# Two Photon Physics at LEP

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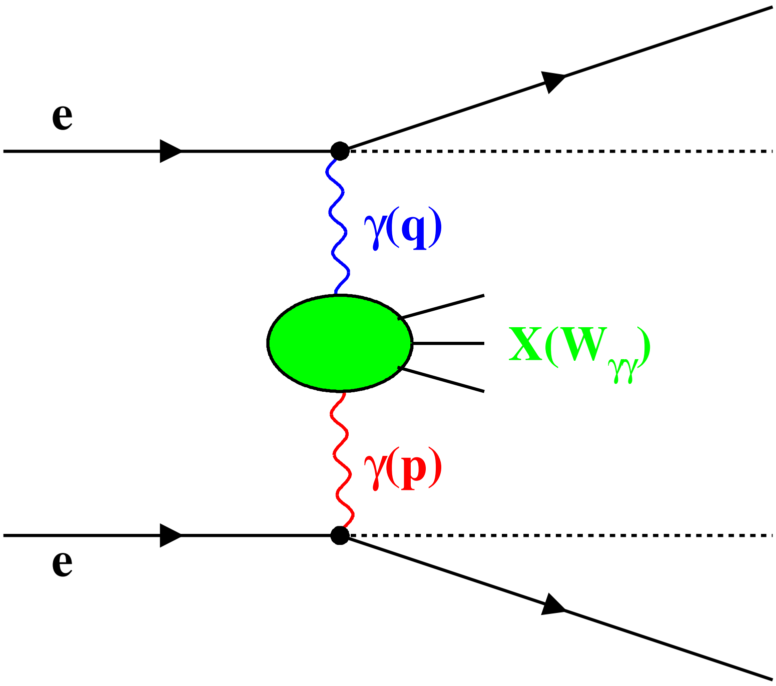
# Outline

- Total $\gamma\gamma$ cross section measurement
- Structure function $F_2^\gamma$, tagged events
- Total $\gamma^*\gamma^*$ cross section
- Heavy flavour production

# Motivation




- High energy behaviour of two-photon collisions (non-perturbative domain, $Q^2 \simeq 0$)
- Perturbative QCD domain – high $Q^2$ photons, heavy flavour production

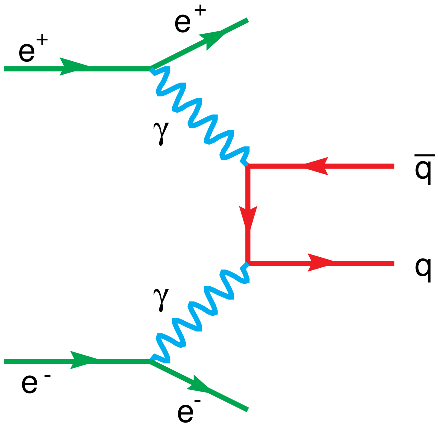
## To sacrifice due to lack of time:

- Leptonic structure function (QED)
- Jets
- Inclusive hadrons
- Exclusive final states, resonances

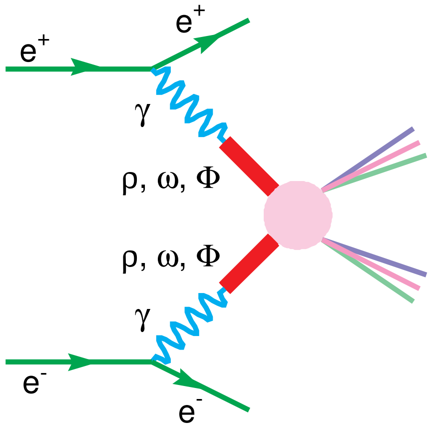

## Many thanks to

S. Frixione
M. Kienzle
M. Kramer
E. Laenen
R. Nisius
S. Soldner-Rembold
M. Wadhwa

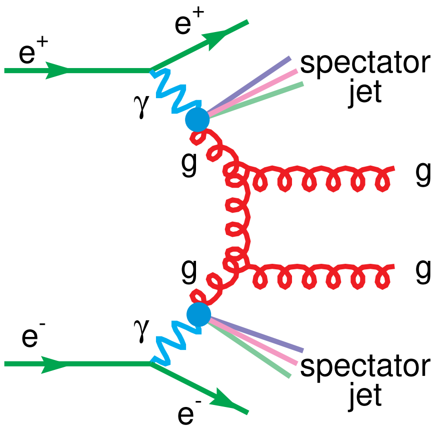
# Hadronic final state in $\gamma\gamma$ collisions



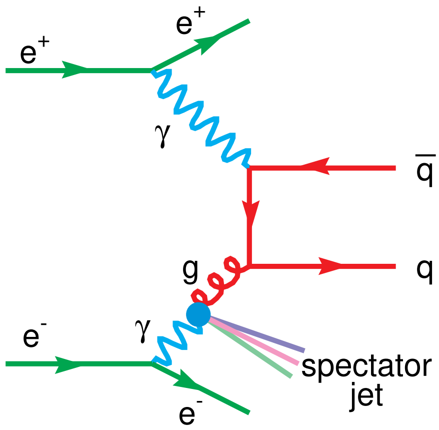

Direct




VDM

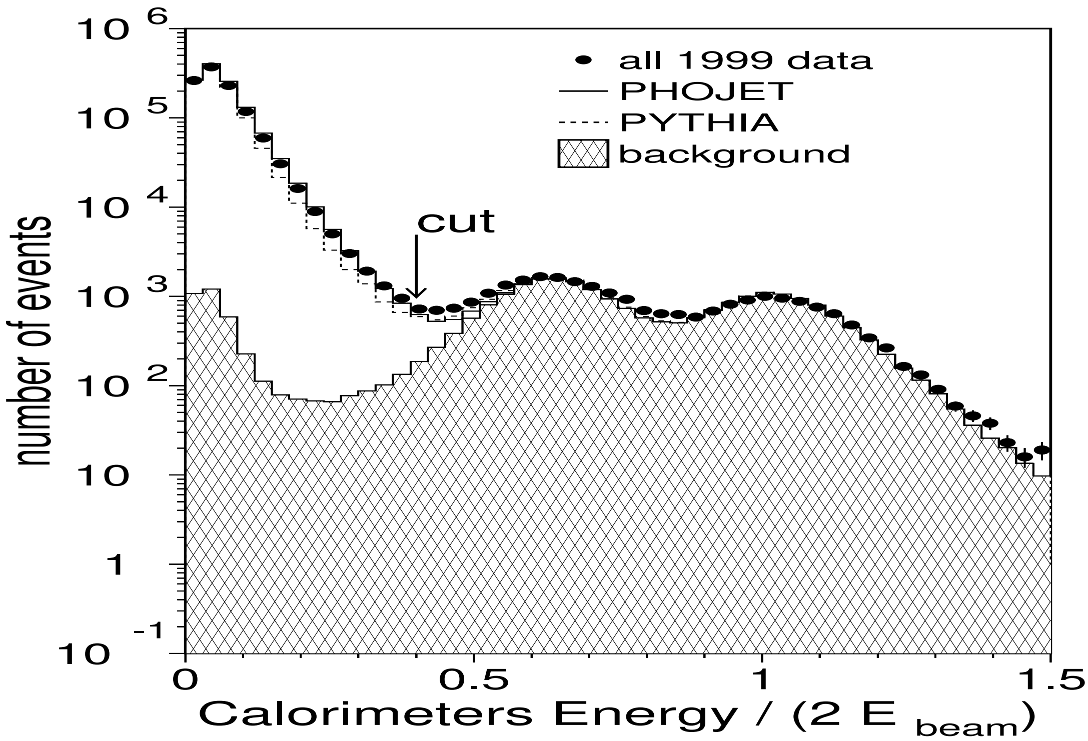



Double Resolved

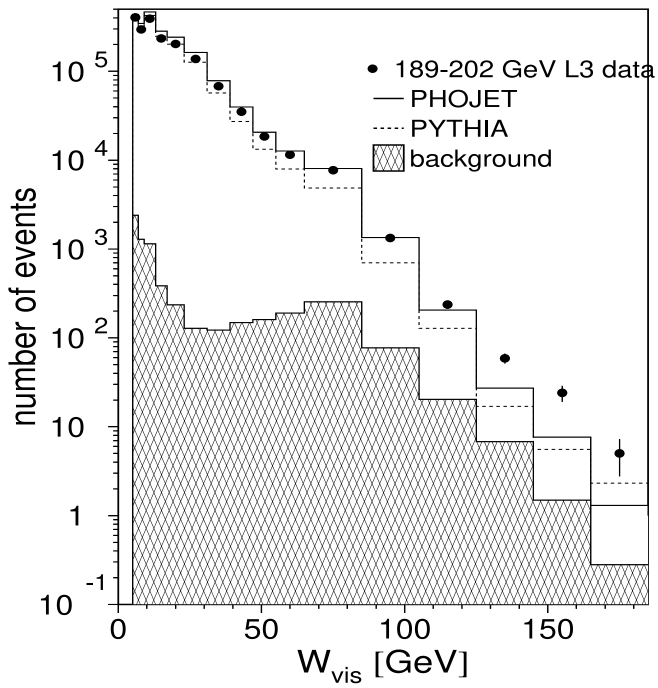


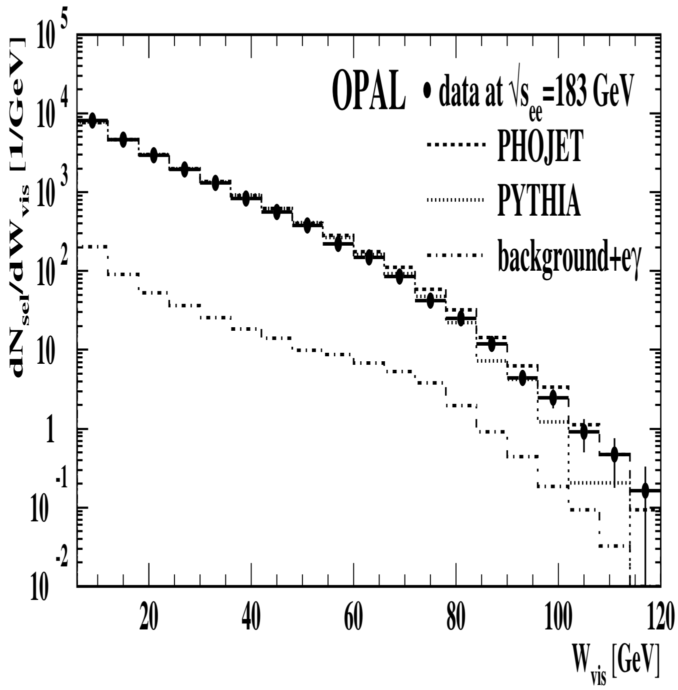

Single Resolved

# Two-photon hadronic selection



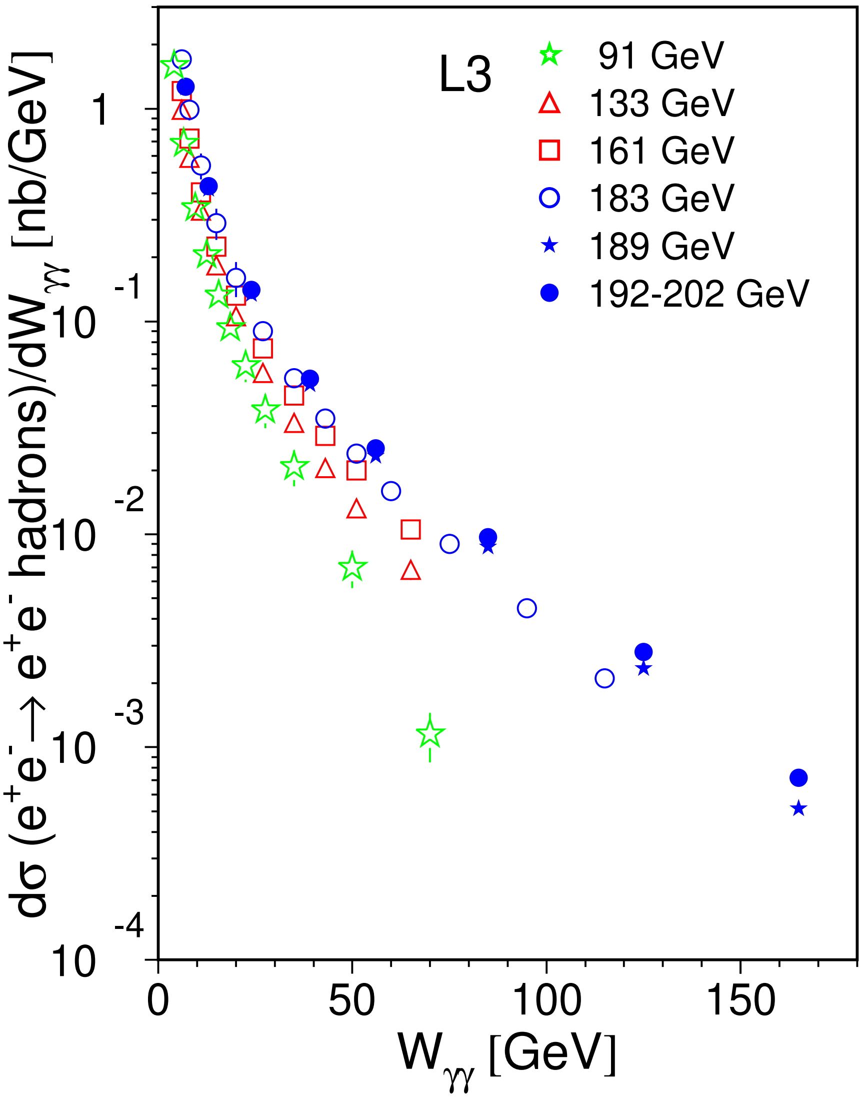

- $W_{vis}$ distribution:



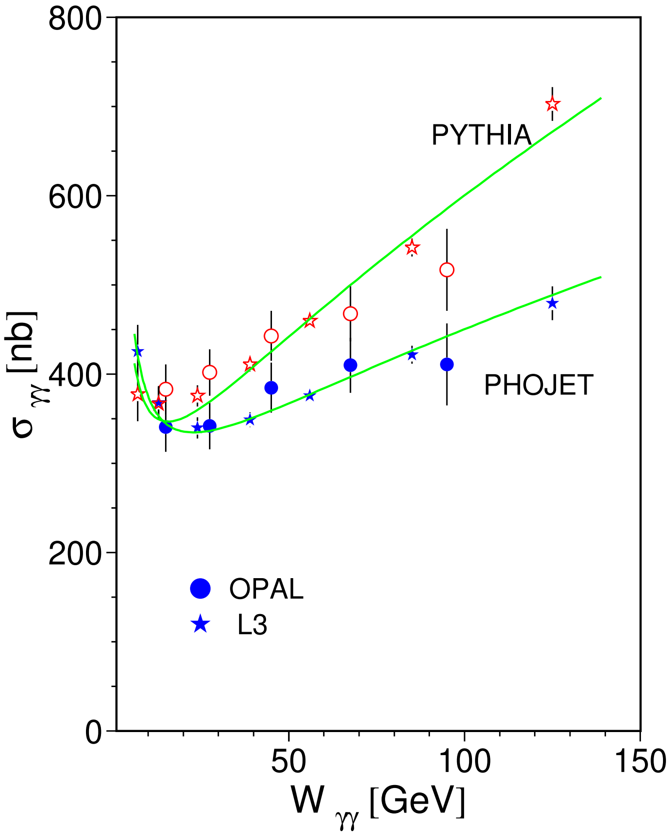

- Two-photon events are easy to separate
- $W_{vis} < W_{\gamma\gamma}$ - need for unfolding

# $ee \longrightarrow eeq\bar{q}$

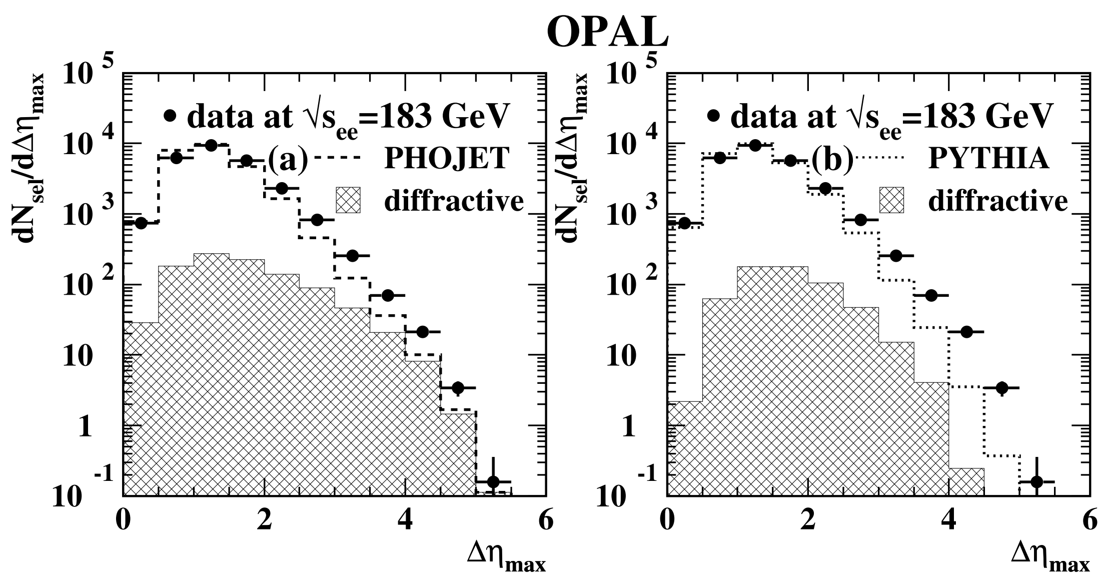



- increase with beam energy
- decrease with $W_{\gamma\gamma}$

# $\gamma\gamma \rightarrow q\bar{q}$

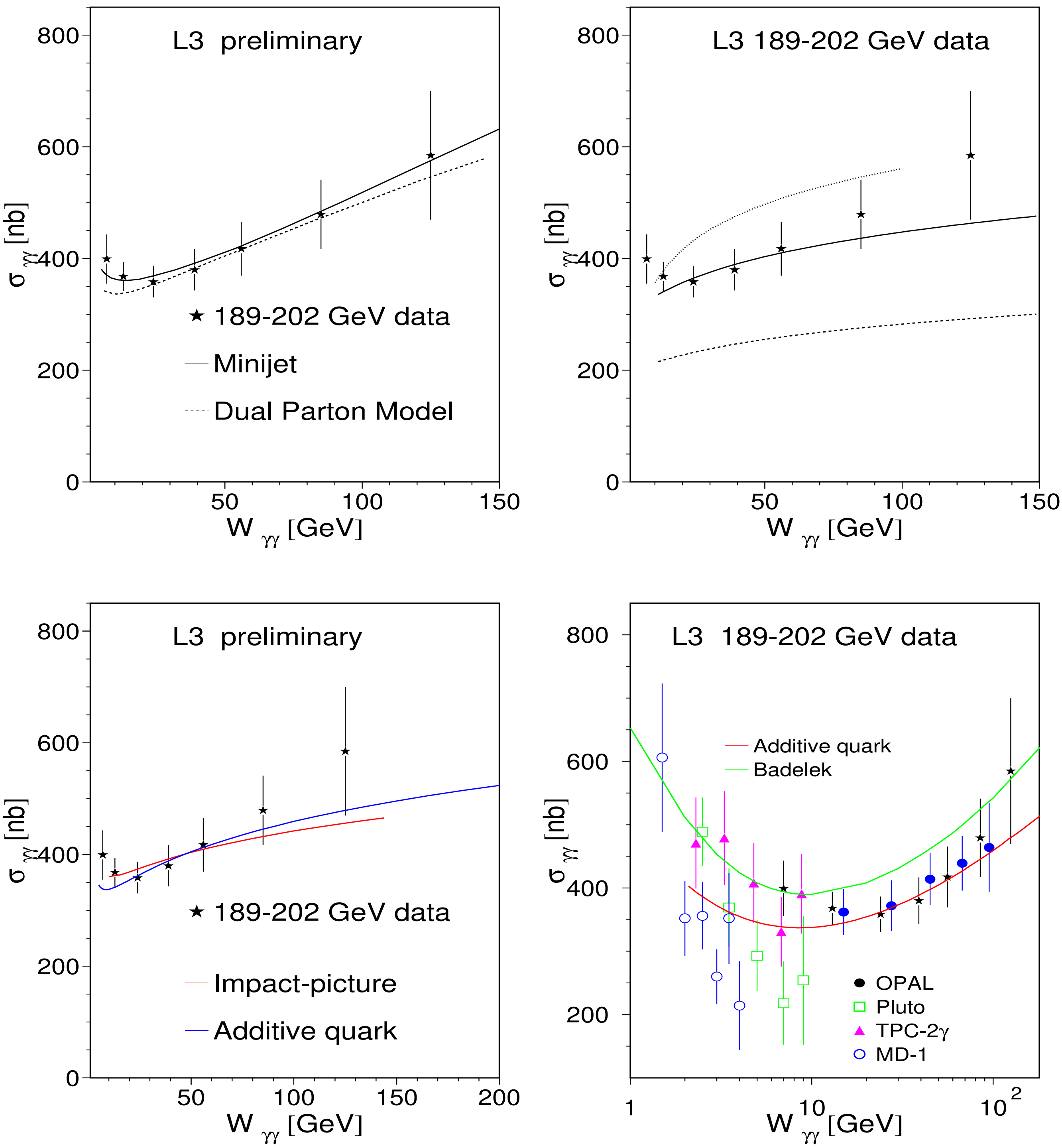



- L3 and OPAL are compatible within errors.

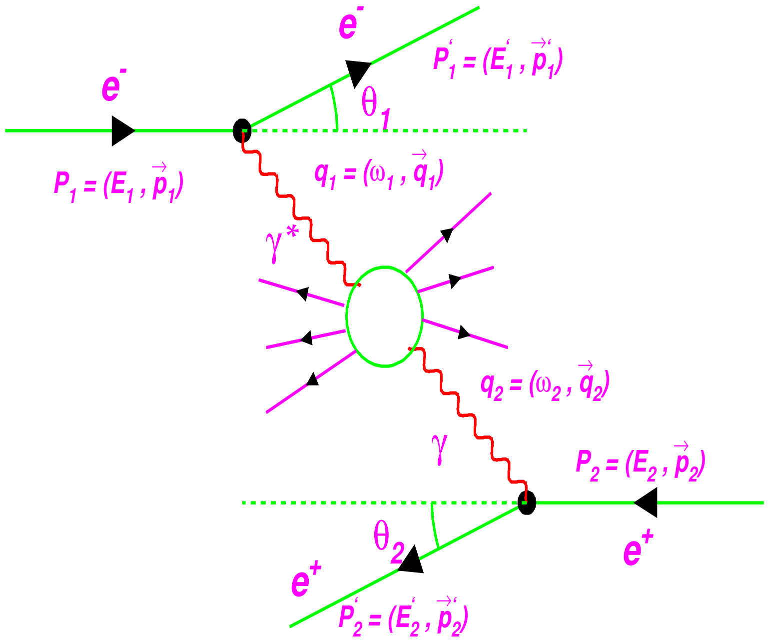



- Diffraction is important to fix the normalization

# Comparison to predictions:



# 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

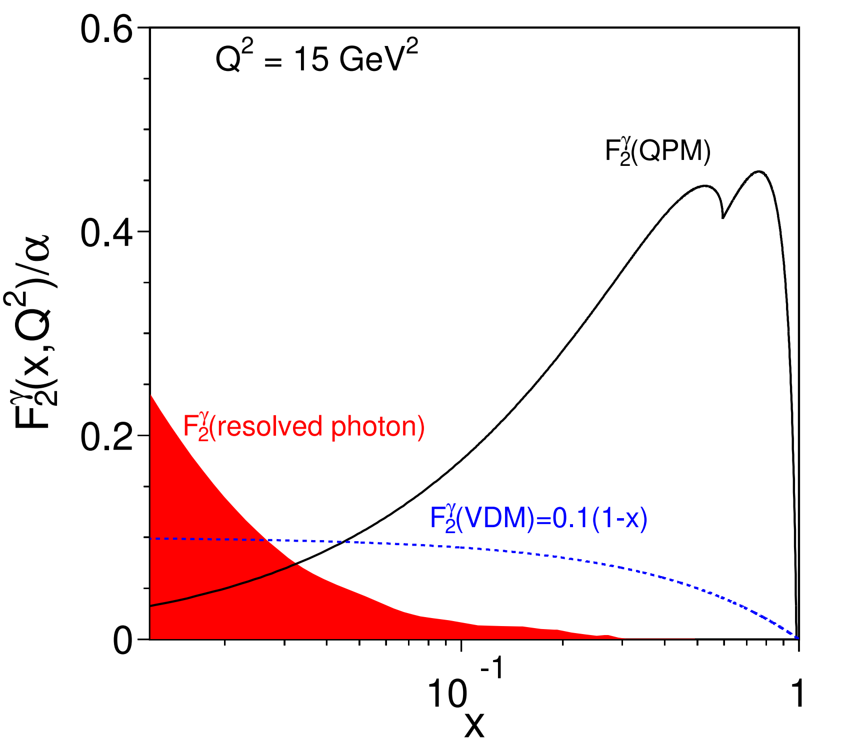
$$x = \frac{Q^2}{Q^2+P^2+W_{\gamma\gamma}^2}$$

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

## ❒ Cross Section

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

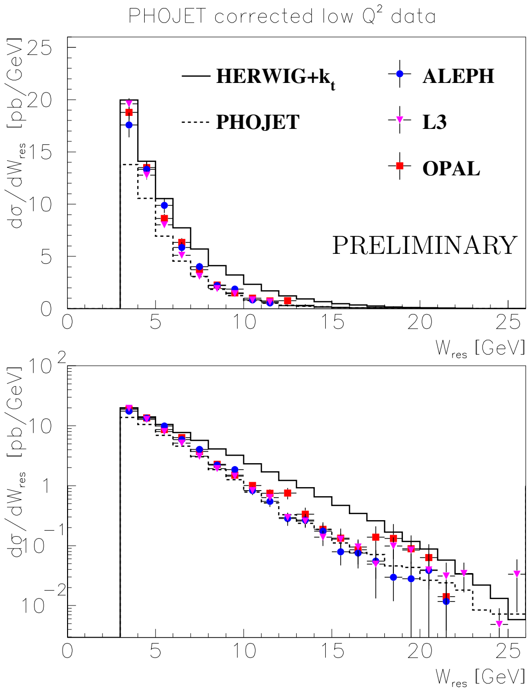
➠ Hadronic $F_2^\gamma(x,Q^2)$

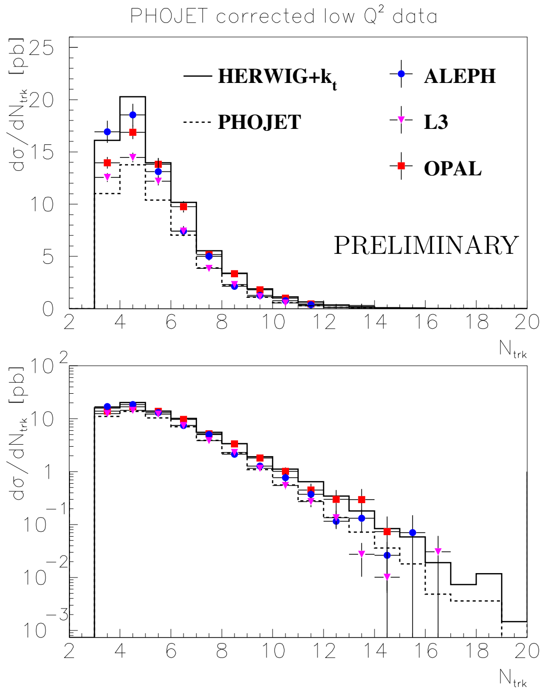


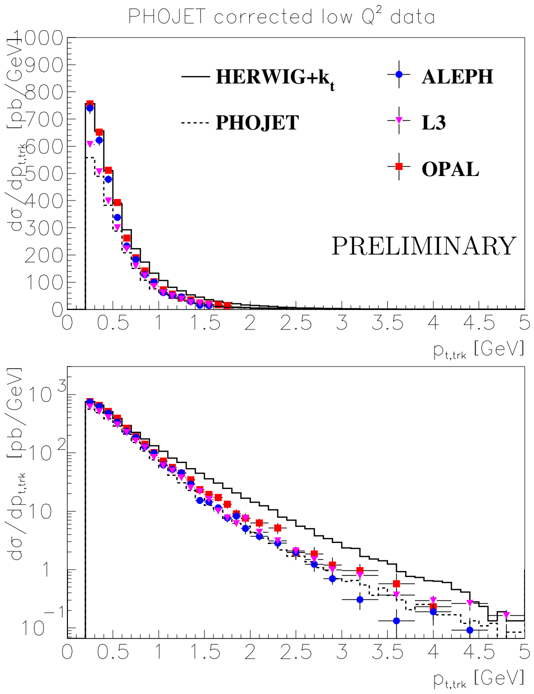
# $F_2^\gamma$: Lep $\gamma\gamma$ Working Group

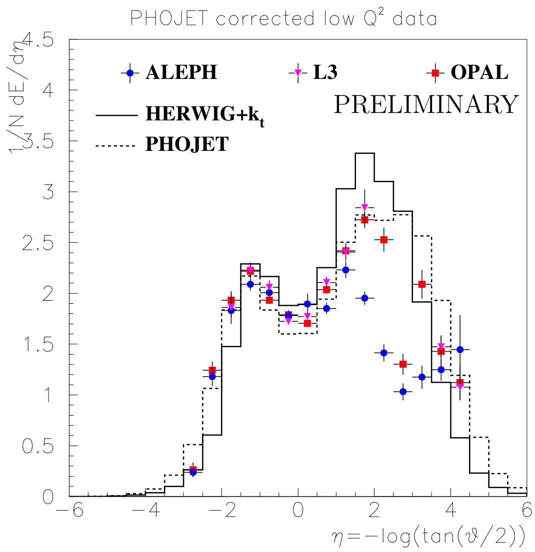
➜ Perform identical analysis in all Experiments

➜ Compare distributions inside the detector acceptance



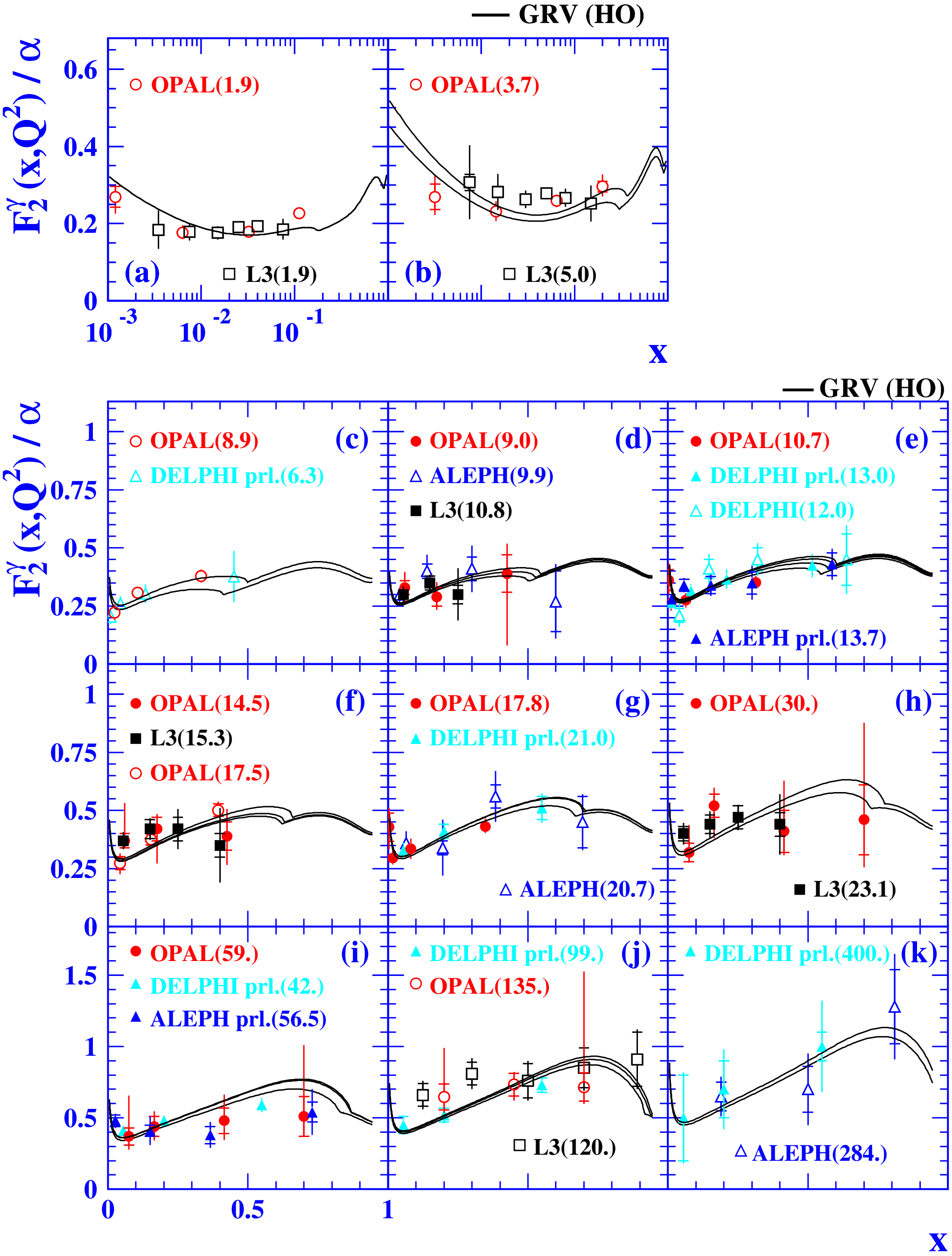



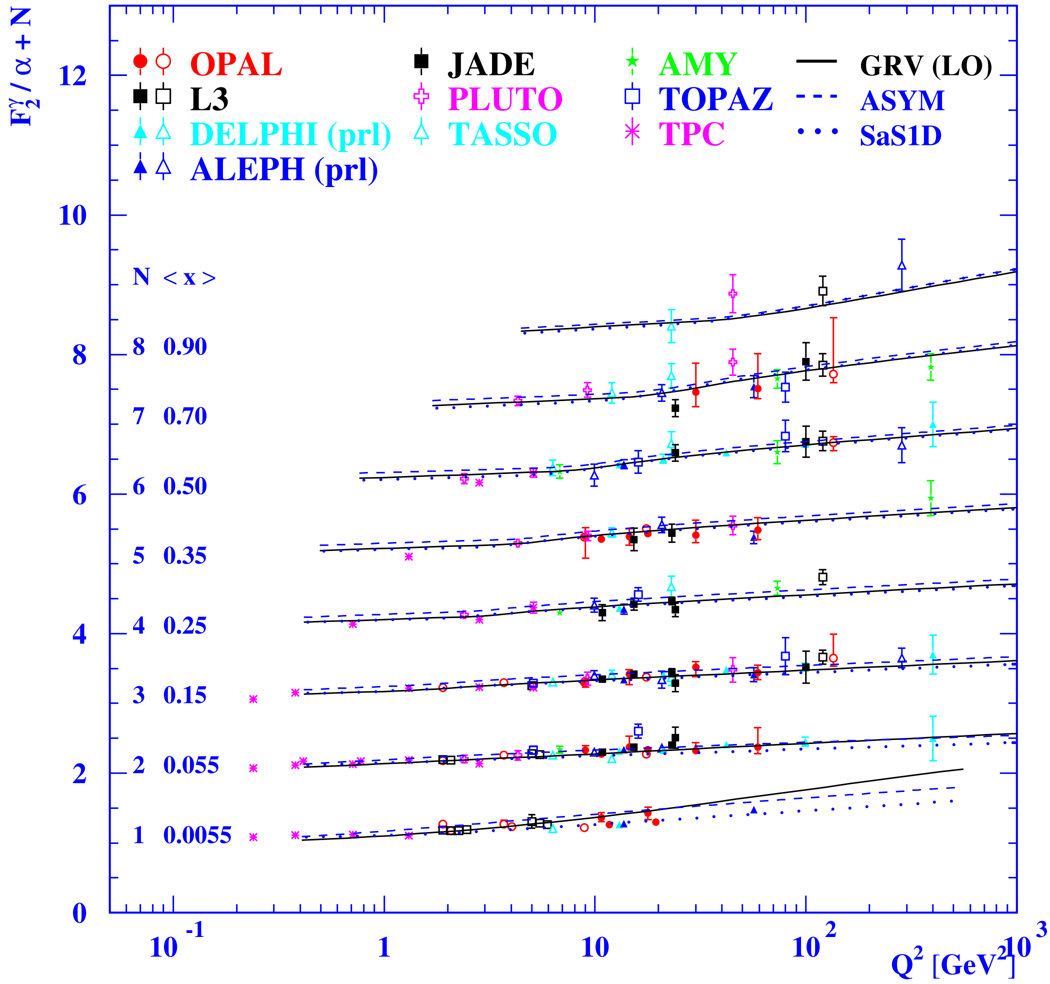




⇨ Smaller differences between experiments than differences between models

# LEP $F_2^{had}$:

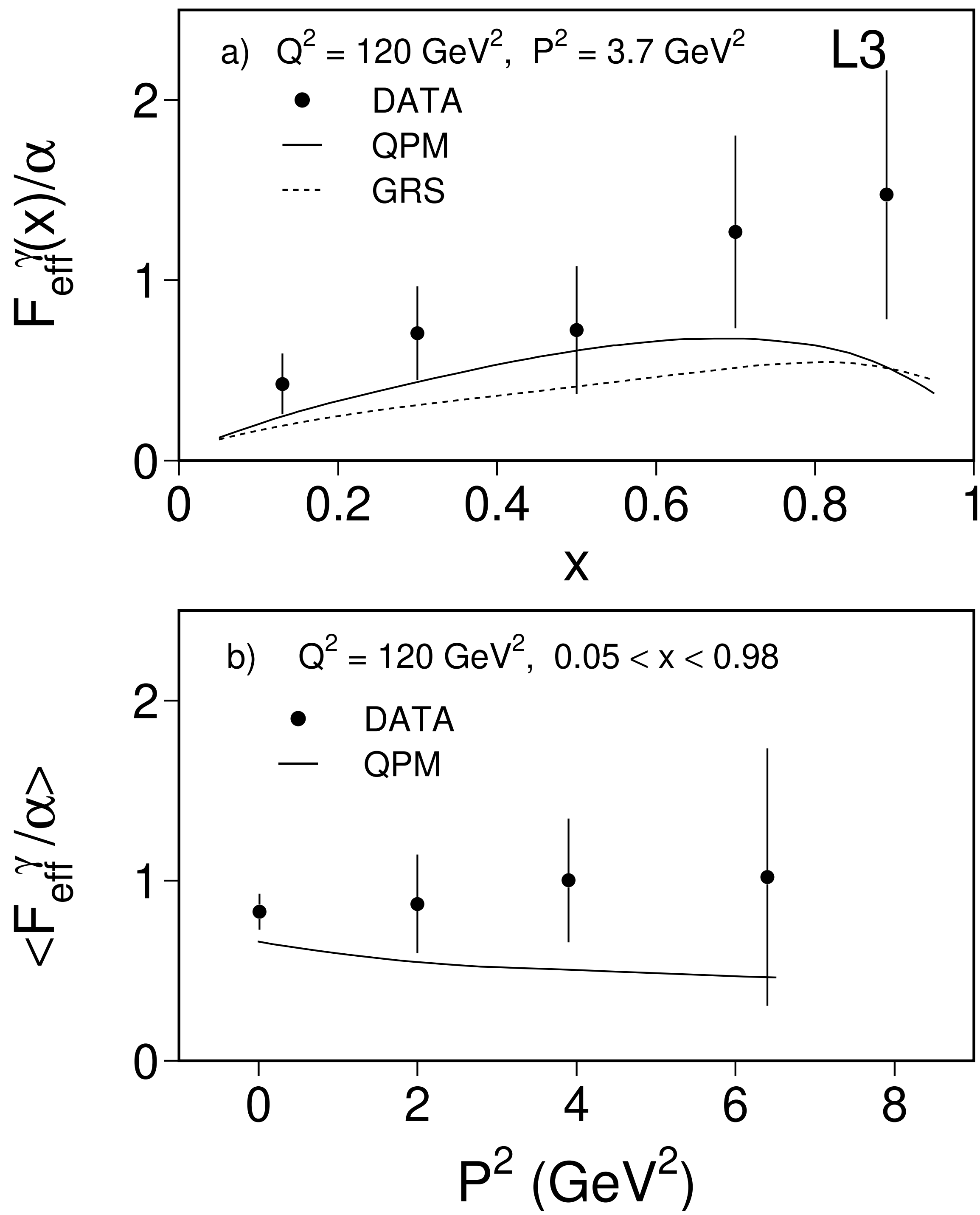

GRV (HO)
$F_2^\gamma(x,Q^2)/\alpha$
OPAL(1.9)
(a)
L3(1.9)
OPAL(3.7)
(b)
L3(5.0)
x
OPAL(8.9)
DELPHI prl.(6.3)
(c)
OPAL(9.0)
ALEPH(9.9)
L3(10.8)
(d)
OPAL(10.7)
DELPHI prl.(13.0)
DELPHI(12.0)
ALEPH prl.(13.7)
(e)
OPAL(14.5)
L3(15.3)
OPAL(17.5)
(f)
OPAL(17.8)
DELPHI prl.(21.0)
ALEPH(20.7)
(g)
OPAL(30.)
L3(23.1)
(h)
OPAL(59.)
DELPHI prl.(42.)
ALEPH prl.(56.5)
(i)
DELPHI prl.(99.)
OPAL(135.)
L3(120.)
(j)
DELPHI prl.(400.)
ALEPH(284.)
(k)
x

# $\mathrm{F}_2^{\mathrm{had}}$ evolution with $Q^2$:



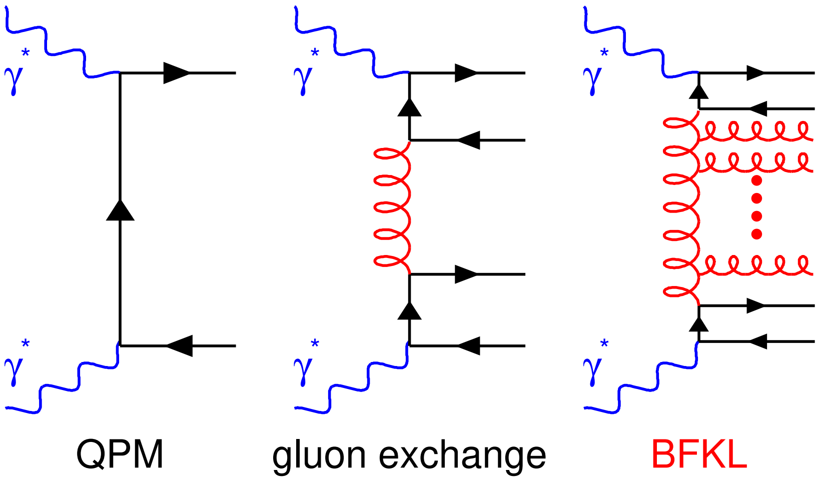

❑ ln $Q^2$ evolution agrees well with QCD

# $F^{\gamma}_{\mathrm{effective}}$ in double-tag events by L3:




❑higher than QPM

# $\gamma^*\gamma^*$ collisions




- ⇨ BFKL diagram is predicted to be dominant at high $Q^2$ and high $W_{\gamma^*\gamma^*}$.
  ⇨ two virtual photons ➜ double-tagged events
- In Leading order approximation :

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

$$s_0 = \frac{\sqrt{Q_1^2 Q_2^2}}{y_1 y_2}; \quad \alpha_P - 1 = 4 \ln 2 \frac{N_c \alpha_s}{\pi}$$

$$Y = \ln(\frac{W^2_{\gamma^*\gamma^*}}{\sqrt{Q_1^2 Q_2^2}}); \qquad < Q_1^2 > \approx < Q_2^2 >$$

- Using $N_c = 3$ , $\alpha_s = 0.2$ ➜ $\alpha_P - 1 \simeq 0.53 > 0.095$

# $\gamma^*\gamma^*$ collisions

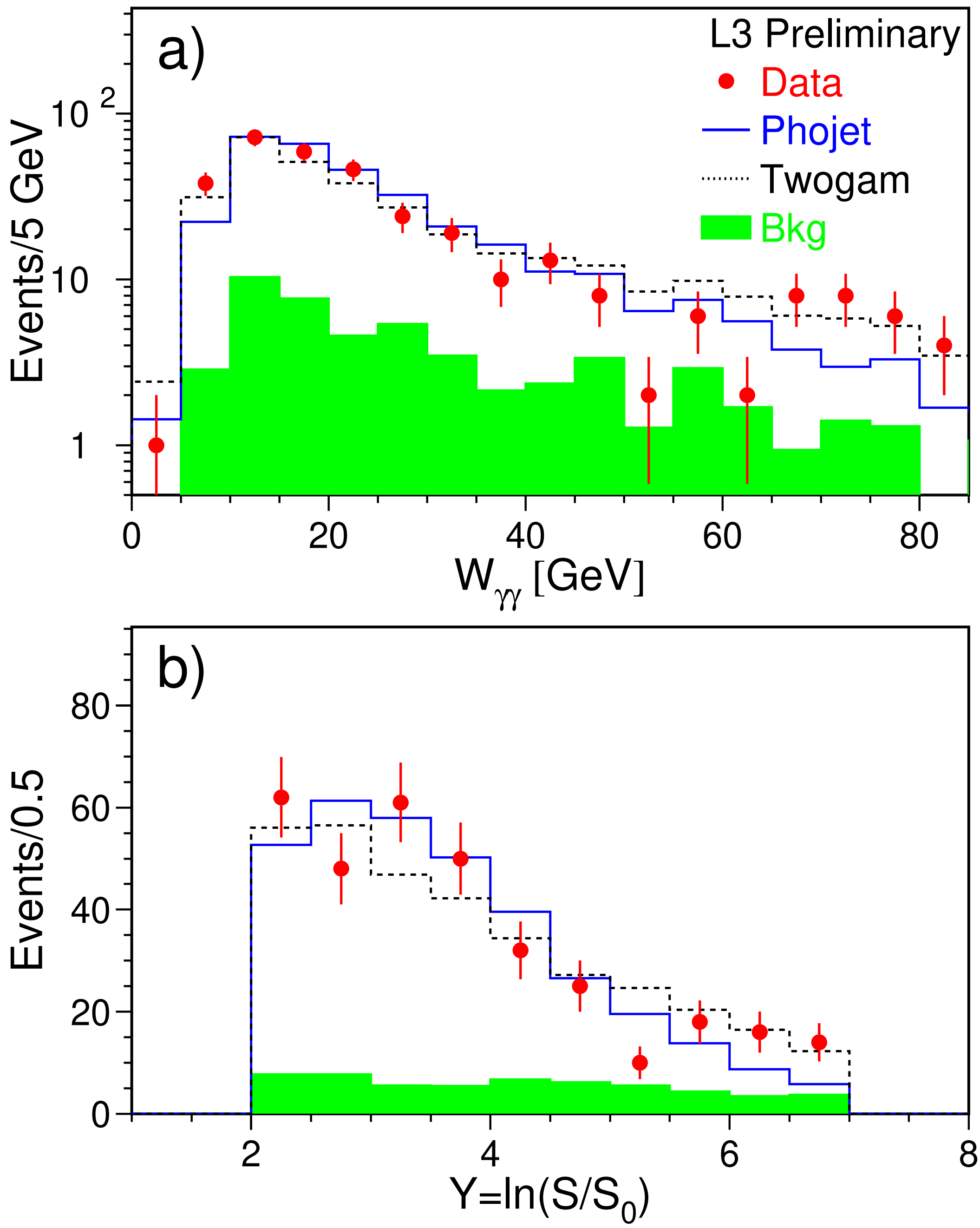
❑ Data: 189 GeV – 202 GeV, 401 pb$^{-1}$

❑ Selection :

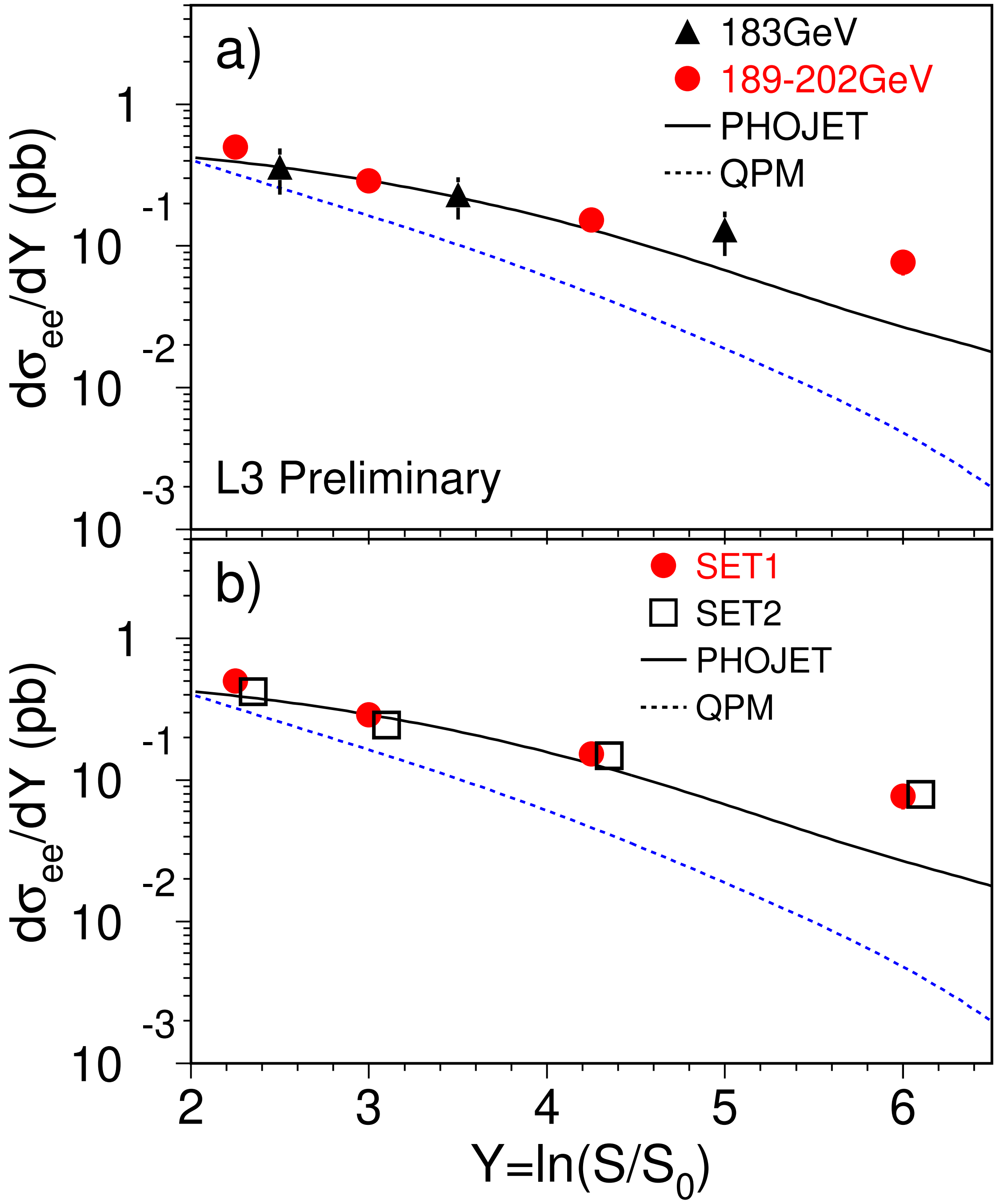
- $E_{tag} > 40$ GeV, $30 < \theta < 66$ mrad
- Number of tracks $> 2$
- $2 < \ln(S/S_0) < 7$

❑ ⇨ 324 events with 17 % bkgnd from $\gamma\gamma \rightarrow \tau\tau$ and single-tag events

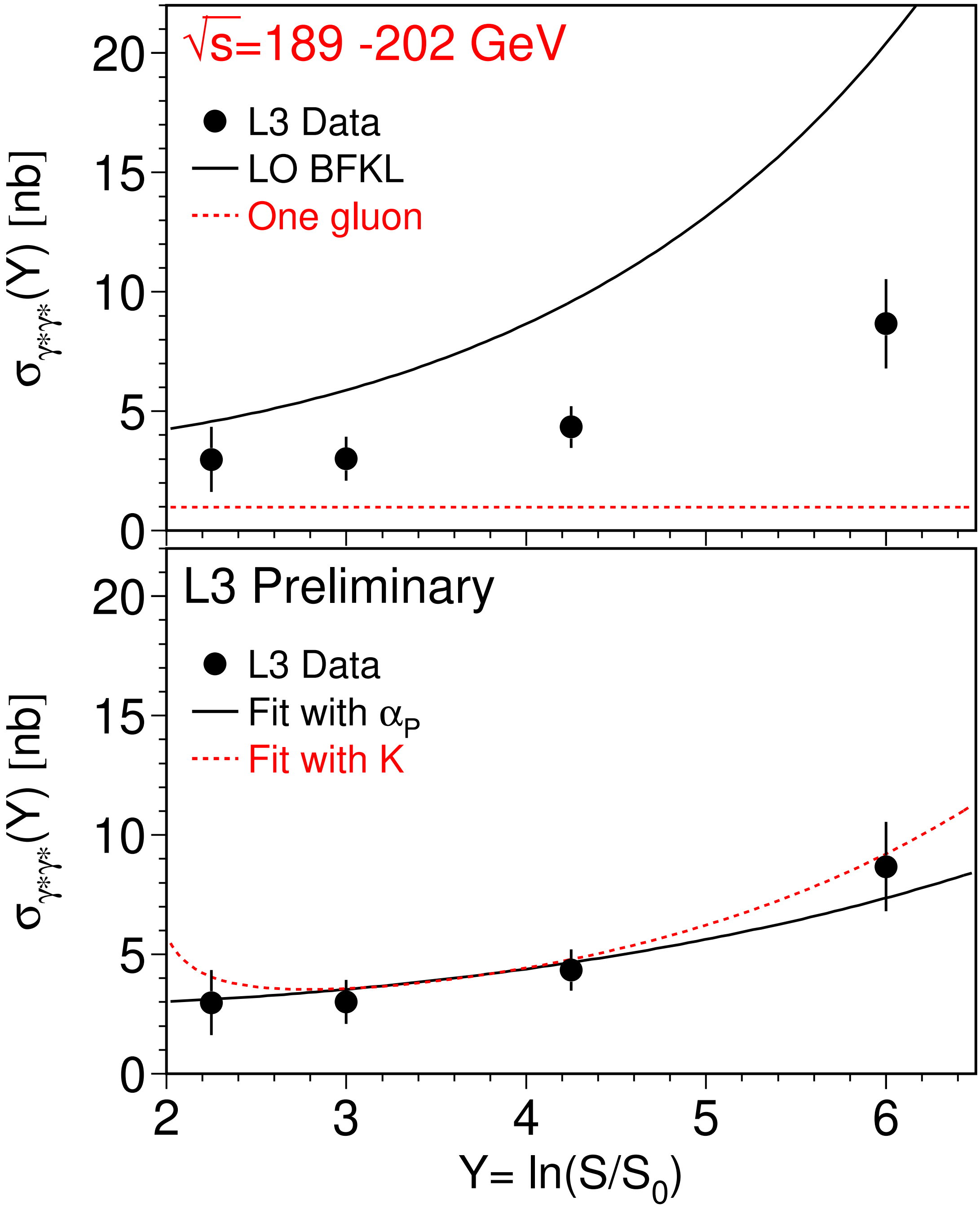
# $\gamma^*\gamma^*$ (double tag) collisions



# $ee \rightarrow eeq\bar{q}$, $\gamma^*\gamma^*$ collisions

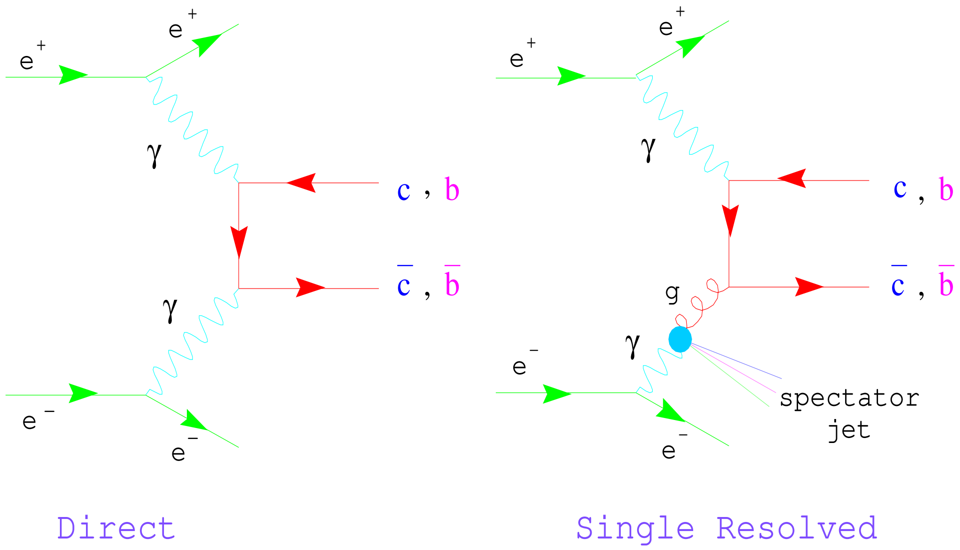


# $\gamma^*\gamma^* \rightarrow hadrons$



# Inclusive Charm and Beauty Production

## Motivation :




- **Test of the perturbative QCD**
  - ➪ Direct Process depends on $m_c(m_b)$ and $\alpha_s$
  - ➪ Resolved Process also depends on **gluon content of the photon.**
    - ∗ **at high energies the resolved processes are of the same order as the direct ones**

# Inclusive Heavy Flavour Production

Data :

**L3 :** 91 - 183 GeV, $\mathcal{L} = 165$ pb$^{-1}$

PLB453(1999)83.

**L3* :** 189 - 202GeV, $\mathcal{L} = 410$ pb$^{-1}$

**OPAL :** 183 - 189 GeV, $\mathcal{L} = 220$ pb$^{-1}$

CERN-EP/99-157.

**ALEPH* :** 183 GeV, $\mathcal{L} = 53$ pb$^{-1}$

$\star$ Preliminary

Charm identification :

**L3:** lepton tag ($c \rightarrow l^{\pm}$X, $l^{\pm} \equiv$ e$^{\pm}, \mu^{\pm}$)
D$^{*+}$ tag

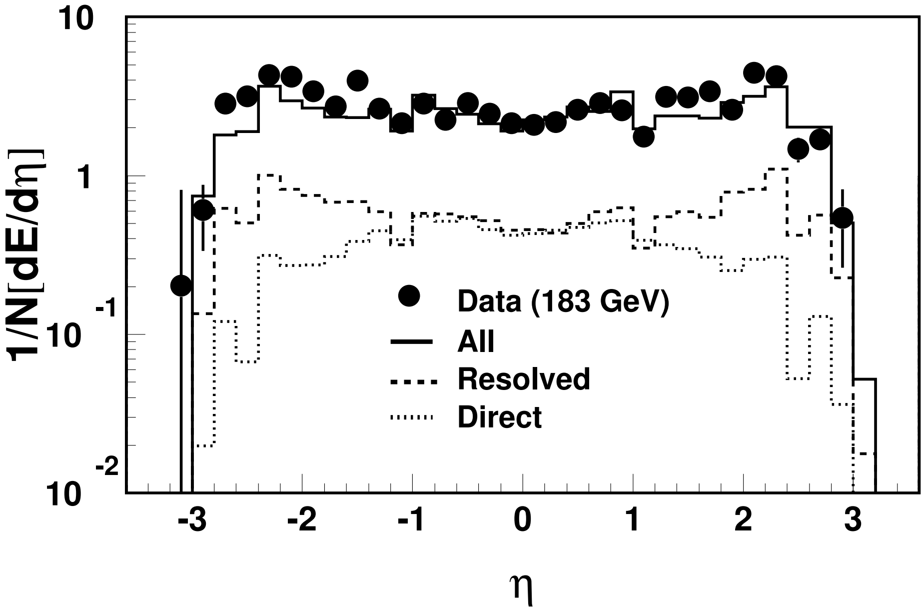
**OPAL:** D$^{*+}$ tag

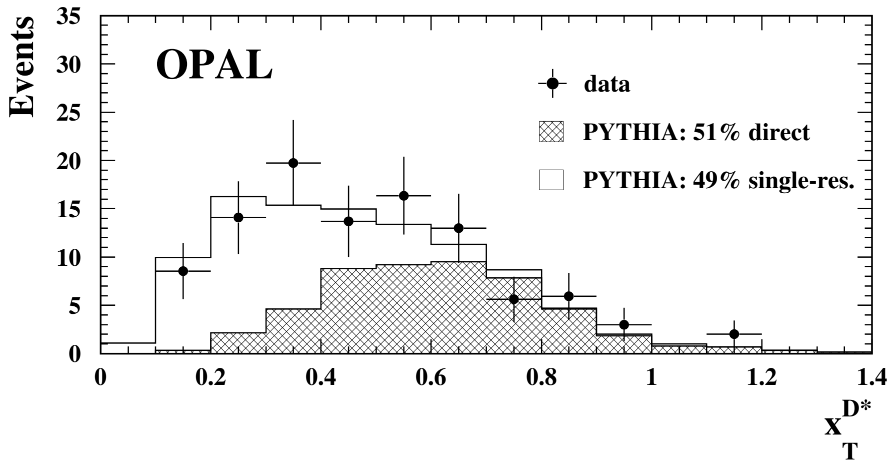
**ALEPH:** lepton tag ($c \rightarrow l^{\pm}$X , $l^{\pm} \equiv \mu^{\pm}$)

Bottom identification :

**L3 :** lepton tag ($c \rightarrow l^{\pm}$X , $l^{\pm} \equiv$ e$^{\pm}, \mu^{\pm}$)

# Direct vs Resolved :



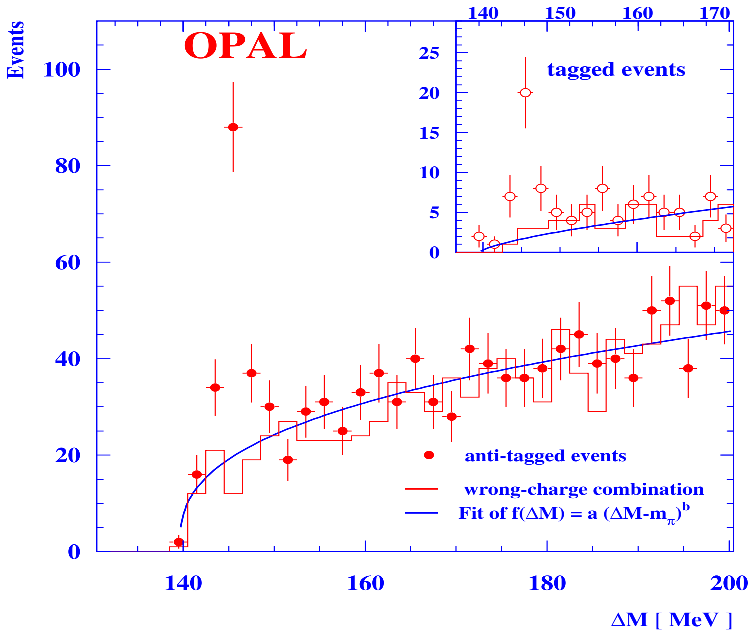

- resolved processes are needed to describe the data

$e^+e^- \rightarrow e^+e^-c\bar{c}$ :

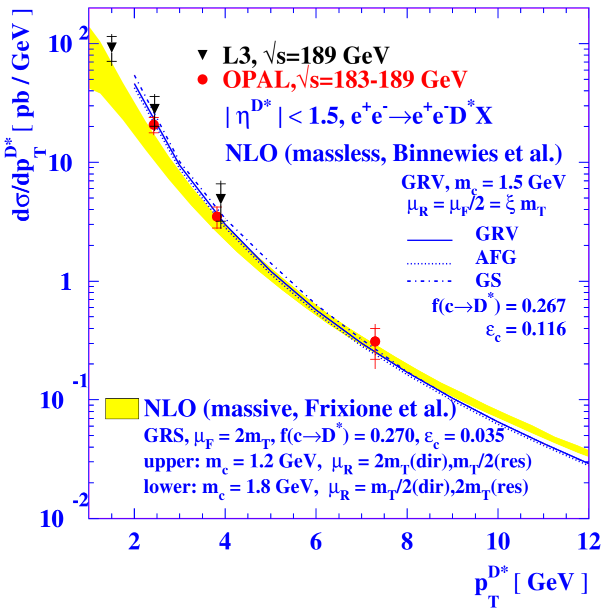
$\sigma_{dir} = 401 \pm 124$ pb $\quad \sigma_{res} = 562 \pm 202$ pb

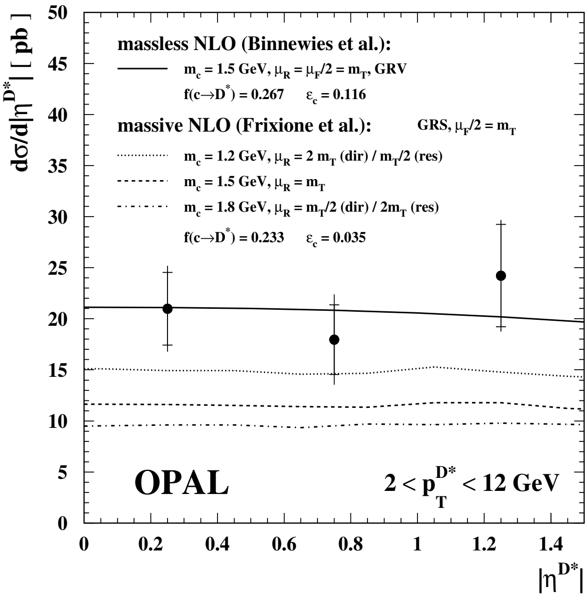
# D* Production :

- Data: $\sqrt{s}$ = 183-189 GeV,
$N_{ev}^{antitag} = 100 \pm 13, N_{ev}^{tag} = 30 \pm 6$
- $D^{*\pm} \to D^0 \pi_s^\pm$,
$D^0 \to K^\pm \pi^\mp, D^0 \to K^\pm \pi^\mp \pi^+ \pi^-$




- Differential cross-sections:

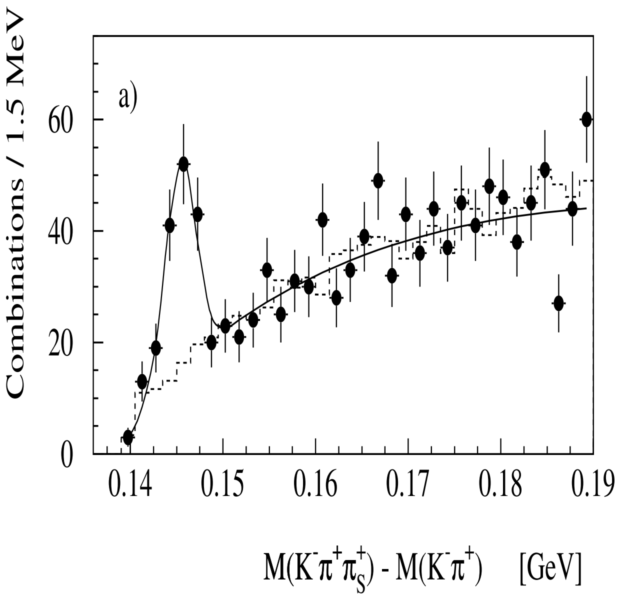


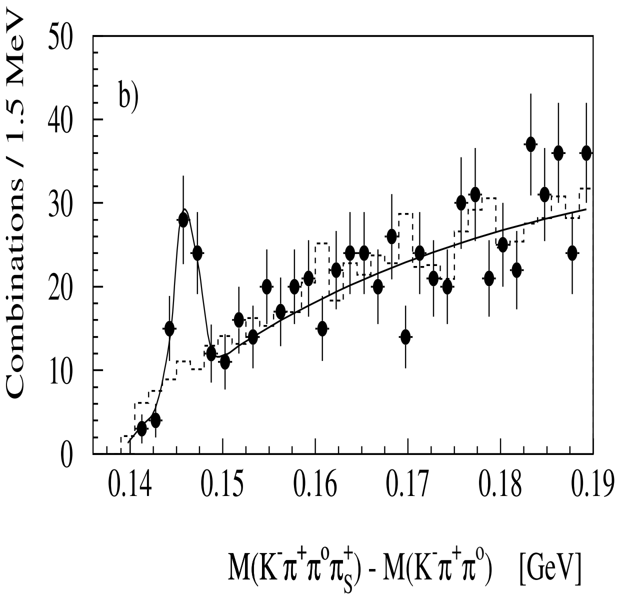



# D* Production :

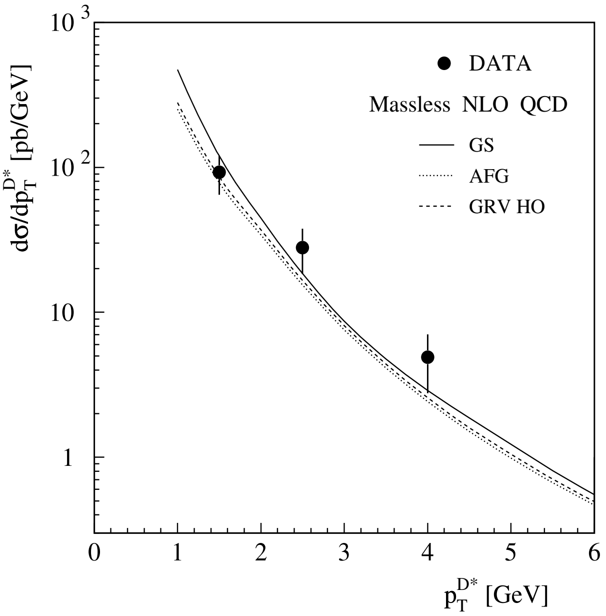
- Data: $\sqrt{s} = 189$ GeV
- $D^{*\pm} \to D^0\pi_s^\pm$,
  $D^0 \to K^\pm\pi^\mp, D^0 \to K^\pm\pi^\mp\pi^0$

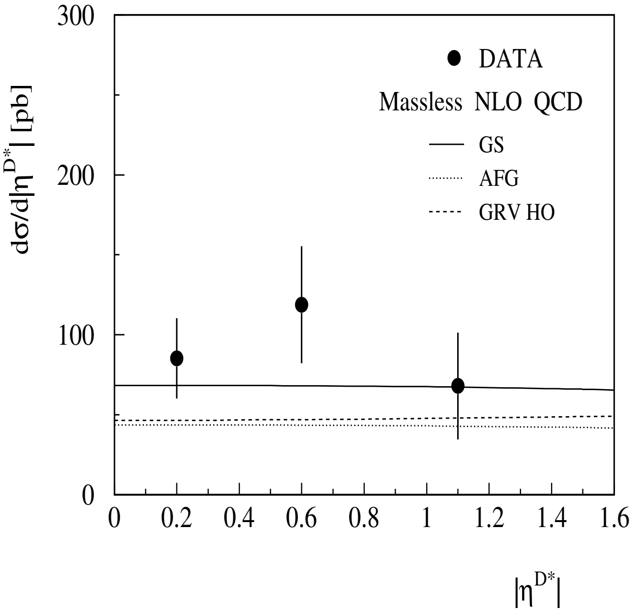
Nevents = 102 ± 17     Nevents = 42 ± 11



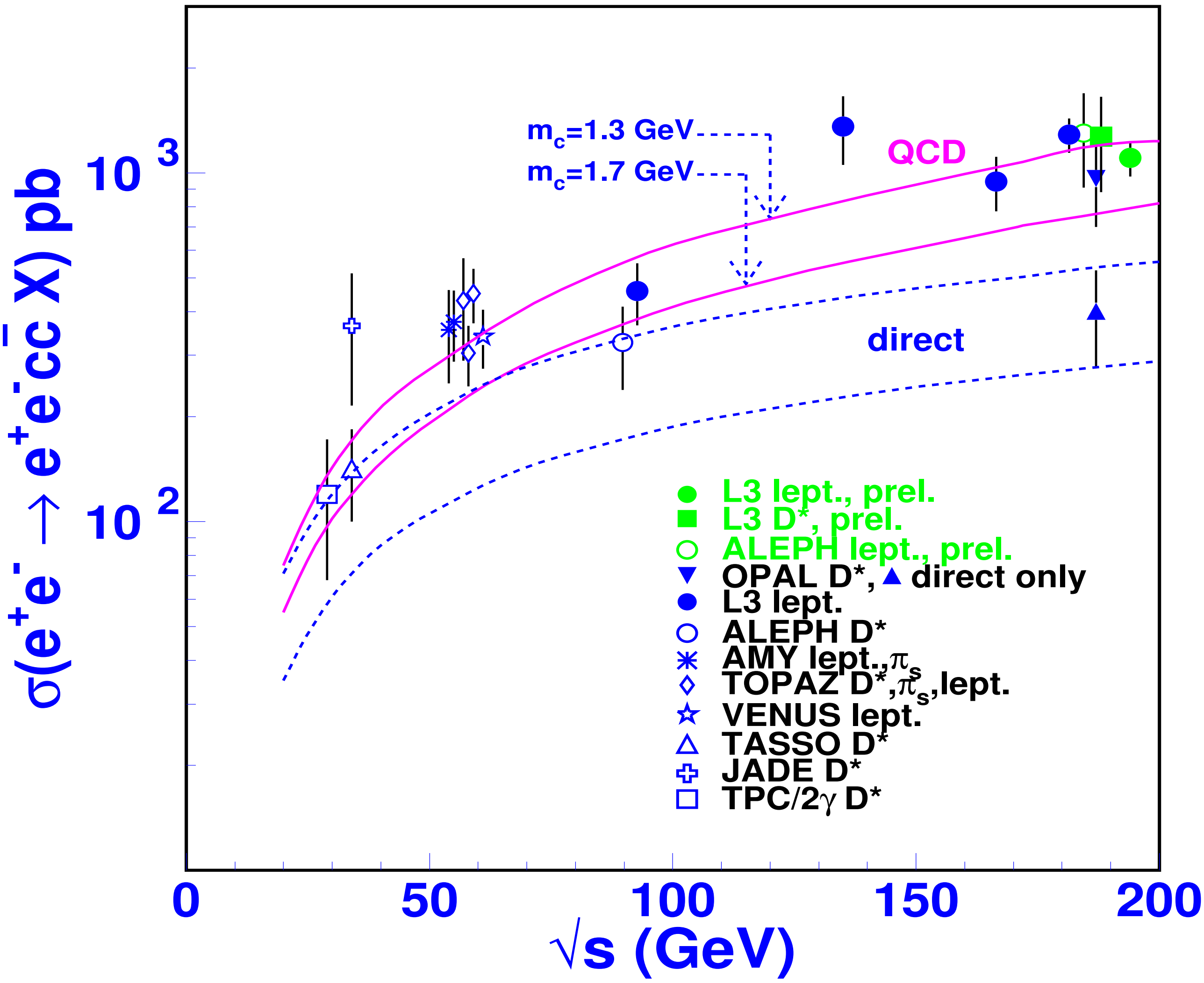




- Differential cross-sections:



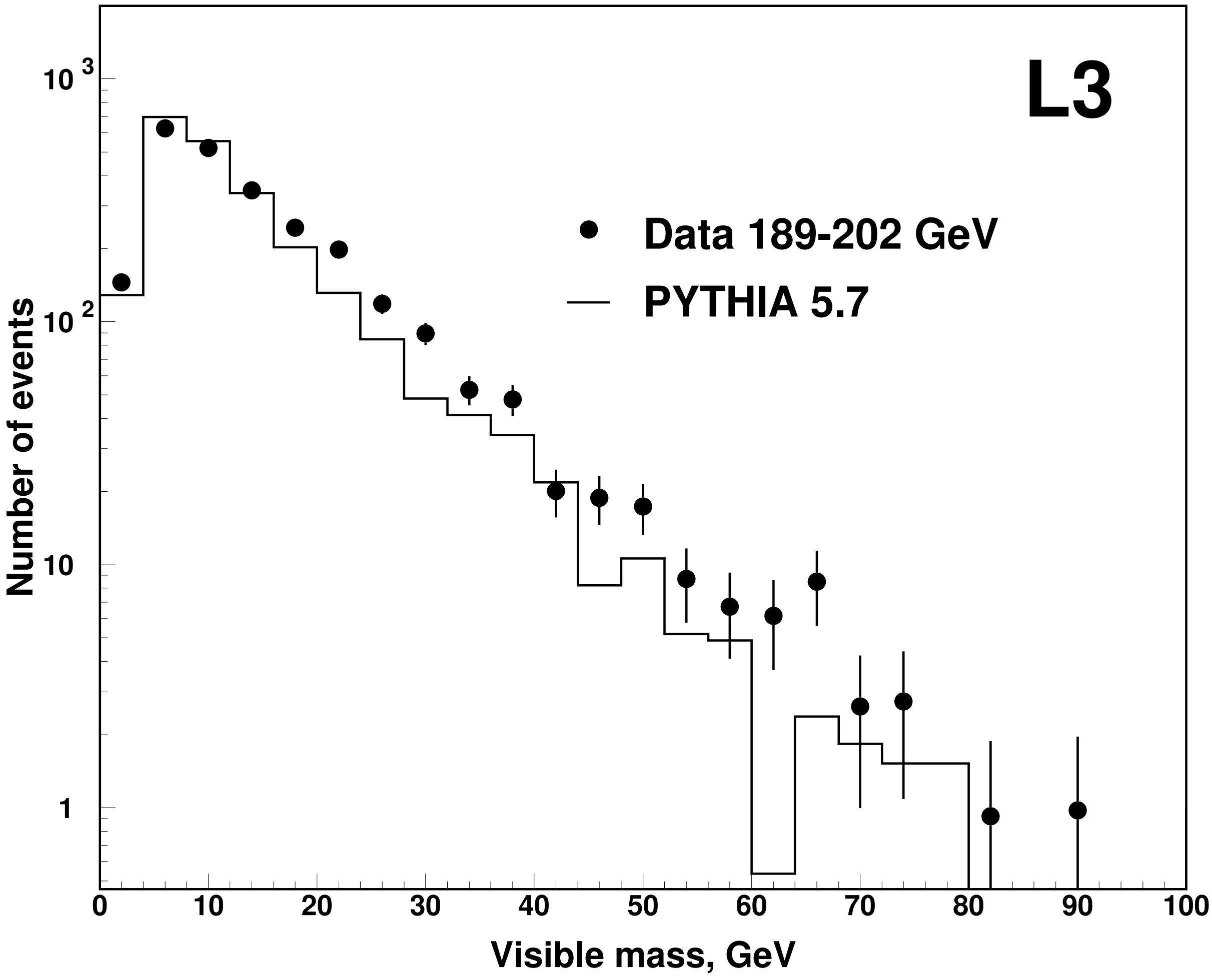
# Charm production in $\gamma\gamma$ collisions




- clear evidence of gluon content of photon

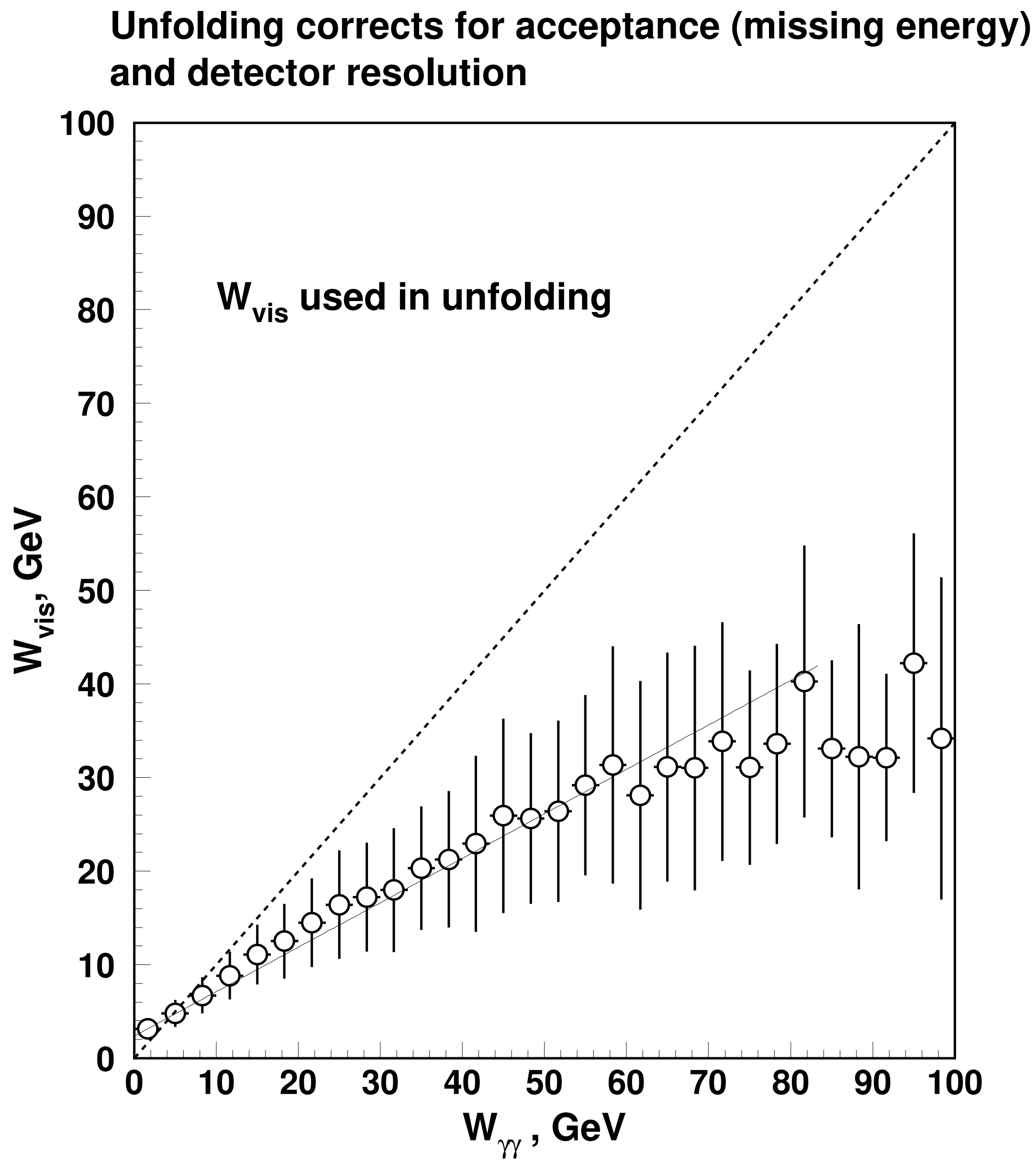
theory prediction from
M.Drees,M.Krämer,J.Zunft and P.M.Zerwas,Phys. Lett. B306 (1993) 371), $M_R = M_F = m_c$; GRV p.d.f.

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



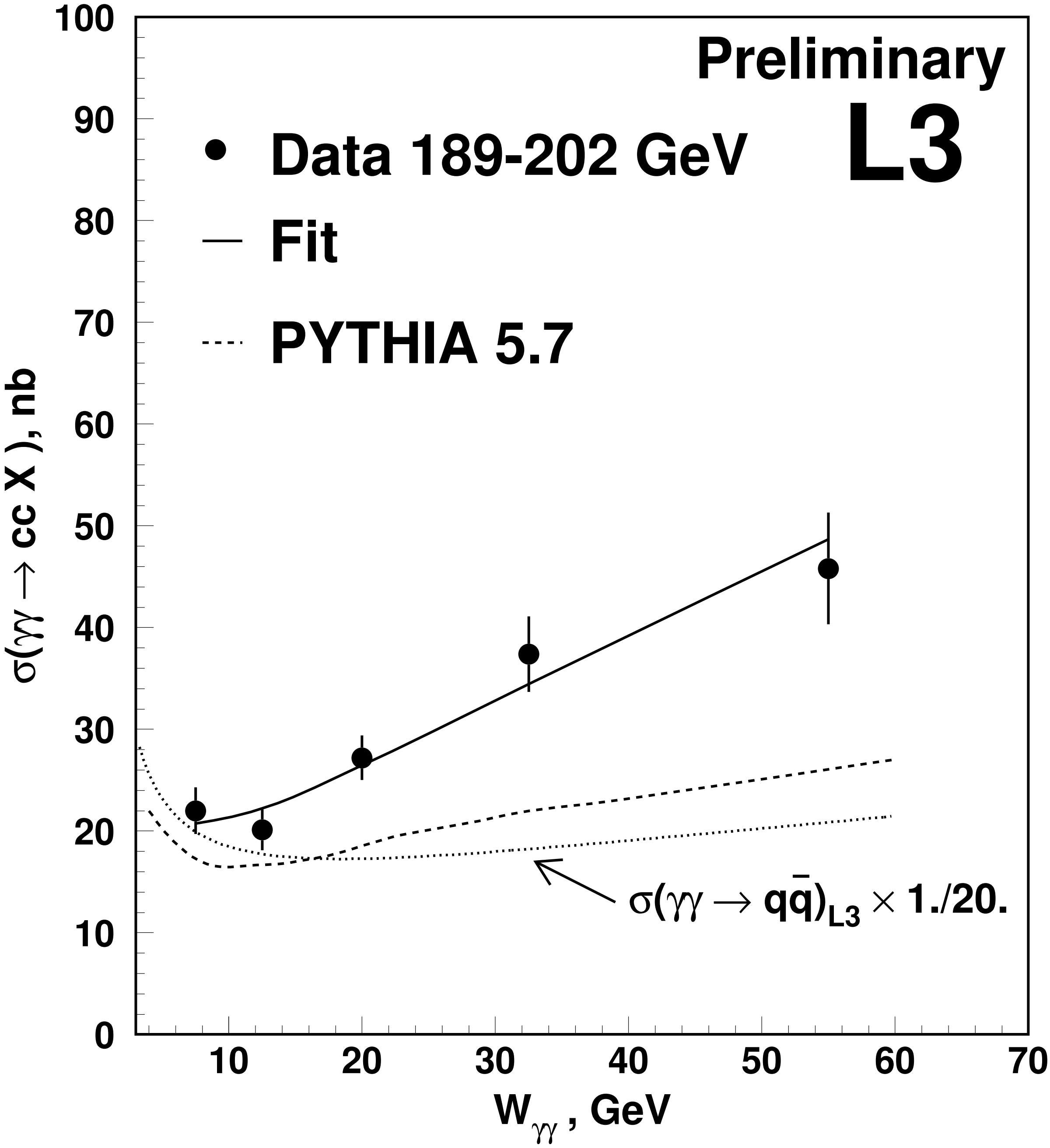

- Data are in excess of MC for high visible mass

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



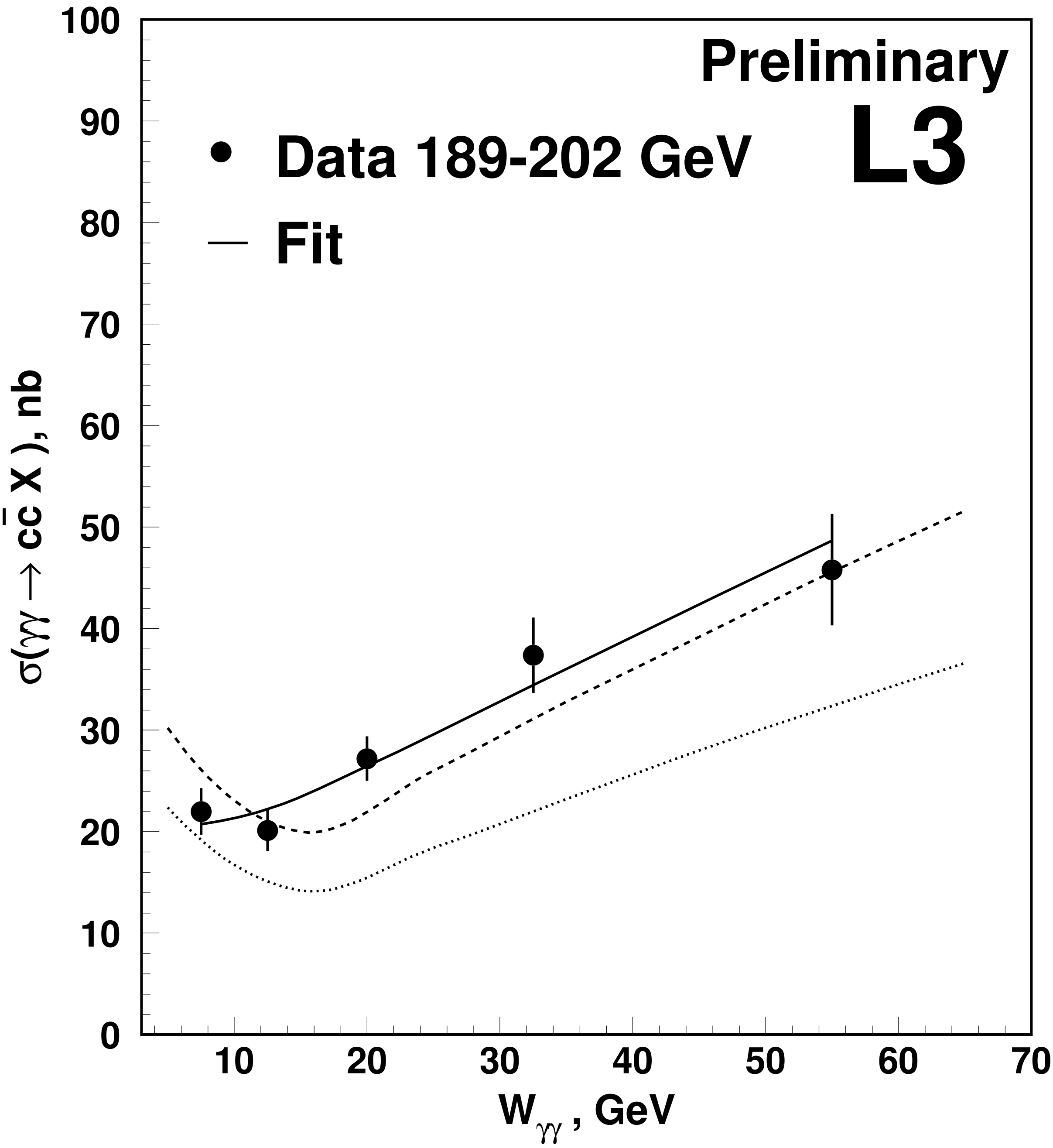

- unfolding with Bayes (G. D'Agostini, NIM A362(1995) 487)
- $\sigma_{ee} = \mathcal{L}_{\gamma\gamma} \otimes \sigma_{\gamma\gamma}$

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




- A steeper rise with energy as compared to $\sigma(\gamma\gamma \to hadrons)$

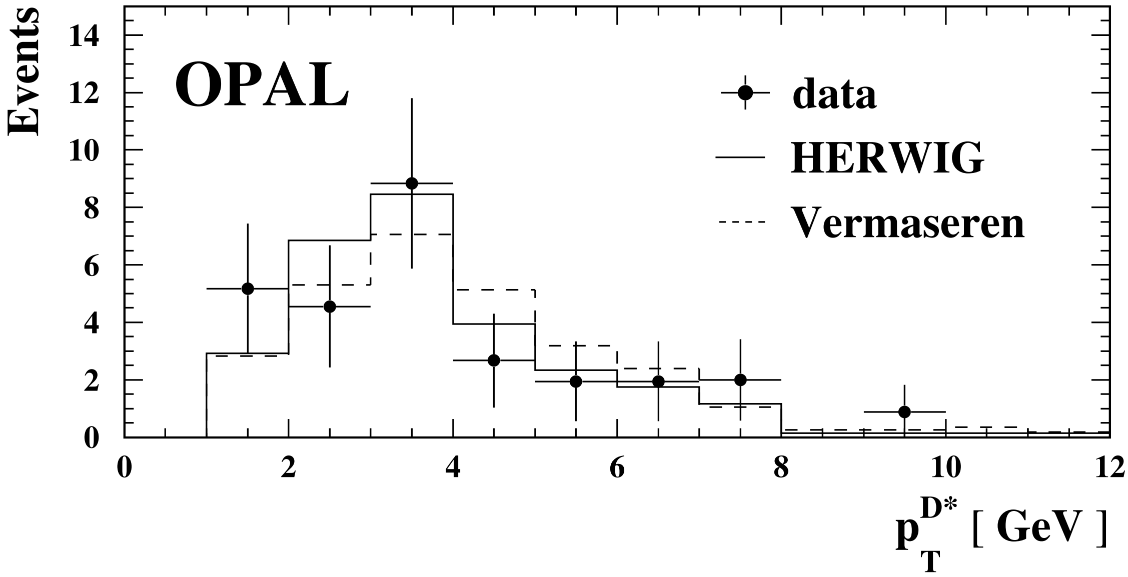
# $\sigma(\gamma\gamma \to c\bar{c})$ vs NLO QCD :

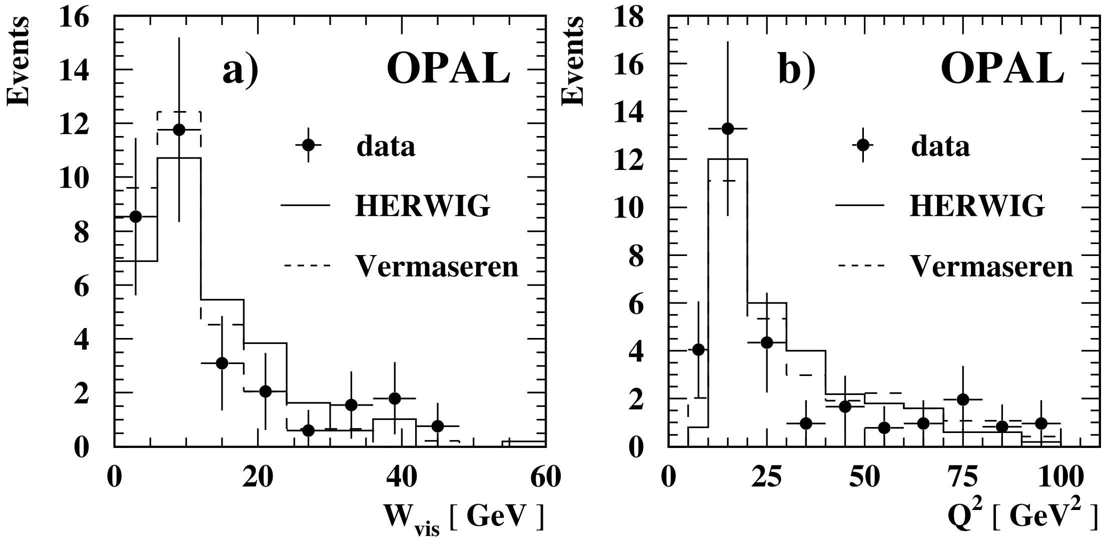



- Prediction by S. Frixione, M. Kramer and E. Laenen scaled by factor 2
- The slope is reproduced, normalization is too low

# Charm structure function

❒ 33 mrad $< \theta' <$ 55 mrad, $P_t^{D^*} > 1$ GeV
❒ 60 mrad $< \theta' <$ 120 mrad, $P_t^{D^*} > 3$ GeV

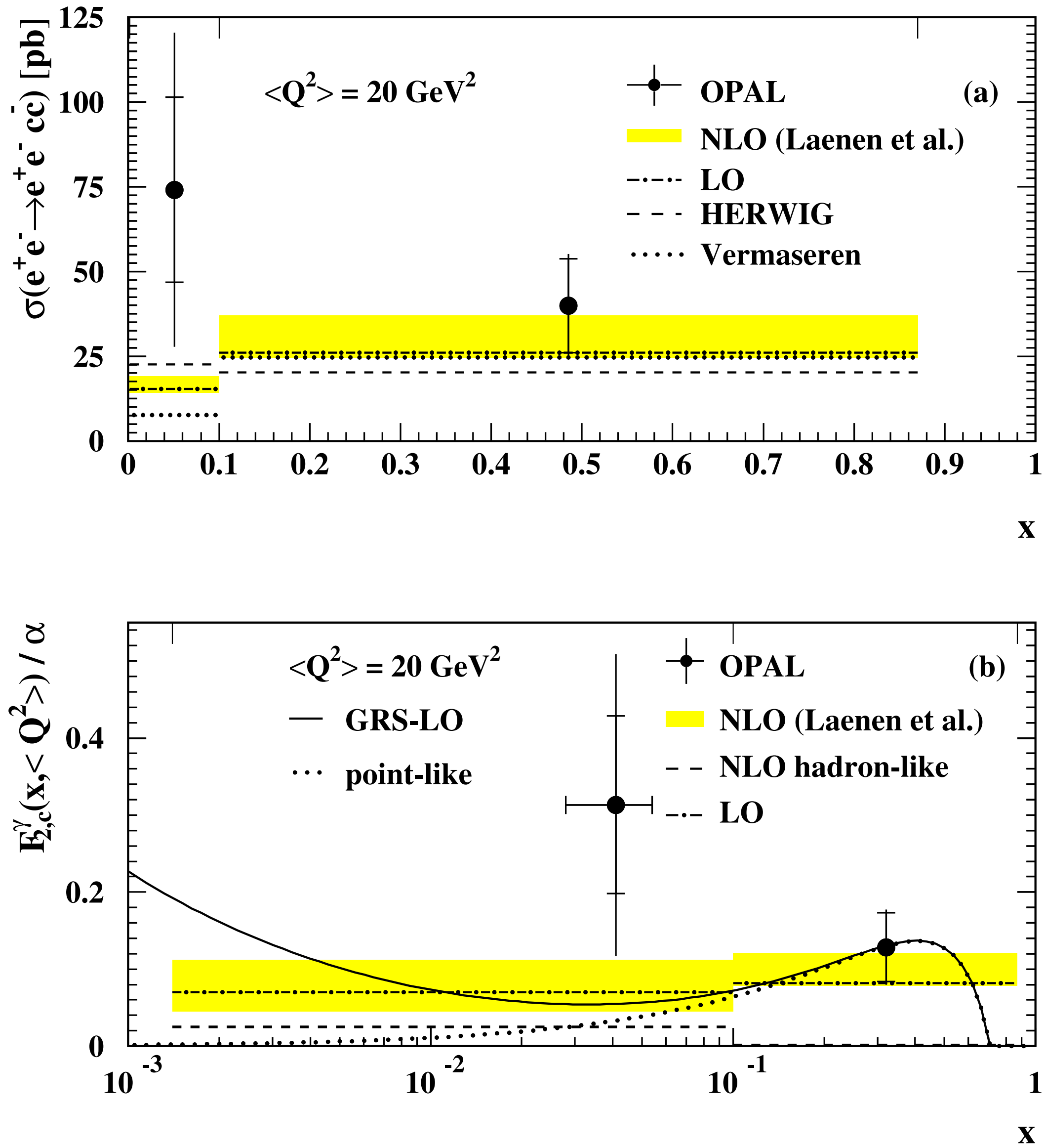



- Both HERWIG and Vermaseren MC describe the shape of the data

# Charm structure function:

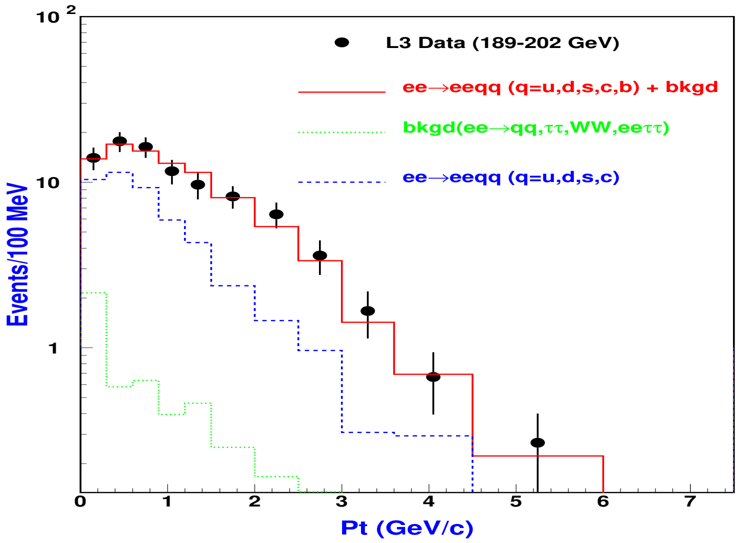
- ❒ $0.0014 < x < 0.1$, $0.1 < x < 0.87$
- ❒ $\langle Q^2 \rangle = 20$ GeV$^2$



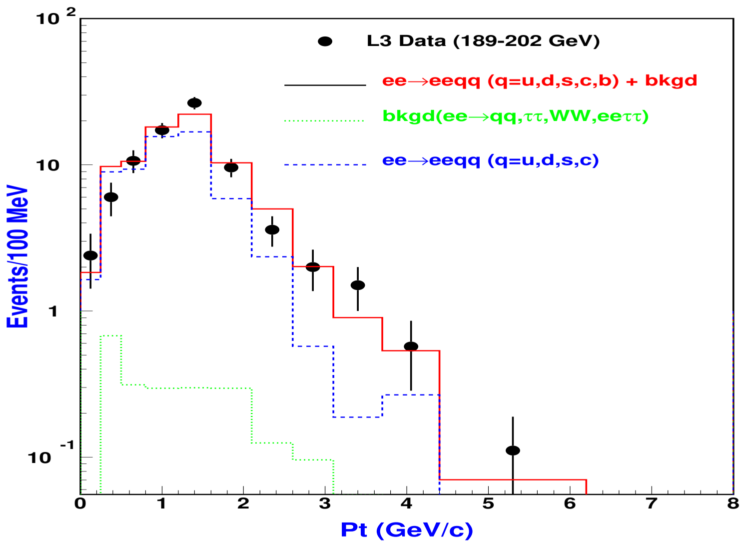

- Hadron-like component of $F_{2,c}^{\gamma}$ is needed
- $F_{2,c}^{\gamma}$ in $\gamma\gamma$ collisions measured for the first time !

# Search for Beauty: L3 Data

## $\mathrm{p}_t$ with respect to the nearest jet




$\mathrm{P}^{\mu} > 2.5$ GeV
$\mathrm{N}^{\mu}_{\mathrm{ev}} = 323$
$\varepsilon^{\mu}_{b} = 2.3\%$
$\Pi^{\mu}_{b} = 55\% \pm 9\%$




$\mathrm{P}^{e} > 1.5$ GeV
$\mathrm{N}^{e}_{\mathrm{ev}} = 320$
$\varepsilon^{e}_{b} = 2.2\%$
$\Pi^{e}_{b} = 29\% \pm 7\%$

Leptons from bottom decays have higher $\mathrm{p}_t$.

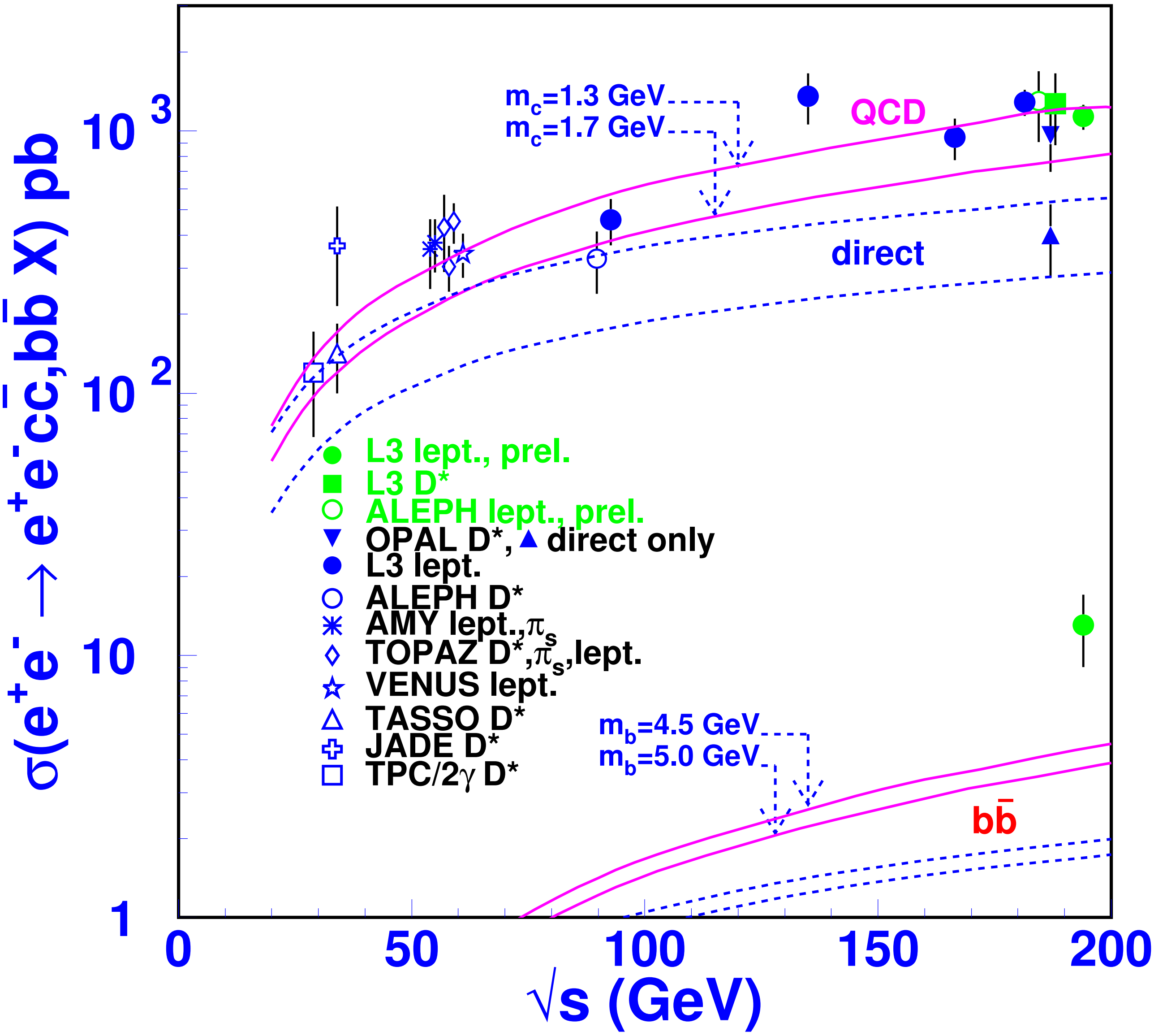
Preliminary:

Muons: $\sigma_{\mathrm{b\bar{b}}} = 15.4 \pm 2.9(\mathrm{stat}) \pm 4.9(\mathrm{syst})$ pb

Electrons: $\sigma_{\mathrm{b\bar{b}}} = 11.5 \pm 2.3(\mathrm{stat}) \pm 3.4(\mathrm{syst})$ pb

Combined: $\sigma_{\mathrm{b\bar{b}}} = 13.0 \pm 1.8(\mathrm{stat}) \pm 3.6(\mathrm{syst})$ pb

# Charm and beauty in $\gamma\gamma$ collisions




**$b\bar{b}$ in $\gamma\gamma$ collisions measured for the first time !**

# Conclusion

- Hadronic cross sections

- $\sigma_{\gamma\gamma}$ increases at high energies – independent of used MC
- fitted Pomeron slope value, is larger than PDG value
- The dominant uncertainty is the modelling dependence
- The $F_2^{had}$ ($F_2^c$) needs resolved processes at low x
- There is no striking growth of $F_2^{\gamma}$ at low x
- Charm production is in agreement with QCD prediction, ➜ $\gamma g \rightarrow c\bar{c}$ is important
- fitted Pomeron slope value for charm production, $\epsilon = 0.29 \pm 0.07$ is larger than PDG value ➜ as expected by QCD
- Beauty production is in disagreement with QCD prediction, about 4 standard deviations higher than expected ! See also Tevatron and HERA similar results
- Virtual photons cross section at LEP has been measured. Fitted Pomeron slope value is $\epsilon = 0.36 \pm 0.02$ for $< Q^2 > = 15$ GeV$^2$, inconsistent with BFKL (0.53) prediction