Results from the OPAL Experiment

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On behalf of the OPAL Collaboration
LEP Fest, 10th October 2000

- Introductory Remarks
  Luminosity .. Y2K Data

- Physics Results
  PRELIMINARY LEP2, including $\sqrt{s} > 202$ GeV
    - Standard Model cross-sections and couplings
    - Indirect limits on new physics
    - Search for SM and MSSM Higgs
    - Searches for new particles

- Where do we go from here?
30 minutes is too short to give adequate recognition to the intensive work over the past few weeks (months) (years) ..

Please consult our public web site

'The OPAL experiment at LEP'

http://opal.web.cern.ch/Opal/PPwelcome.html

where you will find all OPAL physics results and, in particular, 3 Collective Physics Notes prepared for this LEP Fest

• Measurement of Standard Model Processes in e+e- Collisions at $\sqrt{s} > 202$ GeV

• Updated Results of Higgs Boson Searches in e+e- Collisions at the Highest LEP Energies

• New Particle Searches in e+e- Collisions at $\sqrt{s} = 200-209$ GeV
Special People .. Many Thanks

- OPAL Spokesmen
  - Aldo Michelini, early beginnings - 1993
    Design, construction, installation, exploitation LEP1
  - Rolf Heuer, 1994 - mid 1998
    LEP1 to LEP2 transition, precision physics
  - Dave Plane, mid 1998 - present
    LEP2 highest energies/luminosities

- OPAL Secretary
  - Mette Stuwe, early beginnings - present
The OPAL Collaboration .. past/present

- CANADA
  Alberta, Carleton, CRPP/NRC, Montreal, UBC, Victoria

- FRANCE
  Saclay

- GERMANY
  Aachen, Bonn, Freiburg, Hamburg/DESY, Heidelberg, LMU-Munich, MPI-Munich

- HUNGARY
  Budapest, Debrecen

- ISRAEL
  Technion, Tel Aviv, Weizmann

- ITALY
  Bologna

- JAPAN
  ICEPP-Tokyo/Kobe

- CERN

- UK
  Birmingham, Brunel, Cambridge, Manchester, QMW, RAL, UCL/Birkbeck

- USA
  Chicago, Duke, Indiana, Maryland, Oregon, Riverside, Yale
• Special thanks to the LEP Division and all the technical staff associated with the LEP program. Each year, 1989-2000, has been great!

Today: Total luminosity recorded in Y2K almost 200 pb$^{-1}$
OPAL data taking efficiency in Y2K = 92%

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OPAL Data Quality

- Calibration procedures for OPAL have maintained steady and robust resolutions throughout the LEP2 period.

**momentum + $d_0$ resolutions**

$\sigma_{p/p^2} \times 10^{-3}$ (1/GeV)

$Z^0$ calibration runs
Jet + Vertex Chambers + SI Vtx

$\sigma(d_0)$ (µm)


LEP1 1995/96 shutdown: SI Vtx re-installation

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A Bhabha event at 209 GeV

- 10 August 2000, LEP sets energy record at 209 GeV
- Run lasted less than 2 minutes. Pity! 80 nb$^{-1}$

Run:event 14880: 285

Ctrak(N= 2 SumE=162.1) Ecal(N= 14 SumE=216.5)

Ebeam 104.50 Vtx ( -.02, .04, .53) Hcal(N= 0 SumE= .0) Muon(N= 0)

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Standard Model Cross-sections

- from CERN Yellow Report, LEP2 Physics
A Multihadron event at 208 GeV

- One person’s signal is another person’s background!

Run: event 14590: 1495  Ctrk(N= 52 Sump=925.9) Ecal(N= 71 SumE=112.2)
Ebeam 104.10 Vtx ( -.02, .03, .01) Hcal(N=30 SumE= 24.6) Muon(N= 1)
Cross-section for hadrons

- separate full-energy annihilation events from $Z^0$ radiative return

1478 non-radiative events at $\sqrt{s} = 205$ GeV
1709 non-radiative events at $\sqrt{s} = 207$ GeV

Curve is ZFITTER prediction

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Cross-section for mu-pairs

- separate full-energy annihilation events from $Z^0$ radiative return

211 non-radiative events at $\sqrt{s} = 205$ GeV
225 non-radiative events at $\sqrt{s} = 207$ GeV

Curve is ZFITTER prediction

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Forward-backward Asymmetries

- Measure $A_{fb}$ for lepton pairs $e^+e^-, \mu^+\mu^-, \tau^+\tau^-$

Curve is BHWIDE ($e^+e^-$), ZFITTER ($\mu^+\mu^-, \tau^+\tau^-$) prediction
Fine Structure Constant

- Use non-radiative cross-sections and asymmetries
- ZFITTER, with all other pars fixed, gives $\alpha_{\text{em}}(\sqrt{s})$

$$\alpha_{\text{em}}(\sqrt{s} = 190.6 \text{ GeV}) = 128.4^{+2.5}_{-2.3} \text{ (SM: 127.9)}$$

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QCD at 206 GeV

- All QCD observables well represented by PYTHIA, HERWIG
- No evidence for anomalous 4-jet production

![Graph showing n-Jet Fraction vs. y_cut for n=2, 3, 4, 5 in Durham scheme, comparing OPAL, PYTHIA, and HERWIG data.](attachment:graph.png)
Strong Coupling Constant

- Fit distributions of $1-T$, $M_H$, $C$, $B_W$, $B_T$, and $y_{23}^D$ to NLLA $\mathcal{O}(\alpha_s^2)$ QCD calculations
- Results consistent with running of $\alpha_s$

$$\alpha_s(\sqrt{s} = 205.9 \text{ GeV}) = 0.107 \pm 0.002 \pm 0.004$$

Summary of OPAL measurements of $\alpha_s(Q)$

- OPAL (preliminary)

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Cross-section for photon-pairs

- A pure QED process at tree level

At $\sqrt{s}=205$ GeV events observed/expected = 467/463
At $\sqrt{s}=207$ GeV events observed/expected = 534/549
Cross-section for WW-pairs

- Isolate all 3 decay channels $WW \rightarrow q\bar{q}q\bar{q}$, $q\bar{q}\ell\nu\ell$, $\ell\nu\ell\nu\ell$

- Cross-sections assume SM W decay fractions

At $\sqrt{s}=205$ GeV obtain 651, 545, 125 events resp.
At $\sqrt{s}=207$ GeV obtain 887, 708, 162 events resp.

$\sigma(e^+e^- \rightarrow W^+W^-)$

SM prediction via RACOONWW and YFSWW

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A $WW \rightarrow qqqq$ event at 208 GeV
Cross-section for ZZ-pairs

- Isolate decay channels $l l l l, l l \nu \nu, q q l l, q q \nu \nu, q q q q$

- Cross-sections assume SM Z decay fractions

At $\sqrt{s} = 205$ GeV obtain 77 candidates, expected SM bkgd = 37
At $\sqrt{s} = 207$ GeV obtain 85 candidates, expected SM bkgd = 45

No evidence for non-zero neutral TGCs (ZZ$\gamma$, ZZZ)

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A ZZ event at 205 GeV

$M_{mm} \approx 93.1 \text{ GeV}$
$M_{qq} \approx 90.6 \text{ GeV}$

Centre of screen is [ -47.1442, -3.7475, 0.0000 ]
Charged Current TGCs

- Combine WW cross-section and angular distributions with single-W cross-section

No anomalous behaviour: SM values look OK.

Obtain limits on CP-violating TGCs via spin density matrix.

No evidence for anomalous QGCs, eg WWγγ.

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Precision $M_W$ Measurement

- With 480pb$^{-1}$ (prior to Y2K)
  
  $m_W = 80.485 \pm 0.052(stat) \pm 0.039(sys) \text{ GeV}$

- With final statistics, expect
  
  $m_W = 80.xxx \pm 0.040(stat) \pm 0.025(sys) \text{ GeV}$

Data shows no FSI (BEC,CR), $M(qqqq) = M(qql\nu)$.

Emphasise need for good LEP energy determination.

Estimate all-LEP error 30-35 MeV (SM indirect = 26 MeV).

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Non-SM Physics ...indirect limits

$\bar{f}f$, $\gamma\gamma$, $ZZ$, ... cross-sections and couplings in agreement with SM. They provide limits on possible new physics (generally model dependent).

- **4-fermion Contact Interactions**
  
  Mass limits 8-15 TeV with $g^2/4\pi = 1$

- **Sneutrino exchange (RPV) in s-channel**
  
  $\lambda_{131}, \lambda_{121}$ coupling limits within 100-300 GeV range

- **$Z'$ exchange in s-channel**
  
  Exclusion limits in 400-750 GeV range

- **QED $\Lambda$ cut-off parameters in $e^+e^- \rightarrow \gamma\gamma$**
  
  Both $\Lambda_+, \Lambda_-$ above 330 GeV

- **Excited electron in t-channel $\gamma\gamma$**
  
  Mass limit $\sim 300$ GeV assuming $e^*e\gamma = ee\gamma$ coupling

- **Low scale quantum gravity in $\mu^+\mu^-, \tau^+\tau^-, \gamma\gamma, ZZ$**
  
  Mass limits 830-900 GeV

General conclusion: New Physics is far beyond EW scale
OPAL Celebrates the Standard Model

Contact Interactions

OPAL Preliminary

\[ \Lambda^- \quad \Lambda^+ \]

- \( e^+ e^- \)
- \( \mu^+ \mu^- \)
- \( \tau^+ \tau^- \)
- \( \gamma \gamma \)
- \( q\bar{q} \)
- \( q\bar{q} + l\bar{l} \)
- \( u\bar{u} \)
- \( d\bar{d} \)
- \( u\bar{d} \)

\( (\text{TeV}) \)

15 10 5 0 5 10 15

- LL
- RR
- LR
- RL
- VV
- AA
- LLRR
- LRRL
- \( O_{\text{DB}} \)

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Limits on possible $Z'$

![Graph showing limits on possible $Z'$ mass vs. mixing angle for various models.](image-url)
Gravity in Extra Dimensions

95% CL lower limit on $M_S$ is

0.83 TeV with $\lambda = -1$ and 0.90 TeV with $\lambda = +1$
Standard Model Higgs Decays

- $H \rightarrow b\bar{b}$: 60%
  - $Z \rightarrow q\bar{q}$

- $H \rightarrow b\bar{b}$: 18%
  - $Z \rightarrow \nu\bar{\nu}$

- $H \rightarrow b\bar{b}$: 9%
  - $Z \rightarrow e\bar{e}, \mu\mu$

- $H \rightarrow b\bar{b}(\tau\tau)$: 6%
  - $Z \rightarrow \tau\bar{\tau}(q\bar{q})$

4-jet channel, data=18, bkgd=19.1+-2.4
Missing E ch, data=26, bkgd=28.1+-2.9
Tau channel, data=4, bkgd=2.7+-0.4
e/mu channel, data=9, bkgd=5.9+-1.0
TOTAL, data=57, bkgd=55.7+-5.8
Higgs: Individual Channel Mass Distributions

OPAL Preliminary

4 jet

Reconstructed Mass (GeV)

Events/4 GeV

Missing E

Reconstructed Mass (GeV)

Events/4 GeV

Tau

Reconstructed Mass (GeV)

Events/4 GeV

e/µ

Reconstructed Mass (GeV)

Events/4 GeV

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Higgs: Mass Distribution, all Y2K data

Reconstructed Mass (GeV)

Events / 3 GeV

OPAL Preliminary Y2K 200-209 GeV

- Red: Higgs 115 GeV
- Blue: Higgs 110 GeV
- Yellow: Background

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Higgs: Mass Distribution, only 207 GeV data

OPAL Preliminary  206-209 GeV

Events / 3 GeV

Reconstructed Mass (GeV)

- Higgs 115 GeV
- Higgs 110 GeV
- Background
Higgs: $1-\text{CL}_b$: background-only hypothesis

$\sqrt{s}=192-209$ GeV

OPAL Preliminary
$m_H > 107.9 \text{ GeV at } 95\% \text{ CL}$
More Higgs Searches

• SUSY Higgs

  - $e^+e^- \rightarrow h^0Z^0$: as HZ search
  - $e^+e^- \rightarrow A^0h^0 \rightarrow b\bar{b}b\bar{b}$: Data=7, Bkgd=8.4+-1.3
  - $e^+e^- \rightarrow A^0h^0 \rightarrow \tau^+\tau^-bb$: Data=5, Bkgd=3.4+-0.5

  For $\tan(\beta) > 1.2$, determine
  $$m_h > 80.7 \text{ GeV}, \ m_A > 83.2 \text{ GeV}.$$  

  - $e^+e^- \rightarrow H^+H^- \rightarrow \tau^+\nu\tau q\bar{q}'$: Data=160, Bkgd=168
  - $e^+e^- \rightarrow H^+H^- \rightarrow q\bar{q}'q\bar{q}'$: Data=279, Bkgd=302

  $$m_{H^\pm} > 72.3 \text{ GeV}$$ assuming $\text{Br}(\tau\nu + q\bar{q}) = 1$

• Special Higgs Decays

  - Invisible $h^0$, eg. $\rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$: Data=35, Bkgd=53

    $$m_{h^0} > 107.2 \text{ GeV}$$ assuming SM prod rate

  - Fermiophobic $h^0 \rightarrow \gamma\gamma$: Data=16, Bkgd=19

    $$m_{h^0} > 104.6 \text{ GeV}$$ assuming SM prod rate
$m_h$-max: A specific benchmark MSSM scan which provides the most conservative range of excluded $\tan(\beta)$ values.

Exclusion: $\tan(\beta)$ region 0.8-2.0
### Search Channel List

<table>
<thead>
<tr>
<th>Reaction</th>
<th>SM Processes</th>
<th>RPV Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+ e^- \rightarrow hZ$</td>
<td>$h \rightarrow b\bar{b}$</td>
<td>$b\bar{b}q, b\bar{b}\nu\bar{\nu}, b\bar{b}\ell^+\ell^-$</td>
</tr>
<tr>
<td></td>
<td>$h \rightarrow \gamma\gamma$</td>
<td>$(q\bar{q}, \ell^+\ell^-, \nu\bar{\nu})+\gamma\gamma$</td>
</tr>
<tr>
<td></td>
<td>$h \rightarrow \tilde{\chi}^0 \tilde{\chi}^0$</td>
<td>$q\bar{q}, \ell^+\ell^- + E$</td>
</tr>
<tr>
<td>$e^+ e^- \rightarrow hA$</td>
<td>$h, A \rightarrow b\bar{b}, \tau\tau$</td>
<td>$b\bar{b}\bar{b}, b\bar{b}\tau^+\tau^-$</td>
</tr>
<tr>
<td>$e^+ e^- \rightarrow H^+H^-$</td>
<td>$H^+ \rightarrow q\bar{q}, \tau\nu$</td>
<td>$q\bar{q}q\bar{q}, q\bar{q}\tau\nu, \tau\nu\tau\nu$</td>
</tr>
<tr>
<td></td>
<td>$e^+ e^- \rightarrow \tilde{\chi}^+ \tilde{\chi}^-$</td>
<td>$\text{(In)Direct RPV}$</td>
</tr>
<tr>
<td></td>
<td>$\tilde{\chi}^+ \rightarrow W^* \tilde{\chi}^0$</td>
<td>$\text{jets (+}\ell^\pm, \ell^+\ell^- + E)$</td>
</tr>
<tr>
<td></td>
<td>$(\tilde{\chi}^0 \rightarrow \gamma\tilde{G})$</td>
<td>$\text{jets, }\ell^\pm, \nu$</td>
</tr>
<tr>
<td>$e^+ e^- \rightarrow \tilde{\chi}_2 \tilde{\chi}_1$</td>
<td>$\tilde{\chi}_1 \rightarrow Z^0 \tilde{\chi}_1$</td>
<td>$2 \text{ jets } + E$</td>
</tr>
<tr>
<td></td>
<td>$\tilde{\chi}_1 \rightarrow \gamma\tilde{\chi}_1$</td>
<td>$\gamma + E$</td>
</tr>
<tr>
<td></td>
<td>$\tilde{\chi}_1 \rightarrow \gamma G$</td>
<td>$\gamma\gamma + E$</td>
</tr>
<tr>
<td></td>
<td>$\tilde{\chi}_1 \text{ Lifetime}$</td>
<td>$\text{RPV Decays}$</td>
</tr>
<tr>
<td>$e^+ e^- \rightarrow \tilde{\ell}^+ \tilde{\ell}^-$</td>
<td>$\ell^- \rightarrow \ell^- \tilde{\chi}_1^0$</td>
<td>$\ell^+\ell^- + E$</td>
</tr>
<tr>
<td></td>
<td>$(\tilde{\chi}^0 \rightarrow \gamma\tilde{G})$</td>
<td>$\ell^+\ell^- + \gamma\gamma + E$</td>
</tr>
<tr>
<td>$e^+ e^- \rightarrow \nu\bar{\nu}$</td>
<td>$\text{(In)Direct RPV}$</td>
<td>$2,4,6 \times \ell^\pm + E$</td>
</tr>
<tr>
<td></td>
<td>$\ell^\pm \text{ Lifetime}$</td>
<td>$\text{Kinked Tracks}$</td>
</tr>
<tr>
<td></td>
<td>$\nu\bar{\nu}$</td>
<td>$\text{Stable, Charged}$</td>
</tr>
<tr>
<td>$e^+ e^- \rightarrow \tilde{\ell}_1 \tilde{\ell}_1$</td>
<td>$\tilde{\ell}_1 \rightarrow c\tilde{\chi}_1^0$</td>
<td>$\ell^+\ell^- + \ell^+\ell^- + E$</td>
</tr>
<tr>
<td></td>
<td>$\tilde{\ell}_1 \rightarrow b\ell^+\nu$</td>
<td>$\ell^+q\ell^-q$</td>
</tr>
<tr>
<td></td>
<td>$\text{(In)Direct RPV}$</td>
<td>$2 \text{ jets } + E$</td>
</tr>
<tr>
<td>$e^+ e^- \rightarrow N\bar{N}$</td>
<td>$N \rightarrow \ell W$</td>
<td>$\text{jets} + \ell^\pm$</td>
</tr>
<tr>
<td></td>
<td>$e^+ e^- \rightarrow L^+L^-$</td>
<td>$\text{jets, }\ell^\pm + E$</td>
</tr>
<tr>
<td>$e^+ e^- \rightarrow \ell^+\ell^-(*)$</td>
<td>$L^+ \rightarrow \nu W$</td>
<td>$\ell^+\ell^- \gamma(\gamma)$</td>
</tr>
<tr>
<td>$e^+ e^- \rightarrow \nu^<em>\bar{\nu}^</em>$</td>
<td>$\nu^* \rightarrow \nu\gamma$</td>
<td>$\gamma(\gamma) + E$</td>
</tr>
<tr>
<td>$e^+ e^- \rightarrow \ell^<em>\ell, \nu^</em>\nu$</td>
<td>$\ell^* \rightarrow \ell Z$</td>
<td>$\text{jets, }\ell^\pm, \nu$</td>
</tr>
</tbody>
</table>
Single Photon Recoil Mass

Sensitive to Gravity in Extra Dimensions, GMSB scenarios, eg. 
\[ \tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}, \] 
and MSSM \[ \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma, \] and excited neutrinos, eg. 
\[ \nu^* \rightarrow \nu \gamma. \]

Standard Model process is \[ e^+ e^- \rightarrow \nu \bar{\nu} \gamma(\gamma). \]

**2000 data: \( \sqrt{s} = 200 - 209 \text{ GeV} \)**

\[ \int L dt = 166.3 \text{ pb}^{-1} \]
\[ N_{\text{obs}} = 526 \]
\[ N_{\text{exp}} = 530 \pm 26 \]
Non-SM Physics ... direct searches

In general a null search provides limits on cross-sections, couplings, masses, ...

- **Leptoquarks**
  \[ e^+ e^- \rightarrow L_q \bar{L}_q, L_q \rightarrow l q \]  
  Data=54, Bkgd=55

- **Heavy Leptons**
  \[ e^+ e^- \rightarrow N \bar{N}, N \rightarrow l W \]  
  Data=63, Bkgd=51

- **Excited Leptons**
  \[ e^+ e^- \rightarrow l^+ l^- l^*, l^* \rightarrow l \gamma \]  
  Data=6, Bkgd=4
  \[ e^+ e^- \rightarrow l^+ l^- l^*, l^* \rightarrow l \gamma \]  
  Data=642, Bkgd=691

- **Stable, long-lived, massive particles**
  Sensitive to \( Q/e = \pm 1, \pm 2/3 \)  
  Data=0, Bkgd=1

- **Single top via FCNC**
  \[ e^+ e^- \rightarrow t \bar{c}(\bar{u}) \]  
  Data=21, Bkgd=23

\[
M(l^*) > 103 \text{ GeV} \\
M(\tilde{l}) > 97 \text{ GeV}, M(\tilde{\chi}^\pm) > 101 \text{ GeV}, \text{ for long-lived} \\
\sigma_{top} < 0.36 \text{ pb, assuming } Br(t \rightarrow bW) = 1
\]
MSSM searches of two types are conducted

(A) MSUGRA, with/without RPC, where LSP = $\tilde{\chi}^0_1$ (stable),
which leads to topologies with jets, leptons, AND Missing Energy

(B) GMSB, where LSP = $\tilde{G}$ [$\tilde{\chi}^0_1 \rightarrow \gamma \tilde{G}$, $\tilde{\ell} \rightarrow l \tilde{G}$],
which give MORE leptons and photons

- **Scalar Leptons**
  \[ e^+ e^- \rightarrow \tilde{\ell}^+ \tilde{\ell}^-, \tilde{\ell} \rightarrow l \tilde{\chi}^0_1 \]

- **Scalar top/bottom quarks**
  \[ e^+ e^- \rightarrow \tilde{t} \tilde{t}, \tilde{t} \rightarrow c \tilde{\chi}^0_1, b \tilde{\chi}^\pm \]
  \[ e^+ e^- \rightarrow \tilde{b} \tilde{b}, \tilde{b} \rightarrow b \tilde{\chi}^0_1 \]

- **Charginos**
  \[ e^+ e^- \rightarrow \tilde{\chi}^\pm \tilde{\chi}^\mp, \tilde{\chi}^\pm \rightarrow \tilde{\chi}^0_1 W^\pm \]

- **Neutralinos**
  \[ e^+ e^- \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^0_1, \tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 Z^0 \]

No compelling evidence for data in excess of SM bkgd

Cross-section limits are determined

Calculate exclusion regions in MSSM parameter space
MSSM exclusion limit for stop

$\tilde{t} \rightarrow c \tilde{\chi}_1^0$

$\theta_\tilde{t} = 0.98$

$\theta_{{\tilde{t}}} = 0.0$

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MSSM exclusion limit for gauginos

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

\[ m(\tilde{\chi}_1^\pm) \text{ [GeV]} \]

\[ \tan \beta = 1.5 \]

FORBIDDEN (THEORY)

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MSSM exclusion limit for neutralino

Absolute lower limit on lightest neutralino

\( m_{\tilde{\chi}_1^0} > 39.0 \text{ GeV for } m_0 > 500 \text{ GeV} \)

\( m_{\tilde{\chi}_1^0} > 36.0 \text{ GeV for any } m_0 \)
Summary

- OPAL data taking in 2000 very successful
  \[ \int L \, dt \text{ almost } 200 \text{ pb}^{-1} \]
- Many ongoing physics analyses, both LEP1 and LEP2
- All results from LEP data in good agreement with SM predictions.
- We look forward to several years of continuing physics analysis and
  .....perhaps, in some forgotten corner, unexpected new physics