Measurement of the photon structure function $F_2^\gamma (x,Q^2)$ with the LUMI detector at L3

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• Introduction
• Data and Monte Carlo
• Event selection
• Binning
• Unfolding
• Differential cross sections
• $x$ and $Q^2$ dependence of $F_2^\gamma$
• Conclusion and outlook
Analysis goal

• Measure the photon structure function $F_2^\gamma(x,Q^2)$ from the measured differential cross section $\Delta\sigma(e^+e^-\rightarrow e^+e^-\text{hadrons})$

• Centre-of-mass energies:
  \[ \sqrt{s} = 189 - 206 \text{ GeV} \]

• Tagging detector: Luminosity Monitors (LUMI)

• LUMI $Q^2$ range
  
  1998 (189 GeV): 11-34 GeV$^2$
  1999 (194 GeV): 11-37 GeV$^2$
  (200 GeV): 11-38 GeV$^2$
  2000 (206 GeV): 11-40 GeV$^2$

• Compare results with other experiments and theoretical predictions
Single-tag analysis of the $e^+e^-\rightarrow e^+e^-$ hadrons deep inelastic scattering reaction:

- One of the scattered electrons detected (tagged) in LUMI; second electron undetected (scattering angle small, $P^2 \approx 0$)
- Quasy-real target photon probed by the highly virtual photon ($Q^2 >> 0$)
Variables

\[ q_i = (E_{\gamma_i}^*, \vec{p}_{\gamma_i}^*) \quad (i = 1, 2) \]
\[ q_i^2 = E_{\gamma_i}^* - p_{\gamma_i}^2 \]

for single-tagged hadron production:

\[
\begin{aligned}
-q_1^2 &= Q_1^2 = Q^2 > 0 \\
-q_2^2 &= Q_2^2 \approx 0 = P^2
\end{aligned}
\]

mass squared of the outgoing interacting fermion:

\[
k^2 = (xq_2 + q_1)^2 = q_1^2 + 2xq_1 \cdot q_2 \approx 0
\]

\[
\Rightarrow \quad x = -\frac{q_1^2}{2q_1 \cdot q_2} = \frac{Q^2}{2q_1 \cdot q_2} \quad \text{x: Bjorken variable}
\]

Single-tag variables:

\[
Q^2 = -q^2 \approx 2E_{\text{tag}}E_{\text{beam}}(1 - \cos \theta_{\text{tag}})
\]

\[
x = \frac{Q^2}{(Q^2 + W^2 + P^2)} = \frac{Q^2}{2(p \cdot q)}
\]

\[
W = (q_1 + q_2)^2 = (E_{\gamma} + E_{\gamma})^2 - (\vec{q} + \vec{p})^2
\]

\[
q_1 \quad (E_{\gamma}^*, q), \quad q_2 = (E_{\gamma}, p)
\]

For single tagged events: \( P \neq 0 \)

\[
x = \frac{Q^2}{Q^2 + W^2}
\]
**Goal:** measure the cross section for the single-tagged $\gamma^*\gamma$ process to extract the photon structure function $F_2^\gamma (x, Q^2)$

\[
\frac{d\sigma_{e(k)\gamma^*(q)\rightarrow e_{\text{tag}}(k')X}(x, Q^2)}{dx\, dx\, Q^2} = \frac{2\pi \alpha^2}{x\, Q^4} [(1 + (1 - y)^2)] F_2^\gamma (x, Q^2) - y^2 F_L^\gamma (x, Q^2)
\]

\[
y = (p \cdot q)/(p \cdot K) \approx 1 - \left(\frac{E_{\text{tag}}}{E_{\text{beam}}}\right) \cdot \cos^2 (\theta_{\text{tag}}), y \approx 0
\]

**Main Processes contributing to the** $e^+e^- \rightarrow e^+e^-\gamma^*\gamma$

$\rightarrow e^+e^- + \text{hadrons cross section}$

**VDM**

**Direct process (QPM)**

**Single Resolved**
Analysis Method

1. Selection
2. Binning
3. Unfolding
   
   Energy of the target photon is not known: correction with MC (PYTHIA, PHOJET, TWOGAM) 
   BAYES unfolding method

4. Calculate measured cross section
   
   \[
   \frac{N_{\text{unfolded}} - N_{\text{background}}}{L \cdot \text{acceptance} \cdot \text{trigger efficiency}}
   \]

5. Divide measured cross section with analytically calculated cross section 
   [Galuga] to obtain $F_{2\gamma}$

Error calculation

Statistical error (absolute) 
Systematic error: difference between the results obtained with PHOJET, PYTHIA and TWOGAM (systematical error from data selection and unfolding is negligible compared to the systematical error obtained from the unfolding with MC’s ) 
Total error: quadratic sum of the statistical and systematic error

M.N.Kienzle-Focacci

L3-General Meeting, Nov.17, 2003
Selections

1. LUMI tag
   at least one cluster in LUMI with
   
   • Polar angle
     \[ 0.0325 \text{ (rad)} \leq \theta \leq 0.0637 \text{ (rad)} \]
   
   • Energy of the cluster reconstructed as an electromagnetic shower
     \[ E_{\text{clus}} > 0.7 E_{\text{beam}} \]
   
   • Raw energy of the cluster
     \[ E_{\text{raw}} > 0.8 E_{\text{clus}} \]

2. Hadrons in final state
   number of tracks in TEC and photons in ECAL
   \[ N_{\text{tracks}} + N_{\gamma} \geq 6 \]

3. Reject \( e^+ e^- \rightarrow q\bar{q}\gamma \) background
   \[ E_{\text{ECAL+HCAL}} < 0.4\sqrt{s} \]

4. Anti-tag
   for clusters in LUMI opposite to the tag
   \[ E_{\text{clus}}^{\text{opp}} < 0.45 E_{\text{beam}} \]

5. Exclude low masses
   \[ W_{\text{vis}} \geq 5 \text{ GeV} \]
### Data sets and Monte Carlo

<table>
<thead>
<tr>
<th></th>
<th>E(_{\text{beam}})(GeV)</th>
<th>L(pb(^{-1}))</th>
<th>N(_{\text{selected}})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1998</td>
<td>94.3</td>
<td>171.8</td>
<td>6628</td>
</tr>
<tr>
<td>1999a</td>
<td>97.3</td>
<td>111.4</td>
<td>4220</td>
</tr>
<tr>
<td>1999b</td>
<td>100.0</td>
<td>90.1</td>
<td>3095</td>
</tr>
<tr>
<td>2000</td>
<td>103.1</td>
<td>210.5</td>
<td>7990</td>
</tr>
</tbody>
</table>

|     |                     |                |                          |
| **Monte Carlo** |                     |                |                          |
| PHOJET | 94.5 | 2807.4          | 54073                  |
|        | 97.8 | 1817.4          | 33603                  |
|        | 99.8 | 1818.1          | 33341                  |
|        | 102.0| 1754.3          | 33380                  |
| PYTHIA | 94.5 | 318.2           | 21223                  |
|        | 98.7 | 456.4           | 26169                  |
|        | 103  | 453.3           | 28570                  |
| TWOGAM | 94.5 | 5489.1          | 81127                  |
| (QCD+QPM+VDM)| 97.8 | 4264.4          | 61265                  |
|           | 99.8 | 4390.4          | 62067                  |
|           | 102.0| 5298.5          | 73949                  |

|     |                     |                |                          |
| **Background MC** |                     |                |                          |
| \(\gamma^*\gamma^*\rightarrow\tau\tau\) | 94.5 | 1022.7          | 1057                    |
|                         | 98.0 | 224.7           | 211                     |
|                         | 102  | 1100.0          | 1148                    |
| \(Z\gamma\rightarrow qq\gamma\) | 94.3 | 1960.7          | 381                     |
|                         | 97.8 | 1123.5          | 200                     |
|                         | 99.8 | 1141.5          | 210                     |
|                         | 103.3| 11318.4         | 396                     |
SELECTIONS: CUT 2–5 for 1998

![Graphs showing distributions of events with different cuts.](image-url)
Ratio data and MC for $Q^2$, YEAR 1998

- Compare data and Pythia
- MC norm. to nr. of data events

- Compare data and PHOJET

- Compare data and TOWGAM
Ratio data and MC for $W_{vis}$ selected, YEAR 1998

MC norm. to nr. of data events

compare data and pythia

compare data and phojet

compare data and twogam
Ratio data and MC for $x_{vis}$ selected, YEAR 1998

- **Data vs. Pythia**
  - Compare data and pythia
  - MC norm. to nr. of data events

- **Data vs. PHOJET**
  - Compare data and PHOJET

- **Data vs. TwoGOM**
  - Compare data and TwoGOM

$x_{vis}$ selected
Binning

For the $x$ dependence of $\Delta \sigma / \Delta x$, and $F_2^\gamma / \alpha$:

<table>
<thead>
<tr>
<th>Nr. $x$ bins</th>
<th>$\Delta x$</th>
<th>$&lt;x&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01 - 0.035</td>
<td>0.022</td>
</tr>
<tr>
<td>2</td>
<td>0.035 - 0.060</td>
<td>0.047</td>
</tr>
<tr>
<td>3</td>
<td>0.060 - 0.085</td>
<td>0.071</td>
</tr>
<tr>
<td>4</td>
<td>0.085 - 0.110</td>
<td>0.097</td>
</tr>
<tr>
<td>5</td>
<td>0.110 - 0.160</td>
<td>0.13</td>
</tr>
<tr>
<td>6</td>
<td>0.160 - 0.210</td>
<td>0.18</td>
</tr>
<tr>
<td>7</td>
<td>0.210 - 0.260</td>
<td>0.23</td>
</tr>
<tr>
<td>8</td>
<td>0.260 - 0.310</td>
<td>0.28</td>
</tr>
<tr>
<td>9</td>
<td>0.310 - 0.385</td>
<td>0.34</td>
</tr>
<tr>
<td>10</td>
<td>0.385 - 0.510</td>
<td>0.43</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nr. $Q^2$ bins</th>
<th>$\Delta Q^2 [\text{GeV}^2]$</th>
<th>$&lt;Q^2&gt; [\text{GeV}^2]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11-14</td>
<td>12.4</td>
</tr>
<tr>
<td>2</td>
<td>14-20</td>
<td>16.6</td>
</tr>
<tr>
<td>3</td>
<td>20-28</td>
<td>23.6</td>
</tr>
<tr>
<td>4</td>
<td>28-34</td>
<td>30.8</td>
</tr>
</tbody>
</table>

$\Delta Q^2 [\text{GeV}^2]$ | $<Q^2^2> [\text{GeV}^2]$ |
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>0-0.01</td>
<td>0.0007</td>
</tr>
</tbody>
</table>

For the $Q^2$ dependence of $\Delta \sigma / \Delta Q^2$ (*), and $F_2^\gamma / \alpha$:

<table>
<thead>
<tr>
<th>Nr. $x$ Bins</th>
<th>$\Delta x$</th>
<th>$&lt;x&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01-0.1</td>
<td>0.050</td>
</tr>
<tr>
<td>2</td>
<td>0.1-0.2</td>
<td>0.144</td>
</tr>
<tr>
<td>3</td>
<td>0.2-0.3</td>
<td>0.248</td>
</tr>
<tr>
<td>4</td>
<td>0.3-0.5</td>
<td>0.322</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nr. $Q^2$ bins</th>
<th>$\Delta Q^2 [\text{GeV}^2]$</th>
<th>$&lt;Q^2&gt; [\text{GeV}^2]$</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>11-14</td>
<td>12.4</td>
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<td>16.6</td>
</tr>
<tr>
<td>3</td>
<td>20-34</td>
<td>23.6</td>
</tr>
</tbody>
</table>

* under investigation
PHOJET 1998, $Q^2 = 11 - 34 \text{ GeV}^2$, before unfolding
PYTHIA 1998, $Q^2 = 11-34$ GeV$^2$, before unfolding

Graphs showing $X_{VIS}$ vs $X_{GEN}$, $\sqrt{s}$ vs $W_{GEN}$, $Q^2_{\text{VIS}}$ vs $Q^2_{\text{GEN}}$, and $\sqrt{s}$ vs $W_{GEN}$.
TWOCHAM QPM 1998, $Q^2 = 11 - 34 \text{ GeV}^2$, before unfolding
compare xvis, unfolded, and final corrected data, Wcut 5 GeV, 1998
Acceptance = $N_{\text{GEN accepted}} / N_{\text{GEN}}$, Wcut 5 GeV, 1998

PYTHIA

PHOJET

TWOGAM
x dependence of $\Delta \sigma/\Delta x$, YEAR 1998

L3 189 GeV

- data (Phojet)
- data (Pythia)
- data (Twogam)

with stat. error

L3 189 GeV

- data (Phojet)
- data (Pythia)
- data (Twogam)

with sys. error
$x$ dependence of $\Delta \sigma/\Delta x$, YEARS 1998–2000

L3 (Phojet)

- data 189 GeV
- data 194 GeV
- data 200 GeV
- data 206 GeV

with stat. error

L3 (Phojet)

- data 189 GeV
- data 194 GeV
- data 200 GeV
- data 206 GeV

with sys. error
Measurement of $F_2^\gamma$ using GALUGA

(Version 2.0, Author: G.A. Schuler, CERN)

GALUGA calculates total $e^+e^-$ cross section integrated over

$$W_{\text{min}} < W < W_{\text{max}} \quad \text{and} \quad Q^2_{\text{min}} < Q^2 < Q^2_{\text{max}}$$

_model: ρ-pole (Regge theory)_

Reaction:

$$e^+(p_a) + e^-(p_b) \rightarrow e^+(p_1) + X(p_X) + e^-(p_2)$$

The two photon process:

$$\gamma(q_1) + \gamma(q_2) \rightarrow X(p_X)$$

The $\gamma\gamma$ c.m. energy:

$$W^2 = p_X^2$$

The photon virtualities:

$$-Q_1^2 = t_1 = q_1^2 \equiv (p_a - p_1)^2$$

$$-Q_2^2 = t_2 = q_2^2 \equiv (p_b - p_2)^2$$

_Total cross section:

$$\sigma_{ab}(W^2, Q_1^2) = h_a(Q_1^2) h_b(Q_2^2) \sigma_{\gamma\gamma}(W^2)$$

_for ρ-pole:

$$\sigma_{\gamma\gamma} = 1$$

for real photon:

$$h_a(Q^2) = \left( \frac{m_\rho^2}{m_\rho^2 + Q^2} \right)^2$$

for virtual photon:

$$h_b(Q^2) = \frac{\xi Q^2}{m_\rho^2} \left( \frac{m_\rho^2}{m_\rho^2 + Q^2} \right)^2$$

Obtain $F_2^\gamma/\alpha$:

$$F_2^\gamma / \alpha = \frac{\Delta \sigma_{\text{meas}}(e^+e^- \rightarrow e^+e^- X)}{\Delta \sigma_{\text{Galu}}(e^+e^- \rightarrow e^+e^- X)}$$
Integration limits (x dependence):

<table>
<thead>
<tr>
<th>YEAR</th>
<th>$W_{\text{min}}$ [GeV]</th>
<th>$W_{\text{max}}$ [GeV]</th>
<th>$Q^2_{\text{min}}$ [GeV$^2$]</th>
<th>$Q^2_{\text{max}}$ [GeV$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>5</td>
<td>189</td>
<td>11</td>
<td>34</td>
</tr>
<tr>
<td>1999a</td>
<td>5</td>
<td>194</td>
<td>11</td>
<td>34</td>
</tr>
<tr>
<td>1999b</td>
<td>5</td>
<td>200</td>
<td>11</td>
<td>34</td>
</tr>
<tr>
<td>2000</td>
<td>5</td>
<td>206</td>
<td>11</td>
<td>34</td>
</tr>
</tbody>
</table>

Integration limits ($Q^2$ dependence):

<table>
<thead>
<tr>
<th>YEAR</th>
<th>$W_{\text{min}}$ [GeV]</th>
<th>$W_{\text{max}}$ [GeV]</th>
<th>$Q^2_{\text{min}}$ [GeV$^2$]</th>
<th>$Q^2_{\text{max}}$ [GeV$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>5</td>
<td>189</td>
<td>11 14</td>
<td>14 20</td>
</tr>
<tr>
<td>1999a</td>
<td>5</td>
<td>194</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>1999b</td>
<td>5</td>
<td>200</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>2000</td>
<td>5</td>
<td>206</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

* to be analyzed
x dependence of $F_2(x,\langle Q^2 \rangle)/\alpha$, YEAR 1998

- Red circle: L3 data (PHOJET) 189 GeV, $\langle Q^2 \rangle = 18.4$ GeV$^2$, stat. err.
- Green square: L3 data (PYTHIA)
- Blue triangle: L3 data (TWOQAM)
$x$ dependence of $F_2^7(x, <Q^2>/\alpha$). YEARS: 1998–2000

- L3 (PHOJET) 189 GeV, $<Q^2>=18.23$ GeV², stat.err
- L3 (PHOJET) 194 GeV, $<Q^2>=18.47$ GeV²
- L3 (PHOJET) 200 GeV, $<Q^2>=18.41$ GeV²
- L3 (PHOJET) 206 GeV, $<Q^2>=18.63$ GeV²
$Q^2$ dependence of $F_2^\gamma/\alpha$. YEAR 1998

For $x=0.01-0.1$

- L3 (PHOJET) 189 GeV, $\langle Q^2 \rangle = 12.44, 16.75, 25.30$ GeV$^2$, stat. error
- L3 (PHOJET) 183 GeV

For $x=0.1-0.2$

For $x=0.2-0.3$

For $x=0.3-0.5$
$Q^2$ dependence of $F_2^\gamma/\alpha$. YEAR 1998

$x=0.01-0.1$

- L3 (PHOJET) 189 GeV, $<Q^2> = 12.44, 16.75, 25.30$ GeV$^2$, sys. error
- L3 (PHOJET) 183 GeV

$x=0.1-0.2$

$x=0.2-0.3$

$x=0.3-0.5$
Conclusions and outlook

- Used Binning similar to other measurements by L3, OPAL, ALEPH experiments.
- Used unfolding to correct for detector effects and acceptance. Data unfolded with PYTHIA, PHOJET, and TWOGAM: good agreement.
- Calculated measured cross section and analyzed x dependence. Q^2 dependence: under investigation.
- Obtain F_{2\gamma}/\alpha using GALUGA. Evolution of F_{2\gamma}/\alpha with x analyzed and compared to ALEPH and OPAL: good agreement.
- Evolution of F_{2\gamma}/\alpha with Q^2 analyzed and compared to L3 (183 GeV) measurements: good agreement. The x range 0.1-0.6 should be included to be able to compare to other experiments: OPAL, ALEPH.
- Decide how to calculate systematic error (consider error from MODEL separately?)
- Comparison with different parameterizations not decided yet