Experimental Review of Photon Structure Function Data

Hamburg, May 12, 2009

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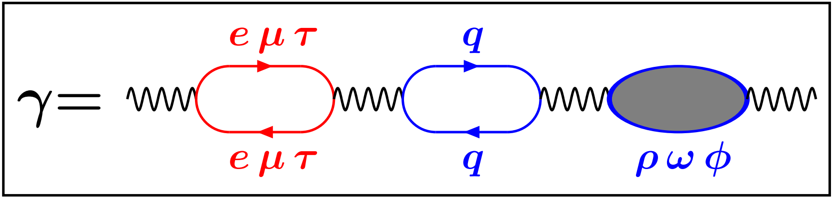
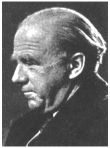
Why do we talk about photon structure?

— The structure of the photon ist a purely quantum mechanical effect.



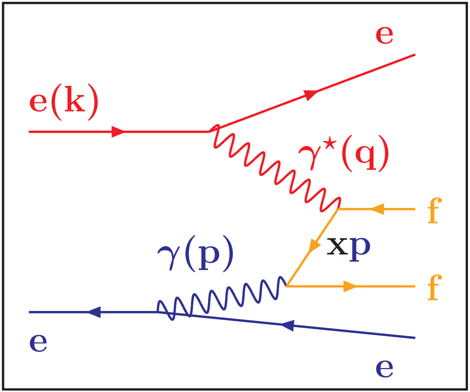
— Due to the Heisenberg uncertainty principle the photon may, for a short amount of time, fluctuate into a leptonic or hadronic state (with the same quantum numbers as the photon).

— The typical life time $\Delta\, t = 1/\Delta E$ of these states increases with the photon energy and decreases with the photon virtuality .



The photon structure is enriched for quasi-real, high energetic photons.

How do we measure photon structure functions?



Deep-inelastic Electron-Photon Scattering

$Q^2 = -q^2 \gg 0 \Rightarrow$ this electron is visible within the detector.

$$x = \frac{Q^2}{Q^2 + W^2}, \qquad y = \frac{\mathrm{pq}}{\mathrm{pk}}$$

$P^2 = -p^2 \approx 0 \Rightarrow$ this electron stays within the beam pipe.

— The differential cross-section:

$$\frac{d^2\sigma}{dx\,dQ^2} \approx k(x, y, Q^2) \cdot F_2^\gamma(x, Q^2, P^2)$$

The structure function F_2^γ parametrises the internal structure of the photon.

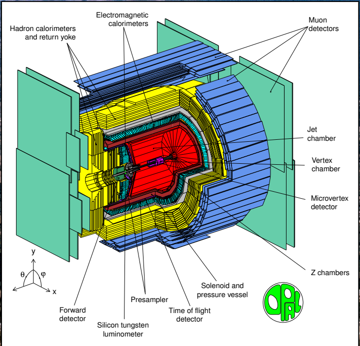
The 'history' of photon structure function measurements

Date	Event
1973	Investigation of two-photon processes in QPM by Walsh and Zerwas
1977	The LO asymptotic behavior of $F_2^\gamma \propto 1/\alpha_s$ was discovered by Witten
1979	Calculation of NLO corrections by Bardeen and Buras
1981	The first measurement of F_2^γ by PLUTO
1986	The first extraction of Λ from F_2^γ data
1990	Start of F_2^γ measurements at TRISTAN
1994	Start of F_2^γ measurements at LEP
2002	NLO extraction of α_s based on a large set of data by Albino et. al
2005	The final LEP2 results are being published
2011	First measurement of F_2^γ by Belle and Babar?
2018	First measurement of F_2^γ at a future Linear Collider?

A long traddition: Unfortunately the last two dates have to be changed from time to time.

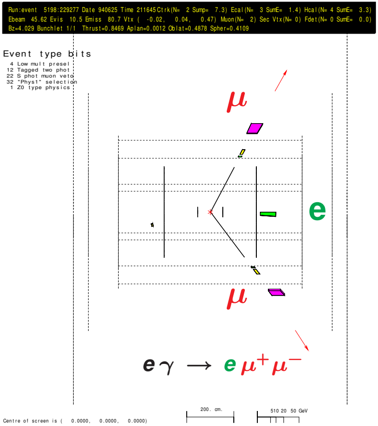
The Large Electron Positron Collider (1989 - 2000): $E_{\mathrm{cm}} = 90 - 209$ GeV

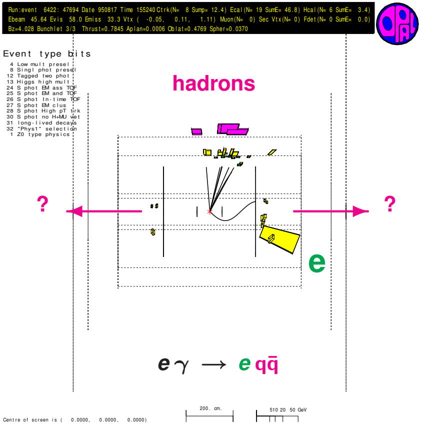
e$^-$
e$^+$



Data statistics:
160/pb at $E_{\mathrm{cm}} \approx 90$ GeV
700/pb at $E_{\mathrm{cm}} > 160$ GeV

Two typical events





— The scattered electron and the two muons are clearly visible.

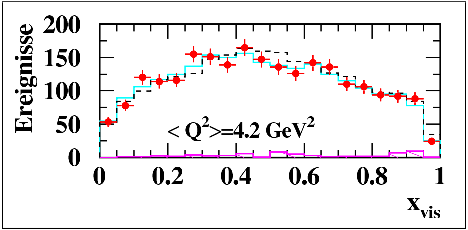
— Clean topology and good mass resolution.

— The scattered electron is clearly visible.

— The hadronic final state may partly disappear along the beam axis.

The hadronic final state is much harder to measure.

The unfolding of F_2^γ from the data



The task

— Deduce the underlying function f(x) from the measured distribution:
$g^{det}(x_{vis}, \mathrm{Da}) = \int A(x_{vis}, x)\, f(x)\, \mathrm{d}x + B(x_{vis})$

The solution

— Monte Carlo (MC) simulation of many events and unfolding of the distribution by:

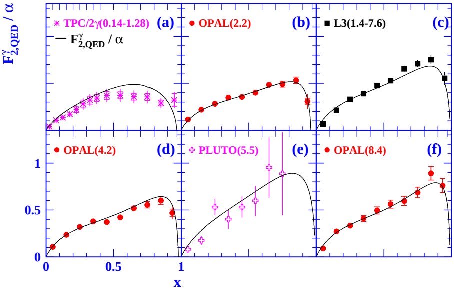
1) Simulation of many MC signal events based on some $\tilde{f}(x) \Rightarrow A(x_{vis}, x)$.
2) Simulation of many MC background events $\Rightarrow B(x_{vis})$.
3) Solve the integral $\longrightarrow$ matrix equation numerically (with regularisation), i.e. fit the $g^{det}(x_{vis},\mathrm{MC})$ to the data distribution $g^{det}(x_{vis},\mathrm{Da})$ by variation of $f(x) = \tilde{f}(x) \cdot c(x)$.

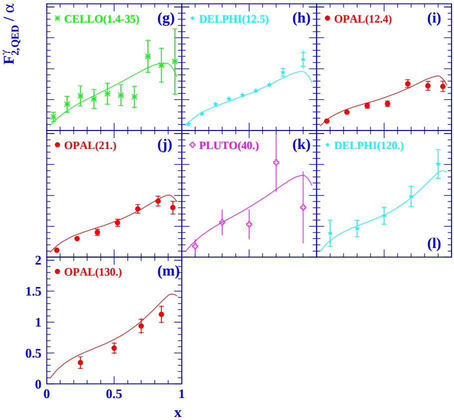
The result

— After the fit, the distribution $g^{det}(x_{vis},\mathrm{MC})$ and $g^{det}(x_{vis},\mathrm{Da})$ are identical within errors, this means the structure function is:

$$F_2^\gamma(x, \mathrm{Da}) = c(x) \cdot F_2^\gamma(x, \mathrm{MC})$$

The world data on $F_{2,\mathrm{QED}}^{\gamma}$



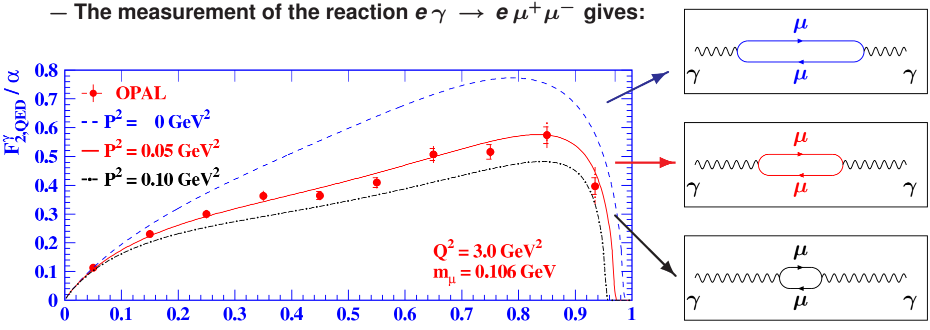


- The data covers the virtuality range $2 < \langle Q^2 \rangle < 130\ \mathrm{GeV}^2$.
- The precision is a few per cent.
- There is even more to come, see talk by K. Dehmelt.

The data on $F_{2,\mathrm{QED}}^{\gamma}$ span two orders of magnitude in Q^2 and are very precise.

The structure of virtual photons is suppressed

— The measurement of the reaction $e\gamma \rightarrow e\mu^+\mu^-$ gives:



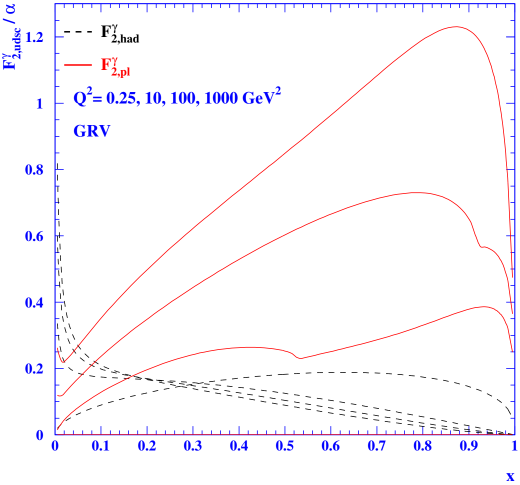
— For $P^2 = 0$ the photon is real and $F^{\gamma}_{2,\mathrm{QED}}$ is maximal.

— The Standard Model prediction is $P^2 = 0.05$ GeV^2.

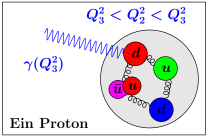
— For $P^2 \gg 0$ the photon is highly virtual and $F^{\gamma}_{2,\mathrm{QED}}$ ist reduced.

The suppresion of the photon structure for virtual photons is clearly seen in the data.

The hadronic structure of the photon

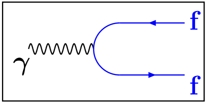


— The proton is a hadron.



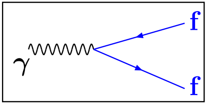
the structure depends on Q^2.

— The photon has a hadron-like



$\equiv$ proton

and a point-like

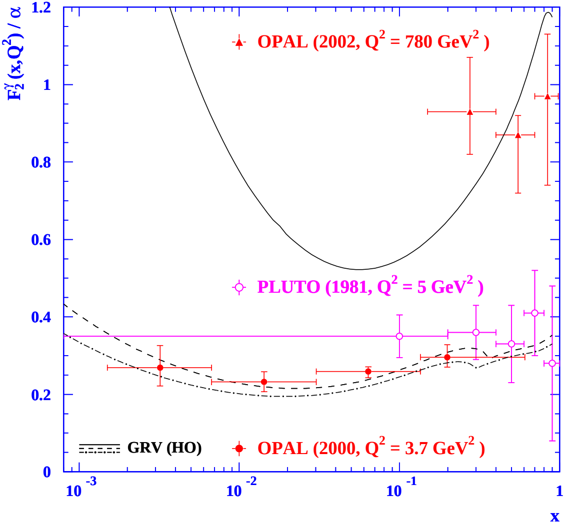


$\neq$ proton

component.

Due to the point-like component F_2^{γ} rises with Q^2 for all values of x.

What a difference 24 years make



Kinematical range covered

- About a factor 100 decrease in x
- About a factor 100 increase in Q^2

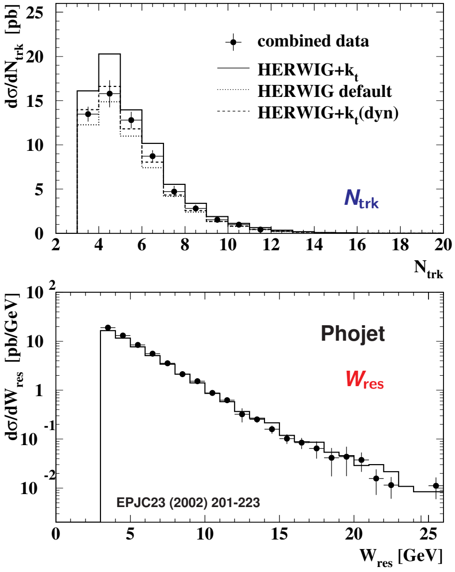
Analysis methods

- Multipurpose MC models
- Radiative corrections
- Sophisticated unfolding methods
- LEP combined effort
- About 50 measurements

⇓

Significantly smaller errors !?

The main problem when extracting F_2^γ



— The quality of the description of the hadronic final state by the Monte Carlo models is far from perfect.

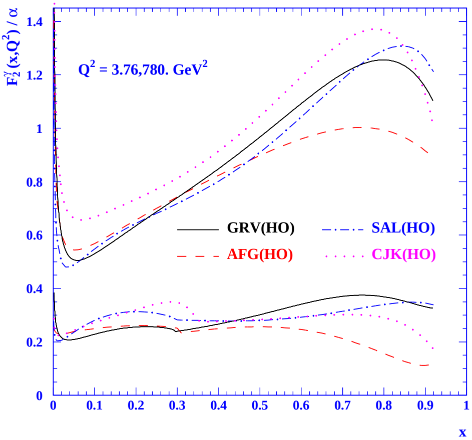
— However, the LEP data show consistent deviations for several observables.

— The combination of the LEP data by the LEP 2γ-WG results in smaller uncertainties for observables like:
1) the charged multiplicity N_{trk}
2) the observed invariant mass W_{res} in a restricted acceptance region

— This helps for adjustments of model parameters in collaboration with the authors of the Monte Carlo programs.

Still, for large parts of the phase space this is the main systematic uncertainty.

Some recent higher order F_2^γ parametrisations



The CJK(HO) parametrisation

— All F_2^γ data incl. TPC/2γ and DELPHI prel. (LEP1).

— $Q_0^2 = 0.765$ GeV^2, $\Lambda_4^{\overline{MS}} = 280$ MeV.

The AFG(HO) parametrisation

— LEP1 data at medium Q^2, incl. DELPHI prel.

— Massless $Q = c, b$, but m_Q^2/Q^2 corrections.

— $Q_0^2 = 0.7$ GeV^2, $\Lambda_4^{\overline{MS}} = 300$ MeV.

The SAL(HO) parametrisation

— All F_2^γ data besides TPC/2γ + ZEUS F_2^p at $x < 0.01$ + ZEUS dijet data.

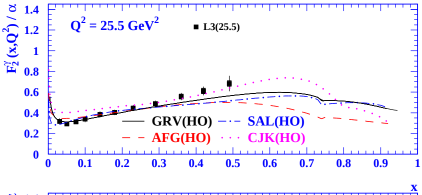
— Gribov facto.: $F_2^\gamma = \frac{\sigma_{\gamma p}(W)}{\sigma_{pp}(W)} \cdot F_2^p \approx 0.43 \cdot F_2^p$

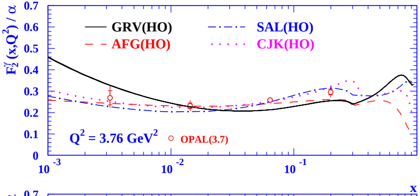
— $Q_0^2 = 2.0$ GeV^2, $\Lambda_4^{\overline{MS}} = 330$ MeV.

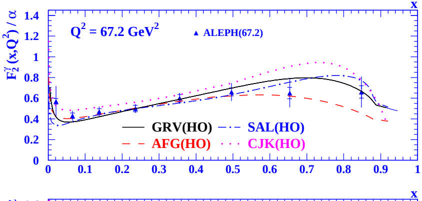
— All groups have problems fitting the DELPHI prel. data $\Rightarrow$ exclusion or error inflation.

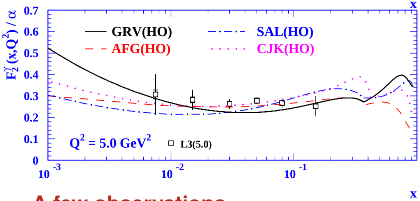
A number of new parametrisations with different theoretical assumptions are available.

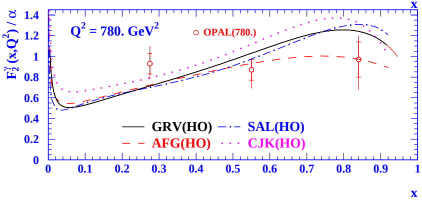
Recent parametrisations compared to F_2^γ data









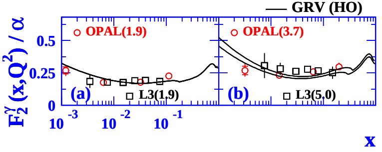


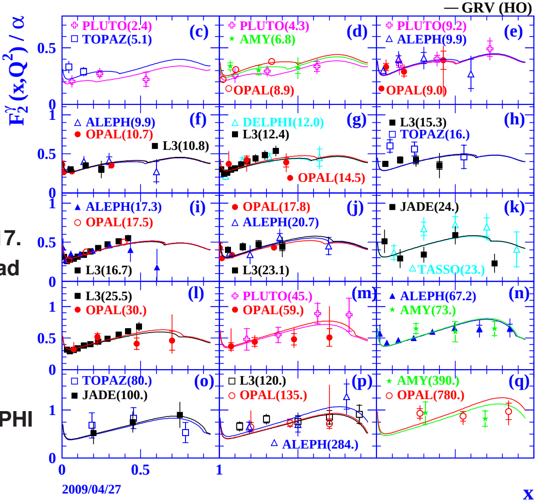
A few observations

- — The lowest Q^2 data is best described by AFG.
- — CJK seems too high at low-x wrt. L3 data.
- — At the highest Q^2 AFG fits the data best.

A complete survey would be needed to find the set that is preferred by the data.

The world data on $F_{2,\mathrm{had}}^{\gamma}$



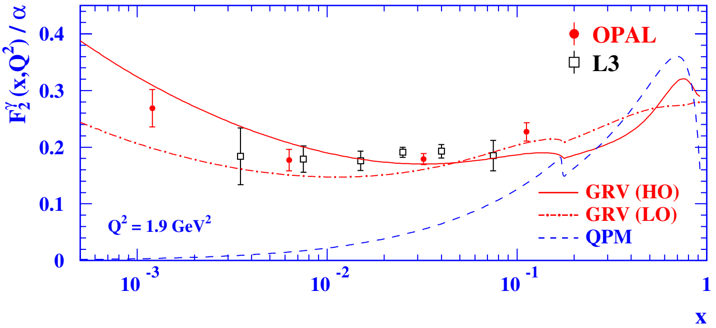


Some details on the selection of data

- Start from Phys.Rep. 332 (2000) 165-317.
- Drop the TPC/2γ results due to very bad χ^2 wrt. various F_2^γ parametrisations (see Tables 4+5) in Phys.Rep. 332.
- Add newly published results from ALEPH and L3.
- Drop the preliminary results from DELPHI which did not get published by now.

Many measurements. The precision is dominated by the results from LEP.

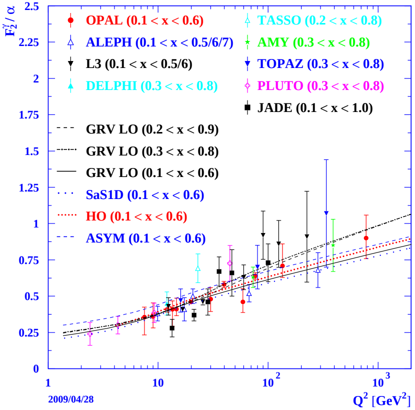
The measurements of F_2^γ at low x and Q^2



- The LEP data are consistent and determine F_2^γ to 5-20% precision.
- The expected rise of F_2^γ is still very moderate.
- The QPM predicion is much too low compared to the data.
- QCD expectations, e.g. the GRV parametrisation are able to account for the data.

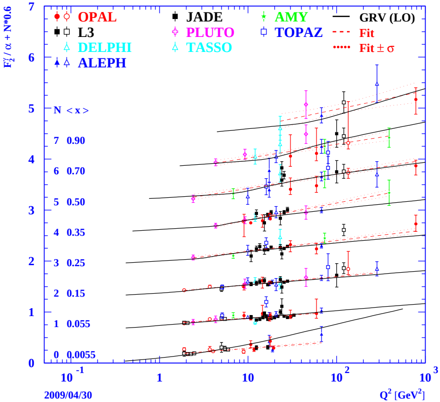
Unfortunately, the kinematical region is too small to test the low-*x* rise.

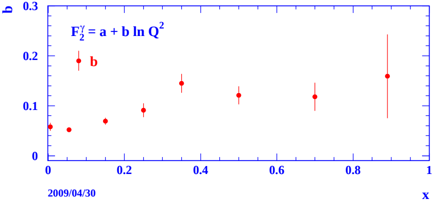
The Q^2 evolution of F_2^γ



— This comparison has to be made by carefully selecting the x range.

F_2^γ rises with Q^2 for all ranges of x.

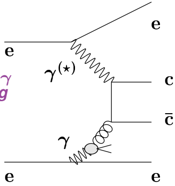




The $F_{2,c}^{\gamma}$ measurement

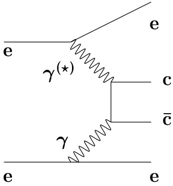
hadron-like:

- depends on f_g^{γ}
- low-x

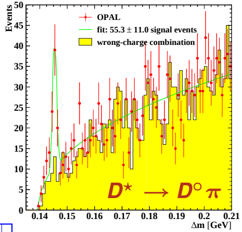


point-like:

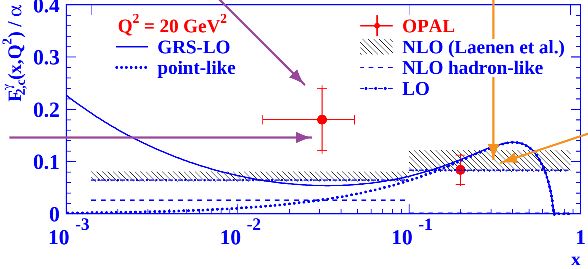
- pQCD
- high-x



Charm tagging



larger f_g^{γ} ?

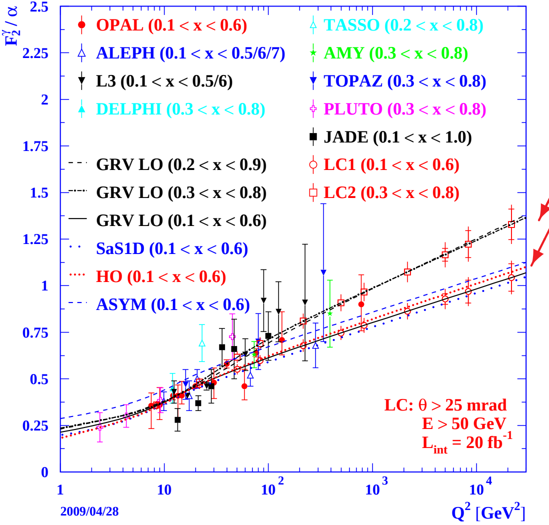


NLO = f(α_s,m_c) perfectly fits

PLB539 (2002) 13-24

This result is not yet conclusive. It needs ALEPH, DELPHI and L3 to confirm .

The future of F_2^γ measurements



The assumptions for the ILC Data

— e^+e^- collider at $\sqrt{s_{ee}} = 500$ GeV.

The two x-ranges studied

LC2: $0.3 < x < 0.8$
LC1: $0.1 < x < 0.6$

The extension of the measurement

— Sys. error = 0.5 OPAL(135 GeV^2).
— At the ILC the Q^2 range can be extended by about a factor of 40.
— At largest Q^2 this pQCD prediction gets most precise: $\Delta\alpha_s(M^2_{Z^0})_{\text{theo.}} \rightarrow \mathcal{O}(0.002)$.

The ILC will help to test this pQCD prediction.

Conclusions and Outlook

— The structure of the photon has been investigated in great detail by measurements of photon structure functions at e^+e^- collider.

— The QED structure shows the expected suppression with Q^2. Also azimuthal correlations and the presence of the interference terms have been observed (both not shown).

— The hadronic structure of the photon is richer than that of the proton due to the presence of both the point-like and the hadron-like components.

— The combined effort of the LEP experiments let to improvements in the description of the hadronic final state by Monte Carlo models.

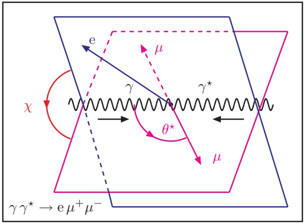
— The low-x reach of F_2^γ is limited. However the charm contribution to F_2^γ as well as the positive scaling violations of F_2^γ for all x have been clearly observed.

— A number of new parametrisations of F_2^γ with different theoretical preference have been obtained in the last years.

— The measurements of F_2^γ should be continued by Babar/Belle and also by the ILC.

I hope that F_2^γ measurements will be performed at present and future experiments.

Azimuthal correlations in muon-pair events



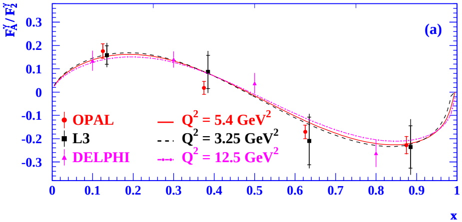
$$- \; d\sigma \propto 1 - \rho(y)\frac{F_A^\gamma}{F_2^\gamma}\cos\chi + \frac{1}{2}\epsilon(y)\frac{F_B^\gamma}{F_2^\gamma}\cos 2\chi$$

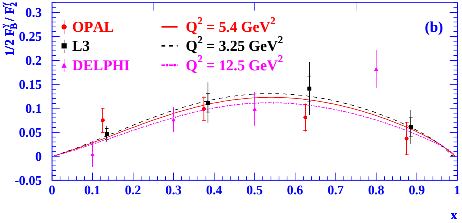
with: $\epsilon(y) = \frac{2(1-y)}{1+(1-y)^2} \approx 1$, and

$$\rho(y) = \frac{(2-y)\sqrt{1-y}}{1+(1-y)^2} \approx 1$$

The probed helicity structure

- F_A^γ transverse-longitudinal interference
- F_B^γ transverse-transverse interference





The χ dependence gives access to other structure functions besides F_2^γ.