Two photon Physics at LEP

Begona de la Cruz
CIEMAT, Madrid

October 3rd, 2000
Hadron Structure 2000

Introduction

γ couples to electric charge $\Rightarrow$

γ fluctuates

- l^+l^- (QED)
- q^+q^- (QCD)

$\gamma\gamma$ collisions allow study and check QED and QCD.

In this talk:

- Photon Structure Functions: describe our knowledge of hadronic and electromag. nature of γ.

Most recent work devoted to $\gamma\gamma \rightarrow$ hadrons

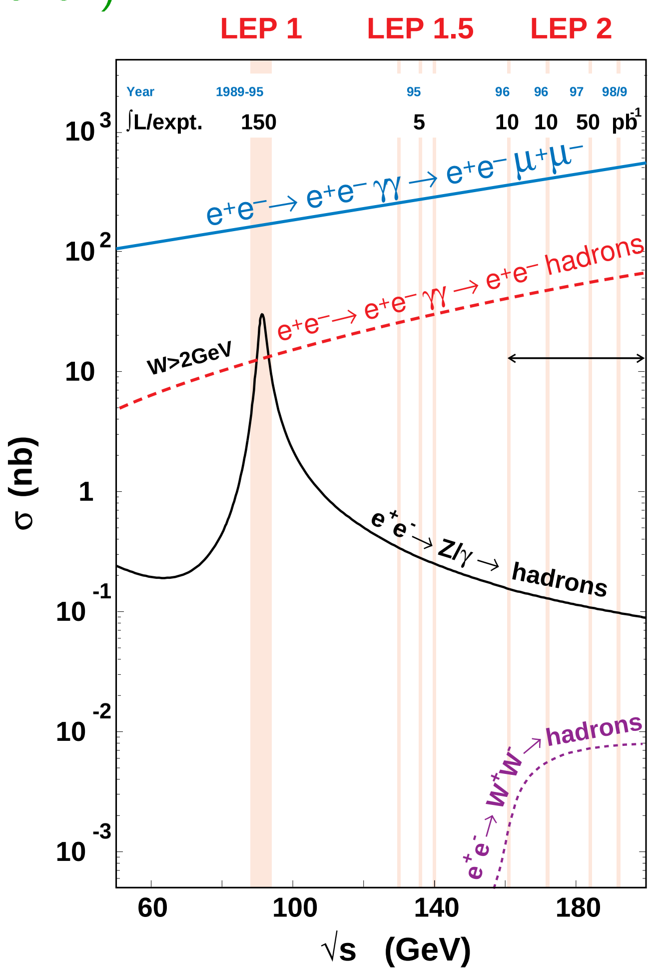
- Total Hadronic Cross Sections
- Heavy Quark Production
- Jet Production

Two-photon Collisions

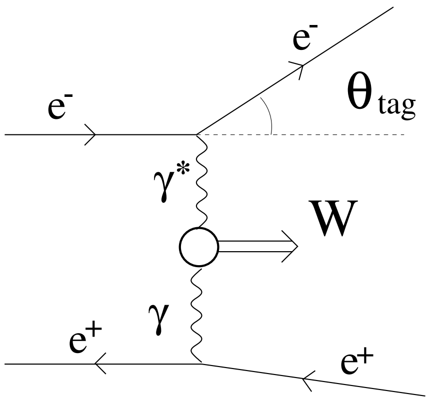
$\gamma\gamma$ collisions are studied at e^+e^- colliders (PEP, PETRA, LEP) and at ep colliders (HERA).

LEP collider is good place to learn from $\gamma\gamma$ physics:

- ee: clean events, with few particles.
- $\sqrt{s}$: several high E_{CMS}, gives access to different x, Q^2 regions.
- $\sigma \propto \ln\sqrt{s}$, opposite to annihilation processes (Z, WW, ZZ production).



Two-photon Collisions



$Q_i^2 = -q_i^2 = 2E_B E_{tag}(1\text{-}\cos\theta_i)$
photon virtuality

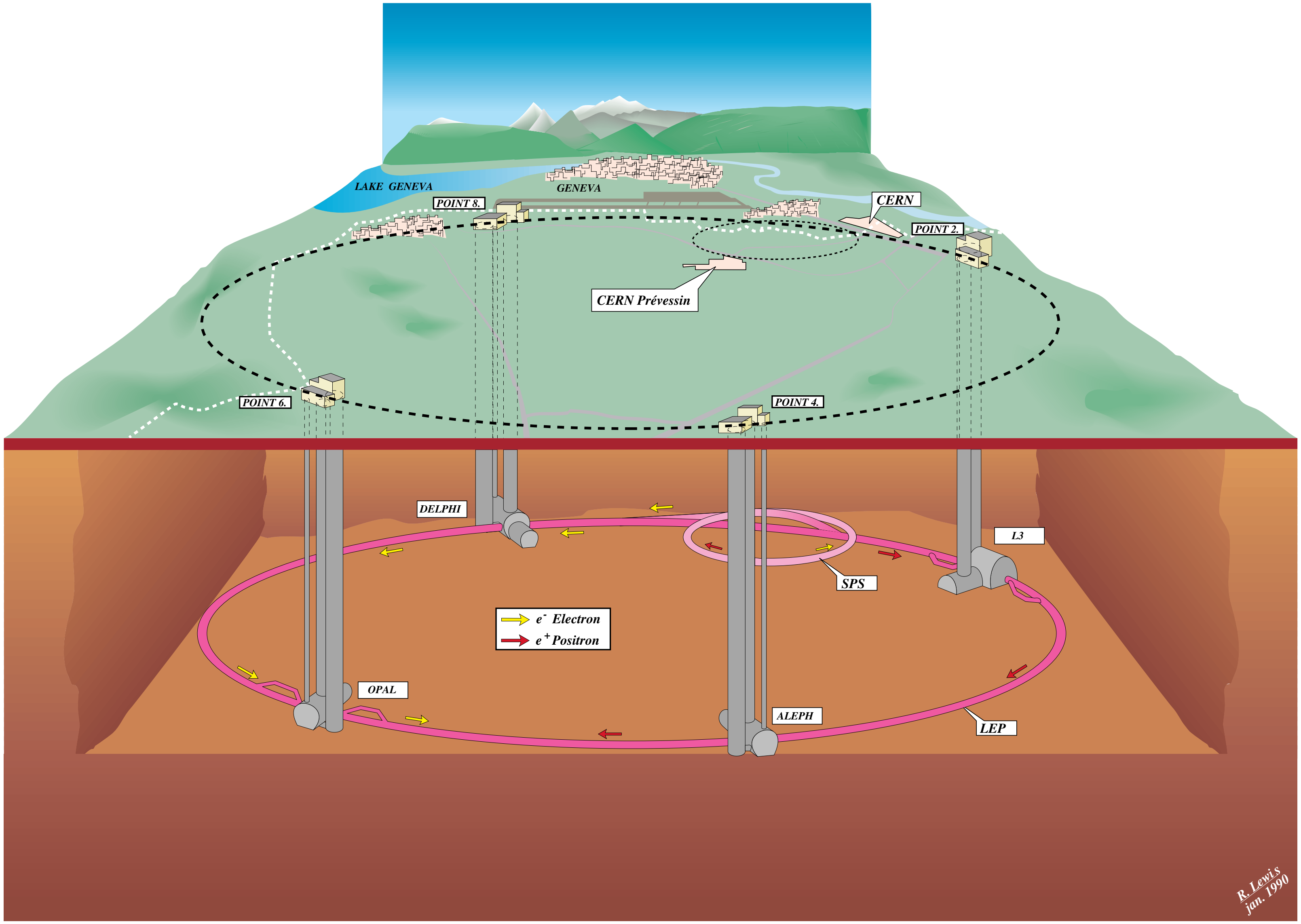
$W_{\gamma\gamma}^2 = (\sum E_p)^2 - (\sum p_p)^2$
$\gamma\gamma$ center of mass energy

After collision, most beam energy and momentum are carried away by scattered electron (positron).

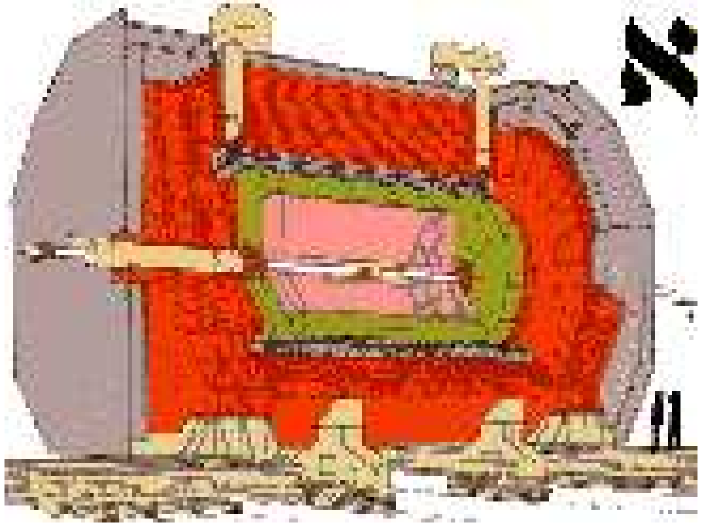
Different Scenarios:

- Real photons scattering ($Q_i^2 \approx 0$) Untagged events
- Electron photon DIS ($Q_1^2 \equiv Q_{tag}^2 > 0$, $Q_2^2 \approx 0$)
  Single tagged events
- $\gamma^*\gamma^*$ collision ($Q_1^2 \equiv Q_{tag}^2 > 0$, $Q_2^2 \equiv Q_{stag}^2 > 0$)
  Double tagged events

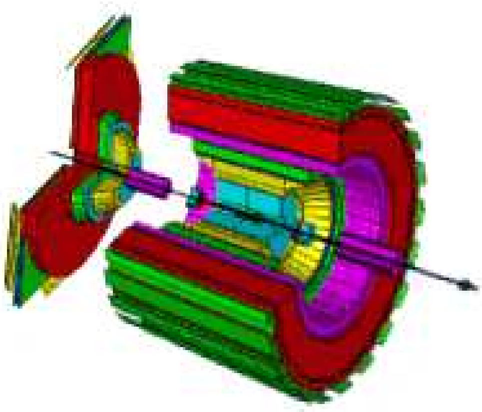
LEP Collider



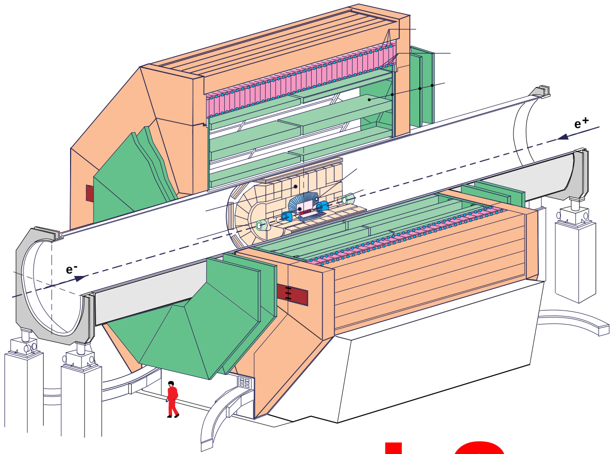
LEP Detectors



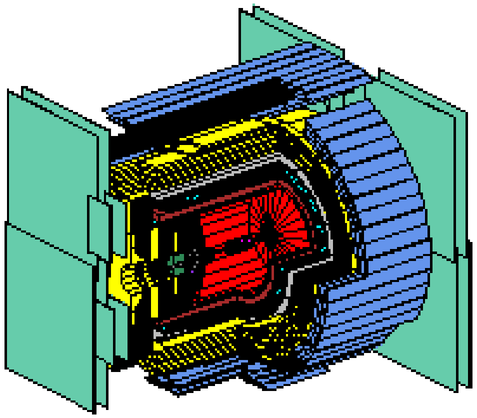
ALEPH



DELPHI

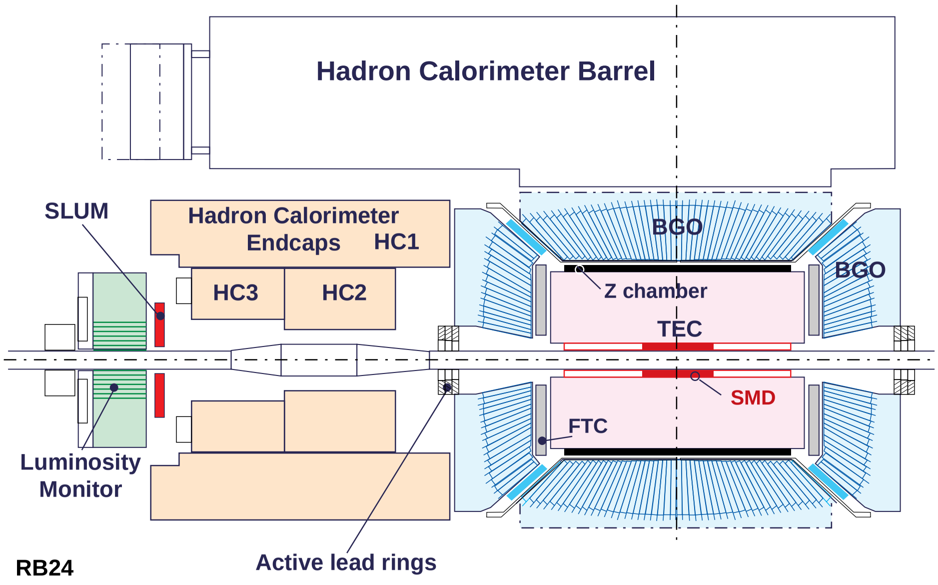


L3



OPAL

Inner L3 Detector



- Central track detector **TEC, SMD**:
  momentum of charged tracks, vertices.

- Electromagnetic calorimeter **BGO**:
  energy and position of electromagnetic clusters.

- Luminosity Monitor **LUMI** $(30 < \theta < 63$ mrad$)$
  and Small Angle Tagger **VSAT** $(5 < \theta < 10$ mrad$)$:
  energy and polar angle from scattered electrons.

e^+e^- collisions at LEP

Year	$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1}) per experiment
1989-95	88–94	150
1995	130 – 140	5
1996	161	10
	170–172	10
1997	183	55
1998	189	175
1999	192	30
	196	80
	200	80
	202	40
2000	200–209 (mainly at 205 and 207)	170

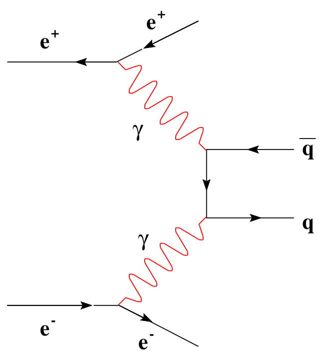
...and continue until 2nd November 2000.

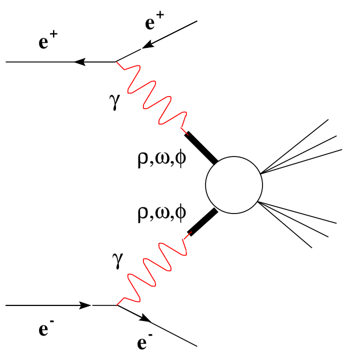
Hadronic Cross Section

The proccess $\gamma\gamma \rightarrow hadrons$ may take place via:

direct coupling: photon couples to $q\bar{q}$ pair

Vector meson coupling: photon fluctuates into $q\bar{q} \equiv$ vector meson (ρ, ω, ϕ ...)

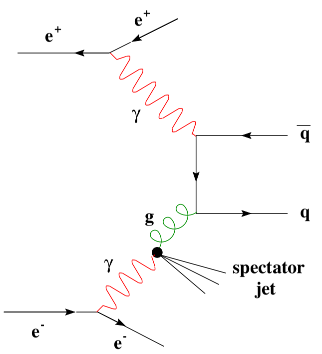


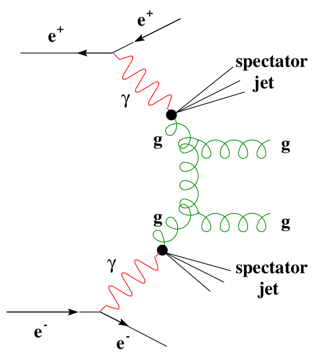


In hard scatterings photon may exhibit its hadronic nature, as a composite particle

single resolved coupling: a gluon from a photon couples 'directly' to the other photon

double resolved coupling: both γ are 'resolved', being the gluons the participants in the collision





The quantities and properties of these components are not yet fully understood

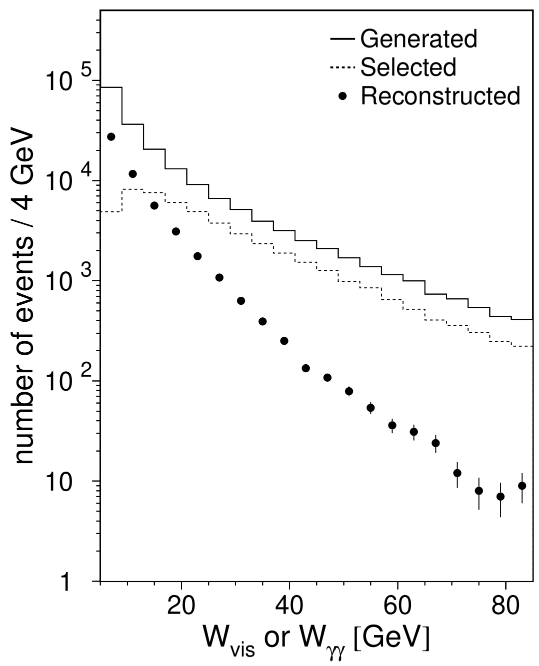
$\sigma_{\gamma\gamma}$ dependence with $\sqrt{s_{\gamma\gamma}}$

Due to detector effects (Lorentz boost of $\gamma\gamma$ system) and to event dynamics (large diffractive cross-section)

$$W_{vis} < W_{\gamma\gamma} \equiv \sqrt{s_{\gamma\gamma}}$$

Procedure $W_{vis} \Longrightarrow W_{\gamma\gamma}$: Unfolding

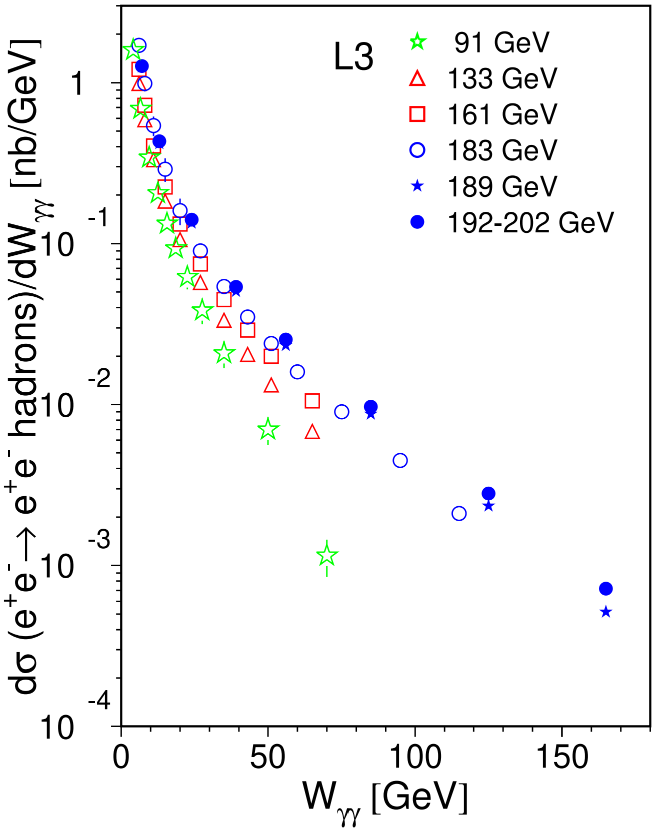
- Relies in good modelling of data (Pythia, Phojet,...)
- Demands high statistics MC.
- Different techniques and programs used by experiments.



Results are MC dependent!!

Hadronic Cross Section

$\boldsymbol{\sigma}$(ee$\longrightarrow$ ee hadrons)



Shape dominated by $\mathcal{L}_{\gamma\gamma}$

$\boldsymbol{\sigma_{ee}}$ decreases with W$_{\gamma\gamma}$

$\boldsymbol{\sigma_{ee}}$ increases with $\sqrt{s_{ee}}$

Extract $\sigma_{\gamma\gamma}$ from σ_{ee}

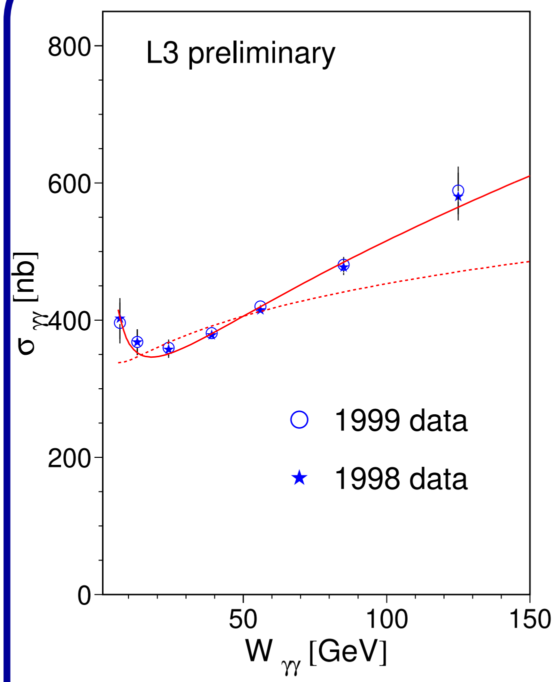
$$\frac{d^4\sigma_{ee}}{dy_1 dQ_1^2 dy_2 dQ_2^2} == \frac{d^4\mathcal{L}_{\gamma\gamma}}{dy_1 dQ_1^2 dy_2 dQ_2^2}\,\sigma_{\gamma\gamma}(W,Q_1^2,Q_2^2)$$

$$\sigma_{\gamma\gamma}(W,Q_1^2,Q_2^2) = F(Q_1^2)F(Q_2^2)\,\sigma_{\gamma\gamma}(W,0,0)$$

$y_i = \frac{E_\gamma}{E_e}$ Quasi-real photons, $< Q^2 >\approx 10^{-3}$ GeV^2

F(Q_1^2) Photon Form Factor

Hadronic Cross Section



$\sigma_{\gamma\gamma}$ expected to behave like σ_{pp} or $\sigma_{\gamma p}$.

Universal Donnachie and Landshoff param.

$\sigma_{\gamma\gamma} = \mathrm{A}s^{\epsilon} + \mathrm{B}\ s^{-\eta}\ ,\quad s = W^2_{\gamma\gamma}$

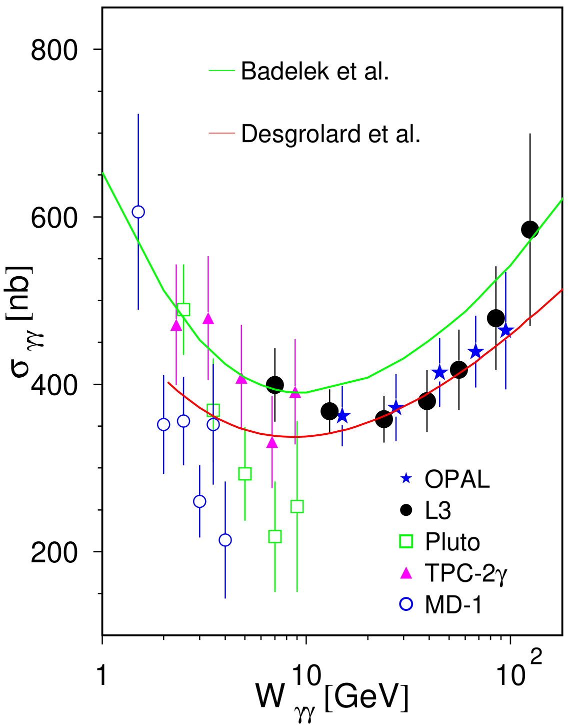
PDG98: $\epsilon = 0.095 \pm 0.002$, $\eta = 0.34 \pm 0.02$, A,B free

Fit to L3 data (η fixed): $\epsilon = 0.250 \pm 0.016$

$\Longrightarrow \sigma_{\gamma\gamma}$ increases faster than σ_{pp} or $\sigma_{\gamma p}$

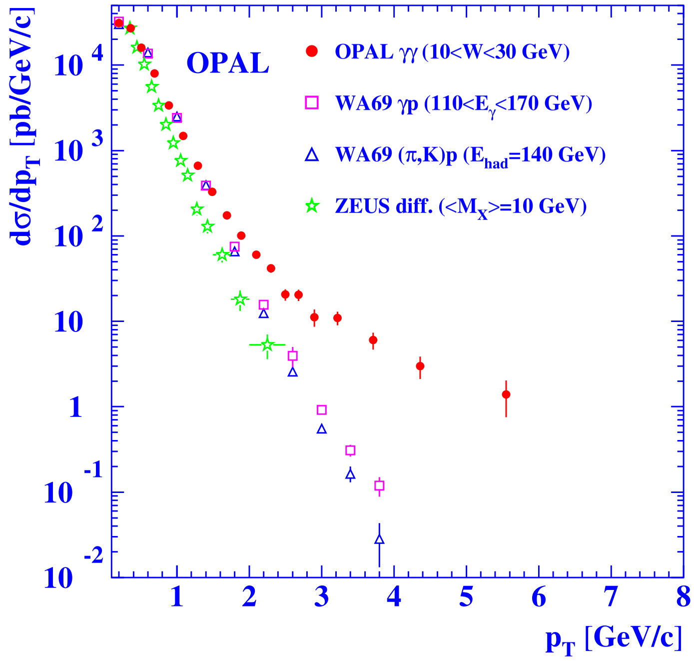
At LEP, first time $W_{\gamma\gamma} > 20$ GeV has been explored.

Good agreement between L3 and OPAL data



Inclusive Hadron and Jet production

$d\sigma/dp_t$ Hadrons

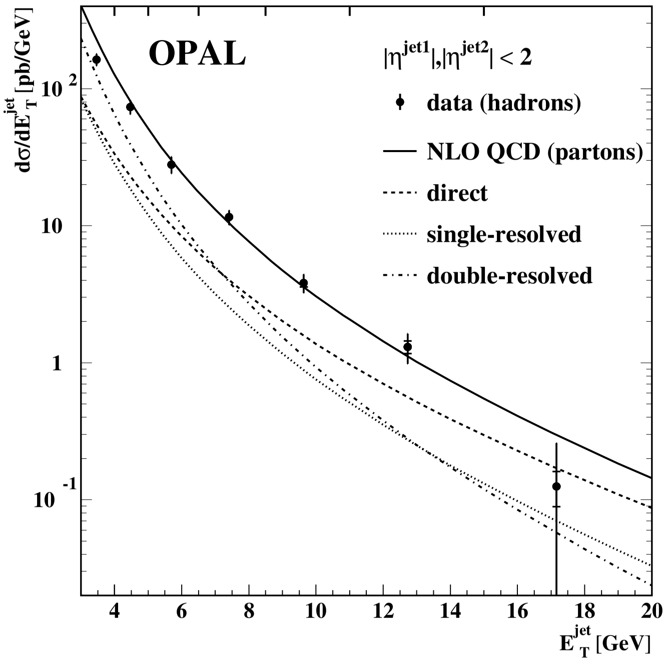


Significant increase of 'hard' ($p_t > 2$ GeV/c) interactions compared to γp or $(\pi,K)p$, due to direct process

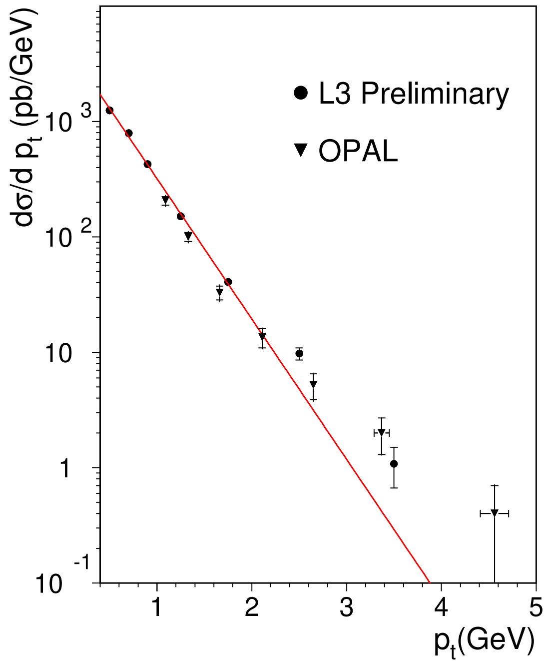
NLO QCD (Binnewies et al.) describes well data.

Note contribution of direct process at high p_t region.

Aleph results also agree with NLO QCD description.

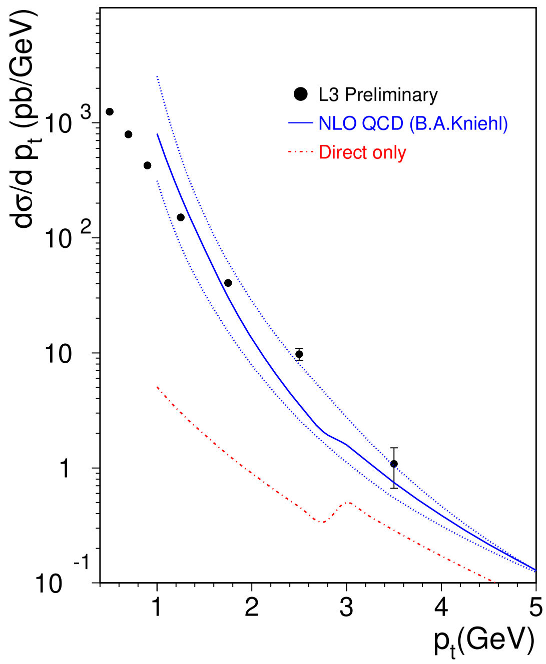


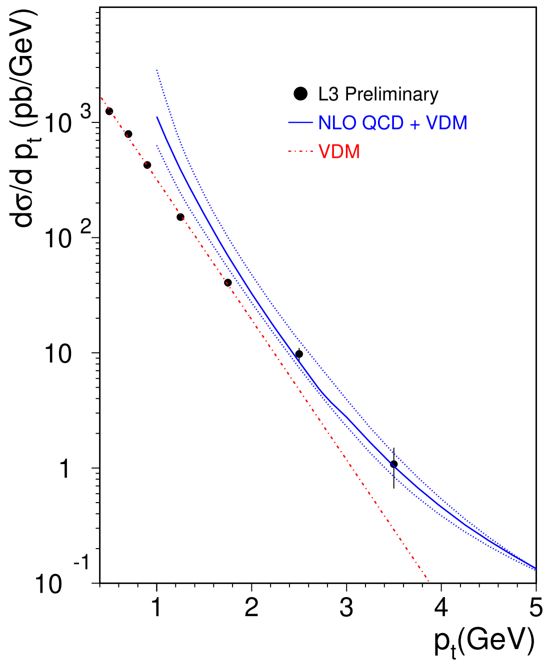
$d\sigma/dp_t\ K^0_S$



Exponential fit in low p_t region
$<p_t> = 357 \pm 8$ MeV

Hard interactions contribute at high p_t.



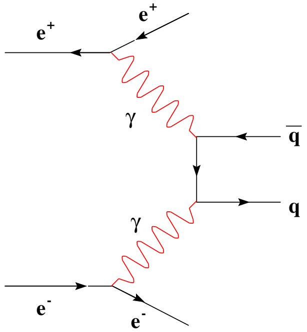


NLO QCD predictions + VDM exponential fit reproduce better data at high p_t.

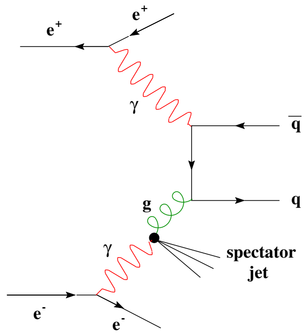
Inclusive Hadron and Jet production

Jet production

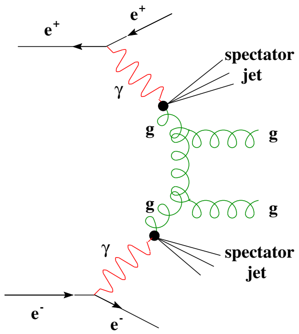
Tool to distinguish direct/resolved processes $\Longrightarrow$ constrain the gluonic content in γ



Direct
2 jets



Single resolv.
3 jets



Double resolv.
4 jets

In similarity with γp events at HERA, define

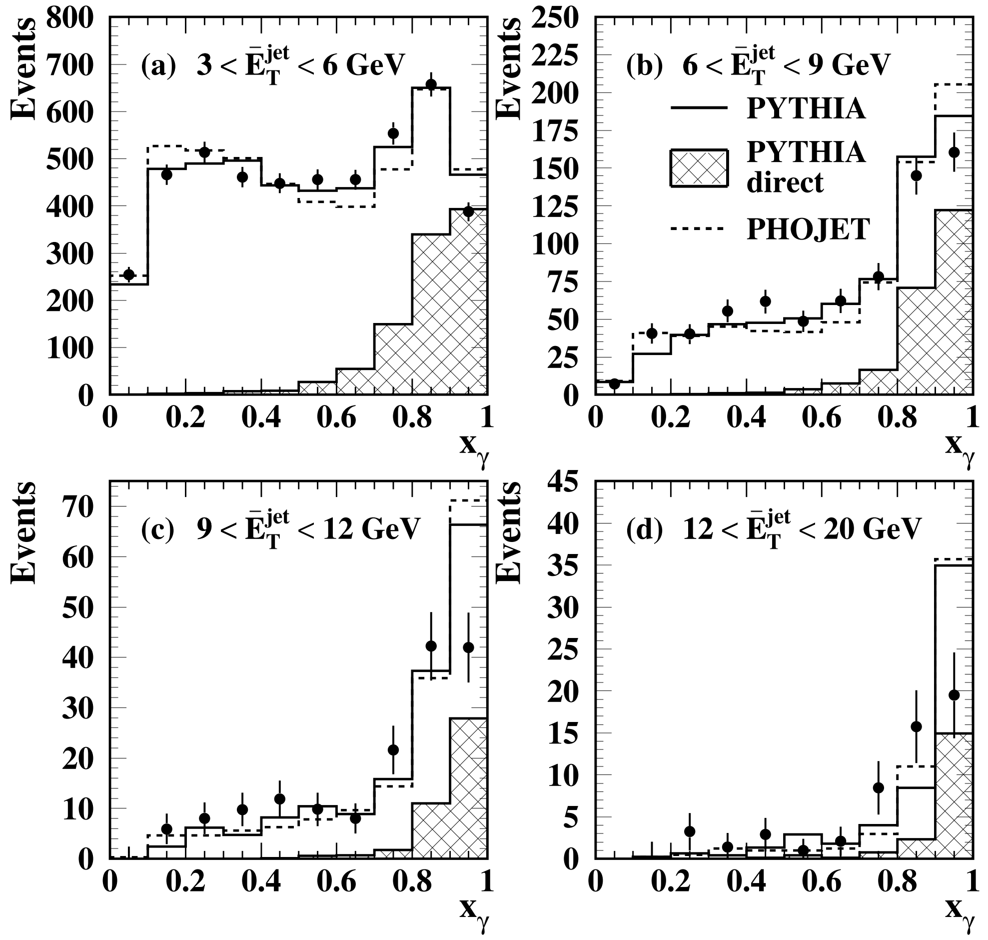
$$x_\gamma^\pm = \frac{\sum_{jets=1,2}(E \pm p_z)}{\sum_{hadrons}(E \pm p_z)}$$

Fraction of the γ energy carried by the parton entering the hard scattering.

$$x_\gamma \begin{cases} = 1 & \text{Direct process} \\ < 1 & \text{Resolved process} \end{cases}$$

Uncorrected x_γ distributions for increasing $\bar{E}_T^{jet}$

OPAL

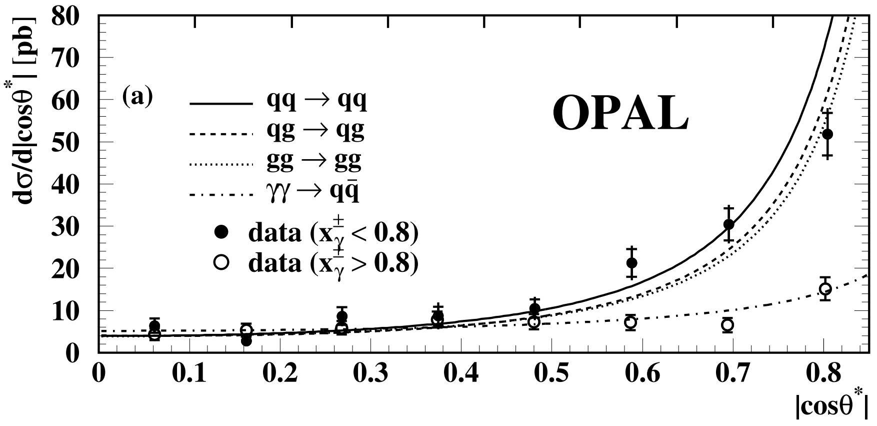


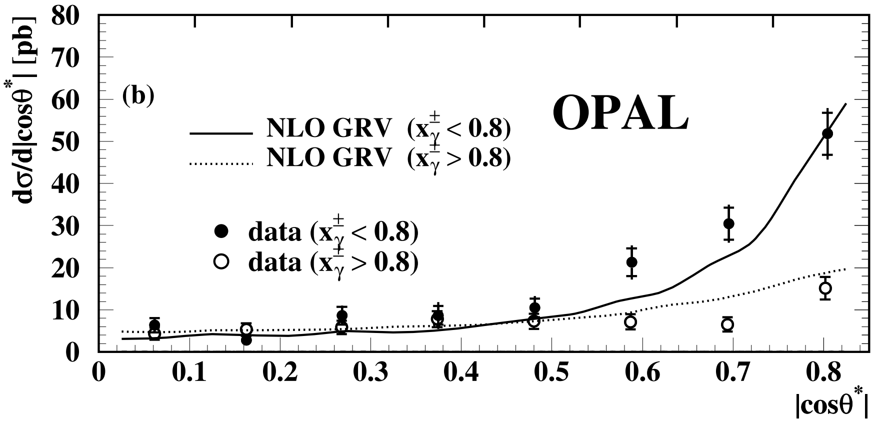
In practice, x_γ(direct process) >0.8,
x_γ(resolved process) <0.8

From Pythia, 86% evts with $x_\gamma^\pm$ >0.8 originate from direct interactions,
81% evts with $x_\gamma^\pm$ <0.8 originate from double-resolved processes.

At high $\bar{E}_T^{jet}$ data is dominated by direct interactions.

Jet angular distribution in the di-jet center-of-mass system





LO QCD predicts angular dependence:

Direct $\propto (1 - \cos^2\theta^*)^{-1}$ $\gamma\gamma \rightarrow$ q $\bar{\text{q}}$ mediated by t-channel spin 1/2 quark exchange

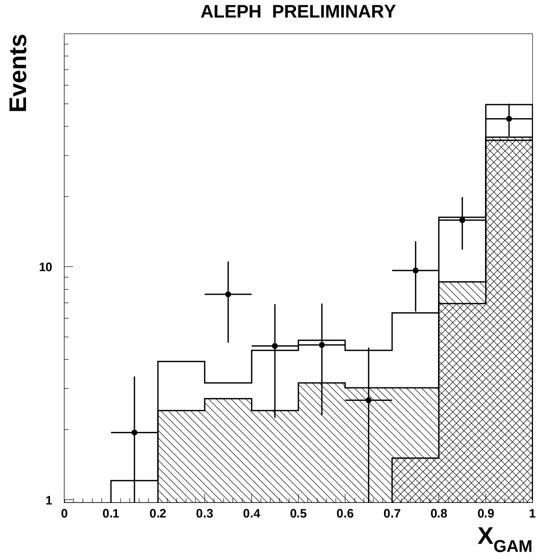
Double resolved $\propto (1 - |\cos\theta^*|)^{-2}$ qq → qq, qg → qg, gg →gg with a large contribution from spin-0 gluon exchange.

The distribution of partons and their momenta inside photon is parametrized by parton density functions (pdf).

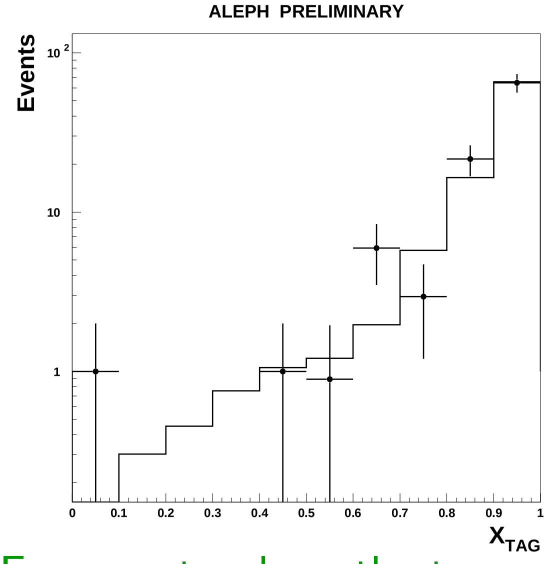
NLO QCD, with GRV (Glück, Reya, Vogt) parametrization, agree well (after normalization) with x_γ discrimination of direct and resolved processes.

Inclusive Hadron and Jet production

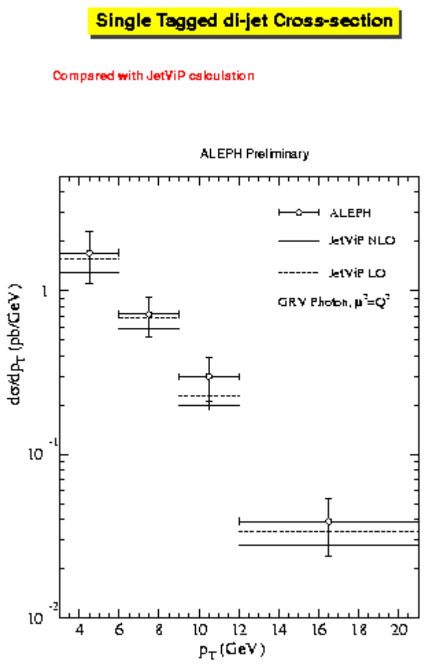
Aleph Dijet production in single-tagged events



Data well described by HERWIG MC



Few events where the tagged photon is resolved (low x_{tag})



Dijet cross section in tagged events is $\sim$ 10 times smaller than in untagged data.

Heavy Quarks

- LO QCD predicts heavy quarks are produced mainly from direct ($\gamma\gamma \to$ qq) or single resolved (γg $\to$qq) processes. Double resolved (gg $\to$ qq) and VDM contributions are negligible.

- Open charm cross-section expected to be sensitive to gluon content in photon.

- Use untagged data, to perform comparison with pQCD (valid for photons on mass-shell).

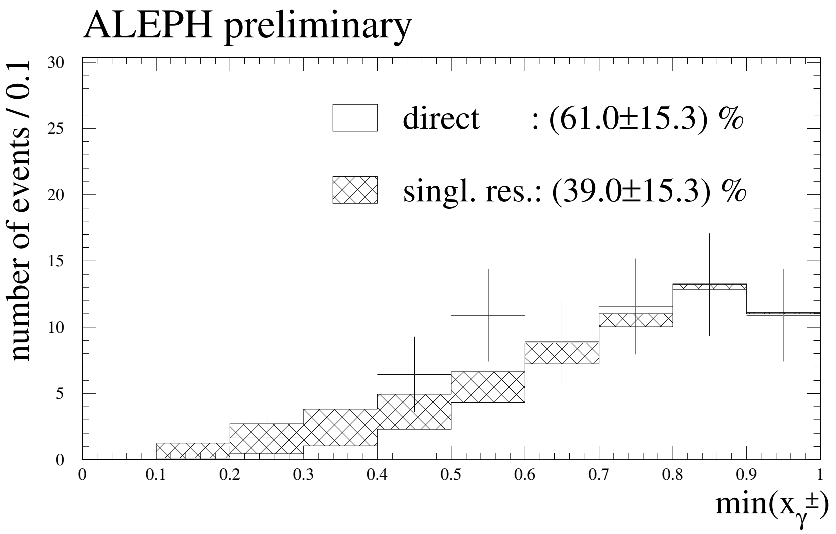
$D^{*\pm}$

Four experiments (ADLO) at LEP reconstruct $D^{*\pm}$ from mass difference technique in

$$D^{*\pm} \to D^0\pi_S^\pm \text{ with } \pi_S^\pm = \text{'soft' pion.}$$

$D^{*\pm}$

- Aleph, Opal define estimators (x_γ, $p_t^{D^*}/W_{vis}$) to compute fraction direct/single resolved processes.
  Fit data to MC with relative fraction as fit parameter.



Fraction (%) of direct interactions

	x_γ	$p_t^{D^*}/W_{vis}$
ALEPH	61.0 ± 15.3	62.7 ± 8.5
OPAL	46 ± 11	51 ± 9

No significant double resolved contribution is observed

- Reasonable agreement is observed between all measured $d\sigma/dp_t^{D^*}$ and $d\sigma/d\eta^{D^*}$ and predictions based on NLO pQCD calculations.

- Delphi has measured D^0, D^+ and Λ_c production cross-section.

Charm Production

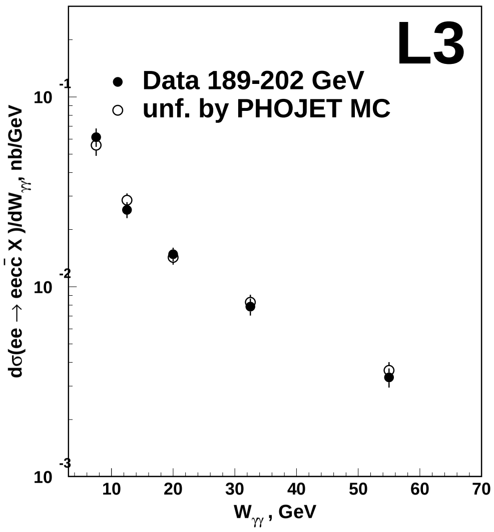
$$\boxed{\sigma(ee \rightarrow ee c\bar{c} X)}$$

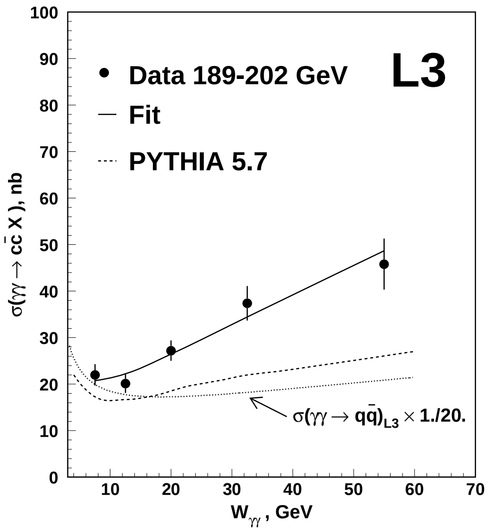
- Direct measurement selecting inclusive charmed evts identifying e (L3), μ (Aleph) from semileptonic decays.

- Indirect measurement from D* cross-section (Delphi, Opal)

$$\boxed{\sigma(\gamma\gamma \rightarrow c\bar{c}X)}$$

- $\sigma(\gamma\gamma \rightarrow c\bar{c}X)$ vs. $\sqrt{s_{\gamma\gamma}}$ extracted for first time (L3) (Unfolding techniques needed).





- Compared to pp and $\gamma\gamma \rightarrow hadrons$ cross-sections, $\sigma(\gamma\gamma \rightarrow c\bar{c}X)$ presents a steeper rise with energy.

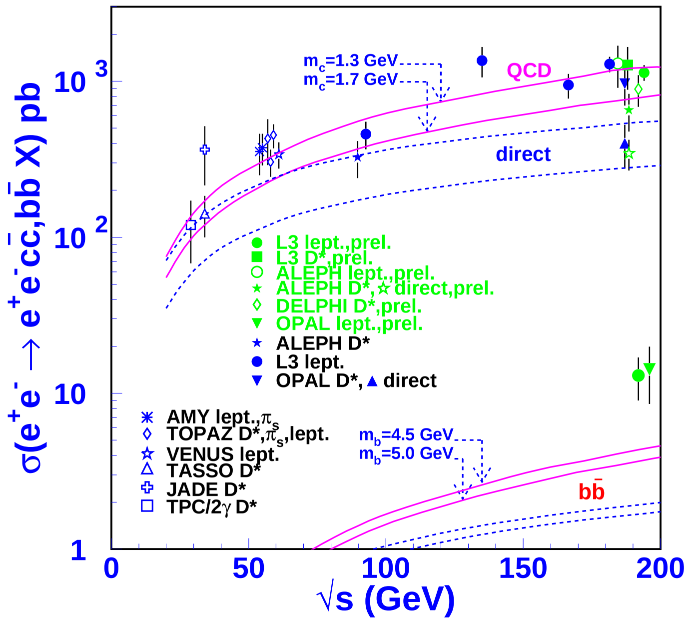
- A fit to Donnachie & Landshoff param. (σ = A s^{ϵ}+B $s^{-\eta}$, ϵ(PDG)=0.095 ±0.002) gives $\epsilon = 0.400 \pm 0.062 \pm 0.096$ (η fixed).

$\sigma(ee\to eeb\bar{b}X)$

At LEP $b\bar{b}$ pair production is suppressed 1-2 orders magnitude with respect to charm production.

- b quark is heavy $\Longrightarrow$ need $\sqrt{s_{\gamma\gamma}} \geq 10$ GeV.
- photon couples to electric charge and q(b)< q(c).

$\sigma(ee\to eeb\bar{b}X)$ has been measured using semileptonic b decays into muons (OPAL, L3) and electrons (L3).



$\sigma(ee\to eeb\bar{b}X)$ is compared to NLO calculations (matrix elements with massive b, GRV pdf), showing a value more than 2 standard deviations higher.

A similar increase in $\sigma(ee\to eeb\bar{b}X)$ respect to NLO calculations has also been observed at γp collisions at HERA.

Photon Structure Function

If any of the scattered electrons are detected (tagged), to lowest order in α,

$$\frac{d^2\sigma_{e\gamma\to eX}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}[(1+(1-y)^2)F_2^\gamma(x,Q^2) - y^2 F_L^\gamma(x,Q^2)]$$

F_2^γ, F_L^γ Photon Structure Functions

$Q^2 = -q^2$, virtuality of the probe photon

$x = \frac{Q^2}{Q^2+P^2+W_{\gamma\gamma}^2}$, $y = 1-(\frac{E_{tag}}{E_b})\cos\theta_{tag}{}^2$, DIS variables

$P^2 = -p^2$, mass of the quasi-real target photon

- Single tagged $P^2 \simeq 0$, e_{tag} detected at small angles ($y \sim 0$) $\Longrightarrow$ cross section measurement is not sensitive to $F_L^\gamma(x,Q^2)$.
- Double tagged Both structure functions contribute in F_{eff}.

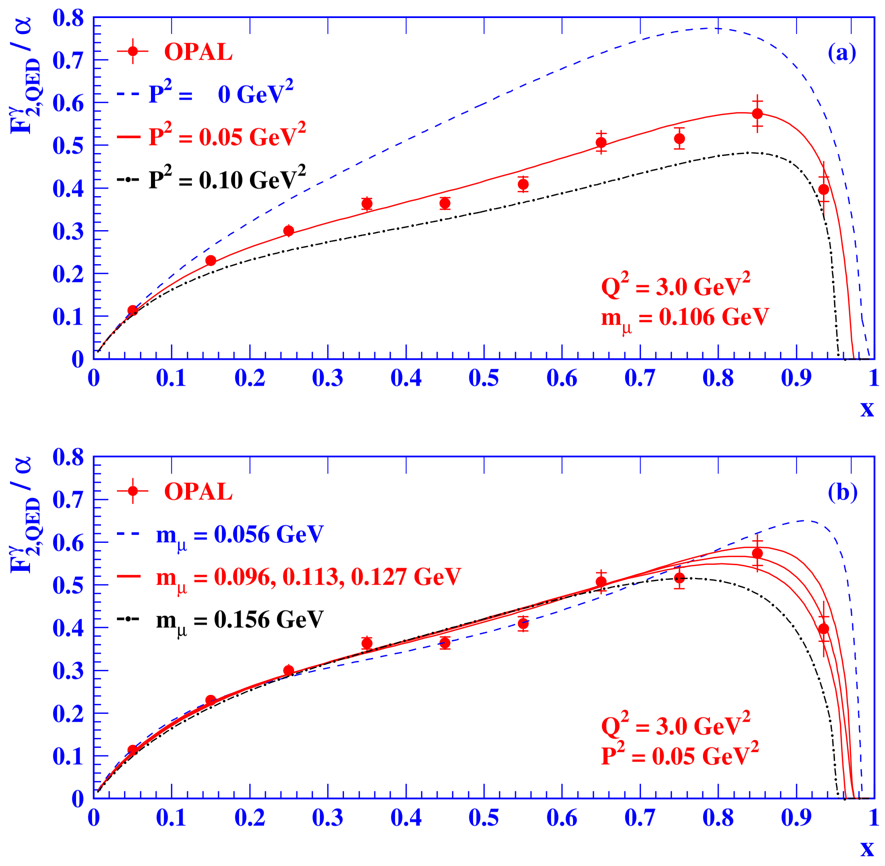
Depending on final state X

- leptonic $(\mu^+\mu^-) \Longrightarrow F_2^\gamma$,QED
- hadronic $\Longrightarrow F_2^\gamma$,QCD

F_2^{γ},QED

- F_2^{γ},QED exactly calculable. Data and QED expectations agree in Q^2 region [0.1 – 400] GeV^2.

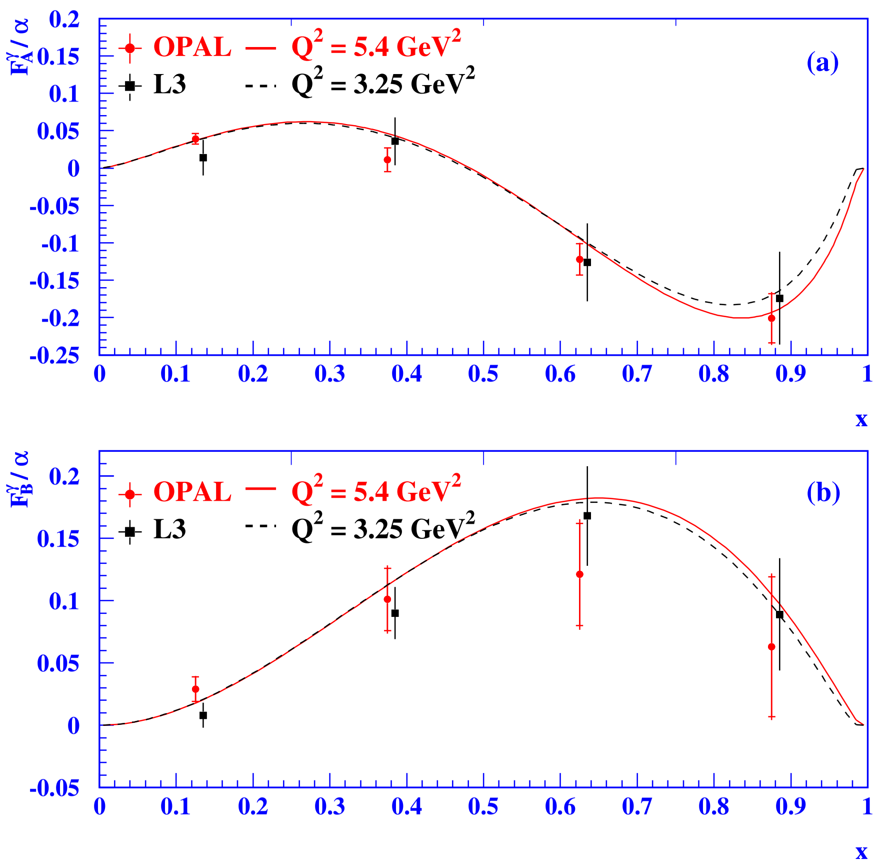
- LEP data so precise, small virtuality of quasi-real γ can be established.



- Also present in F_2^{γ},QCD; pdf must take target photon virtuality into account.

Photon Longitudinal Component

❖ In $\mu^+\mu^-$ final states, the distribution of azimuthal angle χ (between e_{tag} and $\mu^+\mu^-$ pair in $\gamma^*\gamma$ C.M.S.) gives information on F_L^γ, through F_A^γ and F_B^γ



F_A^γ and F_B^γ are different from 0 and vary with x as predicted by QED $\Longrightarrow$ Longitudinal photon component $\neq 0$ in single tag evts.

Photon Structure Function, QED

$\gamma^*\gamma^*$ Collisions

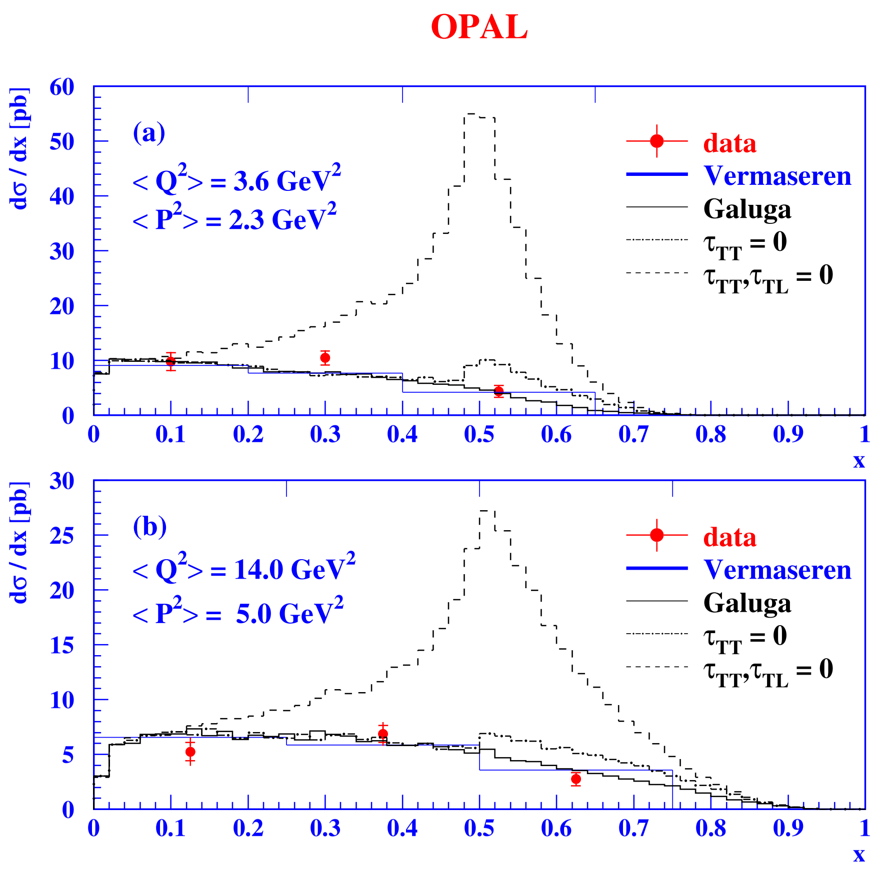
Untagged interactions: both γ real, $\sigma = \sigma_{TT}$

Single Tag interactions: $\gamma\gamma^*$, $\sigma \sim \sigma_{TT} + \sigma_{TL}$ $\sigma_{\mathrm{TargetProbe}}$

Double Tag interactions: $\gamma^*\gamma^*$,

$$\sigma \sim \sigma_{TT} + \sigma_{TL} + \sigma_{LT} + \sigma_{LL} + \tau_{TT}\cos 2\bar{\phi} - \tau_{TL}\cos\bar{\phi}$$

τ_{TT}, τ_{TL} Interference terms



Contributions from interference terms are not negligible, and reduces cross-section, especially at medium x values.

F_2^γ,QCD

QCD expression for F_2^γ has two parts

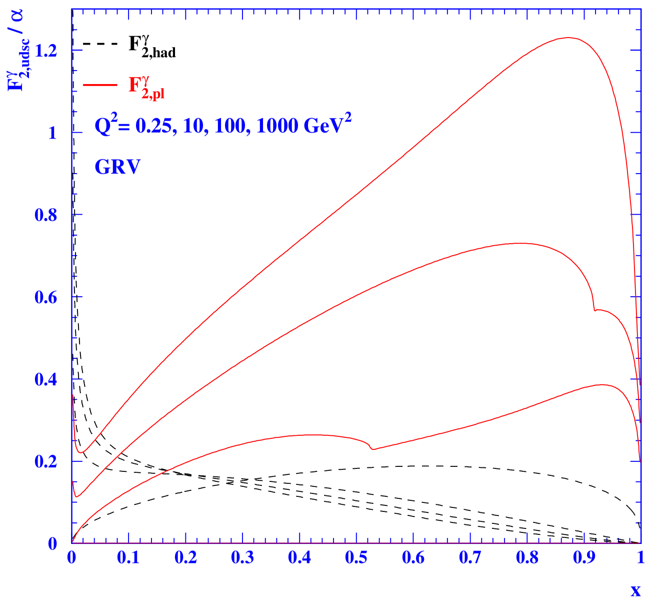
- Pointlike component, calculable in pQCD and dominant at high x and high Q^2.
- Hadronic component, not calculable in pQCD, dominant at small x values.

$$F_2^\gamma(x,Q^2) = x \sum_f e_i^2 q_i^\gamma(x,Q^2)$$

with f number active flavours,

e_i quark charge

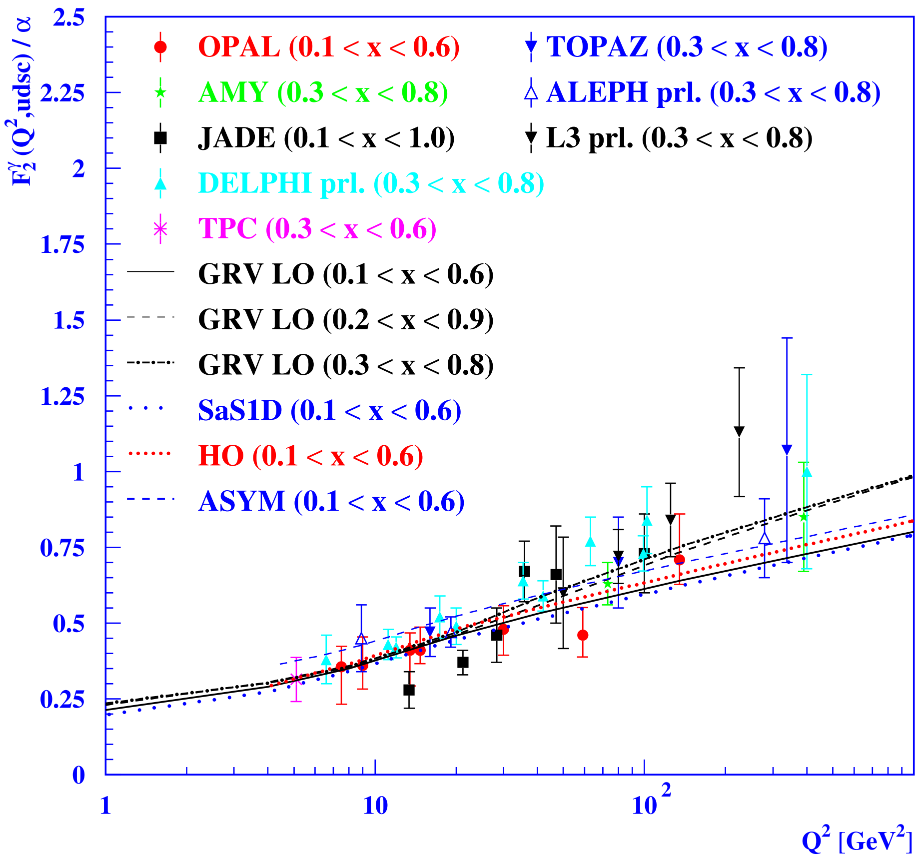
q_i^γ photon parton density function



- LEP has provided an increase in precission and enlarged Q^2, x ranges
- Still, unfolding techniques and big differences in MC lead to big systematic errors in F_2^γ.

F_2^γ,QCD versus Q^2

- pQCD predicts evolution of F_2^γ as $\ln Q^2$.



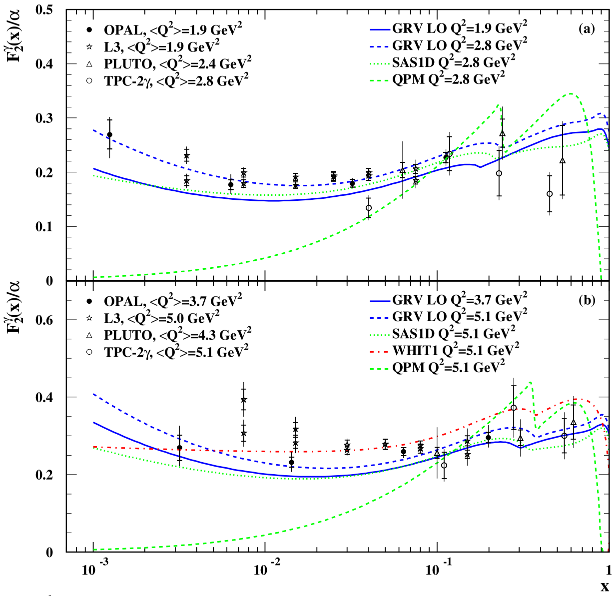
Data is compatible with this behaviour

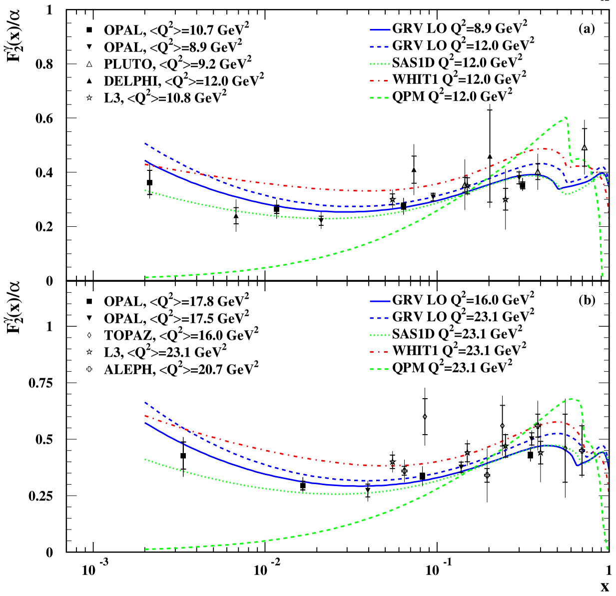
- Different parton densitiy functions used, which account for distribution of quarks and gluons inside photon.

Photon Structure Function, QCD

F_2^γ,QCD at low x

Some theoretical models predict a rise in F_2^γ at low values of Bjorken x (as happens with F_2^{proton}).



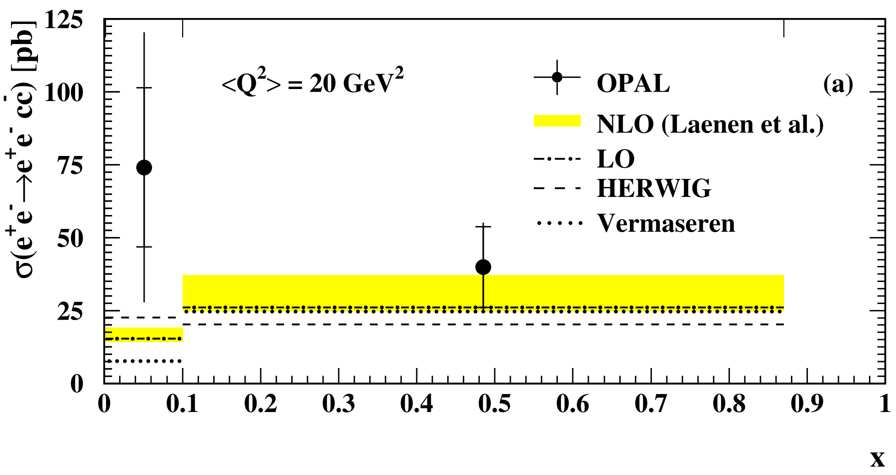


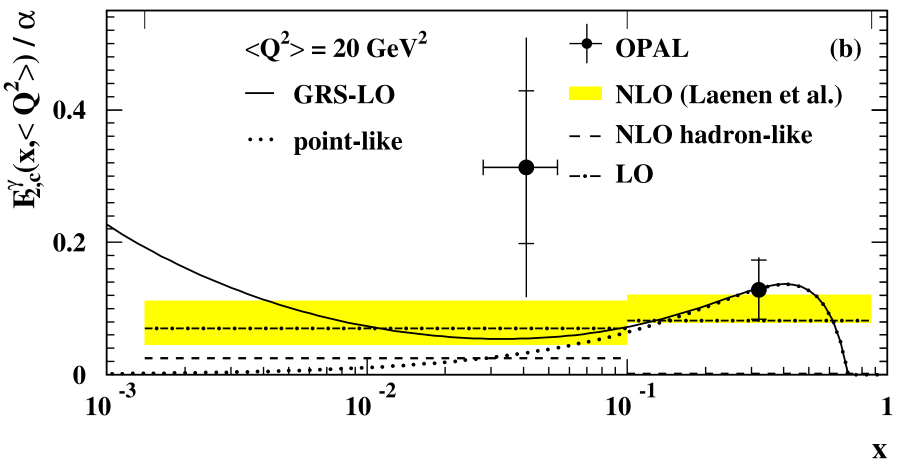
Data is not conclusive enough to confirm or exclude such rise, in spite of improvements (2-d unfolding).

GRV-LO and SaS-1d param. describes data reasonably well, except at low x and low Q^2 values, where more gluon content is needed.

$F^{\gamma}_{2,c}$

- Opal has measured for the first time $F^{\gamma}_{2,c}$, from the charmed events sample ($D^{*\pm}$).





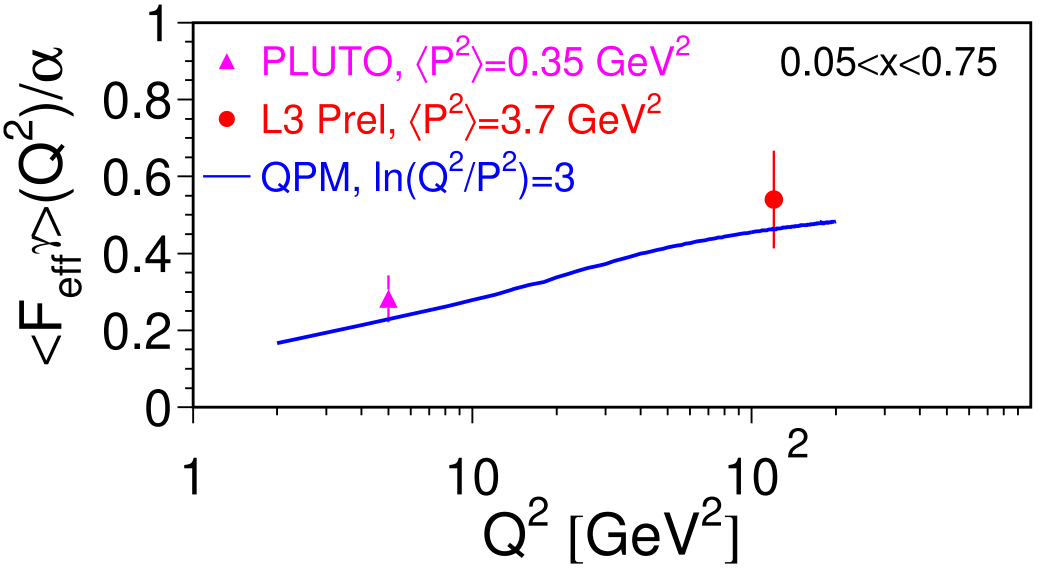
Regions in x: $0.0014 < x < 0.1$, $0.1 < x < 0.87$

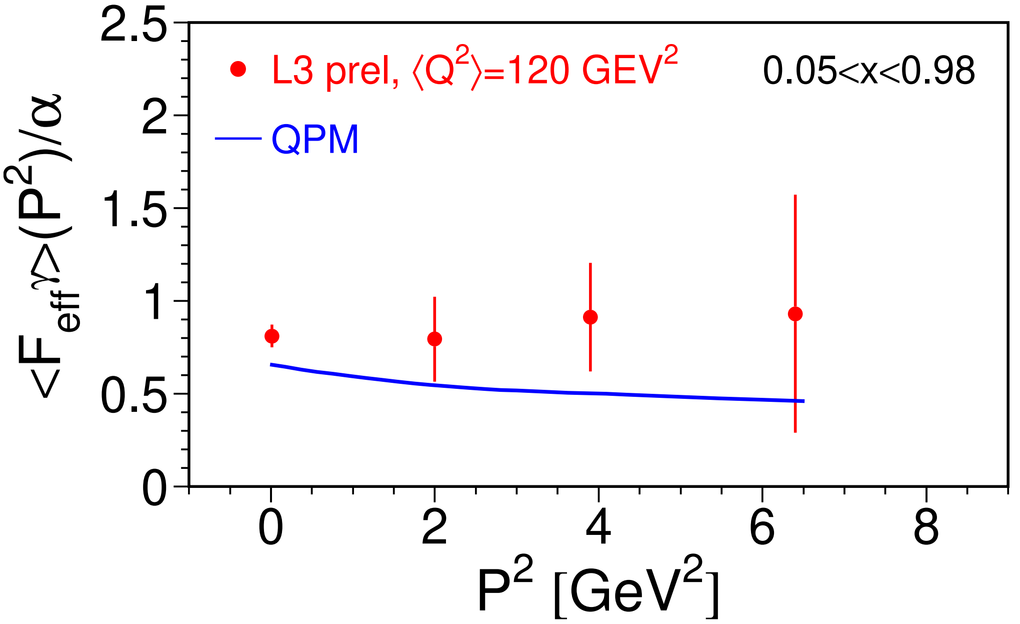
For x<0.1, measurement suffers from large uncertainty due to different MC predictions used in extrapolation and correction factors.

Photon Structure Function, QCD

F^{γ}_{eff}

- Use double tagged events with $<Q^2> = 120$ GeV^2, $<P^2> = 3.7$ GeV^2





In this case, the F^{γ}_{eff} dependence is on $\ln(Q^2/P^2)$.

Conclusions

- Two-photon physics is a very extense field, (Diffractive processes, Resonances...) with many sub-subjects.

- LEP2 is providing us with a lot of two-photon data, which allows achieving greater precission in measurements

- New and encouraging results have been obtained with last data

$\sigma_{\gamma\gamma}$,

dijet studies,

fisrt attempts to disentanle quark–gluon content in photon,

beauty production,

Structure function of the charm quark,

Structure function of virtual photons

- Still, MC simulation of physical processes must be developped beyond their present status, to be able to reproduce experimental data in all different configurations.