Searches for New Physics at LEP

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on behalf of the four LEP collaborations

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Introduction

- **Standard Model at colliders still in pretty good shape**
  (despite neutrino masses, dark matter, dark energy, ...)

- **several open questions, among them:**
  what creates mass and is responsible for EWSB?
  what creates the hierarchy between $M_{PL}$ and $M_{EW}$?

- **LEP: searches for various topologies of new physics,**
  this talk:
  - neutral Higgs bosons (SM, MSSM)
  - supersymmetric particles (cMSSM)
  - effects from extra spatial dimensions

- preference for „newer“ + LEP combined results

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**NO**

discovery of new physics at LEP
  → cross section and mass limits @95%CL
  → restrictions in model parameter spaces
Data Sets, Luminosities and Cross Sections

- LEP combined sample:
  \[ \sim 2.6 \text{ fb}^{-1} \ (E_{\text{CM}} > 183 \text{ GeV}) \]

- at highest energies:
  \[ E_{\text{CM}} > 207.5 \text{ GeV} \ (\text{ADLO}=35.2 \text{ pb}^{-1}) \]

**Cross section sensitivity:**

\[ \text{e.g. 0 background, need } N_{\text{sig}}=3 \text{ 95\%CL exclusion} \]

- \[ L = 2.6 \text{ fb}^{-1} \rightarrow \sigma_{\text{lim}} \sim 1.2 \text{ fb} \]
- \[ L = 35.2 \text{ pb}^{-1} \rightarrow \sigma_{\text{lim}} \sim 0.2 \text{ pb} \]

Production of:

- Charginos: \[ \sigma \sim (1-10)\beta \text{ pb} \]
- Sleptons: \[ \sigma \sim (0.2-2)\beta^3 \text{ pb} \]
- SM Higgs (M=114 GeV): \[ \sigma \sim 0.1 \text{ pb} \]
Search for the SM Higgs Boson

- Mass determines Higgs boson profile:
  - @ 114 GeV: $\sigma \sim 0.1$ pb
  - $\text{BR}(H \rightarrow \text{bb}) \sim 74\%$
  - $\text{BR}(H \rightarrow \tau\tau) \sim 7\%$

- SM searches exploited b-tagging extensively

ALEPH 4-Jet candidate
$M_{bb} = 114.3$ GeV
two b-tags
SM Higgs: the final word from LEP

Mass spectrum after tight selection cuts

Consistency with BG only hypothesis:

Mass limit via $\text{CL}_S = \text{CL}_{S+B}/\text{CL}_B$

Consistency with:

- background only: $\text{CL}_B = 0.08$ @ 115 GeV (1.7σ excess)
- signal + background: $\text{CL}_{S+B} = 0.15$ @ 115 GeV

 Observed Limit: 114.4 GeV  Expected Limit: 115.3

Neutral Higgs bosons in the CP Conserving MSSM

- two Higgs doublets $\rightarrow$ 5 physical bosons: $h, H, A, H^+, H^-$
- at Born level 2 parameters: $\tan\beta, m_A$ $m_h < M_Z$
- large loop corrections $\rightarrow m_h < 137$ GeV for $m_t=178$GeV depending on 5 cMSSM SUSY parameters: $A_t, M_0, M_2, M_{\text{gluino}}, \mu$
- $M_h$ very sensitive to $m_t$ and mixing parameter $X_t = A_\mu \cot\beta$

2 production processes:

- $Zh$: $\sim \sin^2(\alpha-\beta)$
- $Ah$: $\sim \cos^2(\alpha-\beta)$

- $m_h$-max scenario: maximal value for $m_h$ as function of $\tan\beta$
  $\rightarrow$ conservative exclusion in $\tan\beta$
  also new prel. LEP results for nomixing and large $\mu$ scenario

- for final LEP paper: more benchmarks: gluophobic, small alpha, diff. CPV,...
  various value for $m_t$ and $M_{\text{SUSY}}$
**CPC-MSSM: $m_h$-max Scenario** (new LEP prel. August 2004)

- **Mass limits:** robust against change of $m_t$
  - $M_h > 92.9 \text{ obs.} \ (94.8 \text{ exp.}) \ \text{GeV}$
  - $M_A > 93.4 \text{ obs.} \ (95.1 \text{ exp.}) \ \text{GeV}$

- **tan$\beta$ exclusion:**
  - $[0.9;1.5] \ \text{obs.} \ \ ( [0.8;1.6] \ \text{exp.} )$
  - for $m_t = 179.3 \ , \ M_0 = 1 \ \text{TeV}$

No tan$\beta$ exclusion for $m_t$ larger $\sim 183 \ \text{GeV}$!
The CP Violating Complex MSSM

**Beyond Born level CP violation in loops**, if $A_t$, $A_b$ and $M_{\text{gluino}}$ complex

new sources CP violation $\rightarrow$ interesting for baryogenesis

CP eigenstates $h, A, H$

mix to mass

eigenstates $H_1, H_2, H_3$

**Phenomenology:**

- $H_1, H_2, H_3$ may be produced in Higgsstrahlung, $H_1$ may decouple
- all comb. may be produced in pairs, $H_i \rightarrow H_m H_n$ ($m, n < i$) decays

**Maximal CP effect in Higgs sector $\rightarrow$ CPX benchmark scenario**

$\arg(A_t) = \arg(M_{\text{gluino}}) = 90 \text{ deg.}$, large ratio $\mu A_t / m_{\text{susy}}$

$M_{\text{SUSY}} = 500 \text{ GeV}$, $A_t = A_b = M_{\text{gluino}} = 1 \text{ TeV}$, $\mu = 2 \text{ TeV}$, $M_2 = 200 \text{ GeV}$
**CPX-Benchmark Scenario** (first prel. LEP combination)

- $H_1H_2 \rightarrow \tau\tau bb$, Yukawa production $bbH \rightarrow bb\tau\tau$
- $H_1H_2 \rightarrow \tau\tau bb$
- $H_2 \rightarrow H_1H_1 \rightarrow bbbb$ from $H_2Z$, $H_1H_2$
- $H_2Z \rightarrow bbZ$
- $H_1Z \rightarrow bbZ$

Area at small $M_{H_1}$ not excluded due to:

- decoupling of $H_1$ from $Z$
- reduced sensitivity for $H_2 \rightarrow H_1H_1 \rightarrow bbbb$ for $M_{H_2} \sim 100$ to 110 GeV

- no absolute mass limit for $H_1$
- large impact of $m_t$ on excluded area

**tan$\beta$ exclusion:**

$\tan \beta > 2.9, 2.6, 2.5$ obs. $(3.0, 2.7, 2.5$ exp.$)$ for $m_t = 174.3, 179.3, 183.0$ GeV
Further Searches for Higgs Bosons

- **Higgsstrahlung with non SM decay modes** (BR=1., SM cross.sec.)
  
  Flavour ind.: $H \rightarrow qq$ $M > 112.9$ GeV (LEP prel.)
  
  Fermiophobic: $H \rightarrow \gamma\gamma$ $M > 117.2$ GeV (LEP prel.)
  
  $H \rightarrow WW$ $M > 108.1$ GeV (L3)
  
  Invisible: $H \rightarrow \text{inv.}$ $M > 114.4$ GeV (LEP prel.)
  
  Decay mode ind: $H \rightarrow \text{any.}$ $M > 81\text{GeV}$ (OPAL)

- **charged Higgs bosons:** ($\rightarrow \tau\nu, cs$) $M > 78.6$ GeV (LEP, prel.)
  
  (+WA) $M > 76.7/74.4$ GeV in TypeI/II 2HDM (DELPHI)

- **cross section x BR limits for various processes, e.g.**
  
  doubly charged Higgs bosons (single+pair prod.)
  
  $hA \rightarrow qqqq$, $hA \rightarrow 6b$, $hA \rightarrow hhZ \rightarrow bbbbZ$
  
  Yukawa production: $bh/A,h$ with $A \rightarrow bb,\tau\tau$

- **interpretation in various models**
  
  2HDM type I and II, fermiophobic, LR symm.,...
Supersymmetry Scenarios

- general MSSM: masses, $\sigma$ and BR depend on 105 + 19 parameters
- "hopeless" to perform dedicated searches

- identify + classify topologies
- cover all kind of signals from SUGRA, GMSB, AMSB, R-Parity violation, ...
different LSP scenarios

- $\sim$100 topological searches performed $\Rightarrow$ no excess $\Rightarrow$ cross section limits
- mass limits, parameter exclusions in various SUSY models

- this talk: R-parity conservation $\Rightarrow$ pair production of sparticles
  $\Rightarrow$ stable LSP (here: lightest neutralino)
How to search for the sparticles?

- **strategy at LEP:**
  - look for pair production of NLSPs (also NNLSPs) and their direct decays into LSP + SM particles

- sensitivity of search depends on $\Delta M = M(\text{NLSP}) - M(\text{LSP})$, $M(\text{NLSP})$

- **exp. signature:**
  - missing energy + n leptons + m jets (+$\gamma$) @ large $\Delta M$
  - stable particles, kink tracks, sec. vertices @ small $\Delta M$

- sensitivity of search depends on $\Delta M = M(\text{NLSP}) - M(\text{LSP})$, $M(\text{NLSP})$
  - $\sigma \sim$ several nb
  - $\sigma \sim$ 20 pb
Charged Slepton Searches

Production and dominant decay mode

- Righthanded sleptons lighter than lefthanded and have lower cross section
- Smuons: almost model-independent cross section
- Staus: mixing (lighter stau can decouple from Z, reduced cross section)
- Selectrons: t-channel with neutralino exchange (usually constructive interference)

Experimental signature:
2 acoplanar leptons + missing energy

Dominant background WW→llνν
Cross Section and Mass Limits

**Cross section limits:**
- **Selectrons:** $\sim 10 - 80$ fb
- **Smuons:** $\sim 10 - 50$ fb
- **Staus:** $\sim 40 - 150$ fb

For $\Delta M = M(\text{slepton}) - M(\text{LSP}) > 5$ GeV

<table>
<thead>
<tr>
<th>Slpont</th>
<th>RR coupling</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selectron</td>
<td>RR coupling</td>
<td>99.9 GeV</td>
</tr>
<tr>
<td>Smuon</td>
<td>RR coupling</td>
<td>96.6 GeV</td>
</tr>
<tr>
<td>Stau</td>
<td>RR coupling</td>
<td>93.2 GeV</td>
</tr>
<tr>
<td>Z decoupled</td>
<td></td>
<td>92.6 GeV</td>
</tr>
</tbody>
</table>
Search for Charginos

**Production:**
\[ e^+ \gamma/Z e^- \rightarrow \tilde{\chi}^+_1 \]
\[ e^- \rightarrow \tilde{\chi}^-_1 \]

- Negative interference of t-channel
- Cross section depends on composition of chargino (higgsino or gaugino)

**Decay:**
For heavy sfermions

\[ \tilde{\chi}^{+/0}_1 \rightarrow W^{+/0} q, \nu \]

**Exp. Signature:** Missing energy +
- 4 jets
- 1 lepton
- 2 jets
- 2 leptons
Chargino Mass Limits (for heavy sfermions)

Classical search ($\Delta M > 3\text{GeV}$)

- $\tan \beta = 2$
- $\mu = -200 \text{ GeV}$
- ADLO $\sqrt{s} > 206.5 \text{ GeV}$
- Excluded at 95% C.L.

$$M(\text{chargino}) > 103.5 \text{ GeV}$$

For $M(\text{sneutrino}) > 300 \text{ GeV}$

Small $\Delta M$ searches

- ADLO preliminary
- Higgsino - eMSSM
- Lifetime signatures

$$M (\text{Chargino}) > 92.4 \text{ GeV}$$

For Higgsino $|\mu| << M_2$
cMSSM LSP mass limit

cMSSM: $m_{1/2}$ gaugino mass, $\mu$ Higgs mixing par., $m_0$ sfermion mass
A trilinear coupling, $\tan\beta$ ratio of vevs, $M_{A}$ CP odd Higgs mass

For small $m_0$: 2 body decays of chargino

Invisible for $M_{\chi^+} \sim M_{\tilde{\nu}}$: corridor
→use GUT relation for $m_0$
and slepton searches

LSP limit (in CMSSM) set by slepton searches in the corridor for large $\tan\beta$

$M_{\text{LSP}} > 47$ GeV (No stau mixing)
Mixing in stau sector can make stau = NLSP

Critical case:
Small $\Delta m = m(\chi^{+/-}) - m(\tau)$

Dedicated searches needed for

$\chi_1^+\chi_1^- \rightarrow \tilde{\tau}^+\tilde{\nu} \rightarrow \tau\chi^0\nu\chi^0$  

$\chi_2^0\chi_1^0 \rightarrow \tau\tau\tau\chi^0\chi^0$  

$\chi_2^0\chi_1^0 \rightarrow \tau\tau\chi^0\chi^0$  

and $\chi^+\chi^-$ ISR analysis
**LSP Mass Limits**

- **cMSSM**
  - $M(LSP) > 29.7$ GeV
    - (only ALEPH)

- **mSUGRA**
  - $M(LSP) > 50.3$ GeV

- **MSSM:**
  - no GUT unification for sfermions and gauginos
  - $\rightarrow$ no lower limit on LSP mass from colliders

<table>
<thead>
<tr>
<th>Stau mixing</th>
<th>$\tan \beta$ range</th>
<th>Higgs searches</th>
<th>LSP mass lower limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varphi_r = 0.$</td>
<td>&gt; 1.0</td>
<td>none</td>
<td>30.6 GeV/c^2</td>
</tr>
<tr>
<td>$\varphi_r = 0.$</td>
<td>&gt; 1.0</td>
<td>included</td>
<td>43.1 GeV/c^2</td>
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<tr>
<td>Any $\varphi_r$</td>
<td>&gt; 1.0</td>
<td>none</td>
<td>29.7 GeV/c^2</td>
</tr>
<tr>
<td>$</td>
<td>A_r</td>
<td>&lt; 20$ TeV/c^2</td>
<td>&gt; 1.0</td>
</tr>
<tr>
<td>$</td>
<td>A_r</td>
<td>&lt; 4$ TeV/c^2</td>
<td>&gt; 1.0</td>
</tr>
</tbody>
</table>

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

common scalar mass

Higgs + sfermions

~ 1 GeV smaller limit

for 1 GeV larger $m_t$
Search for Signals from Extra Dimensions

- explain hierarchy between $M_{Pl}$ and $M_{EW}$ by introducing extra spatial dimensions (ED)
- simple models: only gravity „lives“ in new dim.

**ADD-Modell:**
- $n$ large flat ED of size $R$

**RS-Modell:**
- 1 small warped ED

\[ M_{Pl}^2 = (2\pi R)^\delta M_D^{2+\delta} \]

\[ \Delta M = \text{meV to 10 MeV} \]

\[ M_{Pl}^2 = \frac{M_D^3}{k} \left(1 - \exp\left(-2kR\pi\right)\right) \]

\[ M(KK1) \sim 1 \text{ TeV} \]
Direct Graviton Production in ADD-Model

\[ e^+e^- \rightarrow G \gamma \rightarrow E_{\text{miss}} + \text{photon} \]

Graviton
Extra Dimensions
Our Universe

\[ \frac{d^2\sigma}{dx_\gamma d\cos\theta_\gamma} = \frac{\alpha}{32\pi} \frac{n^{\delta/2}}{\Gamma(\delta/2)} \left( \frac{\sqrt{s}}{M_D} \right)^{\delta+2} f(x_\gamma, \cos\theta_\gamma) \]

fit of two dim.
photon spectrum
to data for fixed \( \delta \)
\[ \rightarrow \text{lower limit on } M_D \]

L3 DELPHI Preliminary

Markus Schumacher, Searches for New Physics at LEP, PASCOS04
Limits on Planck scale $M_D$ and compactification radius $R$

- **ALEPH DELPHI L3**
  - Preliminary
  - $e^+e^- \rightarrow \gamma G$

**Table:**

<table>
<thead>
<tr>
<th>$\delta$</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$(mm)</td>
<td>.19</td>
<td>2.6x10^{-6}</td>
<td>1.1x10^{-8}</td>
<td>4.1x10^{-10}</td>
<td>4.6x10^{-11}</td>
</tr>
<tr>
<td>$M_D$(TeV)</td>
<td>1.60</td>
<td>1.20</td>
<td>0.94</td>
<td>0.77</td>
<td>0.66</td>
</tr>
</tbody>
</table>

**TEVTATRON limits**

- $\delta$ | 4 | 6 | 7
- CDF Run1 | 0.77 | 0.71
- DO Run2  | 0.68 | 0.66 | 0.68

- **limits at 95%CL**
  - Larger for $n>5$

**Graphs:**

- LEP
- DO Run1
- CDF Run1
- DO Run2
Search For Radions in RS-Model

- in RS-Model 1st KK-excitation of graviton beyond reach of LEP
- radion, associated to interbrane fluctuations, might be light
- radion decays dominantly to gluons and can mix with Higgs boson

Model parameters: masses of radion and Higgs $m_r$ and $m_h$

- mixing parameter $\xi$
- mass scale on SM brane $\Lambda_W$

- **production cross sections**

- **branching ratios**
Results on Search for Radions

exclude parameter space from:
SM, flavor- and decay mode
independent Higgs searches

- $m_h < 58 \text{GeV}$ excluded for $\Lambda_W > 246 \text{ GeV}$
- no limit on $m_r$ independent on mixing

1MeV < $m_r$ < 1TeV
Search For Branons

- Branons $\Pi$ associated with brane fluctuations
- first signal if brane tension $f \ll M_G$
- pair produced in association with photon or Z boson
- exp. signature: missing energy + photon (Z)

$M > 103$ GeV for $f \rightarrow 0$
$f > 180$ for $M = 0$ GeV
Conclusions

- no hints for any kind of new physics at LEP: Higgs, SUSY, ED, Technicolour, Compositeness, Leptoquarks,...
- model independent cross section limits for hundreds of topologies
- mass limits and parameter exclusions in various models
  (watch assumptions carefully!!)

now: wait for discoveries of (hopefully unexpected) new phenomena at TEVATRON, LHC and a future Linear Collider

Many thanks to Christoph Rembser and my colleagues from the LEP Higgs, SUSY and Exotica working groups