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A Fragmentation Model Applied to Exclusive Final States in Photon-Photon Collisions*

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ABSTRACT

Monte Carlo calculations with the Lund string fragmentation model are compared to experimental results on the reactions $\gamma\gamma \rightarrow 2\pi^+2\pi^-$, $\gamma\gamma \rightarrow K^+K^-\pi^+\pi^-$ and $\gamma\gamma \rightarrow p\bar{p}\pi^+\pi^-$. It is found, that when the parameters of the Lund model are tuned to low energy, inclusive multi hadron production in photon-photon collisions, the cross sections of exclusive processes near threshold are qualitatively reproduced.

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In recent years, experiments at e^+e^- colliders have collected data on the exclusive production of hadronic final states in photon-photon collisions. Specific interest in the reaction $\gamma\gamma \to 2\pi^+2\pi^-$ arose in 1980 when the TASSO collaboration observed[1] a large number of these events around the threshold for $\rho^0\rho^0$ production. The yield of events was significantly higher than expected from simple vector-meson dominance models. In addition, it was found that the signal was predominantly $\rho^0\rho^0$ at $\gamma\gamma$ invariant masses below $W_{\gamma\gamma} = 2.0$ GeV, but that the $\rho^0\rho^0$ component vanished above 2.0 GeV, to be replaced by equal contributions from $\rho^0\pi^+\pi^-$ and isotropic $2\pi^+2\pi^-$. These results were confirmed by the MARK II,[2] CELLO,[3] and TPC[4] collaborations. Since then, the reactions $\gamma\gamma \to p\bar{p}\pi^+\pi^-$ and $\gamma\gamma \to K^+K^-\pi^+\pi^-$ were established. It was found[5,6] that the production cross section for $p\bar{p}\pi^+\pi^-$ rises to ≈ 4 nb for $W_{\gamma\gamma}$ between 3.0 and 3.5 GeV, and decreases to zero for higher $W_{\gamma\gamma}$. The presence of the baryons Λ and Δ, either single or in pairs, could not be established in this final state. In analyses of $K^+K^-\pi^+\pi^-$ events,[7,8] fits to several hypotheses yielded that $\approx 50\%$ of the events can be attributed to the reaction $\gamma\gamma \to K^{*0}(890)K\pi$. No significant signal was found for $\gamma\gamma \to K^{*0}\bar{K}^{*0}$. In addition, a few $\phi\pi^+\pi^-$ events were found, however without evidence for $\phi\rho^0$. The cross section for $K^+K^-\pi^+\pi^-$ production (including the $K^{*0}K\pi$ contribution) is according to both the TPC[7] and the TASSO[8] collaborations ≈ 20 nb at $W_{\gamma\gamma} = 2.0$ GeV, and rapidly decreasing towards higher masses.

The Lund string fragmentation model[9] is one of a few models that have been succesfully applied to describe multi hadron production in e^+e^- annihilation. In particular, the topology of three-jet events seems to be best described with the Lund model.[10] The model is based on the assumption that the energy of the primary interaction is shared by two leading quarks, or, if the center-of-mass energy is sufficiently high, by quarks and additional gluons. The confinement of color is provided through a tube-like confinement field (the string) with uniform strength. When the quarks move apart, $q\bar{q}$ pairs are created in a vacuum fluctuation along the string. The probability for this process is expressed in the fragmentation function $f(z)$, where z is the fraction of the parton's momentum transferred to the $q\bar{q}$ pair. After the fragmentation phase, the hadronization occurs and $q\bar{q}$ pairs recombine to form hadrons. Baryon pairs are produced by tunneling of diquark-antidiquark pairs.

Here, the Lund string fragmentation model is applied to photon-photon collisions, and in particular to the production of $2\pi^+2\pi^-$, $K^+K^-\pi^+\pi^-$ and $p\bar{p}\pi^+\pi^-$ final states. The principle is shown in figure 1, where a $u\bar{u}$ pair couples electromagnetically to the two photons and proceeds to extract three $q\bar{q}$ pairs from the vacuum to produce a $2\pi^+2\pi^-$ state. The QED formalism for the formation of lepton pairs in $\gamma\gamma$ collisions was chosen to reproduce the angular distribution of the $q\bar{q}$ pair with respect to the $\gamma\gamma$-axis, and to give the relative rates for $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$ formation. The differential cross section is given by[11]

$$\frac{d\sigma(\gamma\gamma \to q\bar{q})}{d\Omega} = e_i^4 \frac{\alpha^2}{W_{\gamma\gamma}^2} \beta \frac{2\beta^2 \sin^2\theta - \beta^4 \sin^4\theta + 1 - \beta^4}{(1-\beta^2\cos^2\theta)^2}, \tag{1}$$

where θ is the angle of the (anti)quark with respect to the $\gamma\gamma$-axis in the $\gamma\gamma$ center of mass. The quark velocity β is

$$\beta = \sqrt{1 - \frac{4m_i^2}{W_{\gamma\gamma}^2}}, \tag{2}$$

where m_i is the mass of the quark flavor i, and e_i its charge in units of e. The flavor i is produced in a fraction

$$P_i(W_{\gamma\gamma}) = \frac{\sigma(\gamma\gamma \to q_i\bar{q}_i)}{\sum_{j=u,d,s} \sigma(\gamma\gamma \to q_j\bar{q}_j)} \tag{3}$$

of the events.

The Lund string fragmentation model is manifested by the LUND Monte Carlo program, of which version 5.3 was used in the calculations. Input to this Monte Carlo are the energy and direction of the primary quarks. From these, it produces a final state of hadrons. The model is governed by a set of parameters, for which the defaults were obtained by a comparison to high energy e^+e^- annihilation data. In order to efficiently simulate low energy fragmentation, a set of parameters was chosen that was tuned[13] to describe the multi hadron events used in the measurement of the hadronic structure function of the photon.[12]

The Lund model by construction conserves momentum and flavor, but since the initial state is unknown, charge conjugation is not conserved. In particular at low $W_{\gamma\gamma}$, $C = -1$ states like $\rho^0\pi^0$, $\rho^0\eta$, *etc.*, are generated abundantly. These two-particle final states were rejected. In addition, states like $\rho^0\pi^+\pi^-$ have positive charge conjugation if the $\pi^+\pi^-$ pairs are in $P, F, \ldots$ waves. These states are in practice indistinguishable from the S-wave states and may therefore lead to an overestimate of the cross section.

The results of the Monte Carlo calculations are expressed in fractions of the total number of generated events. In order to extract a cross section, the total hadronic cross section must be known. The total cross section has been measured,[14] and was found to be constant at $\sigma_{tot} \approx 360$ nb down to invariant $\gamma\gamma$ masses of 2 GeV. Below 2 GeV, only model calculations exist, which indicate a $1/W_{\gamma\gamma}$ behavior. The results of the calculations are shown in figure 2, where the cross sections (left scale) of $\gamma\gamma \rightarrow 2\pi^+2\pi^-$, $K^+K^-\pi^+\pi^-$ and $p\bar{p}\pi^+\pi^-$ as measured by the TASSO, CELLO and TPC collaborations, are compared to the fractions of LUND Monte Carlo events (right scale). The similarity in the shapes between the data points and the Monte Carlo curves (histograms) is remarkable. The curves are normalized to the data for each distribution separately, by the integral under the curves. The normalization factors are 1090 ± 40 nb for $2\pi^+2\pi^-$, 763 ± 71 nb for $K^+K^-\pi^+\pi^-$ and 569 ± 153 nb for $p\bar{p}\pi^+\pi^-$. These numbers can be directly compared to σ_{tot}, and confirm that the Monte Carlo overestimates the total cross section significantly. However, the factors for $2\pi^+2\pi^-$ and $K^+K^-\pi^+\pi^-$ are in reasonable agreement with each other, indicating the similarity between both processes.

Although the experiments claim to see a large $\rho^0\rho^0$ fraction in the $2\pi^+2\pi^-$ data, no such events are generated in the LUND Monte Carlo. However, a large $\rho^0\pi^+\pi^-$ contribution is visible, rising from 0 at 1.0 GeV to $\approx$ 80% at 1.5 GeV and remaining constant beyond that. The observed production of $\rho^0\rho^0$ is possibly due to final state interactions between the pions, which are not simulated in the Lund model. Intuitively, these interactions are expected to be strongest near the threshold for $\rho^0\rho^0$ production. Similarly, no significant number of $K^{*0}\bar{K}^{*0}$ events is generated, but the fraction of $K^{*0}K\pi$ events contributing to the $K^+K^-\pi^+\pi^-$ final state varies from $\approx$ 65% below $W_{\gamma\gamma} = 2$ GeV to $\approx$ 55% above 2 GeV, which is in agreement with the experimental results. Finally, half of the $p\bar{p}\pi^+\pi^-$ events are accounted for by production of $\Delta^{--}p\pi^+$ and $\Delta^{++}\bar{p}\pi^-$. It should be pointed out that the final states $\phi\rho^0$ and $\phi\pi^+\pi^-$ cannot be produced in this model. A different mechanism must account for the observation of these events.

An interesting preliminary result on angular distributions in $2\pi^+2\pi^-$ events, extending to large $W_{\gamma\gamma}$, was presented[4] by the TPC collaboration: towards higher masses, a peaking was observed in the distribution of the angle of pion pairs with respect to the $\gamma\gamma$ axis in the $\gamma\gamma$ rest frame, as shown in figure 3. This was interpreted as evidence for peripheral production. The Lund model reproduces this phenomenon quite well, as is shown by the curves (histograms), representing events generated with the $q\bar{q}$ angular distribution according to (1).

In conclusion, it is possible to reproduce qualitatively the phenomena observed in the reactions $\gamma\gamma \rightarrow 2\pi^+2\pi^-$, $\gamma\gamma \rightarrow K^+K^-\pi^+\pi^-$ and $\gamma\gamma \rightarrow p\bar{p}\pi^+\pi^-$, by making simple modifications to the Lund string fragmentation model. This suggests that the existence of resonances is not required to describe the observed threshold enhancements.

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FIGURE CAPTIONS

1. The reaction $\gamma\gamma \rightarrow 2\pi^+2\pi^-$ in the string fragmentation model.

2. The production cross sections as a function of invariant $\gamma\gamma$ mass for the processes $\gamma\gamma \rightarrow 2\pi^+2\pi^-$, $\gamma\gamma \rightarrow K^+K^-\pi^+\pi^-$ and $\gamma\gamma \rightarrow p\bar{p}\pi^+\pi^-$. The left scales correspond to the data points. The curves (histograms) show the fraction of events generated by the LUND Monte Carlo (right scale). Data and Monte Carlo are normalized separately for each process. The $2\pi^+2\pi^-$ data are from CELLO[3] and the TPC group[4] (preliminary), the $K^+K^-\pi^+\pi^-$ data are from TPC[7] and TASSO[8] (preliminary), and the $p\bar{p}\pi^+\pi^-$ data are from TASSO[5] and TPC[6] (preliminary).

3. The distribution of events as a function of $\cos\theta_{\pi^+\pi^-}$ (two entries per event) in six bins of $W_{\gamma\gamma}$. $\theta_{\pi^+\pi^-}$ is the angle of a pion pair with respect to the $\gamma\gamma$ axis in the $\gamma\gamma$ center of mass. The curves (histograms) correspond to LUND Monte Carlo calculations, in which quarks are produced with the angular distribution of lepton pairs.

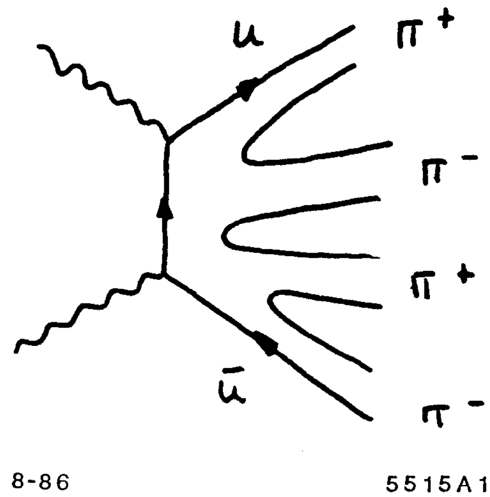
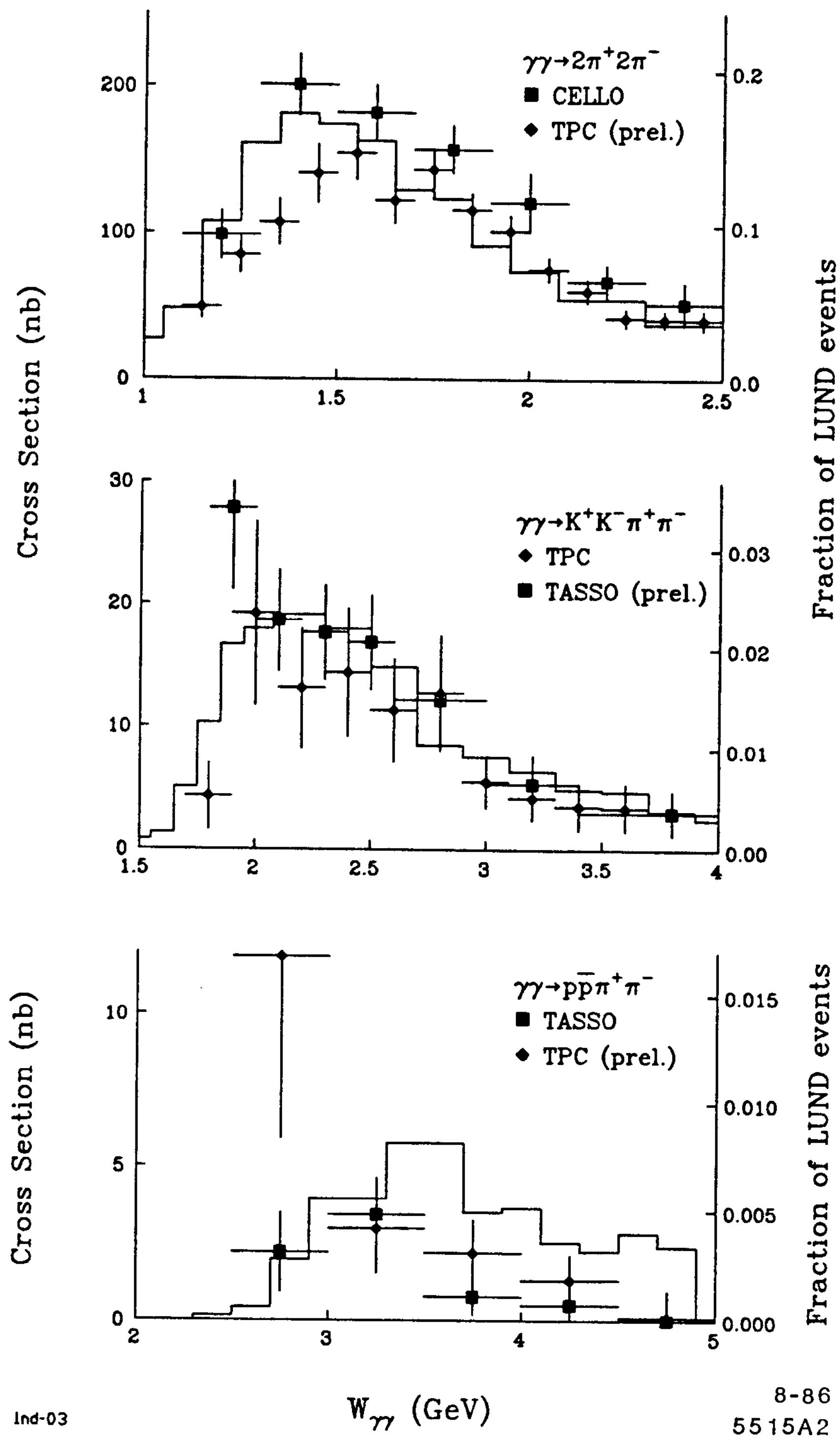
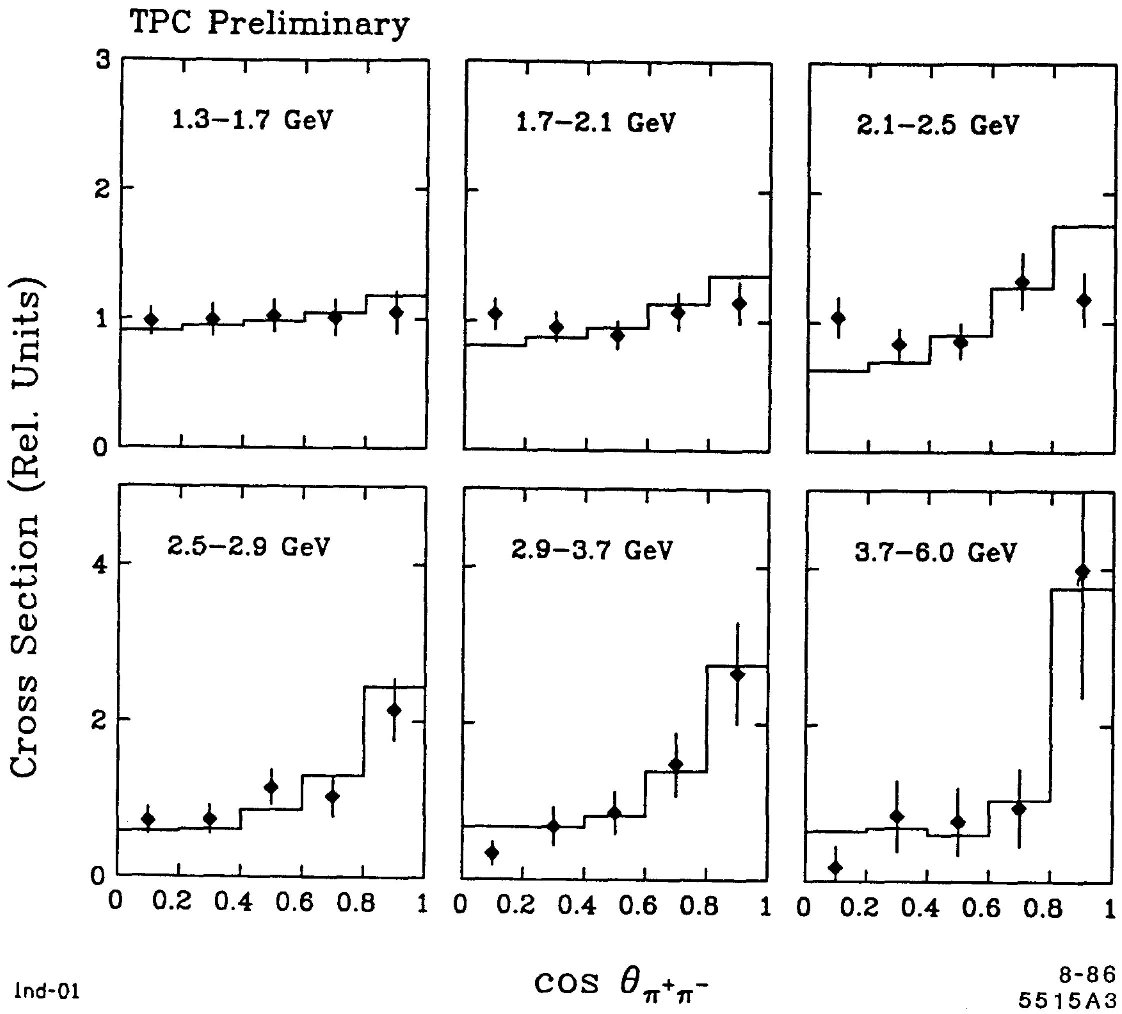


Fig. 1



γγ→2π⁺2π⁻
CELLO
TPC (prel.)
γγ→K⁺K⁻π⁺π⁻
TPC
TASSO (prel.)
γγ→pp̄π⁺π⁻
TASSO
TPC (prel.)
Cross Section (nb)
Fraction of LUND events
W_γγ (GeV)
Ind-03
8-86
5515A2

Fig. 2



TPC Preliminary
1.3–1.7 GeV
1.7–2.1 GeV
2.1–2.5 GeV
2.5–2.9 GeV
2.9–3.7 GeV
3.7–6.0 GeV
Cross Section (Rel. Units)
3
2
1
0
4
2
0
0 0.2 0.4 0.6 0.8 1
0 0.2 0.4 0.6 0.8 1
0 0.2 0.4 0.6 0.8 1
Ind-01
cos $\theta_{\pi^+\pi^-}$
8-86
5515A3

Fig. 3