Two photon results from LEP

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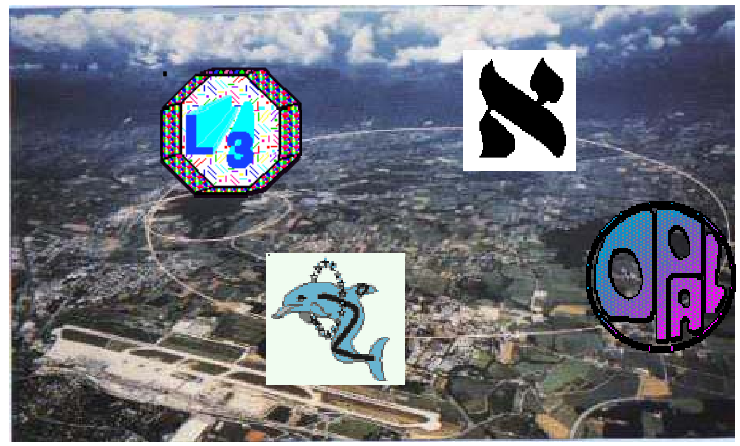
LEP: $e^+ e^-$ collisions at cms energies:

1989 – 1995: $\sqrt{s}$ = 91 GeV (LEP1)

1996 – 2000: $\sqrt{s}$ = 161 – 209 GeV (LEP2)

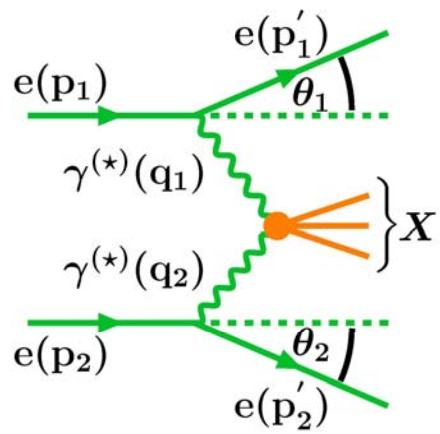
Experiments:

ALEPH, DELPHI, L3, OPAL



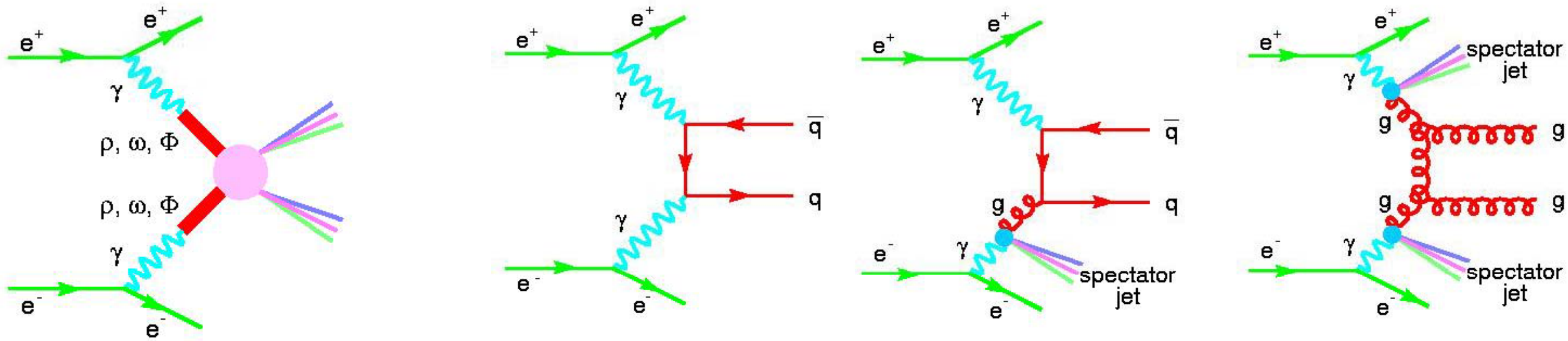
Study of two photon interactions through $e^+e^- \rightarrow e^+e^-\gamma^{(*)}\gamma^{(*)} \rightarrow e^+e^- X$

- Untagged ev. – total cross section, jets production, heavy quarks, exclusive particle production
- Single-tagged ev. – QED and hadronic structure functions of the quasi-real photon
- Double-tagged ev. – dynamics of highly virtual photon collisions



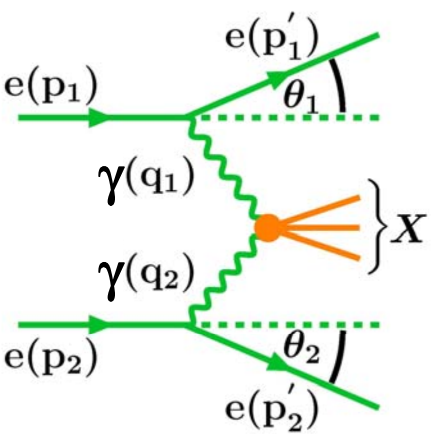
Total cross section for $\gamma\gamma \to$ hadrons

The following LO diagrams contribute to the proces $\gamma\gamma \to$ hadrons:



VMD	Direct	Single-resolved	Double-resolved

Kinematical variables for the process $\gamma\gamma \to$ hadrons:



$$s_{ee} = (p_1 + p_2)^2$$

$$Q_i^2 \equiv -q_i^2 = -(p_i - p_i')^2 \approx 2E_i' E_b (1 - \cos\theta_i)$$

$$Q^2 \equiv \max(Q_1^2, Q_2^2) \qquad P^2 \equiv \min(Q_1^2, Q_2^2)$$

$$W^2 \equiv W_{\gamma\gamma}^2 = (q_1 + q_2)^2 \approx \left(\sum_h E_h\right)^2 - \left(\sum_h \vec{p}_h\right)^2 = E_X^2 - \vec{p}_X^{\,2}$$

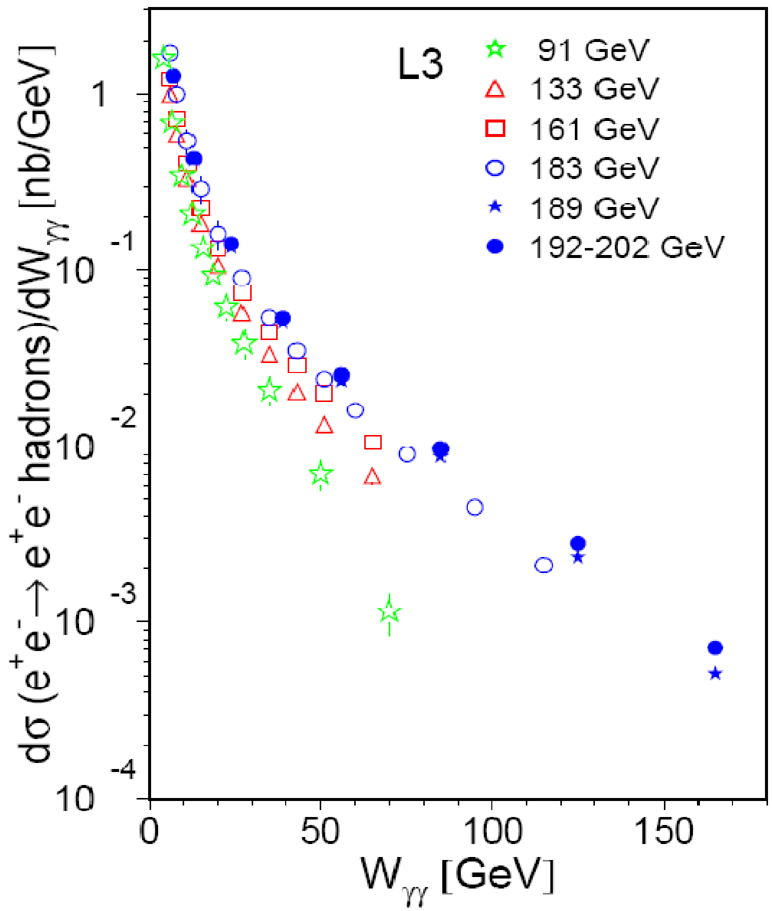
Total cross section for $\gamma\gamma \to$ hadrons

- photon-photon scattering has the largest hadronic cross section at LEP2 energies
- in the framework of Regge theory $\sigma_{\gamma\gamma}$ is related to $\sigma_{\gamma p}$ and $\mathbf{s}_{hh}$ and a slow rise with $W_{\gamma\gamma}$ is predicted

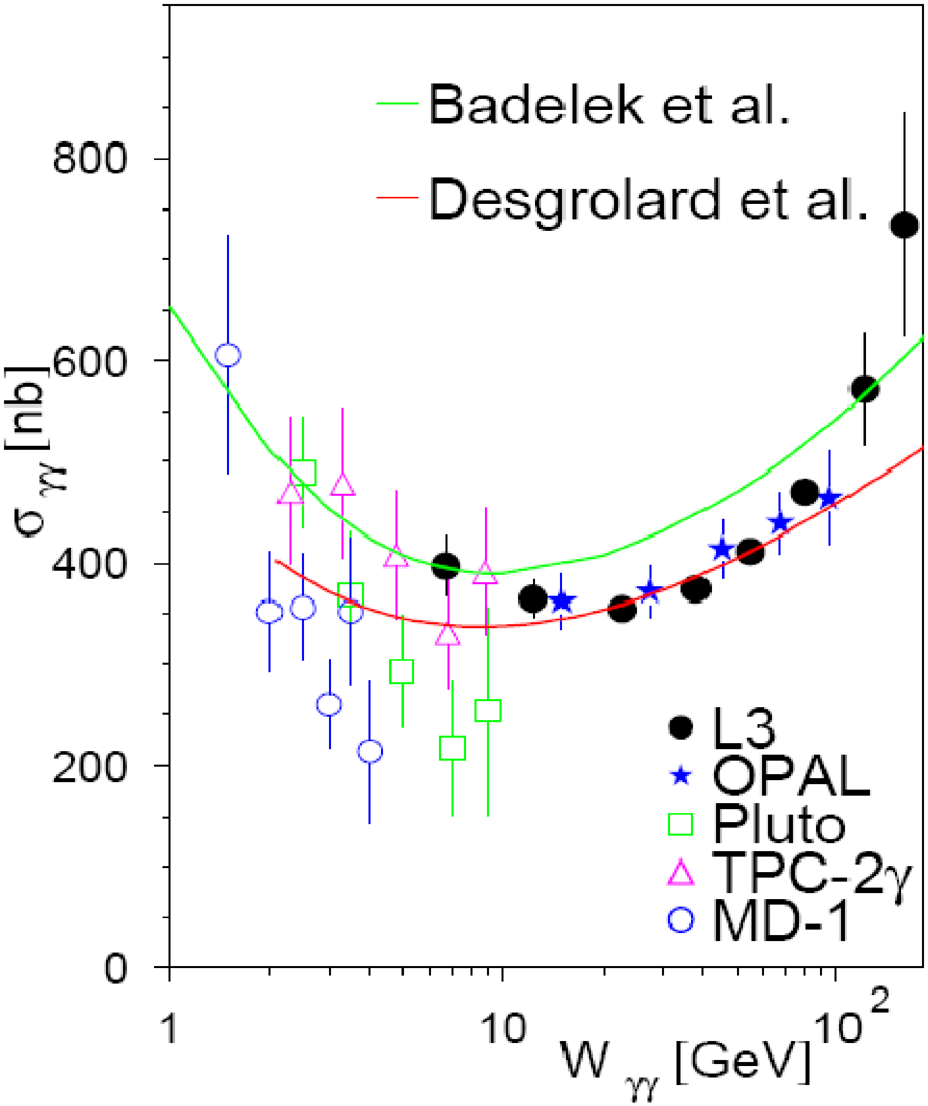
<u>Measurement (L3, OPAL):</u>

- first measure the differential cross section $d\sigma_{ee}/dW$ for the process: $e^+e^- \to e^+e^- +$ hadrons
  - increasing with the beam energy
  - decreasing with $W_{\gamma\gamma}$ (efect of the $L_{\gamma\gamma}$)
- extract $\sigma_{\gamma\gamma}$ using the luminosity function $L_{\gamma\gamma}$ and form factors $F(Q^2)$ which describe the Q^2 dependence of the hadronic cross section

$$\frac{d\sigma_{ee}}{dW} = L_{\gamma\gamma} \otimes \sigma_{\gamma\gamma}$$



Total cross section for $\gamma\gamma \to$ hadrons



OPAL: $\sqrt{s}$ = 161 – 183 GeV^2
10 < W < 110 GeV

L3: $\sqrt{s}$ = 161 – 202 GeV^2
5 < W < 185 GeV

- Good agreement with previous measurements in the overlaping region
- Rise with W for W > 10 GeV^2 which is characteristic for hadronic cross sections
- L3 data show steeper rise then expected for hadron-hadron or photon-proton cross sections.

Total cross section for $\gamma\gamma \to$ hadrons

<u>OPAL fit:</u> Regge parametrization with soft and hard pomeron:

$$\sigma_{\gamma\gamma}(W^2) = X_{1\gamma\gamma}(W^2)^{\varepsilon_1} + X_{2\gamma\gamma}(W^2)^{\varepsilon_2} + Y_{1\gamma\gamma}(W^2)^{-\eta_1}$$

fix reggeon term: $\eta_1 = 0.34$ oraz $Y_{1\gamma\gamma} = 320$ nb

results of the fit: $X_{2\gamma\gamma} = 0.5 \pm 0.2(\text{stat})^{+1.5}_{-1.0}(\text{sys})$ nb
what is consistent with zero (no hard pomeron)

results of the fit:

$$\varepsilon_1 = 0.101 \pm 0.004(\text{stat})^{+0.025}_{-0.019}(\text{sys})$$

$$X_{1\gamma\gamma} = 180 \pm 5(\text{stat})^{+30}_{-32}(\text{sys})\ \text{nb}$$

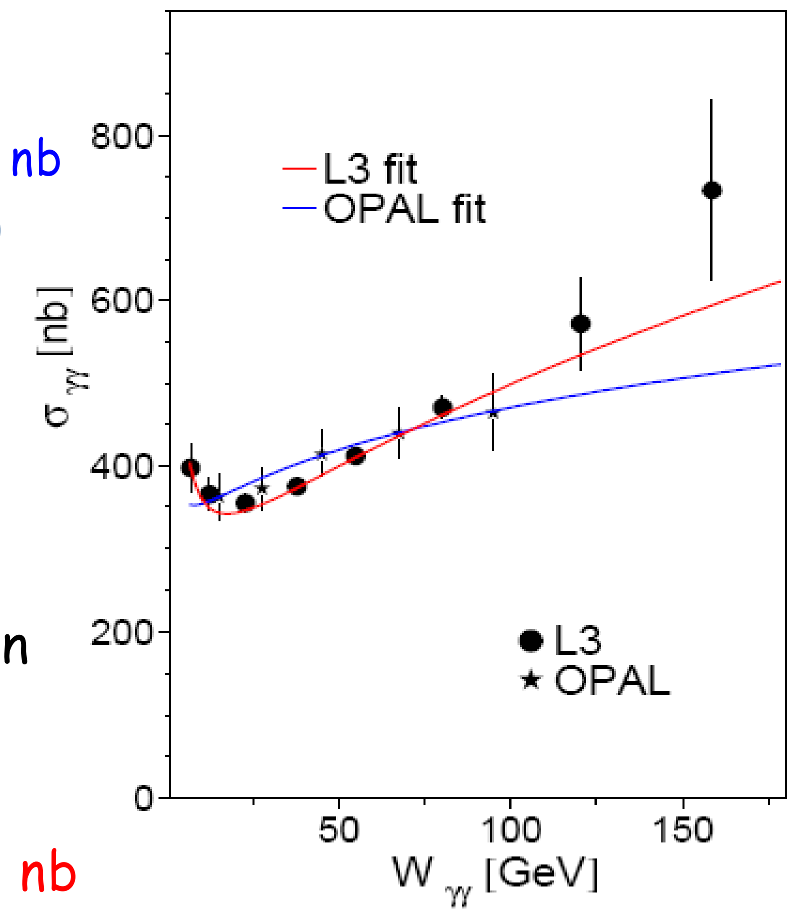
<u>L3 fit:</u>

Regge parametrization with soft pomeron

fix reggeon term: $\eta_1 = 0.358$

results of the fit: $\varepsilon_1 = 0.225 \pm 0.021$

$X_{1\gamma\gamma} = 58 \pm 10$ nb $\quad Y_{1\gamma\gamma} = 1020 \pm 146$ nb



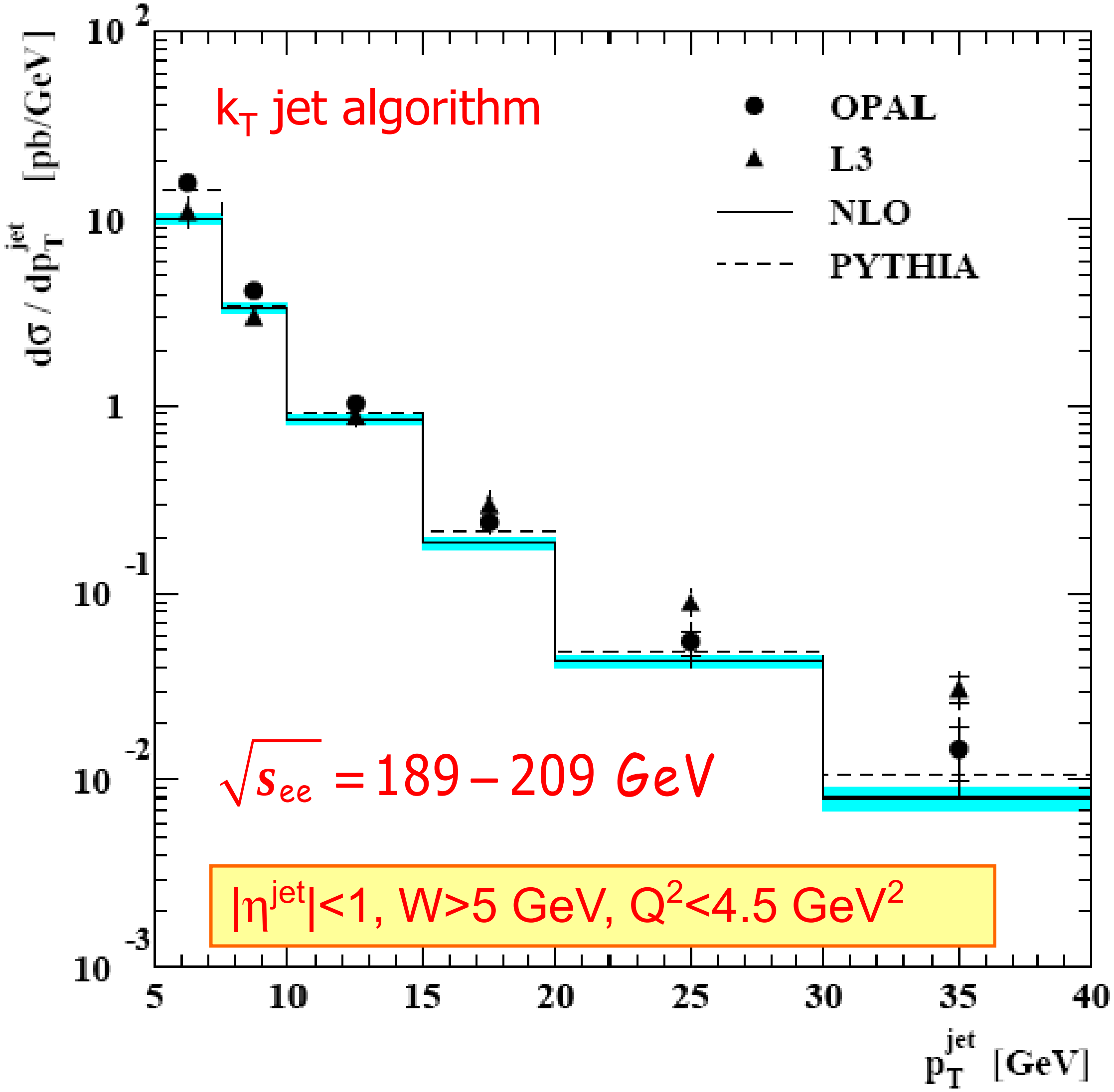
Inclusive jet cross section

NLO cross section calculated using QCD partonic cross sections in NLO for direct, single- and double-resolved procesess convoluted with photon flux + hadronization corrections.

OPAL data well described by both Pythia and NLO.

Discrepancy in shape between L3 and NLO.

Disagreement between L3 and OPAL.



Di-jet cross production

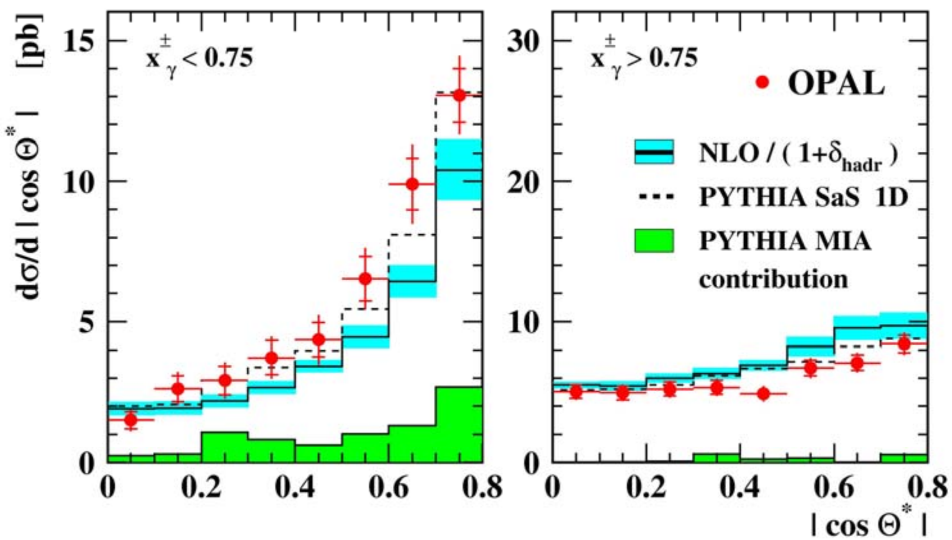
Experimentaly, direct and double-resolved interactions can be clearly separated using the quantity:

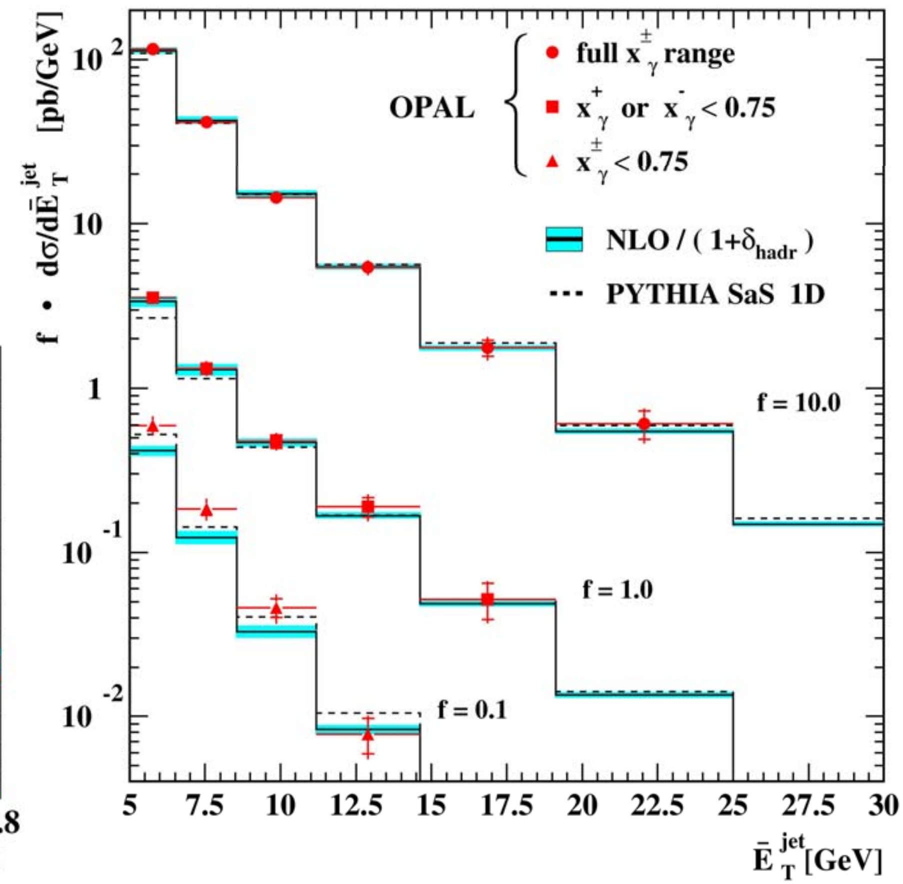
$$x_\gamma^\pm = \frac{\sum_{jets=1,2}(E \pm p_z)}{\sum_{hadrons}(E \pm p_z)}$$

The scattering angle θ^Σ in the two photon cms:

$$\cos\theta^* = \tanh\frac{\eta^{jet1} - \eta^{jet2}}{2}$$

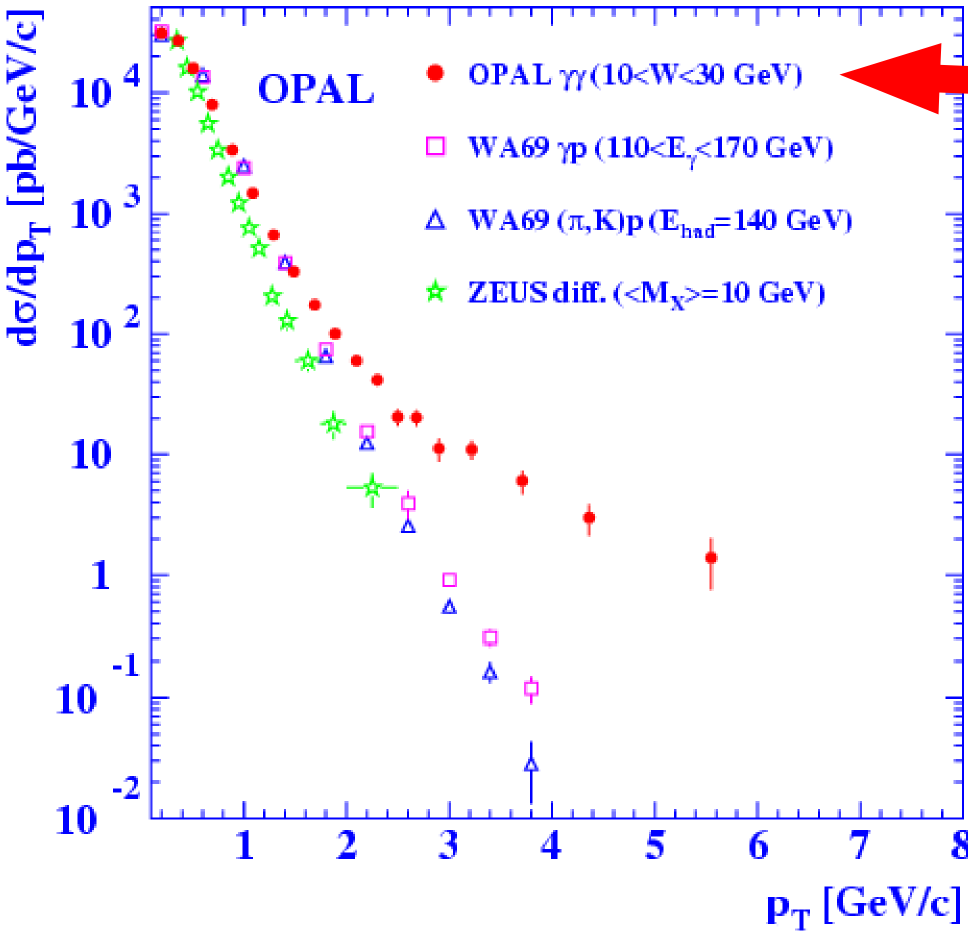
NLO – contribution from underlying event which is largest at $x_\gamma^\pm$<0.75 is not included!





Production of charged hadrons

Sensitivity to the structure of γ-γ interactions without theoretical and experimental problems related to definition and reconstruction of jets.

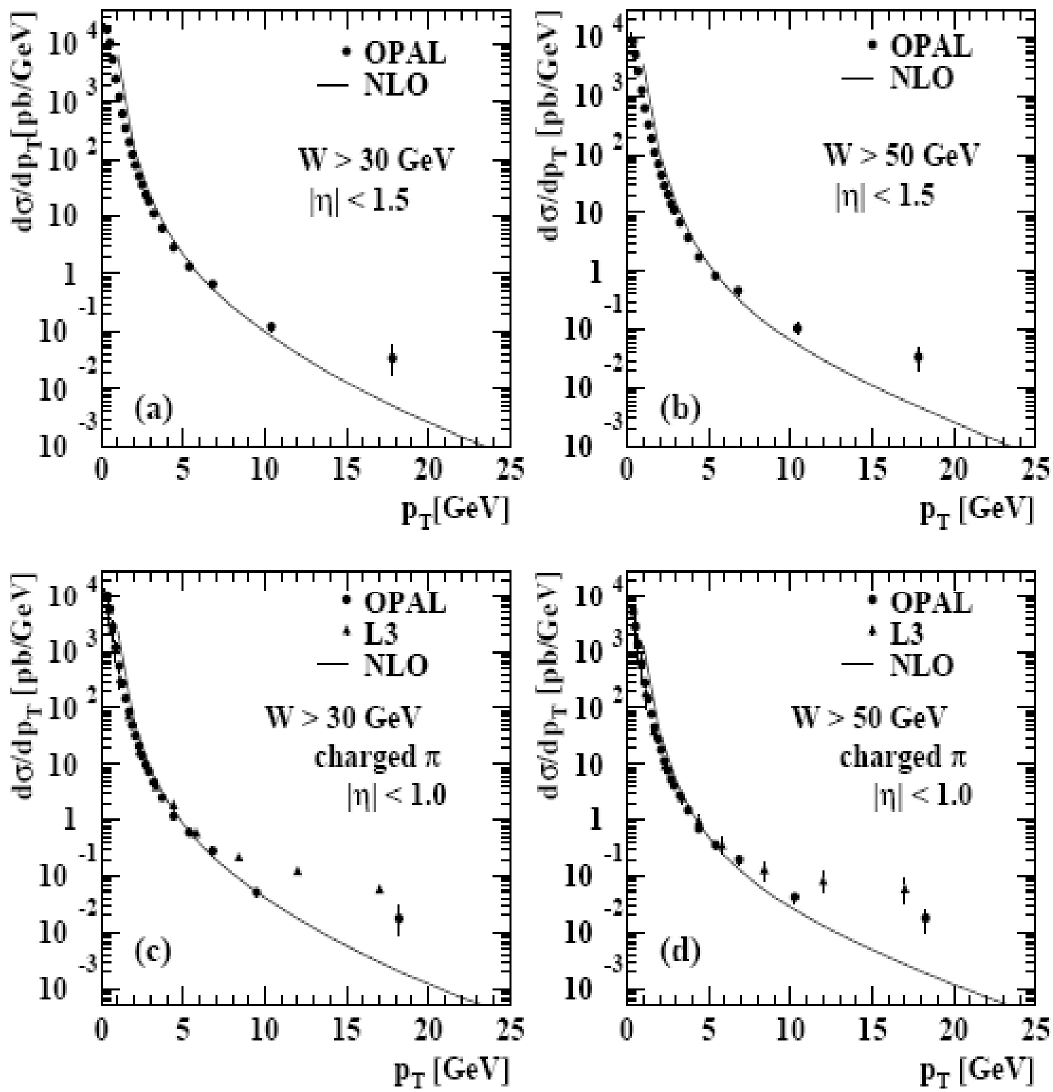


OPAL: $\sqrt{s_{ee}} = 161 - 172$ GeV

The spectrum of transverse momentum of charged hadrons in γ-γ scattering is much harder than in the case of γ-p, (π,K)-p and γ-IP.

This can be atributed to the direct component of the γ-γ interactions.

Production of charged hadrons

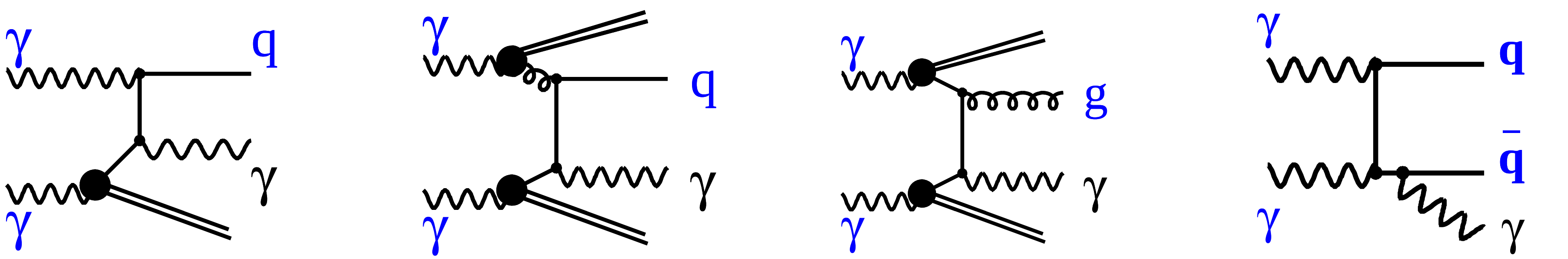


Differential cross sections measured by OPAL fall more rapidly towards high transverse momenta than those measured by L3, leading to a disagreement between the two experiments and to a better description of the OPAL data by NLO QCD.

For the puprose of this comparison OPAL data have been scaled to reduced |c| range and to the fraction of pions in all charged hadrons.

Isolated prompt photons

In LO only single and double resolved diagrams contribute to production of prompt photons $\gamma+\gamma \to \gamma$+hadrons:



Single-resolved

Double-resolved

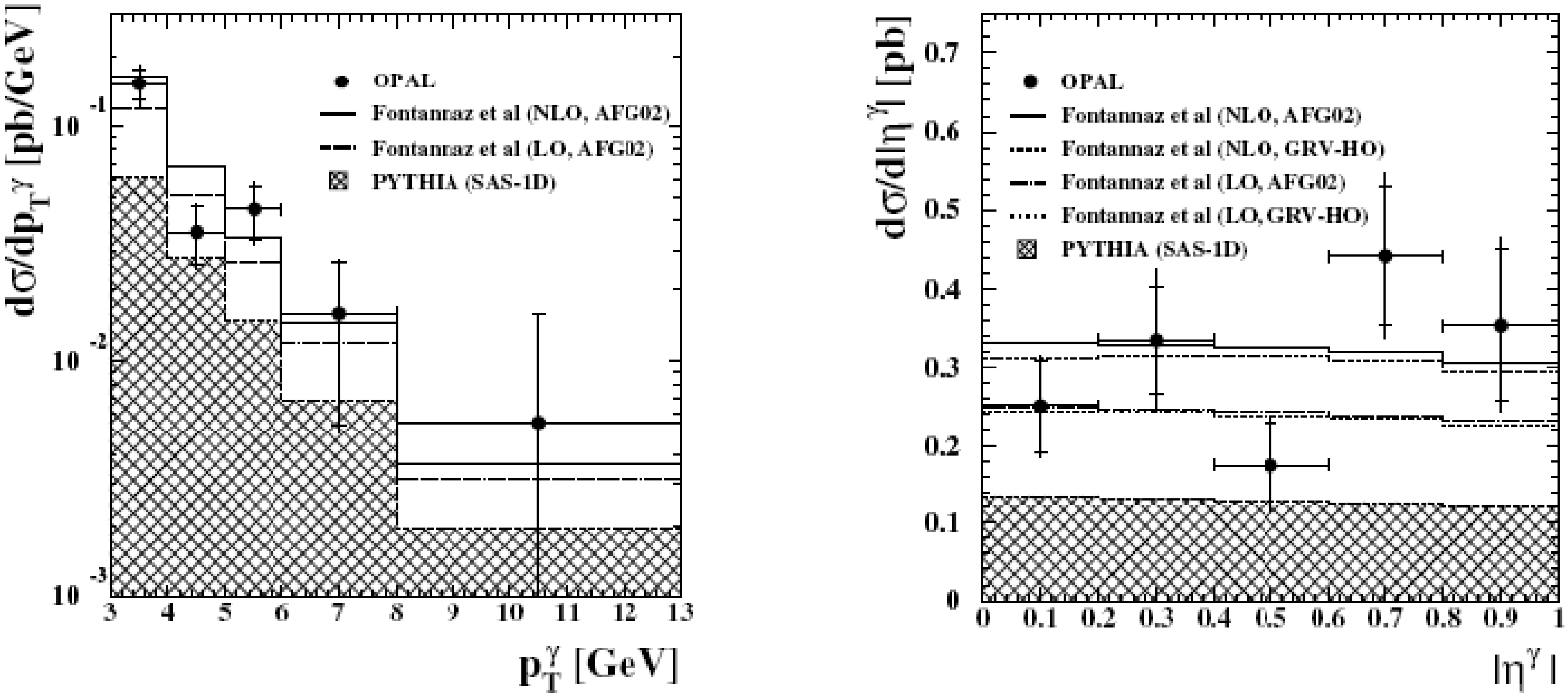
Direct with FSR

Small cross section, but also small hadronisation corrections!

Total cross section in the kinematic range defined by anti-tagging condition, measured by OPAL at $\sqrt{s_{ee}}$=183-209 GeV:

$$\sigma_{tot} = 0.32 \pm 0.04(stat) \pm 0.04(sys)$$

Differential cross sections for $\gamma+\gamma \rightarrow \gamma+X$

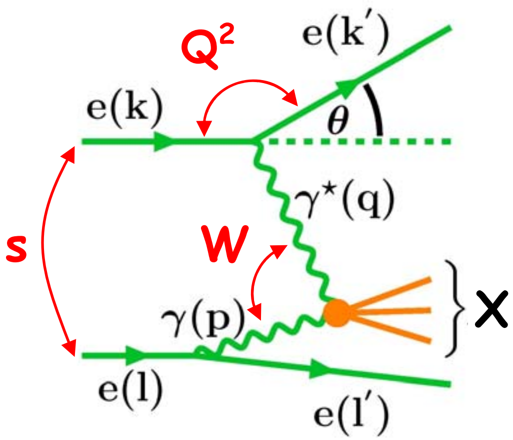


Cross sections measured in the kinematic range $|\eta^\gamma|<1$ and $p^\gamma_T > 3$ GeV

- Pythia reproduces the shape of the distributions well, but underestimate the normalisation.
- NLO calculations describe well shape and normalisation.

Kinematics of e-γ and e-e DIS

e-γ DIS



$s = (k + l)^2$ $W^2 = (p + q)^2$

s: e^+e^- cms energy squared
W^2: γ*-γ cms energy squared

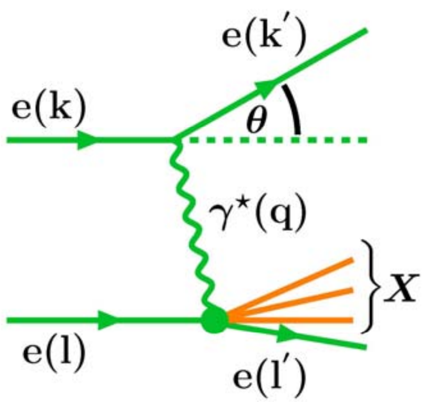
$Q^2 \equiv -q^2 = -(k - k')^2 > 0$
$P^2 \equiv -p^2 = -(l - l')^2 \approx 0$

Q^2: virtuality of the probe photon
P^2: virtuality of the target photon

$y_e = \frac{l \cdot q}{l \cdot k}$ $x = \frac{Q^2}{2p \cdot q}$ $z = \frac{Q^2}{2l \cdot q}$

y_e: inelasticity, fraction of the elec. mom carried by the virtual photon
x: fraction of the target photon mom carried by the struck parton
z: fraction of the target electron mom carried by the struck parton

e-e DIS



Reconstruction of the kinematical variables is based on the measurement of the scattered electron and the hadronic final state:

$$Q^2 = 2E'E_b(1 - \cos\theta)$$

$$W^2 = \left(\sum_h E_h\right)^2 - \left(\sum_h \vec{p}_h\right)^2$$

$$y_e = 1 - \frac{E}{E_b}\cos^2(\theta/2)$$

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

$$z = \frac{Q^2}{y_e s}$$

Cross section for $e^+e^- \to e^+e^-\gamma^\Sigma\gamma \to e^+e^-X$

The cross section in terms of the photon structure functions F^γ_2 and F^γ_L:

$$\frac{d^4\sigma_{ee}}{dx\,dQ^2\,dz\,dP^2} = \frac{2\pi\alpha^2}{x^2Q^4}\left[\left(1+(1-y_e)^2\right)F_2^\gamma\left(x,Q^2,P^2\right) - y_e^2 F_L^\gamma\left(x,Q^2,P^2\right)\right]\hat{f}_{\gamma/e}\left(z/x,P^2\right)$$

where the flux of (transverse) quasi-real photons given by EPA reads:

$$\hat{f}_{\gamma/e}\left(y,P^2\right) = \frac{\alpha}{2\pi}\frac{1}{P^2}\left[\frac{1+(1-y)^2}{y} - 2y\frac{m_e^2}{P^2}\right]$$

$$P^2_{min}(y) = \frac{m_e^2 y^2}{1-y}$$

$$P^2_{max}(y) = (1-y)E^2\theta^2_{max}$$

Integrating over z and P^2 we obtain:

$$\frac{d^2\sigma_{ee}}{dx\,dQ^2} \approx \frac{2\pi\alpha^2}{xQ^4}F_2^\gamma\left(x,Q^2,P^2_{eff}\right)K\left(\frac{Q^2}{xs},\frac{P^2_{max}}{m_e^2}\right)$$

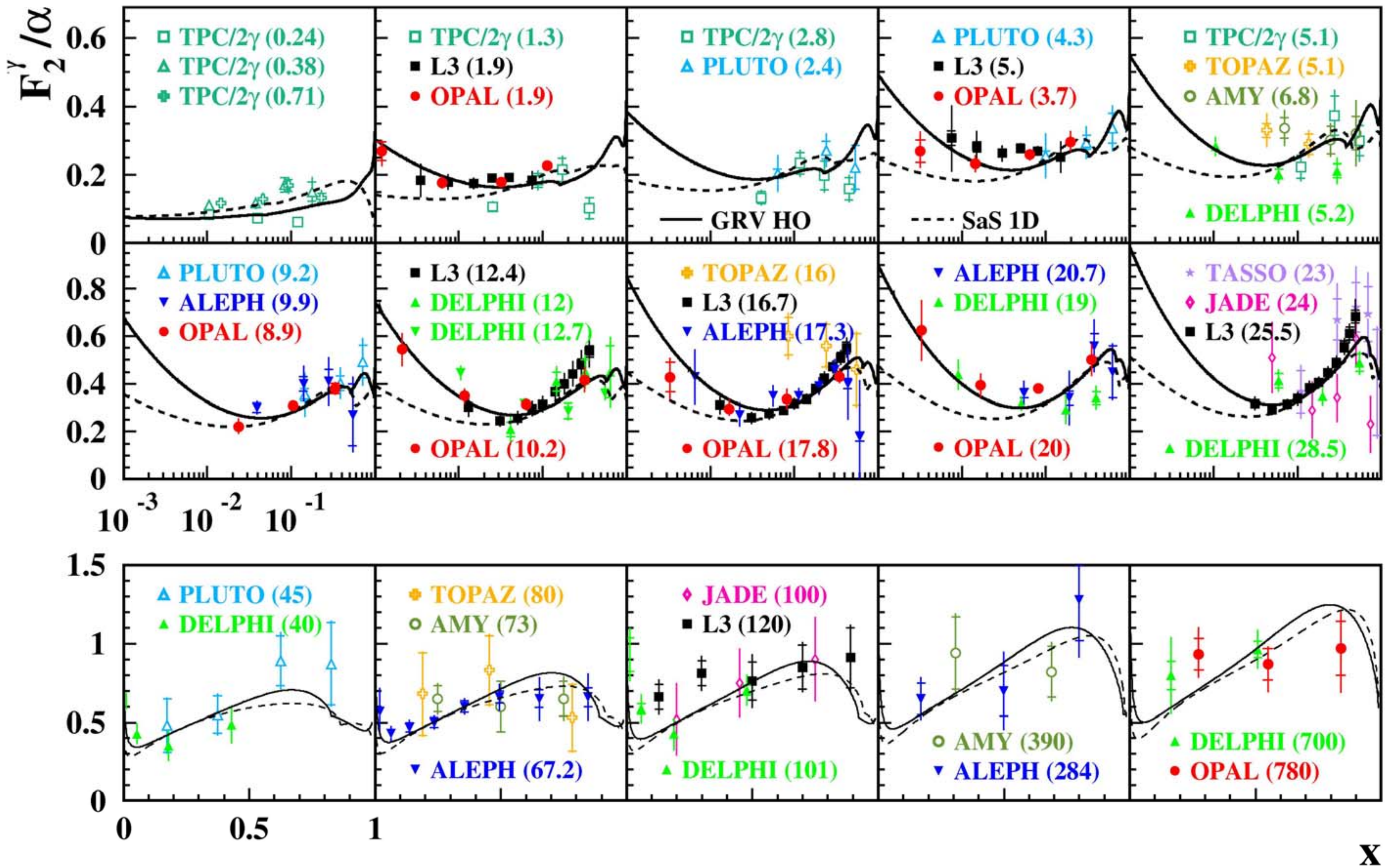
$$\left\langle F_2^\gamma\left(P^2\right)\right\rangle = F_2^\gamma\left(P^2_{eff}\right)$$

Usually the formula for the cross section for the process $e\gamma \to eX$ is used for extraction of the F^γ_2 based on MC and known input pdf:

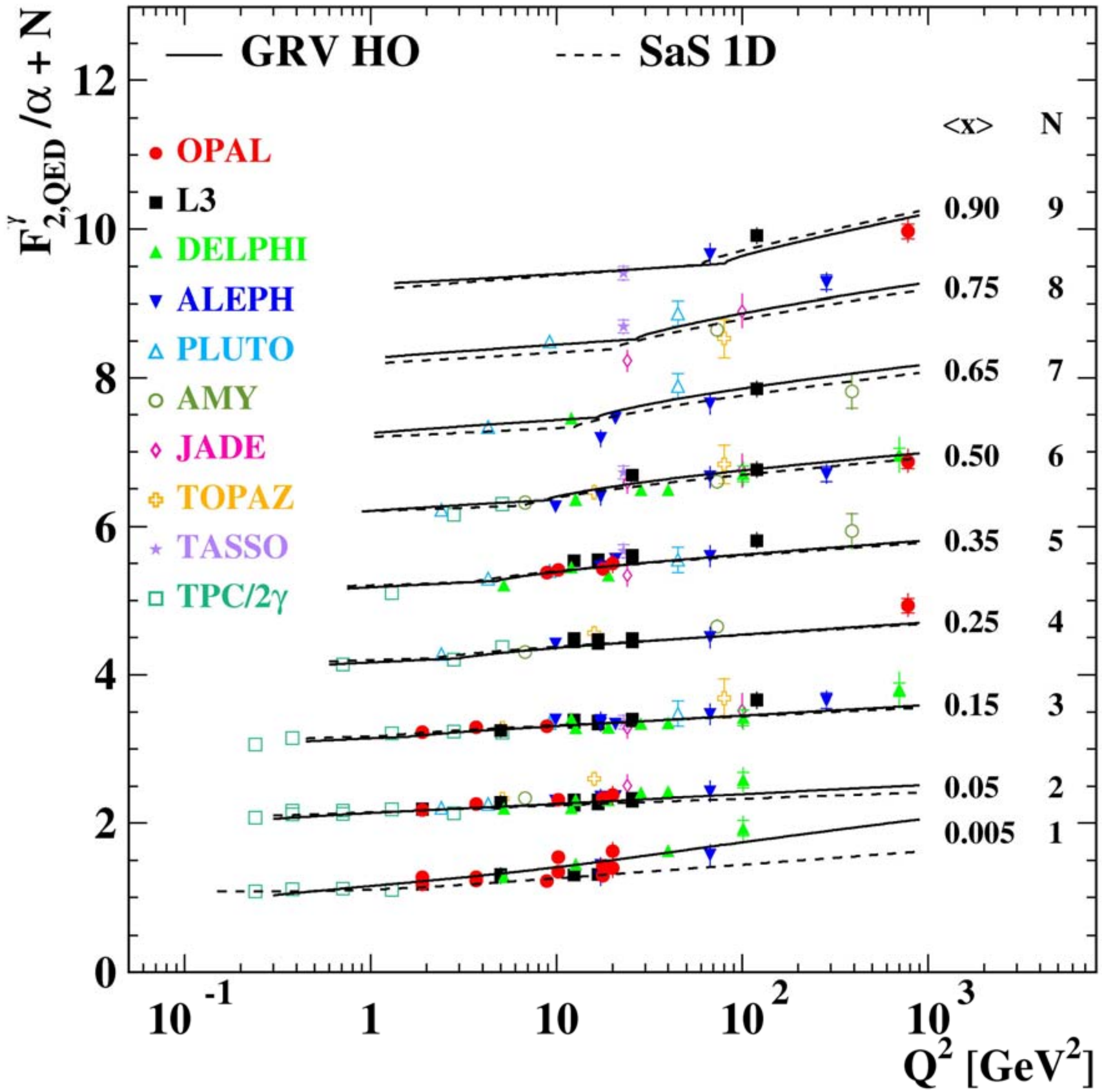
$$\frac{d^2\sigma_{e\gamma}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[\left(1+(1-y_e)^2\right)F_2^\gamma\left(x,Q^2,P^2_{eff}\right)\right]$$

usualy we assume $P^2_{eff} = 0$

World data on F_2^γ vs. x



World data on F^{γ}_2 vs. Q^2



About 50 measurements

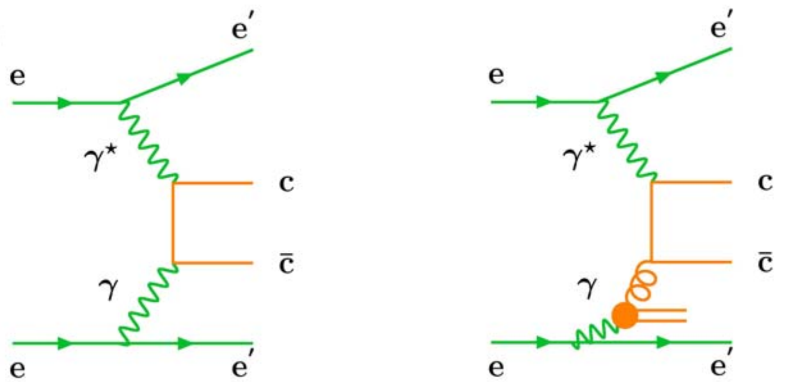
Kinematical range:
$10^{-3} \leq x \leq 0.9$
$1.9 \leq \langle Q^2 \rangle \leq 780\ GeV^2$

Good agreement between experiments

Significant hadron-like component

Positive scaling violation in whole x range (significant increase of the slope with increasing x)

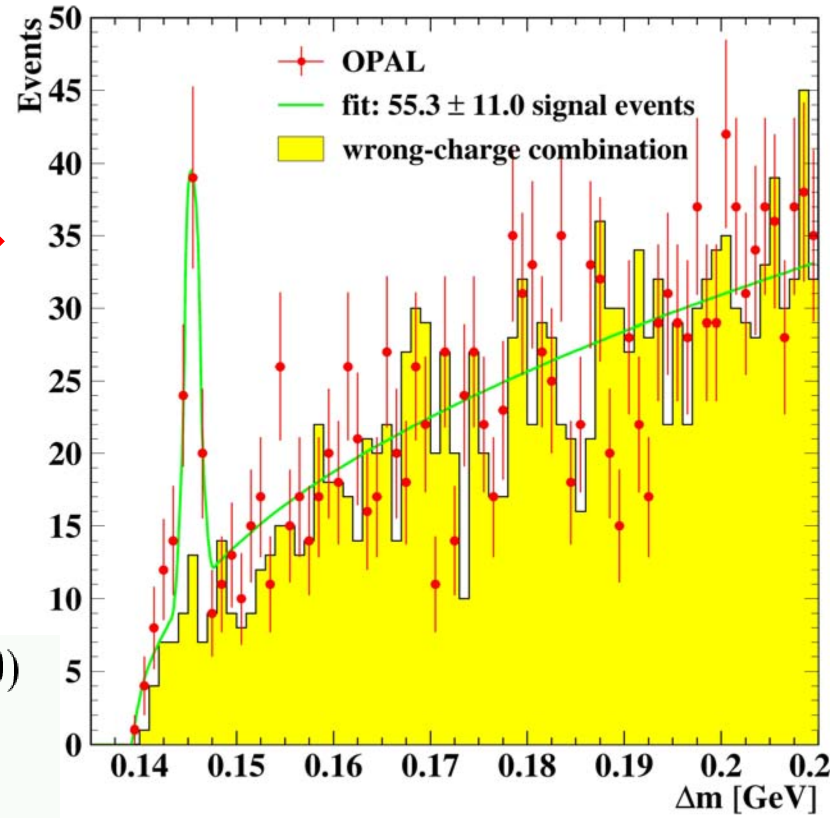
Measurement of F_2^{charm}



Point-like part (pQCD)

Hadron-like part depends on gluon in the photon

D^{Σ}



$\mathcal{L} = 654.1\text{pb}^{-1}$ at $183 - 209$ GeV $(1997 - 2000)$

$\langle\sqrt{s_{ee}}\rangle = 196.6$ GeV

$5 < Q^2 < 100$ GeV^2, $\langle Q^2\rangle \approx 20$ GeV^2

55.3 ± 11.0 events

$x < 0.1$: 23.6 ± 7.4 events

$x > 0.1$: 31.4 ± 8.1 events

Δm - mass difference of

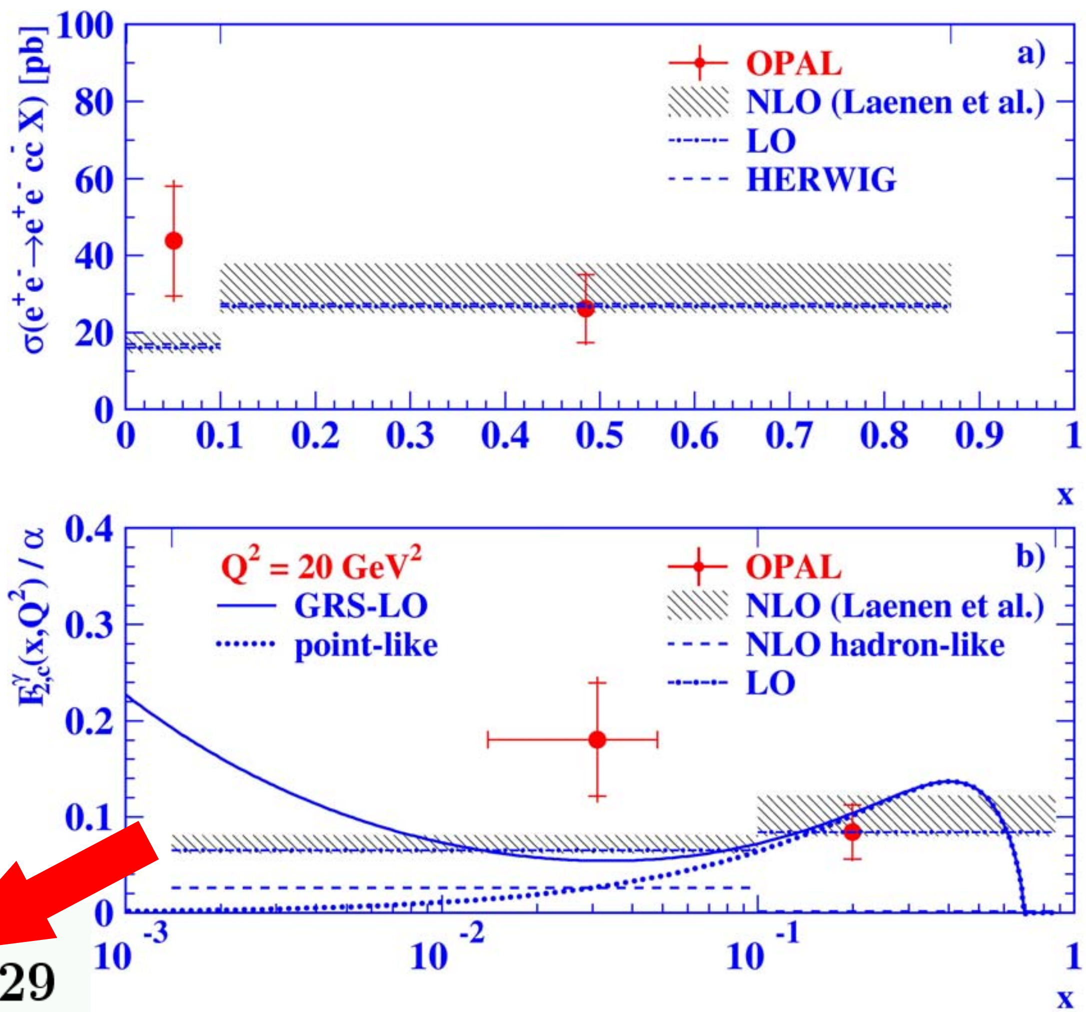
$D^{\Sigma+} \rightarrow D^0 p^+$ and $D^0 \rightarrow K^-\pi^+(\pi^-\pi^+)$

Measurement of F_2^{charm}

Limited by statistics

High-x:
well described by pQCD calculation, essentially pointlike

Low-x:
somewhat higher than predicted, but large error



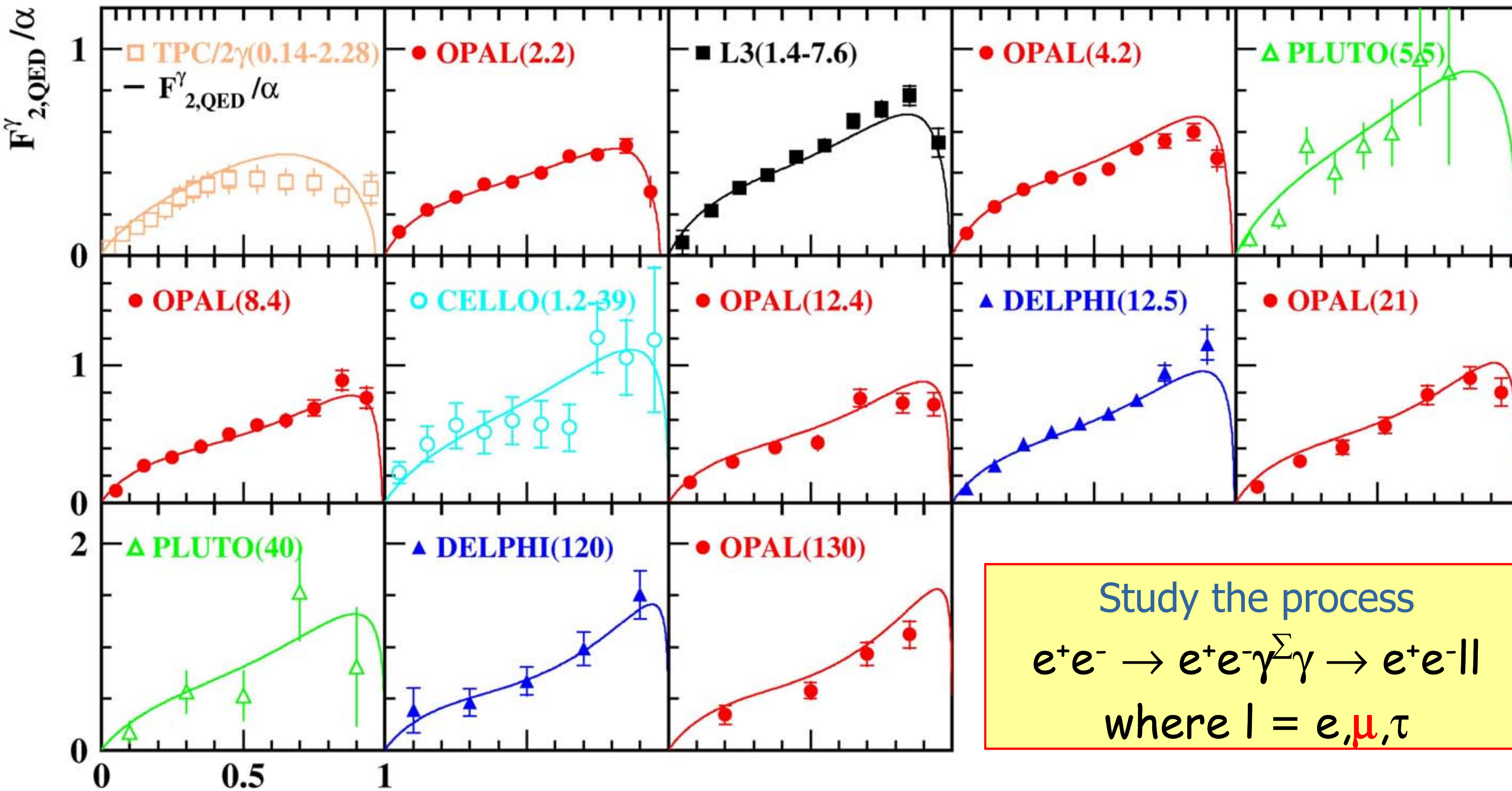
Subtract NLO pointlike part at low x we obtain:

$$F_{2,c}^{\gamma,\mathrm{HL}} = 0.136 \pm 0.059 \pm 0.029$$

NLO prediction: $0.026^{+0.007}_{-0.005}$

Hadron-like component of $F^{\gamma}_{2,c}$ is needed

World data on $F^{\gamma}_{2,QED}$ vs. x



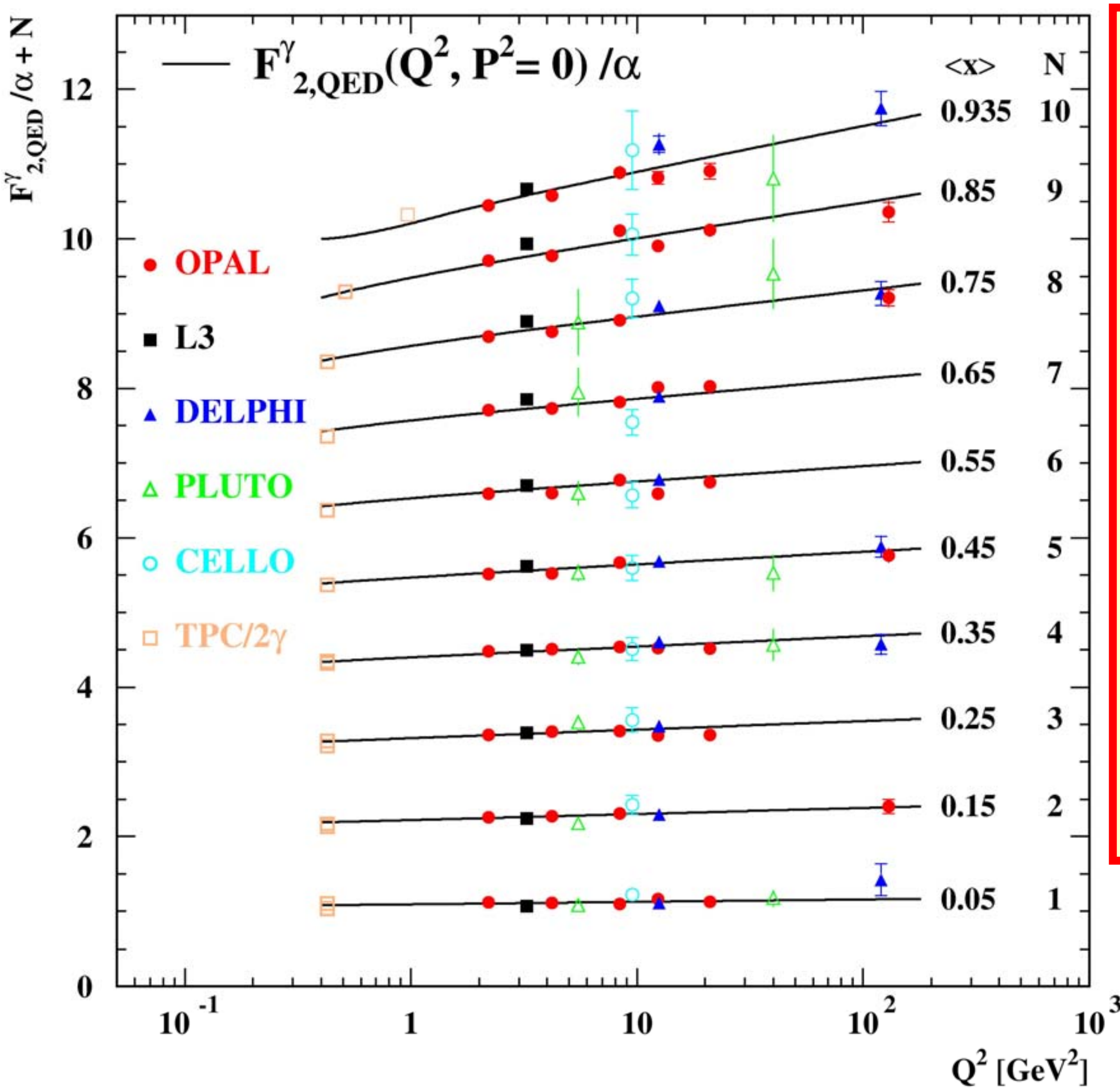
Study the process

$e^+e^- \to e^+e^-\gamma^{\Sigma}\gamma \to e^+e^- ll$

where $l = e, \mu, \tau$

$$\frac{d^2\sigma_{e\gamma\to e\mu^+\mu^-}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[\left(1+\left(1-y_e\right)^2\right)F^{\gamma}_{2,QED}\left(x,Q^2,P^2\right) - y_e^2 F^{\gamma}_{L,QED}\left(x,Q^2,P^2\right)\right]$$

World data on $F^{\gamma}_{2,QED}$ vs. Q^2



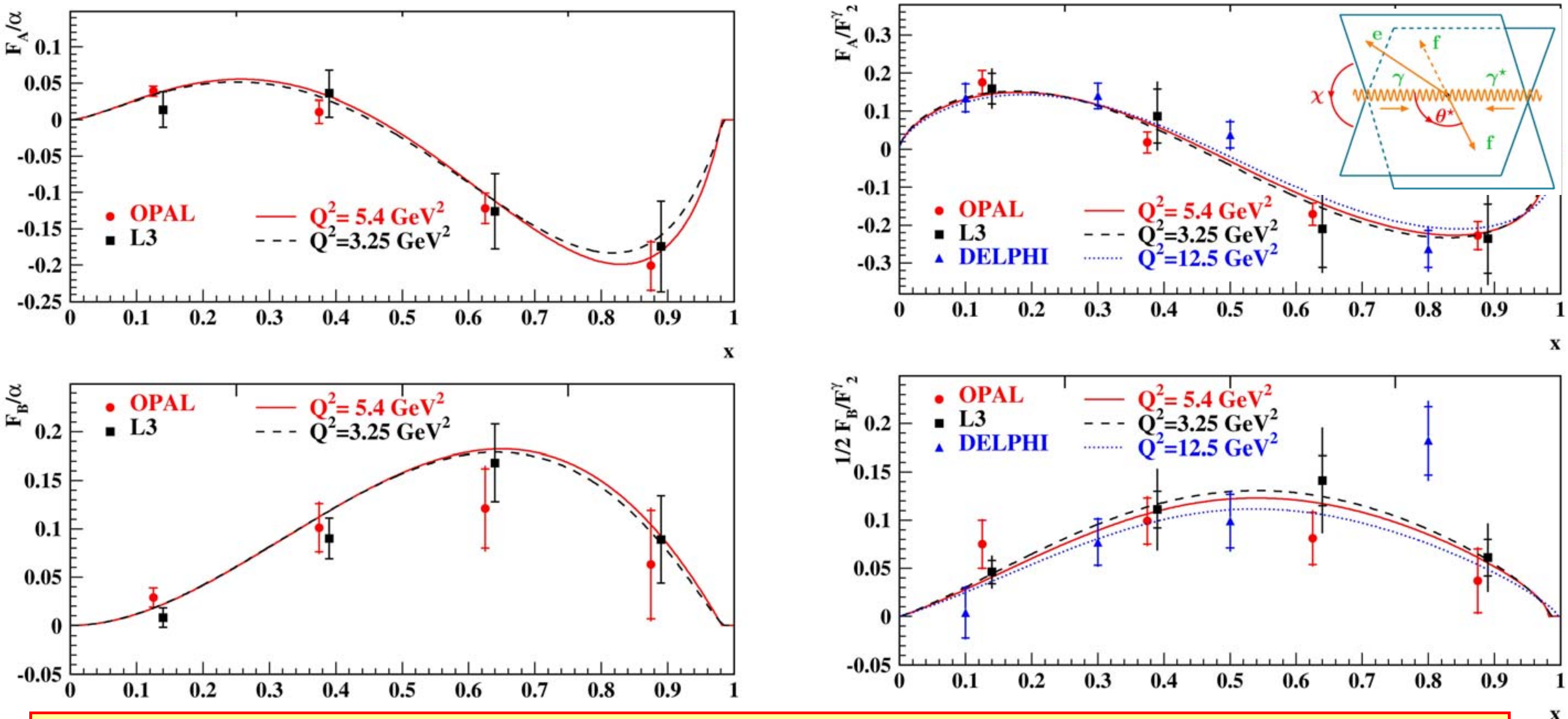
All data points with known P^2 are corrected to P^2=0

If for a particular data set the range of Q^2 is given, than for each data point at given x a separate average value of Q^2 has been calculatd (TPC/2γ)

Data clearly follow increasing slope with increasing x

$$0.43 < \langle Q^2 \rangle < 130\ GeV^2$$

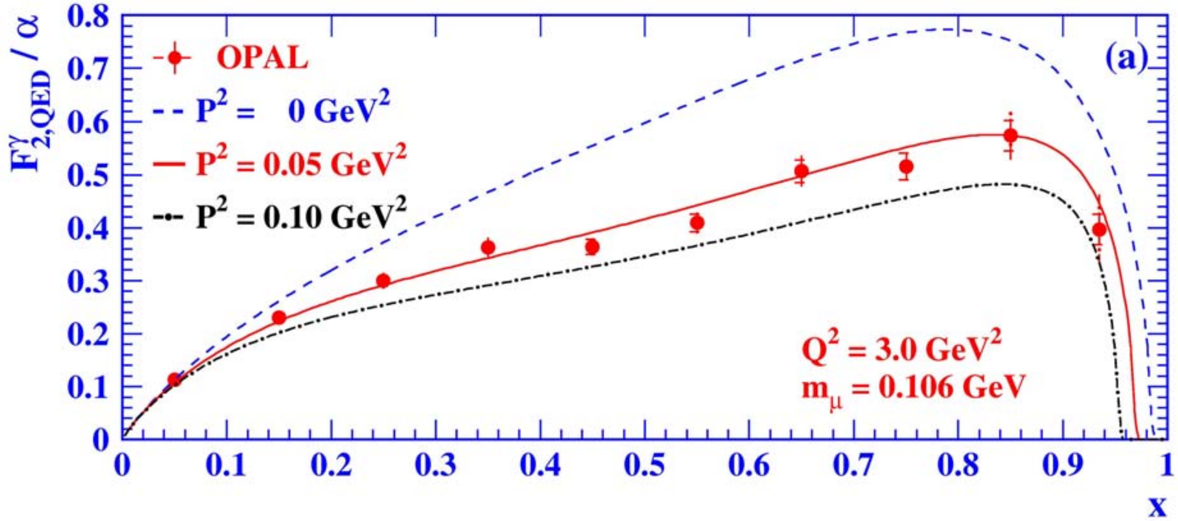
QED structure of the photon



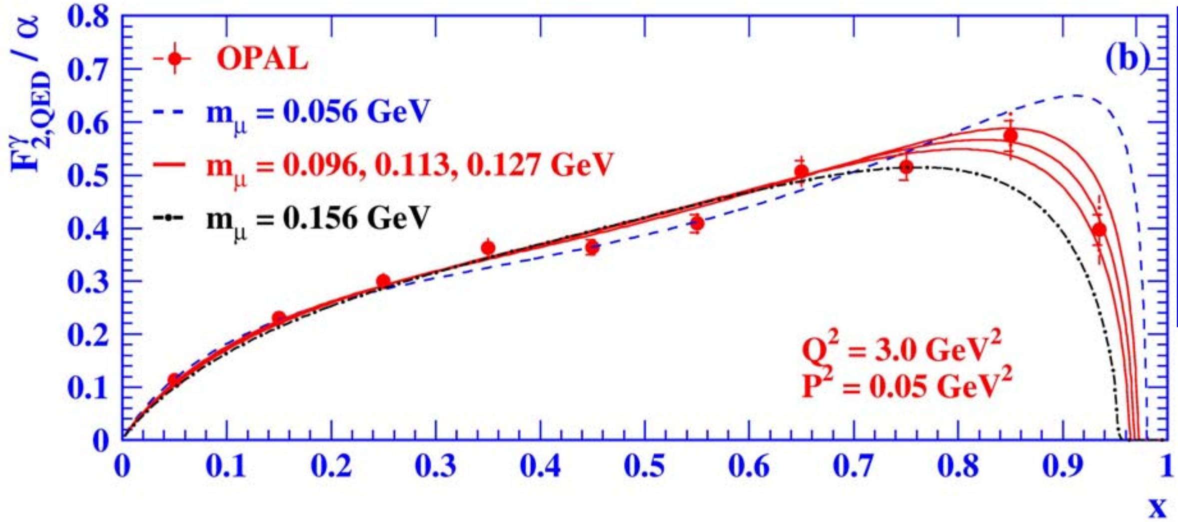
$$\frac{d^3\sigma_{e\gamma\to eff}}{dx\,dQ^2\,d\chi/2\pi} \approx \frac{2\pi\alpha^2}{xQ^4}\left(1+(1-y_e)^2\right)\left[F^\gamma_{2,\mathrm{QED}}(x,Q^2) - F^\gamma_{A,\mathrm{QED}}\cos\chi + \tfrac{1}{2}F^\gamma_{B,\mathrm{QED}}\cos 2\chi\right]$$

Experimentally verified that both F^γ_A and F^γ_B are different from zero and not constant (const fit: F^γ_B/α = 0.032 (0.034) OPAL (L3) with χ^2/ndf = 8.9 (3.1))

Precision of QED measurements



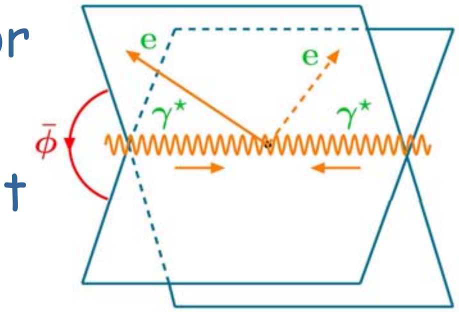
Data are precise enough to observe the efect of small virtuality P^2 of the quasi-real target photon.



From the fit to the data the mass of the muon can be measured with precision of about 14%.

Interactions of virtual photons

The general form of the differential cross section for the process $e(p_1)e(p_2) \to e(p_1')e(p_2')X$ which proceeds via the exchange of two photons $\gamma(q_1)$, $\gamma(q_2)$ in the limit $Q_i^2 \gg m_e^2$, is given by:



$$d^6\sigma = \frac{d^3p_1' d^3p_2'}{E_1'E_2'} \frac{\alpha^2}{16\pi^4 q_1^2 q_2^2} \left[\frac{(q_1 \cdot q_2)^2 - q_1^2 q_2^2}{(p_1 \cdot p_2)^2 - m_e^2 m_e^2} \right]^{1/2} 4\rho_1^{++}\rho_2^{++} \cdot$$

$$\cdot \left(\sigma_{TT} + \varepsilon_1\sigma_{LT} + \varepsilon_2\sigma_{TL} + \varepsilon_1\varepsilon_1\sigma_{LL} + \tfrac{1}{2}\varepsilon_1\varepsilon_2\tau_{TT}\cos 2\bar{\phi} - 2\sqrt{\varepsilon_1(1+\varepsilon_1)}\sqrt{\varepsilon_2(1+\varepsilon_2)}\tau_{TL}\cos\bar{\phi} \right)$$

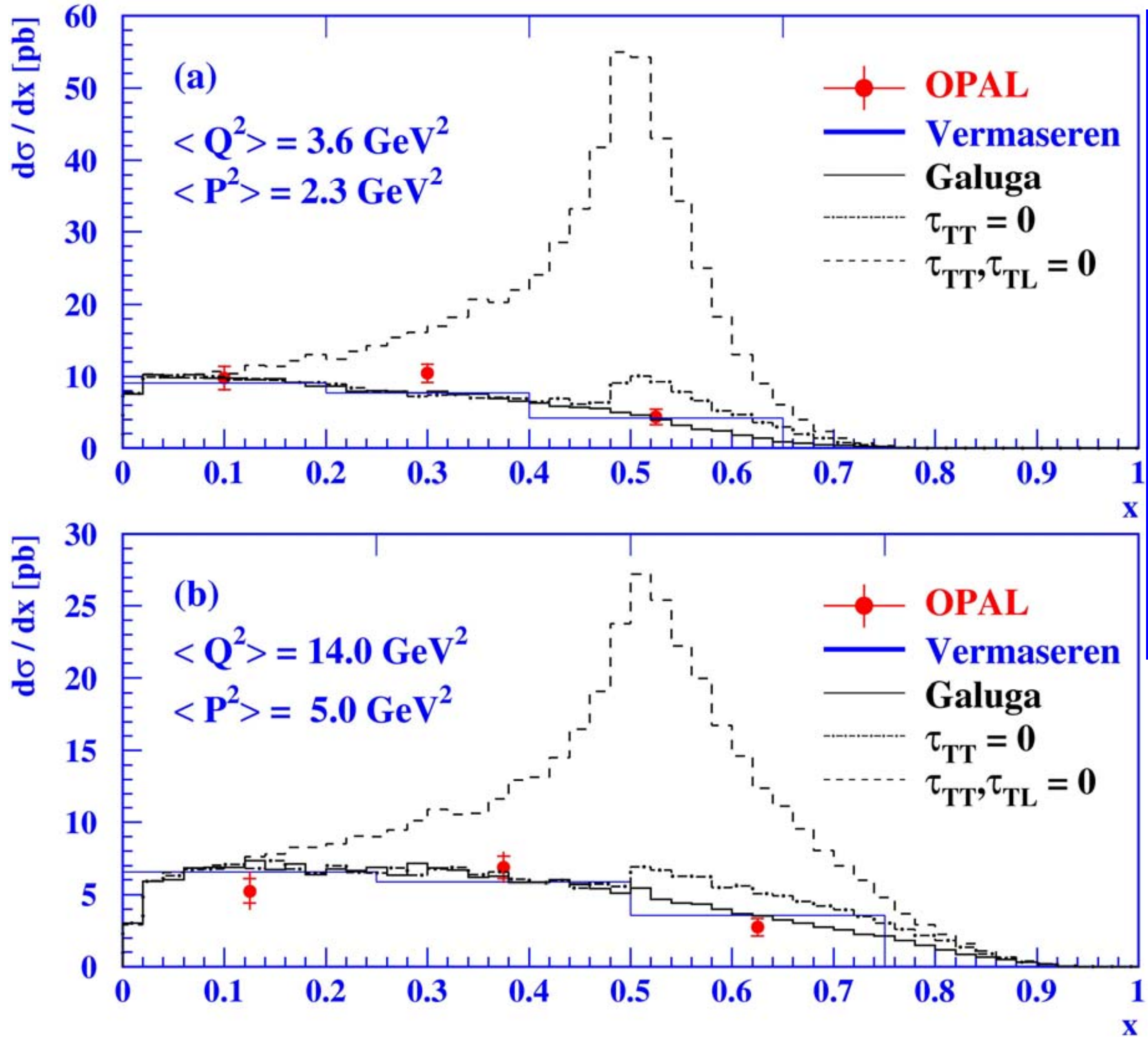
Introducing the luminosity function, we define the cross section for the scattering of two virtual photons $\gamma^{\Sigma}\gamma^{\Sigma} \to X$:

$$d^6\sigma = \frac{d^3p_1' d^3p_2'}{E_1'E_2'} L_{TT}\sigma_{\gamma^*\gamma^*}$$

$$\sigma_{\gamma^*\gamma^*} = \sigma_{TT} + \sigma_{LT} + \sigma_{TL} + \sigma_{LL} + \tfrac{1}{2}\tau_{TT}\cos 2\bar{\phi} - 4\tau_{TL}\cos\bar{\phi}$$

$$\mathcal{L}_{TT} = \frac{d^3p_1' d^3p_2'}{E_1'E_2'} L_{TT}$$

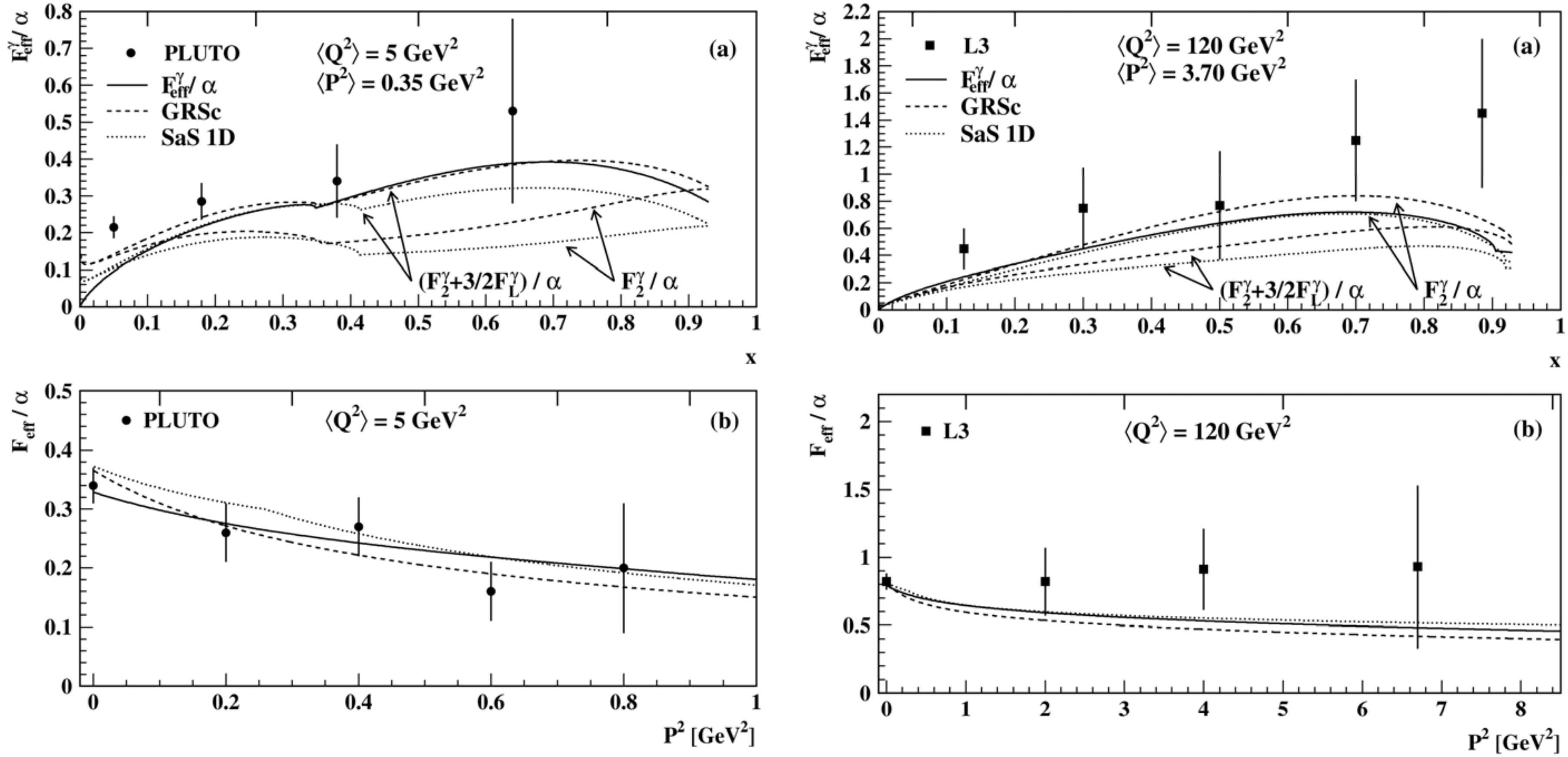
QED structure of the virtual photon



Data are well described by the predictions of programs based onthe full cross section formula.

It is clearly seen that the terms τ_{TT} and τ_{TL} are present mainly at x>0.1

Structure function of virtual photon



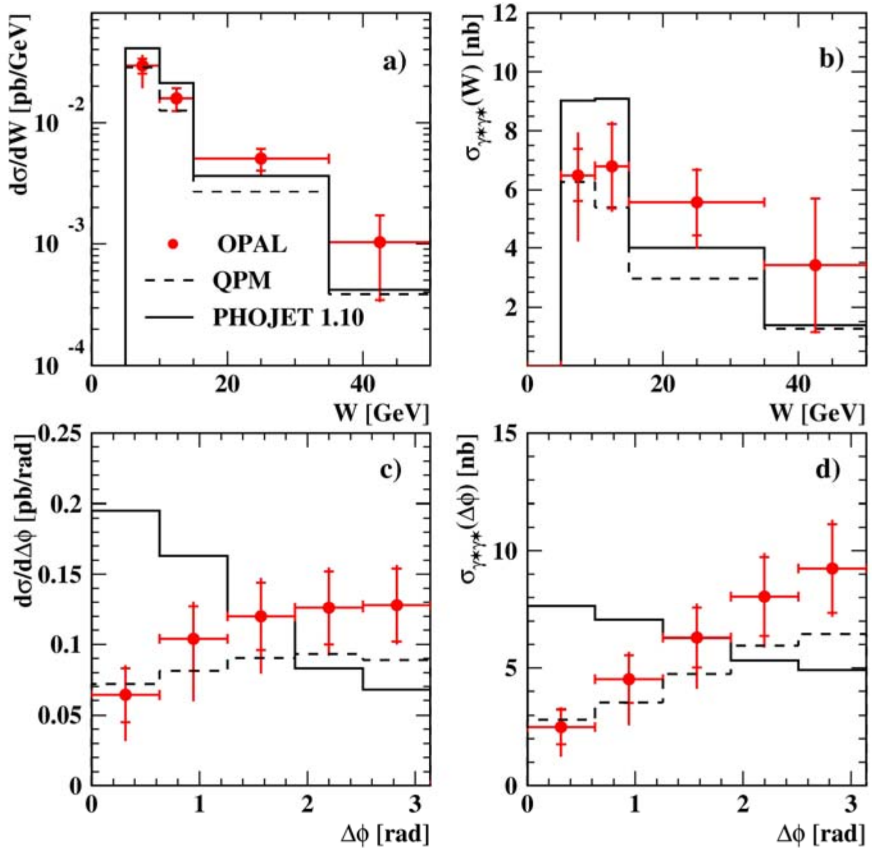
Experimentally one can access only an effective structure function:

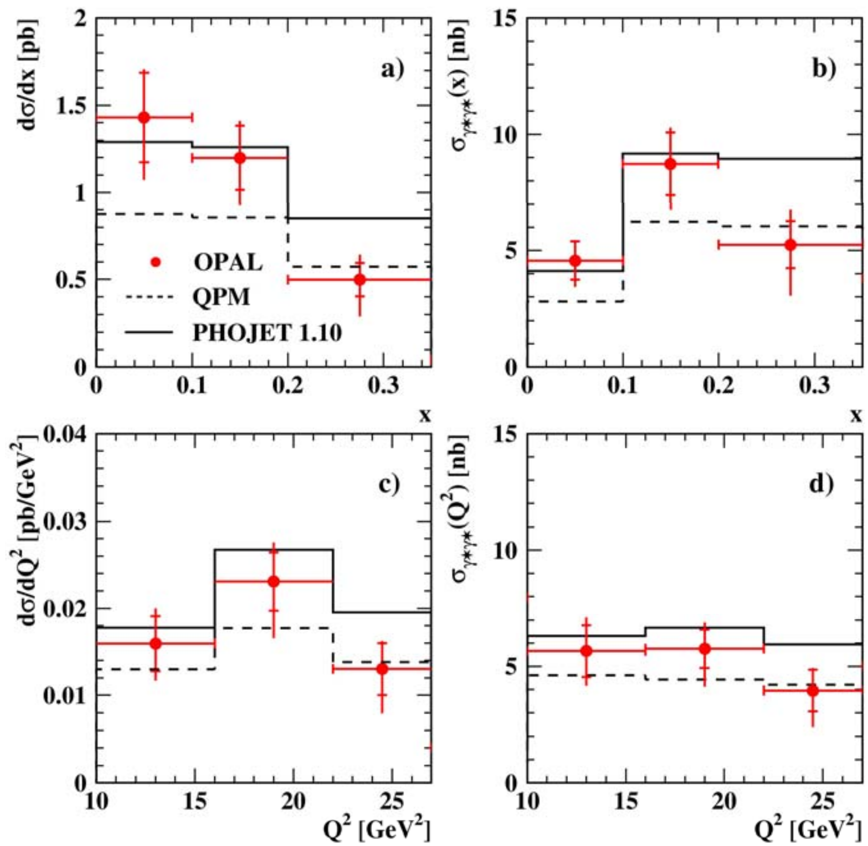
$$F_{eff}^{\gamma} \propto \sigma_{\gamma^*\gamma^*} \qquad F_{eff}^{\gamma} \equiv F_2^{\gamma} + \tfrac{3}{2} F_L^{\gamma}$$

Good agreement within statistical errors with QPM predictions.

PLUTO data suggest, as expected slow decrease with increasing P^2

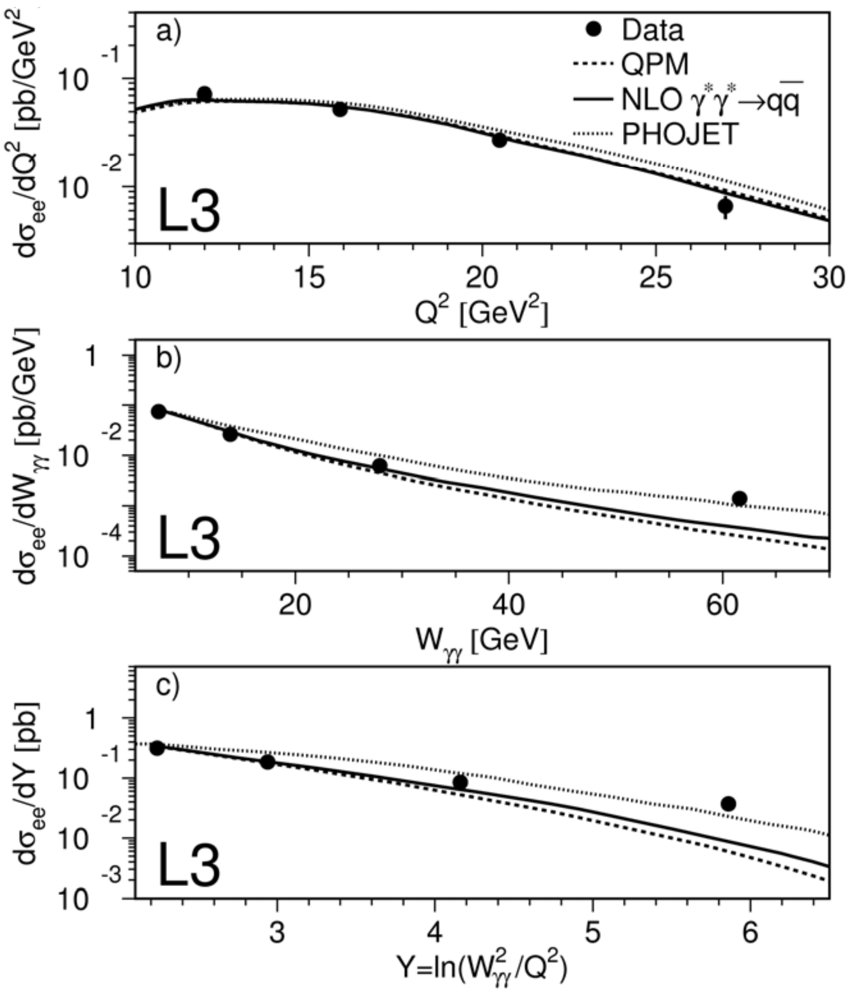
Structure of virtual photon interactions

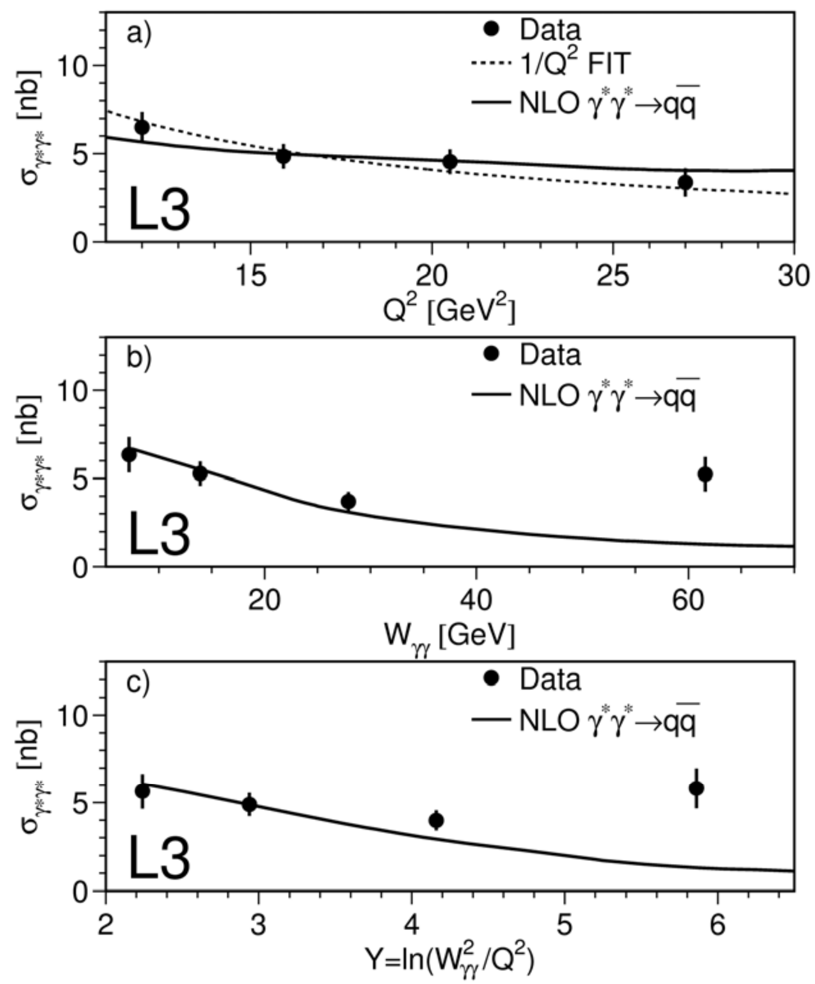




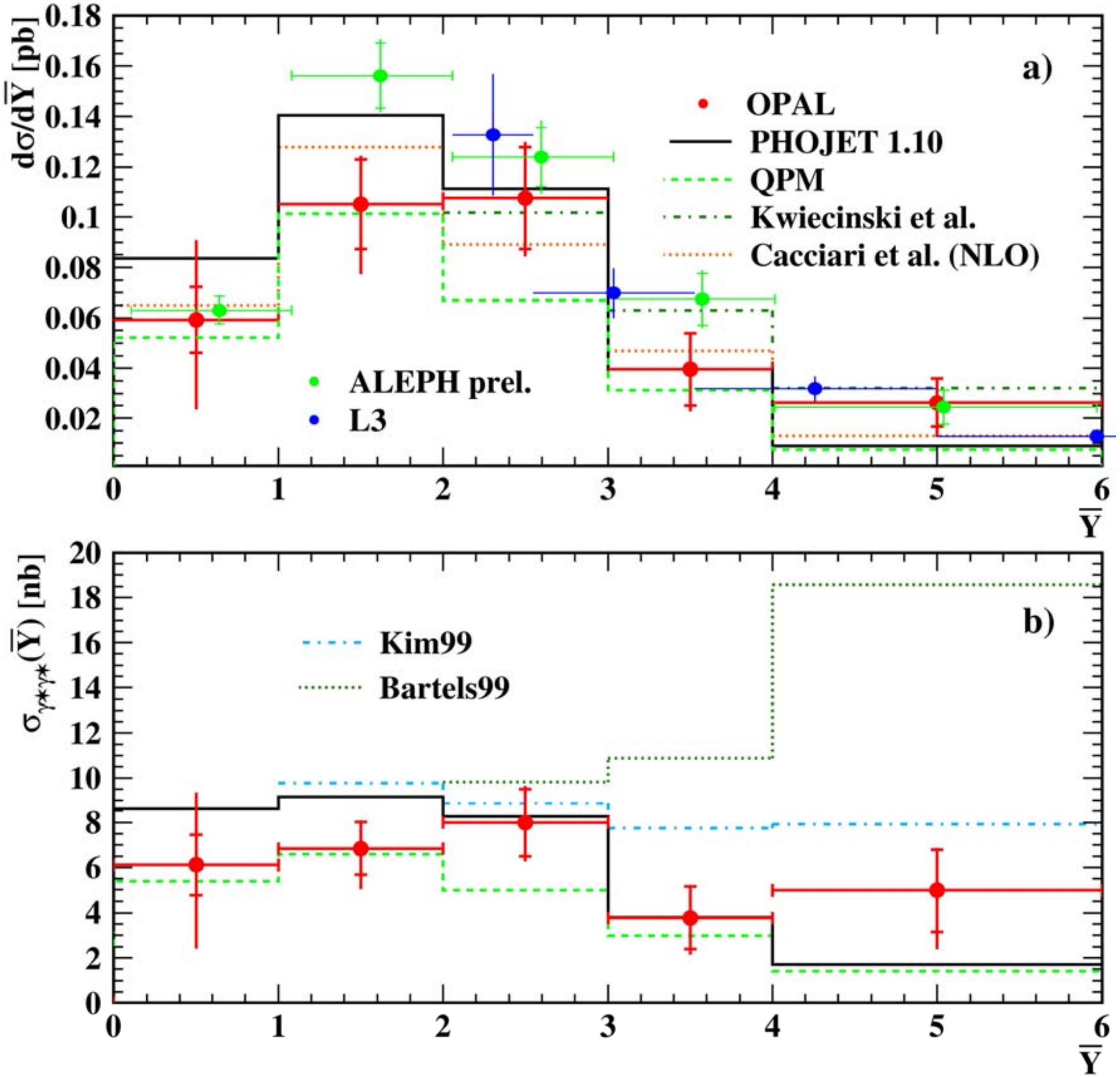
Cross sections for the processes $e^+e^- \rightarrow e^+e^-$hadrons and $\gamma^{\Sigma}\gamma^{\Sigma} \rightarrow$ hadrons, in the phase space region E_i>0.4E_b, 34<θ_i<55 mrad, W>5 GeV; <Q^2>=17.9 GeV^2

Scattering of virtual photons





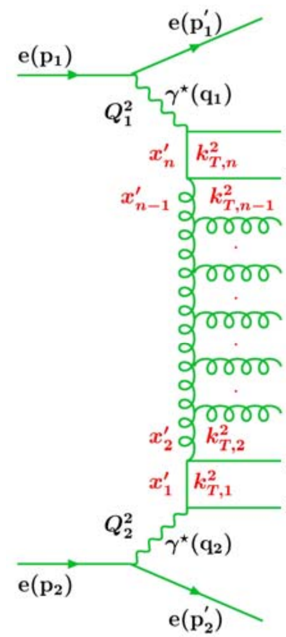
Dynamics of interactions of virtual photons



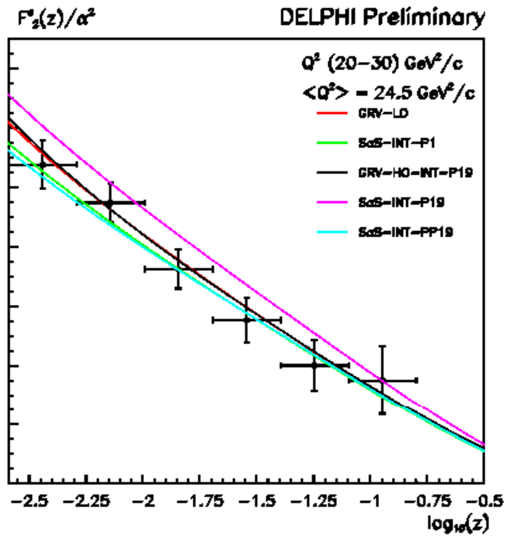
For comparison with BFKL calculations

$$Y \equiv \ln\left(\frac{s_{ee} y_1 y_2}{\sqrt{Q_1^2 Q_2^2}}\right) \approx$$

$$\approx \ln\left(\frac{W^2}{\sqrt{Q_1^2 Q_2^2}}\right) \equiv \bar{Y}$$



Electron structure function

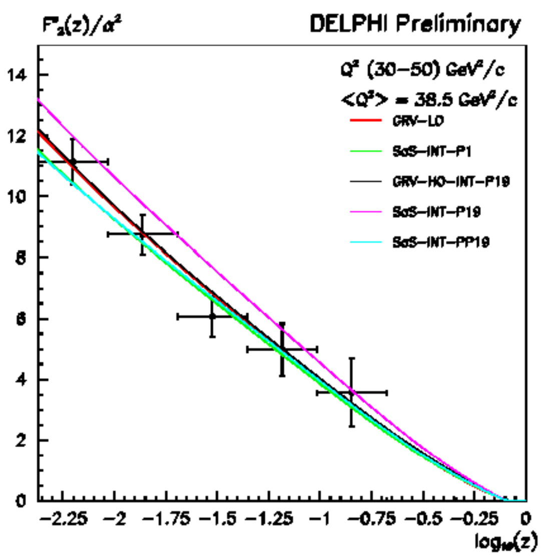


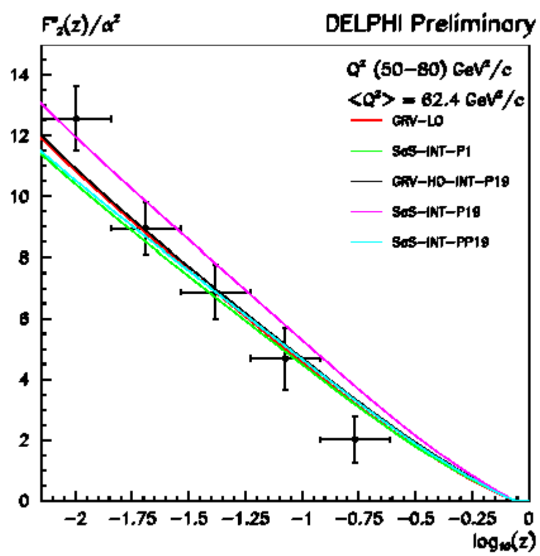
Cross section in terms of electron structure functions:

$$\frac{d^2\sigma_{ee}}{dz dQ^2 dz dP^2} = \frac{2\pi\alpha^2}{zQ^4}\left[\left(1+(1-y_e)^2\right)F_2^e(z,Q^2) - y_e^2 F_L^e(z,Q^2)\right]$$

Photon and electron structure functions are related:

$$F_a^e(z,Q^2;P_{max}^2) \equiv \int_z^1 dx \int_{P_{min}^2(z/x)}^{P_{max}^2} dP^2 \frac{z}{x^2} F_a^\gamma(x,Q^2,P^2)\, \hat{f}_{\gamma^*/e}(z/x,P^2)$$





- unknown P^2 of target γ
- F^e do not depends on the form of equivalent photon formula
- shape dominated by strongly peaked flux of target photons

Summary

LEP2 – the best place to study two photon interactions:

~100 published papers from all four experiments (mainly from LEP2)

Untagged measurements:

- total cross section
- jet and di-jet production
- production of resonances, charged hadrons, prompt photons, charm and beauty

Single tagged measurements:

- QED and hadronic structure functions of the quasi-real photon

Double tagged measurements:

- QED and hadronic structure of interactions of virtual photons
- total and differential cross sections and effective structure function of the virtual photon

More about tagged measurements in http://home.agh.edu.pl/mariuszp