Search for Exotica

(Preliminary Exotica results up to $\sqrt{s}=209$ GeV from the LEP experiments)

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Outline

- **LEP EXOTICA WG**: Combination of all non-Higgs and non-SUSY searches at LEP2.
  - Technicolor
  - Excited leptons
  - Single top production, FCNC
  - Leptoquarks
  - Gravity in extra dimensions

- **Data Samples used**:
  - About 2.4 fb\(^{-1}\) (~600 pb\(^{-1}\) per experiment) at \(\sqrt{s} = 189-209\) GeV

- Statistical procedure adopted for the combination of the different channels (same or different experiments), is the likelihood ratio method
Technicolor model

- **Technicolor Model** is an alternative to the Standard Model Mechanism of Electroweak symmetry breaking.
- Role of Higgs boson is performed by bound states of new fundamental fermions, *techniquarks*, which mix with W and Z and generate their masses.
- Minimal TC model with one doublet of TC-quarks is not confirmed by LEP1 and elsewhere precision measurements.
- Extensions of TC model with many doublets, *Walking Technicolor*, overcome disagreement with experimental results. A large number of doublets is required, which generate huge number of bound states.
Technicolor model

- These extensions call for a large number $N_D$ of technidoublets $(T_U, T_D)$, with $Q_U = Q_D + 1$
- Important simplification: “Technicolor Straw Man Model” the lowest lying bound states of the lightest technifermion model can be considered in isolation.
  - **Pseudoscalars:** $\Pi_T^{\pm,0}$, $\Pi_T'$
  - **Vectors:** $\rho_T^{\pm,0}$, $\omega_T$ (nearly mass degenerate)
- Scalar bound states are mixtures of $W_L^{\pm}$, $Z_L^0$, and the lightest **mass-eigenstate technipions** $\pi_T^{\pm} \pi_T^0$
  
  $|\Pi_T> = \sin \chi |W_L> + \cos \chi |\pi_T>$
- Mixing angle $\chi$ is related with the number of TC-doublets: $\sin^2\chi = 1/N_D$
Decays of $\rho_T$

- The dominant decay modes of the $\rho_T$ mediated by the TC interaction are:

$$\rho_T \rightarrow \Pi_T \Pi_T \rightarrow \pi_T \pi_T (\sim \cos^4 \chi)$$
$$\rightarrow W_L \pi_T (\sim \sin^2 \chi \cos^2 \chi)$$
$$\rightarrow W_L W_L (\sim \sin^4 \chi)$$

- In addition the $\rho_T$ decays via the electroweak interaction either into one technipion and a SM gauge boson or into a pair of SM fermions (becomes important if other decay channels are kinematically closed)

- Total width depends on many parameters but does not exceed $\sim 15$ GeV for $m_{\rho_T} \leq 200$ GeV.
Decays of $\pi_T$

- The technipions $\pi_T^\pm \pi_T^0$ decays, are induced mainly by ETC interactions which couples them to fermions

$$\pi_T^- \rightarrow f_i \bar{f}_i ; \ \Gamma (\pi_T^- \rightarrow f_i \bar{f}_i) \propto (m_f + m_{f'})^2$$

- The $\pi_T$ preferentially decay into the **heaviest fermion pairs allowed**, main modes being:

$$\pi_T^- \rightarrow b \bar{c} (\approx 90\% ), \ s \bar{c} (\approx 5\% ), \ \tau \bar{\nu}_\tau (\approx 5\% )$$
$$\pi_T^0 \rightarrow b \bar{b} (\approx 90\% ), \ c \bar{c} (\approx 5\% ), \ \tau \bar{\tau} (\approx 5\% )$$

- Total width $< 1$ GeV for $M_\pi \sim 100$ GeV.
Technicolor at LEP

- Although TC model is rather complicated, the phenomenology of the lightest bound states which it predicts is relatively simple with few free parameters:
  - $M_{\pi_T}$ mass of $\pi_T$
  - $M_{\rho_T}$ mass of $\rho_T$
  - $\sin^2\chi = 1/N_D$ number of doublets, or mixing angle of $\pi_T$ and $W_L$

- For $\omega_T$ production and decay, a scale parameter and $Q_U + Q_D$ must be specified. By analogy with QCD it is supposed that $M_{\rho_T} \sim M_{\omega_T}$, and $M_{\pi_T^0} \sim M_{\pi_T^+}$. 
Technicolor production at LEP

- $\rho_T$ couples with $\gamma$ and $Z^0$ and can be produced at LEP in s-channel.

- If $M_{\rho_T} < \sqrt{s}$, $\rho_T$ can be produced in RR process and can be observed as a narrow resonance in $s'$ distribution.

- Technipions can be produced through virtual $\rho_T$ exchange in pairs or in association with $W_L$:

$$e^+e^- \rightarrow \rho_T^* \rightarrow \pi_T\pi_T$$

$$e^+e^- \rightarrow \rho_T^* \rightarrow \pi_T W_L$$

- Production cross-section of TC objects was expected to be reasonably high, which allowed search at LEP.
Expected cross-section

Cross-section [pb]

\begin{align*}
e^+e^- \rightarrow \rho T \gamma \\
e^+e^- \rightarrow \rho^+ \pi^- \pi^0 \\
e^+e^- \rightarrow \rho^+ \omega T \pi^- \\
e^+e^- \rightarrow \rho^+ \omega T^* \pi^- \\
e^+e^- \rightarrow \rho^+ \omega T^* \pi^- \gamma
\end{align*}

\[ M(\rho_T) \text{ [GeV/c}^2\text{]} \]

\[ \sqrt{s} = 200 \text{ GeV} \]

\[ M_{\pi_T} = 90 \text{ GeV} \]
\[ N_D = 9 \]
\[ M_V = 200 \text{ GeV} \]
\[ (Q_U + Q_D) = 4/3 \]
\[ \alpha_p = 2.91(3/N_{TC}) \]
\[ (\text{TC coupling constant}) \]
\[ N_{TC} = 4 \]
\[ e^+e^- \rightarrow \rho_T^* \rightarrow \pi_T^+\pi_T^-\pi_TW_L \]

- This process is searched for in 4 jet and in 2 jet + lepton + neutrino final states.
- In both cases, a Neural Network is used which combines topological variables and b-tagging.
- The most important background for \( \pi_T \) search is \( e^+e^-\rightarrow W^+W^- \). The main difference between \( W^+W^- \) and \( \pi^+\pi^- \) production is the presence of b-quark in the decays of \( \pi_T \). b-tagging is essential.
- The mass is estimated after a 5c constrained fit imposing energy and momentum conservation and equal masses of the two fermion objects (qq or l\nu).
Discriminating Variables

- **NNW (4j channel):**
  - 2 b-tagging variables.
  - 7 topological (antiQCD, almost same as higgs 4j)
  - 3 based on boson production properties.

- **Semileptonic channel:**
  \[ \pi^+_T \pi^-_T \rightarrow \tau \nu q \overline{q} \]
  \[ W^+_L \pi^-_T \rightarrow l \nu q \overline{q} \]

- **Isolated lepton (3 NN)**
- **b-tagging (jet)**
- **Boson production angle**
Mass distribution in the 4jet channel

Expected technicolor signal for
\( M_{\pi_T} = 100 \text{ GeV} \)
\( N_D = 9 \)
\( M_{\rho_T} = 220 \text{ GeV} \)
Mass distribution in the semileptonic channel

Expected technicolor signal for
$M_{\pi_T}=100 \text{ GeV}$
$N_D=9$
$M_{\rho_T}=220 \text{ GeV}$

Small decay rate
$\pi \rightarrow \tau \nu$
Background suppression

Good agreement between data and SM prediction

Results used to set limits on Technicolor production
Limits on Technicolor

Limit based on CL$_s$, using NN and mass.

Lower limit on $M_{\pi_T}$ for $M_{\rho_T} \to \infty$, point like coupling between gauge bosons and $\pi_T\pi_T$

$M_{\pi_T} > 79.8$ GeV/c$^2$ (95% CL)

(81.1 GeV/c$^2$ expected)
Limits on Technicolor

Lower limit on $M_{\pi_T}$ for $M_{\rho_T} \to \infty$, point like coupling

$M_{\pi_T} > 89.1 \text{ GeV}/c^2$ (95% CL)

(88.1 GeV/c$^2$ expected)

$\rho_T$ production excluded

$90 < M_{\rho_T} < 206.7$ GeV/c$^2$
OPAL results

Based on ~ 209.4 pb$^{-1}$ up to 209 GeV. **No excess was observed**

Lower limit on $M_{\pi^T}$ for $M_{\rho^T} \rightarrow \infty$,

- $M_{\pi^T} > 62 \text{ GeV}/c^2$ ($N_d = 2$)
- $M_{\pi^T} > 77 \text{ GeV}/c^2$ ($N_d = 9$)

\[(95\% \text{ CL})\]
Search for $\rho_T$ with $M_{\rho_T} < \sqrt{s}$

- $\rho_T$ with $M_{\rho_T} < \sqrt{s}$ can be produced on mass shell in the process $e^+e^- \rightarrow \rho_T(\gamma)$ with subsequent decays into different final states.

- It can be observed as relatively narrow resonance in the corresponding mass distribution $\Gamma_{\rho_T} \leq 15$ GeV for $m_{\rho_T} \leq 200$ GeV.

- It also gives additional contribution in the production cross-sections of SM final states, e.g.
  
  $$e^+e^- \rightarrow \rho_T^* \rightarrow W^+W^-$$

- $\rho_T$ is searched for in all main decay modes:
  
  $$\rho_T \rightarrow \text{hadrons} \ (\pi_T\pi_T, qq), \ \pi_T^0\gamma, \ W_L^+W_L^-$$
Direct Search for $\rho_T \to \pi_T^0 \gamma$

- Narrow resonance should be observed in the mass spectra of:
  
  \[ q\bar{q}\gamma \text{ from } \rho_T \]
  
  \[ \pi_T^0 \to q\bar{q} \]

- Again the use of \textit{b}-tagging is important, since the main $\pi_T^0$ decay is into \textit{b}-quarks.

- Result obtained:
  
  $\text{BR}(\rho_T \to \pi_T^0 \gamma) < 7\%$, \((95\%\text{CL})\)

\[ M_{\rho_T} > \sqrt{s} \]
**Indirect search for $\rho_T \rightarrow W^+W^-$**

- In the presence of $\rho_T \rightarrow W^+W^-$, measured cross section $e^+e^- \rightarrow W^+W^-$ should differ significantly from the SM prediction. Predicted additional contribution are quite large:

<table>
<thead>
<tr>
<th>$M_{\rho_T}$ (GeV/c^2)</th>
<th>$\sqrt{s}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>183</td>
</tr>
<tr>
<td>175</td>
<td>7.00</td>
</tr>
<tr>
<td>185</td>
<td>−</td>
</tr>
<tr>
<td>195</td>
<td>−</td>
</tr>
</tbody>
</table>

- These values can be compared with experimental precision, e.g. Delphi at $\sqrt{s} = 189$ GeV gives $\sigma(e^+e^- \rightarrow W^+W^-) = 15.83 \pm 0.38 \pm 0.20$ pb and the expected SM value is $\sim 16.25$ pb

- As no additional contribution is observed in the cross-section, $\text{BR}(\rho_T \rightarrow W^+W^-) < 30\%, (95\%\text{CL})$
Indirect Search for $\rho_T \rightarrow \text{hadrons} \ (\pi_T \pi_T, qq)$

- $\rho_T$ should also give an additional contribution to the process
  \[ e^+ e^- \rightarrow q\bar{q}(\gamma) \]

- It should be observed as a peak in the hadronic mass distribution.

- $\text{BR}(\rho_T \rightarrow \text{hadrons}) < 55\%, \ (95\% \text{CL})$
LEP vs. Tevatron

- Results at Tevatron using the same TC model are based on l+2j channel (counting experiment, in mass windows).
- No excess was observed, then, data is used to exclude mass regions in the $M_{\rho_T}$ vs. $M_{\pi_T}$ plane.
- Using INDIRECT searches at LEP this plane is almost completely covered.
Excited leptons (Compositeness)

- **Substructure at an energy scale** $\Lambda \rightarrow$ Excited leptons
  - Decay promptly:
    - $l^* \rightarrow l\gamma, \nu W, lZ$
    - $\nu^* \rightarrow \nu\gamma, lW, \nu Z$
  - $f/\Lambda, f'/\Lambda$ vs. $m_{l*}$ ($|f|=|f'|$)

- Direct searches were performed in pairs ($\sim \sqrt{s}/2$), and in single production ($\sim \sqrt{s}$).

- Indirect searches for excited electrons, using the measured $\gamma\gamma(\gamma)$ differential cross-section.

- Opal and Delphi results already combined, Aleph and L3, similar sensitivities.
Excited leptons (direct searches)

- No excess of events was observed with respect to the Standard Model prediction:
- Exclusion for $f/\Lambda$ vs. $M_{l^*}$ at $\sqrt{s} = 189-210$ GeV

![Graph showing exclusion limits for excited leptons](image-url)
Excited leptons (indirect searches)

- No excess of events was observed with respect to the Standard Model expectation.
- Exclusion for $f/\Lambda$ vs. $M_{l^*}$ at $\sqrt{s} = 189-210$ GeV
Summary

- **LEP** provided data samples to look for new physics beyond the Standard Model, allowing investigation of new phenomena and search for new particles.

- **Results obtained**, either combined among the four LEP experiments or coming from individual experiments **gives NO evidence of the presence of new physics**,
  - No evidence of Technicolor contribution is observed
  - A 95% CL lower mass limit of **79.8 GeV/c²** is set independently of other parameters of the TC model.
  - **90 < M_{ρ_T} < 206.7 GeV/c²** is set regardless other model parameters.
  - **f/Λ ≤ 0.1 TeV⁻¹ (e*)**, **1 TeV⁻¹ (μ*,τ*)**

- **Final LEP combined results**, coming soon from LEP EXOTICA WG.