# Hadronic Cross-Sections for Untagged and Double Tagged Events in Two Photon Collisions at LEP.

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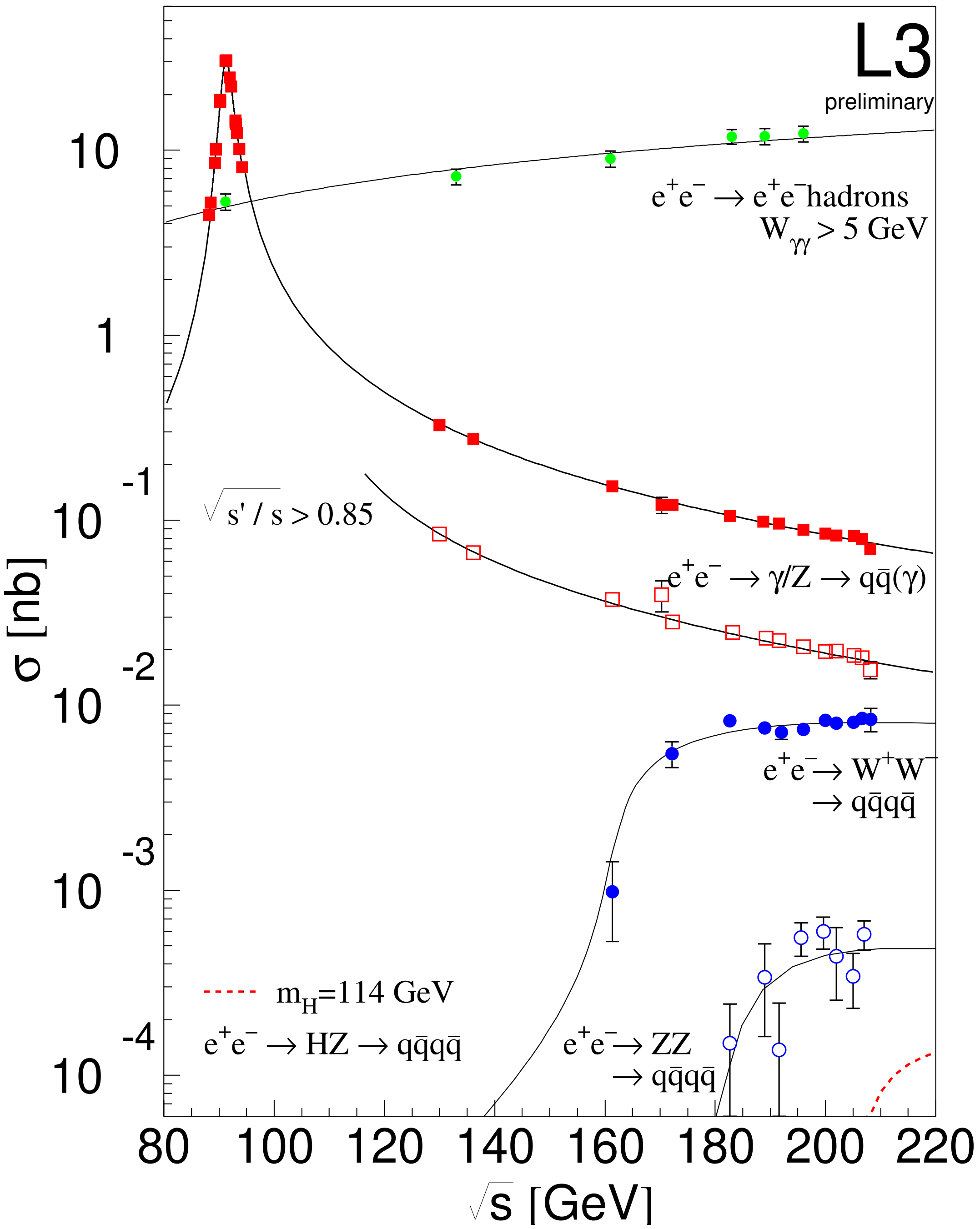
## *Hadron production at LEP*




$\gamma\gamma$ interaction has a dominant cross section at LEP2 - it is a copious source of hadron production.

## Total $\sigma_{\gamma\gamma} : \gamma\gamma \rightarrow hadrons$

$$\underbrace{\mathrm{e}^+_{p_1}\mathrm{e}^-_{p_2} \longrightarrow \mathrm{e}^+_{p_1'}}_{Q^2}\mathrm{e}^-_{p_2'}\underbrace{\gamma^*_{q_1}\gamma^*_{q_2}}_{\mathrm{W}_{\gamma\gamma}} \longrightarrow \mathrm{e}^+\mathrm{e}^-\underbrace{hadrons}_{W_{\mathrm{vis}}}$$

$Q_1^2 = -q_1^2,\ Q_2^2 = -q_2^2$ – Photon virtuality

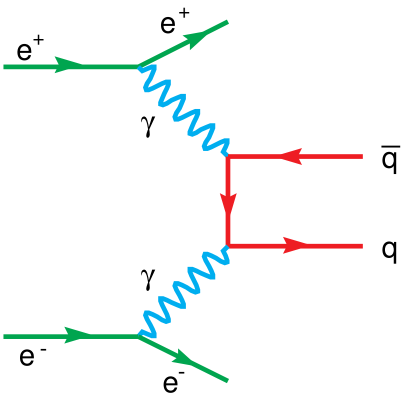
$\mathrm{W}^2_{\gamma\gamma} = (q_1 + q_2)^2$ – Center of mass energy squared of $\gamma^*\gamma^*$

$W_{\mathrm{vis}}$ – Effective mass of detected hadrons

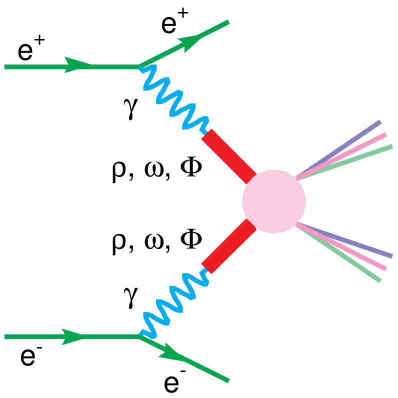
- Both $Q^2 \simeq 0 \longrightarrow$ quasi real photons. Electron and positron escape undetected along the beam pipe.
- Two-photon c.m. energy $\mathrm{W}_{\gamma\gamma}$ is measured from $W_{vis}$.
  - A large fraction of hadrons escape detection: $W_{vis} < W_{\gamma\gamma}$
  - Use unfolding for $W_{vis} \rightarrow W_{\gamma\gamma}$
  - Need MC which reproduce well the data.

# *Total* $\sigma_{\gamma\gamma}$ *: Monte Carlo used*

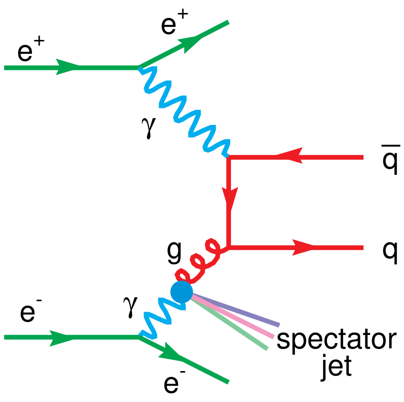
- Monte Carlo :
  - PHOJET v.1.05c : R. Engel and J. Ranft. (Phys. Rev. D54, 4246, 1996)
  - PYTHIA v.5.718: T. Sjöstrand (CPC 82, 74, 1994)



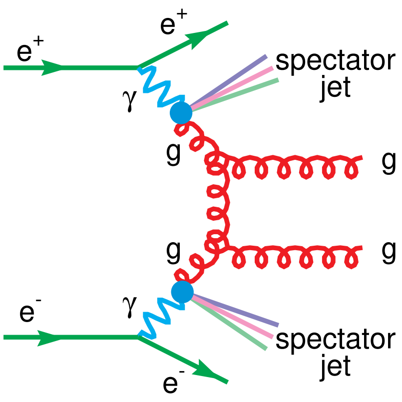

QPM




VDM




Single Resolved




Double Resolved

# *Total $\sigma_{\gamma\gamma}$: LEP data*

- Data :

L3 Collab. Phys. Lett. B 408 (1997) 450.

| | |
|---|---|
| 130 - 140 GeV | 4.98 pb$^{-1}$ |
| 161 GeV | 10.4 pb$^{-1}$ |

$$\boxed{5 < \mathrm{W}_{\gamma\gamma} < 75 \text{ GeV}.}$$

L3 Collab. CERN-EP/2001-012
(Accepted by Physics Letters B).

| | |
|---|---|
| 183 GeV | 51.4 pb $^{-1}$ |
| 189 GeV | 171.8 pb $^{-1}$ |
| 192 - 202 GeV | 220.8 pb $^{-1}$ |

$$\boxed{5 < \mathrm{W}_{\gamma\gamma} < 185 \text{ GeV}.}$$

OPAL Coll. Eur. Phys. J. C14 (2000) 199.

| | |
|---|---|
| 161 GeV | 9.9 pb$^{-1}$ |
| 172 GeV | 10.0 pb$^{-1}$ |
| 183 GeV | 54.4 pb$^{-1}$ |

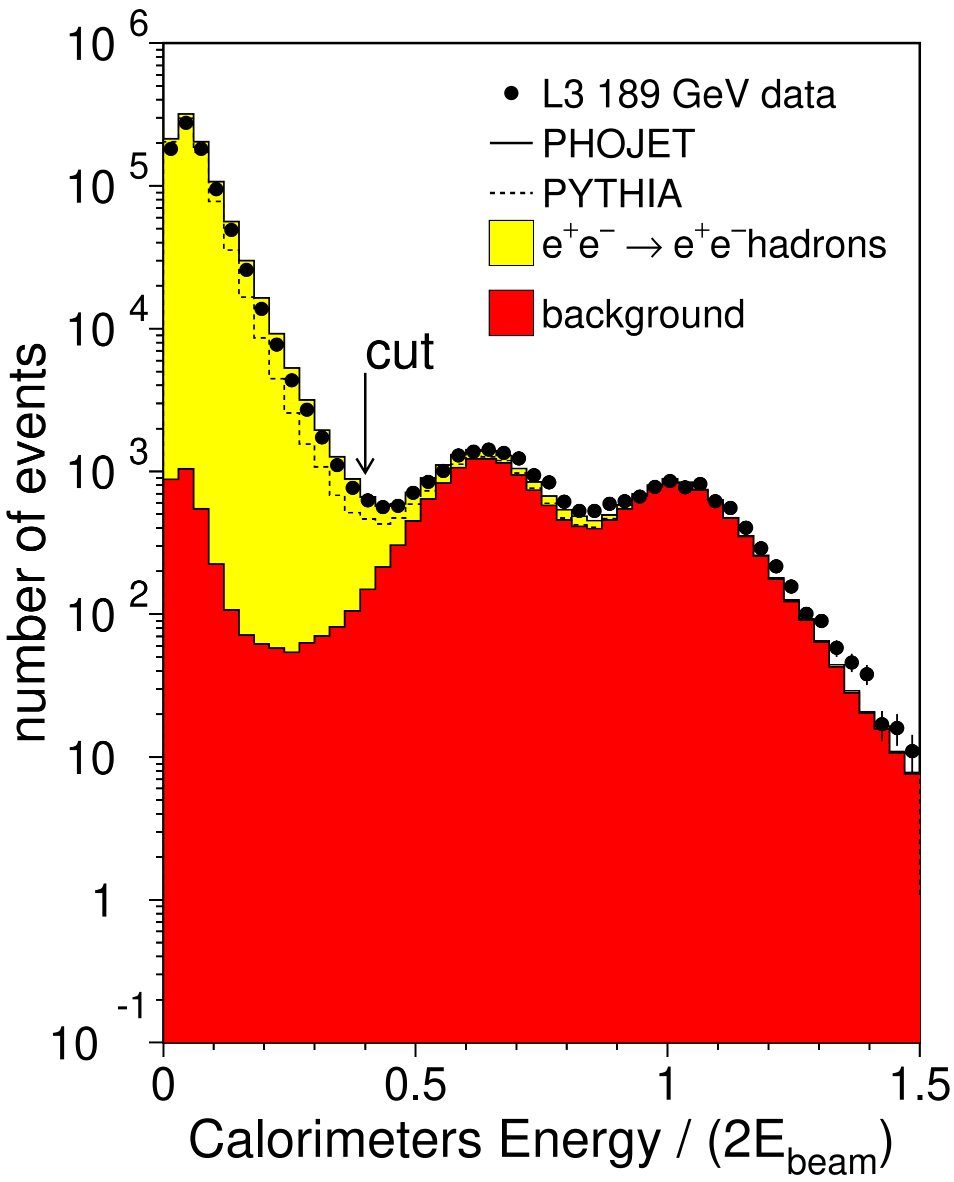
$$\boxed{10 < \mathrm{W}_{\gamma\gamma} < 110 \text{ GeV}.}$$

# Total $\sigma_{\gamma\gamma}$ : event selection

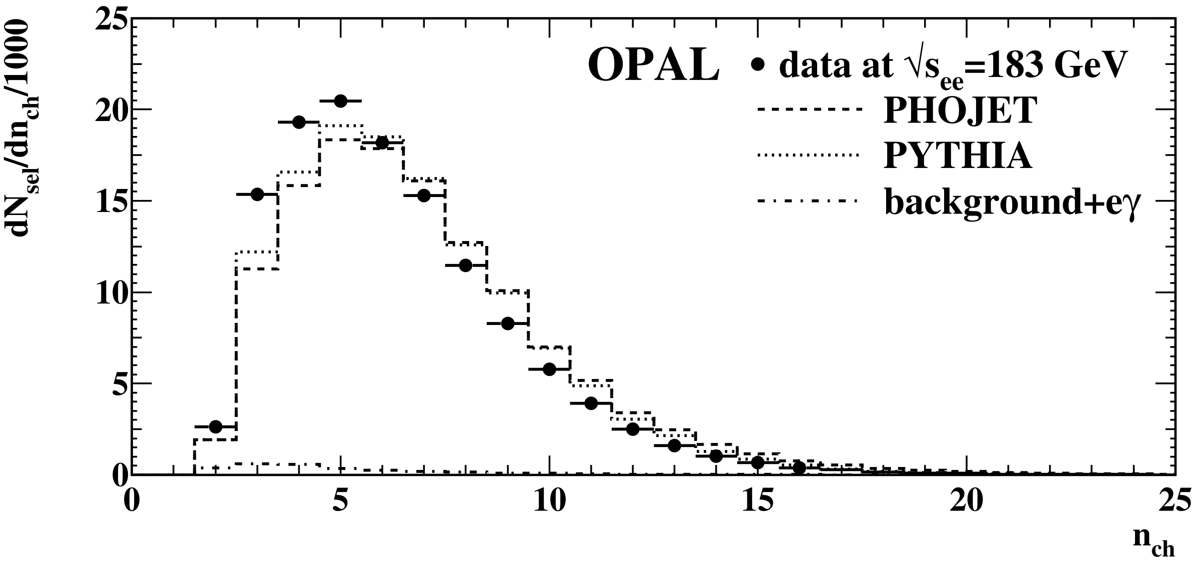
Typical $\gamma\gamma \rightarrow hadrons$ selection :

a) low visible energy
b) at least a few particles in the detector
c) anti tag condition on scattered electrons with the small angle calorimeters

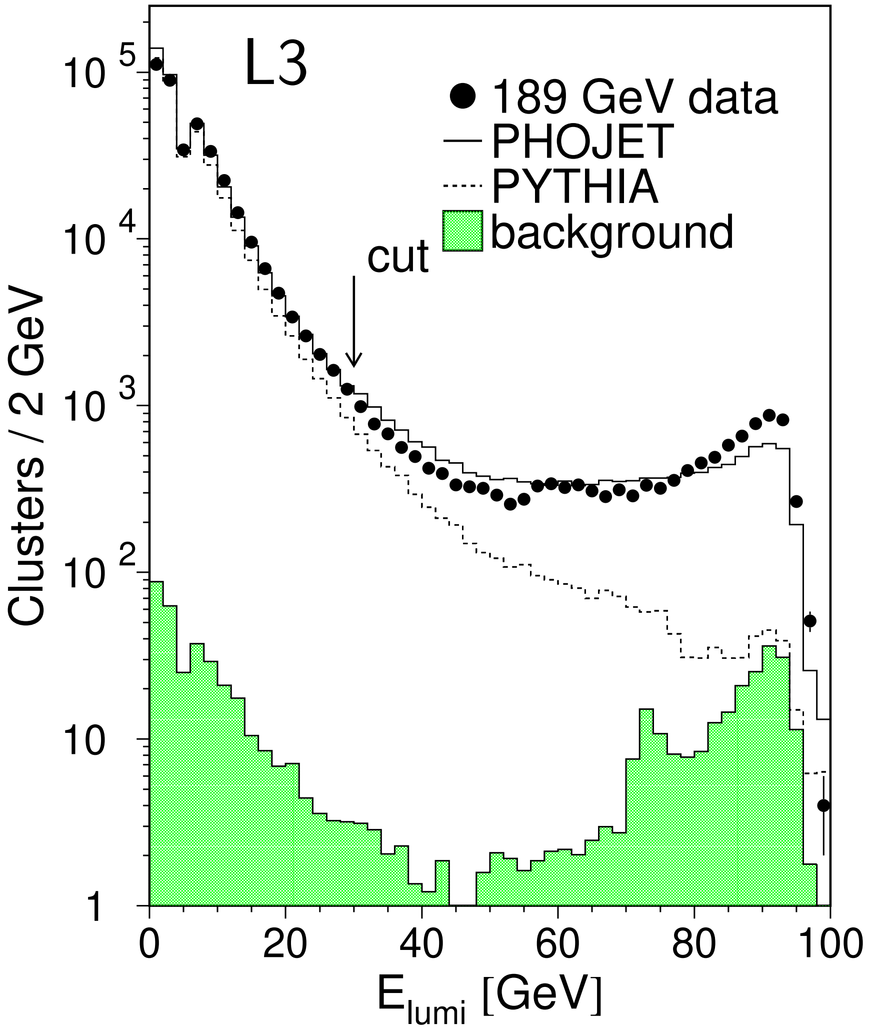
a)



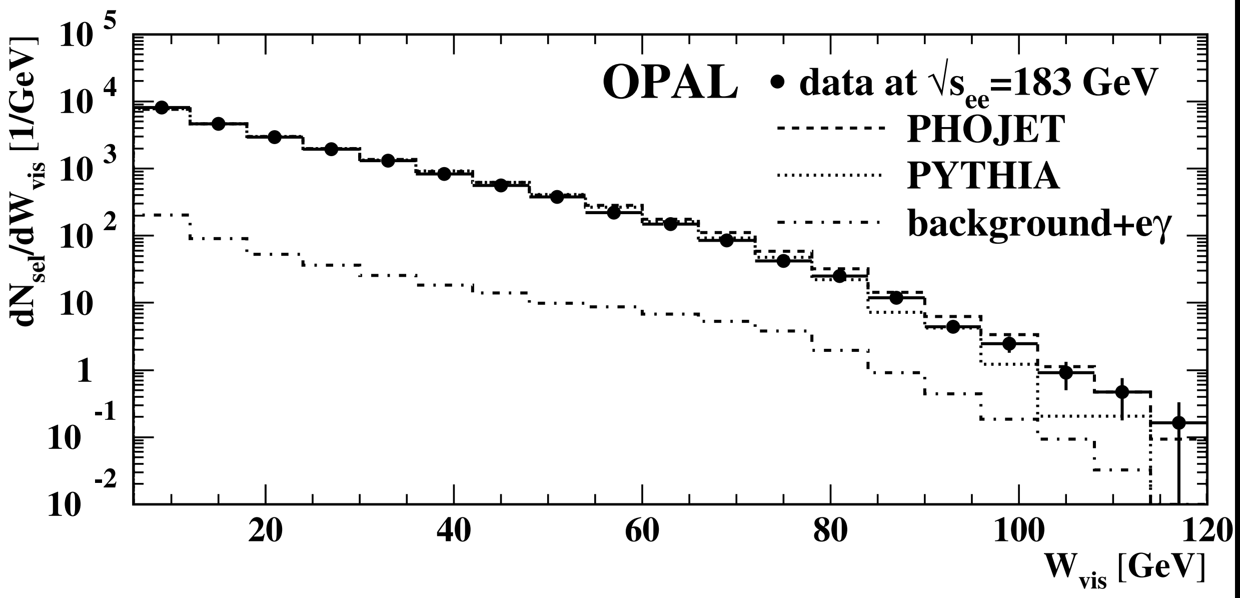
b)


OPAL
data at $\sqrt{s_{ee}}$=183 GeV
PHOJET
PYTHIA
background+eγ
$dN_{sel}/dn_{ch}/1000$
$n_{ch}$
0
5
10
15
20
25

c)


L3
189 GeV data
PHOJET
PYTHIA
background
cut
Clusters / 2 GeV
$E_{lumi}$ [GeV]
$10^5$
$10^4$
$10^3$
$10^2$
10
1
0
20
40
60
80
100

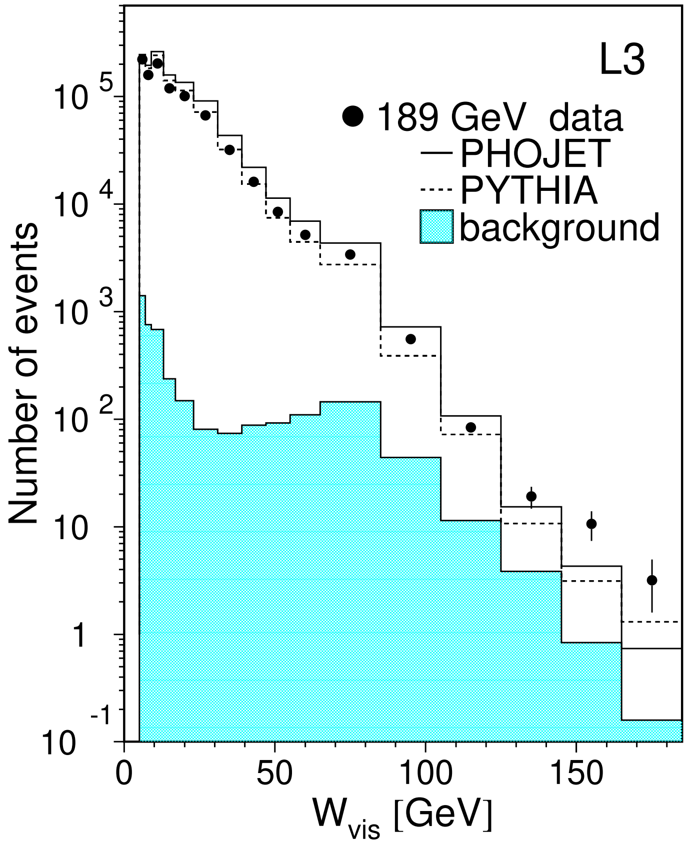
# *Total $\sigma_{\gamma\gamma}$ : Selected events*

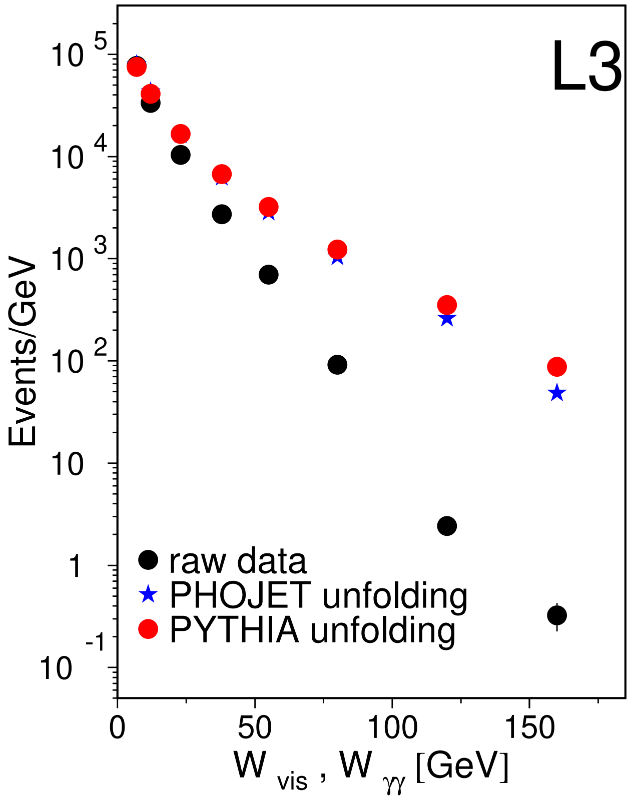



- OPAL 23250 events at $\sqrt{s}$= 161 GeV,
  25643 at $\sqrt{s}$= 172 GeV,
  144147 at $\sqrt{s}$= 183 GeV

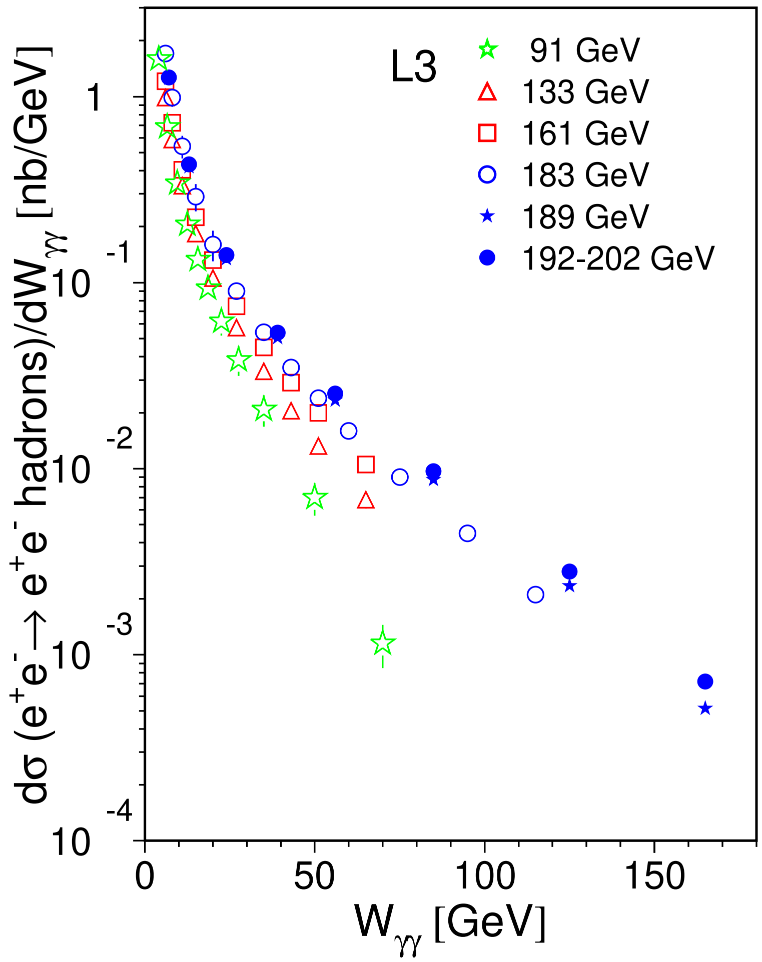
- L3 159012 events at $\sqrt{s}$= 183 GeV,
  781511 events at $\sqrt{s}$= 189 GeV,
  1027939 events at $\sqrt{s}$= 192–202 GeV

# Total $\sigma_{\gamma\gamma}$ : Unfolding



## Total $\sigma_{\gamma\gamma}$ : $d\sigma_{ee} \to \sigma_{\gamma\gamma}$




Effect of the $\gamma\gamma$ luminosity function

➜ $d\sigma_{ee}$ increases with increasing beam energy.

➜ $d\sigma_{ee}$ decreases with increasing $W_{\gamma\gamma}$.

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

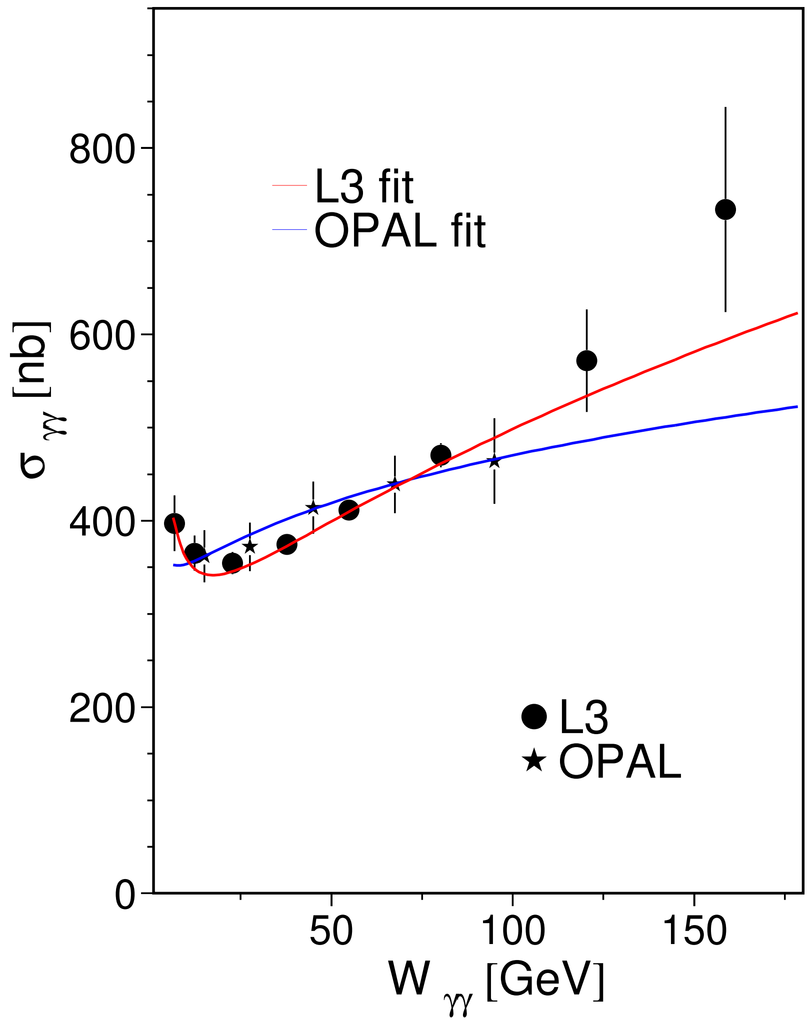
$$\frac{d\sigma_{ee}}{d(W^2_{\gamma\gamma}/s)} = \int \frac{dQ^2}{Q^2}\frac{dP^2}{P^2}\sum_{a,b=T,S}\mathcal{L}_{ab}\sigma^{\gamma\gamma}_{ab}(W_{\gamma\gamma},P^2,Q^2)$$

$$\sigma^{\gamma\gamma}_{ab}(W_{\gamma\gamma},P^2,Q^2) = F_a(Q^2)F_b(P^2)\sigma^{\gamma\gamma}_{ab}(W_{\gamma\gamma})$$

T and S are Transverse and Scalar photon helicity indices.

# Total $\sigma_{\gamma\gamma}$ : DL fit

Average of Pythia and Phojet
Statistic and detector related systematic errors only



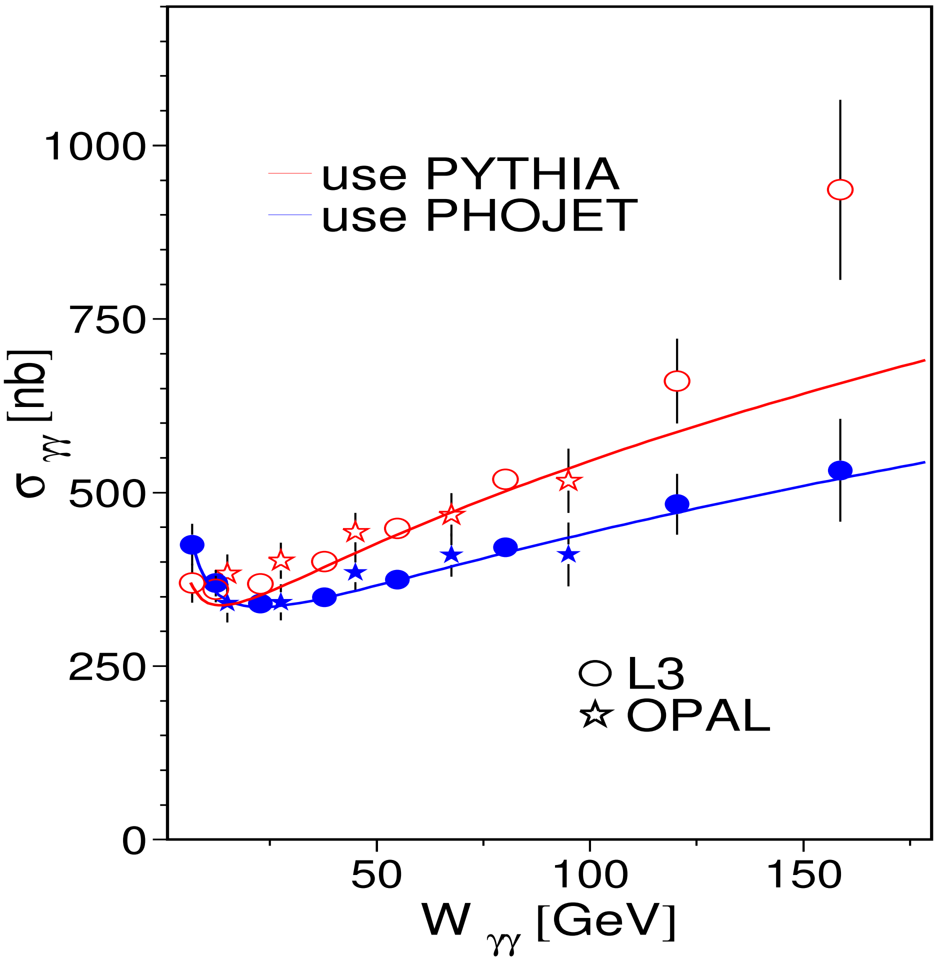

- Fit with Donnachie and Landshoff parametrisation (Phys. Lett., B296 (1992) 227):

$$\sigma_{\gamma\gamma} = As^{\varepsilon} + Bs^{-\eta} \ , \ \ s = W^2_{\gamma\gamma}$$

- 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
  $\varepsilon = 0.101^{+0.025}_{-0.019}$ $\quad 10 < \mathrm{W}_{\gamma\gamma} < 110\mathrm{GeV}$
- L3 fit to 183–202 GeV data, $\eta = 0.358$ fixed, A,B free
  $\varepsilon = 0.225 \pm 0.021$ $\quad 5 < \mathrm{W}_{\gamma\gamma} < 185\mathrm{GeV}$

# Total $\sigma_{\gamma\gamma}$ : $\sigma_{\gamma\gamma}$ MC dependence

Result obtained depends on Monte Carlo model used.




But slope is almost independent (L3 fit):

$\eta = 0.358$ fixed, A,B free

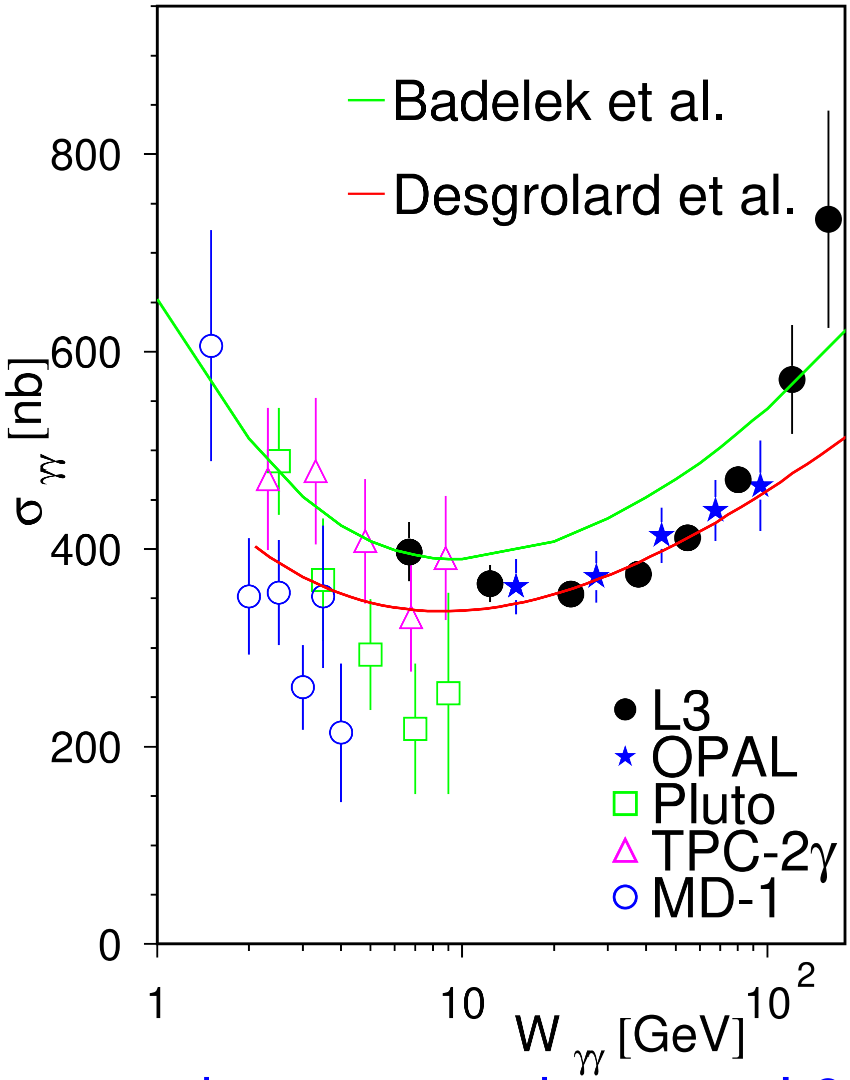
PHOJET

$\varepsilon = 0.221 \pm 0.023,\ \chi^2/d.o.f. = 8.6/5,\ CL = 12\%$

PYTHIA

$\varepsilon = 0.228 \pm 0.018,\ \chi^2/d.o.f. = 19/5,\ CL = 0.2\%$

## Total $\sigma_{\gamma\gamma}$ : models

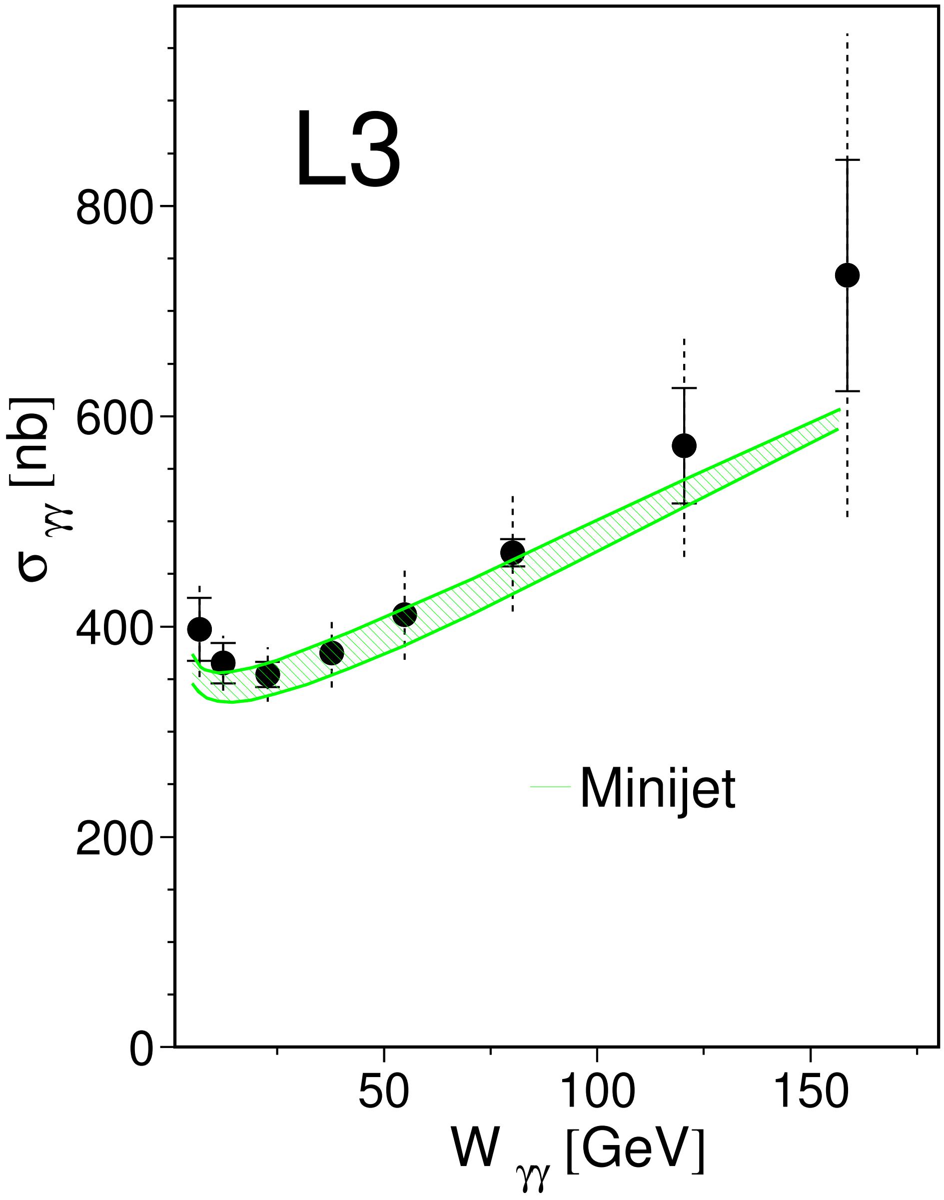



Very good agreement between L3 and OPAL data.

B. Badelek, J. Kwiecinski and A.M. Stasto,
Acta Phys. Polon. **30**(1999) 1807 and hep-ph/0001161.
P. Desgrolard, M. Giffon, E. Martynov and E. Predazzi,
Eur. Phys. J **C 9** (1999) 623.

G.A. Schuler and T. Sjöstrand , Z. Phys. C 73 (1997) 677.
C. Bourrely, J. Soffer, T.T. Wu, hep-ph/9903438.
E. Gotsman, E. Levin, U. Maor and E. Naftali,
hep-ph/0001080.

## *Total $\sigma_{\gamma\gamma}$ : models*




"Minijet" :

R.M. Godbole, A. Grau and G. Pancheri : Nucl. Phys. B 82 (2000) 246.

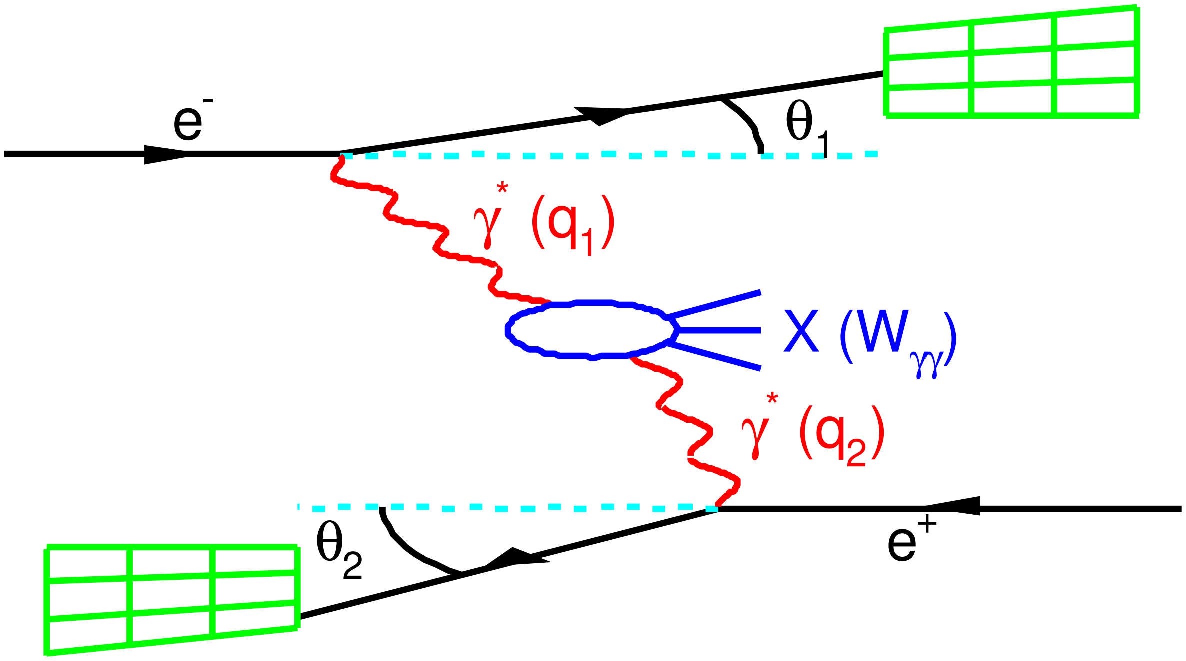
"Hard Pomeron" :

A. Donnachie, H.G. Dosch and M. Rueter Phys. Rev. D59 (1999) 074011.

## *Total $\sigma_{\gamma\gamma}$ : Conclusions*

- The total cross–sections for quasi real photons are measured at LEP in the range $5\ \mathrm{GeV} < \mathrm{W}_{\gamma\gamma} < 185\ \mathrm{GeV}$
- OPAL and L3 measurements well agree in the range $10 < \mathrm{W}_{\gamma\gamma} < 110$ GeV.
- $\sigma_{\gamma\gamma}$ increases faster than $\gamma$p and hadron–hadron total cross-sections, as expected by some QCD models.
- The biggest uncertainty is due to Monte Carlo models.
- Improvements can come from a better understanding and modelling of the underlying processes.

## *Double Tag*




$$Y = \ln(\frac{s}{s_0}) \simeq \ln(\frac{\mathrm{W}^2{}_{\gamma^*\gamma^*}}{\sqrt{{Q_1}^2{Q_2}^2}})$$

- Both electrons are seen in the detector
  – $\gamma^*\gamma^*$ collisions (double tag)
- $W_{\gamma\gamma}$ can be measured directly
  – No unfolding needed
- Radiative corrections should be taken into account

# *Double Tag: Data*

## L3 :

Published (Phys. Lett. B 453 (1999) 333-342):

91 GeV ($\mathcal{L} = 140\ pb^{-1}$)
183 GeV ($\mathcal{L} = 53\ pb^{-1}$)

Preliminary:

189 - 208 GeV ($\mathcal{L} = 628\ pb^{-1}$)

➜ $E_{tag} > 40$ GeV, 30 mrad $< \theta_{tag} <$ 66 mrad
➜ $\mathrm{W}_{\gamma\gamma}$ calculated from $\mathrm{e^+e^-}$

❑ Selected :

137 events at 91 GeV ($\langle Q^2 \rangle = 3.5\ \mathrm{GeV}^2$)
34 events at 183 GeV ($\langle Q^2 \rangle = 14\ \mathrm{GeV}^2$)
489 events at 189-208 GeV ($\langle Q^2 \rangle = 15\ \mathrm{GeV}^2$)

## OPAL :

Preliminary:

189 - 202 GeV ($\mathcal{L} = 378\ pb^{-1}$)

➜ $E_{tag} > 0.4 \cdot E_{beam}$, 34 mrad $< \theta_{tag} <$ 55 mrad
➜ $\mathrm{W}_{\gamma\gamma}$ calculated from hadrons

❑ Selected :

129 events at 189-202 GeV ($\langle Q^2 \rangle = 15\ \mathrm{GeV}^2$)

# L3: Data/MC comparison

Monte Carlo used :

→ PHOJET

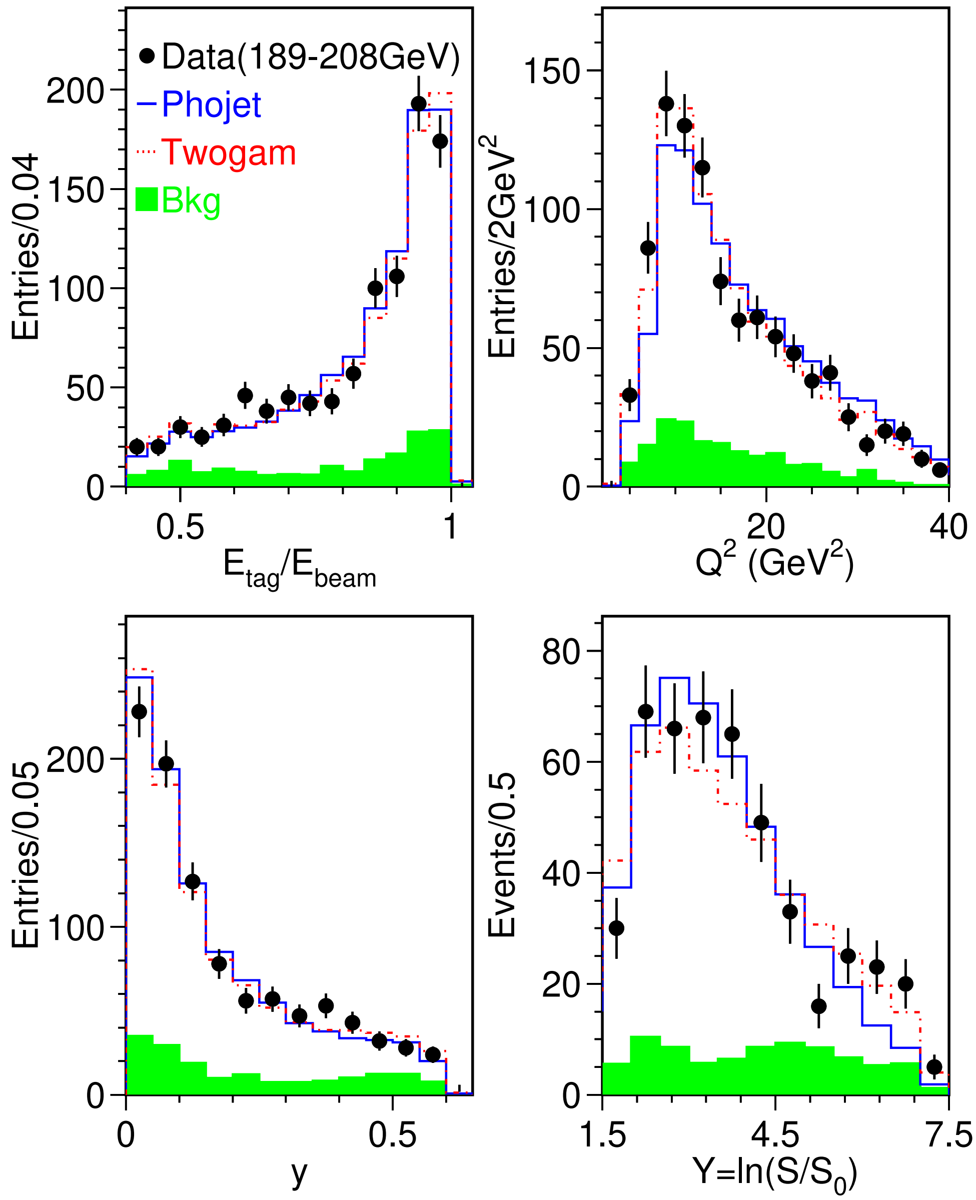
→ TWOGAM (v.2.04) - radiative corrections

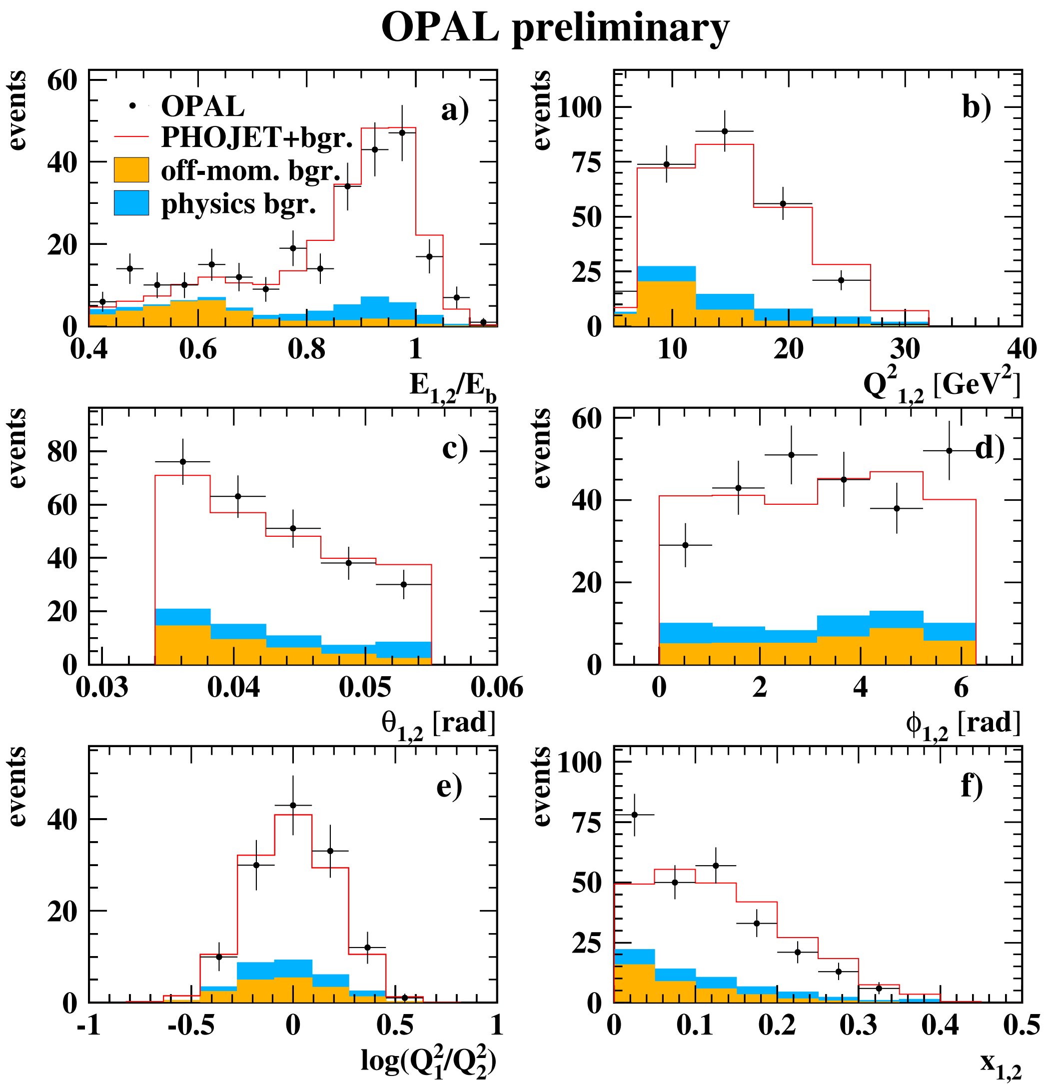
S. Nova, A. Olshevski, T. Todorov (CERN 96-01 (1996), vol.2)

→ QPM contribution :

JAMVG J.A.M. Vermaseren, Nucl. Phys. B229(1983)347

GALUGA G.A. Schuler, Comp. Phys. Comm.108(1998)279






Monte Carlo used :

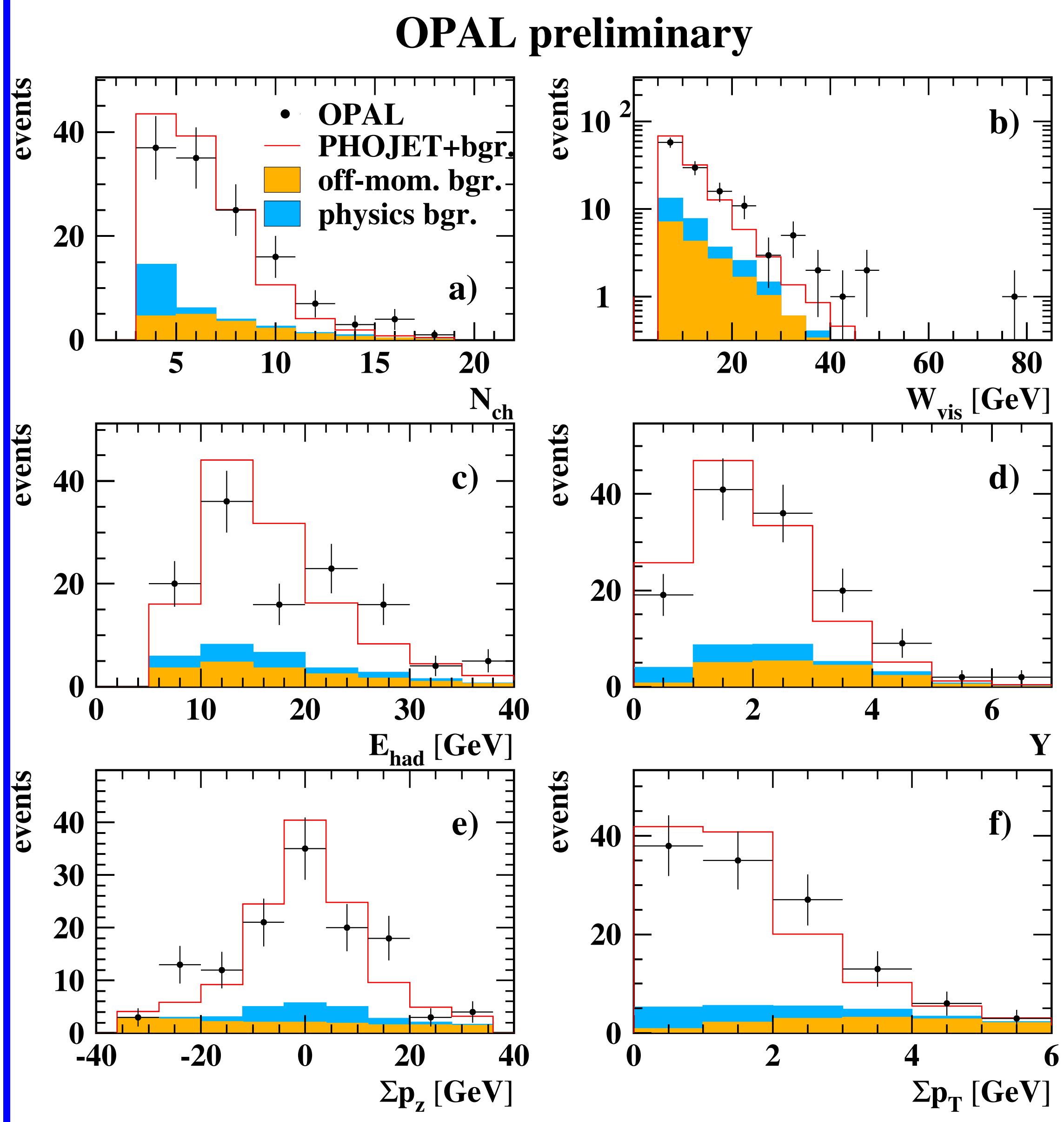
➜ PHOJET, PYTHIA

➜ GALUGA - QPM contribution

➜ BDK - estimation of radiative corrections

F.A. Berends, P.H. Daverveldt, R. Kleiss, Comp. Phys. Comm. 40 (1986) 271, 285; Nucl. Phys. B264 (1986) 243

# Values related to hadrons

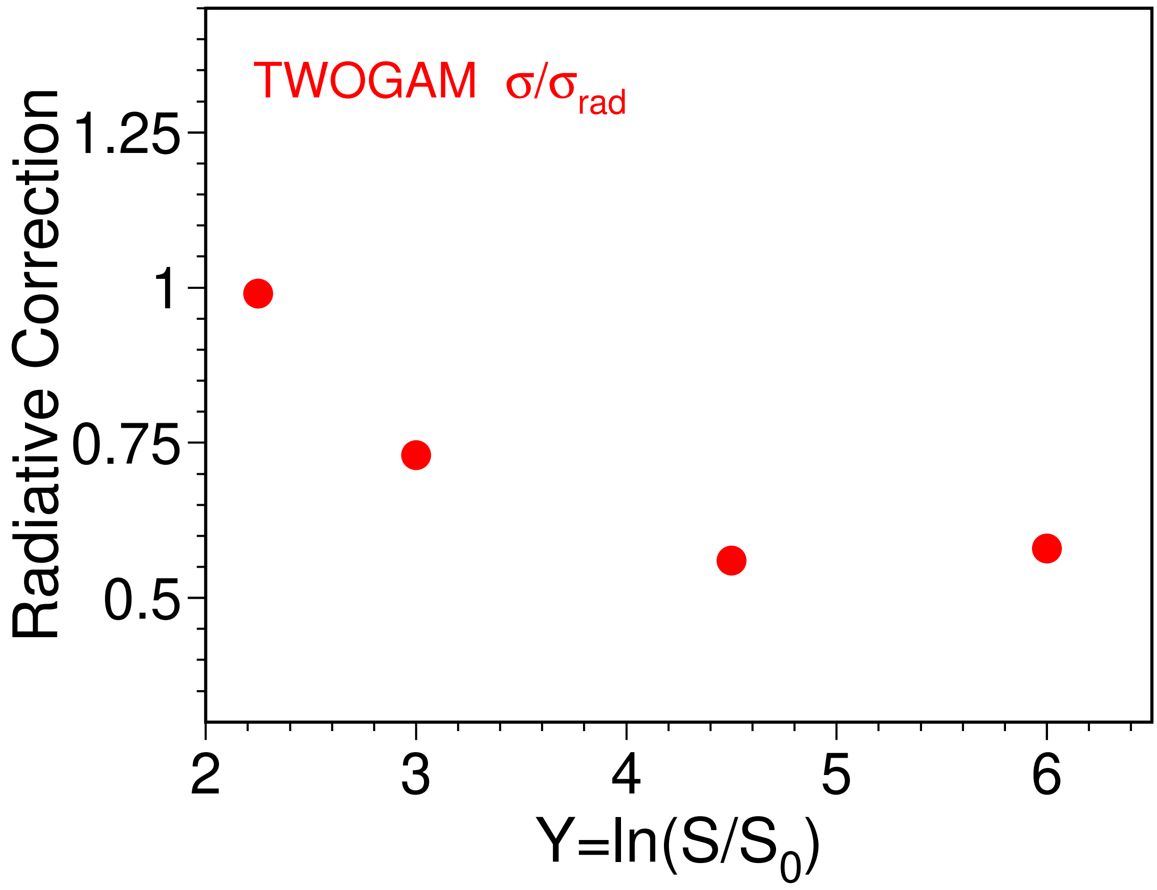


# *Double Tag: Radiative corrections (L3)*

L3 :

$W_{\gamma\gamma}$ is calculated from $e^+e^-$

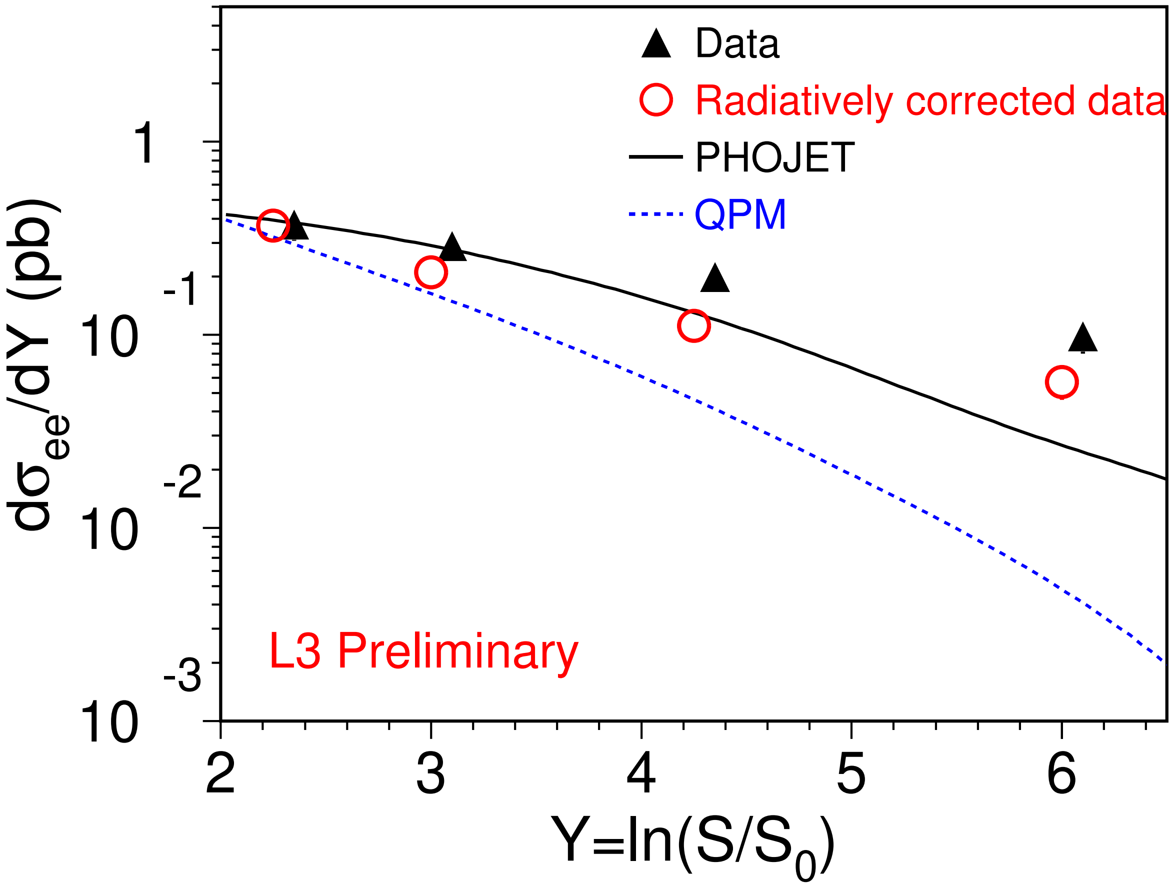
Radiative corrections in kinematical range
$E_{tag} > 30$ GeV, $30$ mrad $< \theta_{tag} < 66$ mrad



# Double Tag: $\sigma(e^+e^- \to e^+e^- hadrons)$

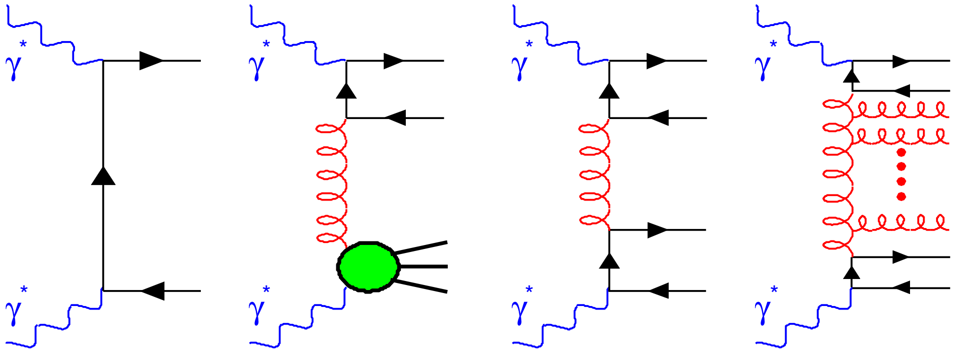
## ➤ L3 :

$\sigma(e^+e^- \to e^+e^- hadrons)$ in defined phase space.




- ➜ QPM is insufficient
- ➜ PHOJET rather well describes data.
- ➜ Some excess of data at $Y > 5$.
- ➜ Room for other processes?

# Double Tag: BFKL physics




- BFKL Pomeron - Ya.Ya.Balitski, V.S.Fadin, E.A.Kuraev and L.N.Lipatov

- In Leading Order approximation:

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

➜ $\alpha_P - 1 \simeq 0.53 > 0.093$ ("soft Pomeron")

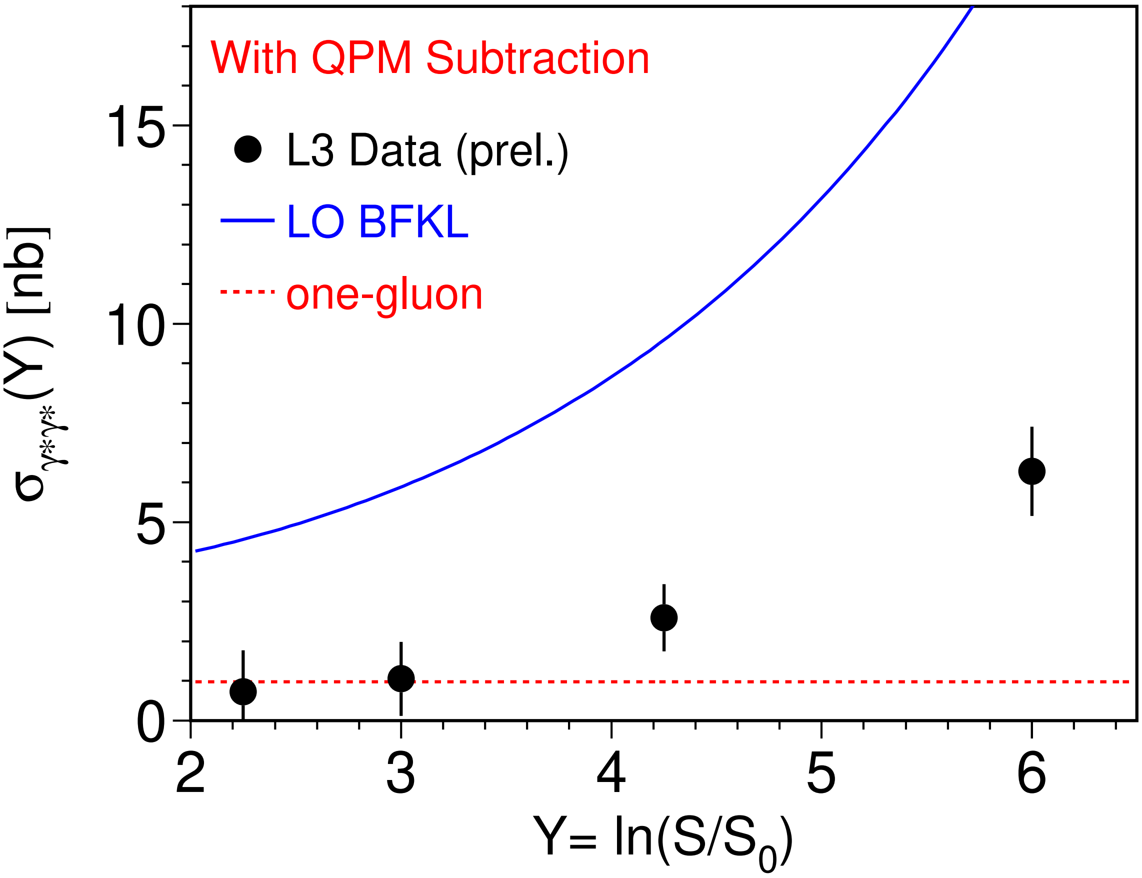
- Next to LO corrections :
  - ➜ NLO BFKL + BLM optimal scale
    (Brodsky, Fadin, Kim, Lipatov and Pivovarov, hep-ph/9901229)
    (Kim, Lipatov and Pivovarov, hep-ph/9911228, hep-ph/9911242 )
  - ➜ Color dipole BFKL
    (Nikolaev, Speth and Zoller, hep-ph/0001120 )
  - ➜ Double logs resummations
    (Ciafaloni, Colferai and Salam, PRD 60 (1999) 114036)

## Double Tag: $\sigma_{\gamma^*\gamma^*}$ (L3)

➤ L3 :

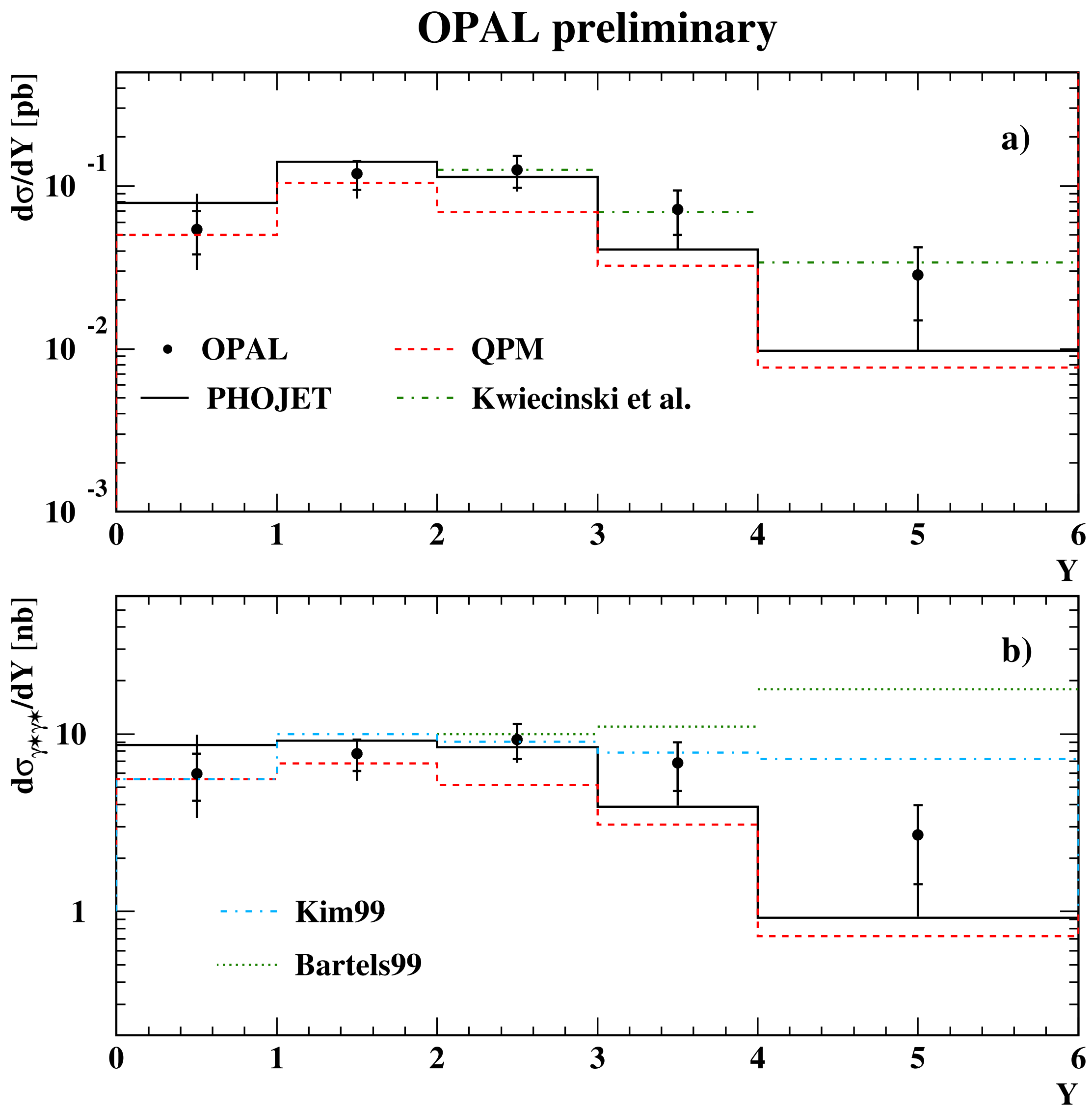
- ❑ $\sigma_{ee} = \mathcal{L}_{TT} \times \sigma_{\gamma^*\gamma^*}$
- ❑ Subtract the QPM contribution.

189 - 208 GeV



# Double Tag: OPAL results

➤ OPAL :




J. Kwiecinski, L. Motyka, Phys. Lett. B462 (1999) 203.

Kim99: S.J. Brodsky, V.S. Fadin, V.T. Kim, L.N. Lipatov, G.B. Pivovarov, JETP Lett. 70 (1999) 155.
V.T. Kim, private communication.

Bartels99: J. Bartels, C. Ewerz, R. Staritzbichler, hep-ph/0004029.

Consistent with L3 ➜ excess at large Y.

## *Double Tag: Conclusions*

- $\gamma^*\gamma^*$ collisions have been measured at LEP with $\langle Q^2 \rangle = 15\ \mathrm{GeV}^2$ and up to Y$\approx \ln(\frac{W^2_{\gamma^*\gamma^*}}{\sqrt{Q_1^2 Q_2^2}}) = 7$ $(\frac{W^2_{\gamma^*\gamma^*}}{\sqrt{Q_1^2 Q_2^2}} \simeq 1000)$
- Radiative corrections are taken into account.
- Agreement between data and PHOJET Monte-Carlo model is reasonable for Y$<$5
- Some excess at Y$>$5 probably needs BFKL contribution (?)