4-fermion production at LEP2

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The running of LEP at centre-of-mass energies $\sqrt{s} \approx 200$ GeV offered the first opportunity to study four-fermion (4f) processes in e^+e^- collisions. In this paper the non resonant 4f production, the main source of weak bosons at the future Linear Collider, is discussed.

1. Introduction

The running of the LEP collider at centre-of-mass energies above the Z mass (LEP2) offered a unique opportunity to study the production of four-fermion final states (Table 1).

Table 1
The running of LEP at high energy.

$\sqrt{s}$ (GeV)	183	189	192-202	205	>207
$\mathcal{L}_{\rm int}$/exp (pb^{-1})	55	170	230	75	130

The $e^+e^- \to 4f$ reactions are usually classified according to the subset of diagrams which are more relevant for a particular final state. In the LEP2 energy range, depending on the behavior of the cross-section as a function of $\sqrt{s}$, one can identify doubly resonant processes as WW or ZZ production, proceeding through conversion type diagrams (cf. Figure 1.b) and non resonant processes like single-W, single-Z and $Z\gamma^*$ production. In this contribution the non resonant processes are discussed. In the LEP2 energy range their cross-section has a weak dependence on $\sqrt{s}$ not exhibiting a threshold behavior. The expected cross-sections for these processes are typically below 1 pb. Therefore common definitions of the cross-sections were agreed among the LEP experiments to increase the significance of the comparison with the theoretical predictions [1].

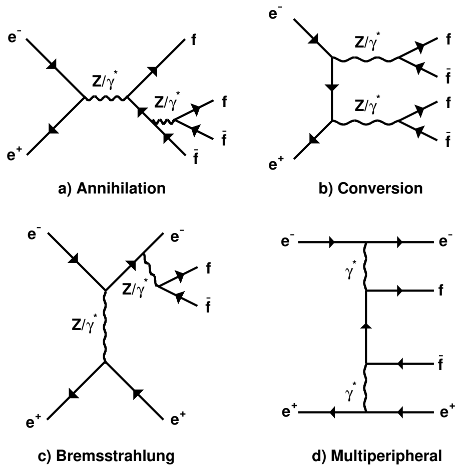

Figure 1. Diagrams contributing to $e^+e^- \to 4f$ at the lowest order.

2. Single-W

The study of single-W production is motivated mainly by testing the non-abelian sector of the electroweak Standard Model (SM). The final states investigated [1], $e^-\bar{\nu}_e q\bar{q}'$, $e^-\bar{\nu}_e \ell^+\nu_\ell$ ($\ell = \mu, \tau$) and $e^-\bar{\nu}_e e^+\nu_e$, are the same of the WW physics but here the analysis focuses on topologies with an electron lost along the beam-line. To enhance this contribution, the signal was defined considering only t-channel graphs with additional

[1]Charge conjugation is implied throughout the text.

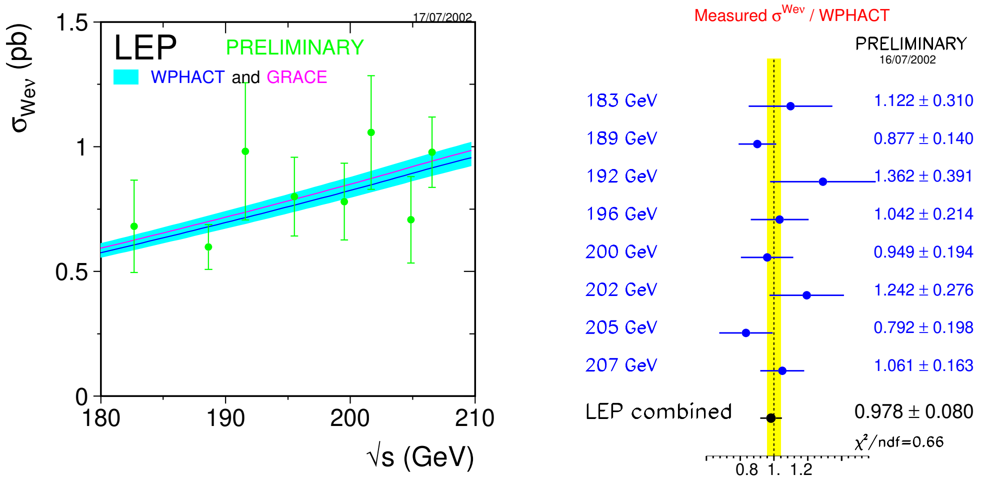

Figure 2. Measured single-W cross-sections as a function of $\sqrt{s}$ together with the SM predictions computed with GRC4f [3] and WPHACT [4] (left). Ratio of the measured to predicted cross-sections (right).

cuts on the phase space to reject the multiperipheral contributions:

- $m_{\mathrm{q\bar{q}'}} > 45$ GeV$/c^2$ for $\mathrm{e}^- \bar{\nu}_e \mathrm{q\bar{q}'}$,
- $E_{\ell^+} > 20$ GeV for $\mathrm{e}^- \bar{\nu}_e \ell^+ \nu_\ell$,
- $|\cos\theta_{\mathrm{e}^+}| < 0.95$, $E_{\mathrm{e}^+} > 20$ GeV and $|\cos\theta_{\mathrm{e}^-}| > 0.95$ (veto on e^-) for $\mathrm{e}^- \bar{\nu}_e \mathrm{e}^+ \nu_\mathrm{e}$.

From the technical point of view, the accurate prediction of the cross-section is challenging because having a collinear singularity, it requires a fully massive calculation of the amplitudes. From the physics point of view, the process is interesting because of the different energy scales involved:

- the scale of the electromagnetic coupling which could range from $\alpha_{\mathrm{QED}}(t \sim 0) = 1/137$ to $\alpha_{\mathrm{QED}}(s \sim M_{\mathrm{W}}^2) = 1/128$, leading to a change of the cross-section

$$\left.\frac{\delta\sigma}{\sigma}\right|_{\alpha_{\mathrm{QED}}(M_{\mathrm{W}}^2) \to \alpha_{\mathrm{QED}}(0)} \approx -5\%;$$

- the scale of the QED Initial State Radiation (ISR)

$$\left.\frac{\delta\sigma}{\sigma}\right|_{\mathrm{ISR}(q^2=s) \to \mathrm{ISR}(q^2=0)} \approx +8\%.$$

The accuracy of the codes used by the experiments is determined by the comparison with higher order calculations [2]. In the case of the electromagnetic coupling, approximate methods exist which are in agreement with higher calculations better than 2%. In the case of ISR no higher order prediction is available. An overall uncertainty of 5% is assumed on the expected cross-section.
Experimentally the measurement is dominated by the $\mathrm{e}^- \bar{\nu}_e \mathrm{q\bar{q}'}$ channel ($\approx$ 400-600 fb) which represents about 80% of the overall cross-section. The largest experimental error is the limited data statistics. The measured cross-sections as a function of $\sqrt{s}$ are shown in Figure 2 together with the theoretical predictions. The agreement with the SM expectations is expressed by the energy averaged ratio of the measured to the predicted cross-sections: $R = 0.978 \pm 0.080$ with about 80% of the full LEP2 sample analyzed by the experiments so far.

3. Single-Z

The process of single-Z production is dominated by the scattering of a quasi-real photon

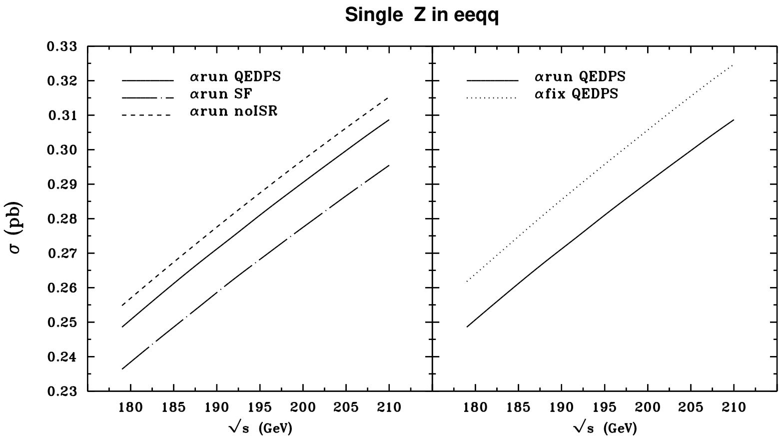

Figure 3. Predicted single-Z cross-section, $(\mathrm{e}^-)\mathrm{e}^+\mathrm{q\bar{q}}$ channel positron tag only, as a function of $\sqrt{s}$: effect of different ISR implementations (left) and of running α_{QED} (right) [4].

emitted by an electron on a positron of the other beam. The process is forward peaked, characterized by a backscattered positron, an electron lost along the beam-line and the decay products of the Z in the barrel. A common definition of the cross-section was established for $(\mathrm{e}^-)\mathrm{e}^+\mathrm{q\bar{q}}$ and $(\mathrm{e}^-)\mathrm{e}^+\mu^+\mu^-$ channels. It includes the entire set of 48 diagrams with additional cuts on the phase space to suppress the multiperipheral and s-channel contributions [2]:

- $m_{\mathrm{f\bar{f}}} > 60$ GeV/c^2 $(\mathrm{f} = \mu, \mathrm{q})$,
- $\theta_{\mathrm{e}^-} < 12^\circ$,
- $12^\circ < \theta_{\mathrm{e}^+} < 120^\circ$, $E_{\mathrm{e}^+} > 3$ GeV,

corresponding to a cross-section of about 500 fb for $(\mathrm{e}^-)\mathrm{e}^+\mathrm{q\bar{q}}$ and 50 fb for $(\mathrm{e}^-)\mathrm{e}^+\mu^+\mu^-$. within this kinematic limits At $\sqrt{s} = 200$ GeV the bremsstrahlung contribution, Figure 1.c, amounts to about 97% for $(\mathrm{e}^-)\mathrm{e}^+\mathrm{q\bar{q}}$ and to 67% for $(\mathrm{e}^-)\mathrm{e}^+\mu^+\mu^-$ final states. The sensitivity of the process to the scale of the electromagnetic coupling and of the ISR is similar to that of the single-W (Figure 3).

[2]LEP experiments assume the z-axis oriented along the direction of the incoming electron beam.

Experimentally single-Z events are selected requiring 2 jets or 2 identified muons accompanied with an isolated electron and the missing momentum of the event pointing in the beam-line direction. Signal efficiency is about 30-40% in the $(\mathrm{e}^-)\mathrm{e}^+\mathrm{q\bar{q}}$ channel and about 25% in the $(\mathrm{e}^-)\mathrm{e}^+\mu^+\mu^-$ channel. Background level is about 20% in the $(\mathrm{e}^-)\mathrm{e}^+\mathrm{q\bar{q}}$ channel, mainly from $\mathrm{q\bar{q}}(\gamma)$ and $\mathrm{e}^-\bar{\nu}_e\mathrm{q\bar{q}}'$ events, while it is below 2% for $(\mathrm{e}^-)\mathrm{e}^+\mu^+\mu^-$. The error is dominated by the data statistics, the largest experimental systematics being related to the electron selection. The measured cross-sections as a function of $\sqrt{s}$ are shown in Figure 4 together with the theoretical predictions. The energy averaged ratio of the measured to the predicted cross-sections is $R = 0.951 \pm 0.083$ for $(\mathrm{e}^-)\mathrm{e}^+\mathrm{q\bar{q}}$ and $R = 1.42 \pm 0.26$ for $(\mathrm{e}^-)\mathrm{e}^+\mu^+\mu^-$ with about 50% of the full LEP2 sample analyzed by the experiments so far.

4. Zγ^*

Four-fermion final states from Zγ^* production were the first non resonant 4f processes observed already in the LEP pilot run at 130-136 GeV in November 1995. They are characterized by all the four fermions detected with one pair, typi-

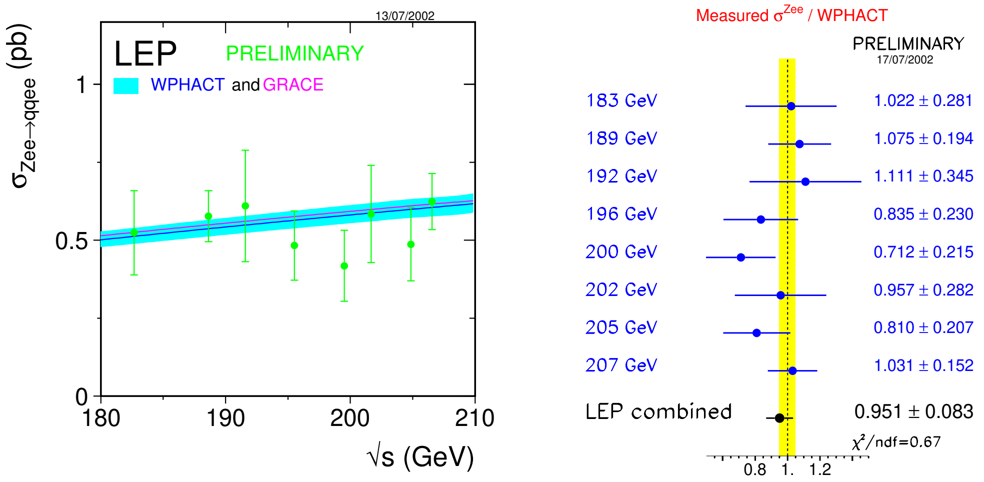

Figure 4. Measured single-Z cross-sections as a function of $\sqrt{s}$ together with SM predictions computed with GRC4f [3] and WPHACT [4] (left). Ratio of the measured to predicted cross-sections (right).

cally 2 jets, forming an invariant mass closed to the Z mass and the other, usually 2 leptons, at lower invariant masses. Currently only the OPAL collaboration has completed the analysis of the full LEP2 sample [5]. The analysis is done on $\mu^+\mu^-\mathrm{q\bar{q}}$ and $\mathrm{e^-e^+q\bar{q}}$ final states. The signal is defined topologically with the following cuts:

- $|\cos\theta_\ell| < 0.95 \quad (\ell = \mathrm{e}, \mu)$,
- $m_{\mathrm{q\bar{q}}} > 5\ \mathrm{GeV}/c^2$,
- $m_{\mathrm{ee}} > 2\ \mathrm{GeV}/c^2$, no cut on $m_{\mu\mu}$.

For $\mu^+\mu^-\mathrm{q\bar{q}}$ all the 8 contributing diagrams are included in the signal definition (Figure 1.a and 1.b). For the $\mathrm{e^-e^+q\bar{q}}$ final state two additional classes of diagrams contribute (Figure 1.c and 1.d): the bremsstrahlung is retained in the signal while the multiperipheral contribution is subtracted. The energy averaged cross-sections are:

$$\sigma_{\mathrm{eeqq}} = 199 \pm 27(\mathrm{stat.}) \pm 30(\mathrm{syst.})\ \mathrm{fb}\ (\mathrm{SM}: 180\ \mathrm{fb}),$$
$$\sigma_{\mu\mu\mathrm{qq}} = 160 \pm 26(\mathrm{stat.}) \pm 13(\mathrm{syst.})\ \mathrm{fb}\ (\mathrm{SM}: 165\ \mathrm{fb}),$$

where the SM predictions are computed with GRC4f and $\alpha_{\mathrm{QED}} = 1/128$.

5. Conclusions

The LEP2 run offered a unique opportunity to study non resonant 4f production which will be the main source of weak bosons at the future Linear Collider. The expected final accuracy on these processes is $\sim 7\%$ for single-W and $\sim 6.5\%$ on single-Z.

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