QCD Measurements in Two-Photon Collisions at LEP

Ákos Csilling
University College London

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- Total hadronic cross-section
- Heavy quark production (charm + beauty)
- Dijet production (untagged + tagged)
- Inclusive hadron production ($\pi^0, K^0_S$)
- Photon structure function (low $x$, high $Q^2$, charm)
- Double-tag cross-section
The reaction $e e \rightarrow ee f \bar{f}$

$$d^6\sigma = \frac{d^6p_1' d^3p_2'}{E_1' E_2'} \frac{\alpha^2}{16\pi^4 q^2 p^2} \left[ \frac{(q \cdot p)^2 - q^2p^2}{(p_1 \cdot p_2)^2 - m_e^2 m_e^2} \right]^{1/2} \cdot$$

$$\left( 4\rho_1^{++} \rho_2^{++} \sigma_{TT} + 2\rho_1^{++} \rho_2^{00} \sigma_{TL} + 2\rho_1^{00} \rho_2^{++} \sigma_{LT} + \rho_1^{00} \rho_2^{00} \sigma_{LL} + 2|\rho_1^{+-} \rho_2^{++}|\tau_{TT} \cos 2\phi - 8|\rho_1^{+-} \rho_2^{0+}|\tau_{TL} \cos \phi \right)$$

$$Q^2 = 2 E_b E_{\text{tag}} (1 - \cos \theta_{\text{tag}})$$

$$P^2 = 2 E_b E_{\text{stag}} (1 - \cos \theta_{\text{stag}})$$

$$x = \frac{Q^2}{Q^2 + W^2 + P^2}$$
Physical Photon:

bare $\gamma$ + $g^0, \omega, \phi$...

$q, \bar{q}, g, (e^\pm)$

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a) Direct

b) VDM

c) Double Resolved

d) Single Resolved
Hadronic Final State

- Good separation from annihilation events
- Low invariant mass or tagged electron(s)
- Longitudinal imbalance

Figure 2: $W_{vis}$ distributions for the data at $<\sqrt{s_{ee}}>=192$ GeV and for the simulated $\gamma\gamma \rightarrow$ hadrons, $e^+e^- \rightarrow Z^0\gamma$ and $e^+e^- \rightarrow W^+W^-$ events at $\sqrt{s_{ee}}=200$ GeV
Visible hadronic invariant mass

- Reasonable MC description
- Undetected particles ⇒ need unfolding (limited acceptance)

- Diffraction, quasi-elastic component uncertain
Figure 3: a) The measured hadronic mass $W_{\text{vis}}$. The backgrounds due to $e^+e^-$-annihilation and $e^+e^- \rightarrow e^+e^- \tau\tau$ are indicated as a shaded area. b) The unfolding of the data from $W_{\text{vis}}$ to $W_{\gamma\gamma}$. c) Ratio of selected over generated events as a function of the two-photon mass, as calculated by the two generators PHOJET and PYTHIA. d) The cross section $d\sigma(e^+e^- \rightarrow e^+e^- \text{ hadrons})/dW_{\gamma\gamma}$ measured at various beam energies, $91 \text{ GeV} \leq \sqrt{s} \leq 202 \text{ GeV}$. The statistical and systematic errors are added in quadrature.
Total hadronic cross-section $\sigma(\gamma\gamma \rightarrow \text{hadrons})$

Figure 4: a) The data of 1998 at $\sqrt{s} = 189$ GeV are compared to the data of 1999 at $\sqrt{s} = 192 - 202$ GeV. b) The two-photon total cross section obtained by correcting the full data sample with PHOJET (stars) and with PYTHIA (open points). The Regge fits described in the text (Table 3) are superimposed to the data. The continuous lines are fits with the coefficient $c$ left as a free parameter, the dashed line is the fit with $c$ fixed to 0.095.
Figure 5: The two-photon total cross section compared to various models. a) Predictions of the minijet model [22] and of the Dual Parton Model [5]. b) The calculation of G. Schuler and T. Sjöstrand [24] for the best estimation (full line), for the VDM contribution (dashed line) and for a maximum QCD contribution (dotted line). c) Predictions of the Additive Quark Model [28] and the Impact Picture model [29]. d) The predictions of the Additive Quark Model [28] and of [27] are compared to all two-photon total cross section data. The statistical and full systematic errors are added in quadrature.

- Many models describe the data
- L3 and OPAL agree on data
Diffractive component - mostly unseen

- No direct measurement
- Significant impact on $\Gamma_{\text{tot}}$
- Different event properties, smaller det. effic
Diffractive $\sigma^{0}$ production

- Quasi-elastic VDM $\sigma\sigma \rightarrow \sigma^{0}\sigma^{0} \rightarrow 4\pi$
- Diffractive dissociation $\sigma\sigma \rightarrow \sigma^{0}X$

\[\sigma\sigma \rightarrow 4\pi\]

\[\sigma\sigma \rightarrow \sigma^{0}\sigma^{0}\]

**Phojet**

\[E_{\text{vis}}(\text{GeV})\]

**Phojet reasonable**

\[\sigma\sigma \rightarrow \sigma^{0}X\]

diffractive

**Pythia too flat**

**Phojet not present**
Inclusive charm production

$M_c \approx 1.5 \text{ GeV}$: Large scale: perturbative QCD

Direct:

Sensitive: $M_c$

Resolved:

Sensitive: gluon content

$D^* \rightarrow D^0 \pi_{\text{slow}}$ or Lepton tag

A clear electron signal of the semileptonic charm decays is observed
\[ D^* \text{ tag:} \]
\[ D^*_\pm \rightarrow D^0 \pi^\pm_{\text{slow}} \]

\[ M(D^*) - M(D^0) \approx M(\pi) \]

- Small phase-space \[ \Rightarrow \text{low background} \]

**Figure 2:** Combined mass difference distribution for \( D^0 \) decay channels \( K^-\pi^+ \) and \( K^-\pi^+\pi^0 \). The points are data and the line is the result of the fit used to evaluate the \( D^{**} \) signal.
$D^0 \rightarrow K^- \pi^+$
$K^- \pi^+ \pi^0$
$K^- \pi^+ \pi^- \pi^+$
Also $D^0, D^+, \Lambda_c$ production measured by DELPHI
Figure 1: Mass difference $\Delta M \equiv M_{D^0}^{\text{cand}} - M_{D^0}^{\text{cand}}$ for both decay modes for the anti-tagged and tagged sample. In both samples, a clear peak is visible around $\Delta M \equiv M_{D^+} - M_{D^0} = 145.4$ MeV. The result of a fit of the background function $f(\Delta M) = a \cdot (\Delta M - m_{\pi})^b$ to the upper sidebands is superimposed. The fit regions are $\Delta M > 160.5$ MeV for the anti-tagged events and $\Delta M > 154.5$ MeV for the tagged events. The open histograms represent the corresponding wrong-charge background samples which give a good description of the combinatorial background.
Direct / Resolved contributions

About 50:50 Direct / Resolved
(no double-resolved)
Direct/Resolved: about 50:50

\[ x^\pm_\sigma = \frac{\sum_{\text{jets}} (E \pm p)}{\sum_{\text{hadrons}} (E \pm p)} \]

\[ x^\min_\sigma = \min (x^{+}_\sigma, x^{-}_\sigma) \]

2-jet events only

ALEPH preliminary

Figure 3: \( x^\min_\gamma \) distribution for reconstructed di-jet events containing a D\( ^{**+} \). The crosses show data. Contributions of the two MC samples considered are fitted to data with the relative fraction as a fit parameter. The direct part is given by the open histogram, the single resolved one by the hatched histogram.
Direct, Resolved contributions: about 50:50 %, no 2-resolved (also consistent with 2:1 ratio)

Efficiency and extrapolation depend on this ratio

![Histogram](image)

**Figure 2:** $p^D_\text{T}/W_{\text{vis}}$ distribution for reconstructed $D^{*+}$ events. The crosses show data. Contributions of the two MC samples considered are fitted to data with the relative fraction as a fit parameter. The *direct* part is given by the open histogram, the *single resolved* one by the hatched histogram.
$D^*$ production, differential cross-section

L3 and OPAL agree with massless calculation, with massive only above 3 GeV. ALEPH has different slope.

\begin{itemize}
  \item ALEPH, $\sqrt{s}=183-189$ GeV (prel.)
  \item OPAL, $\sqrt{s}=183-189$ GeV
  \item L3, $\sqrt{s}=189$ GeV
  \item $|\eta^{D^*}| < 1.5$, $e^+ e^- \rightarrow e^+ e^- D^* X$
\end{itemize}

NLO (massless, Binnewies et al.)

- GRV, $m_c = 1.5$ GeV
- $\mu_R = \mu_F/2 = \xi m_T$
  \begin{itemize}
    \item GRV
    \item AFG
    \item GS
  \end{itemize}

- $f(c \rightarrow D^*) = 0.267$
  \begin{itemize}
    \item $\varepsilon_c = 0.116$
  \end{itemize}

NLO (massive, Frixione et al.)

- GRS, $\mu_F = 2m_T$, $f(c \rightarrow D^*) = 0.270$, $\varepsilon_c = 0.035$
  \begin{itemize}
    \item upper: $m_c = 1.2$ GeV, $\mu_R = 2m_T \text{(dir)}, m_T / 2 \text{(res)}$
    \item lower: $m_c = 1.8$ GeV, $\mu_R = m_T / 2 \text{(dir)}, 2m_T \text{(res)}$
  \end{itemize}
Charm cross-section vs. $W_{\gamma\gamma}$
- electron tag
- $W_{\gamma\gamma}$ unfolded
- Steeper rise than in total xsection

Figure 7: The cross section $\gamma\gamma \rightarrow c\bar{c}$ as function of $W_{\gamma\gamma}$ at $\sqrt{s} = 189 - 202$ GeV. The continuous line is the Regge fit, with fixed value of $\eta$ as described in the text. The unfolding is done with PYTHIA Monte Carlo. The dashed curve shows the expectation from the PYTHIA model. The dotted curve is the total cross section $\sigma(\gamma\gamma \rightarrow \text{hadrons})$ measured by L3 scaled by an arbitrary factor 1/20.
Bottom production:
  use lepton tag, 
  \( P_T (\text{electron}) \) with respect to closest jet
  subtract other contributions:
  \( \rightarrow \) depends on charm measurement

Figure 5: The distribution of the transverse momentum, \( P_T \), of the electron candidate with respect to the closest jet.
Bottom production in ...

- Subtract charm and uds (MC)
- More than expected

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Figure 6: The distribution of the transverse momentum, $P_t$, of the muon candidate with respect to the closest jet.
Charm and Beauty production

Inclusive cross-section
charm: good agreement.
bottom: much larger than predicted.

largest error from extrapolation to unseen phase-space region
Inclusive Dijet Production

- At least 2 jets (\(K_T\) clustering)
- \(E_T\) or \(p_T\): Hard scale
- NLO calculations (Klasen et al.)
- Gluon content of photon tested in resolved proc.
  \(q \neq 1\) for direct
  \(q = 1\) for hard
  Whether \(q \neq 1\) for \(p_T\)

\[
X_\pm^2 = \frac{\sum_\text{jets} (E^\pm p_x)}{\sum_\text{hadrons} (E^\pm p_x)}
\]

- Tagged measurements: \(\langle R \rangle \approx 1 \pm 2\%\)
Inclusive Dijet Production
At least 2 jets, highest $p_T$ jet plotted.

**ALEPH Preliminary**
Good agreement w. ALC

Figure 4: $d\sigma/dp_T$ for di-jet events in $\gamma\gamma$ collisions. The points are data corrected back to hadron level. The inner error bars are the statistical error, the outer ones are the total error. The histogram is the parton level prediction obtained from the program provided by M.Klasen.
2-jet events, untagged, \( \frac{d\Gamma}{dE_T} \)

**Figure 5:** The \( \bar{E}_T^{\text{jet}} \) distribution in the data in comparison to the sum of signal and background processes in the simulation. The statistical error is shown where larger than the marker size. The label \( \gamma^*\gamma \) stands for simulated photon-photon collision events in which one of the photons has a virtuality larger than 4.5 GeV\(^2\) as defined in Section 6. MH is short for the multi-hadron final states of \( Z^0 \)-decays.
Good agreement with NLO and MC

Figure 11: The di-jet cross-section as a function of the mean transverse energy $\bar{E}^\text{jet}_T$ of the di-jet system. The total of statistical and systematic uncertainties added in quadrature is shown where larger than the marker size. Predictions of the LO programs PHOJET and PYTHIA and an NLO calculation by Klasen et al. [27] are compared with the data.
\[ X^\pm = \frac{\sum_{\text{jets}} (E + P_z)}{\sum_{\text{hadrons}} (E + P_z)} \]

Figure 14: The di-jet cross-section as a function of \( x_\gamma \) and \( \log_{10}(x_\gamma) \) for the regions of the mean transverse energy \( E_T^{\text{jet}} \) of the di-jet system indicated in the figures. The total of statistical and systematic uncertainties added in quadrature is shown where larger than the marker size. Predictions of the LO program PHOJET are shown for three different parton density functions. PDFs with large gluon content disfavored.
Perturbative NLO QCD calculation was good for $E_T$.

NLO (Klasen et al.)

Figure 15: The di-jet cross-section as a function of $x_\gamma$ and $\log_{10}(x_\gamma)$ for the regions of the mean transverse energy $\overline{E}_T^{jet}$ of the di-jet system indicated in the figures. The total of statistical and systematic uncertainties added in quadrature is shown where larger than the marker size. Predictions of an NLO calculation by Klasen et al. [27] are compared with the data.
Dijet cross-section in \( z < 0 \) side

- Good agreement with Herwig
- No agreement with JetVip (NLO QCD)
Inclusive $\pi^0$ production in $\sigma \sigma$

- complement charged hadron prod. data
- Avoid jet definition problems

Figure 1: The mass of the two photon state for $p_t > 0.2$ GeV and $|\eta| < 0.5$. The data are fitted with a gaussian for the signal and a Chebyshev polynomial parametrisation of the background.
Inclusive $\pi^0 \sim$ inclusive charged hadrons

$W\gamma > 10$ GeV
- L3 $\pi^0$ prelim.
- OPAL $h^\pm$

$\frac{d\sigma}{dp_T} [pb/GeV]$ vs $p_T [GeV]$
Figure 3: The $d\sigma/dp_t$ cross-section for $|\eta| < 0.5$ fitted with an exponential in the low $p_t$ region. The inner bars represent statistical errors, the full bars statistical and systematic errors added in quadrature.
Figure 4: The \( \pi^0 \) differential cross-section, \( d\sigma/dp_T \), for \(|\eta| < 0.5\), compared, in the high \( p_T \) region, to NLO QCD predictions. The NLO calculations are given for the QCD scale equal to \( p_T \) (full line) and for the scales \( 0.5p_T \) (upper dashed line) and \( 2p_T \) (lower dashed line). The contribution of the direct process is indicated as a dashed dotted line. The inner bars on the data points represent statistical errors, the full bars statistical and systematic errors added in quadrature.
Inclusive $K_S^0$ production

- Similar results

Figure 8: The measured differential cross section as a function of $p_t$ for $|\eta| < 1.5$ is compared to OPAL data. The line corresponds to the exponential fit performed in the interval $0.4 < p_t < 2$ GeV.
Inclusive $K^0$ production

Figure 12: The measured differential cross section as a function of $p_t$ for $|\eta| < 1.5$ is compared to the NLO QCD predictions by B.A. Kniehl. The solid line corresponds to the scale factor (see text) $x = 1$ while the upper dotted line to $x = 0.5$ and the lower dotted line to $x = 2$. The dash-dotted line corresponds to the direct contribution where the distortion at 3 GeV is due to the threshold for charm production.
The formalism for deep inelastic electron-photon scattering

\[ 2x F_1^\gamma = \frac{-q^2}{4\pi^2\alpha} \frac{\sqrt{(q \cdot p)^2 - q^2p^2}}{q \cdot p} \left( \sigma_{TT}(x, q^2, p^2) - \frac{1}{2} \sigma_{TL}(x, q^2, p^2) \right) \]

\[ F_2^\gamma = \frac{-q^2}{4\pi^2\alpha} \frac{q \cdot p}{\sqrt{(q \cdot p)^2 - q^2p^2}} \left( \sigma_{TT}(x, q^2, p^2) + \sigma_{LT}(x, q^2, p^2) \right) \]

\[ F_L^\gamma = F_2^\gamma - 2xF_1^\gamma \]

\[ \frac{d^4\sigma_{ee\to ee\bar{e}}}{dx \, dQ^2 \, d\bar{z} \, dP^2} = \frac{d^2N_\gamma}{d\bar{z}dP^2} \cdot \frac{2\pi\alpha^2}{x \, Q^4} \cdot \left[ (1 + (1 - y)^2) F_2^\gamma(x, Q^2, P^2) \right. \]

\[ \left. - y^2 F_L^\gamma(x, Q^2, P^2) \right] \]
Unfolding $W_{vis} \rightarrow W_{TRUE}$

- Incoming photon energy unknown $\Rightarrow$ need $W$.
- Limited acceptance: $W_{vis} < W_{TRUE}$

Figure 12: Tests of the unfolding procedure using the LEP1 SW low $Q^2$ data unfolded with the HERWIG 5.9+$k_t$(dyn) Monte Carlo sample. (a) Comparison of the results using GURU, RUN and BAYES. (b) Different degrees of freedom for one dimensional unfolding. (c) Different measured $x$ variables for one dimensional unfolding. (d) Different degrees of freedom for two dimensional unfolding using a random number as the second variable. The errors are statistical only.
Photon Structure Function at low $X$

- much reduced stat + syst. errors
- much lower $X$

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure20}
\caption{The measurement of $F_2^\gamma/\alpha$ using the LEP1 SW sample, for $\langle Q^2 \rangle$ values of (a) 1.9 and (b) 3.7 GeV$^2$. Also shown are the results from L3 \cite{18}, PLUTO \cite{10}, and TPC/2$\gamma$ \cite{13}. For L3 the two sets of points were unfolded using different Monte Carlo programs. The lower / upper points correspond to PHOJET 1.05 / TWOGAM. For each point, the inner error bars show the statistical error and the full error bars show the total error. The positions of the new OPAL points are as given in Table 6. The other points with closed symbols are shown at the centre of the $\log(x)$ bin, and those with open symbols are shown at the average $x$ value of the bin. The curves show the GRV LO, SaS1D, WHIT1 and QPM structure functions.}
\end{figure}
Photon structure function at low $x$

Much reduced errors

Figure 21: The measurement of $F_2^/$ using the LEP1 FD and LEP2 SW samples for $\langle Q^2 \rangle$ values of (a) 8.9 (10.7) and (b) 17.5 (17.8) GeV$^2$ for LEP1 (LEP2). Also shown is a selection of results from other experiments: ALEPH [19], DELPHI [17], L3 [18], PLUTO [10], and TOPAZ [15]. For each point, the inner error bars show the statistical error and the full error bars show the total error. The positions of the new OPAL points are as given in Table 6. The other points with closed symbols are shown at the centre of the log($x$) bin, and those with open symbols are shown at the average $x$ value of the bin. The curves show the GRV LO, SaS1D, WHIT1 and QPM structure functions.
Kinematic fit to improve $W$ resolution at large $Q^2$. Big improvement for 2-tag events.

Large $Q^2$: 40-500 GeV$^2$

$p^2$: 0-8 GeV$^2$

Figure 2: a) Correlation between the generated value of $W_{\gamma\gamma}$ and the measured value after the kinematic fit. In all cases the JAMVG Monte Carlo has been used. b) Correlation between the generated value of $x$ and the measured value after the kinematic fit. c) The hadronic mass resolution before and after the fit for single-tag events. d) The hadronic mass resolution before and after the fit for double-tag events.
Figure 7: a) The structure function $F_2^\gamma/\alpha$ for real photons at $Q^2 = 120 \text{ GeV}^2$ compared with the QPM calculation and the QCD calculations GRV, AGF and LRSN described in the text. b) Dependence on $Q^2$ of $F_2^\gamma/\alpha$ averaged over $x = 0.05 - 0.98$ for single-tag data, compared with the QPM indicated by a full line and with the LRSN calculation described in the text. The errors are statistical and systematic added in quadrature.
Effective structure function:

- $P^2$ dependence for 2-tag events

- $Q^2 \gg P^2$ Structure of the virtual photon

Figure 8: a) $F_{\text{eff}}^\gamma/\alpha$ for virtual photons at $Q^2 = 120$ GeV$^2$ and $P^2 = 3.7$ GeV$^2$, compared with the QPM calculation and the QCD calculation described in the text. The QCD calculation considers only transverse photons; therefore it is not really comparable with the double-tag data. b) Dependence on $P^2$ of $F_{\text{eff}}^\gamma/\alpha$ averaged over $x = 0.05 - 0.98$ for single-tag and double-tag data at $Q^2 = 120$ GeV$^2$, compared with the QPM prediction, indicated as a full line. The errors are statistical and systematic added in quadrature.
Figure 11: OPAL results for a) the deep inelastic electron-photon scattering cross-section \( \sigma(e^+e^- \rightarrow e^+e^-c\bar{c}) \), with 5 GeV\(^2\) < \( Q^2 \) < 100 GeV\(^2\) and b) for the charm structure function of the photon divided by the fine structure constant, \( F_{2,c}(x, \langle Q^2 \rangle)/\alpha \), for an average \( \langle Q^2 \rangle \) of 20 GeV\(^2\). The data points are obtained averaging the results obtained with the HERWIG and Vermaseren Monte Carlo models. The outer error bar is the total error and the inner error bar the statistical error. The \( x \) values of the data points are obtained by averaging the mean \( x \) values taken from the HERWIG and Vermaseren generators. The data are compared to the calculation of Laenen et al. [4] performed in LO and NLO. The band for the NLO calculation indicates the theoretical uncertainties assessed by varying the charm quark mass and renormalisation and factorisation scales. In a) the cross-section predictions of the Monte Carlo generators HERWIG and Vermaseren are also given. b) also shows the prediction of the GRS-LO parametrisation for the whole structure function at \( \langle Q^2 \rangle = 20 \) GeV\(^2\) and the point-like component alone.
Double-tag cross-section

\[ Q_1^2 \approx Q_2^2 \]

\[ \langle Q^2 \rangle = 15 \text{ GeV}^2 \]

Figure 6: a) The cross-section of \( e^+e^- \rightarrow e^+e^- \text{hadrons} \) as a function of \( Y \) in the kinematical region defined in the text at \( \sqrt{s} \approx 189-202 \text{ GeV} \) compared to our previous results \( \sqrt{s} \approx 183 \text{ GeV} \).
b) Comparison of the measured cross-sections corrected for acceptance using PHOJET(SET1) or TWOGAM(SET2). SET2 is shifted for better visibility. In both figures the predictions of PHOJET (continuous line) and of the QPM model GALUGA (dashed line) are indicated.
Figure 8: Two-photon cross sections, $\sigma_{\gamma\gamma\rightarrow}$, after the subtraction of the QPM contribution at $\sqrt{s} \approx 189 - 202$ GeV ($Q^2 = 15$ GeV$^2$). (top) The data are compared to the predictions of the LO BFKL calculation at saddle point approximation (eq.1) (solid line) with $K=1$ and $(\alpha_p - 1) = 0.58$ and of the one-gluon exchange diagram (dashed line). (bottom) The solid line is the fit to the data of the LO BFKL (eq.1) with $K=1$ and the coefficient $(\alpha_p - 1)$ as a free parameter. The dashed line is the fit with $(\alpha_p - 1) = 0.53$ and the scale factor $K$ as a free parameter.
Conclusions

- New and improved measurements to test QCD in photon-photon interactions
- Reasonable agreement with LO Monte Carlo models
- Good agreement with NLO QCD calculations
- Some open questions
- More data to analyse