RADIATIVE CORRECTIONS TO BHABHA SCATTERING IN SU(2) × U(1)

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We present the results of an accurate investigation of the electromagnetic and weak radiative corrections to Bhabha scattering at PETRA/PEP energies and around the Z^0 in the electroweak standard model. Using the on shell renormalization scheme with the electric charge and the boson and fermion masses as renormalized parameters we find that the photonic corrections to the γ and Z^0 exchange contributions are the most important ones at PETRA energies, on resonance, and in the radiative tail region above the Z^0. The dominating weak correction is the Z^0 self energy which gives visible effects around the resonance.

The discovery of the $W^{\pm}$ and Z^0 bosons at the CERN collider [1] appears to confirm the Glashow–Salam–Weinberg (GSW) model [2] of the electroweak interaction. Combining the $p\bar{p}$ results with the e^+e^- experiments at PETRA and PEP [3], and in the near future at LEP/SLC, provides powerful tests of the electroweak structure. The purely leptonic e^+e^- experiments [3] have meanwhile reached an accuracy that requires the inclusion of higher order contributions for an adequate theoretical discussion.

In ref. [4] we have calculated the one-loop corrections to the $e^+e^- \to \mu^+\mu^-$ forward–backward asymmetry, based on the on-shell renormalization scheme presented in ref. [5] with the electric charge and particle masses as renormalized physical parameters. We found that both the QED corrections to Z^0 exchange and the weak corrections give significant contributions to A_{FB}.

The more complicated process of elastic e^+e^- scattering offers the possibility to determine the weak coupling constants of the electron without assumptions about weak universality. But also from another actual point of view Bhabha scattering has recently received high interest: The scenario, where fermions and $W^{\pm}$, Z^0 bosons are composite [6] with interactions that mimic the GSW model on the tree level for $E \lesssim 300$ GeV, allows to interpret the recently discovered two

$$Z^0 \to e^+e^-\gamma\,, \tag{1}$$

decays [1] with a hard photon in the final state via $Z^0 \to X\gamma \to e^+e^-\gamma$ [7]. Bhabha scattering at PETRA turns out to be sensitive to such a spin-0 particle X with mass well above 45 GeV [8,9]. As shown in ref. [8] the $\gamma(t)$–$X(s)$ interference causes deviations from QED in the angular distribution of $e^+e^- \to e^+e^-$ with the opposite sign as the GSW prediction. The Z^0 and X contributions with $M_X \gtrsim 50$ GeV would nearly cancel each other such that the net deviation from QED tends to zero. Since, however, an interpretation of the events (1) as statistical fluctuations is not ruled out, the GSW predictions for Bhabha scattering be-

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yond the tree level have to be known more urgently than ever. Otherwise it could happen that deviations from the naive GSW expectations, which are due to the standard model radiative corrections, would be interpreted as effects coming from extra particles.

In this paper we have calculated the electroweak one-loop corrections to $e^+e^- \to e^+e^-$ within the renormalization scheme presented in ref. [5] for PETRA energies and around the Z^0. The first calculation of these corrections by Consoli [10] does not include hadronic contributions to the diagonal and non-diagonal boson self energies and effects coming from mass renormalization of the vector bosons. The pure QED corrections to s- and t-channel γ exchange with hard photons can be found in ref. [11] and with polarized beams in ref. [12]. The finite width effects of the electromagnetic corrections around the Z^0 have been discussed by Consoli et al. [13] and the full virtual photonic one-loop corrections also to Z^0 exchanges in the s- and t-channel by Sommer et al. [14].

The differential cross section for Bhabha scattering to lowest order in the standard model contains the contributions of the photonic s- and t-channel exchange giving the Coulomb peak in the forward direction, the γZ interference terms and the pure Z-exchange contributions. The γZ and ZZ s-channel terms show resonance behaviour for $s = M_Z^2$. For $s \gg m_e^2$ and with $t = -s/2(1-c)$, $c = \cos\theta$, the cross section can be written in the form:

$$(4s^2/\alpha^2)\,\mathrm{d}\sigma^{\mathrm{Born}}/\mathrm{d}\Omega = T_{0,s}^{\gamma\gamma} + 2\,\mathrm{Re}\,T_{0,st}^{\gamma\gamma} + T_{0,t}^{\gamma\gamma} + 2\,\mathrm{Re}\,T_{0,s}^{\gamma Z} + 2\,\mathrm{Re}\,T_{0,st}^{\gamma Z} + 2\,\mathrm{Re}\,T_{0,st}^{Z\gamma} + 2\,\mathrm{Re}\,T_{0,t}^{\gamma Z} + T_{0,s}^{ZZ} + 2\,\mathrm{Re}\,T_{0,st}^{ZZ} + T_{0,t}^{ZZ}, \qquad (2)$$

with

$$T_{0,s}^{ij} = [F^{ij}(1+c^2) + G^{ij}\cdot 2c]\,\chi^{i*}(s)\chi^j(s),$$
$$T_{0,st}^{ij} = -(F^{ij}+G^{ij})\,[(1+c)^2/(1-c)]\,\chi^{i*}(s)\chi^j(t),$$
$$T_{0,t}^{ij} = 2\{F^{ij}[(1+c)^2+4]/(1-c)^2 + G^{ij}[(1+c)^2-4]/(1-c)^2\}\,\chi^{i*}(t)\chi^j(t), \qquad (3)$$

where F^{ij}, G^{ij} are composed from the coupling constants v^i, a^i with $v^\gamma = 1, a^\gamma = 0, v^Z = (4s_W^2-1)/4s_Wc_W$, $a^Z = -1/4s_Wc_W$, $c_W = M_W/M_Z = (1-s_W^2)^{1/2}$ in the following way:

$$F^{ij} = (v^iv^j + a^ia^j)^2, \quad G^{ij} = (v^ia^j + a^iv^j)^2. \qquad (4)$$

The reduced propagators $\chi^i(s)$:

$$\chi(s) = 1, \quad \chi^Z(s) = s/(s-M^2), \qquad (5)$$

contain the complex mass of the Z boson: $M^2 = M_Z^2 - \mathrm{i}M_Z\Gamma_Z$.

The radiatively corrected Bhabha cross section can be classified in the following way:

– photonic virtual and real corrections to the γ-exchange diagrams only (reduced QED corrections) [11],

– photonic virtual and real corrections to the γ- and Z-exchange diagrams (full QED corrections) [14],

– all one-loop diagrams of the standard model for Bhabha scattering plus real bremsstrahlung (complete one-loop corrections).

In this paper we are especially interested in the purely weak radiative corrections which extend the full QED corrections to the complete electroweak one-loop corrections. They get contributions from the gauge field part of the photon self energy, the γZ-mixing energy, the Z-boson self energy, the weak vertex corrections and the weak box diagrams containing two W- or Z-boson lines. We have calculated them [15] using the renormalization scheme [5] with e, M_W, M_Z, M_H, m_f as physical parameters and having ordinary QED as simple substructure.

In table 1 we give a detailed list of these contributions for PETRA/PEP energies, around the Z-resonance and at 110 GeV for 90° scattering angle. The results for 44 GeV are normalized to the pure one-loop electromagnetic cross section, the others to the Born cross section (2). We use as parameters M_W = 82 GeV, M_Z = 93.2 GeV, M_H = 100 GeV, the quark masses of ref. [16]. The bremsstrahlung is calculated with $\Delta E/E = 0.1$ corresponding roughly to an acollinearity cut of 6°–7°. Hard photon effects are respected in the resonance parts. They produce the radiative tail above the resonance as the main effect. The table shows (at 90°) that the complete QED corrections are very important whereas the purely weak corrections are small at PETRA–PEP energies [‡1], but have sensible effects around and above the Z-resonance. The main contribution in the energy range considered comes from the Z self energy and the weak vertex corrections.

[‡1] This is different from the $e^+e^- \to \mu^+\mu^-$ asymmetry, where the purely weak corrections are of the same order as the QED corrections to Z^0 and interference parts [4].

Table 1
Percentage corrections to Bhabha scattering at 90° normalized to pure QED (44 GeV) and to the electroweak Born cross section (92.0 – 110.0 GeV).

Corrections	$\sqrt{s}$ (GeV) 44.0	92.0	93.2	94.5	110.0	
reduced QED	−3.66	−1.86	−1.15	−1.86	−33.98	
full QED	0.79	−36.36	−34.61	−12.02	13.03	
Z self energy	−0.13	4.64	−0.05	4.29	−0.98	weak radiative corrections
γ self energy	−0.01	0.00	0.00	0.00	−0.04	
γZ mixing	0.00	0.10	0.13	0.19	0.05	
vertex corrections	−0.01	−0.45	−0.54	−0.77	−0.12	
box diagrams	0.02	0.15	0.16	0.20	0.06	
total weak	−0.14	4.44	−0.30	3.91	−1.03	

The differential cross section normalized to the QED cross section for 44 GeV is shown in fig. 1. As expected we find no correction in the forward direction but sensible corrections around 90° and in the backward direction. The cross section is decreased (90°)/increased (180°) by the weak Born contributions. The complete QED corrections diminish this effect, whereas the purely weak corrections enlarge it. The amount of the purely weak corrections is about 1/6 of the amount of the photonic corrections to the Z-exchange.

In fig. 2 are plotted the Bhabha cross sections

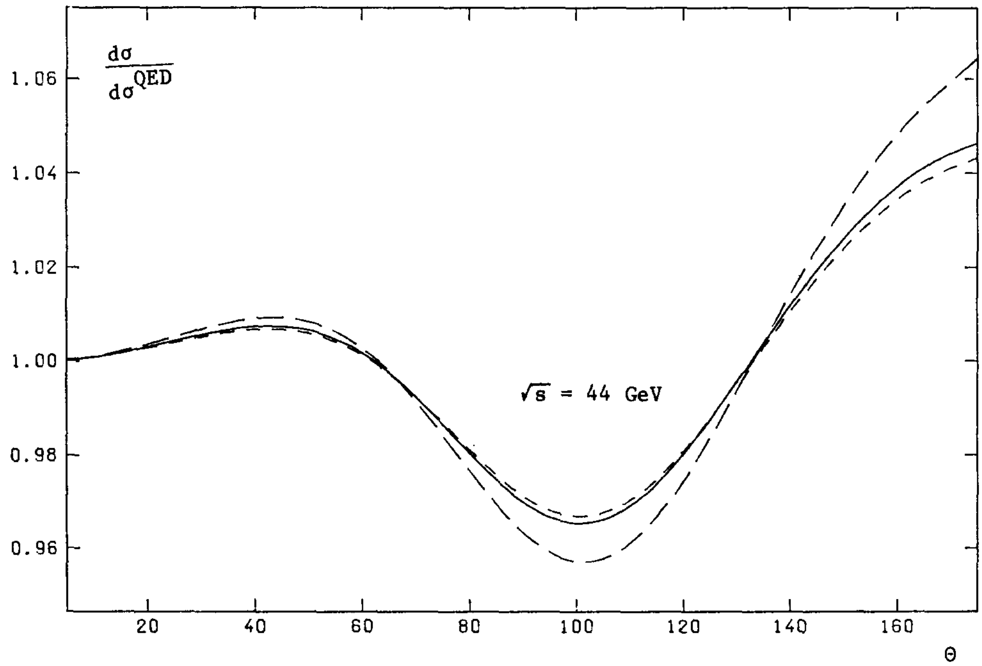

Fig. 1. Differential cross section for Bhabha scattering ($\sqrt{s}$ = 44 GeV) normalized to the pure, radiatively corrected QED cross section including photonic corrections to $d\sigma^{\gamma\gamma}$ only (long dashed lines), complete photonic corrections (short dashed lines) and the complete electroweak corrections ($\Delta E/E$ = 0.1) (solid lines).

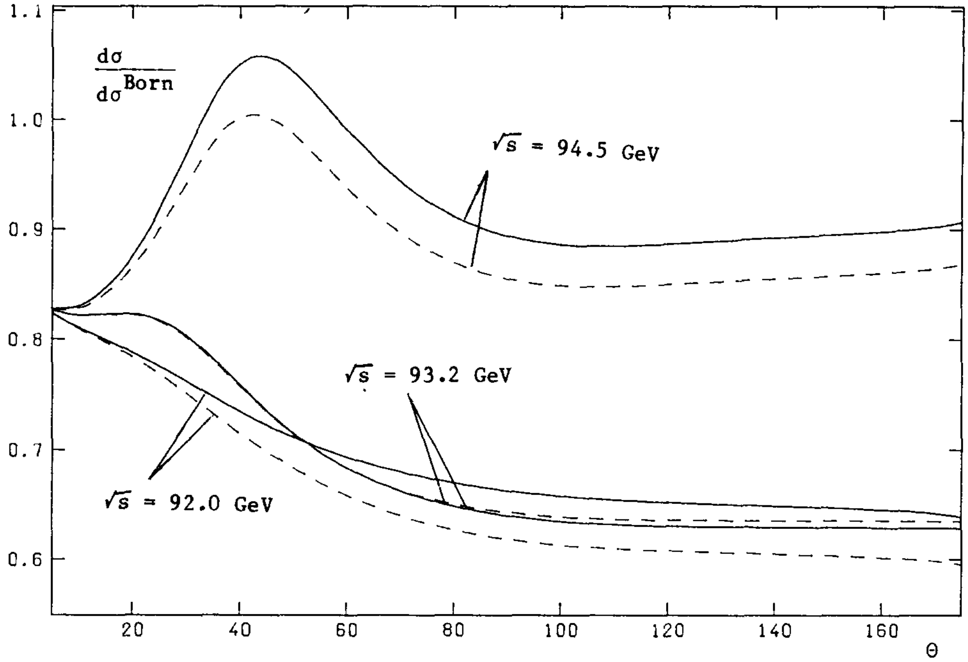

Fig. 2. The differential Bhabha cross section around 93 GeV normalized to the electroweak Born cross section including full QED corrections (dashed lines) and the complete electroweak corrections (solid lines).

around the Z mass. Since they are dominated by the s-channel Z-exchange mechanism we have divided by $(d\sigma/d\Omega)^{Born}$, eq. (2). We find large effects from radiative corrections. The Coulomb peak in the forward direction is reduced by 17%. The scattering at bigger angles gets strongly energy dependent corrections, most of them are photonic but also the purely weak corrections reach levels up to 10%. They are dominated again by the Z self energy and consequently are small on top of the resonance (leaving mainly the vertex corrections, -0.3% at $90°$) but significant e.g. at 92.0 and 94.5 GeV. Therefore their consideration is important when investigating the Z peak in Bhabha scattering in order to decide the question whether the GSW model or extended or subconstituent models are in agreement with the experimental data.

References

[1] UA1 Collab., G. Arnison et al., Phys. Lett. 126B (1983) 398;
UA2 Collab., P. Bagnaia et al., Phys. Lett. 129B (1983) 130;
UA1 Collab., G. Arnison et al., Phys. Lett. 135B (1984) 250.

[2] S.L. Glashow, Nucl. Phys. 22 (1961) 579;
A. Salam, in: Elementary particle theory, ed. N. Svartholm (Almqvist and Wiksell, Stockholm, 1968);
S. Weinberg, Phys. Rev. Lett. 19 (1967) 1264.

[3] PLUTO Collab., Ch. Berger et al., Z. Phys. C 21 (1983) 53;
P. Grosse-Weismann, DESY 83-087;
TASSO Collab., M. Althoff et al., Z. Phys. C 22 (1984) 13;
G. Herten, Brighton Conf. (Brighton, UK, 1983);
E. Lohrmann, DESY 83-102;
A. Böhm, DESY 83-103;
B. Naroska, DESY 83-111;
E. Fernandez et al., Phys. Rev. Lett. 50 (1983) 1238;
SLAC-PUB 3133 (1983);
MARK-J Collab., B. Adeva et al., MIT-Report 131 (1983).

[4] M. Böhm and W. Hollik, Phys. Lett. 139B (1983) 213.

[5] M. Böhm and W. Hollik and H. Spiesberger, DESY 84-027.

[6] H. Harari and N. Seiberg, Phys. Lett. 90B (1981) 269;
Nucl. Phys. B 204 (1982) 141;
O.W. Greenberg and J. Sucher, Phys. Lett. 99B (1981) 339;
L. Abbott and E. Farhi, Phys. Lett. 101B (1981) 69;
Nucl. Phys. B 189 (1981) 547;
H. Fritzsch and G. Mandelbaum, Phys. Lett. 102 B (1981) 319;

B. Schrempp and F. Schrempp, Nucl. Phys. B 231 (1984) 109;
C.H. Albright, Phys. Lett. 126B (1983) 231;
W. Buchmüller, R.D. Peccei and T. Yanagida, MPI-PAE/PTH 41/83 (1983).
[7] F.M. Renard, Phys. Lett. 126B (1983) 59; 139B (1984) 449;
H. Fritzsch, MPI-PAE/PTh80/83 (1983);
U. Baur, H. Fritzsch and H. Faissner, MPI-PAE/PTh86/83 (1983);
R.D. Peccei, Phys. Lett. 136B (1984) 121.
[8] W. Hollik, B. Schrempp and F. Schrempp, Phys. Lett. 140B (1984) 424.
[9] F.W. Bopp, S. Brandt, H.D. Dahmen, D.H. Schiller and D. Wähner, Siegen preprint SI-83-24 (1983), extended version (1984).
[10] M. Consoli, Nucl. Phys. B 160 (1979) 208.
[11] F.A. Berends, K.J.F. Gaemers and F. Gastmans, Nucl. Phys. B 68 (1974) 541.
[12] W. Hollik, Phys. Lett. 123 B (1983) 259.
[13] M. Consoli, M. Greco and S. LoPresti, Phys. Lett. 113B (1982) 415.
[14] R. Sommer, M. Böhm and W. Hollik, Würzburg preprint (1983).
[15] M. Böhm, A. Denner, W. Hollik and R. Sommer, in preparation.
[16] J. Gasser and H. Leutwyler, Ann. Phys. (NY) 136 (1981) 62; Phys. Rep. 87 C (1982) 77.