Boson Gauge Couplings at LEP

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For the Four LEP Collaborations ADLO

40th Rencontres De Moriond On Electroweak Interactions And Unified Theories
8 Mar 2005, La Thuile, Aosta Valley, Italy

March 8 2005
LEP: $e^+e^-$ collider at CERN
LEP1: $E_{CM} \sim M_Z$ from 1989 to 1995
LEP2: $\sim 700\text{ pb}^{-1}$ /exp above WW production threshold from 1996 to 2000
Results from the LEP experiments

- Main analyses (cross section, W mass, TGC) by all experiments
  - Results combined by joint LEP Working Groups
  - Common systematics and correlations
  - Almost all the statistics analyzed
  - A lot of results still preliminary, many final publications this year !!

<table>
<thead>
<tr>
<th></th>
<th>ALEPH</th>
<th>DELPHI</th>
<th>L3</th>
<th>OPAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>2003</td>
<td>2004</td>
<td>2002</td>
<td>2003</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>2005</td>
<td>2003</td>
<td>2003</td>
<td>2004</td>
</tr>
<tr>
<td>$W+W-$</td>
<td>2004</td>
<td>2004</td>
<td>2004</td>
<td>2005</td>
</tr>
<tr>
<td>TGC</td>
<td>2005</td>
<td>2005</td>
<td>2004</td>
<td>2004</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>2005</td>
<td>2005</td>
<td>2004</td>
<td>2004</td>
</tr>
<tr>
<td>$m_W$</td>
<td>2005</td>
<td>2005</td>
<td>2005</td>
<td>2005</td>
</tr>
</tbody>
</table>
Physics processes at LEP2

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**Boson Gauge Couplings**

- **Standard Model**: non-Abelian SU(2)xU(1) gauge symmetry
  - cTGC charged triple Gauge Couplings: \(WW\gamma, WWZ\)
  - cQGC charged quartic Gauge Couplings: \(WW\gamma\gamma, WWZ\gamma, WWZZ, WWWW\) (small or negligible at LEP)

- Search for **anomalous Gauge Couplings**
  - charged: beyond the SM
  - neutral: not in the SM: nTGC: \(ZZZ, ZZ\gamma, Z\gamma\gamma\) and nQGC: \(ZZ\gamma\gamma\)

- Gauge bosons production required

  \(\Rightarrow\) **LEP2 energy allowed these studies for the “first time”**

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Charged Triple Gauge Couplings

- Sensitivity to TGCs in 3 processes
  - **WW pairs production**
  - single W production
  - single photon production
W-pair events

WWW → evqq (~15%)

\[ e^+ e^- \rightarrow W^+ W^- \]

<table>
<thead>
<tr>
<th>Channel</th>
<th>efficiency</th>
<th>purity</th>
<th>bkg</th>
</tr>
</thead>
<tbody>
<tr>
<td>ℓννν</td>
<td>11%</td>
<td>50-80%</td>
<td>80-90%ττ,γγττ, llνν</td>
</tr>
<tr>
<td>evqq</td>
<td>15%</td>
<td>75-90%</td>
<td>~90% qq, Zee</td>
</tr>
<tr>
<td>μνqq</td>
<td>15%</td>
<td>75-90%</td>
<td>~95% qq</td>
</tr>
<tr>
<td>τνqq</td>
<td>15%</td>
<td>50-80%</td>
<td>80-85% qq,Weν</td>
</tr>
<tr>
<td>qqqq</td>
<td>45%</td>
<td>80-90%</td>
<td>75-80% qq</td>
</tr>
</tbody>
</table>

Gauge Couplings!
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$WW \rightarrow qqqq \ (\sim 45\%)$

$WW \rightarrow \mu\nuqq \ (\sim 15\%)$
$WW \rightarrow \tau \nu qq$ (~15%)

$WW \rightarrow e \nu \mu \nu$ (~4%)

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Backgrounds in WW cross section

All 4f diagrams (evqq)

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Devo mettere altro ??
quanto grande correzione 4f-cc03 ?
Andrea Venturi; 01/06/2003
LEP combination

- $\sigma_{WW}$ from each exp combined
  - Precision better than 1%
  - systematics correlation matrix
  - test the SM radiative correction to CC03 diagrams

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W-pair cross sections


\[ \nu e \text{ exchange t channel ONLY} \]

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W-pair cross sections

\[ \sigma_{WW} \text{ (pb)} \]

\( \sqrt{s} \) (GeV)

- no ZWW vertex (Gentle)
- only \( \nu_e \) exchange (Gentle)

\[ \nu \text{ exchange and } \gamma_{WW} \text{ vertex} \]
Clear proof of SU(2)xU(1) gauge couplings!
Charged Triple Gauge Couplings

- Sensitivity to TGCs in 3 processes
  - WW pairs production
  - single $W$ production
  - single photon production
Single W....

In agreement with SM within 8% precision

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In agreement with SM within 7% precision
Charged Triple Gauge Couplings

- Sensitivity to TGCs in 3 processes
  - WW pairs production
  - single W production
  - single photon production

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Single $\gamma$

$N_\nu = 2.84 \pm 0.08$

$e^+ e^- \rightarrow \nu \bar{\nu} \gamma$

Sensitive to the $WW\gamma$ couplings outside Z resonance !!
Triple Gauge Couplings

Standard electroweak theory

$$\mathcal{L}_B = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} F_{\mu\nu}^i F^{\mu\nu i}$$

U(1)

SU(2)

triple and quartic SU(2) gauge boson self couplings are the signature of the non-Abelian SU(2) electroweak structure!

The most general Lorentz Invariant $WWV$ ($V=\gamma + Z$) vertex has $7+7 = 14$ complex couplings

$$B_{\mu\nu} = \partial_\nu B_\mu - \partial_\mu B_\nu$$

$$F_{\mu\nu}^i = \partial_\nu W_\mu^i - \partial_\mu W_\nu^i + g\epsilon_{ijk} W_\mu^j W_\nu^k.$$
**Triple Gauge Couplings**

<table>
<thead>
<tr>
<th></th>
<th>$g_1^V$</th>
<th>$\kappa_V$</th>
<th>$\lambda_V$</th>
<th>$g_5^V$</th>
<th>$g_4^V$</th>
<th>$\tilde{\kappa}_V$</th>
<th>$\tilde{\lambda}_V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C$</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>$P$</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SM</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

C and P conservation $\rightarrow$ only 6 real out of 14 complex parameters

SU(2)$_L \otimes$ U(1)$_Y$ $\rightarrow$ only 3 free parameters $g_1^Z \kappa_\gamma \lambda_\gamma$

\[ \Delta \kappa_Z = -\Delta \kappa_\gamma \tan^2 \theta_W + \Delta g_1^Z \]
\[ \lambda_Z = \lambda_\gamma \]
\[ g_1^\gamma = 1 \]

all other TGCs = 0

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Most important process for studying TGCs is $e^+e^- \rightarrow W^+W^-$

The $WWZ$ and $WW_\gamma$ gauge couplings can be measured in $W$-pair events, fitting the $W$-pair event rates and the $W$ production and decay angular distributions.

The $W$ Polar angle

$\theta^*_q$ fermion polar angle wrt the $W$ direction

$\phi^*_i$ fermion azimuthal angle wrt the $WW$ plane

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Triple Gauge Couplings: $W^+W^-$ Analysis

Use angular distributions from all event topologies:

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

Do $W$ charge tagging to obtain $W^-$ direction in $q\bar{q}q\bar{q}$ events

Use Monte Carlo to correct for detector effects and to implement radiative corrections

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Triple Gauge Couplings: 1d & 2d Fit
LEP Results

3 parameters fit with C and P cons. and SU(2)_L \otimes U(1)_Y

LEP preliminary

\[ \kappa_\gamma = 0.984 \pm 0.042 \]
\[ \lambda_\gamma = -0.016 \pm 0.021 \]
\[ g_1^2 = 0.991 \pm 0.021 \]

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Triple Gauge Couplings: 3d Fit Results

3 parameters fit with C and P cons. and SU(2)_L \otimes U(1)_Y
Triple Gauge Couplings

Relaxing all constraints and fitting for any of the 28 $WWZ$ and $WW_\gamma$ couplings

one-dimensional fit results for the SM non-zero TGC values (ALEPH data only)

... all other 24 couplings are consistent with zero (within 5-20%)!

Proof of the Standard Model $SU(2)_L \otimes U(1)_Y$ Structure

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Neutral TGC (excluded by SM)

- Investigated in ZZ and $Z\gamma$ processes
- ZZ on shell: 4 parameters $f_{4Z}^Z$, $f_{4\gamma}^Z$, $f_{5Z}^Z$, $f_{5\gamma}^Z$
- $Z\gamma$ on shell: 8 parameters $h_{iZ}^Z$, $h_{i\gamma}^Z$ ($i=1,4$)

**DELPHI (PRELIMINARY)**

Z angular distrib in boosted frame

**LEP PRELIMINARY**

ZZ on shell: 4 parameters $f_{4Z}^Z$, $f_{4\gamma}^Z$, $f_{5Z}^Z$, $f_{5\gamma}^Z$

**ZZ**

DATA

- $qq\gamma$
- back

$Z\gamma$ on shell: 8 parameters $h_{iZ}^Z$, $h_{i\gamma}^Z$ ($i=1,4$)
precisione R per ZZ
Andrea Venturi; 04/06/2003
nTGC combined results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>95% C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_1^\gamma$</td>
<td>$[-0.056, +0.055]$</td>
</tr>
<tr>
<td>$h_2^\gamma$</td>
<td>$[-0.045, +0.025]$</td>
</tr>
<tr>
<td>$h_3^\gamma$</td>
<td>$[-0.049, -0.008]$</td>
</tr>
<tr>
<td>$h_4^\gamma$</td>
<td>$[-0.002, +0.034]$</td>
</tr>
<tr>
<td>$h_1^Z$</td>
<td>$[-0.13, +0.13]$</td>
</tr>
<tr>
<td>$h_2^Z$</td>
<td>$[-0.078, +0.071]$</td>
</tr>
<tr>
<td>$h_3^Z$</td>
<td>$[-0.20, +0.07]$</td>
</tr>
<tr>
<td>$h_4^Z$</td>
<td>$[-0.05, +0.12]$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$f_4^\gamma$</td>
<td>$[-0.17, +0.19]$</td>
</tr>
<tr>
<td>$f_4^Z$</td>
<td>$[-0.31, +0.28]$</td>
</tr>
<tr>
<td>$f_5^\gamma$</td>
<td>$[-0.36, +0.40]$</td>
</tr>
<tr>
<td>$f_5^Z$</td>
<td>$[-0.36, +0.39]$</td>
</tr>
</tbody>
</table>

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Quartic Gauge Couplings

- QGC at LEP: $WW\gamma\gamma$, $WWZ\gamma$, $ZZ\gamma\gamma$
  - 5 parameters: $a_{W0}^W$, $a_{Wc}^W$, $a_{Wn}^W$, $a_0^Z$, $a_c^Z$
- Total cross section
- Photon energy and angular distribution

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95% C.L. Limits on quartic couplings in $\text{GeV}^{-2}$ from $W^+W^-\gamma$

<table>
<thead>
<tr>
<th>Parameter</th>
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<th>OPAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_o / \Lambda^2$</td>
<td>$-0.020 &lt; a_o / \Lambda^2 &lt; 0.020$</td>
<td>$-0.017 &lt; a_o / \Lambda^2 &lt; 0.017$</td>
<td>$-0.020 &lt; a_o / \Lambda^2 &lt; 0.020$</td>
</tr>
<tr>
<td>$a_c / \Lambda^2$</td>
<td>$-0.063 &lt; a_c / \Lambda^2 &lt; 0.032$</td>
<td>$-0.052 &lt; a_c / \Lambda^2 &lt; 0.026$</td>
<td>$-0.053 &lt; a_c / \Lambda^2 &lt; 0.037$</td>
</tr>
<tr>
<td>$a_n / \Lambda^2$</td>
<td>$-0.180 &lt; a_n / \Lambda^2 &lt; 0.140$</td>
<td>$-0.140 &lt; a_n / \Lambda^2 &lt; 0.130$</td>
<td>$-0.160 &lt; a_n / \Lambda^2 &lt; 0.150$</td>
</tr>
</tbody>
</table>

95% C.L. Limits on quartic couplings in $\text{GeV}^{-2}$ from $ZZ\gamma\gamma$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ALEPH</th>
<th>L3</th>
<th>OPAL</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_c / \Lambda^2$</td>
<td>$[-0.041, +0.044]$</td>
<td>$[-0.037, +0.054]$</td>
<td>$[-0.045, +0.050]$</td>
<td>$[-0.029, +0.039]$</td>
</tr>
<tr>
<td>$a_o / \Lambda^2$</td>
<td>$[-0.012, +0.019]$</td>
<td>$[-0.014, +0.027]$</td>
<td>$[-0.012, +0.031]$</td>
<td>$[-0.008, +0.021]$</td>
</tr>
</tbody>
</table>
CONCLUSIONS

- The Standard Model non-Abelian $SU(2)\times U(1)$ gauge symmetry PROVED!!!
  - MEASURED $cTGC$s charged triple Gauge Couplings: $WW\gamma, WWZ$
  - NEGLIGIBLE $cQGC$s quartic Gauge Couplings: $WW\gamma\gamma, WWZ\gamma, WWZZ, WWWW$

- EXCLUDED anomalous Gauge Couplings
  - charged: beyond the SM
  - neutral: not in the SM: $nTGC: ZZZ, ZZ\gamma, Z\gamma\gamma$ and $nQGC: ZZ\gamma\gamma$

$\Rightarrow$ one of the most important results of LEP2
W Polarization in $e^+e^- \rightarrow W^+W^-$

Measure spin density matrices $\rho_{kk}(s, \cos \theta_W)$ and extract polarized diff cross sec

Fit for $\rho_{kk}$ (L3)

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos \theta_W} = \rho_{--} \frac{3}{8} \left(1 + \cos \theta_f^x\right)^2 + \rho_{00} \frac{3}{4} \sin^2 \theta_f^x$$

$$+ \rho_{++} \frac{3}{8} \left(1 - \cos \theta_f^x\right)^2 .$$

Use avg value of projection op $\Lambda_{kk}$ (OPAL)

$$\rho_{\tau\tau^{-}}(s, \cos \theta_W) = \int \frac{d^3\sigma}{d\cos \theta_W d\cos \theta_f^x d\phi_f^x} \cdot \Lambda_{\tau\tau'} d\cos \theta_f^x d\phi_f^x$$

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Form Factor $F_T$ for Vector Resonance Enhancement of $e^+e^- \rightarrow W_L^+W_L^-$

$$F_T = 1 + \left( 1 + \frac{\Gamma_{\rho}^2}{M_{\rho}^2} \right)^{-1} \frac{s}{M_{\rho}^2} + i \frac{\Gamma_{\rho}}{M_{\rho}} \left( 1 + \frac{\Gamma_{\rho}^2}{M_{\rho}^2} \right)^{-1} \frac{s}{M_{\rho}^2}$$

Map triangle onto $(M_\rho, \Gamma_\rho / M_\rho)$ plane

Triangle corresponds to 95% CL allowed region with $\Delta \text{Re}(F_T), \text{Im}(F_T) > 0$

For $\frac{\Gamma_\rho}{M_\rho} < 1$ the technirho mass $M_\rho > 675 \text{GeV}$ at 95% C.L.

For $\frac{\Gamma_\rho}{M_\rho} < 0.5$ the technirho mass $M_\rho > 775 \text{GeV}$ at 95% C.L.

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W Boson Production at LEP2

- $e^+e^- \rightarrow W^+W^-$

- $e^+e^- \rightarrow W\nu_e$

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Event selection: $qqqq$

- Event properties
  - Large multiplicity
  - no missing momentum
  - 4jet-like
- Main background: $qq(g)$
- Multidimensional techniques ($NN$, $pdf$, ...)
- Eff. ~ 90%, purity ~ 85 %

Main systematics ~1.3 ± 2. %:
  - hadronization models (signal and bkg)
    - correlated among experiments !!
  - detector simulation

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controllare i sistematici
scrivere valore sistematico %
Andrea Venturi; 01/06/2003
Event selection: $l\nu qq$

- Two jets + high energy and isolated lepton (or $\tau$ jet) + missing $p_t$
- Main backgrounds: $qq(\gamma)$ and 4f (non-WW)
- Multivariable selections
- Eff. 60-90%, purity ~ 80-95%

Main systematics ~1.4 ÷ 2.5%:
- lepton-id
- background subtraction

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verificare sistematici
verificare efficienze e bkg
valore syst %

Andrea Venturi; 01/06/2003
Event selection: $l\nu l\nu$

- **Low multiplicity**
  - two leptons or thin jets ($\tau$ jets)
- **Missing $p_{t}$ and acoplanarity**
  - cuts depend on lepton flavour
- **Main background:**
  - two photons, di-leptons, 4f non-WW
- **Eff. ~50-80%, purity ~80-90%**

- **Main systematics ~1.3-4.5%:**
  - background subtraction
  - lepton identification
  - beam related detector noise

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verificare sistematici
verificare eff e bkg
valore syst %
Andrea Venturi; 01/06/2003
O(\(\alpha\)) radiative correction to WW production

Not available at the beginning of LEP2

W mass: peak distortions and radiation: compensation: < 5-10 MeV

No correction: ~2% higher cross section. No effect on acceptance

TGC: ~1% change in WW production angle

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