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CONFIRMATION OF A SOFT PHOTON SIGNAL IN EXCESS OF Q.E.D. EXPECTATIONS IN $\pi^- p$ INTERACTIONS AT 280 GeV/c

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Abstract

Photons produced in $\pi^- p$ interactions at 280 GeV/c were detected by reconstructing the e^+e^- pairs produced via the materialisation of the photons in a 1 mm thick lead sheet placed in front of the MWPC's of the OMEGA spectrometer at CERN. A soft photon signal 7.8 ± 1.5 times the Q.E.D. inner bremsstrahlung prediction was observed confirming the results of a previous experiment.

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1 Introduction

The first observation of a soft photon signal in excess of the Q.E.D. inner bremsstrahlung prediction was observed in a K^+p hydrogen bubble chamber experiment at 70 GeV/c[1]. Since then apparently conflicting results have been published, some experiments observe a signal of soft photons[2, 3] whilst others observe no excess signal[4]. It appears that these results can be reconciled if the signal exists only in the region $Y_{cms} > 0$. Experiment WA83[3], which was performed in order to confirm the original K^+p BEBC result, found a signal of one soft photon per six π^-p interactions at 280 GeV/c in the kinematic region $0.2 < E_\gamma < 1$ GeV/c and $P_T < 10$ MeV/c. This is a factor 7.9 times the Q.E.D. inner bremsstrahlung prediction.

In experiment WA83 the soft photons were detected with a Pb-scintillating fiber calorimeter. The origin of the photons was assumed to be the main interaction vertex for the determination of their otherwise unmeasurable direction. The rapidity range covered was $1.4 \leq Y_{cms} \leq 5$. The calculated probability of background soft photon production from various sources in the apparatus was found to be negligible in this rapidity range. However, we think that a direct measurement of the photon production point would give an experimental check of this type of background. The present experiment, using a different technique, but exploring the same kinematic region, was motivated by this idea.

Thus, we present in this paper the results of the study of the soft photon production in the energy range of $0.2 < E_\gamma < 1$ GeV, and in the angular (polar angle θ) range restricted to 20 mrad. The conversion of photons to e^+e^- pairs in a thin lead sheet was used to detect the photons.

2 Experimental technique

The data for this experiment were collected using the set-up of the WA91 experiment in the CERN OMEGA spectrometer shown in figure 1. A 280 GeV/c π^- beam incident on a 60 cm long hydrogen target, was used to reproduce similar conditions to the WA83 exposure. The magnetic field (B = 1.1 T) direction was along the z (vertical) axis of the OMEGA coordinate system in which the beam is along the x-axis. All interaction triggers (minimum bias) were collected. Out of them only the interactions with less than 8 charged tracks have been used for analysis. This requirement was necessary in order to select the cleaner events for which the pattern recognition results are safe. A 50×50 cm^2 Pb sheet of 1 mm thickness was placed just before the B set of MWPC's at a distance of 73 cm downstream from the centre of the hydrogen target.

The photons were detected via the materialisation in the Pb sheet into an electron-positron pair. The e^+e^- were reconstructed as V^0's from the digitisations produced in the MWPC's using a modified version of the standard TRIDENT[5] reconstruction program which enabled reconstruction of tracks originating in the Pb sheet with momenta down to 40 MeV/c. It was thus possible to determine the line of flight of the photon with an average error of $\pm$ 10 mrad by measuring its momentum. This error is mainly due to the multiple scattering of the electrons and positrons in the lead sheet in the energy range $0.2 < E_\gamma < 1$ GeV used in the present analysis. However, for the production angle of the soft photon projected on the x-y plane (θ_R), we preferred the more precise direction, given by using the reconstructed interaction point in the hydrogen target and the photon materialisation point in the lead sheet. This gives an error of ± 1 mrad. Analogously, for the calculation of the photon polar angle θ and the associated variable of transverse momentum P_T the geometrical coordinates have been used.

The requirements for accepting a positive and negative particle pair (V^0) as a materialised photon candidate were:

a) that each track had at least 4 reconstructed space points;

b) that the mass of the V^0 found by the TRIDENT reconstruction program, assuming electron masses for the tracks, was less than 70 MeV/c^2;

c) that the x coordinate of the photon apex, defined to be at the position where the two tracks have zero angle between them, was within ± 3 cm of the middle of the lead sheet;

d) that the distance between the two tracks in the x-y plane when the tracks had zero angle between them was less than 3 mm, and

e) only those photons were taken where the spatial separation of their e^+e^- vertex from any charged track at the lead sheet was greater than 3 mm in the x-y plane. This was necessary to avoid including soft photons which were produced in the lead sheet by electrons or positrons originating upstream of the sheet. Moreover, this cut suppressed a large fraction of the bremsstrahlung photons radiated by these particles upstream of the lead sheet, since both the parent particle and its radiation arrive on the lead sheet with a small separation.

The above defined criteria (c), (d) and (e) have been arrived at after a visual scanning of a large number of reconstructed real events including all the soft photon candidates and MC simulated events (using the simulation described in the next paragraphs).

The efficiency for reconstructing photons was determined by a method involving implanting simulated photons into the real data . The method generates photons with a bremsstrahlung-like spectrum, converts them in the lead sheet using the EGS4 code[6] , transports the resulting e^+e^- pairs through the lead sheet and the MWPC's and simulates clusters in the MWPC's at the position where the e^+ and e^- cross the MWPC's. After digitizing these clusters were implanted on actual events which passed through the TRIDENT reconstruction program followed by a standard selection and analysis algorithm. The efficiency has been studied as a two-dimensional function of energy and emission angle of the photons, with non-equidistant binning (down to 50 MeV in energy and 0.5 mrad in θ). The error on the overall correction factor is estimated to be less than 20% even in the bins with the smallest statistics. The validity of the efficiency correction can be assessed by comparing the efficiency corrected photon P_T spectrum, in a region of P_T where photons from hadronic decays dominate, with the predictions of the FRITIOF Monte Carlo program for hadronic interactions[7] as we will see below (Sect.4).

We used this Monte Carlo technique to prove that the P_T measurement, based on the γ apex coordinate finding, is not distorted by multiple scattering. The P_T error comes mainly from the reconstruction error in the γ apex z coordinate, and was found to be ± 2.4 MeV/c, with the θ accuracy of ± 5.6 mrad. As to the γ energy measurement, it was accurate to within 5 MeV (All errors quoted in this paragraph are average and relevant to the photon energy range of $0.2 - 1$ GeV).

3 Study of backgrounds

The following sources of soft photons were considered:

a) inner bremsstrahlung;

b) photons from hadronic decays;

c) Dalitz pairs from π^0, η and ω decays;

d) knock-on electrons from energetic tracks;

e) spurious V^0 consisting of hadronic tracks which nevertheless satisfy the photon selection criteria.

f) secondary photons: when a high energy photon generates an e^+e^- pair in the material upstream of the lead sheet (target, target walls, Silicon detector, etc.) the pair particles may radiate bremsstrahlung photons, which can enter our kinematic region. In most cases such photons come to the lead sheet close to their parent charged paricles and are rejected by the isolation cut (cut (e), Sect.2). However, there is a fraction of such photons which are not rejected because their parent particles bend in the OMEGA magnetic field. Additionally, pairs from photons of $E_\gamma > 1$ GeV converted in the lead sheet can degrade to energies below 1 GeV due to bremsstrahlung.

In order to calculate the yields of soft photons from (a) to (f) we have developed a Monte Carlo program which transports the particles generated by the FRITIOF code [7] (γ's and Dalitz e^+e^- pairs included) through our experimental set up. The EGS4 code [6] was involved for the proper treatment of the e^+e^- pairs and photons. A generator of inner bremsstrahlung photons was added to the FRITIOF code. The bremsstrahlung calculations were based on:

i) the exact Low formula [8a]

$$\frac{d\sigma}{d^3\vec{k}} = \frac{\alpha}{(2\pi)^2}\frac{1}{\omega}\int d^3\vec{p}_1...d^3\vec{p}_N \sum_{i,j}\eta_i\eta_j \frac{(P_iP_j)}{(P_iK)(P_jK)}\frac{d\sigma^H}{d^3\vec{p}_1...d^3\vec{p}_N} \tag{1}$$

where K and $\vec{k}$ denote photon four- and three-momenta, P and $\vec{p}$ are 4- and 3-momenta of charged hadrons, $\eta = 1$ for beam pion and for positive outgoing particles, $\eta = -1$ for the target proton and negative outgoing particles, and the sum being extended over all charged particles;

ii) the Haissinski formula [8b], which is expected to be more stable with respect to lost (undetected) particles (when it is applied to the real data events). It has the same form as (1) with the scalar products of 4−vectors (P_iP_j) being replaced by $(\vec{p}_{i\perp}\vec{p}_{j\perp})$, where $\vec{p}_{i\perp} = \vec{p}_i - (\vec{n}\vec{p}_i)\vec{n}$, $\vec{n}$ is the photon unit vector.

Both formulae give results coinciding within 10%, so we take this number as a systematic uncertainty for the bremsstrahlung calculations.

The results of the Monte Carlo estimations for the soft gamma yields from the sources listed above are given in Table 1.

4 Experimental results

The P_T^2 spectrum of reconstructed photons emitted inside a cone of half angle of 215 mrad around the beam direction and with energy $0.2 < E_\gamma < 1$ GeV, uncorrected for efficiency is shown in figure 2. The shape expected from γ's of hadronic decays in the same kinematic region has been obtained using the FRITIOF Monte Carlo and is shown by the dashed line. The Monte Carlo data have been normalised by a constant factor to the higher P_T^2 region of the experimental sample. Since we know that the photon detection efficiency falls off with decreasing P_T^2 the presence of an increase in the observed uncorrected spectrum at small P_T^2 ($P_T < 10$ MeV/c or $P_T^2 < 10^{-4}$ (GeV/$c)^2$) is evidence for a low P_T^2 signal not originating from hadronic decays.

Figure 3a shows the efficiency corrected P_T spectrum upon which are superimposed the predictions of the FRITIOF Monte Carlo increased by 20% to fit the data above a P_T of 50 MeV/c. This factor can be attributed to the residual systematic errors in the γ detection and reconstruction procedure (15 % as was evaluated by varying the parameters of the efficiency finding code), and to the FRITIOF Monte Carlo systematics (about 10 %). In this figure, while the data follow well the expected P_T distribution of photons coming from hadronic decays above a P_T of 50 MeV/c where the contribution coming from Q.E.D. inner bremsstrahlung is small, below P_T <50 MeV/c an excess exists which rises rapidly towards zero P_T . As can be seen by comparing figures 3a and 3b, this excess is essentially concentrated in angles $\theta < 20$ mrad [1].

The rate of photons to interactions in this kinematic region is (13.1 ± 0.4)%. The quoted error is statistical. The systematic error , due to uncertainty in the efficiency, is 15% of the rate. Reducing the photon rate by the sum of contributions (b) to (f) of Table 1 we find that, in the defined kinematic region, the signal of the soft photons is $(9.8 \pm 0.4 \pm 1.5)$% , and the ratio for the observed signal to the expected Q.E.D. inner bremsstrahlung is 7.8 ± 1.5 , where the main contribution to the error comes from the uncertainties in the efficiency correction and the inner bremsstrahlung calculation. This value may be compared to the value of 7.9 ± 1.4 found in the WA83 experiment for the same kinematic region.

[1] We note, that the number of photons selected under this cut ($\theta < 20$ mrad) is not affected by the experimental accuracy in the θ angle ($\pm$5.6 mrad) since the angular distribution of the soft photons ($E_\gamma < 1$ GeV) is almost uniform around the $\theta = 20$ mrad.

In order to see whether the low P_T photons observed in figure 3b originate from the interaction point we show, in figure 4a, a correlation plot of θ_R against θ_P which is the production angle of the photons defined by the line of flight of the photon in the x-y plane as measured by the vector sum of the e^+ and e^- momenta. A 45^0 correlation is observed with a spread about this line of $\pm$ 10 mrad, which is what is expected from the Monte Carlo study and comes mainly from the multiple scattering of the e^+e^- in the lead sheet. The $\delta\theta = \theta_P - \theta_R$ distribution, shown in figure 4b, was found to be of a Breit-Wigner shape which is expected for a resolution function in this experiment (superposition of many Gaussian distributions of a variable width depending on the multiple scattering angle which varies with E_γ), [9] [2] . The Γ (full width) of the Breit-Wigner was fitted to be (19.2 ± 0.6) mrad, its position being centered at zero within 0.3 mrad and the fit χ^2 being 85.6 per $n.f.d = 92$. As can be seen from this figure, the yield of the non-correlated photons to the signal is consistent with zero, with the upper limit for it being less than 0.2 % per event (at 99% C.L.). This upper limit was obtained by adding a constant term to the fit form (Breit-Wigner), increased from zero until the total χ^2 increases by 6.6, the 99 % confidence level for the fit with a single parameter.

Thus, the fact that we observe a strong correlation is evidence that the photons originate from the point of interaction. Furthermore, the angular precision offered by θ_R and θ_P angles can be exploited for the comparison of WA91 and WA83 experiments. Having observed the same signal in the very forward direction in both experiments, with the interaction and materialisation points entering into the angle measurement (WA91), we obtain evidence that the soft photons in WA83 also originate from the target interactions. Otherwise, in WA91 where the material between target and photon detection is significantly less than in WA83, we should observe less signal.

5 Conclusion

This experiment confirms the existence of an anomalous soft photon signal in the kinematic region 0.2 GeV $< E_\gamma <$ 1 GeV and $\theta <$ 20 mrad at a level 7.8 ± 1.5 times the expected from Q.E.D. inner bremsstrahlung.

[2]The conditions under which the resolution function was obtained in [9] to be of a Breit-Wigner form, are very close to those we have in the experiment: fast fall-off of the multiple scattering error distribution with the energy increase since it comes from the bremsstrahlung-like spectrum, and a sharp cut-off at small energies due to decreasing detection efficiency.

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Table 1.
Calculated soft gamma yields ($0.2 < E_\gamma < 1$ GeV, $\theta < 20$ mrad). The quoted errors are statistical. The systematic errors for background calculations are estimated to be 10 %.

	Source	Number of γ per event (%) corrected for conversion efficiency (factor 8)
a.	Inner bremsstrahlung	1.25 ± 0.05
b.	Hadronic γ's	1.53 ± 0.05
c.	Dalitz pairs	0.09 ± 0.01
d.	Knock-on electrons	0.12 ± 0.02
e.	Spurious γ's	$(2 \pm 2)10^{-3}$
f.	Secondary γ's	1.52 ± 0.05
	Sum over sources a to f	4.50 ± 0.09

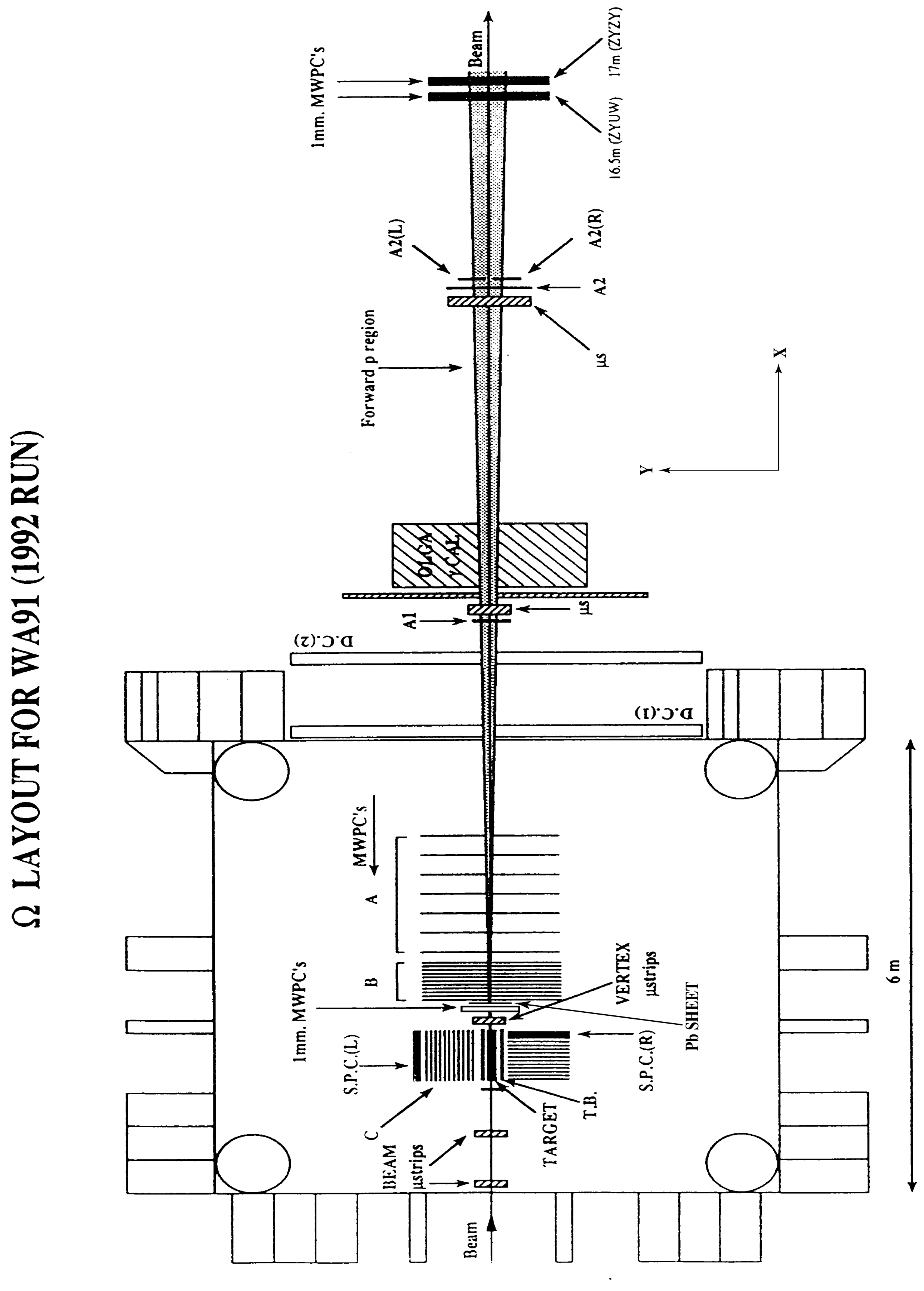

Figure 1: Layout of the OMEGA spectrometer for the experiment

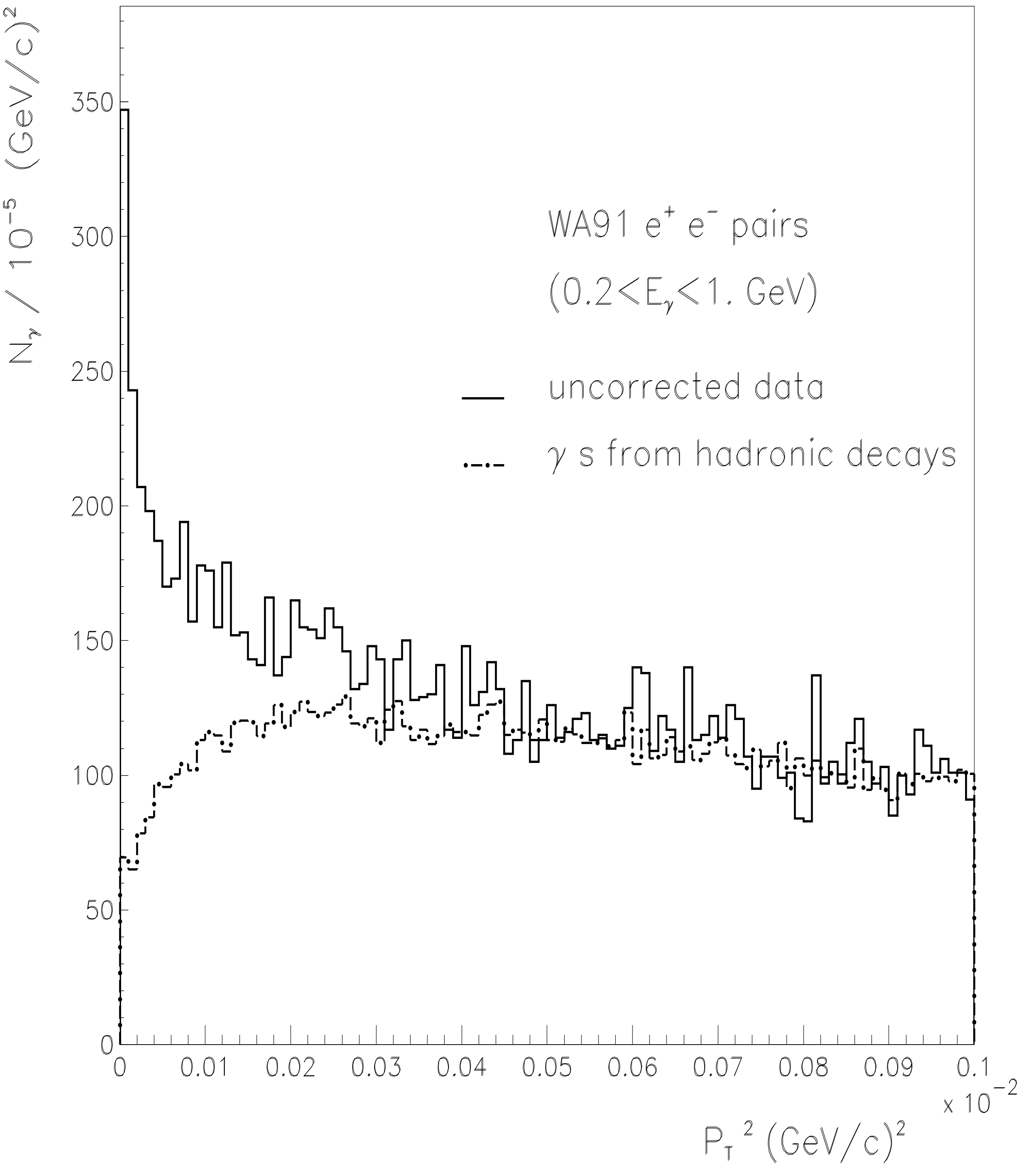

Figure 2: P_T^2 distribution for photons with energy $0.2 < E_\gamma < 1.0$ GeV uncorrected for detector efficiency.

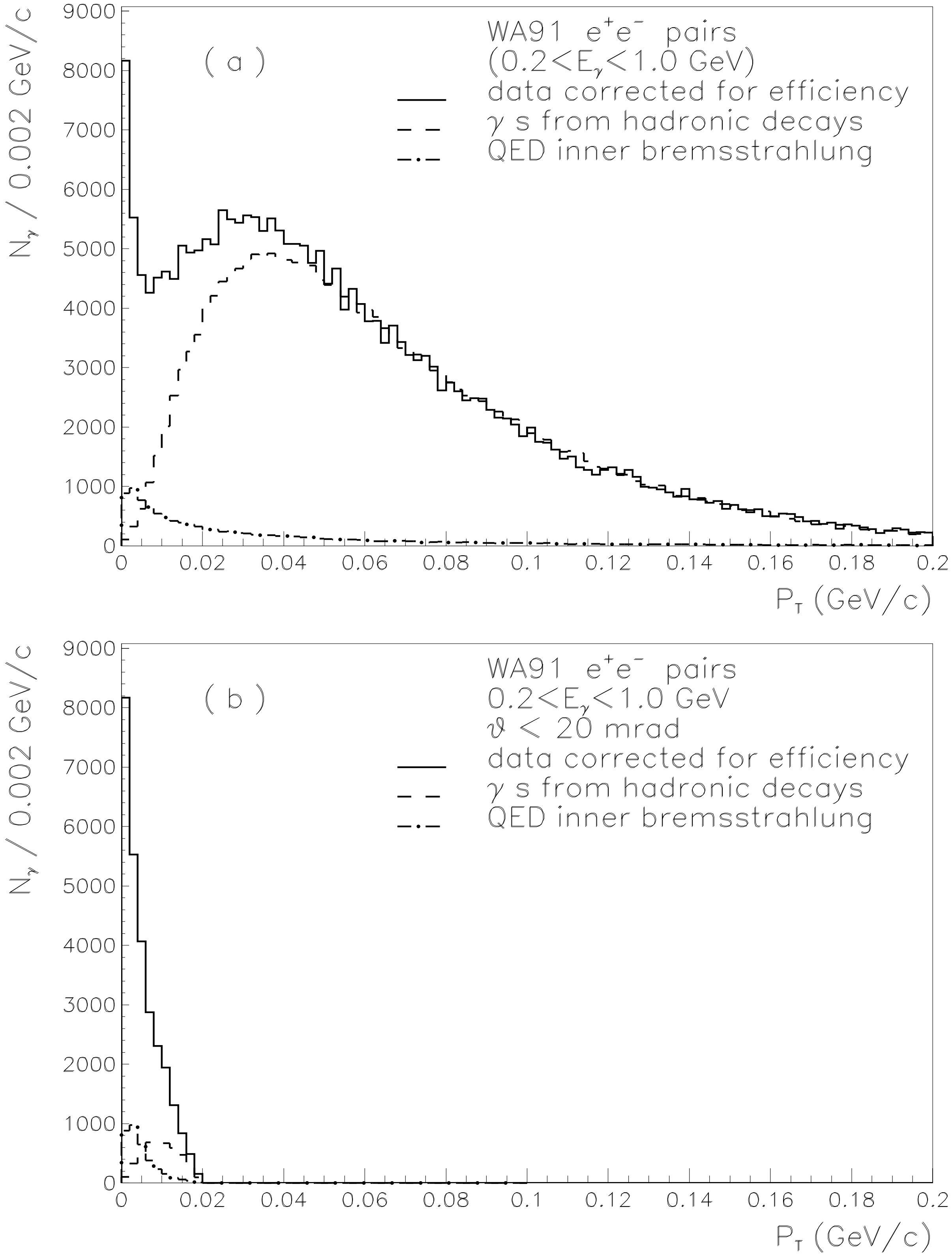

Figure 3: a) P_T distribution for photons with energy $0.2 < E_\gamma < 1.0 GeV$ corrected for detection efficiency; b) Same as figure 3a but with additional restriction of $\theta < 20$ mrad.

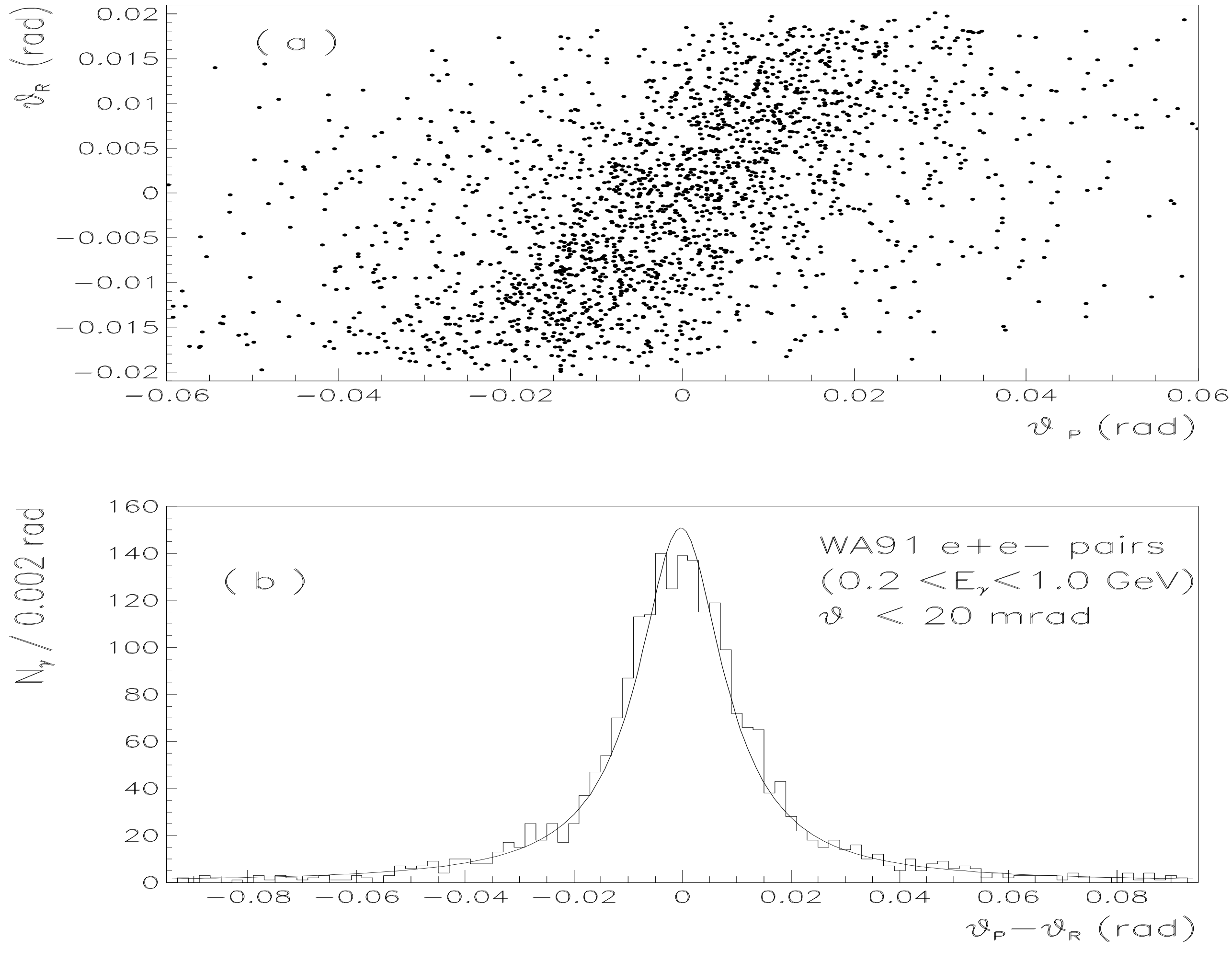

Figure 4: a) Correlation of θ_P versus θ_R, as defined in the text, for the sample of e^+e^- pairs in figure 3b ; b) The difference $\theta_P - \theta_R$ for the small P_T photons of figure 4a (histogram) with the result of a fit with a Breit-Wigner (full line).