Production of light vector mesons at LEP

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We have computed the production cross section of light vector mesons in conjunction with muons at LEP. Cross sections are O(0.1 pb) and form a small but irreducible background to the search for light Higgs particles.

The process $e^+e^- \to \mu^+\mu^- +$hadrons is of interest since it is the main standard model background to Higgs production and decay via the Bjorken [1] mechanism. Although recent LEP results already rule out the standard model Higgs in the mass range 32 MeV–24 GeV [2] it is still useful to calculate what Higgs candidate events will be generated by standard model processes. Such information is needed, for instance to place limits on possible non-standard Higgses, for which the couplings to fermions are not constrained like the couplings of the standard Higgs.

If the invariant mass of the hadronic final state is high enough one can use perturbative QCD and the cross section may be calculated by considering quark and gluon final states [3]. This is not the case for light hadrons, where an alternative approach is required. A solution is to consider the process $e^+e^- \to \mu^+\mu^+\gamma^*$, where the off-shell photon is converted into a hadronic final state. This process is dominated by the presence of the ρ, ω and ϕ vector meson resonances [4]. Therefore we consider in this paper the tree level cross sections for the processes $e^+e^- \to \mu^+\mu^-\rho, \omega, \phi$. The cross sections are calculated in the vicinity of the Z resonance using vector meson dominance (VMD) [5].

The feature of the VMD hypothesis that is most relevant for us is the assumption that an off-shell photon with the right invariant mass is, up to a dimensionless coupling constant, a valid interpolating field for a vector meson. We have then, an interaction of the form $em_V^2/f_V\, V^\mu A_\mu$, where f_V is the decay constant of the vector meson. As is shown in ref. [5] this term in the interaction lagrangian violates gauge invariance, but can be combined with a photon mass term to give acceptable gauge invariant results if the photon couples only to conserved currents. The procedure is equivalent to introducing a current–current mixing of the form $F^{\mu\nu}(\partial_\mu V_\nu - \partial_\nu V_\mu)$ in the lagrangian. The constant f_V is related to the decay width Γ_{ee}^V of the meson to two electrons by the formula

$$\Gamma_{ee}^V = \frac{4\pi\alpha^2}{3f_V^2} M_V. \tag{1}$$

The cross section for vector meson production can now simply be obtained from the evaluation of the tree graphs for $e^+e^- \to \mu^+\mu^-\gamma^*$, with the relevant conversion factor from the $V^\mu A_\mu$ coupling folded in. We neglect graphs containing virtual photons in the s-channel since at LEP energies virtual Z exchange is dominant. This leaves us with a total of four Feynman graphs, two where the vector meson is produced by bremsstrahlung from the incoming electron or positron and two from final state radiation. In both cases a real or virtual Z is present in the s-channel. The graphs are shown in fig. 1.

In principle one can also consider the possibility of the vector meson being radiated from the Z propagator or of a Z boson converting to a ρ, but these processes are suppressed by discrete symmetries or extra factors of G_F and can safely be neglected. As a further approximation we neglect the masses for the incoming and outgoing leptons. We checked numerically that neglecting the muon mass gives no significant deviation from the results where the muon mass is kept. We work in the narrow width approximation, which is justified for the ω and ϕ and for the ρ to within about 20%. We also ignore all complications due to ω–ρ mixing as we do not expect this to significantly affect the total cross sections. The resulting matrix elements were generated by the symbolic manipulation programs FORM of J.A.M. Vermaseren and SCHOONSCHIP of M.J.G. Veltman. The expressions are too complicated to be given here.

With the above approximations a simple formula can be given for the total decay width of a Z boson into two muons and a vector meson of mass M_V and decay constant f_V:

$$\Gamma(Z\to V\mu^+\mu^-) = M_Z \frac{\alpha^3\{[1-4\sin^2(\theta_w)]^2+1\}}{24\sin^2(\theta_w)\cos^2(\theta_w) f_V^2} \times [4\log^2(M_Z/M_V) - 6\log(M_Z/M_V) + 5 - \pi^2/3]. \quad (2)$$

With this formula we find a decay width $\Gamma(Z\to V\mu^+\mu^-)$ of 22, 1.8 and 2.8 keV for ρ, ω and ϕ, respectively. The total cross section for final state radiation can be easily found from formula (2) by simply multiplying the known cross section $\sigma(e^+e^-\to\mu^+\mu^-)$ with the ratio of decay widths $\Gamma(Z\to V\mu^+\mu^-)/\Gamma(Z\to\mu^+\mu^-)$.

For initial state radiation a simple formula exists for the invariant mass distribution of the muons $\hat{s}$

$$\frac{d\sigma_{in}}{d\hat{s}} = \frac{\pi\alpha^4}{24\sin^4(\theta_w)\cos^4(\theta_w) f_V^2} \times \frac{\{[1-4\sin^2(\theta_w)]^2+1\}^2}{(\hat{s}-M_Z^2)^2+M_Z^2\Gamma_Z^2} \times \left[\left(\frac{\hat{s}(s+\hat{s}+m_V^2)}{2s^2} - \frac{\hat{s}}{s-\hat{s}-m_V^2}\right) \times \log\left(\frac{s-\hat{s}-m_V^2-\lambda^{1/2}(s,\hat{s},m_V^2)}{s-\hat{s}-m_V^2+\lambda^{1/2}(s,\hat{s},m_V^2)}\right) - \frac{\hat{s}\lambda^{1/2}(s,\hat{s},m_V^2)}{s^2}\right], \quad (3)$$

with

$$\lambda(x,y,z) = x^2+y^2+z^2-2xy-2xz-2yz.$$

The total cross section consists essentially of the sum of the contributions of initial state radiation and final state radiation. The interference between initial and final state radiation is never larger than 1% and to within the accuracy of our Monte Carlos is 0, as one would expect for a total cross section [#1]. For most energies in the range we have considered, the bulk of the cross section comes either from initial state or final state radiation; final state radiation being dominant for low energies and initial state radiation for energies much larger than the Z mass. It is only around 93 GeV that the two contributions are comparable.

While the above formulas represent simple results for the total cross sections, they are not directly useful for a comparison with experiment, where one makes some cuts in order to have clearly identifiable events. To get some idea of the effect of experimental cuts on the cross sections we have repeated the calculation with the OPAL [6] cuts folded in. The most relevant cuts are

(a) the cosine of the angle made by each of the fi-

[#1] We are indebted to K.J.F. Gaemers for pointing this out to us.

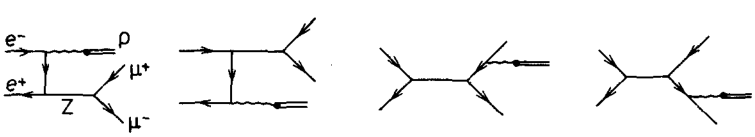

Fig. 1. The various graphs contributing to $e^+e^-\to V\mu^+\mu^-$ in the vicinity of the Z resonance. For convenience only one of the graphs has the particles labeled.

nal state particles with the beam axis must not exceed 0.8,

(b) the meson must make an angle of at least $\pi/6$ with each of the leptons, and finally

(c) the lepton energies must exceed 10 GeV.

The cross sections in the range 80–110 GeV are shown in fig. 2. One notices that the shape of the cross section around the Z peak is asymmetric. The cross section rises quickly approaching the Z mass from low energies, but falls off slower at high energies. This tail effect is well known from the photonic radiative corrections to the Z line shape. The absolute size of the cross section at the Z peak (91.1 GeV), 0.15 pb with and 0.52 pb without cuts for the ρ particle, makes the process visible at LEP luminosities. One expects roughly 20 events per 100 pb^{-1}, taking also the ω and ϕ into account. This number is not significant as a background to standard model Higgs detection, which has a cross section of about 15 pb, but has to be kept in mind if one wishes to consider more exotic possibilities.

Finally we remark that the results derived above cannot directly be carried over to final states with electron–positron pairs. For final states with electron–positron pairs extra graphs corresponding to radiative Bhabha events are present. Such processes have been considered at lower energies [7] and in the asymptotic limit [8]. From the results of ref. [8] one expects a total cross section of about 0.8 nb at LEP energies, for the production of vector mesons in association with electrons. This is clearly far bigger than the production via the *s*-channel Z boson graphs. However, as the bulk of the cross section is generated by graphs with an almost real photon in the *t*-channel, there is a pronounced forward peak. How much of the cross section will survive experimental cuts is strongly dependent on the experimental setup and cannot be easily estimated from the differential plots in ref. [7], since this calculation is at lower energies.

In conclusion we have used vector meson dominance to compute the production cross sections of light vector mesons at LEP1 in association with a muon pair. With the projected luminosities experimental detection is feasible. The process is unimportant as a background to the standard model Higgs, but could play a role in more exotic cases. The production of vector mesons with an electron pair deserves a further study including radiative Bhabha events.

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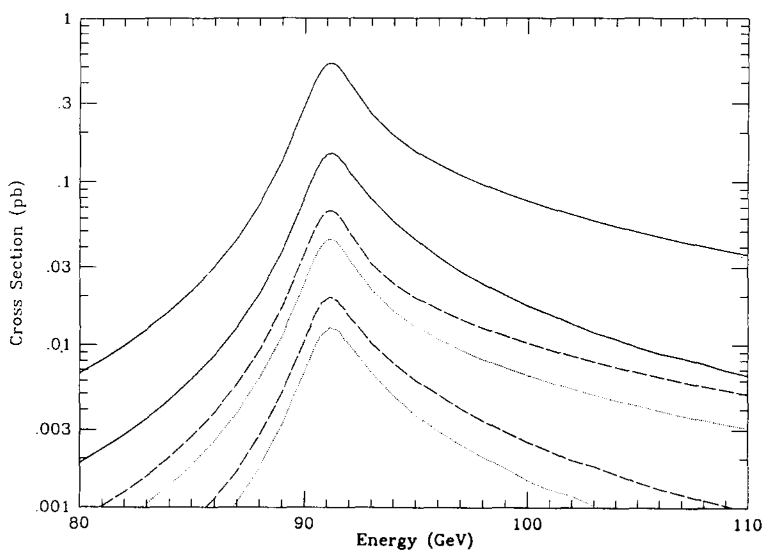

Fig. 2. The cross sections for ρ, ω and ϕ production with and without cuts. Solid lines denote the ρ, dotted lines the ω, and dashed lines the ϕ cross sections respectively.

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