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STANDARD MODEL RESULTS FROM LEP

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Recent results from the LEP experiments in the area of Standard Model physics are summarized. Measurements of cross-sections, gauge boson couplings and the mass of the W boson are discussed, and the current limit on the mass of the Higgs boson arising from fitting electroweak data is presented. Measurements of $\alpha_{\rm s}$ and recent results in QCD and two-photon physics are discussed.

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1 Introduction

The LEP Collider at CERN operated from 1989–1995 at $\rm e^+e^-$ centre-of-mass energies around the Z peak (LEP1), and from 1996–2000 at energies between 161 GeV and 209 GeV (LEP2). During the LEP1 phase, each of the four LEP experiments (ALEPH, DELPHI, L3, OPAL) collected around 4.5M Z events, while during the LEP2 phase each acquired around 10k W pairs. Although LEP was shut down at the end of 2000, many new physics results are still being published: in the last two years the four LEP experiments have submitted for publication a total of more than 100 papers, and this summer have submitted more than 120 contributed papers to the ICHEP04 conference in Beijing. The majority of these papers cover measurements of Standard Model parameters, and are generally final results – although a few new preliminary results are also being produced. This report summarizes some of the LEP results in the area of Standard Model physics; in particular attention is drawn to those which have been finalized, or are new, in the last year. Full details of these results are available on the web pages of the experiments [1].

2 LEP1 Electroweak Physics

Measurements of the Z lineshape parameters have been final since summer 2000 (see for example [2]), but DELPHI has recently published a new measurement of the forward-backward asymmetry in $\rm b\overline{b}$ events [3], and thus a new LEP combination of heavy-flavour results has been performed [2]. The resulting value of the $\rm b\overline{b}$ pole asymmetry is $A_{\rm FB}^{0,\rm b} = 0.0998 \pm 0.0017$.

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[2]Details and results of combinations performed by the LEP Electroweak Working Group are available in [4].

OPAL have published new measurements of the Z partial width to up- and down-type quarks [5], using hadronic events with final-state radiation which are enriched in up-type quarks. The results are in good agreement with the Standard Model expectations, and are more precise than earlier measurements.

3 Two-fermion Production at LEP2

Cross-sections and asymmetries have been measured both for inclusive events and for 'non-radiative' events, i.e. excluding radiative return to the Z. Preliminary combined LEP results [2], shown in Fig. 1 are in good agreement with the Standard Model. OPAL and DELPHI have now finalized their two-fermion measurements [6], but a new LEP combination awaits final results from all experiments; small improvements to the errors on the hadronic cross-sections may be anticipated, but the lepton measurements are dominated by statistics.

At LEP2 energies, photon exchange becomes important, and it is thus possible to measure the contribution of γ–Z interference to the hadronic cross-section, and hence make a precise, almost model-independent, measurement of the Z mass using the S-matrix formalism [7]. For example, the recent DELPHI results are shown in Fig. 2; the error on m_Z from the fit is 3.4 MeV, only slightly larger than the value of 2.8 MeV resulting from the fit to LEP1 DELPHI data in which the interference term ($j_{\rm had}^{\rm tot}$) is fixed to its Standard Model value.

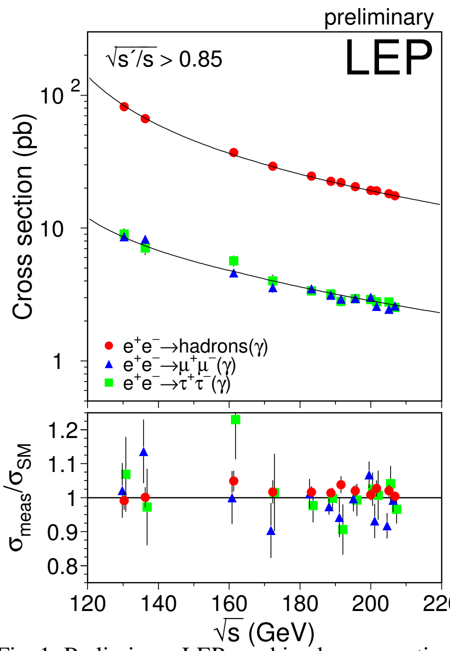

Fig. 1. Preliminary LEP combined cross-sections for fermion-pair production.

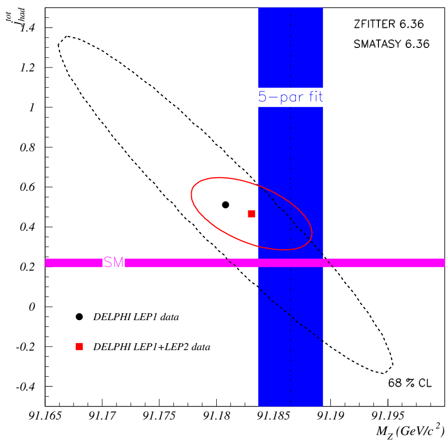

Fig. 2. Confidence level contours in the m_Z - $j_{\rm had}^{\rm tot}$ plane from S-matrix fits to DELPHI data. The dashed curve shows the 68% confidence level contour from the fit to LEP1 data alone, while the full curve shows the 68% confidence level contour from a fit to LEP1 and LEP2 data. The horizontal band indicates the Standard Model value of $j_{\rm had}^{\rm tot}$. The vertical band is the 1σ error on the Z mass from a five parameter fit in which $j_{\rm had}^{\rm tot}$ is fixed to the Standard Model value.

4 W-pair Production and Triple Gauge-Boson Couplings

Final measurements of the W-pair cross-section and W branching ratios are now available from ALEPH, DELPHI and L3, with preliminary results from OPAL [8]. The LEP combined cross-section measurements are shown in Fig. 3; they are in good agreement with the Standard Model prediction. The W leptonic branching ratio measurements from each experiment are shown in Fig. 4. While the overall leptonic branching ratio is in good agreement with the Standard Model, the W $\to \tau\nu$ branching ratio is higher than the average of W $\to \mu\nu$ and W $\to$ eν by about 3 standard deviations.

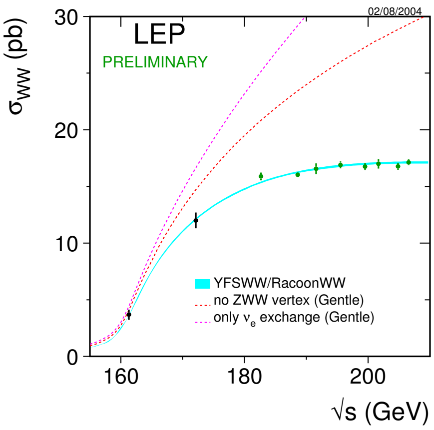

Fig. 3. Preliminary LEP WW cross-section measurements.

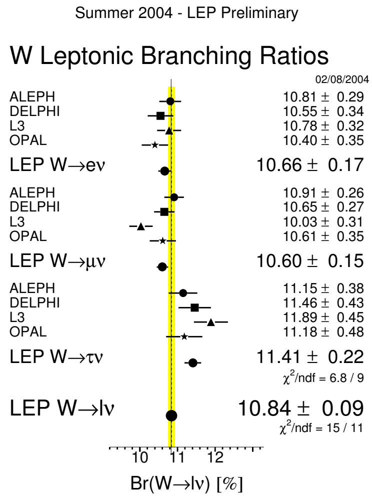

Fig. 4. Preliminary LEP W leptonic branching ratios.

Charged triple gauge boson couplings (ZWW and γWW) are measured from various properties of WW events: the total cross-section, the W production angular distribution and the W decay angular distribution. The cross-sections for $e^+e^- \to$ Weν and $e^+e^- \to \nu\overline{\nu}\gamma$ are also sensitive. In the standard analysis, the 14 couplings of the most general Lagrangian are reduced to 3 by assuming C and P conservation and applying gauge constraints. Fits to each coupling in turn, assuming the other couplings have their Standard Model value, are performed, and results from the four experiments are combined by combining $\log\mathcal{L}$ curves including correlated systematics. The current results [2] (L3 and OPAL final, ALEPH and DELPHI preliminary) are:

$$
\begin{aligned}
g_1^{\mathrm{Z}} &= 0.991^{+0.022}_{-0.021} \\
\kappa_\gamma &= 0.984^{+0.042}_{-0.047} \\
\lambda_\gamma &= -0.016^{+0.021}_{-0.023}
\end{aligned}
$$

The measured values are in good agreement with the Standard Model predictions (1, 1 and 0 respectively), and the couplings are measured with a precision of 2–4%. Confidence level regions derived from fits allowing two free parameters are shown in Fig. 5.

Neutral triple gauge boson couplings (ZZγ, Z$\gamma\gamma$) are zero in the Standard Model; limits on these have been set from measurements of ZZ and Zγ final states. Standard Model quartic gauge couplings are either zero or too small to be observed at LEP. Limits are set from measurements of WWγ, Z$\gamma\gamma$ and $\nu\overline{\nu}\gamma\gamma$ final states, for example the OPAL measurements [9] of the $\mathrm{q\overline{q}}\gamma\gamma$ cross-section shown in Fig. 6.

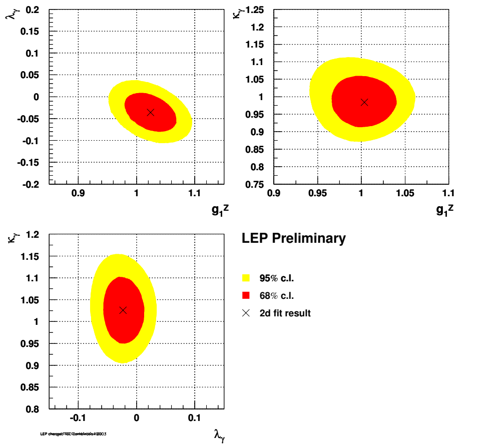

Fig. 5. LEP combined confidence level contours on charged current triple gauge couplings resulting from fits in which two parameters are varied.

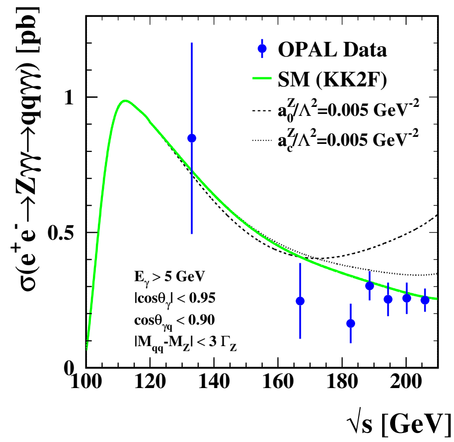

Fig. 6. Cross-sections for $e^+e^- \rightarrow \mathrm{q\overline{q}}\gamma\gamma$ measured by OPAL. The curves show the predictions of the Standard Model and of models with anomalous quartic gauge boson couplings.

5 W Mass Measurement

Measurement of the mass of the W boson is one of the principal aims of LEP2. A comparison of the direct measurement with the indirect determination from electroweak fits (Fig. 9) is an important test of the Standard Model. The W mass is measured by direct reconstruction of the $\mathrm{q\overline{q}}$ or $\ell\overline{\nu}_\ell$ mass in $\mathrm{W^+W^-} \rightarrow \mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ and $\mathrm{W^+W^-} \rightarrow \mathrm{q\overline{q}q\overline{q}}$ events. The event-by-event mass is reconstructed using a beam energy constraint to improve resolution; mass distributions from OPAL events are shown in Fig. 7. Various techniques are using to fit such distributions to obtain m_W; all use Monte Carlo programs to correct measurements for bias. The preliminary LEP values in each channel, unchanged since 2003, are [2]:

$$m_\mathrm{W}(\mathrm{q\overline{q}}\ell\overline{\nu}_\ell) = 80.411 \pm 0.032(\mathrm{stat}) \pm 0.030(\mathrm{sys})\ \mathrm{GeV}$$
$$m_\mathrm{W}(\mathrm{q\overline{q}q\overline{q}}) = 80.420 \pm 0.035(\mathrm{stat}) \pm 0.101(\mathrm{sys})\ \mathrm{GeV}$$

giving a combined measurement of:

$$m_\mathrm{W} = 80.412 \pm 0.042\ \mathrm{GeV}$$

Systematics completely dominate the $q\bar{q}q\bar{q}$ channel, and are important in the $q\bar{q}\ell\overline{\nu}_\ell$ channel. The main effort of the experiments in the last year or so has been directed towards reducing these systematic errors for the final measurements. The largest uncertainties in the $q\bar{q}q\bar{q}$ channel arise from final state interactions. The separation of the W decay vertices is ∼0.1 fm, much smaller than the hadronization scale of ∼1 fm. The W decays therefore have space-time overlap and may exchange colour – a phenomenon known as colour reconnection. In addition, there may be Bose-Einstein correlations between identical particles from different W's. These effects, which are not included in the standard Monte Carlo programs used to calibrate the W mass measurements, may shift the measured value by a large amount (∼100 MeV).

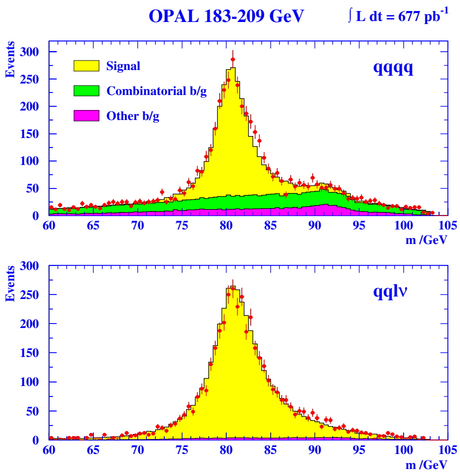

Fig. 7. Distributions of reconstructed W mass in $W^+W^- \to q\bar{q}q\bar{q}$ and $W^+W^- \to q\bar{q}\ell\overline{\nu}_\ell$ events in OPAL.

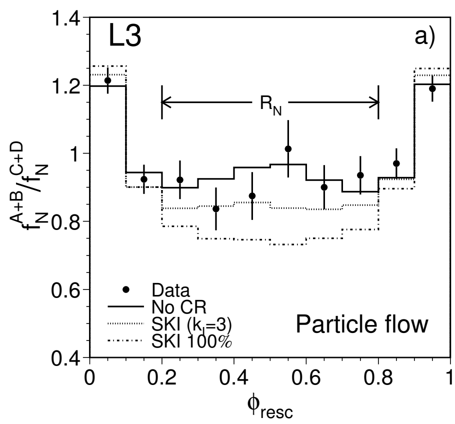

Fig. 8. Ratio of particle flow in the intra-W region to that in the inter-W region in $W^+W^- \to q\bar{q}q\bar{q}$ events measured by L3, compared to Monte Carlo predictions with and without colour reconnection.

Colour reconnection effects are estimated using phenomenological models. One method is to study the particle flow between jets in $W^+W^- \to q\bar{q}q\bar{q}$ events, comparing the number of particles in the inter-W region with the number in the intra-W region. This ratio is shown for L3 data [10] in Fig. 8. The largest reconnection probability compatible with the data is used to set the error on m_W; the current LEP combination [2] uses κ=2.1 in the SK1 [11] model (∼ 55% reconnection), giving an error of 90 MeV in the $q\bar{q}q\bar{q}$ channel.

Bose-Einstein correlations currently contribute and error of 35 MeV in the $q\bar{q}q\bar{q}$ channel. They are studied using two-particle correlations. To study inter-W correlations, $W^+W^- \to q\bar{q}\ell\overline{\nu}_\ell$ events are used to estimate intra-W effects and mixed events (or Monte Carlo) to estimate kinematic correlations. The L3 and OPAL (final) results are compatible with no inter-W correlations, while the DELPHI (final) results indicate a significant effect [12].

Soft particles are most affected by final state interactions, so the effects can be reduced by removing these when reconstructing jet directions. This reduces the FSI error at the expense of increasing the statistical error on m_W, as jet directions are less precisely determined. The final m_W analyses will optimize jet reconstruction. Further reductions in uncertainties due to hadronization and detector effects may be anticipated, and the uncertainty due to the LEP beam energy will be reduced from 21 MeV to ∼10 MeV [13]. The final total error on the LEP measurement will probably be in the range 32–40 MeV.

6 Standard Model Fit and Constraint on $\mathrm{m_H}$

The Standard Model Fit performed by the LEP Electroweak Working Group [4] uses 17 inputs from LEP, SLD and the Tevatron: Z lineshape parameters (m_Z, Γ_Z, $\sigma^0_{\rm had}$, R_ℓ, $A^{0,\ell}_{\rm fb}$), τ polarisation (P_τ), polarised lepton asymmetry ($\mathcal{A}_\ell$(SLD)), heavy flavour parameters ($R_{\rm b}$, $R_{\rm c}$, $A^{0,{\rm b}}_{\rm FB}$, $A^{0,{\rm c}}_{\rm FB}$, $\mathcal{A}_{\rm b}$, $\mathcal{A}_{\rm c}$), inclusive hadronic charge asymmetry, $m_{\rm t}$, $m_{\rm W}$ and $\Gamma_{\rm W}$. Since summer 2003, there is an updated value of the top mass (178.0±2.7±3.3 GeV) and the LEP heavy flavour combination has been updated. The theory calculations include full two-loop corrections for $m_{\rm W}$ and $\sin^2\theta^{\rm lept}_{\rm eff}$ [14]. The fit has a χ^2 of 15.8 for 13 degrees of freedom, the largest contribution arising from $A^{0,{\rm b}}_{\rm FB}$ (2.4σ). Fig. 10 shows $\Delta\chi^2$ as a function of the Higgs boson mass; the 95% confidence level lower limit on $m_{\rm H}$ is 260 GeV.

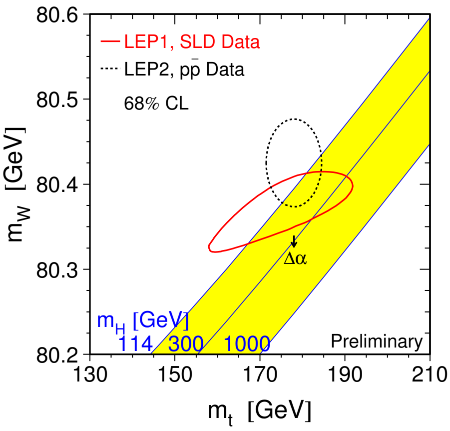

Fig. 9. Confidence level contours in the $m_{\rm W}$–$m_{\rm t}$ plane from the Standard Model fit compared with the direct measurements.

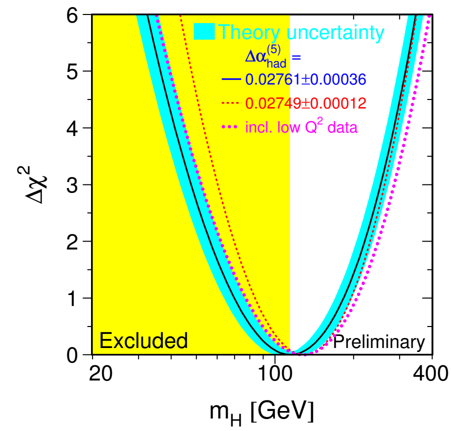

Fig. 10. $\Delta\chi^2$ curve from the Standard Model fit to 17 parameters as a function of $m_{\rm H}$.

7 Measurements of $\alpha_{\rm s}$ and QCD

Distributions of event-shape variables in hadronic events, for example thrust shown in Fig. 11, are sensitive to gluon emission, and have been fitted with $\mathcal{O}(\alpha_{\rm s}^2)$ + NLLA ($\log R$ matching) QCD predictions to determine $\alpha_{\rm s}$. Final measurements are now available from all experiments [15], and have been combined by the LEP QCD group [16]. Fig. 12 shows values as a function of centre-of-mass energy, where α_s can be seen to run as expected from QCD. Combining all experiments, variables and energies, the measured value of α_s is:

$$\alpha_s(m_Z) = 0.1202 \pm 0.0003(\text{stat.}) \pm 0.0007(\text{exp.}) \pm 0.0015(\text{hadr.}) \pm 0.0044(\text{theo.}).$$

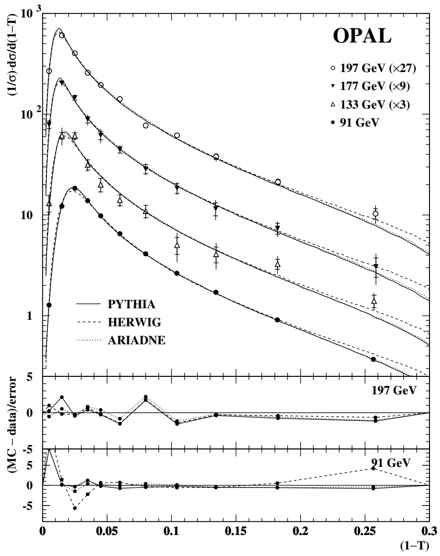

Fig. 11. Distributions of thrust measured by OPAL in $e^+e^- \rightarrow q\overline{q}$ events at various c.m. energies.

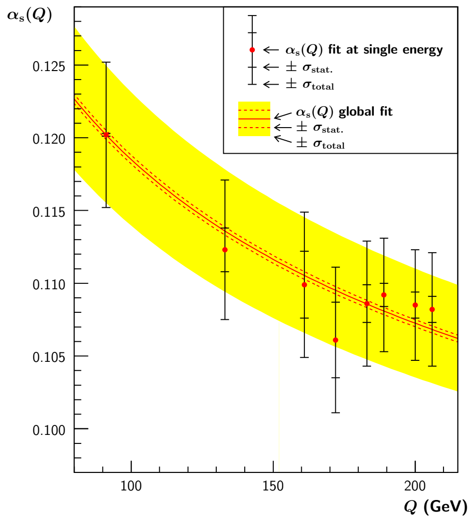

Fig. 12. LEP combined values of α_s determined from event shapes as a function of c.m. energy.

α_s has also been measured from the rate of 4-jet events. A new measurement from DELPHI [17] uses the Cambridge jet algorithm and fits to an $\mathcal{O}(\alpha_s^3)$ QCD prediction [18] using an experimentally optimized renormalization scale. OPAL [19] uses the Durham jet algorithm and fits to an $\mathcal{O}(\alpha_s^3)$ + NLLA QCD prediction with x_μ=1. The results from both experiments (Figs. 13 and 14) are in good agreement with the value measured from event shapes.

Fig. 15 shows the mean charged multiplicity in hadronic events measured by ALEPH [15]; the results are well-described by theoretical and Monte Carlo predictions. OPAL have made new measurements of charged multiplicity in gluon jets using a jet boost algorithm [20]; the results are the most precise in the energy range 5–20 GeV. DELPHI have obtained the first direct evidence for coherence effects in soft particle production [21]. They have also made the first direct observation [22] of the 'dead cone' effect, whereby gluon radiation off heavy quarks is suppressed at small angles. The results are shown in Fig. 16, which shows the ratio of the angular distribution of fragmentation particles in b-jets to that in c-jets; a clear reduction is seen at low angles for b-jets.

8 Two-photon Physics

Two-photon physics is an active area, with several new measurements testing QCD. Fig. 17 shows new measurements of the total hadronic cross-section at low Q^2 from DELPHI [23].

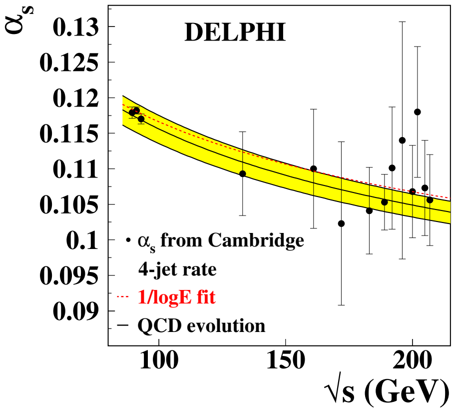

Fig. 13. Measurements of α_s determined from the four-jet rate by DELPHI.

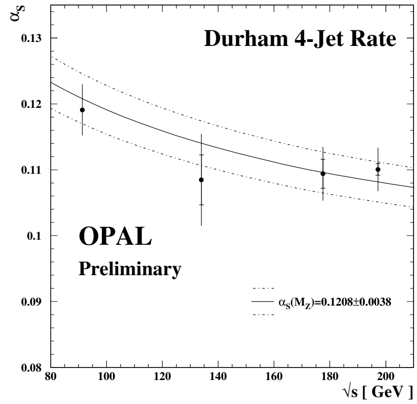

Fig. 14. Measurements of α_s determined from the four-jet rate by OPAL.

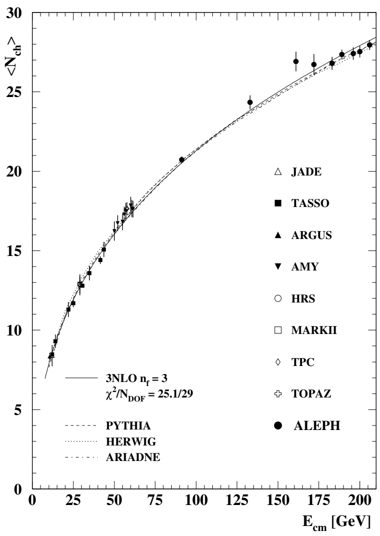

Fig. 15. Mean charged multiplicity in $e^+e^- \to q\overline{q}$ events measured by ALEPH.

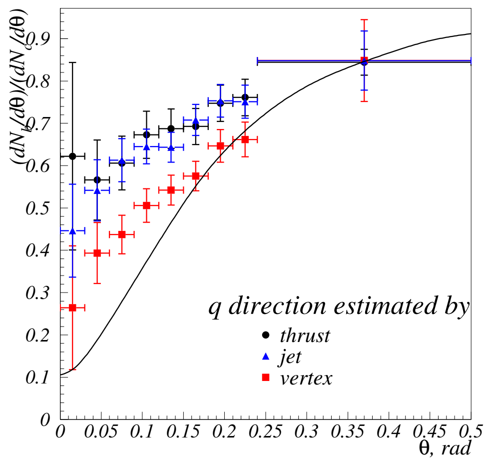

Fig. 16. Ratio of the fragmentation particle density in b-jets to that in c-jets as a function of cone size around the jet, measured by DELPHI.

These use the Very Small Angle Tagger situated at ∼3–15 mrad from the beam; this allowed direct event-by-event reconstruction of $W_{\gamma\gamma}$ for double-tagged events without unfolding, leading to small systematic errors. The DELPHI measurements are somewhat higher than existing measurements from L3 and OPAL.

L3 measurements of inclusive $\pi^{\pm}$ and π^0 production in two-photon collisions [24] have shown an excess compared with NLO QCD calculations at high p_t. L3 measurements of inclusive jet production [25] show a similar large excess. However a new DELPHI measurement of inclusive hadron production [26] shows good agreement with NLO QCD for $p_t < 6$ GeV, and a slight excess at higher p_t, but not at the L3 level; the DELPHI data are shown in Fig. 18.

There are several measurements of exclusive particle production in two-photon events. For example, L3 have recently measured $\rho^+\rho^-$ production [27], and compared it with their existing measurements of $\rho^0\rho^0$ [28]. The measured value of the charged/neutral ratio, 1.81±0.47±0.22, is in good agreement with the value of 2 expected from isospin, and the Q^2 distribution is in good agreement with the QCD expectation.

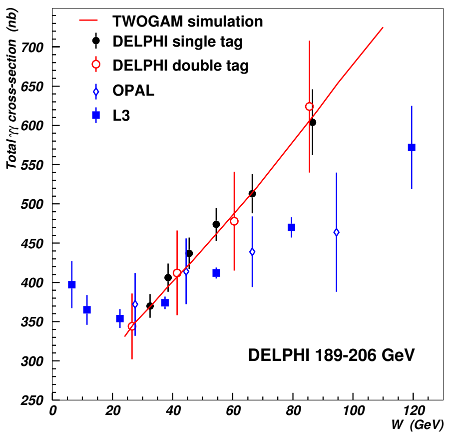

Fig. 17. Total hadronic cross-section in two-photon events measured by DELPHI.

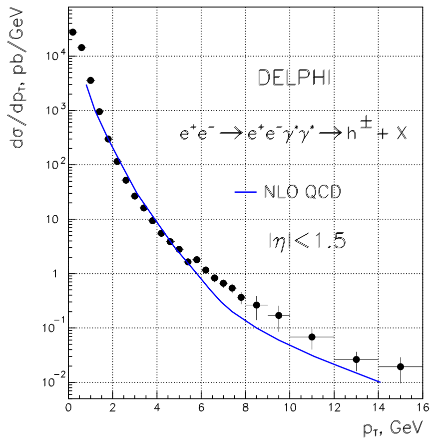

Fig. 18. Inclusive charged particle transverse momentum spectrum in two-photon collisions measured by DELPHI.

9 Summary

Since LEP finished running at the end of 2000, the experiments have continued to produce a lot of new physics results covering a wide range of topics. Some important LEP2 measurements are still to be finalized, particularly the measurement of the W boson mass. It is important that the plentiful, high-quality data produced at LEP be fully exploited.

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