SUBSTRUCTURE TESTS WITH POLARIZED $e^+e^- \to 2\gamma$

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It is shown that two-quantum pair annihilation with polarized beams is useful in the search for electron substructure at high-energy e^+e^- colliders. We consider modification models with excited electrons of spin 1/2 and 3/2. The test will be most sensitive for longitudinally polarized beams of equal handedness.

The importance of two-quantum pair annihilation for testing the structure of the electron has been recognized already a long time ago [1]. Since in the lowest order of perturbation theory this is a pure quantum electrodynamics (QED) process, deviations which are, e.g., due to compositeness of the electron could be detected easily in this simple reaction even in the scope of the standard model of today.

However, this test cannot be performed model-independently as in e^+e^- scattering [2] because of gauge invariance [3,2]. We have to choose certain modification models, which, in our case, can be interpreted as excited electrons e^* of spin 1/2 and 3/2. Such states would be a natural consequence of compositeness. We will respect first P, C, T symmetries but make some remarks about their implications at the end. The models considered here are parameterized by the mass m^* of e^* and the coupling strength λ of e^* to the normal electron and the photon.

A few years ago we have shown that high-energy e^+e^- collisions with polarized beams are much more sensitive in the search for electroweak interference effects as the unpolarized reaction [4]. Recently, polarized e^+e^- beams have also been proposed in the search for residual contact interactions from substructure of quarks and leptons [5] and for supersymmetric extensions of the standard model [6]. Therefore, we will study the effect of beam polarization also for the following substructure tests of the electron.

More in detail we will consider the following models:

(1) Spin 1/2 excited electron with magnetic moment coupling [7]. The propagator of the excited electron is $(\not p - m^*)^{-1}$. Its coupling to the normal electron and the photon is given by the interaction lagrangian

$$L_{\text{int}} = \frac{e\lambda}{2m^*} \bar\Psi^{(*)} \sigma_{\mu\nu} F^{\mu\nu} \Psi + \text{h.c.} \tag{1}$$

$\Psi^{(*)}$ is the spinor of the excited electron, $\not p = p_\mu \gamma^\mu$,

(2) Excited electron with spin 3/2 and Dirac coupling. We use the Rarita–Schwinger propagator [8]

$$\frac{\not p + m^*}{p^2 - m^{*2}} \left(-g^{\mu\nu} + \tfrac{1}{3}\gamma^\mu\gamma^\nu + \frac{1}{3m^*}(\gamma^\mu p^\nu - p^\mu \gamma^\nu) + \frac{2}{3m^{*2}} p^\mu p^\nu \right). \tag{2}$$

The Dirac coupling is described by the lagrangian [9]

$$L_{\text{int}} = \frac{e\lambda}{m^*} \bar\Psi^{(*)}_\mu F^{\mu\nu} \gamma_\nu \Psi + \text{h.c.} \tag{3}$$

Here, $\Psi^{(*)}_\mu$ is the Rarita–Schwinger spinor of e^*.

The helicity amplitudes for the pair annihilation process have been calculated [10] according to the diagrams of fig. 1 using an efficient method [11]. With the helicity amplitudes and the helicity density matrices we have derived the polarized cross sections. The reaction parameters [12], which contain all of the dynamics of the polarized process, can be evaluated easily in terms of the helicity amplitudes [12].

The kinematics in the CMS and the definition of the polarization parameters are shown in fig. 2. To describe the polarization of the particles we have used their helicity rest frames. In this paper, we study polarization for the incoming particles only.

In high-energy approximation, $\sqrt{s} \gg m$, and for excited electron masses $m^* \gg m$, the deviations of our models from QED are much smaller for scattering angles $\Theta \approx m/\sqrt{s}$ than for $\Theta \gg m/\sqrt{s}$. Hence, wide-angle scattering is of main interest here, and we give formulas valid for $\sqrt{s} \gg m$ and $\Theta \gg m/\sqrt{s}$.

We find for masses $m^* \geqslant \sqrt{s}$, that terms in the cross section $\sim \lambda^4$ may be of the same order of magnitude as terms $\sim \lambda^2$, even for small $\lambda \leqslant 1$ and, therefore, cannot be neglected in general.

The polarized cross sections are

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\text{spin } 1/2} = \frac{\alpha^2}{s}\Bigg[(1-s_{\mathrm{L1}}s_{\mathrm{L2}})\left(\frac{\gamma_+^2+\gamma_-^2}{2\sigma^2} - \tfrac{1}{4}\lambda^2\frac{s^2}{m^{*2}}(\gamma_-^2\tau+\gamma_+^2\mu) + \tfrac{1}{32}\lambda^4\frac{s^4}{m^{*4}}\sigma^2[(\gamma_-\tau)^2+(\gamma_+\mu)^2]\right)$$
$$+(1+s_{\mathrm{L1}}s_{\mathrm{L2}})\tfrac{1}{8}\lambda^4\frac{s^3}{m^{*2}}(\gamma_-\tau+\gamma_+\mu)^2 + (s_{\mathrm{S1}}s_{\mathrm{S2}}+s_{\mathrm{N1}}s_{\mathrm{N2}})\left(-1+\tfrac{1}{4}\lambda^2\frac{s^2}{m^{*2}}\sigma^2(\tau+\mu) - \tfrac{1}{16}\lambda^4\frac{s^4}{m^{*4}}\sigma^4\tau\mu\right)\Bigg], \quad (4)$$

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)^{\text{spin } 3/2} = \frac{\alpha^2}{s}\Bigg[(1-s_{\mathrm{L1}}s_{\mathrm{L2}})\left(\frac{\gamma_+^2+\gamma_-^2}{2\sigma^2} - \tfrac{1}{24}\lambda^2\frac{s^2}{m^{*4}}(\gamma_+^2\hat{\tau}\tau+\gamma_-^2\hat{\mu}\mu) + \tfrac{1}{1152}\lambda^4\frac{s^4}{m^{*8}}\sigma^2[(\gamma_+\hat{\tau}\tau)^2+(\gamma_-\hat{\mu}\mu)^2]\right)$$
$$+(1+s_{\mathrm{L1}}s_{\mathrm{L2}})\tfrac{1}{2}\lambda^4\frac{s^3}{m^{*6}}[\tfrac{1}{9}+\tfrac{1}{4}m^{*4}(\tau+\mu)^2]$$
$$+(s_{\mathrm{S1}}s_{\mathrm{S2}}+s_{\mathrm{N1}}s_{\mathrm{N2}})\left(-1+\tfrac{1}{24}\lambda^2\frac{s^2}{m^{*4}}\sigma^2(\hat{\tau}\tau+\hat{\mu}\mu) - \tfrac{1}{576}\lambda^4\frac{s^4}{m^{*8}}\sigma^4\hat{\tau}\tau\hat{\mu}\mu\right)$$
$$-(s_{\mathrm{S1}}s_{\mathrm{S2}}-s_{\mathrm{N1}}s_{\mathrm{N2}})\tfrac{1}{6}\lambda^4\frac{s^3}{m^{*4}}(\tau+\mu)\Bigg]. \quad (5)$$

We have used the abbreviations $\gamma_+ = 1+\cos\theta$, $\gamma_- = 1-\cos\theta$, $\sigma = \sin\theta$, $\tau = (t-m^{*2})^{-1}$, $\mu = (u-m^{*2})^{-1}$, $\hat{\tau} = t+2m^{*2}$, $\hat{\mu} = u+2m^{*2}$; s, t, u are the Mandelstam variables. $s_{..1}$ and $s_{..2}$ denote the various degrees of polarization

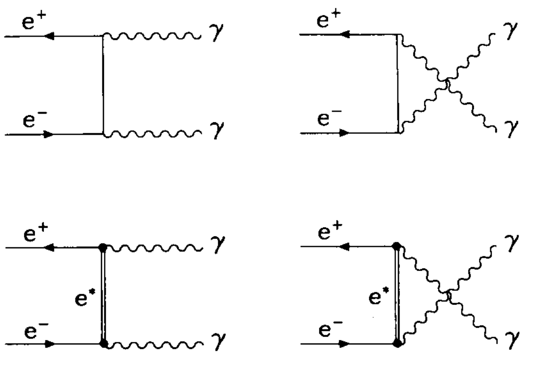

Fig. 1. Feynman graphs for $e^+e^- \to 2\gamma$ including exchange of e^*.

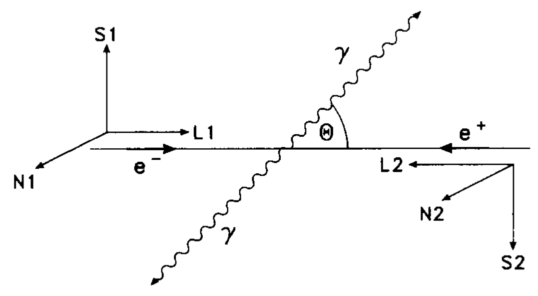

Fig. 2. Kinematics and polarization configurations for two-quantum pair annihilation in the CMS. The scattering plane is in the plane of the paper. $L..$, $S..$, $N..$ signify the spin directions in the rest frames of the particles.

of the electron and positron beams, respectively (see fig. 2). Note that there are no contributions if only one particle is polarized, and if one particle is polarized longitudinally and the other transversely.

Fig. 3 shows the boundaries for the coupling strengths and the masses in the models if a deviation from QED or experimental error of 5% is assumed at some fixed scattering angles in the unpolarized case.

Because of the well-known helicity conservation along fermion lines in Feynman graphs of gauge theories in high-energy approximation, the normal QED reaction can be suppressed by a factor $(1-s_{L1}s_{L2})$ relative to the unpolarized case, if beams of equal handedness $(s_{L1}s_{L2}>0)$ are used. In this way, deviations from QED,

$$\delta_{LL}=\frac{(d\sigma/d\Omega)^{\text{model,LL}}}{(d\sigma/d\Omega)^{\text{QED,LL}}}-1, \tag{6}$$

can become especially large compared to the deviations δ_0 with unpolarized beams. In other words, the sensitivity of the experiment to modifications could be enhanced. Fig. 4 shows numerical examples.

For transverse beam polarization which appears to be achieved relatively easy in storage-rings like LEP one would expect additional deviations from QED compared to the unpolarized case according to eqs. (4) and (5). But for this polarization, there is no possibility to suppress the QED background efficiently for all scattering angles as in the case of longitudinal polarization (fig. 4). Nevertheless, (natural) transverse polarization, too, can be used to derive stronger limits on λ and m^* from experiments (fig. 5).

The models constructed here obey *C*-, *P*-, and *T*-invariance. Chiral versions of models with excited electrons,

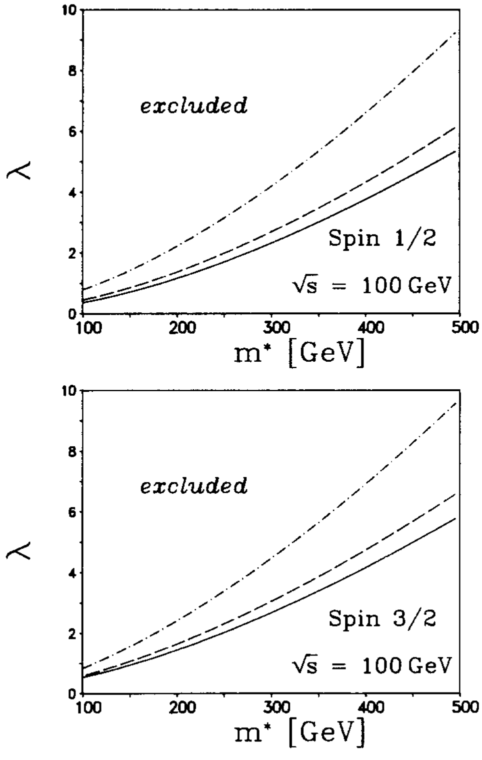

Fig. 3. Boundaries for the coupling strength λ and the mass m^* in QED models with excited electrons at a CMS energy of 100 GeV. A deviation of the unpolarized differential cross section from QED or experimental error of $\delta_0=5\%$ is assumed at scattering angles 30° (dash-dotted line), 60° (dashed line), and 90° (solid line).

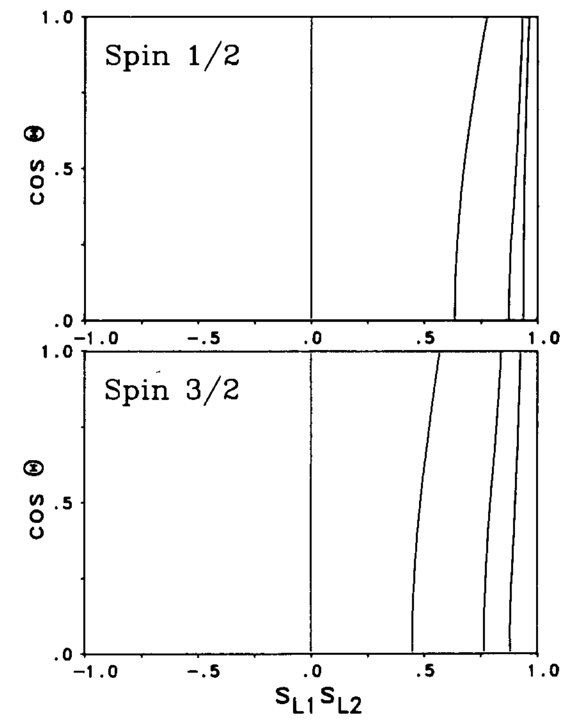

Fig. 4. Ratio of deviations δ_{LL}/δ_0 for the spin 1/2 model and the spin 3/2 model as a function of the degree of longitudinal polarization $s_{L1}s_{L2}$ and the scattering angle Θ. $\sqrt{s}=100$ GeV, $m^*=140$ GeV, $\lambda=1$. The $(\cos\Theta, s_{L1}s_{L2})$ plane is divided from left to right into regions where $\delta_{LL}/\delta_0<1$, >1, >2, >5, and >10.

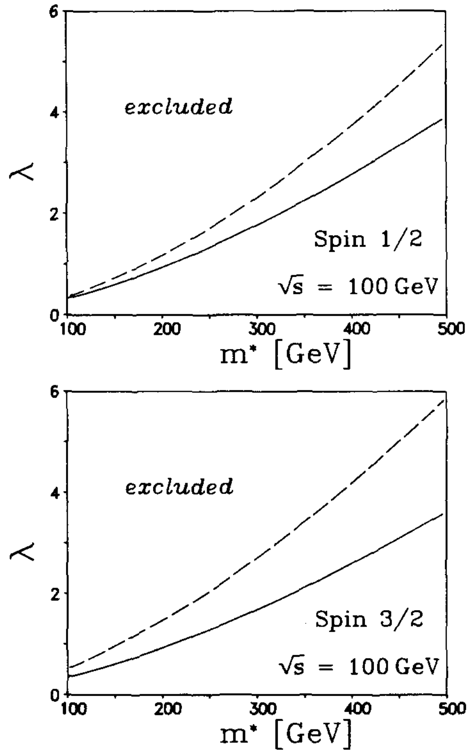

Fig. 5. Effect of transverse polarization on the limits on λ and m^*. In sideward scattering a deviation of the polarized and unpolarized differential cross section from QED or experimental error of $\delta = 5\%$ is assumed. Dashed line: unpolarized beams (compare fig. 3). Solid line: both beams 90% transversely polarized with $s_{S1}s_{S2} = +0.81$.

where the electron field Ψ is replaced by $\frac{1}{2}(1 \pm \gamma_5)\Psi$, motivated by the fascinating agreement of $(g-2)$ measurements of the electron and the muon with the standard model, can easily be calculated once the helicity amplitudes for the non-chiral versions are given [11]. These chiral models would violate C- and P-invariance. In this case, certain asymmetries (one-particle polarization asymmetries) could be detected if only one beam is polarized.

We conclude that $e^+e^- \to \gamma\gamma$ experiments with polarized beams are useful for the search of excited electrons of spin 1/2 and 3/2. Longitudinal and transverse polarization of both beams can enhance the sensitivity to excited electron states of masses larger than the CMS energy $\sqrt{s}$ and, thereby, compensate for higher beam energy. We want to stress that for $\lambda = O(1)$ this enhancement of signals from excited electrons at higher energies is especially large if beams are longitudinally polarized and the masses m^* are close to the CMS energy. Our models are obviously non-renormalizable and exhibit unitarity violating high-energy behaviour. However, it can be shown that in the range of parameters considered here the partial waves of the models raise no problems with unitarity [13].

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References

[1] H. Salecker, Z. Phys. 160 (1960) 385.
[2] K. Ringhofer and H. Salecker, Found. Phys. 10 (1980) 185, presented in part at 1975 Stanford Symp. on Lepton and photon interactions at high energies (Stanford University, Stanford, CA).
[3] N.M. Kroll, Nuovo Cimento 45 (1966) 65;
K. Ringhofer, Acta Phys. Austr. 31 (1970) 67.

[4] T. Anders, W. Jachmann, H. Salecker and K. Wadan, in: Old and new questions in physics, cosmology, philosophy, and theoretical biology. Essays in honour of Wolfgang Yourgrau, ed. Alwin van der Merve (Plenum, New York, 1983) p. 411.
[5] B. Schrempp, F. Schrempp, N. Wermes and D. Zeppenfeld, Nucl. Phys. B 296 (1988) 1.
[6] C. Dionisi et al., in: Proc. ECFA Workshop on LEP 200, eds. A. Böhm and W. Hoogland (CERN, Geneva), CERN report CERN 87-08, p. 280.
[7] F.E. Low, Phys. Rev. Lett. 14 (1965) 238.
[8] W. Rarita and J. Schwinger, Phys. Rev. 60 (1941) 61;
R.E. Behrends and C. Fronsdal, Phys. Rev. 106 (1957) 345.
[9] Ph. Salin, Nuovo Cimento 32 (1964) 521.
[10] A. Feldmeier, diploma thesis, Universität München (1987).
[11] T.B. Anders and W. Jachmann, J. Math. Phys. 24 (1983) 2847; 28 (1987) 221.
[12] C. Bourrely, E. Leader and J. Soffer, Phys. Rep. 59 (1980) 95.
[13] F.C. Simm, doctoral thesis, Universität München (1989), to be published.