Physics at Electron Positron Colliders

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University of Hamburg
DESY Summer Student Lecture, 08/2002

- Introduction
- The LEP collider and detectors
- Physics highlights from LEP
- The future: TESLA
- Prospects for TESLA physics
A few technical but important preliminaries:

- Ask questions!
- Tell me if too fast or too slow
- Tell me if things have been shown before and are too boring for you ;-)  
- There is no ‘pensum’ we have to fulfil – understanding one thing is better than not understanding many things.

Remember (most important): There are no stupid questions!!!
Particle Physics Today

“Particle physics today is in an excellent yet curious state”

(TESLA TDR)

excellent:

experimental discovery of the fundamental constituents of matter:

and of the force carriers:

Gravitation?
A beautiful theoretical concept to describe particles and their interactions:

- Quantum field theory

\[ \mathcal{L} = \ldots + \bar{\psi} (i \gamma^\mu \partial_\mu - m) \psi + \ldots \]

- Symmetry principle: local gauge invariance

\[ \psi \rightarrow e^{i\alpha(x)} \psi \Rightarrow \partial_\mu \rightarrow D_\mu \]

- Perturbation theory: precise predictions at the loop-level

\[ \mathcal{M} = \begin{array}{c}
\begin{array}{c}
+ \\
+ \\
+ \ldots
\end{array}
\end{array} \]
Excellent:

Impressive agreement between experimental results and theoretical predictions:

A major part of these results comes from LEP and SLD!

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
<th>Pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta a^{(s)}_{\text{had}}(m_Z)$</td>
<td>$0.02761 \pm 0.00036$</td>
<td>-0.27</td>
</tr>
<tr>
<td>$m_Z$ [GeV]</td>
<td>$91.1875 \pm 0.0021$</td>
<td>0.01</td>
</tr>
<tr>
<td>$\Gamma_Z$ [GeV]</td>
<td>$2.4952 \pm 0.0023$</td>
<td>-0.42</td>
</tr>
<tr>
<td>$a^{\phi}_{\text{had}}$ [nb]</td>
<td>$41.540 \pm 0.037$</td>
<td>1.63</td>
</tr>
<tr>
<td>$R_b$</td>
<td>$20.767 \pm 0.025$</td>
<td>1.05</td>
</tr>
<tr>
<td>$A_{\text{b}}^{\phi}$</td>
<td>$0.01714 \pm 0.00095$</td>
<td>0.70</td>
</tr>
<tr>
<td>$A_{\text{b}}(P_L)$</td>
<td>$0.1465 \pm 0.0033$</td>
<td>-0.53</td>
</tr>
<tr>
<td>$R_w$</td>
<td>$0.21646 \pm 0.00065$</td>
<td>1.06</td>
</tr>
<tr>
<td>$R_s$</td>
<td>$0.1719 \pm 0.0031$</td>
<td>-0.11</td>
</tr>
<tr>
<td>$A_{\text{b}}^{0,b}$</td>
<td>$0.0994 \pm 0.0017$</td>
<td>-2.64</td>
</tr>
<tr>
<td>$A_{\text{b}}^{0,c}$</td>
<td>$0.0707 \pm 0.0034$</td>
<td>-1.05</td>
</tr>
<tr>
<td>$A_{\text{b}}$</td>
<td>$0.922 \pm 0.020$</td>
<td>-0.64</td>
</tr>
<tr>
<td>$A_{\text{c}}$</td>
<td>$0.670 \pm 0.026$</td>
<td>0.06</td>
</tr>
<tr>
<td>$A_{\text{b}}(\text{SLD})$</td>
<td>$0.1513 \pm 0.0021$</td>
<td>1.50</td>
</tr>
<tr>
<td>$\sin^2\theta_{\text{eff}}(Q_{\text{b}})$</td>
<td>$0.2324 \pm 0.0012$</td>
<td>0.86</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>$80.451 \pm 0.033$</td>
<td>1.73</td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>$2.134 \pm 0.069$</td>
<td>0.59</td>
</tr>
<tr>
<td>$m_t$ [GeV]</td>
<td>$174.3 \pm 5.1$</td>
<td>-0.08</td>
</tr>
<tr>
<td>$\sin^2\theta_W(vN)$</td>
<td>$0.2277 \pm 0.0016$</td>
<td>3.00</td>
</tr>
<tr>
<td>$Q_W(Cs)$</td>
<td>$-72.39 \pm 0.59$</td>
<td>0.84</td>
</tr>
</tbody>
</table>
## Experiments!

<table>
<thead>
<tr>
<th>Electron positron colliders</th>
<th>Hadron (proton proton) colliders</th>
</tr>
</thead>
<tbody>
<tr>
<td>pointlike particles collide</td>
<td>composite particles collide</td>
</tr>
<tr>
<td>$E(\text{CM}) = 2 \ E(\text{beam})$</td>
<td>$E(\text{CM}) &lt; 2 \ E(\text{beam})$</td>
</tr>
<tr>
<td>clean final states</td>
<td>superposition with spectator jets:</td>
</tr>
<tr>
<td></td>
<td>large backgrounds</td>
</tr>
<tr>
<td>well known quantum numbers</td>
<td>quantum numbers of hard collision</td>
</tr>
<tr>
<td>of initial state</td>
<td>are not well known</td>
</tr>
<tr>
<td>very high energies are difficult</td>
<td>very high energies are comparatively</td>
</tr>
<tr>
<td>(synchrotron radiation)</td>
<td>easier</td>
</tr>
<tr>
<td>well suited for discovery and precision measurements</td>
<td>best suited for discovery</td>
</tr>
<tr>
<td></td>
<td>some precision measurements are possible</td>
</tr>
</tbody>
</table>

Lepton and Hadron machines are complementary!
Precision in Physics

example: astronomy

- observed: small deviations from the expected trajectories of the planets
- predicted: an additional planet can explain the observation
- discovery: PLUTO was found

example: Particle physics

- indirect prediction for mass of the top quark
- discovery: 1995, Tevatron (USA) at the predicted mass
Brief History of Colliders

The first colliding beam accelerator (electron-electron)

PRIN-STAN (Stanford) ~1966
Brief History of Colliders

Hadron Colliders

e+e- Colliders

10 TeV

1 TeV

100 GeV

10 GeV

1 GeV

Year of First Physics

Year 1960

1970

1980

1990

2000

2010

Constituent Center-of-Mass Energy

PRIN-STAN (Stanford)

VEPP II (Novosibirsk)

ACO (France)

SPEAR II

SPEAR (SLAC)

DORIS (DESY)

VEPP II (Novosibirsk)

VEPP IV (Novosibirsk)

CESR (Cornell)

PEP (SLAC)

PETRA (DESY)

TRISTAN (KEK)

SLC (SLAC)

LEP II

LEP (CERN)

TESLA

TEVATRON (Fermilab)

SPPS (CERN)

ISR (CERN)

ADONE (Italy)

LHC (CERN)

NLC

Klaus Desch, Physics at e+e- Colliders, DESY Summer Student Lecture 08/2002
Brief History of Colliders

![Graph showing the history of colliders with luminosity on the y-axis and center-of-mass energy on the x-axis, with markers for different colliders and luminosity levels.]

- e+e- Collider (operational)
- e+e- Collider (planned)
- Hadron Collider (operational)
- Hadron Collider (planned)
- e+p Collider

Colliders mentioned include:
- TESLA
- SPS
- HERA
- LHC
CERN
The LEP collider at CERN
### The LEP collider at CERN

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>~27 km</td>
</tr>
<tr>
<td>Centre-of-mass energy</td>
<td>92.1 GeV (LEP1) to 209 GeV (LEP2)</td>
</tr>
<tr>
<td>Accelerating gradient</td>
<td>Up to 7 MV/m (SC cavities)</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>4 x 4</td>
</tr>
<tr>
<td>Current per bunch</td>
<td>~ 750 µA</td>
</tr>
<tr>
<td>Luminosity (at Z0)</td>
<td>~ 24 x 10^{30} cm^{-2}s^{-1} (~1 Z0/sec)</td>
</tr>
<tr>
<td>Luminosity (at LEP2)</td>
<td>~ 50 x 10^{30} cm^{-2}s^{-1} (3 WW/hour)</td>
</tr>
<tr>
<td>Interaction regions</td>
<td>4 (ALEPH, DELPHI, L3, OPAL)</td>
</tr>
<tr>
<td>Energy calibration</td>
<td>&lt; 1 MeV (at Z0)</td>
</tr>
</tbody>
</table>
The LEP collider at CERN

Integrated luminosities seen by experiments from 1989 to 2000

1000 pb-1 since 1989

LEP 1
- 1990-1995: ~91 GeV
- 1995: Test phase for LEP2: 130 GeV
- 1997: 183 GeV
- 1998: 189 GeV
- 1999: 192-200 GeV
- 2000: 200-209 GeV

LEP 2
- 1990-1995: 4 Million Z0’s
- 1995: 1000 W-pairs
- 1996: 2500 W-pairs
- 1997: 3000 W-pairs
- 1998: 2500 W-pairs
- 1999: 3000 W-pairs

LEP was shut down and dismantled to make room for the LHC in Nov 2000
Detectors

The ALEPH Detector

DELPHI

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Detectors

A detector cross-section, showing particle paths
Detectors

electron
charged hadron + muon
photon
neutral pion
??

VTX
Tracking
ECAL
HCAL
Muon

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Identifying events

http://www.hep.man.ac.uk/~events/home.html

e^+e^- \rightarrow e^+e^-$
Identifying events

\[ e^+ e^- \rightarrow \mu^+ \mu^- \]
Identifying events

\[ e^+ e^- \rightarrow \tau^+ \tau^- \]
Identifying events

\[ e^+ e^- \rightarrow q\bar{q} \]
A little quiz

???
Physics highlights from LEP

- The basic process at LEP1
- Z-mass
- Asymmetries: electro-weak interference
- Testing the strong interaction: QCD
- LEP2: W-Bosons
- LEP2: The Higgs hunt
- Status of the SM: where is the Higgs?

Of course this is only a personal selection, many more (interesting) topics will be left out

Until today **1199** published papers by the 4 LEP experiments
The basic process at LEP1

Elektron → Positron

Photon(el-mag.)
Z-Boson(schwach)

Lepton, Quark, W-Boson, ...

Anti-Lepton, Anti-Quark, Anti-W-Boson, Anti-...
The total cross section

\[ \frac{d\sigma}{d\Omega} = N_e \frac{\alpha^2}{4s} \left\{ (1 + \cos^2 \theta) \left[ Q_f^2 - 2\chi_1 v_e v_f Q_f - \chi_2 (a_e^2 + v_e^2) (a_f^2 + v_f^2) \right] \right\} \]

\[ + 2 \cos \theta \left\{ -2\chi_1 a_e a_f Q_f + 4\chi_2 a_e a_f v_e v_f \right\} \]

\[
\begin{align*}
\chi_1 &= \frac{1}{16 \sin^2 \theta_W \cos^2 \theta_W} \frac{s(s - M_Z^2)}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \\
\chi_2 &= \frac{1}{256 \sin^4 \theta_W \cos^4 \theta_W} \frac{s(s - M_Z^2)}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \\
a_e &= -1 \\
v_e &= -1 + 4 \sin^2 \theta_W \\
a_f &= 2T_{3f} \\
v_f &= 2T_{3f} - 4Q_f \sin^2 \theta_W
\end{align*}
\]
The total cross section

- $\gamma$-exchange dominant for low $\sqrt{s}$
- $Z^0$ is a dramatic resonance!
- Theory curve describes the data extremely well
- Theory curve is not the one from previous page but includes higher-order corrections
The mass of the Z-Boson

Error only 2.1 MeV!
Need to understand many tiny theoretical + experimental effects
Important: Beam energy calibration
Beam energy measurement

- Measure polarization with Compton Polarimeter
- Photon detector
- Laser

Permanent synchrotron radiation polarizes beam

Weak radial oscillating B-field destroys polarization if in resonance with Larmor frequency

Spin precesses in B field

\[ v = \frac{g-2}{2} \frac{E}{mc^2} \text{ (Larmor frequency)} \]

Achieved precision: \( \sim 1 \text{ MeV} \)
Beam energy measurement: tiny effects

Moon pulls the LEP ring
→ change ring radius
by 1 mm
→ 10 MeV energy change
Beam energy measurement: very tiny effects

Water level in lake Geneva causes deformation of LEP ring → up to 20 MeV energy change
Beam energy measurement: very tiny effects

Correlation between trains and LEP

![Diagram of LEP and train paths]
One step further: classifying the events

SM makes precise prediction for the branching ratios of the Z0:

\[ \Gamma_{\nu \nu} = \frac{G_FM_Z^3}{12\pi\sqrt{2}} \approx 167 \text{ MeV} \quad \text{for each neutrino family} \]

\[ \Gamma_{ee} = \Gamma_{\mu\mu} = \Gamma_{\tau\tau} = 4x_w^2 \Gamma_{\nu \nu} \approx 84 \text{ MeV} \]

\[ \Gamma_{uu} = \Gamma_{cc} = 3 \left( \frac{32}{9} x_w^2 - \frac{8}{3} x_w + 1 \right) \Gamma_{\nu \nu} \approx 287 \text{ MeV} \]

\[ \Gamma_{dd} = \Gamma_{ss} = \Gamma_{bb} = 3 \left( \frac{8}{9} x_w^2 - \frac{4}{3} x_w + 1 \right) \Gamma_{\nu \nu} \approx 370 \text{ MeV} \]

(neglecting the quarks masses)

How can one measure \( \Gamma_{\nu \nu} \)?

\[ BR(Z \rightarrow X) = \frac{\frac{\Gamma_X}{\Gamma_{tot}}}{\Gamma_{\nu \nu}} \]

\[ (x_w = \sin^2 \theta_W) \]
Counting neutrinos

prefers 3 families
but rather large error...
Counting neutrinos: smarter way

\[ \Gamma_{\text{tot}} = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{qq} + \left( N_{\text{families}} \right) \Gamma_{\nu\nu} \]

i.e. the total width of the Z depends on the number of (light) neutrinos:

Result:

\[ N_{\text{families}} = 2.9841 \pm 0.0083 \]

before LEP:

\[ N_{\text{families}} < 5.9 \]
Yet another step further: angular distributions

Linear term in $\cos(\theta)$ leads to a forward backward asymmetry:

$$A_{FB} = \frac{\sigma(\cos \theta > 0) - \sigma(\cos \theta < 0)}{\sigma(\cos \theta > 0) + \sigma(\cos \theta < 0)}$$

better method (smaller systematics) than fit to whole distribution, since detector efficiency cancels out (only forward-backward-symmetric detector needed)
Yet another step further: angular distributions

OPAL Preliminary

**ee**

Data - Fit

**μμ**

Data - Fit
Yet another step further: angular distributions

FB asymmetries allow determination of vector- and axialvector coupling of the fermions to the Z.

Test of lepton universality!
Interpretation of the Asymmetries

Asymmetry measurements
Can be interpreted as
Measurement of the
Electro-weak mixing angle

\[ \sin^2 \theta_W \]
Too precise measurements! – Radiative corrections

The measured observables can be predicted in the SM as a function of the following parameters:

\[ \mathcal{O} = \mathcal{O}(m_Z, m_t, m_H, \alpha(m_Z), \alpha_\alpha(m_Z); G_F) \]

**LEP**
- Lineshape: \( m_Z, \Gamma_Z, \sigma_H^0, R_\ell, A_{FB}^{0,\ell} \)
- \( P(\tau) \): \( A_e, A_r \)
- \( b, c \): \( R_b, R_c, A_{FB}^{0,b}, A_{FB}^{0,c} \)
- \( Q_{FB}^{\text{eff}} \): \( \sin^2\theta_{\text{eff}} \)

**SLD**
- \( b, c \): \( R_b, R_c, A_{FB}^{0,b}, A_{FB}^{0,c} \)
- L-R asym: \( A_\ell, A_{\ell b}, A_c \)
- \( p\bar{p}, \text{LEP2} \)
- \( m_t, m_W, \nu N \)
- \( \sin^2\theta_W \)

\[
R_\ell = \frac{\Gamma_{\text{had}}}{\Gamma_\ell}, \quad A_{FB}^{0,\ell} = \frac{3}{4} A_e A_\ell \\
A_\ell = \frac{2g_{V\ell}g_{A\ell}}{g_{V\ell}^2 + g_{A\ell}^2} \\
g_{V\ell}/g_{A\ell} = 1 - 4 \sin^2\theta_{\text{eff}}^{\text{lept}} \\
\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}
\]
Too precise measurements! – Radiative corrections

They depend on the unknown parameters

\[ m_{\text{top}} \] linearly

\[ m_{\text{Higgs}} \] only logarithmically

Lead to prediction of top-mass before its discovery:
Quarks and gluons are not observed as free objects, but manifest themselves as jets.

String effect
Testing the theory of the strong interaction: QCD

Process can be described in 4 Steps:
1. EW creation (exactly calculable)
2. Parton shower (pert. QCD treatment)
3. Fragmentation of Quarks+Gluons into Hadrons (only phen. Models)
4. Decay of Hadrons (mostly phenomenological)

Phases 3 and 4 implemented into Computer-Programs: important tools.
Testing the theory of the strong interaction: QCD

Quarks and Gluons show up as Jets. Need a definition of a jet!

Cluster Algorithm:

1. All reconstructed particles are considered "Pseudo-Jets"

2. For all pairs of Pseudo-Jets their distance $y_{ik}$ is calculated

   $$y_{ik} = \frac{2\min(E_{i}^{2}, E_{k}^{2})(1 - \cos \theta_{ik})}{E_{vis}^{2}}$$

3. The pair with smallest distance $y_{ik}$ is joined into a new Pseudo-Jet unless it’s distance is larger than a free parameter $y_{cut}$. Then the procedure is stopped and all remaining Pseudo-Jets are jets, otherwise the procedure is iterated from 2.
Testing the theory of the strong interaction: QCD

number of jets depends upon how close one looks at them...
Testing the theory of the strong interaction: QCD

Measure the strong coupling constant:

\[ \alpha_s(Q)^2 \sim \alpha_s^2 \]

But there are more fancy methods...
Summary: LEP1

- Precision study of the properties of the Z-Boson
- Triumph of the Standard Model
- Sensitivity to virtual effects from top-Quark
- Prediction of top mass before discovery
- Precise measurement of electroweak mixing angle

\[ 1 - \sin^2 \theta_w = \frac{M_W}{M_Z} \]

Would like to know more \( \Rightarrow \) LEP2!

Precisely known from LEP1
Increasing the energy: LEP2

Main targets:

• Precise measurement of the W-mass
• Testing the non-abelian structure of the electroweak interaction
• Hunt for the Higgs boson
• Searches for new particles
W-Pair production

- no resonance! ⇔ much smaller cross section than for Z at LEP1
- only pair-production (why?)
- expect a few thousand events / year
- again precise SM predictions (e.g.):
  - mass
  - branching ratios
  - structure of couplings (self-coupling!)
**W-Pair production**

Three different event topologies:

\[ W^+W^- \rightarrow q\bar{q}q\bar{q} \]

\[ W^+W^- \rightarrow \ell\nu\ell\nu \]

\[ W^+W^- \rightarrow \ell\nu q\bar{q} \]
**W-Pair production**

**Measurement of the W-mass**

![Graph showing the measurement of W mass](image)

**Summer 2001 - LEP Preliminary**

- **ALEPH [1996-2000]**: $80.47 \pm 0.049$
- **DELPHI [1996-2000]**: $80.40 \pm 0.066$
- **L3 [1996-2000]**: $80.39 \pm 0.069$
- **OPAL [1996-1999]**: $80.49 \pm 0.055$
- **LEP**

**LEP working group**

$\chi^2/\text{dof} = 32.5 / 39$

Error: $\sim 40$ MeV
i.e. $\sim 20x$ error on Z-mass
Non-abelian structure of EW-interactions

First direct observation of gauge boson self-coupling in EW interactions
Non-abelian structure of EW-interactions

More precise information about this coupling from angular distributions of the W-Bosons and their decay products

\[ E_{CM} > 202.5 \text{ GeV} \]

- data
- \( \lambda = 0 \)
- \( \lambda = +0.5 \)
- \( \lambda = -0.5 \)

background
Again too precise: Radiative corrections part 2:

Direct measurements of $M_W$ and $M_{\text{top}}$ can be compared to their Indirect predictions from LEP1 measurements:

- They agree!
- They prefer a rather Light Higgs Boson!
Sensitivity to the last SM particle: the Higgs

Perform a global fit to all measurements within the SM to obtain the most likely Higgs mass:

\[ M(\text{Higgs}) < \sim 200 \text{ GeV at 95\% C.L.} \]

What is the yellow bar?
Hunting the Higgs Boson

If not too heavy, the Higgs could be observed directly at LEP:

Higgs Branchiong ratios:

⇒ dominant decays:

\[ H \rightarrow b\bar{b} \]

and

\[ H \rightarrow \tau^+\tau^- \]
Hunting the Higgs Boson

...leads together with Z decay modes to many different final states:

- **4-Jet-Kanal**
  \[ H \to b\bar{b}, \quad Z \to q\bar{q} \]
  \[ 51\% \quad WW \to q\bar{q}q\bar{q}, ZZ \to bbq \quad \text{QCD 4jets} \]

- **Neutrino-Kanal**
  \[ H \to b\bar{b}, \quad Z \to \nu\bar{\nu} \]
  \[ 15\% \quad WW \to q\bar{q}\nu, ZZ \to bb\nu \]

- **Tau-Kanal**
  \[ H \to b\bar{b}, \quad Z \to \tau^+\tau^- \]
  \[ 2.4\% \quad WW \to q\bar{q}\tau, ZZ \to q\bar{q}\tau \quad \text{QCD (low-mult jets)} \]

- **Lepton-Kanal**
  \[ H \to b\bar{b}, \quad Z \to e^+e^-, \mu^+\mu^- \]
  \[ 4.9\% \quad ZZ \to b\bar{b}ll \]

~80% aller Endzustände (für \( m_H = 115 \text{ GeV} \))

Selektionseffizienz: 40-50%
Hunting the Higgs Boson

A nice candidate event (m = 115 GeV)
Hunting the Higgs Boson

Are there many of these?

Hard to say from plot... statistical analysis needed:
Hunting the Higgs Boson

No significant excess observed.

Final word from LEP: \( M_{\text{Higgs}} > 114.4 \text{ GeV} @ 95\% \text{ C.L.} \)
Summary of Day 1

- Hadron and Lepton Colliders have complementary properties
- LEP1 provided confirmed the SM with excellent precision
  -> led to prediction for top mass
- LEP2 precision study of $W$ bosons
  -> prediction for Higgs mass
- Direct Higgs search: $m > 114$ GeV