Measurements of the Cross Section for the Process $\gamma\gamma \rightarrow p\bar{p}$ at $\sqrt{s_{ee}} = 183 - 189$ GeV with the OPAL Detector at LEP

Teresa Barillari, MPI Munich  Photon 2003, Frascati  10 April 2003

- Introduction
- Kinematics
- Theory
- Event selection for $\gamma\gamma \rightarrow p\bar{p}$ events
- Data analysis and results
- Conclusions
Introduction

- OPAL paper “Measurement of the Cross-Section for the Process $\gamma\gamma \rightarrow p\bar{p}$ at $\sqrt{s_{ee}} = 183 - 189$ GeV at LEP” accepted for publication in Eur. Phys. J. C
  - see: G. Abbiendi et al., hep-ex/0209052

- Work motivated by the quark-diquark model to test non pQCD calculations

- Three quark model yields cross-sections about one order of magnitude smaller than the experimental results for $W > 2.5$ GeV
Kinematics

\[ e^+ e^- \rightarrow e^+ e^- \gamma\gamma \rightarrow e^+ e^- X \]

\[ Q_i^2 \approx 2E_i E_i' (1 - \cos \theta_i) \]

\[ Q_i^2 = (q_i^2 - w_i^2) \]

\( \gamma\gamma \) center-of-mass system (CMS)

\( W_{\gamma\gamma} \), invariant mass in the \( \gamma\gamma \) CMS

\( \theta^* \), polar angle in the \( \gamma\gamma \) CMS

- “Untagged \( \gamma\gamma \) events”: both scattered electrons go undetected
- The final state \( X \) has small \( p_\perp \) and low mass
- The \( \gamma\gamma \) CMS is boosted along the beam axis, the produced particles are close to the beam direction and they are almost back-to-back in x-y

Detection and trigger efficiencies limited
**Hard scattering picture (HSP)**

In pQCD (or HSP) an exclusive process: \( A + B \rightarrow C + D \)

is described by the exclusive hadronic amplitude

\[
\mathcal{M} = \frac{1}{\mathcal{Z}} \int T_H(x_j, p_\perp) \prod_{H_i} \left( \phi_{H_i}(x_j, \tilde{p}_\perp) \delta(1 - \sum_{k=1}^{n_i} x_k) \prod_{j=1}^{n_i} d x_j \right)
\]

- \( \mathcal{M} \) separates: “short-range” from “long-range” phenomena
- \( \phi_{H_i} \): Parton distribution amplitude (DA) for each hadron in the process
- \( T_H \): Hard scattering amplitude

\( \mathcal{M} \) has “two” phenomenological consequences

- The dimensional counting rules:
  \[
  \mathcal{M} \approx \frac{1}{(p_\perp^2)^{(n-4)/2}} f(\theta_{c.m.})
  \]
  with \( \frac{d\sigma(\gamma\gamma \rightarrow p\bar{p})}{dt} \sim s^{-6} \)

- The hadron helicity conservation rules:
  \[
  \lambda_A + \lambda_B = \lambda_C + \lambda_D
  \]

Hadron helicity conservation rules not in agreement with data

**References**

Quark-diquark model

There are applications of the quark-diquark model to the reactions:
$$\gamma\gamma \rightarrow B\bar{B}$$
where $$B = p, \Lambda, \Xi^-, \text{etc.},$$


Diquarks modify the dimensional counting rules by decreasing $$n$$ and can violate the hadron helicity conservation rules.

▷ For the power law, we have now:
$$\frac{d\sigma(\gamma\gamma \rightarrow p\bar{p})}{dt} \sim s^{-4}$$

Recent contribution in studying annihilation of $$\gamma\gamma \rightarrow B\bar{B}$$ processes comes from: “Handbag Mechanism”

see: M. Diehl, P. Kroll, C. Vogt, hep-ph/0206288 (2002);
The OPAL detector at LEP

Hadron calorimeters and return yoke
Electromagnetic calorimeters
Muon detectors
Jet chamber
Vertex chamber
Microvertex detector
Z chambers
Forward detector
Silicon tungsten luminometer
Presampler
Time of flight detector
Solenoid and pressure vessel
The $e^+e^- \rightarrow e^+e^-\gamma\gamma \rightarrow e^+e^-p\bar{p}$ events

A typical $\gamma\gamma \rightarrow p\bar{p}$ event selected with the **OPAL** detector at LEP2.
**Event selection**

- **Applied cuts**
  - Number of hits in CJ $> 20$
  - 2 tracks with $Q_{\text{Tot}} = 0$
  - $|d_0| < 1.0$
  - $|\cos \theta| < 0.75$
  - $p_\perp > 0.4 \text{GeV}$
  - $|\cos \theta^*| < 0.6$
  - **Trigger Conditions**
    - $|\sum \vec{p}_\perp|^2 < 0.04 \text{GeV}^2$
    - $dE/dx$ to eliminate background
    - $W > 2.15 \text{ GeV}$

- 163 $\gamma\gamma \rightarrow p\bar{p}$ events remained after the selection
- No events with acoplanarity more than 0.262 rad
- $W = 2.15 - 3.95 \text{ GeV}$

$\sim 500 p\bar{p}$ events at LEP2 (data from 1997 to 2000)

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Cross section measurements

- The $e^+e^- \rightarrow e^+e^-p\bar{p}$ differential cross section is given by:

\[
\frac{d\sigma(e^+e^- \rightarrow e^+e^-p\bar{p})}{dW \, d|\cos \theta^*|} = \frac{N_{ev}(W,|\cos \theta^*|)}{L_{e^+e^-} \, \varepsilon_{TRIG} \, \varepsilon_{DET}(W,|\cos \theta^*|) \, \Delta W \, \Delta|\cos \theta^*|}
\]

\(L_{e^+e^-} = \) Measured integr. luminosity = 249.10±0.22±0.43 pb\(^{-1}\)

- The total cross section $\sigma(\gamma\gamma \rightarrow p\bar{p})$ is given by:

\[
\sigma(\gamma\gamma \rightarrow p\bar{p}) = \frac{d\sigma(e^+e^- \rightarrow e^+e^-p\bar{p})}{dW} \sqrt{\frac{dL_{\gamma\gamma}}{dW}}
\]

\(dL_{\gamma\gamma}/dW = \text{GALUGA } \gamma\gamma \text{ luminosity function}


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### Invariant mass, efficiencies, and systematics

#### Source of Systematic uncertainties

<table>
<thead>
<tr>
<th>Source of Systematic uncertainties</th>
<th>Systematic uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity Function</td>
<td>5.0</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td>5.0</td>
</tr>
<tr>
<td>Monte Carlo statistics (W &lt; 2.55,\text{GeV})</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>(W &gt; 2.55,\text{GeV})</td>
</tr>
<tr>
<td>(dE/dx) cuts (W &lt; 2.55,\text{GeV})</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>(W &gt; 2.55,\text{GeV})</td>
</tr>
<tr>
<td>Residual Background</td>
<td>6.0</td>
</tr>
<tr>
<td>Total (W &lt; 2.55,\text{GeV})</td>
<td>10.3</td>
</tr>
<tr>
<td>Total (W &gt; 2.55,\text{GeV})</td>
<td>12.1</td>
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</table>
OPAL cross section measurements

<table>
<thead>
<tr>
<th>$W$ range (GeV)</th>
<th>$\langle W \rangle$ (GeV)</th>
<th>Events</th>
<th>$\sigma(\gamma\gamma \rightarrow p\bar{p})$ (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.15-2.25</td>
<td>2.20</td>
<td>52</td>
<td>$2.69 \pm 0.39 \pm 0.28$</td>
</tr>
<tr>
<td>2.25-2.35</td>
<td>2.30</td>
<td>33</td>
<td>$1.53 \pm 0.27 \pm 0.16$</td>
</tr>
<tr>
<td>2.35-2.45</td>
<td>2.40</td>
<td>32</td>
<td>$1.39 \pm 0.26 \pm 0.14$</td>
</tr>
<tr>
<td>2.45-2.55</td>
<td>2.50</td>
<td>20</td>
<td>$0.96 \pm 0.22 \pm 0.10$</td>
</tr>
<tr>
<td>2.55-2.75</td>
<td>2.65</td>
<td>18</td>
<td>$0.62 \pm 0.22 \pm 0.08$</td>
</tr>
<tr>
<td>2.75-2.95</td>
<td>2.85</td>
<td>6</td>
<td>$0.19 \pm 0.11 \pm 0.02$</td>
</tr>
<tr>
<td>2.95-3.45</td>
<td>3.14</td>
<td>1</td>
<td>$0.05^{+0.11}_{-0.04} \pm 0.01$</td>
</tr>
<tr>
<td>3.45-3.95</td>
<td>3.64</td>
<td>1</td>
<td>$0.05^{+0.11}_{-0.04} \pm 0.01$</td>
</tr>
</tbody>
</table>

- Good agreement between our results and the quark-diquark model predictions
- Power law compared to the data with $\sigma(\gamma\gamma \rightarrow p\bar{p}) \approx -W^{-2(n-3)}$ for three values of $n$. For data with $W > 2.5\text{GeV}$ we obtain $n = 9 \pm 2$
Existing $\gamma\gamma \rightarrow p\bar{p}$ cross section measurements

<table>
<thead>
<tr>
<th>e$^+e^-$ Experiments</th>
<th>$E_{\text{Beam}}$ (GeV)</th>
<th>Integrated Luminosity (pb$^{-1}$)</th>
<th>$W$ (GeV)</th>
<th>Number of $p\bar{p}$ events</th>
</tr>
</thead>
<tbody>
<tr>
<td>TASSO (DESY) 1982</td>
<td>15 - 18.3</td>
<td>19.685</td>
<td>2.0 - 2.6</td>
<td>8</td>
</tr>
<tr>
<td>TASSO (DESY) 1983</td>
<td>17</td>
<td>74</td>
<td>2.0 - 3.1</td>
<td>72</td>
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<tr>
<td>JADE (DESY) 1986</td>
<td>17.4 - 21.9</td>
<td>59.3 + 24.2</td>
<td>2.0 - 2.6</td>
<td>41</td>
</tr>
<tr>
<td>TPC/2$\gamma$ (SLAC)</td>
<td>14.5</td>
<td>75</td>
<td>2.0 - 2.8</td>
<td>50</td>
</tr>
<tr>
<td>ARGUS (DESY) 1989</td>
<td>4.5 - 5.3</td>
<td>234</td>
<td>2.6 - 3.0</td>
<td>60</td>
</tr>
<tr>
<td>CLEO (CESR) 1994</td>
<td>5.29</td>
<td>1310</td>
<td>2.0 - 3.25</td>
<td>484</td>
</tr>
<tr>
<td>VENUS (TRISTAN) 1997</td>
<td>57 - 64</td>
<td>331</td>
<td>2.2 - 3.3</td>
<td>311</td>
</tr>
<tr>
<td>OPAL (LEP) 2003</td>
<td>91.5 - 94.5</td>
<td>249</td>
<td>2.15 - 3.95</td>
<td>163</td>
</tr>
</tbody>
</table>
Comparison with other experiments

- Agreement between the **OPAL** and the other experiments results for $W > 2.3$ GeV
Comparisons with the **OPAL**, CLEO, VENUS and TASSO measurements
Angular dependence of the cross section

QED angular distribution for massless and pointlike fermions

\[ \frac{d\sigma(\gamma\gamma \rightarrow p\overline{p})}{d|\cos \theta|} \propto \frac{1 + \cos^2 \theta}{1 - \cos^2 \theta} \]

- At high $W$, the pointlike $p$ approximation agrees with the data, the diquark and the pure quark model curves.
- At low $W$, pointlike $p$ approximation not valid anymore.

More experimental investigation needed
Conclusions

OPAL published results for $\gamma\gamma \rightarrow p\bar{p}$ cross-section measurements

- Range covered: $2.15 \text{ GeV} < W < 3.95 \text{ GeV}$ and $|\cos \theta^*| < 0.6$
- our $\sigma(\gamma\gamma \rightarrow p\bar{p})$ measurements are in agreement with:
  - The other experimental results for $W > 2.3 \text{ GeV}$
  - The quark-diquark model predictions

- The QCD power law fit yields an exponent $n = 7.5 \pm 0.8$ with statistical uncertainty only. More data needed to distinguish the proton seen as a state of three quarks or as a state of quark-diquark system.

- The shape of $d\sigma(\gamma\gamma \rightarrow p\bar{p})/d|\cos \theta|$ agrees with the other experiments results in comparable $W$ range

- At low $W$ values the $d\sigma(\gamma\gamma \rightarrow p\bar{p})/d|\cos \theta|$ does not agree with the models. More investigation are needed in this region of $W$

This is the first $\gamma\gamma \rightarrow p\bar{p}$ cross section measurement performed at LEP