FERMION-PAIR PRODUCTION ABOVE THE Z AND SEARCH FOR NEW PHENOMENA

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Abstract

A review of the measurements of hadron, flavour-tagged and lepton-pair production cross-sections and lepton-pair forward-backward asymmetries performed by the four LEP experiments ALEPH, DELPHI, L3 and OPAL at energies between 130 and 183 GeV is given. All 183 GeV results are preliminary. The searches by the four collaborations for new physics phenomena like contact interactions and compositeness, exchange of R-parity violating sneutrinos or squarks, leptoquarks or additional heavy gauge bosons Z' are summarized. No evidence for deviations from the Standard Model expectations is found and new or improved limits are derived.

Fermion-pair Production above the Z

The successful running of LEP in 1995-1997 at centre–of–mass energies well above the Z resonance allows to search for new physics beyond the Standard Model (SM). Any significant deviation from the SM predictions in the electron-positron annihilation into fermion-pairs would herald the presence of new phenomena. The differential cross section for fermion-pair production is described by the γ or Z exchange amplitudes in the s-channel, and for $\mathrm{e^+e^-}$ final states also in the t-channel

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = |\gamma_{\mathrm{s}} + \mathrm{Z_s} + \mathrm{elec} * (\gamma_{\mathrm{t}} + \mathrm{Z_t}) + \text{New Physics ?!}|^2 \tag{1}$$

The presence of additional amplitudes will signal new physics effects and can be observed through modifications in the measured differential cross section. In the helicity amplitudes formalism

$$\mathcal{A}^{\mathrm{ef}}_{\mathrm{LR(RL)}}(\mathrm{s}) = (\mathcal{A}^{\mathrm{SM}}_{\mathrm{LR(RL)}}(\mathrm{s}) + \mathcal{A}^{\mathrm{NP}}_{\mathrm{LR(RL)}}(\mathrm{s}))\frac{\mathrm{t}}{\mathrm{s}} \tag{2}$$

$$\mathcal{A}^{\mathrm{ef}}_{\mathrm{LL(RR)}}(\mathrm{s}) = (\mathcal{A}^{\mathrm{SM}}_{\mathrm{LL(RR)}}(\mathrm{s}) + \mathcal{A}^{\mathrm{NP}}_{\mathrm{LL(RR)}}(\mathrm{s}))\frac{\mathrm{u}}{\mathrm{s}} \tag{3}$$

where $\mathcal{A}^{SM}$ ($\mathcal{A}^{NP}$) are the SM (or New Phenomena) amplitudes, L (or R) denote the helicities of the ingoing and outgoing fermion, s, t, u are the Mandelstam variables. For a generic new interaction with coupling g and typical energy (or mass) scale Λ the differential cross section can be decomposed as follows

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \mathrm{SM}(\mathrm{s},\mathrm{t}) + \frac{\mathrm{g}^2}{\Lambda^2}\mathrm{C}_{\mathrm{Interference}}(\mathrm{s},\mathrm{t}) + \frac{\mathrm{g}^4}{\Lambda^4}\mathrm{C}_{\text{New Phenomena}}(\mathrm{s},\mathrm{t}) \tag{4}$$

If the new phenomena are strong enough (like resonance formation), they can be observed directly through the $C_{New\ Phenomena}$ term. Otherwise, the interference with the SM amplitudes can lead to observable (but smaller) effects. If no deviations from the SM are found, we can constrain g/Λ.

Measurements of Cross Sections and Asymmetries at LEP2

All four LEP experiments have presented results at centre–of–mass energies 130–172 GeV. All 183 GeV results are preliminary [1]. The collected luminosity ranges from 6 pb^{-1} at 130 GeV to 55 pb^{-1} at 183 GeV. Up to 172 GeV the statistical errors are dominant. The 183 GeV data mark the point where systematic effects gain in importance.

The event selection is an extension of selections on the Z peak with some important new features:

- two distinctive event classes depending on the effective CMS energy $\sqrt{\mathrm{s'}}$:
  - inclusive events - $\sqrt{\mathrm{s'}}/\sqrt{\mathrm{s}} > 0.1$ ('return to the Z')
  - non-radiative events - $\sqrt{\mathrm{s'}}/\sqrt{\mathrm{s}} > 0.85 - 0.90$
- cross section $\sim 10^{-2}$ of Z peak values
  - higher non-annihilation background (beam-wall/gas, cosmic muons)
  - higher 2-γ background ($\mathrm{e^+e^-} \longrightarrow \mathrm{e^+e^-}\, f\bar{f}$)
- 4-fermion 'background' (W^+W^-, ZZ, $Z\,\mathrm{e^+e^-}$, $We\nu$, ...)

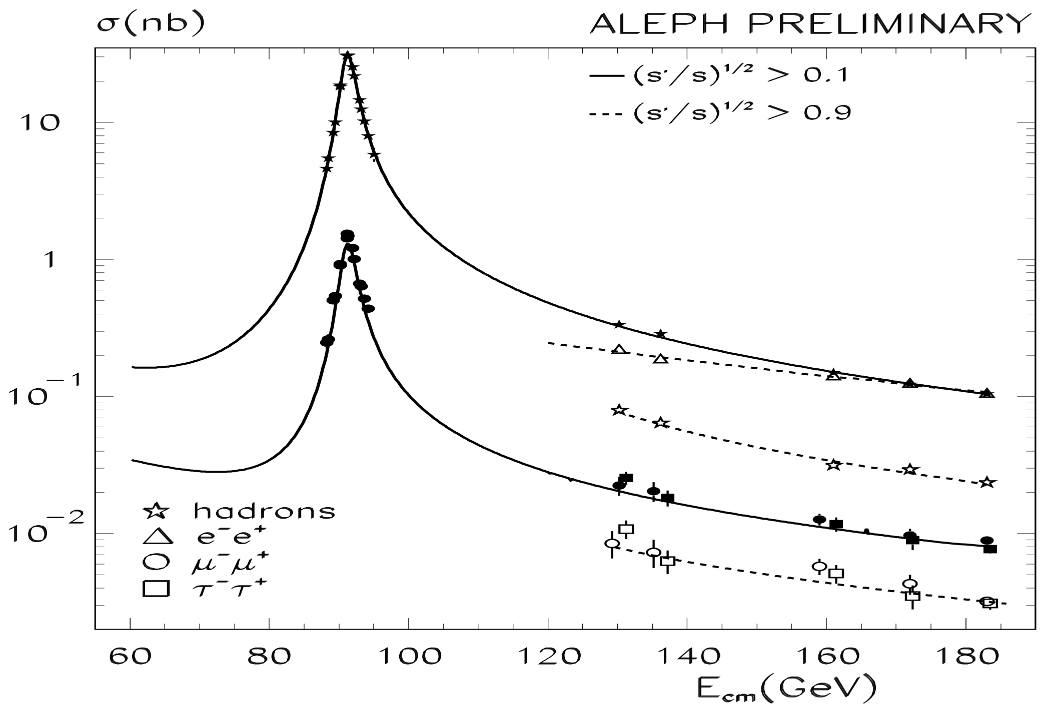

Figure 1: Total cross section measurements from ALEPH, including 183 GeV data.

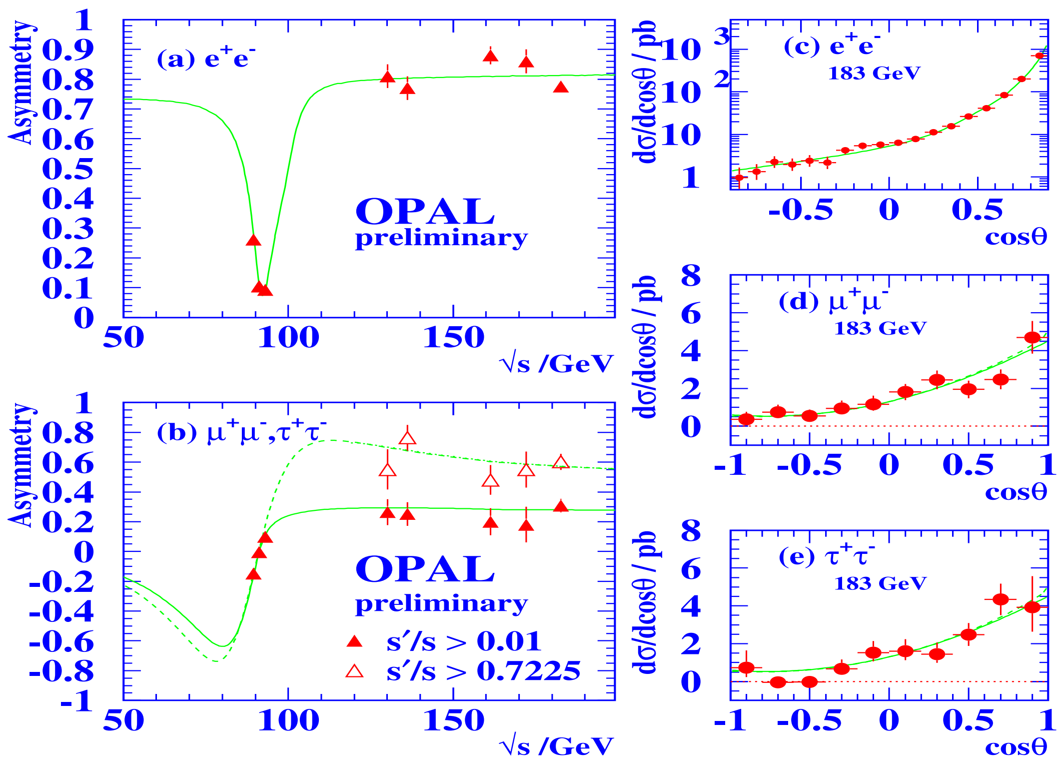

Figure 2: Differential cross section measurements and leptonic forward-backward asymmetries from OPAL, including 183 GeV data.

Cross sections and asymmetries are measured for the inclusive and the non-radiative events. The latter sample is the main search field for new physics. $\sqrt{s'}$ is calculated from the initial state radiation photon(s) if seen in the detector or from the angles of the outgoing fermions or kinematic fits. The definition of $\sqrt{s'}$ is not unique due to interference between initial- and final-state radiation. One solution (favoured by OPAL) is to correct the measured cross sections to 'no interference'. The corrections can reach $\sim$ 1-2 % for $\sqrt{s'}/\sqrt{s} > 0.85$ and rely on the theoretical estimate calculated only to $\mathcal{O}(\alpha)$. A second option is an inclusive approach, where $\sqrt{s'}$ is defined as the effective mass of the outgoing fermion pair.

The preliminary results of all four experiments at 183 GeV show good agreement with the SM predictions, as seen in Figure 1 and Figure 2. Applying flavour tagging for the hadron sample, ALEPH and OPAL measure the fraction of b-quarks R_b up to 183 GeV. DELPHI measures R_b, R_c and R_{uds} up to 172 GeV.

Searches for New Phenomena

The four-fermion contact interaction (CI) offers a general framework for a new interaction with coupling g and typical energy scale $\Lambda \gg \sqrt{s}$. By convention it is assumed that $\frac{g^2}{4\pi} = 1$ and $|\eta_{ij}| \leq 1$ $(i, j = L, R)$, where η_{ij} are the parameters defining the helicity structure of the new interaction. The corresponding amplitudes have the form [2]

$$\mathcal{A}^{\mathrm{CI}}_{\mathrm{ij}}(\mathrm{s}) = \eta_{\mathrm{ij}} \frac{\mathrm{s}}{\alpha} \frac{1}{\Lambda^2} \tag{5}$$

α is the electromagnetic fine structure constant. The models considered here are defined in

Table 1: Models of contact interaction considered. The parameters η_{ij} define the helicity amplitudes, $\mathcal{A}_{ij}$, which are active. Also shown are the amplitudes for the exchange of possible new particles, where the CI gives the limiting case.

Model	η_{LL}	η_{RR}	η_{LR}	η_{RL}	$\tilde{\nu}$	$\tilde{\mathrm{q}}$	Lepto-q
LL	±1	0	0	0		$\tilde{d}$-type	$S_0(\mathrm{g}_L)$
RR	0	±1	0	0			
LR	0	0	±1	0	$\star$	$\tilde{u}$-type	$\tilde{S}_{1/2}$
RL	0	0	0	±1	$\star$		
VV	±1	±1	±1	±1			
AA	±1	±1	∓1	∓1			

Table 1. In the same table the amplitudes contributing in the specific cases of new particle exchange, considered further, are highlighted.

The four collaborations express the results of their fits as 95 % CL lower limits on the scale Λ for e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, l^+l^- (leptons), $q\bar{q}$, $u\bar{u}$, $d\bar{d}$ (one up or down flavour is affected), flavour-tagged $q\bar{q}$, $f\bar{f}$ (all fermions combined) final states. The limits Λ_+ (Λ_-) correspond to the upper (lower) sign combination in Table 1. ALEPH, L3 and OPAL have updated their results using 183 GeV data, as shown in Table 2. Only the combined l^+l^- and $q\bar{q}$ results are given, when available.

The fermion-pair cross section can be sensitive to exchange of single supersymmetric particles [3] if R-parity is violated ($\not{R}_{\mathrm{p}}$). The most general superpotential even for a minimal

Table 2: Limits on Λ_+ (Λ_-) in TeV at 95 % CL for l^+l^- and $q\bar{q}$ final states.

l^+l^-	ALEPH		DELPHI		L3		OPAL	
	Λ_-	Λ_+	Λ_-	Λ_+	Λ_-	Λ_+	Λ_-	Λ_+
LL	5.4	6.1	4.4	3.8	4.1	5.8	5.3	5.2
RR	5.2	5.9	4.2	3.7	4.0	5.6	5.1	5.0
LR	5.2	6.5	4.7	4.1	5.4	3.9	5.2	5.6
VV	9.4	11.8	8.2	7.1	8.5	8.5	9.3	9.6
AA	9.0	8.2	6.1	6.2	5.3	9.3	8.3	7.7
$q\bar{q}$	ALEPH		DELPHI		L3		OPAL	
	Λ_-	Λ_+	Λ_-	Λ_+	Λ_-	Λ_+	Λ_-	Λ_+
LL	2.7	3.9	tag		2.5	3.8	2.8	4.4
RR	3.6	2.9			3.5	2.8	3.9	3.0
LR	3.4	3.1			3.2	3.0	3.6	3.3
RL	4.3	2.4			4.3	2.3	4.9	2.5
VV	5.2	4.0			5.0	3.8	5.7	4.1
AA	3.7	5.6			3.5	5.6	3.8	6.3

supersymmetric model contains interactions violating the lepton number L and coupling sparticles to lepton-lepton or lepton-quark pairs

$$W_{\not{R}} = \lambda_{ijk} L^i_L L^j_L \bar{E}^k_R + \lambda'_{ijk} L^i_L Q^j_L \bar{D}^k_R + ... \tag{6}$$

where (L,Q) are left-handed doublets of leptons, quarks, (E,D) are right-handed singlets of charged leptons, down-type quarks and *ijk* are generation indices. These terms introduce 9 λ and 27 λ' independent Yukawa couplings (as $\lambda_{ijk} \neq 0$ only for $i \neq j$). Lower energy measurements place (in some cases severe) constrains on the possible values of λ and λ' as a function of the sparticle mass. We will assume that one (or two) λ are much stronger than the others in the searches that follow. For heavy sparticle masses the LEP2 data reaches higher sensitivity in some cases.

The most exciting possibility is resonance formation of single sneutrinos $\tilde{\nu}$ if the sneutrino mass is close to the centre–of–mass energy. Then large effects can occur. Also t- or u-channel exchange of single $\tilde{\nu}$ or squark $\tilde{q}$ is possible in $\not{R}_p$ theories. L3, OPAL and DELPHI have searched for the most dramatic s-channel effects involving $\tilde{\nu}$. In Figure 3 the L3 results including 183 GeV data are shown for e^+e^- and $\mu^+\mu^-$ final states. The t- or u-channel $\tilde{q}$ exchange leads to similar effects as the exchange of leptoquarks, which appear in many unification theories. The CDF and DØ collaborations exclude scalar leptoquarks with mass below 225 GeV and branching $\beta(LQ \to l^{\pm}q) = 1$. At LEP2 higher masses can be probed if the coupling is sizeable. From the many possible leptoquark states two are of special interest, as they give limits also for squarks:

- $S_0(L)$ - limit on λ'_{1jk}, $(j = 1, 2)$ - final state $u - type$, $(k = 1, 2, 3)$ - exchanged $\tilde{d}_R - type$
- $\tilde{S}_{1/2}$ - limit on λ'_{1jk}, $(j = 1, 2, 3)$ - exchanged $\tilde{u}_L - type$, $(k = 1, 2, 3)$ - final state $d - type$

L3 and OPAL have updated their limits using 183 GeV data. For an exchanged mass of 200 GeV typical 95 % CL upper limits for the couplings g or λ' are 0.25 for $S_0(L)$ and 0.65 for $\tilde{S}_{1/2}$.

A complimentary search for an additional heavy gauge boson Z' is performed by the L3 and DELPHI collaborations. For specific models of the Z' couplings exclusion limits in the plane of

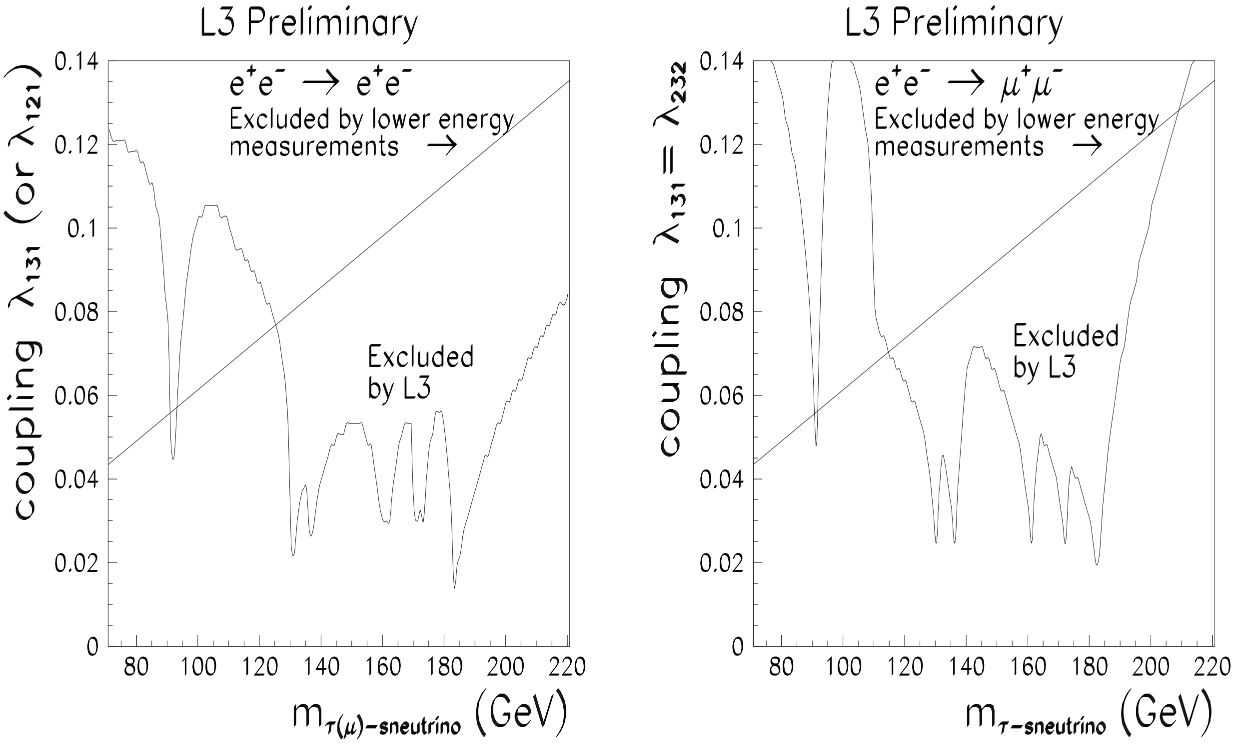

Figure 3: Limits on the couplings λ_{121}, λ_{131}, λ_{232} as function of the sneutrino mass at 95 % CL.

the Z′ mass and the mixing angle θ_M with the SM Z boson are derived. For most of the models typical values are $|\theta_{\rm M}| < 0.003$ and $m_{Z'} > 300$ GeV.

Outlook

The production of fermion-pairs above the Z resonance is a precise testing ground, where the Standard Model can be probed to the largest momentum transfers, and a lively hunting field for new particles in the several hundred GeV mass range, which couple to lepton-lepton or lepton-quark pairs. In the four-fermion contact interaction framework the measurements are sensitive to scales approaching 10 TeV.

In summary:

- the Standard Model describes all fermion-pair production measurements up to 183 GeV
- no hint for new phenomena so far
- new or improved limits obtained: contact interactions, $\tilde{\nu}/\tilde{\rm q}$, leptoquarks, Z'
- the LEP2 discovery potential is large; the LEP community is looking forward to more data at higher energies

References

[1] Contributions to the 1998 winter conferences by the four LEP collaborations (from the home pages of the experiments).

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