Stau could be charged LSP
affects cross-section => decouple from Z

\[ \tilde{\ell} \rightarrow \ell \tilde{\chi}^0_1 \]

=> 2 acoplanar leptons

BR:
\[ \begin{align*}
&\text{BR} = 1 \\
&\text{BR @ } \mu=-200, \tan \beta=1.5
\end{align*} \]
If light enough to be observed, seriously affect production and decay of charginos and neutralinos
More constrained models: CMSSM

$m_0, m_{1/2}, \tan\beta, \mu, A_\tau, A_b, A_t$

... Combining negative results of different searches:

Charginos  Higgs  Sleptons  Neutralinos  Squarks

Exclusion in $(M_2, \mu)$ plane for different $\tan\beta$, $m_0$ values

Lower limits on smasses ($M_{LSP}$)
LSP mass limit in CMSSM

(A) High $m_0$ Low $\tan\beta$ Cascades

(B) MSSM Higgs

(C) Low $m_0$

(D) Mixing 3rd family
(A) LSP mass limit in CMSSM – High $m_0$

Heavy sfermions $\Rightarrow$ no effect on phenomenology

Chargino exclusion dominates

Cascades:

$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma$ $\Rightarrow$ Cover topologies with $\gamma$'s in chargino/neutralino searches (low $M_2$ & $\mu$)

$\tilde{\chi}_3^0 \tilde{\chi}_2^0, \tilde{\chi}_4^0 \tilde{\chi}_2^0$ $\Rightarrow$ Allow to go slightly beyond chargino kinematic limit ($M_2<120$)

Neutralino cascades with photons

\[ \tan^2 \beta = 1 \]
Low $\tan\beta$ covered by Higgs exclusions if included

0.54 < $\tan\beta$ < 2.36 \quad (M_{\text{top}} = 174.3 \text{ GeV/c}^2)

MSSM Higgs search in maximal $M_{h_0}$ scenario:

$M_A \leq 1000 \text{ GeV/c}^2$, $A_t-\mu/\tan\beta = \sqrt{6} \text{ TeV/c}^2$

$A_t-\mu/\tan\beta \Rightarrow M_{h_0}$ maximal

$M_{h_0}$ maximised by tuning mixing in the stop sector

Dependence on $m_{\text{top}}$

0.6 < $\tan\beta$ < 2.0 \quad (M_{\text{top}} = 179 \text{ GeV/c}^2)
Light Sleptons:

Effect on chargino cross-section

(OK down to $m_0 \sim 200$ GeV/c$^2$)

$\Rightarrow$ Increased neutralino cross-section!

Chargino invisible decays:

$\tilde{\chi}_1^\pm \rightarrow \tilde{\nu} \ell^\pm$ with $m(\tilde{\chi}_1^\pm) \approx m(\tilde{\nu})$

$\Rightarrow$ Charginos cannot exclude

GUT scale unification:

$m_{\tilde{f}} \equiv m_{\tilde{f}}(\tan \beta, m_0, M_2)$

$\tilde{e}$ search $\Rightarrow m_{\tilde{e}}$ limit $\Rightarrow m_{\tilde{\nu}}$ limit $\Rightarrow m_{\tilde{\chi}_1^\pm}$ limit $\Rightarrow m_{\text{LSP}}$ limit

Neutralinos can play a role in low cross-section (chargino or selectron) areas
LSP mass limit in CMSSM – Mixing

$\tilde{\tau}_R, \tilde{\tau}_L \xrightarrow{\text{mixing}} \tilde{\tau}_1, \tilde{\tau}_2$

3rd family L-R mixing can give light $\tilde{\tau}_1, \tilde{b}_1, \tilde{t}_1$

Mass splitting $\propto A_\tau - \mu \tan \beta$

$A_b - \mu \tan \beta$

$A_t - \mu / \tan \beta$

Large $\tan \beta$

More studied cases:
- No mixing
- $A=0$

then study variation with mixing

Example: $(\tan \beta = 35)$
Light squarks

direct squark search...
... down to low $\Delta M$

Obtained limit (set by squarks and stau cascades) robust with mixing

Invisible higgs search can exclude some points but not for any mixing
Stau mixing

A conservative limit on $m_{\text{LSP}}$ valid for any $\tilde{\tau}$ mixing

model with mixing only in the stau sector

$\Rightarrow$ maximises (LSP, stau) degeneracy region

$M_{\text{LSP}} > 39 \text{ GeV/c}^2$
LSP mass limit – ADLO combinations

CMSSM

$\mu > 0$

$\mu < 0$

No stau mixing included

$M_{\text{LSP}} > 45 \text{ GeV/c}^2$

$mSUGRA$

$A_0=0, m_0<1 \text{ TeV/c}^2$
RpV

• Explicit RpV breaking trilinear superpotential terms:

\[ \lambda_{ijk} L^i_L L^j_L \overline{E}^k_R + \lambda'_{ijk} L^i_L Q^j_L \overline{D}^k_R + \lambda''_{ijk} \overline{U}^i_R \overline{D}^j_R \overline{D}^k_R \]

- 9 couplings \((i \neq j)\)
- 27 couplings

• Sfermions can decay directly into fermions
• SUSY particles can be singly produced
• The LSP is no longer stable

• Only one \(\lambda\)-coupling non-negligible at a time
• Prompt decay of sparticles (\(L < 1\) cm)
Resonant and non-resonant sneutrino production

At production

\[ e^+ e^- \rightarrow \tilde{\nu}_{\mu,\tau}, \lambda_{121}, \lambda_{131} \]

\[ \tilde{e}^+, \tilde{\chi}_i^0, \tilde{\chi}_j^\pm, e^-, \nu, l^\pm \]

At decay

Direct...

\[ \tilde{f} \rightarrow f f \]

\[ \chi_1^0 \rightarrow f^* f f \]

Indirect

\[ \chi_1^\pm (\tilde{f}) \rightarrow W(f) f f \]

Different channels and couplings => many possible final state topologies !!
Direct Decays

Limits on RpV couplings $\lambda, \lambda', \lambda''$

Indirect decays tend to dominate, when kinematically allowed
SUSY at LEP - Summary

... Many analyses, scenarios, results!

- Cross-section limits: ≈ model-independent
- Mass limits => Assumptions (BR, ΔM, m, ...)
- Exclusion of parameter space regions

More constrained scenarios:
Need to increase predictive power...
Still trying to cover most realistic scenarios

In general:

- Excluded ranges comparable in different scenarios
  » SUSY limits proved to be robust
  » Chargino: close to kinematic limit
  » LSP: ~ 40 GeV/c²
- General exclusions not easy to set

### Sparticle mass limits (GeV/c²)

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass (GeV/c²)</th>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tilde{\chi}^\pm )</td>
<td>103.5</td>
<td>SUGRA, large m₀, ΔM&gt;3</td>
</tr>
<tr>
<td></td>
<td>92</td>
<td>CMSSM</td>
</tr>
<tr>
<td></td>
<td>96</td>
<td>RpV “CMSSM”</td>
</tr>
<tr>
<td></td>
<td>68</td>
<td>AMSB</td>
</tr>
<tr>
<td>( \tilde{\chi}^0 )</td>
<td>45</td>
<td>CMSSM</td>
</tr>
<tr>
<td></td>
<td>38</td>
<td>RpV “CMSSM”</td>
</tr>
<tr>
<td></td>
<td>89</td>
<td>GMSB</td>
</tr>
<tr>
<td></td>
<td>68</td>
<td>AMSB</td>
</tr>
<tr>
<td>( \tilde{\nu} )</td>
<td>85</td>
<td>RpV</td>
</tr>
<tr>
<td></td>
<td>98</td>
<td>GMSB, slepton NSLP</td>
</tr>
<tr>
<td>( \tilde{b}, \tilde{t} )</td>
<td>76</td>
<td>SUGRA, ΔM&gt;7</td>
</tr>
<tr>
<td></td>
<td>77</td>
<td>RpV (LLE), ΔM&gt;5</td>
</tr>
</tbody>
</table>

» SUSY limits proved to be robust
» Chargino: close to kinematic limit
» LSP: ~ 40 GeV/c²
» General exclusions not easy to set
Searches at LEP - Perspective

No signal in any of the channels...

Final results are currently being prepared

70% of Beyond the SM session ICHEP 2002 contributed papers

What matters now? What did Searches at LEP leave to us?

Many constraints
• Complete interpretations in the frame of models
• Complete model-independent results in case of new ideas

Important to keep LEP data accessible

Analysis experience
• Methods for sensitivity improvement
• Statistical treatment
• Generators

Important to keep LEP data accessible
Searches at LEP - Perspective

LEP did a great job for the last 12 years!
...Great opportunities for searches at next colliders

<table>
<thead>
<tr>
<th>Tevatron</th>
<th>LHC</th>
<th>Linear collider</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tevatron</strong>: the next step - the future is already here!</td>
<td><strong>LHC</strong>: Acessing yet unexplored regions... First observations of SUSY?</td>
<td><strong>LC</strong>: detailed map of SUSY</td>
</tr>
<tr>
<td>High precision measurement (masses, cross-section, couplings, mixings)</td>
<td></td>
<td>Extrapolation to GUT, Planck =&gt; origin of SUSY breaking</td>
</tr>
</tbody>
</table>

Most scenarios involve rich new physics at $E \sim 1$ TeV

In the next decade, we hope to find a key... ... At least the one leading us to the next puzzle!