Two Photon Physics

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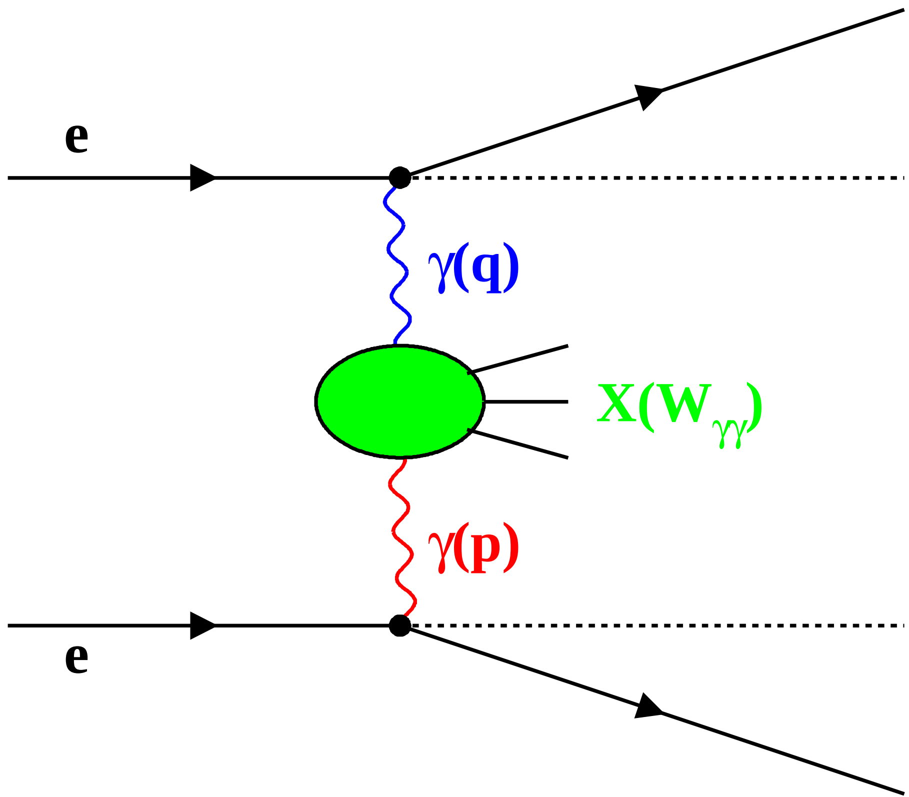
- Total $\gamma\gamma$ cross section
- Heavy flavour production
- $\gamma^*\gamma^*$ cross section
- Inclusive hadrons
- Exclusive final states
- Conclusions

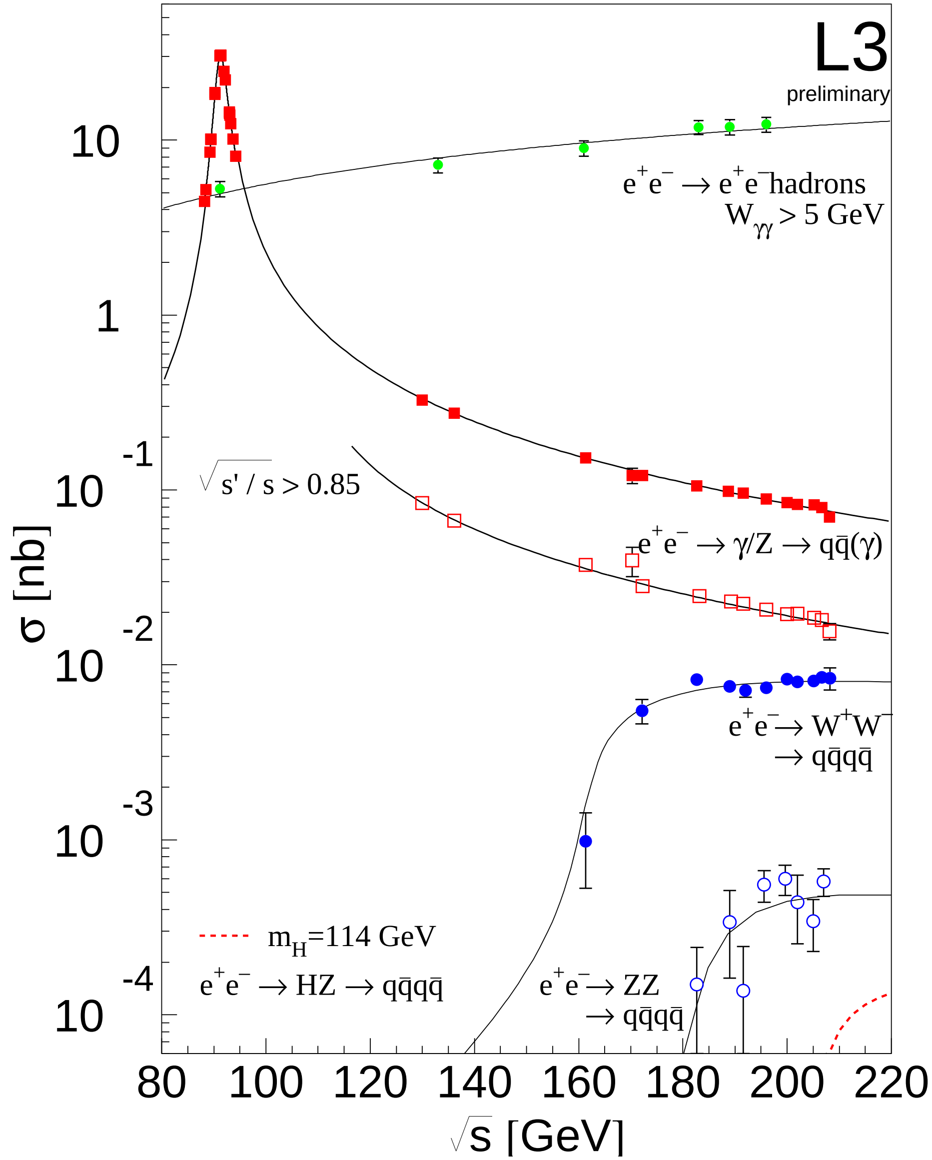
Selected results are presented

Two photon physics at LEP



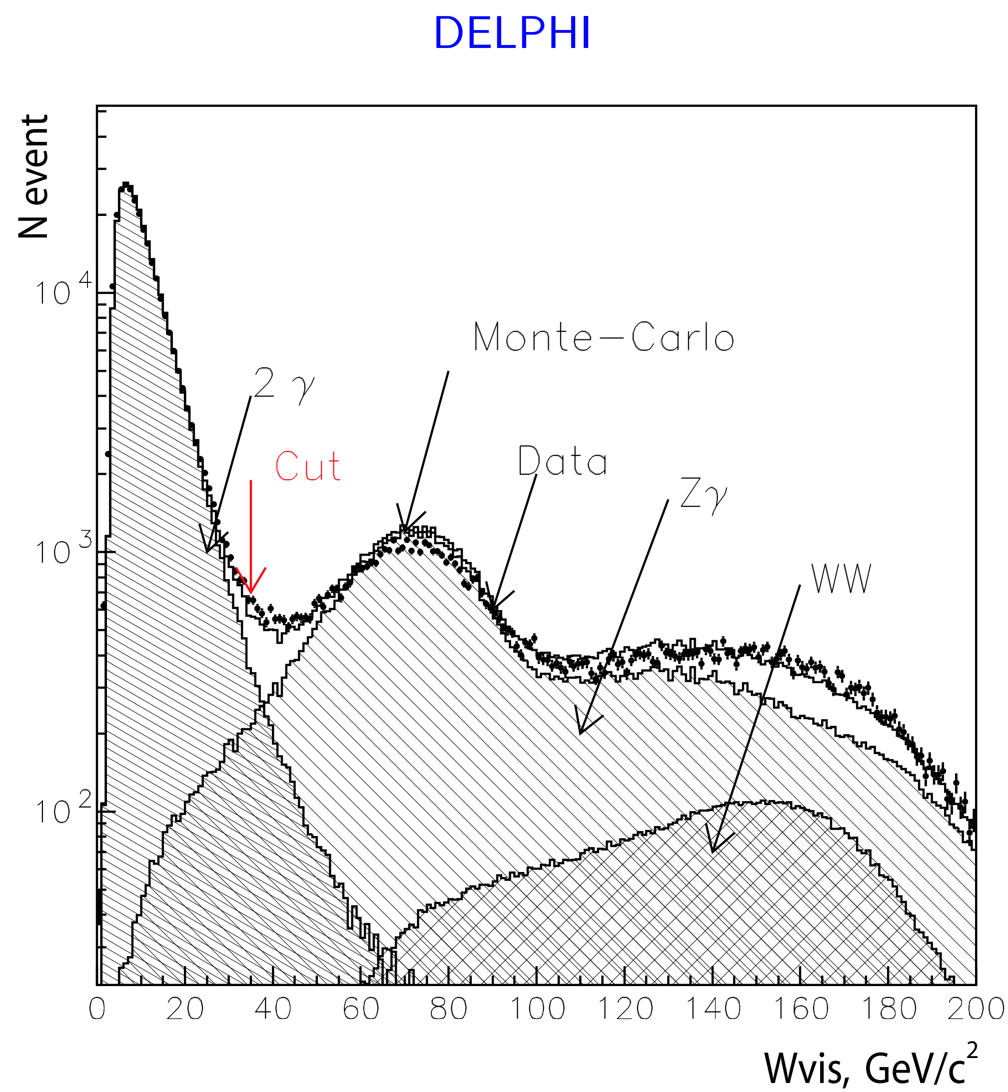
Hadron production at LEP

Two-photon collisions are the dominant source of hadrons at LEP2



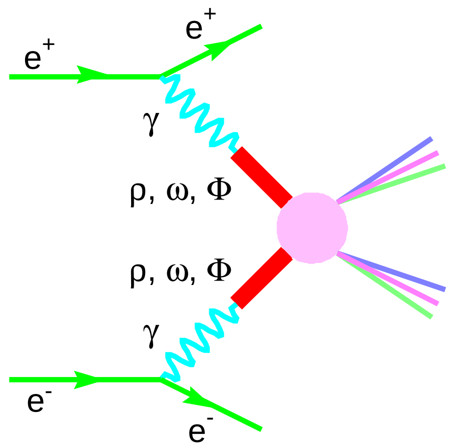
Selection of two photon events

Two-photon events have low visible mass or visible energy (energy escape with beam electrons and forward hadrons)



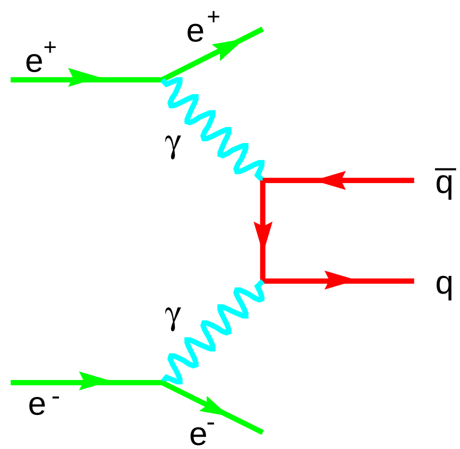
Hadronic final state in $\gamma\gamma$ collisions

SOFT:

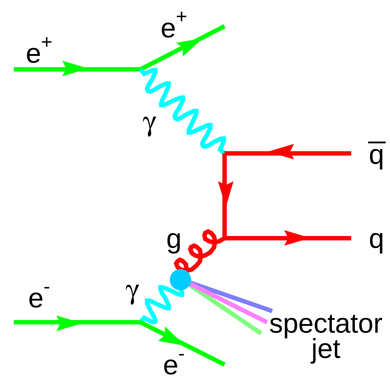


VDM

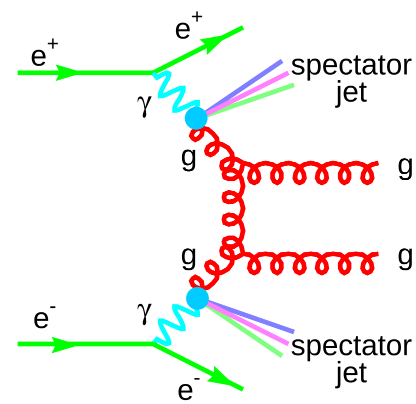
HARD:



Direct



Single Resolved



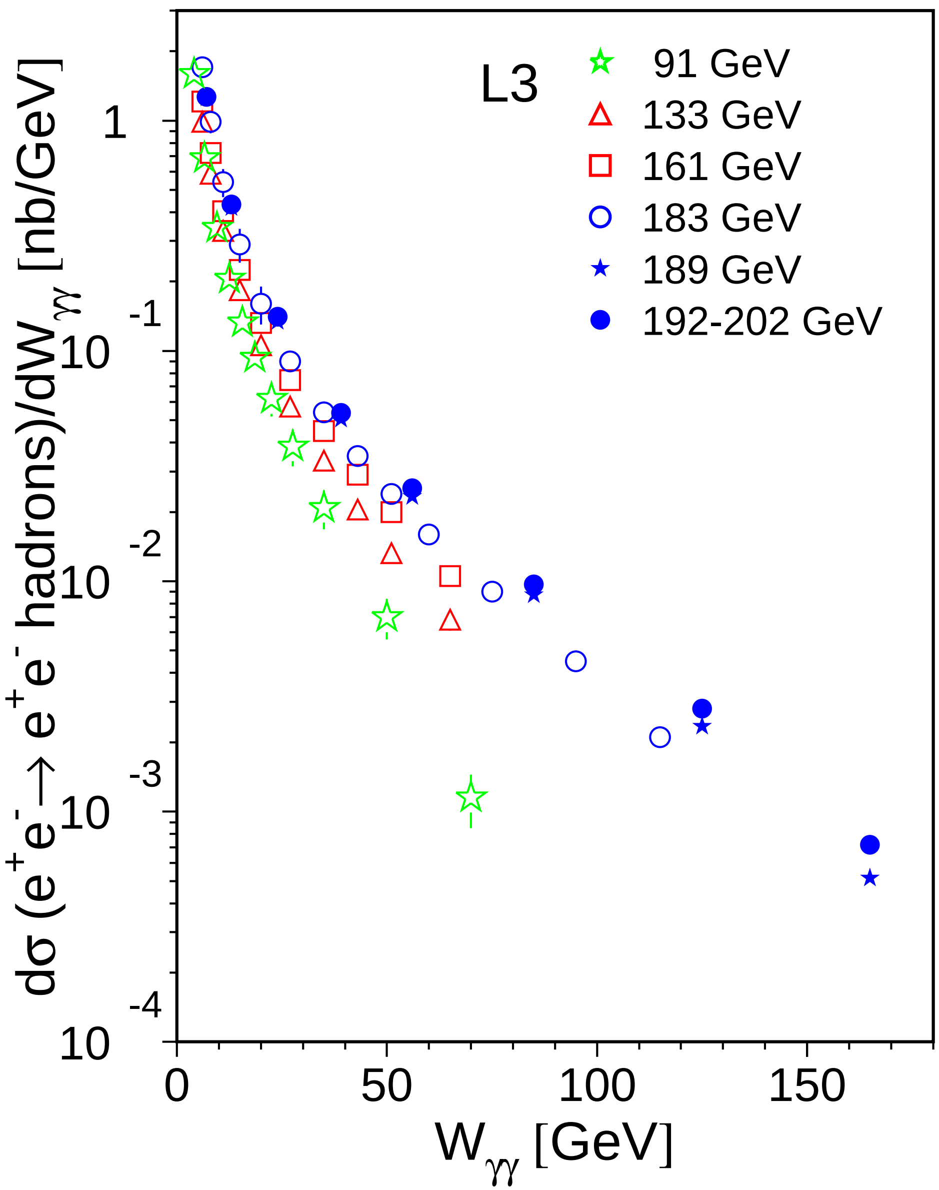
Double Resolved

Total $\gamma\gamma$ cross section

- increase with beam energy
- decrease with $W_{\gamma\gamma}$

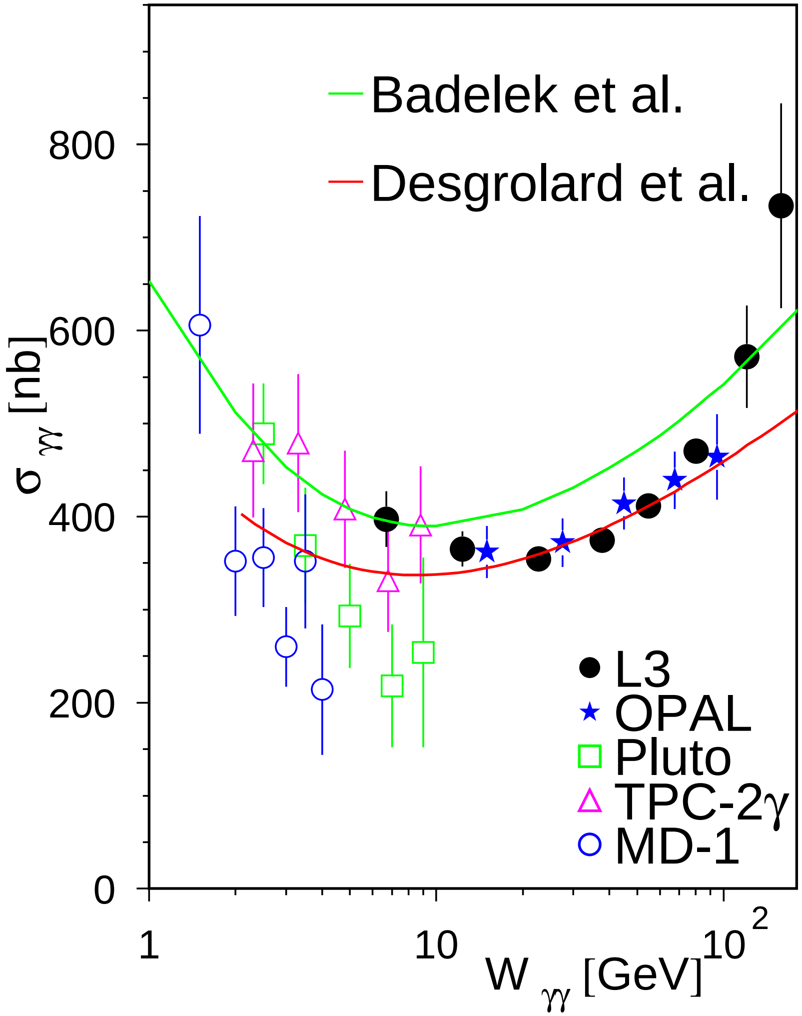
effect of the $\gamma\gamma$ luminosity function

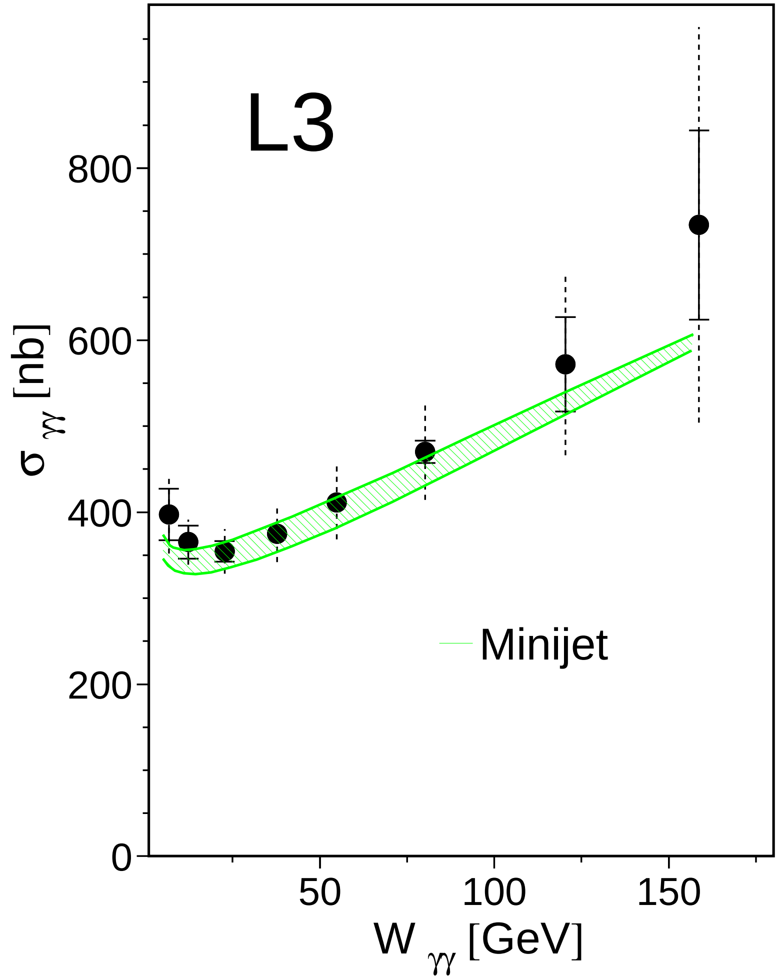
$$\Rightarrow \sigma_{ee} = \mathcal{L}_{\gamma\gamma} \otimes \sigma_{\gamma\gamma}$$



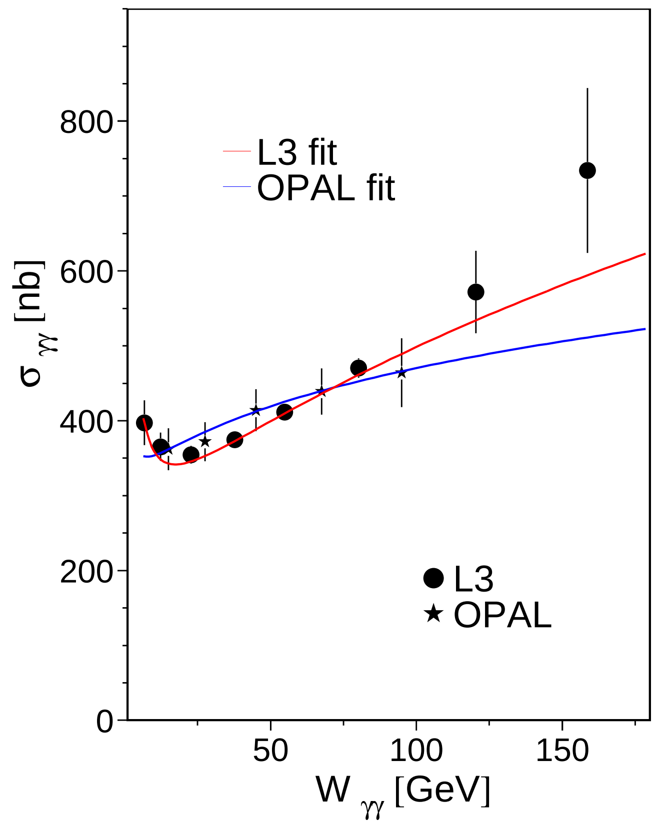
$\gamma\gamma \rightarrow q\bar{q}$, total cross section

growing cross section



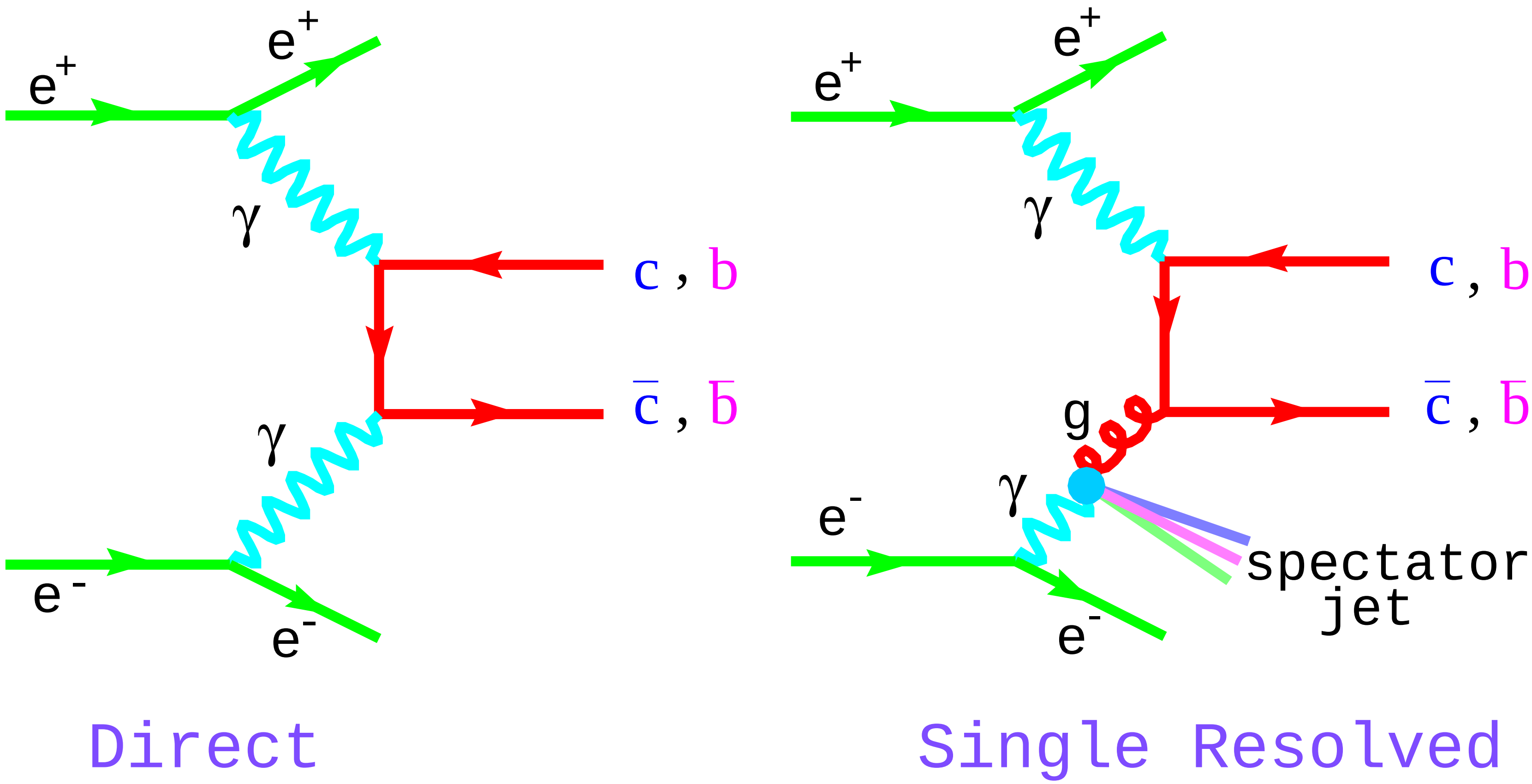


$\gamma\gamma \rightarrow q\bar{q}$, DL fit



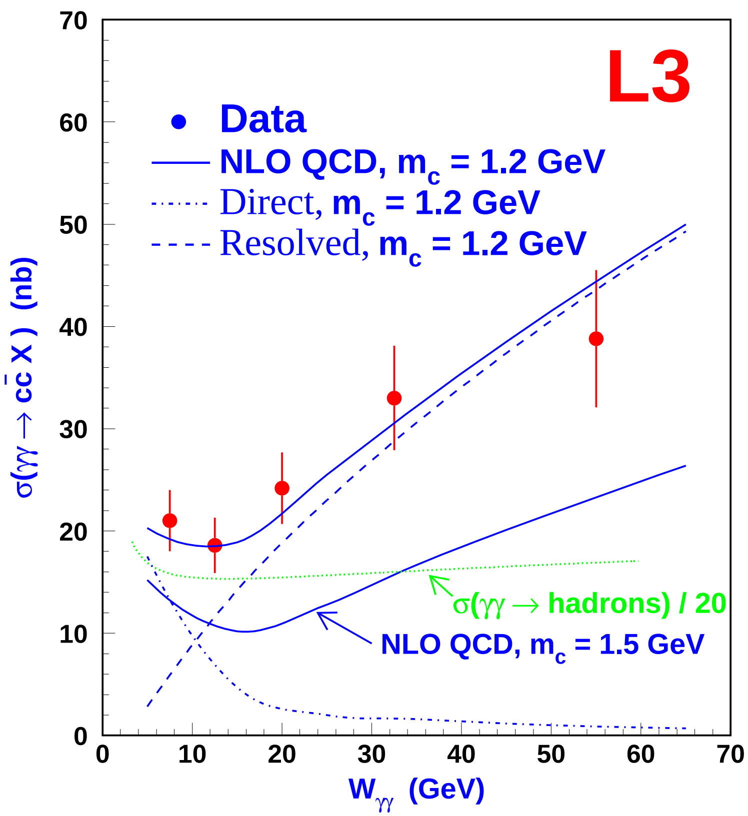
- Fit with Donnachie and Landshoff parametrisation (Phys. Lett., B296 (1992) 227):
  $$\sigma_{\gamma\gamma} = As^{\varepsilon} + Bs^{-\eta}\ ,\ s = W^2_{\gamma\gamma}$$
- Universal fit (PDG 2000):
  $\varepsilon = 0.093 \pm 0.002$, $\eta = 0.358 \pm 0.015$, A, B free
- OPAL fit, $\eta = 0.34$ fixed, A,B free
  $\varepsilon = 0.101^{+0.025}_{-0.019}$ $10 < \mathrm{W}_{\gamma\gamma} < 110$GeV
- L3 fit to 183–202 GeV data, $\eta = 0.358$ fixed, A,B free
  $\varepsilon = 0.225 \pm 0.021$ $5 < \mathrm{W}_{\gamma\gamma} < 185$GeV

Heavy flavour production in two-photon collisions

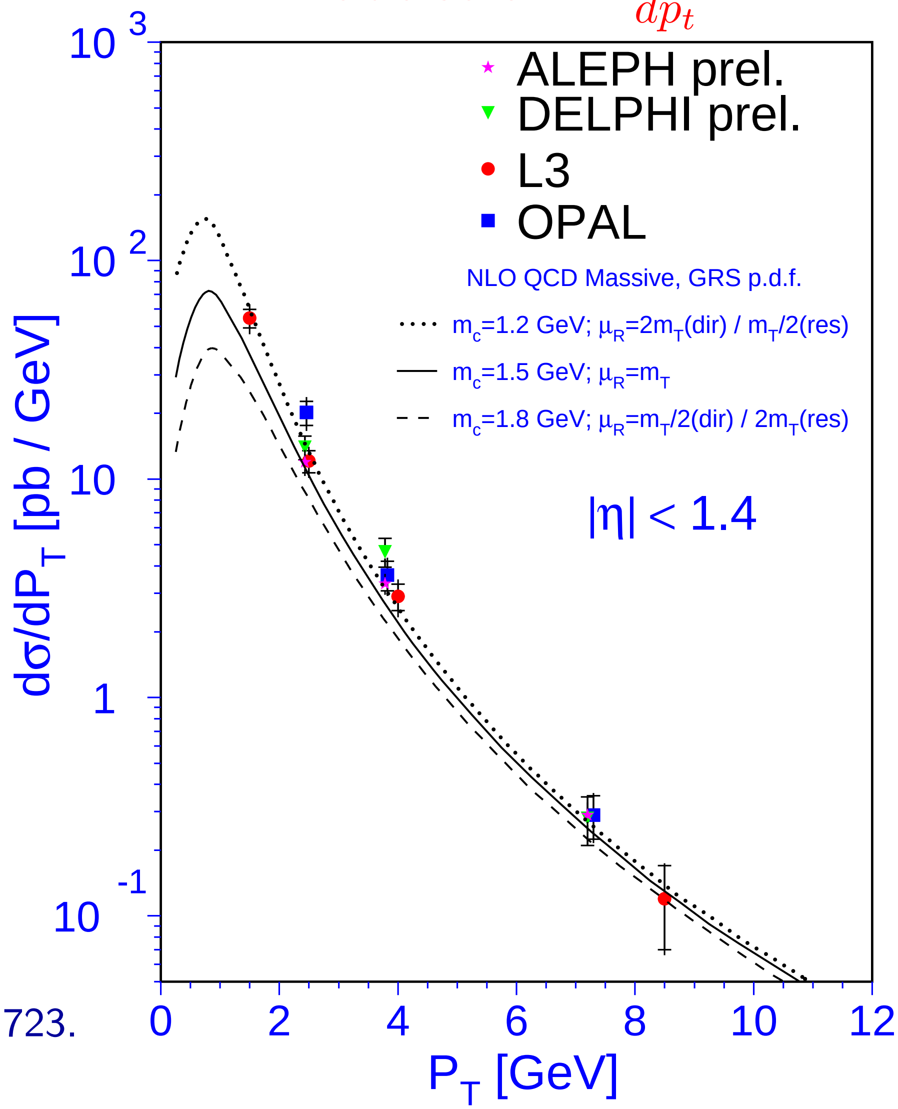


Charm production in two-photon collisions

$\sigma(\gamma\gamma \to c\bar{c})$ vs $W_{\gamma\gamma}$



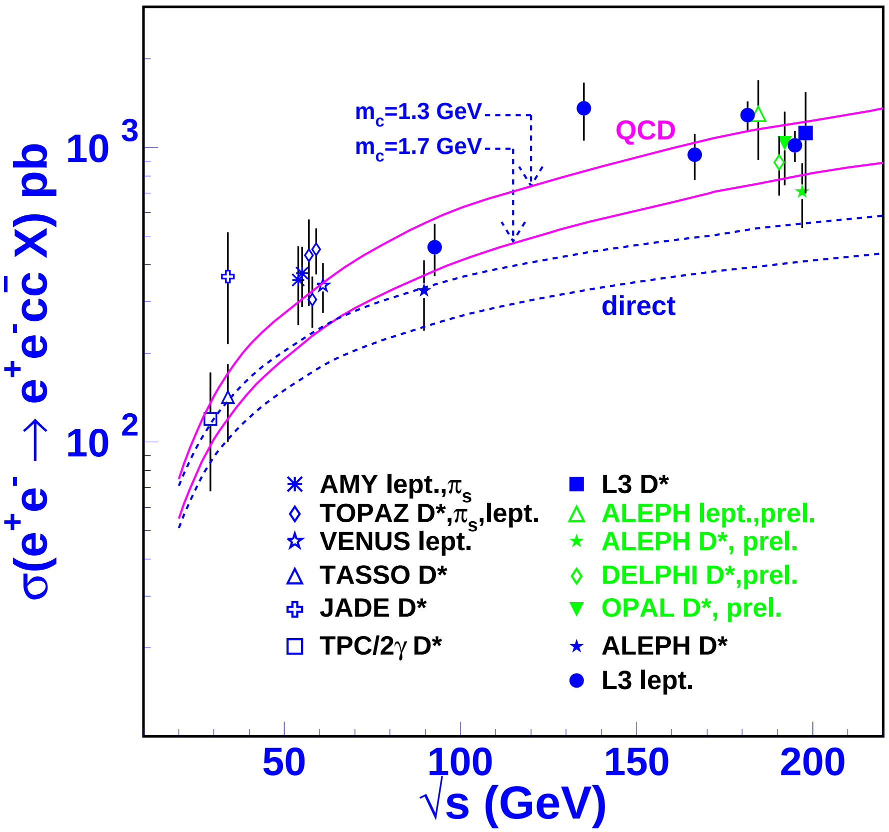
D* Production : $\frac{d\sigma}{dp_t}$



theory prediction from
S.Frixione,E.Laenen and M.Krämer,
Nucl.Phys.B571(2000)169;J.Phys.G26(2000)723.

Charm production in two-photon collisions

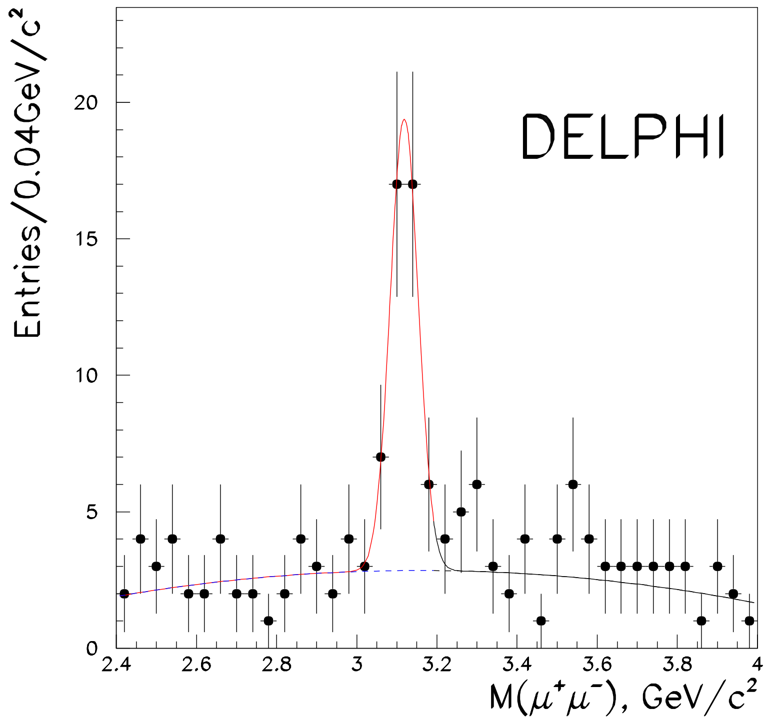
- clear evidence of gluon content of photon



theory prediction from
M.Drees,M.Krämer,J.Zunft,P.M.Zerwas,
Phys.Lett.B306(1993) 371,
$M_R = M_F = m_c$; GRV p.d.f.

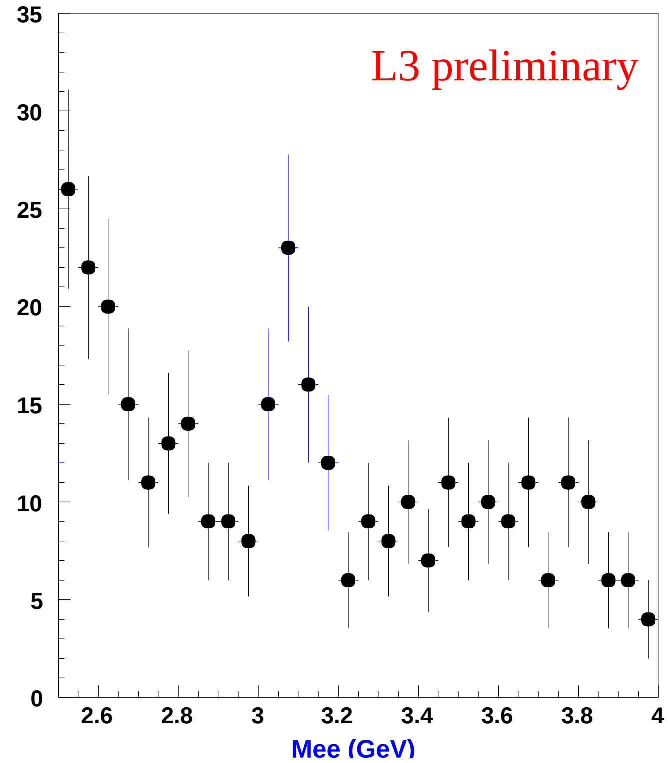
Inclusive J/Ψ production

$J/\Psi \to \mu^+\mu^-$



$$N_{events} = 36 \pm 7$$
$$M_{J/\Psi} = 3119 \pm 8 MeV$$
$$resolution = 35 \pm 7 MeV$$

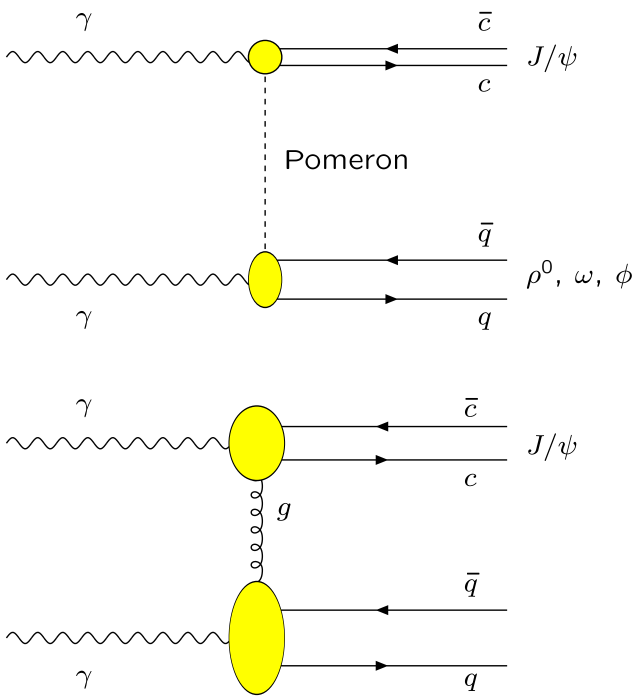
$J/\Psi \to e^+e^-$

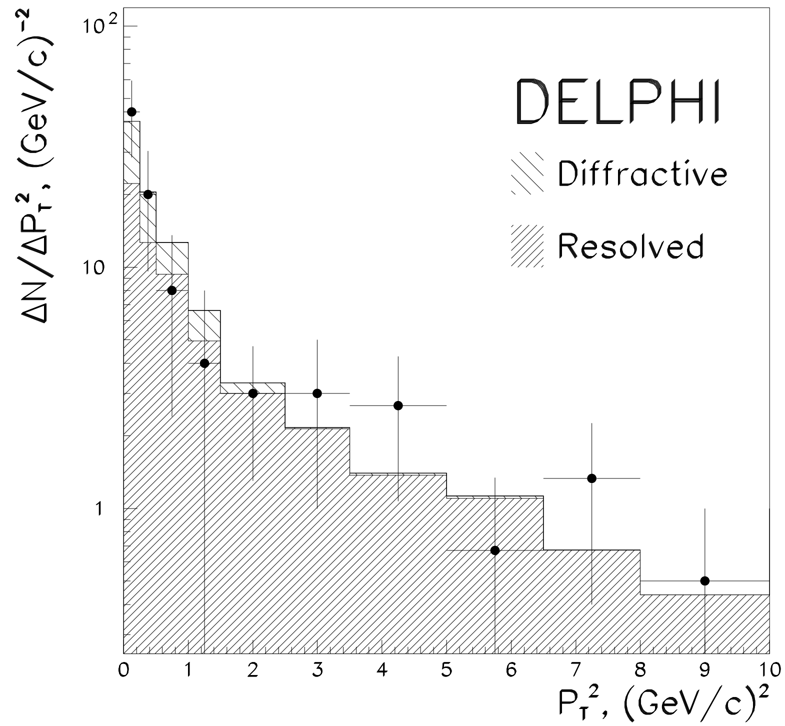


$$N_{events} = 33 \pm 10$$
$$M_{J/\Psi} = 3090 \pm 10 MeV$$
$$resolution = 34 \pm 8 MeV$$

Inclusive J/Ψ production (DELPHI)

Diffractive vs Gluon Fusion



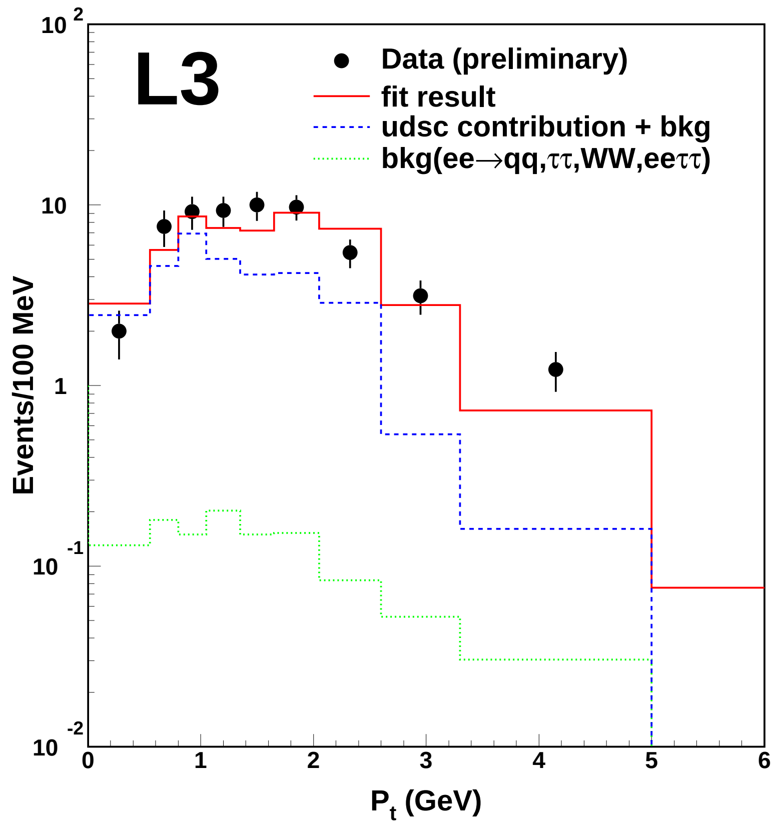


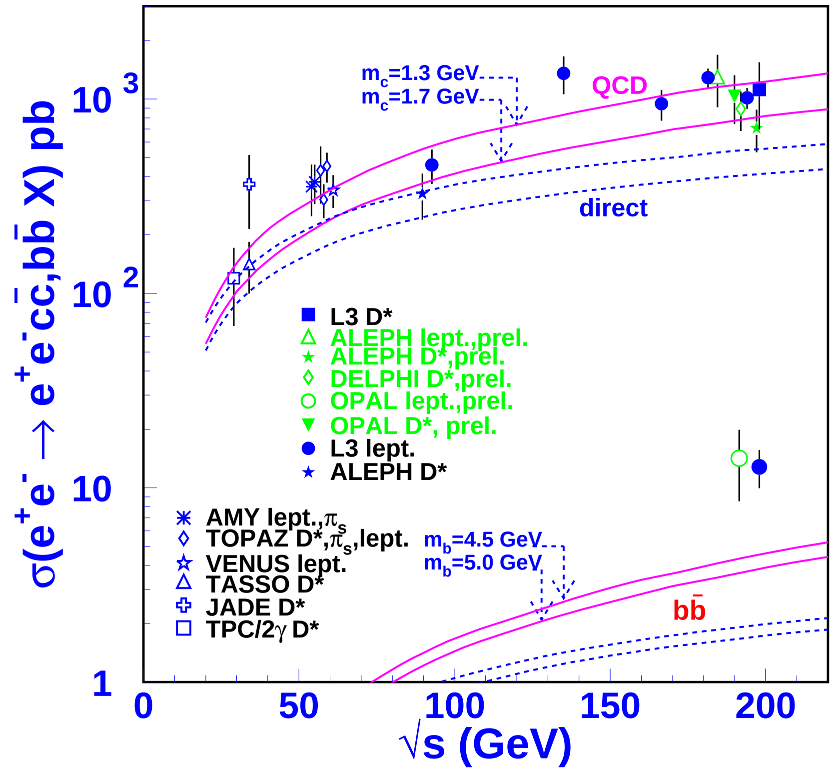
$$f_{diffr.} = 26 \pm 22\%, f_{resolved} = 74 \pm 2$$

$$\sigma_{J/\Psi X} = 45 \pm 19 pb$$

$$\sigma_{diffr.} = 24 pb, \sigma_{resolved} = 20 pb$$

Open $b\bar{b}$ production

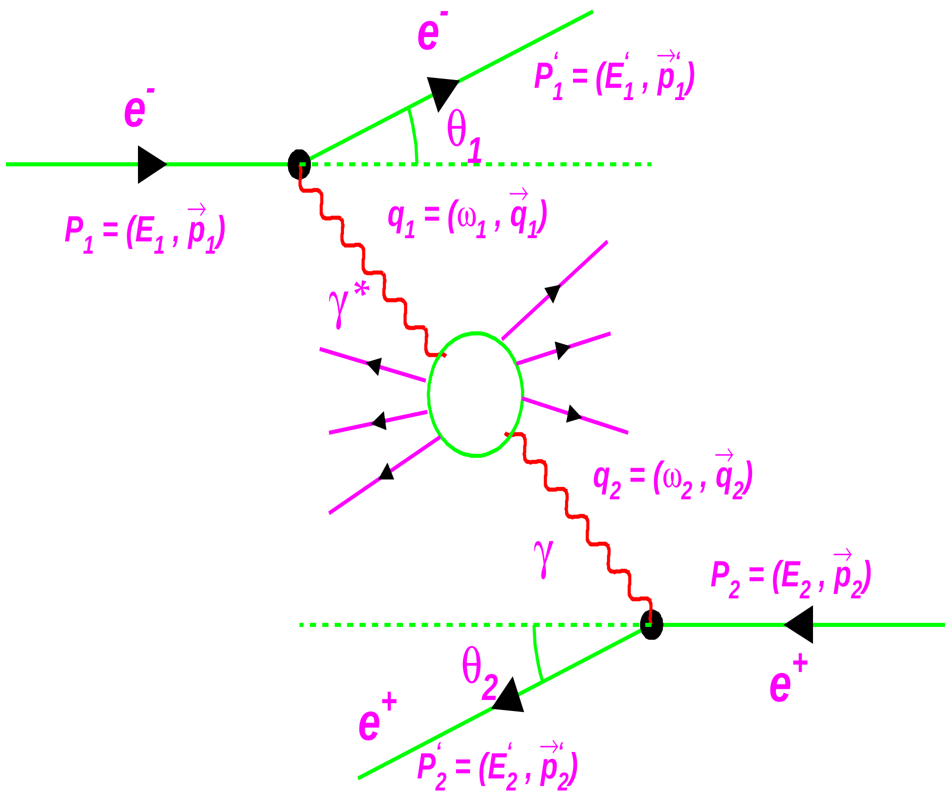




$b\bar{b}$ excess at the 5σ level

$\sigma_{b\bar{b}} \approx 3$ times the theory prediction

Electron-Photon DIS



$$Q^2 = -q_1^2 = 2E_1E_1'(1-\cos\theta_1)$$

$$P^2 = -q_2^2$$

$$W_{\gamma\gamma}^2 = (\sum_i E_i)^2 - (\sum_i \vec{p}_i)^2$$

Bjorken scaling variable

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

$$y \simeq 1 - \frac{E_1}{E_{beam}}\cos^2\frac{\theta_1}{2}$$

❒ Cross Section

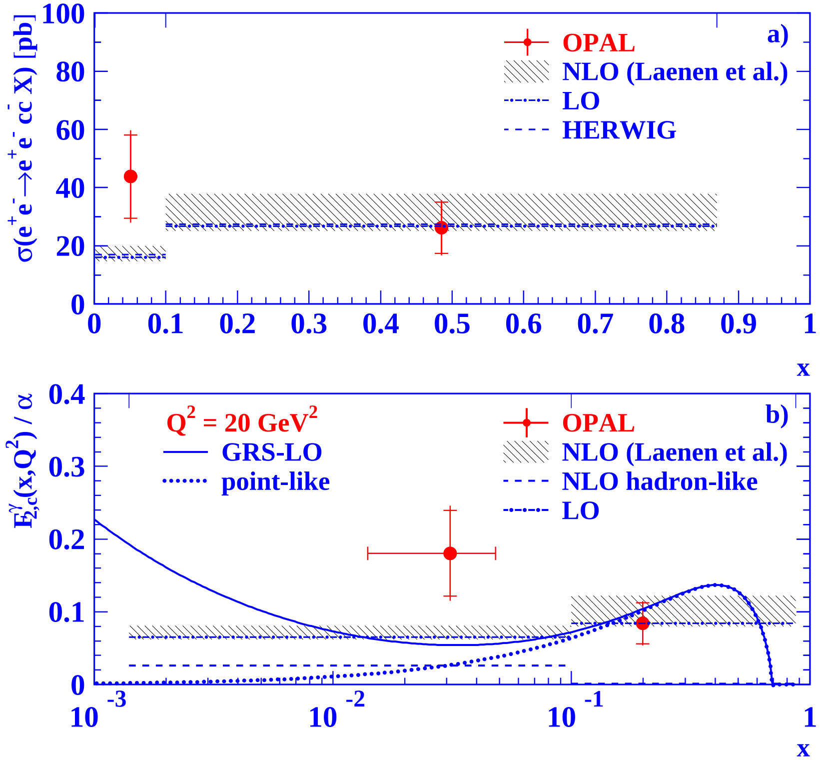
$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4}\frac{1}{x}\left\{1+(1-y)^2 F_2^\gamma(x,Q^2) - \frac{y^2}{2}F_L^\gamma(x,Q^2)\right\}$$

➠ Hadronic $F_2^\gamma(x, Q^2)$

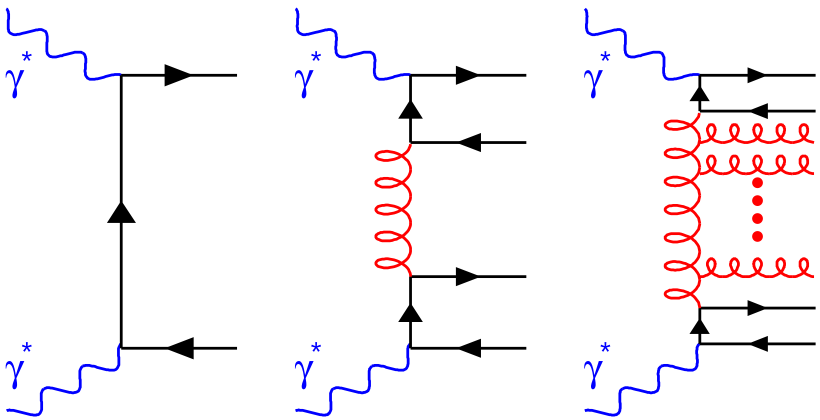
Charm structure function

- $0.0014 < x < 0.1$,
$0.1 < x < 0.87$
- $\langle Q^2 \rangle = 20$ GeV^2

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



$\gamma^*\gamma^*$ collisions



➩ BFKL diagram is predicted to be dominant at high Q^2 and high $W_{\gamma^*\gamma^*}$

➩ two virtual photons ➜ double-tagged events

$$< Q_1^2 > \approx < Q_2^2 >$$

❑ In Leading order approximation :

$$\sigma_{\gamma^*\gamma^*} = \sigma_0 \left(\frac{s}{s_0}\right)^{\alpha_P - 1} \simeq \sigma_0 \left(\frac{W^2_{\gamma^*\gamma^*}}{\sqrt{Q_1^2 Q_2^2}}\right)^{\alpha_P - 1}$$

$$s_0 = \frac{\sqrt{Q_1^2 Q_2^2}}{y_1 y_2}$$

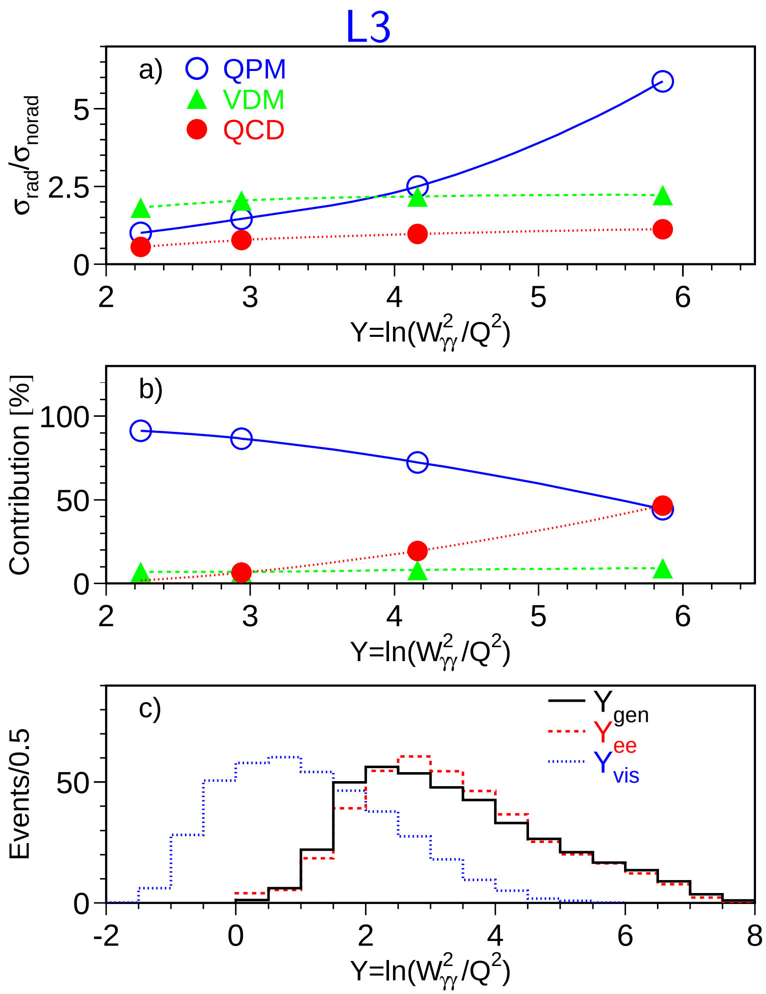
$$\alpha_P - 1 = 4 \ln 2 \frac{N_c \alpha_s}{\pi}$$

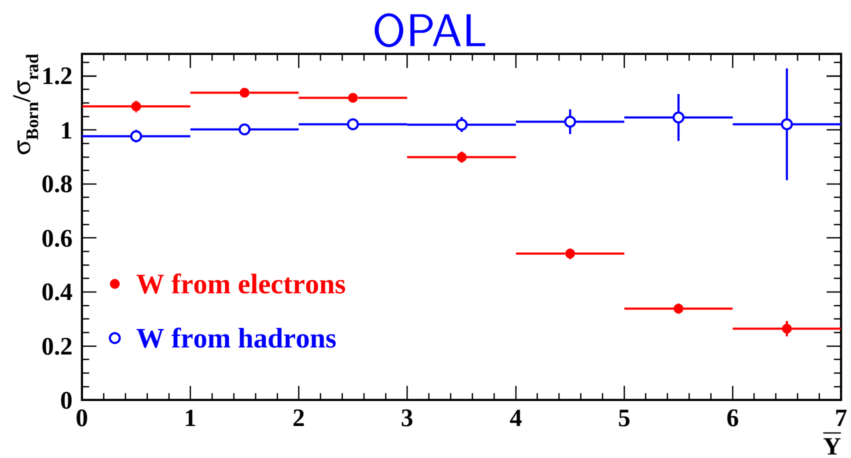
$$Y = \ln\left(\frac{W^2_{\gamma^*\gamma^*}}{\sqrt{Q_1^2 Q_2^2}}\right);$$

❑ Using $N_c = 3$, $\alpha_s = 0.2$ ➜ $\alpha_P - 1 \simeq 0.53 > 0.093$

$\gamma^*\gamma^*$ collisions

- either large radiative corrections or large unfolding errors





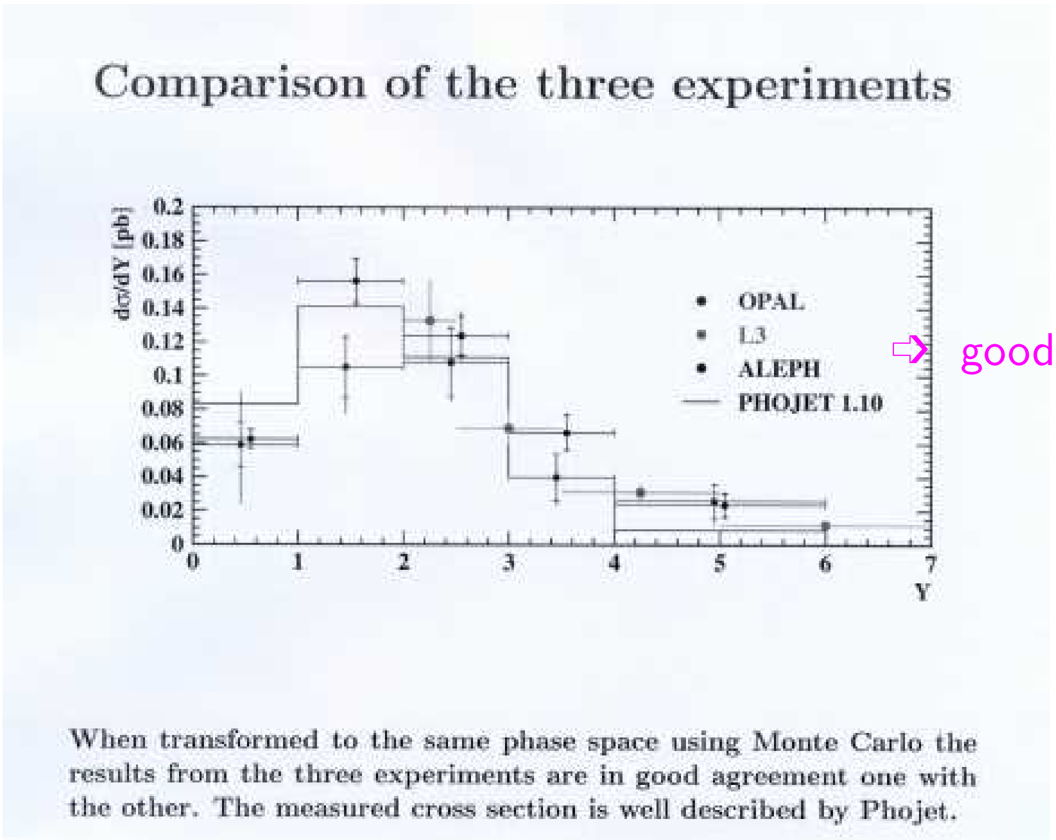
Double-tagged events at LEP

✦ Event statistics

	ALEPH (preliminary)	L3	OPAL
Luminosity, pb^{-1}	640	617	593
N_{events}	891	491	179
Bkgd, %	23	18	24
$< Q^2 >$, GeV^2		16	18

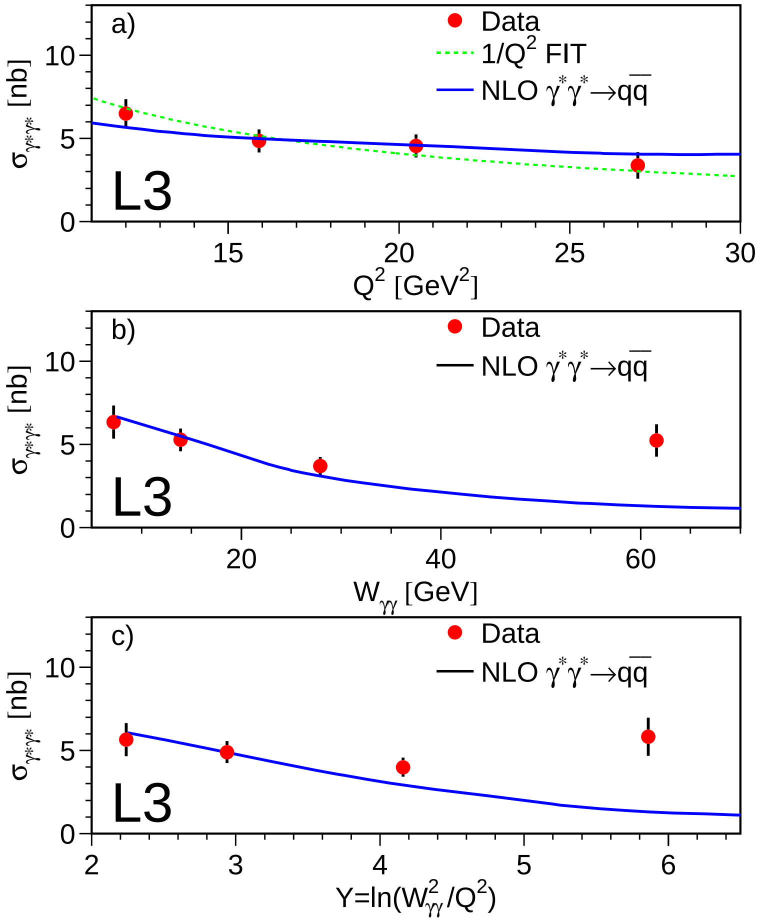
Double-tagged events at LEP

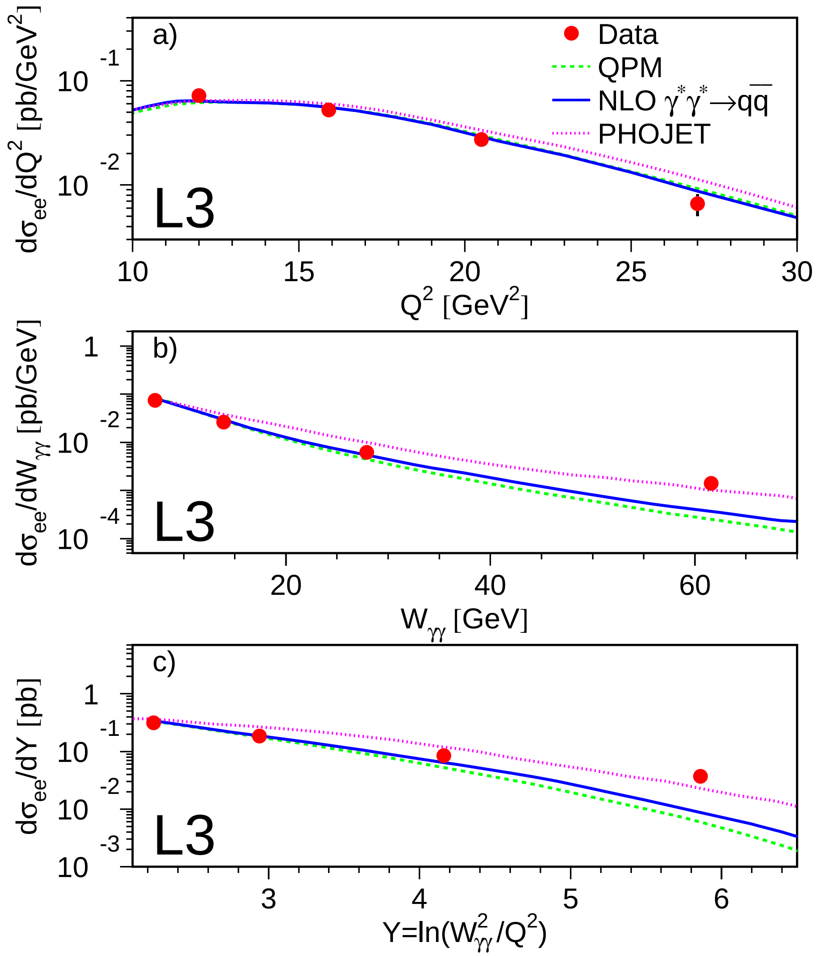
M. Przybycien, EPS2001 Budapest



⇨ good agreement between experiments

$\gamma^*\gamma^*$ cross section

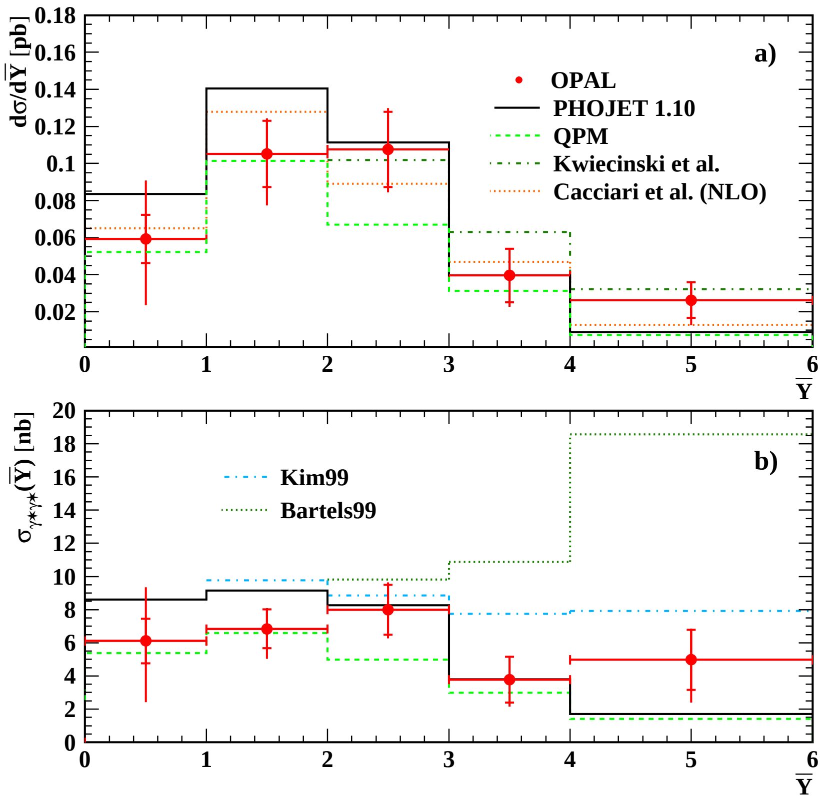


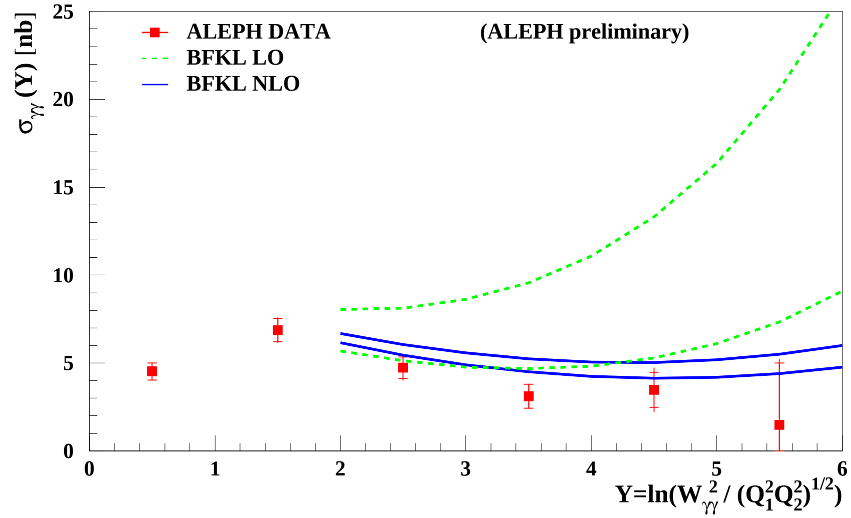


- ➜ NLO QPM is insufficient
- ➜ Data in excess at $Y > 5$
- ➜ BFKL ?

➜ DGLAP describes the data

$\gamma^*\gamma^*$ *cross section*



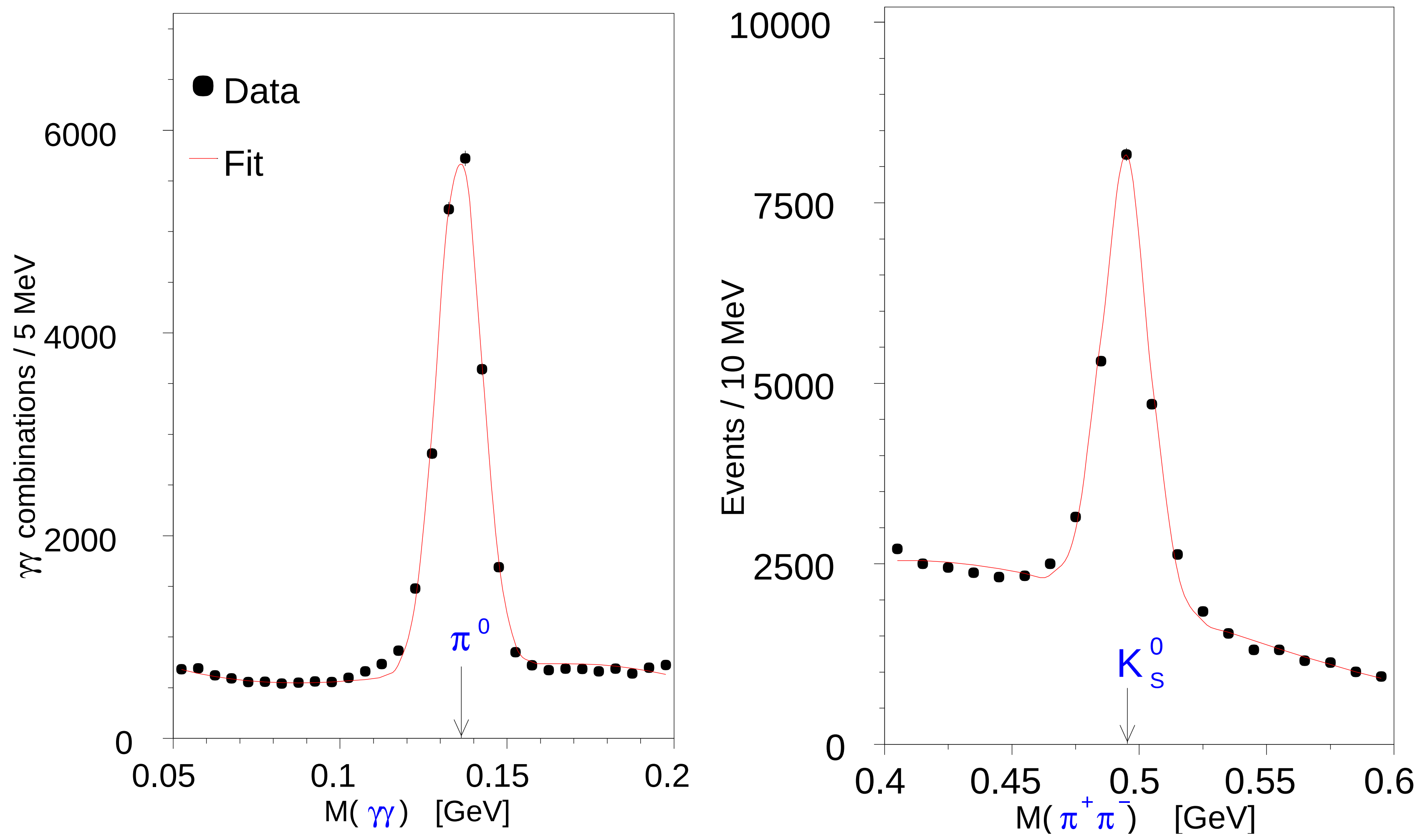


- NLO BFKL describes the data

- DGLAP describes the data

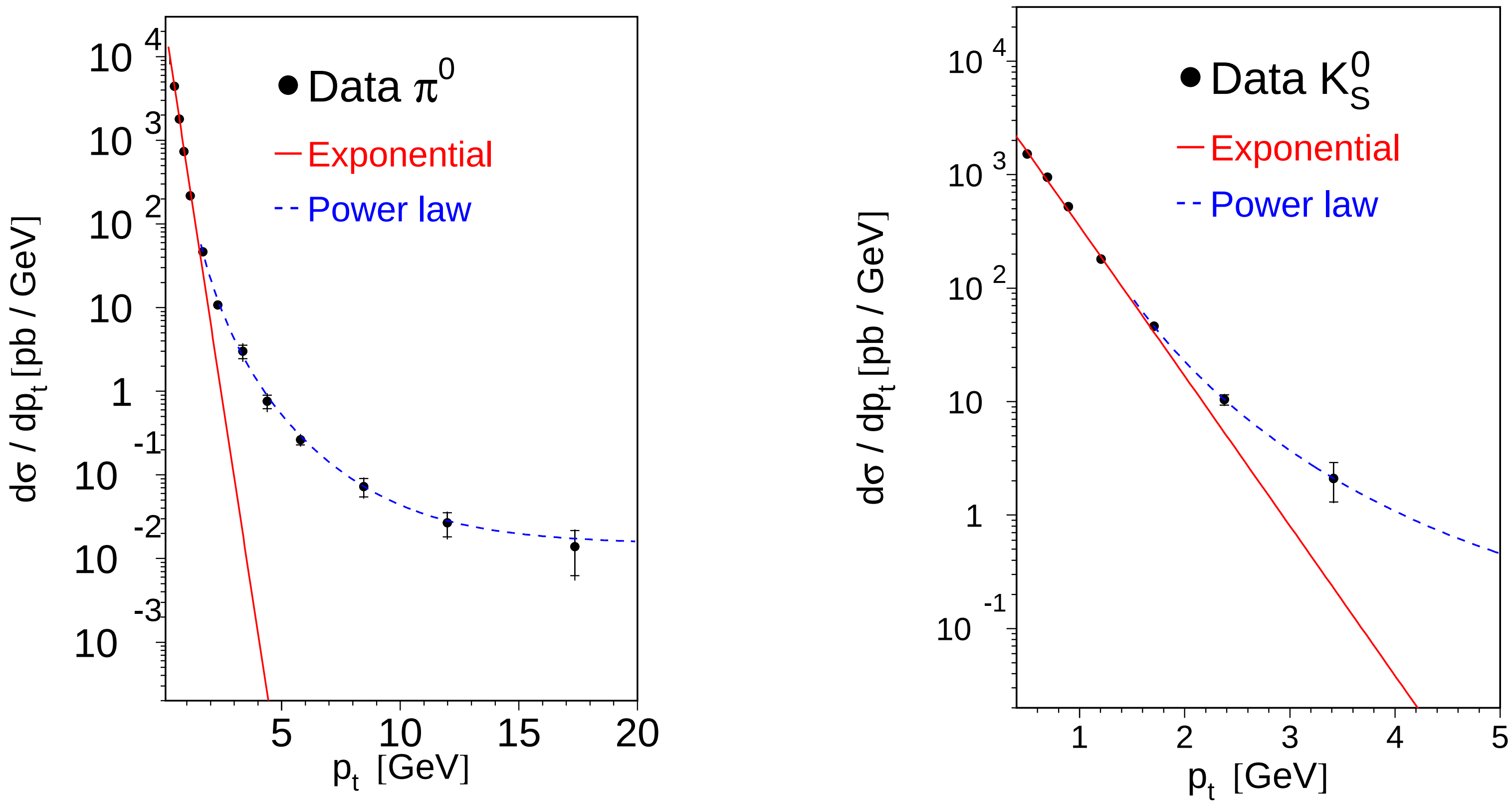
Inclusive single hadron production

- L3: for each p_t and and $|\eta|$ bin



Inclusive single hadron production

L3: $\frac{d\sigma}{dp_t}$ - fits to the data



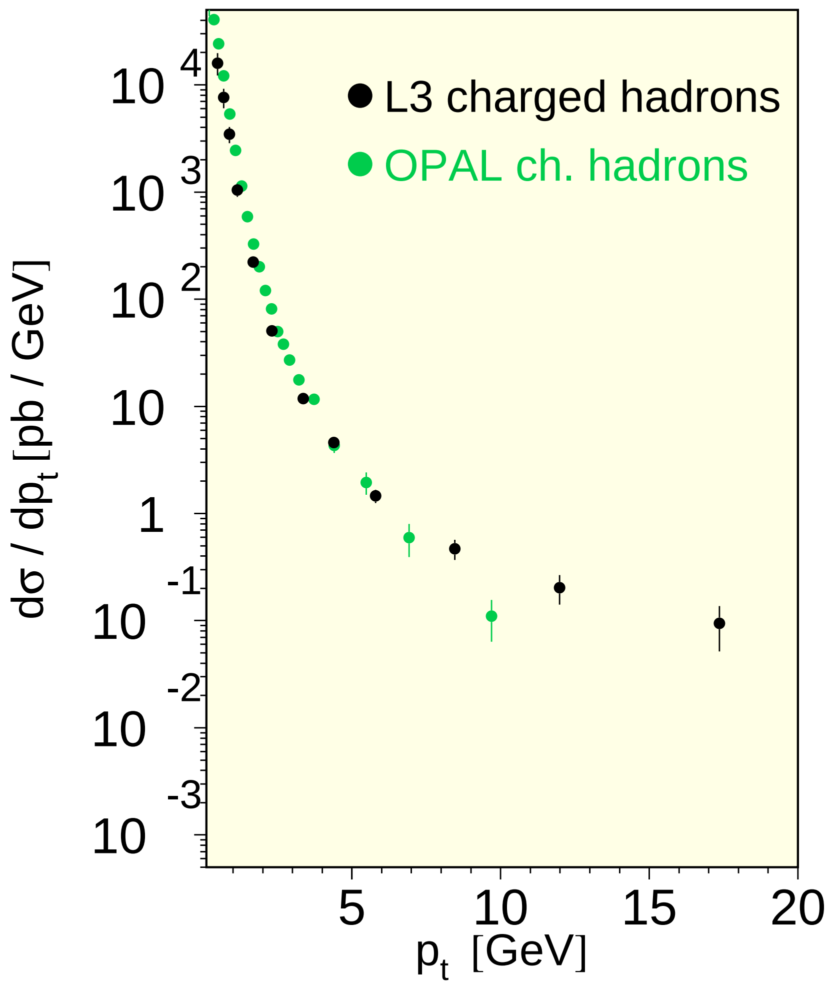
Exponential $A \times e^{-p_t/\langle p_t \rangle}$: $\langle p_t \rangle \simeq$ 234 MeV for π_0

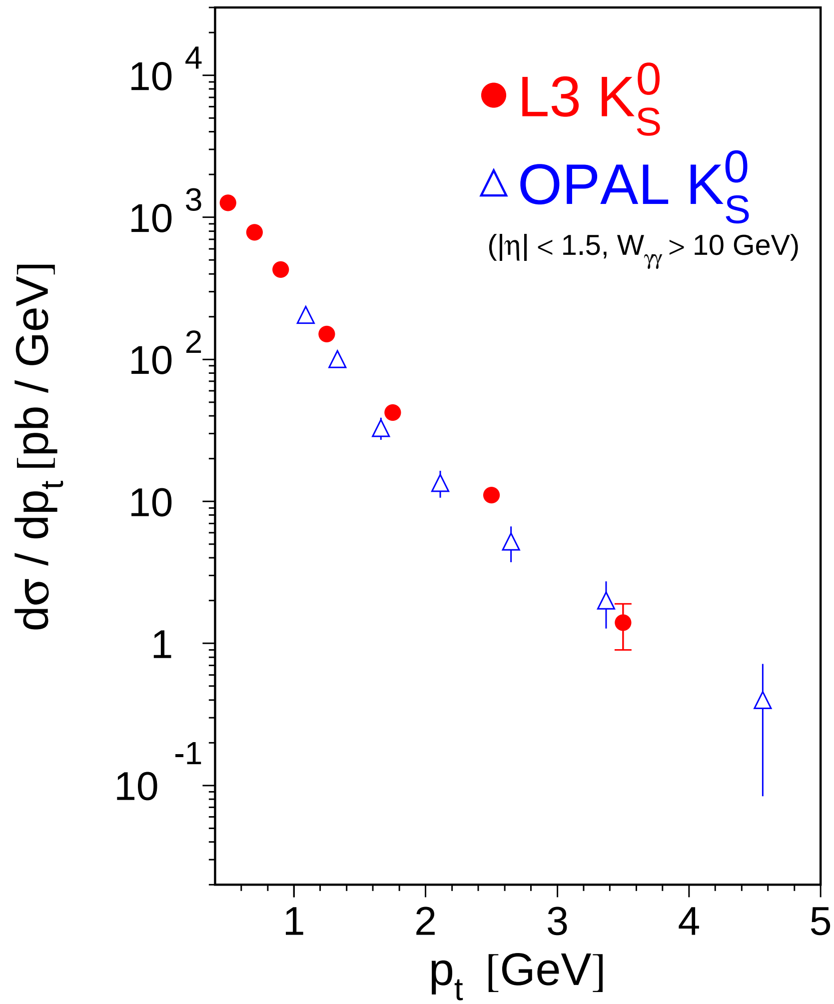
290 MeV for K^0_S

Power law $A \times p_t^{-B}$: B $\simeq$ 4. for π_0, K^0_S

Inclusive single hadron production

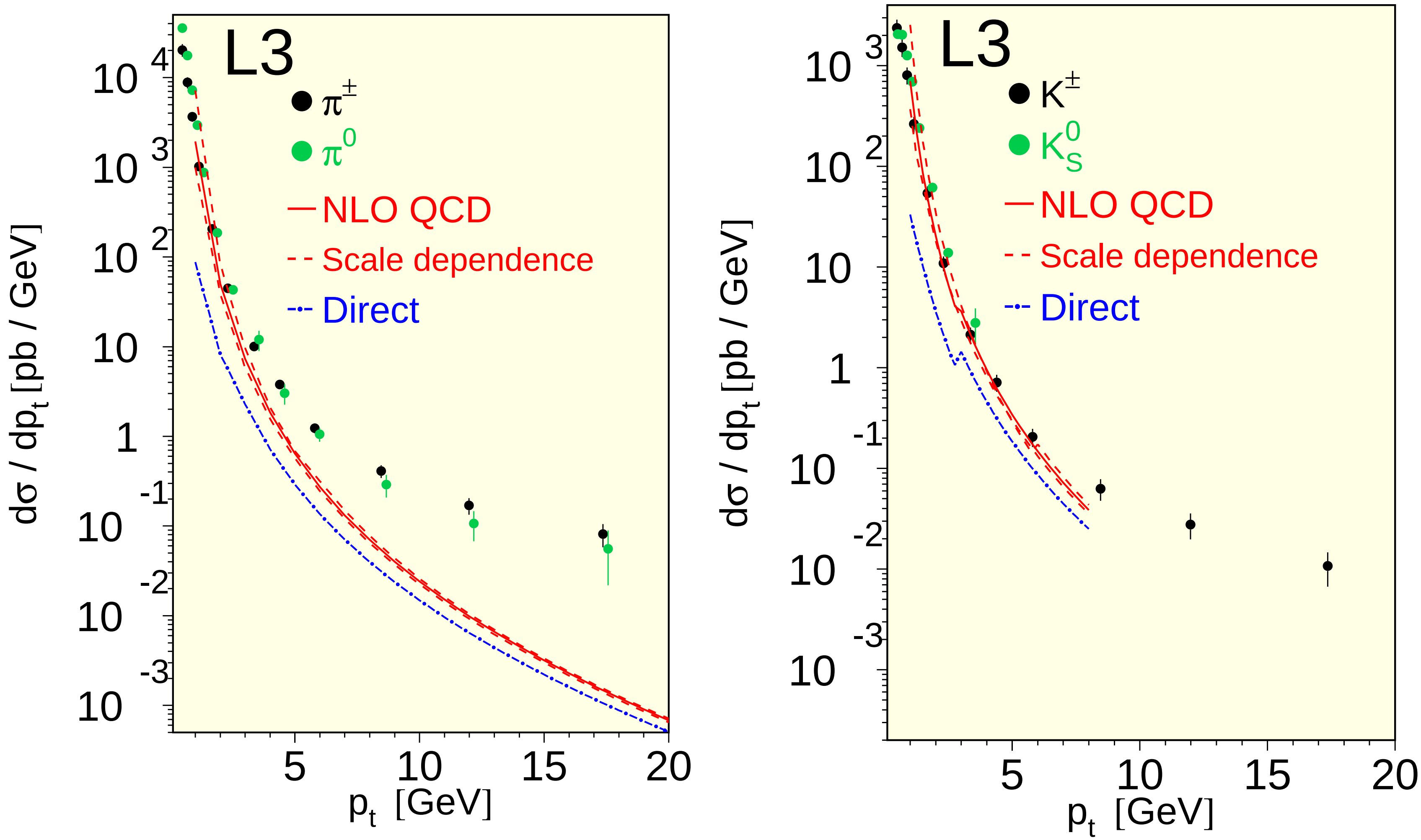
❖ Comparison: L3 and OPAL





⇨ good agreement between experiments

Inclusive hadron production in two-photon collisions



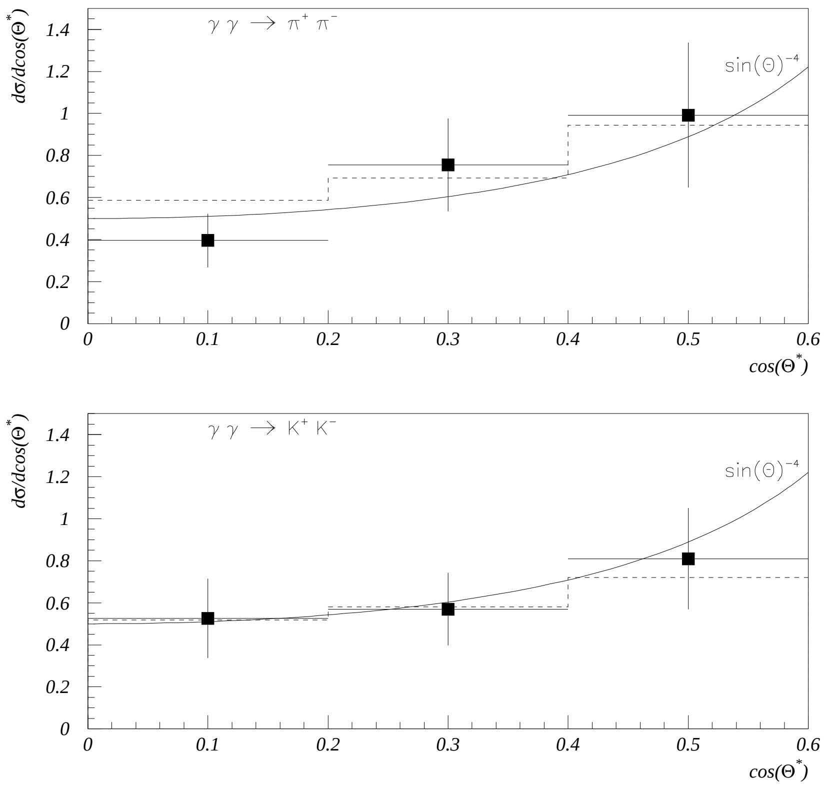
- Measurements exceed QCD predictions at high p_t
- Overall consistency of the picture: $\pi^{\pm}$, π^{0}, $\mathrm{K}^{\pm}$, K^0_S

Exclusive final states

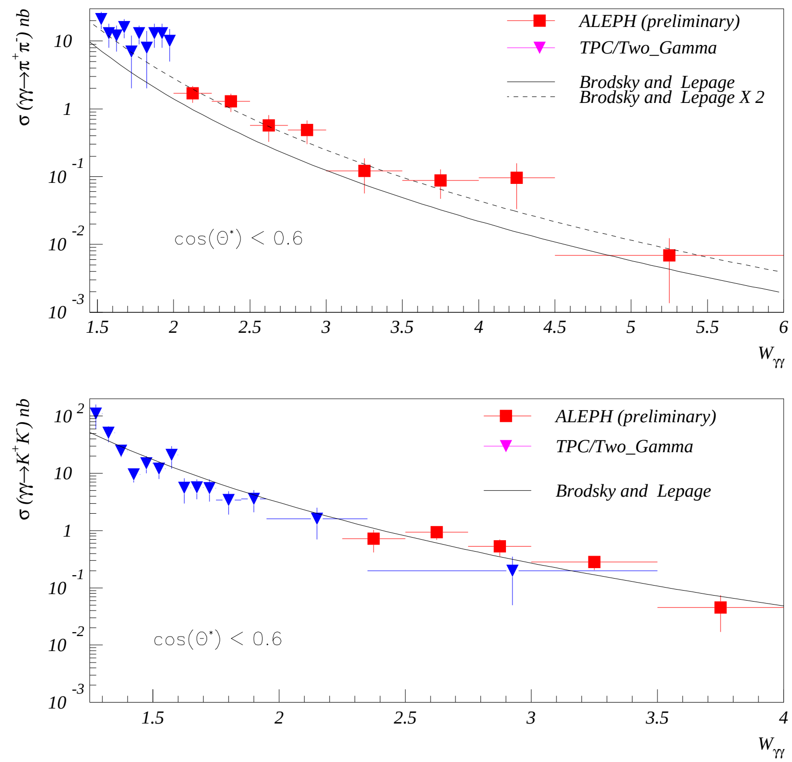
- $\gamma\gamma \rightarrow \pi^+\pi^-$
- $\gamma\gamma \rightarrow \mathrm{K}^+\mathrm{K}^-$
- $\gamma\gamma \rightarrow \mathrm{p}\bar{\mathrm{p}}$
- $\gamma\gamma \rightarrow \Lambda\bar{\Lambda}$
- $\gamma\gamma \rightarrow \Sigma\bar{\Sigma}$

$\gamma\gamma \rightarrow \pi^+\pi^-, K^+K^-$

ALEPH



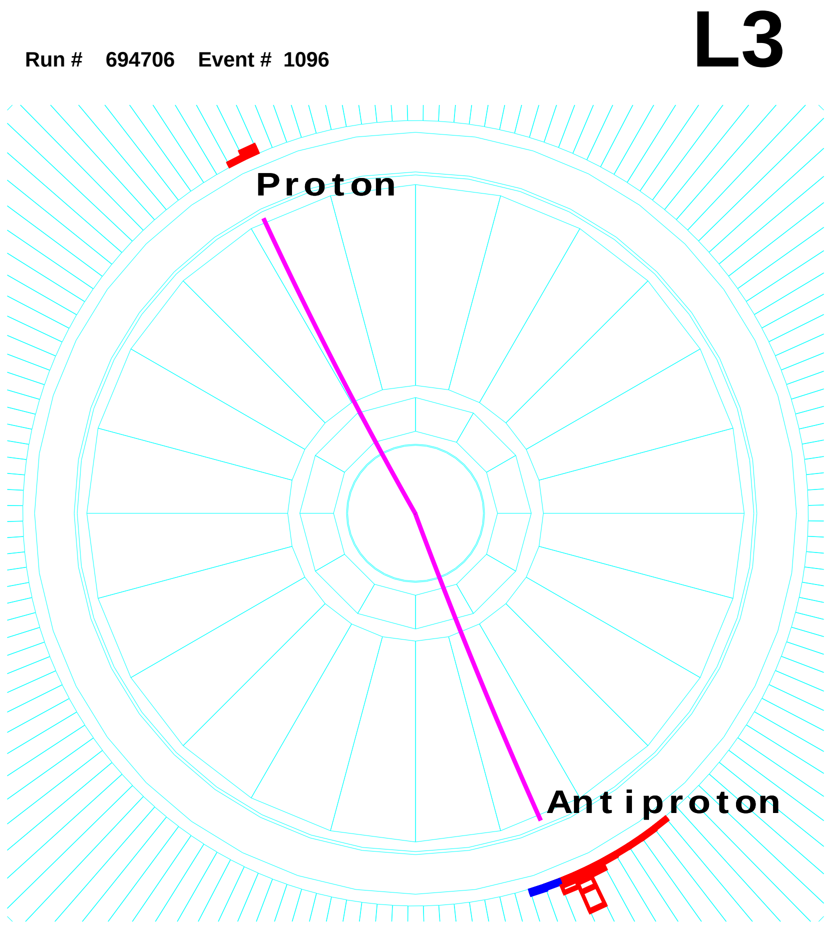
ALEPH



the angular distribution shape in agreement with QCD

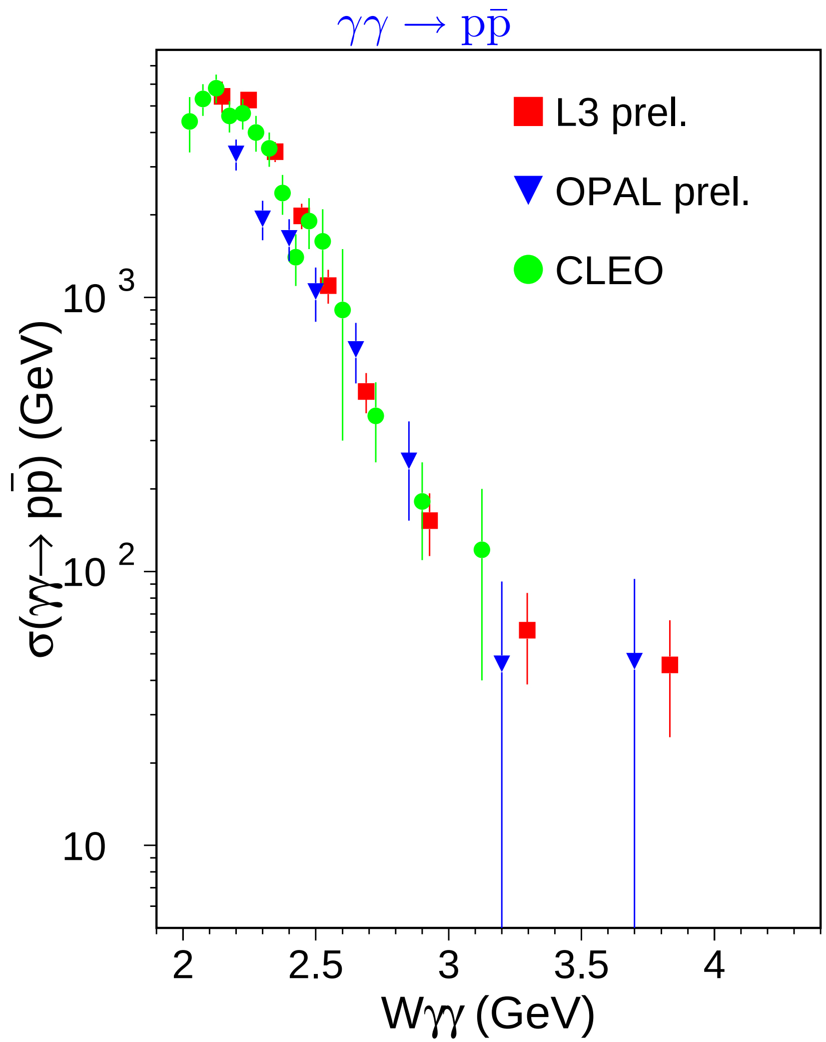
$\gamma\gamma \rightarrow \pi^+\pi^-$ data two times higher than expectation

Baryon production in two-photon collisions



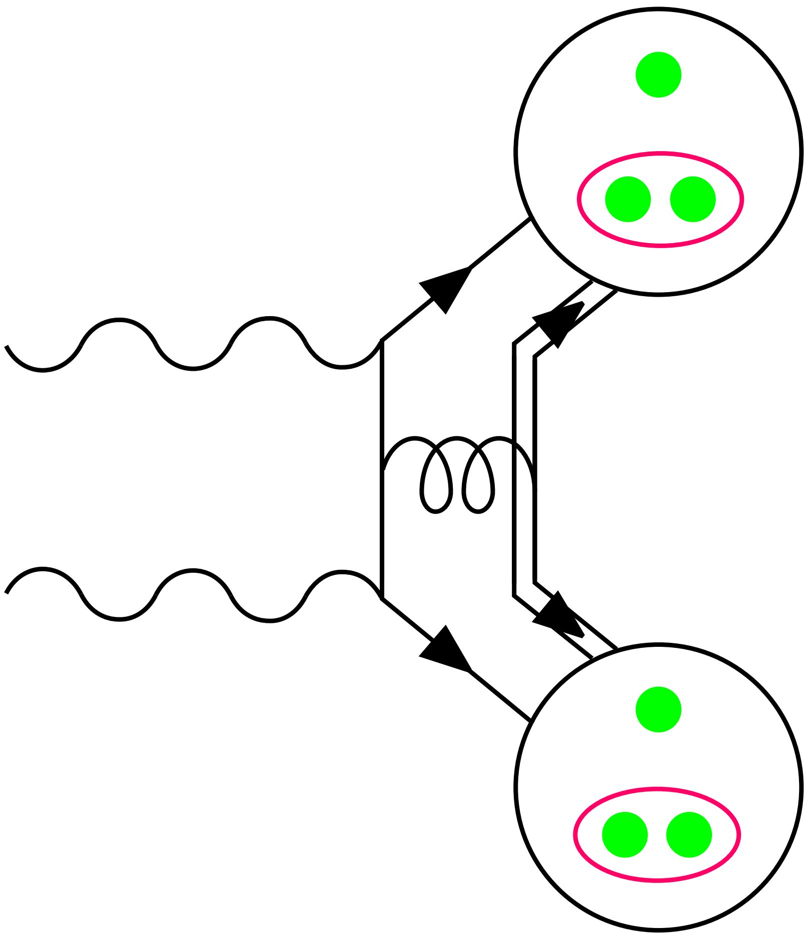
Antiproton identification criteria:

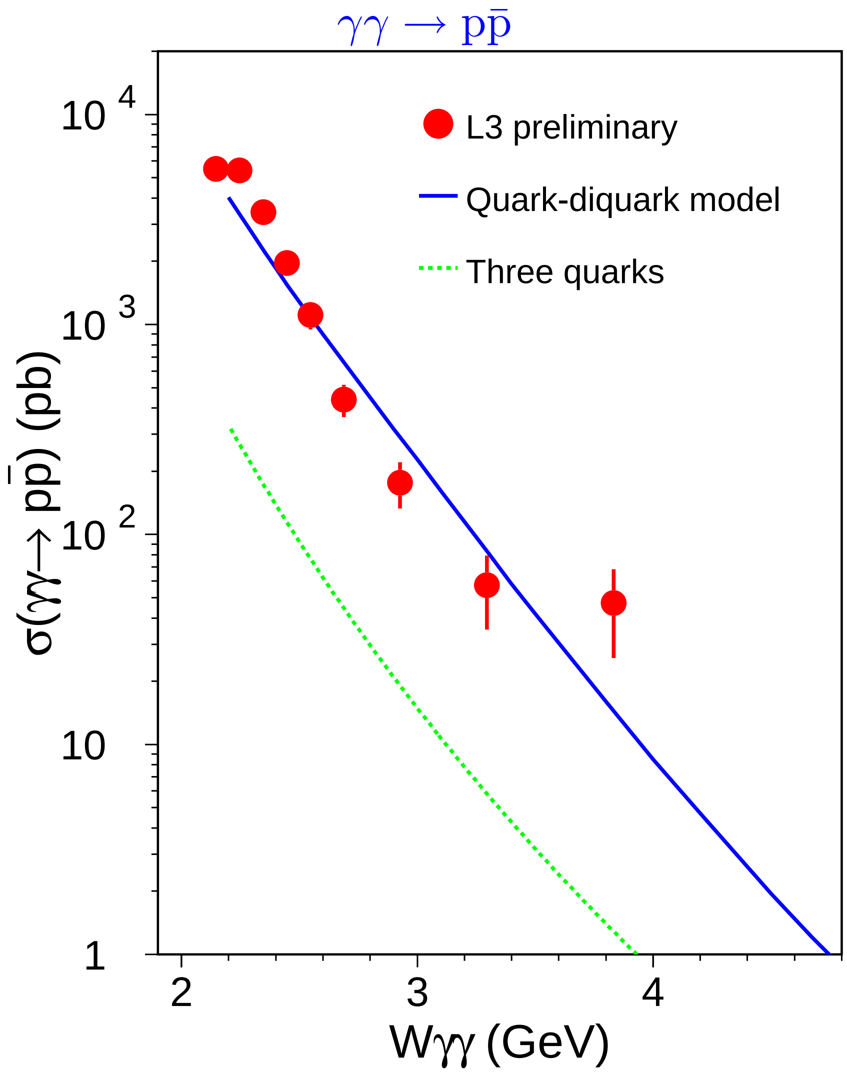
- dE/dx
- Calorimeter energy vs momentum
- Cluster shape



Agreement between measurements at high masses

Baryon production in two-photon collisions

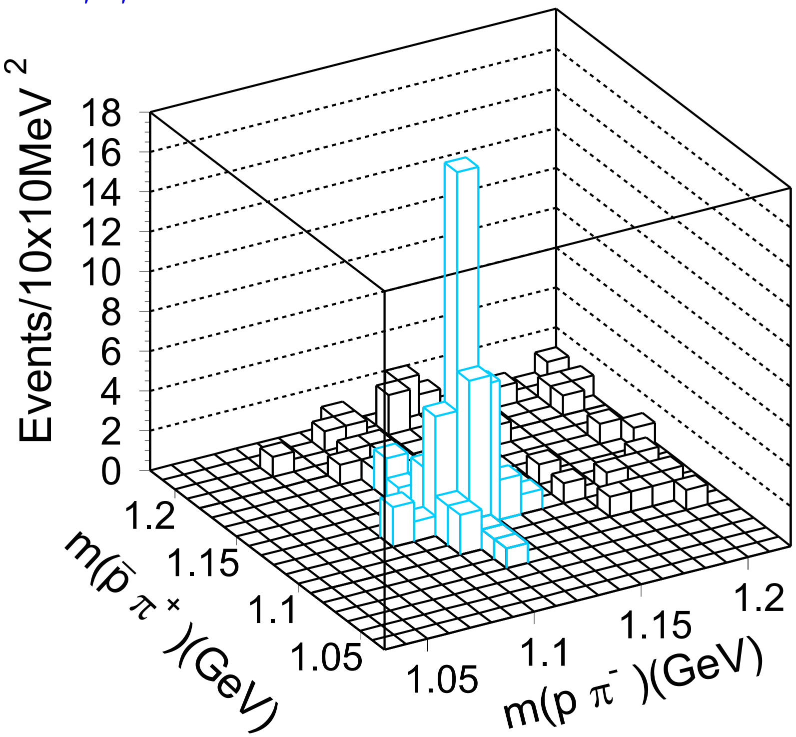


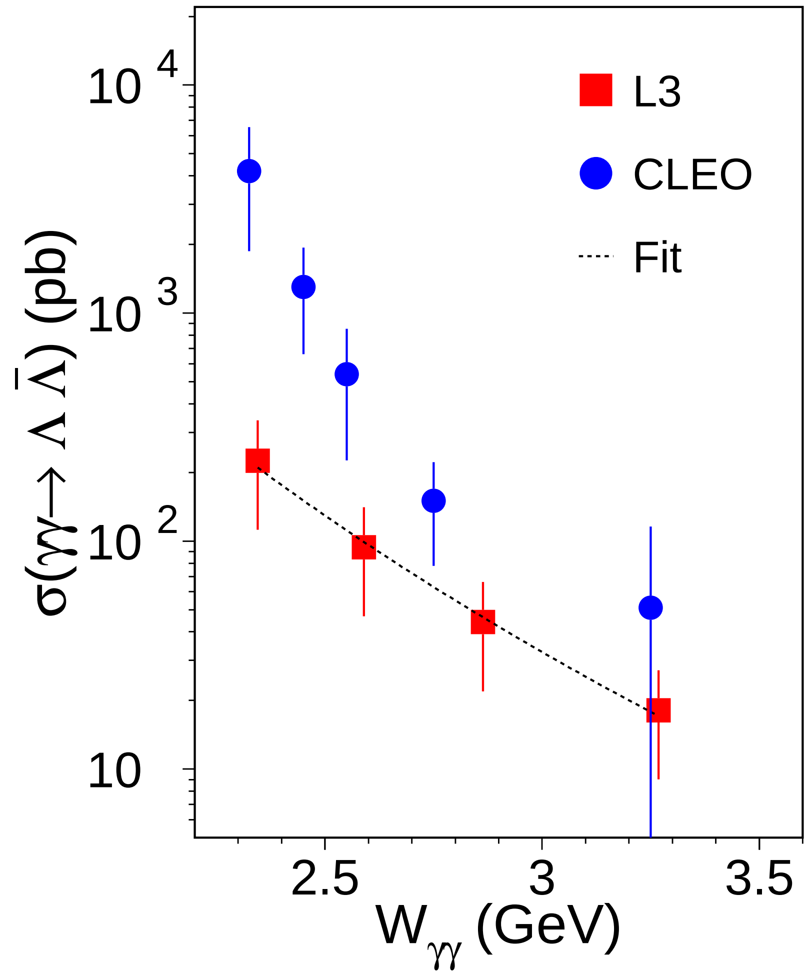


Baryons behave effectively as a quark-diquark system

Baryon production in two-photon collisions

L3: $\gamma\gamma \to \Lambda\bar{\Lambda}$

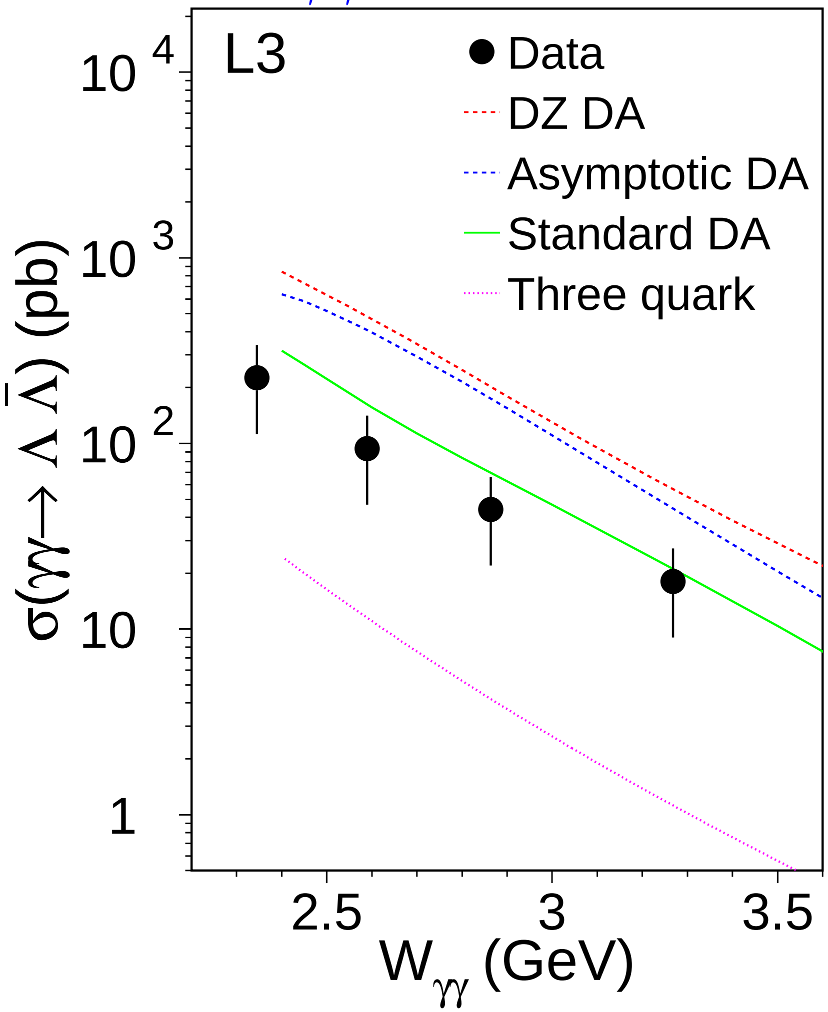




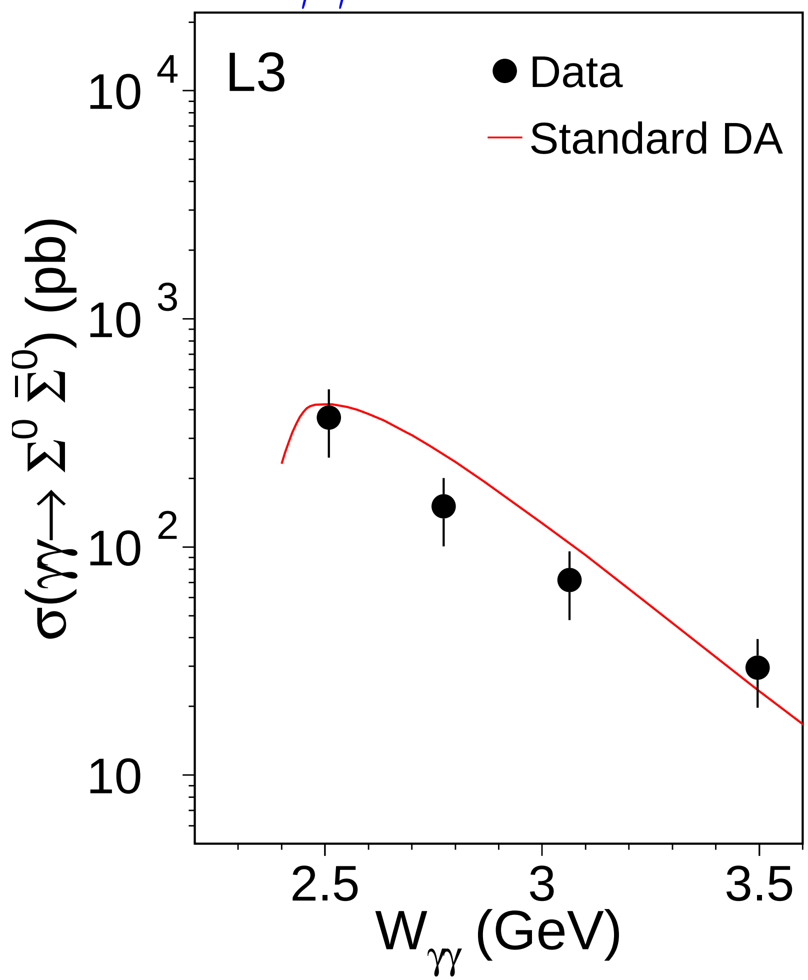
Baryons behave effectively as a quark-diquark system

Baryon production in two-photon collisions

$\gamma\gamma \to \Lambda\bar{\Lambda}$



$\gamma\gamma \to \Sigma\bar{\Sigma}$



$p\bar{p}, \Lambda\bar{\Lambda}, \Sigma\bar{\Sigma}$ described by the same approach

Summary

- Hadronic cross sections
  - $\sigma_{\gamma\gamma}$ increases at high energies
  - Charm is in agreement with QCD, but low m_c
  - F_2^{charm} needs resolved processes at low x
  - Beauty is in disagreement with QCD
  - $\sigma_{\gamma^*\gamma^*}$ inconsistent with LO BFKL prediction
  - High-p_t hadrons: NLO QCD prediction is too low
  - Baryons as a quark-diquark system

Outlook

- Many interesting results

- LEP two-photon analyses still going on

- Several discrepancies with QCD