Two Photon Physics at LEP

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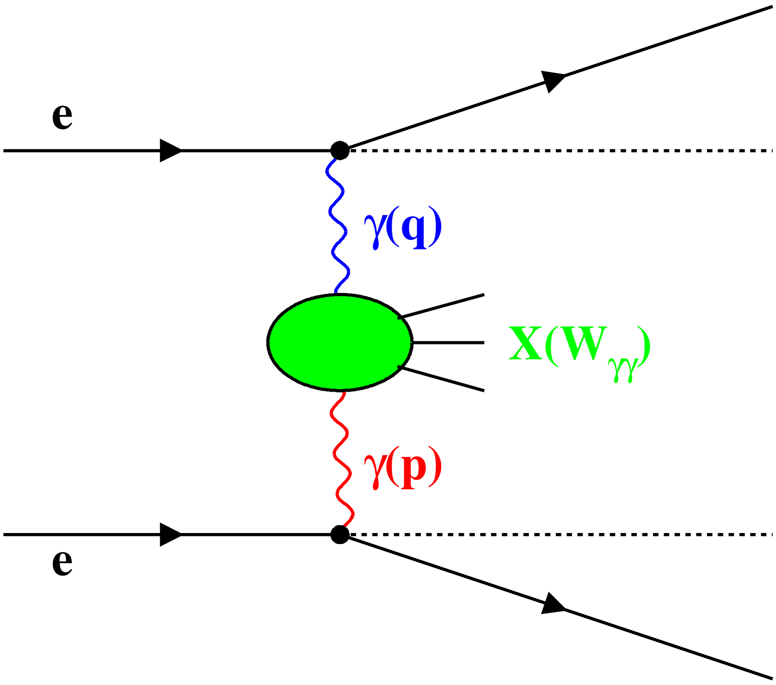
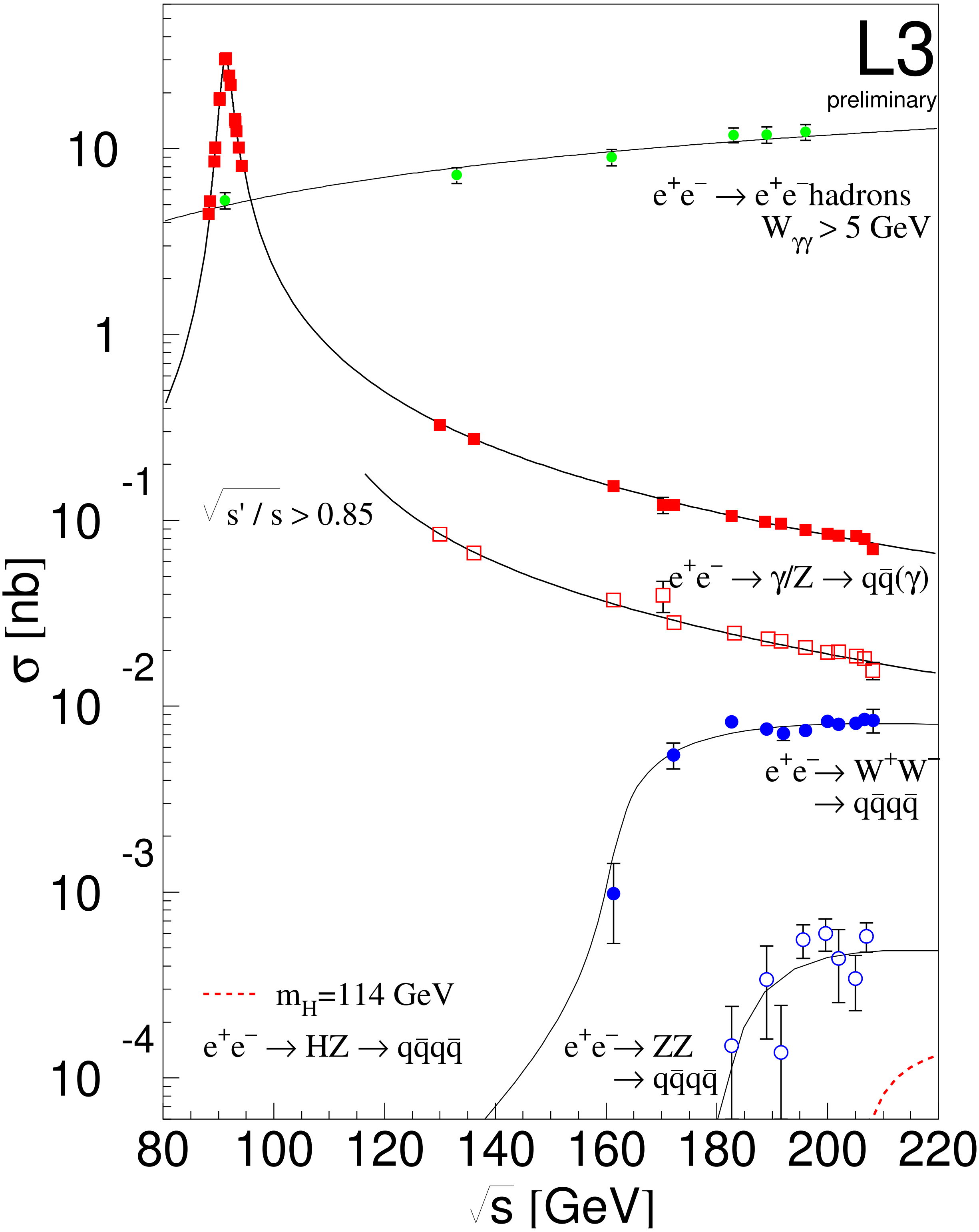
Outline (selected measurements):

- ❑ Total $\gamma\gamma$ cross section
- ❑ Heavy flavour production
- ❑ Inclusive hadrons
- ❑ Structure function F_2^γ
- ❑ $\gamma^*\gamma^*$ cross section



- recent measurements, energy dependence of the cross sections

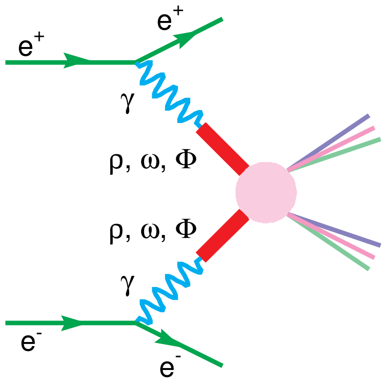
Hadron production at LEP



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

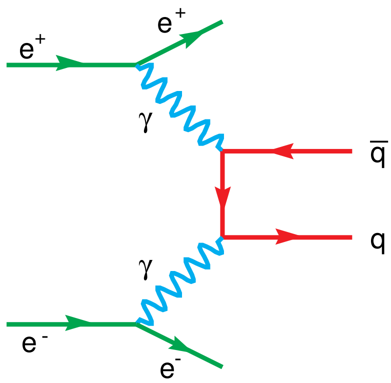
Hadronic final state in $\gamma\gamma$ collisions

SOFT:

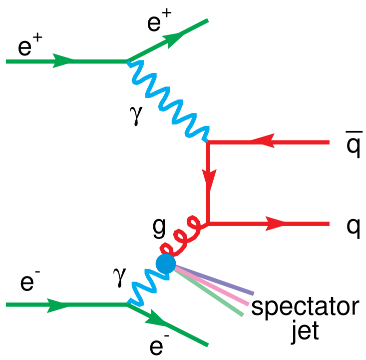


VDM

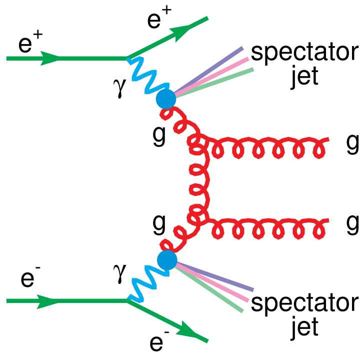
HARD:



Direct



Single Resolved



Double Resolved

- **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)

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}

$\boxed{5 < W_{\gamma\gamma} < 75 \text{ GeV.}}$

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 $^{-1}$

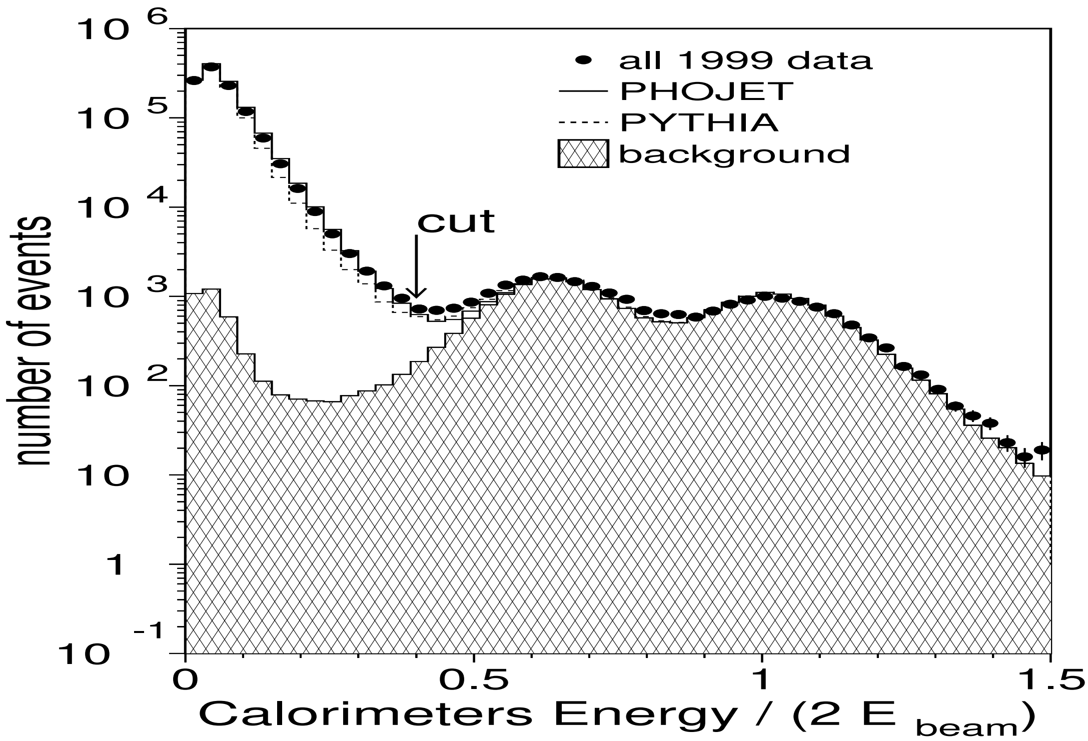
$\boxed{5 < W_{\gamma\gamma} < 185 \text{ GeV.}}$

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

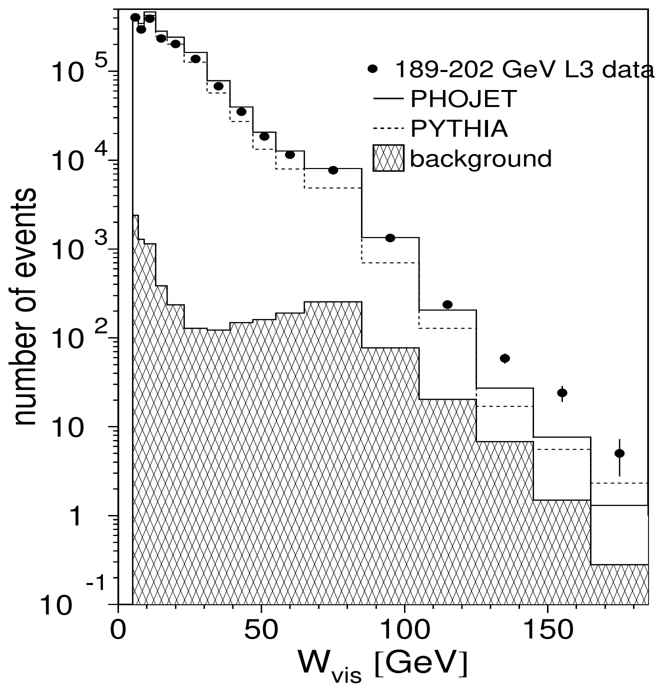
161 GeV 9.9 pb^{-1}
172 GeV 10.0 pb^{-1}
183 GeV 54.4 pb^{-1}

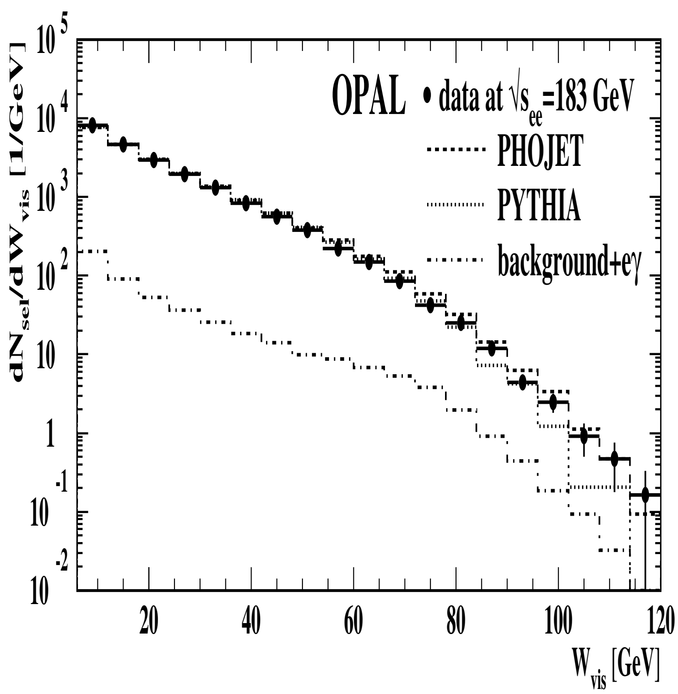
$\boxed{10 < W_{\gamma\gamma} < 110 \text{ GeV.}}$

Two-photon hadronic selection



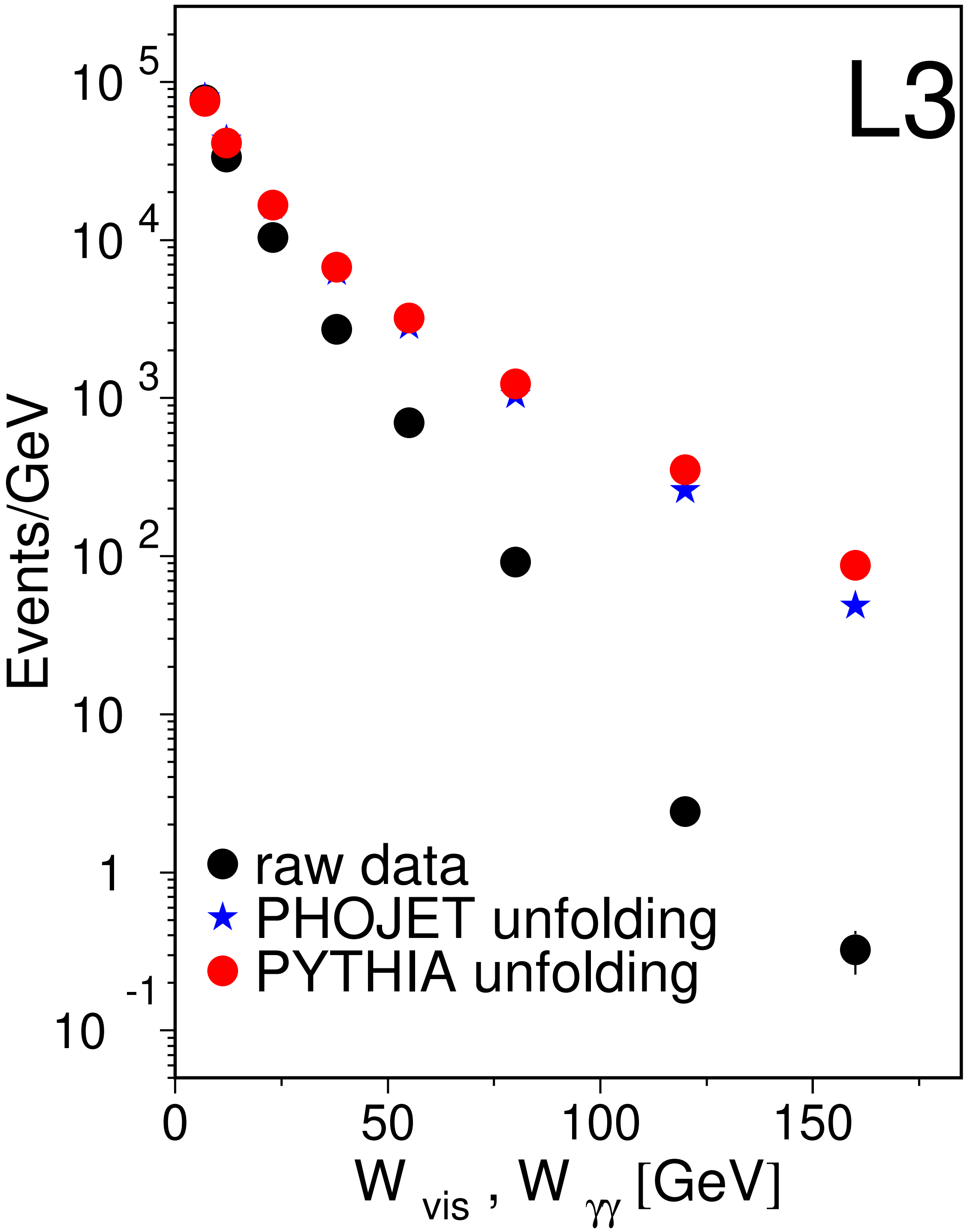
- W_{vis} distribution:





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

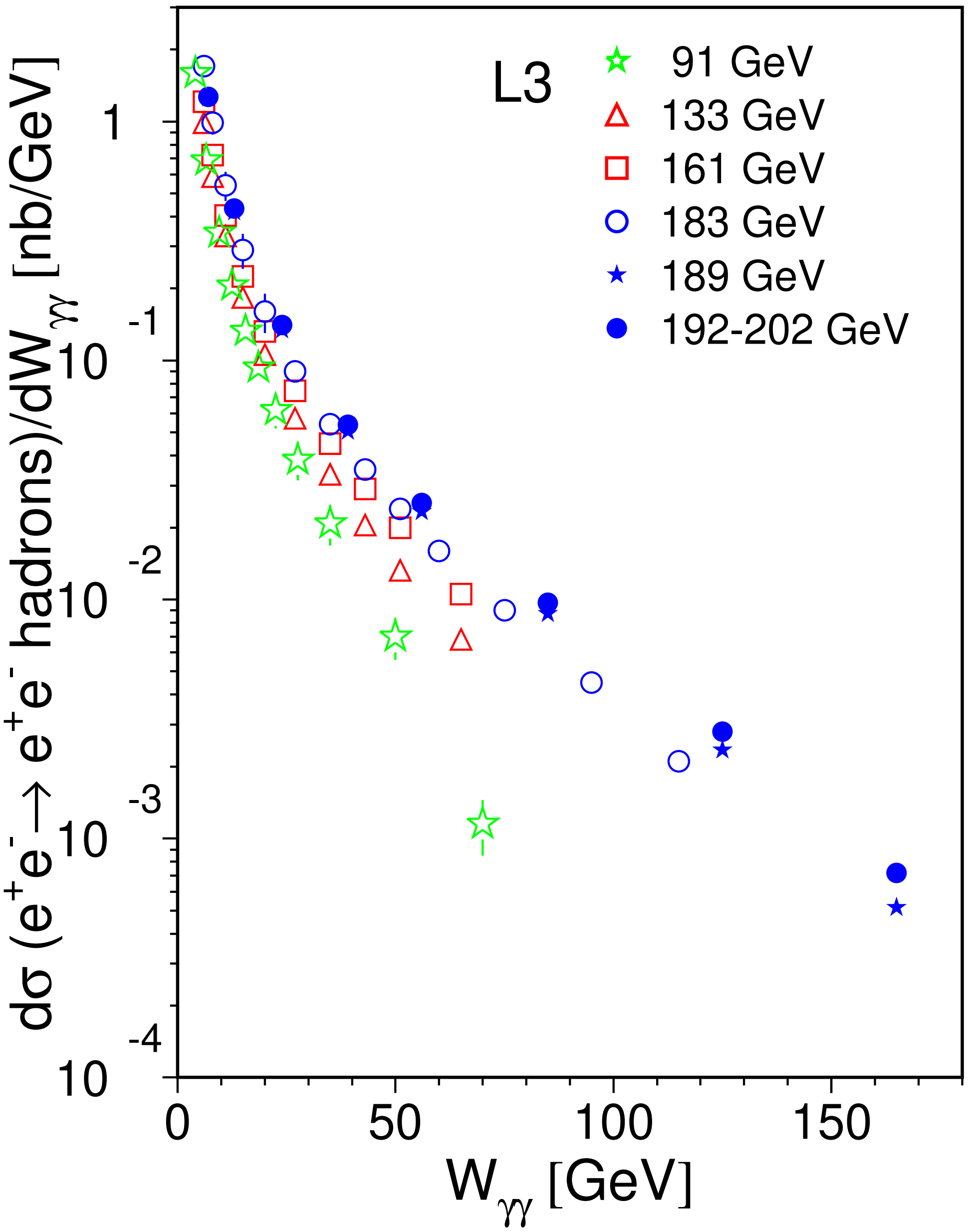
$\sigma_{\gamma\gamma}$ vs $W_{\gamma\gamma}$, Unfolding



❑ unfolding with Bayes (G. D'Agostini, NIM A362(1995) 487)

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

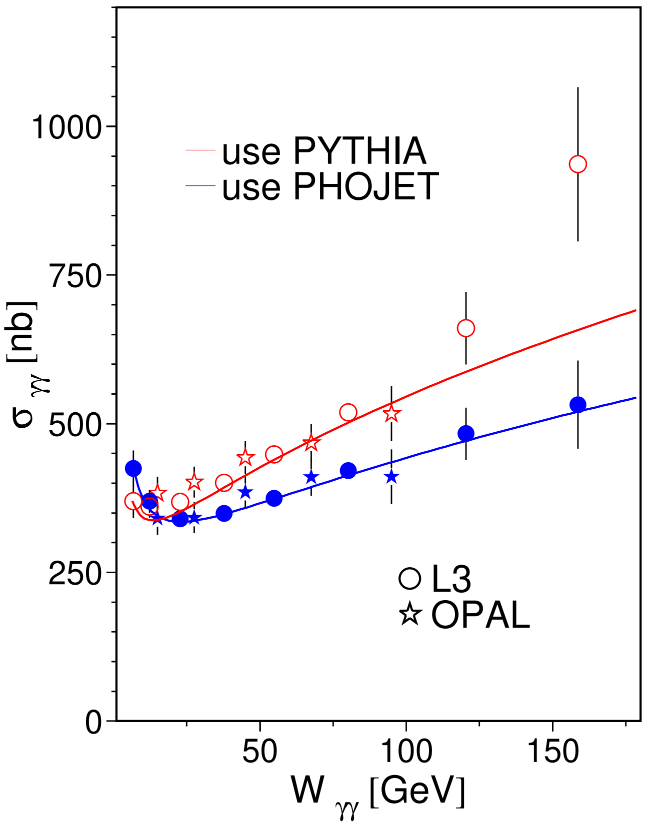
$ee \longrightarrow eeq\bar{q}$



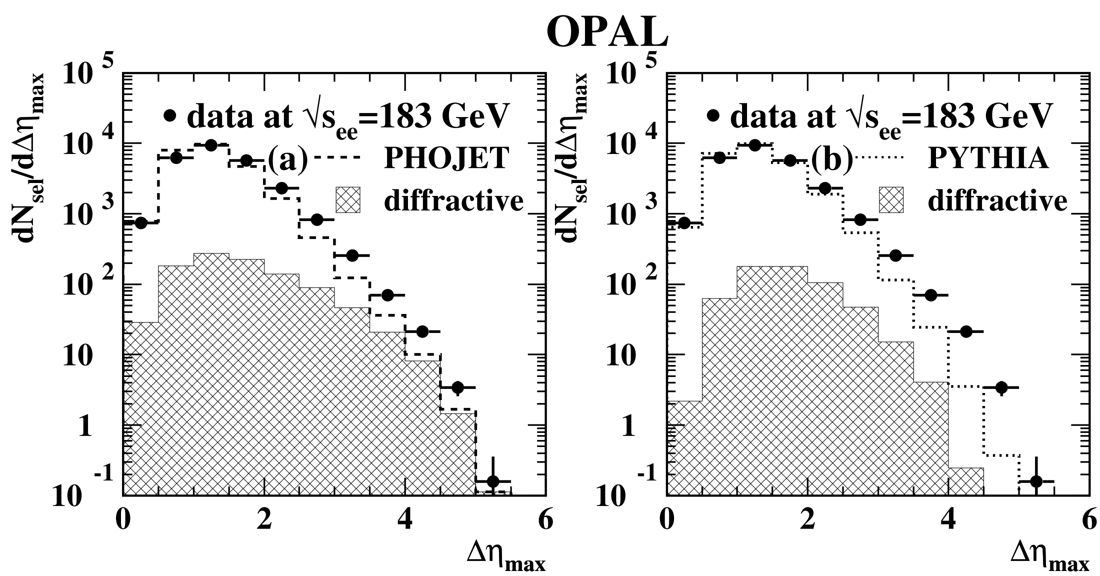
- increase with beam energy
- decrease with $W_{\gamma\gamma}$

effect of the $\gamma\gamma$ luminosity function

$\gamma\gamma \to q\bar{q}$

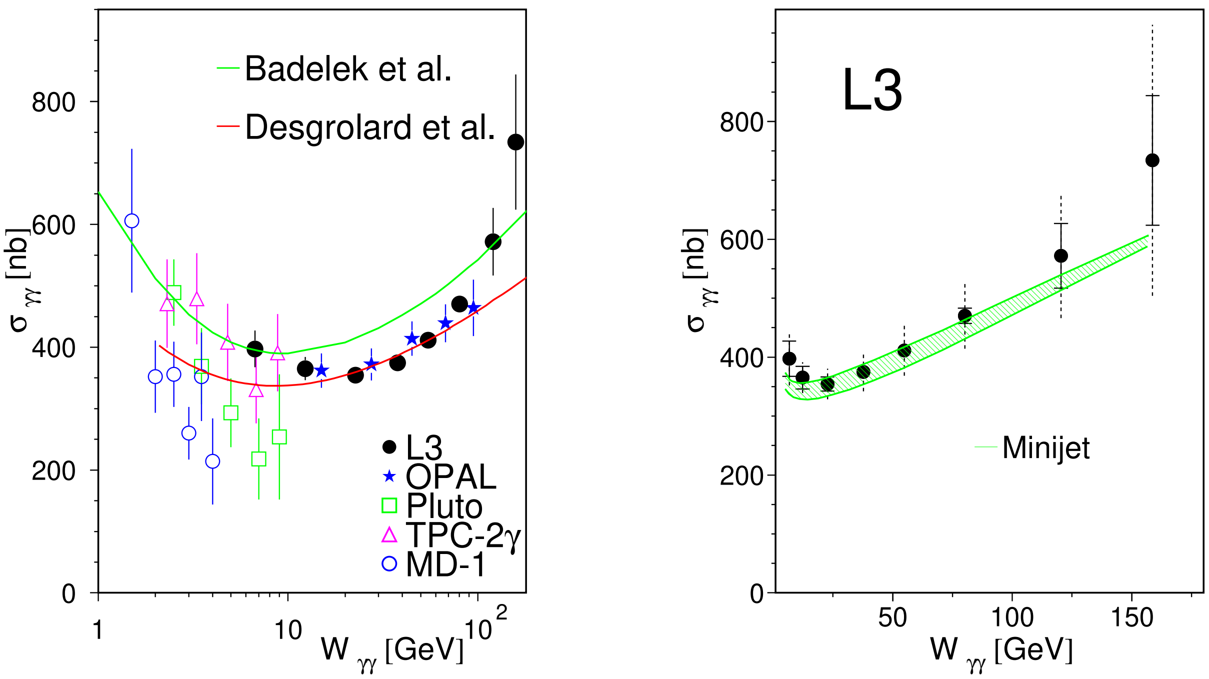


- L3 and OPAL are compatible within errors.



- Diffraction is important to fix the normalization

Comparison to predictions:

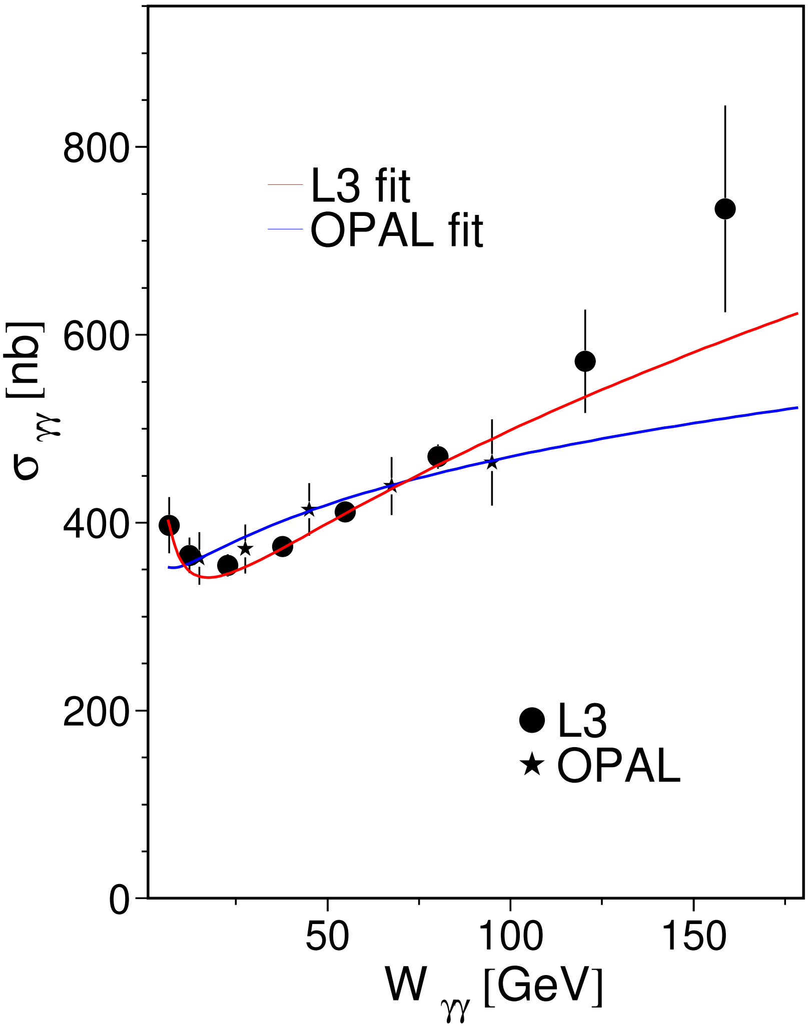


B. Badelek, J. Kwiecinski and A.M. Stasto, Acta Phys. Polon. 30(1999) 1807 and hep-ph/0001161.
P. Desgrolard, M. Giffon, E. Martynov and E. Predazzi, Eur. Phys. J C 9 (1999) 623.
G.A. Schuler and T. Sjöstrand, Z. Phys. C 73 (1997) 677.
C. Bourrely, J. Soffer, T.T. Wu, hep-ph/9903438.
E. Gotsman, E. Levin, U. Maor and E. Naftali, hep-ph/0001080.

"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.

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):

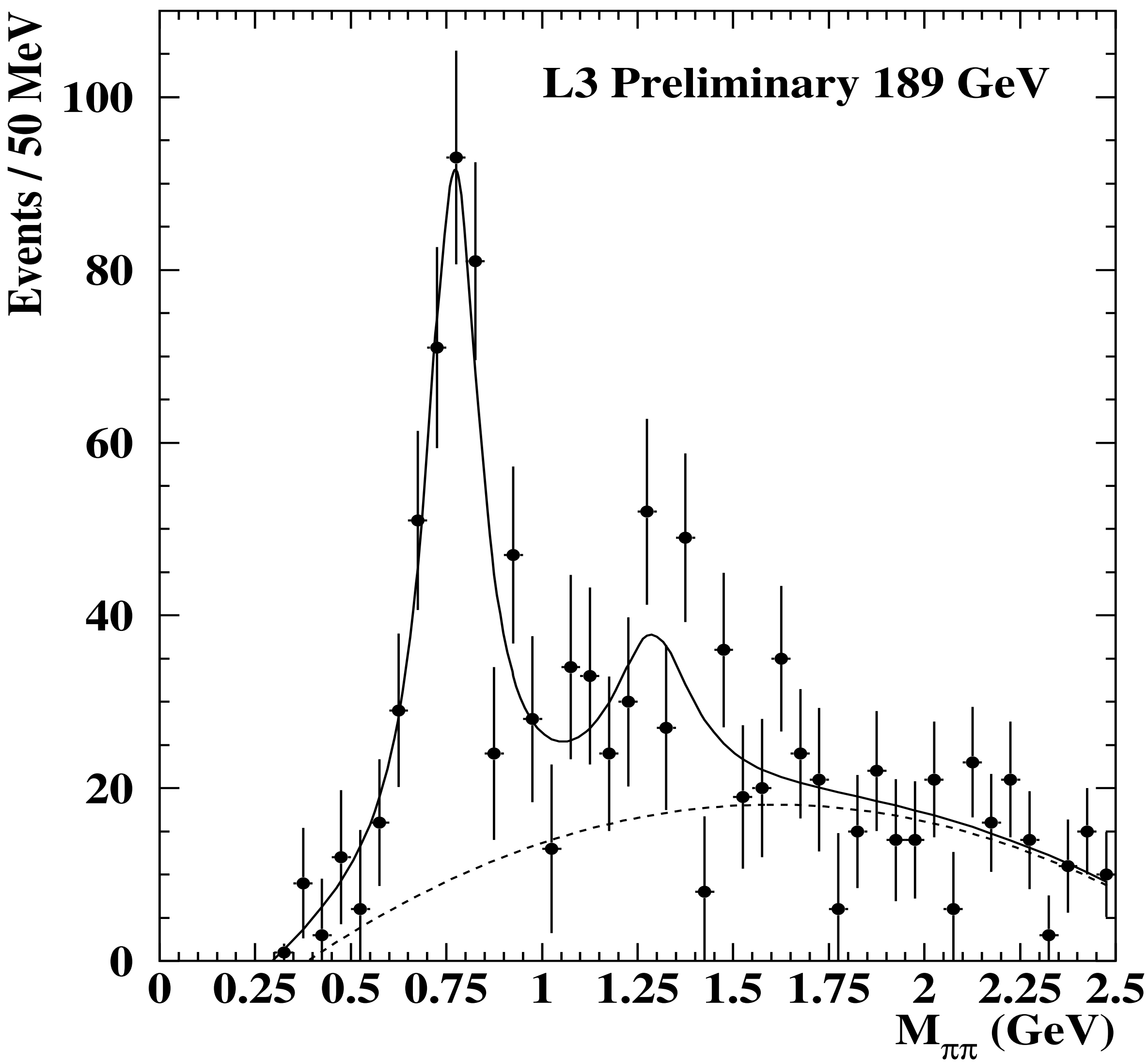
$$\sigma_{\gamma\gamma} = As^{\varepsilon} + Bs^{-\eta}\ ,\ \ s = W^2_{\gamma\gamma}$$

- **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
  $\varepsilon = 0.101^{+0.025}_{-0.019}$ $10 < \mathrm{W}_{\gamma\gamma} < 110\mathrm{GeV}$

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

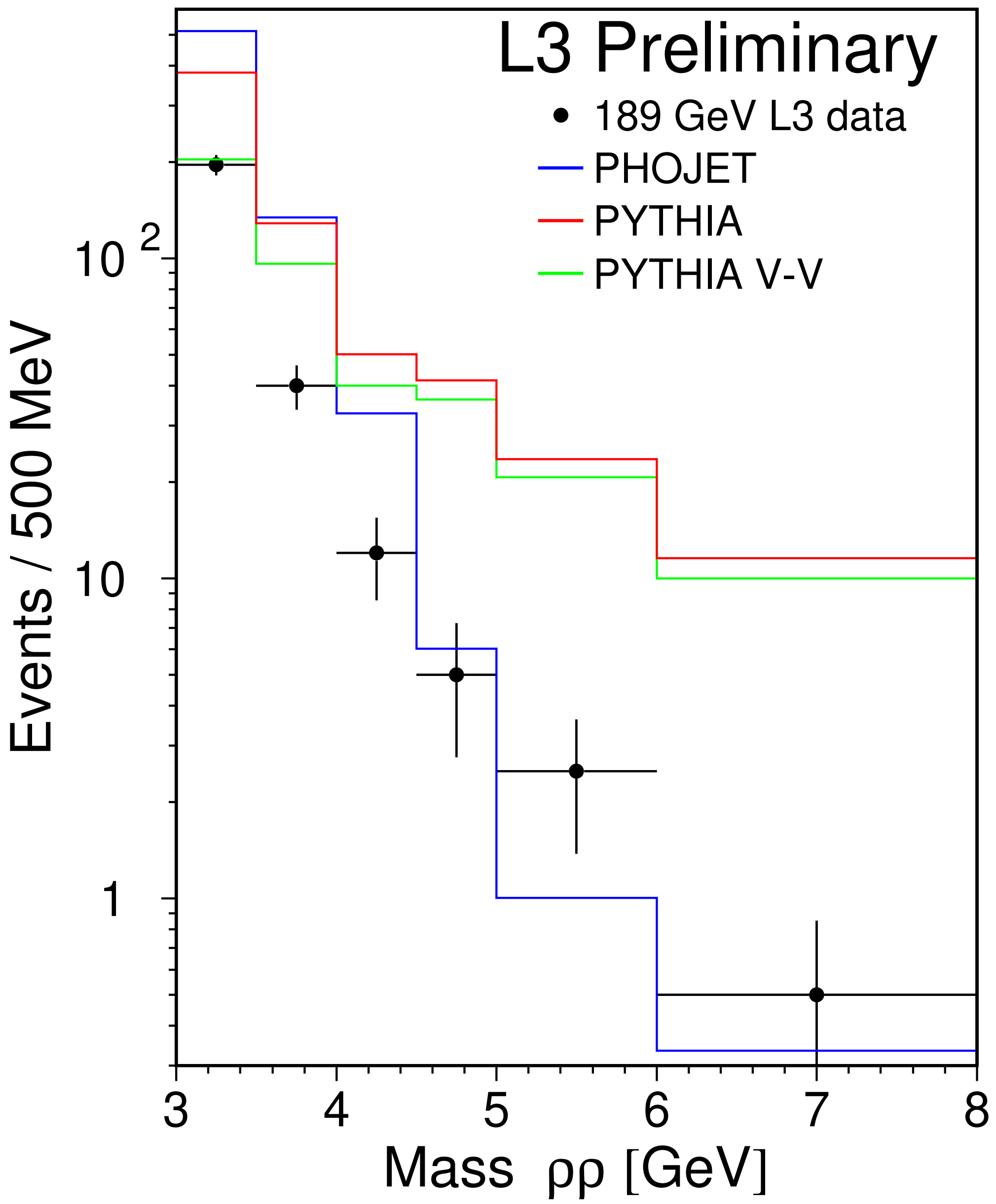
$\rho^0\rho^0$: 4 entries/event, $W_{\gamma\gamma} > 3$ GeV



	Area	M (MeV)	Γ (MeV)
Fitted ρ^0	460 ± 47	768 ± 7	170 ± 20
PDG'00		769 ± 1	150 ± 1
Fitted f_2	187 ± 89	1288 ± 22	258 ± 135
PDG'00		1275 ± 1	185 ± 3

f_2 present: not only diffractive

$\gamma\gamma \rightarrow$ "$\rho^0\rho^0$" at $\sqrt{s} = 189$ GeV

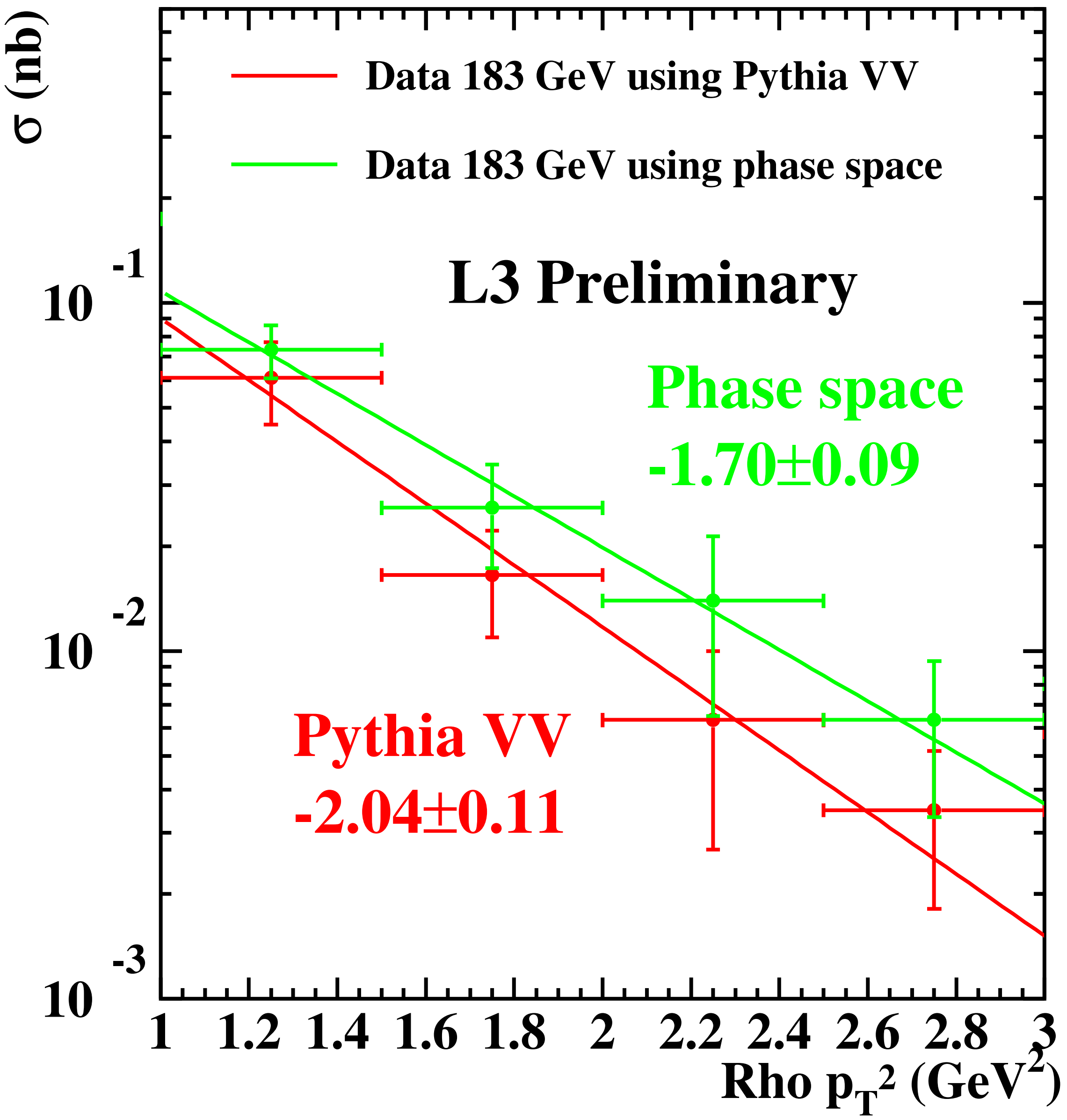


MC normalized to data luminosity statistical errors only

- Only $W_{\gamma\gamma} < 8$ GeV is accessible, theory is for $W_{\gamma\gamma} > 10 - 20$ GeV!
- Data are not reproduced in this range:
  - Phojet too steep
  - Pythia too flat

Inclusive ρ^0: P_T^2 distribution

Background subtracted in each P_T^2 bin
by sepatate mass fits: BW+bkg.
with fixed $M_{\rho^0} = 770$ MeV, $\Gamma_{\rho^0} = 150$ MeV



- Corrected using different MC generators
- Slope of the exponential fit is given

ρ^0 polarization

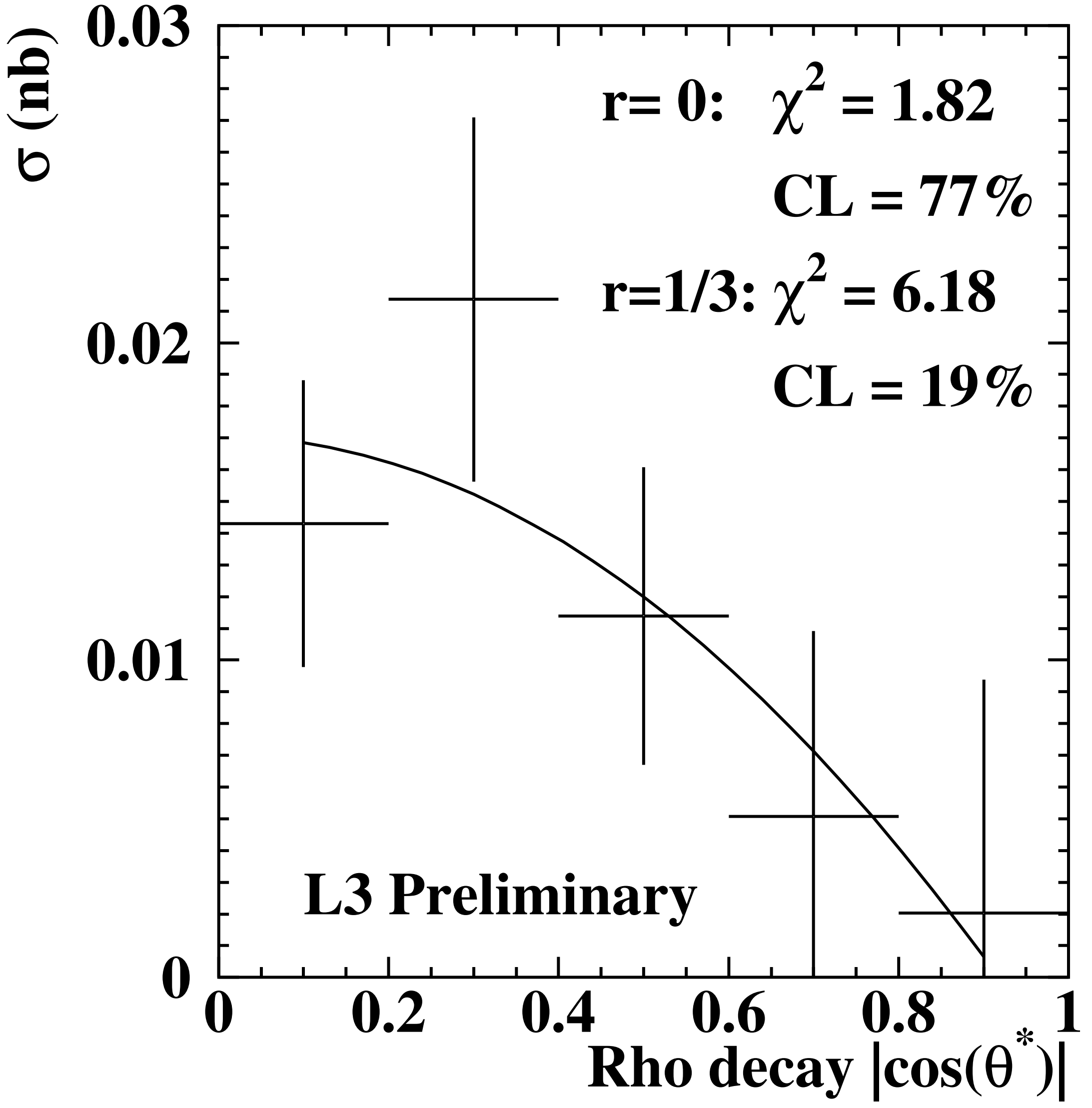
π^+ momentum in ρ^0 rest frame

ρ^0 momentum in visible $\gamma\gamma$ frame

r: fraction of longitudinal polarization.

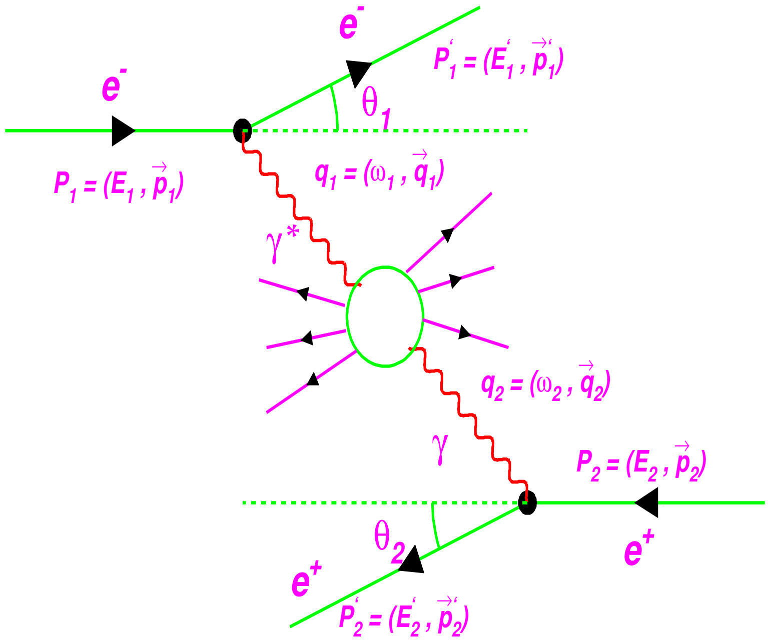
$0 \leq r \leq 1$,

transverse:	$r = 0$	$1 - \cos^2\theta^*$
unpolarized:	$r = 1/3$	const.
longitudinal:	$r = 1$	$\cos^2\theta^*$



Consistent with purely transverse polarization

Electron Photon DIS



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

$$\mathbf{P^2 = -q_2^2}$$

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

Bjorken scaling variable

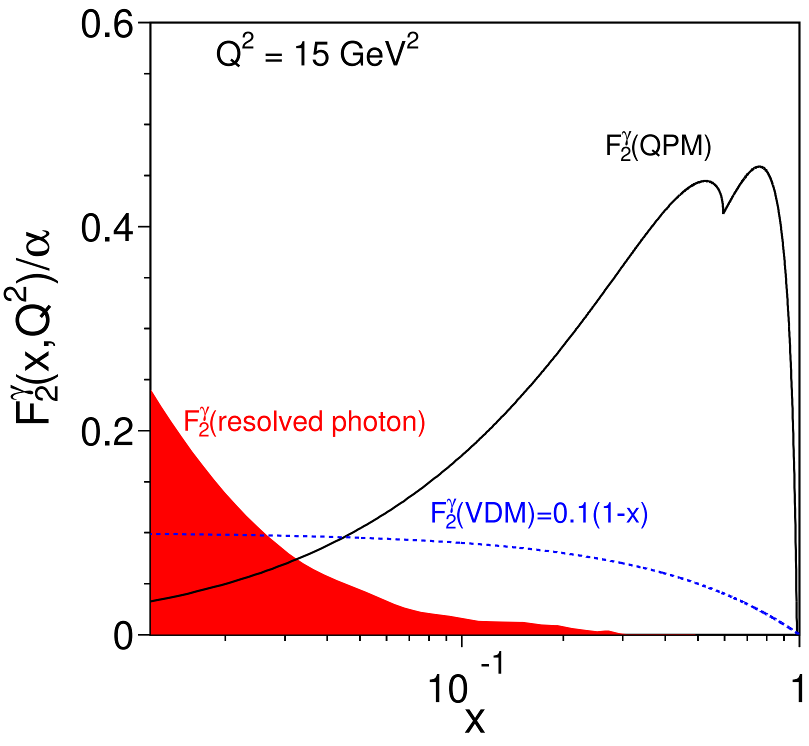
$$x = \frac{Q^2}{Q^2+P^2+W_{\gamma\gamma}^2}$$

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

❒ **Cross Section**

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

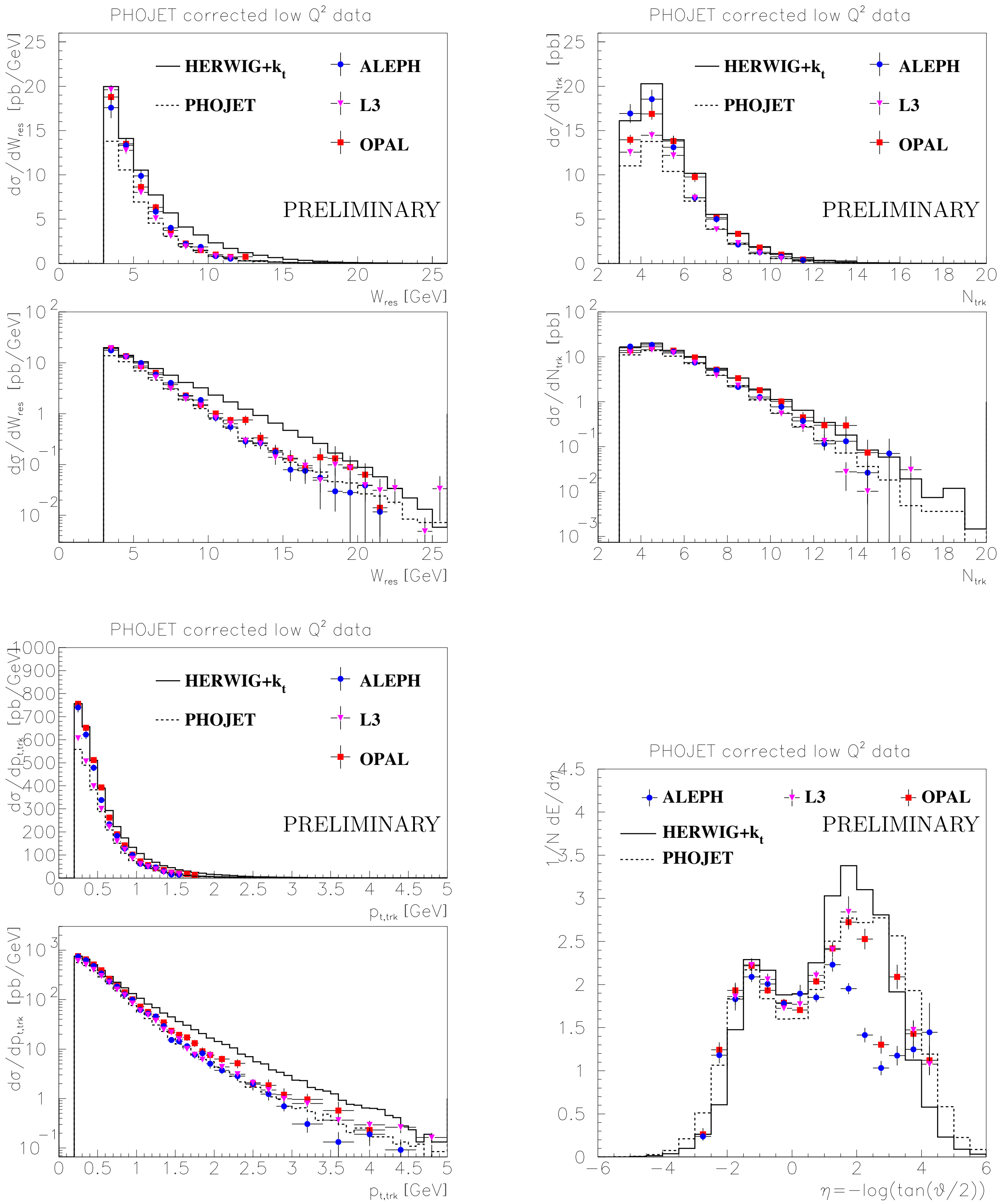
➠ **Hadronic $F_2^\gamma(x, Q^2)$**



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

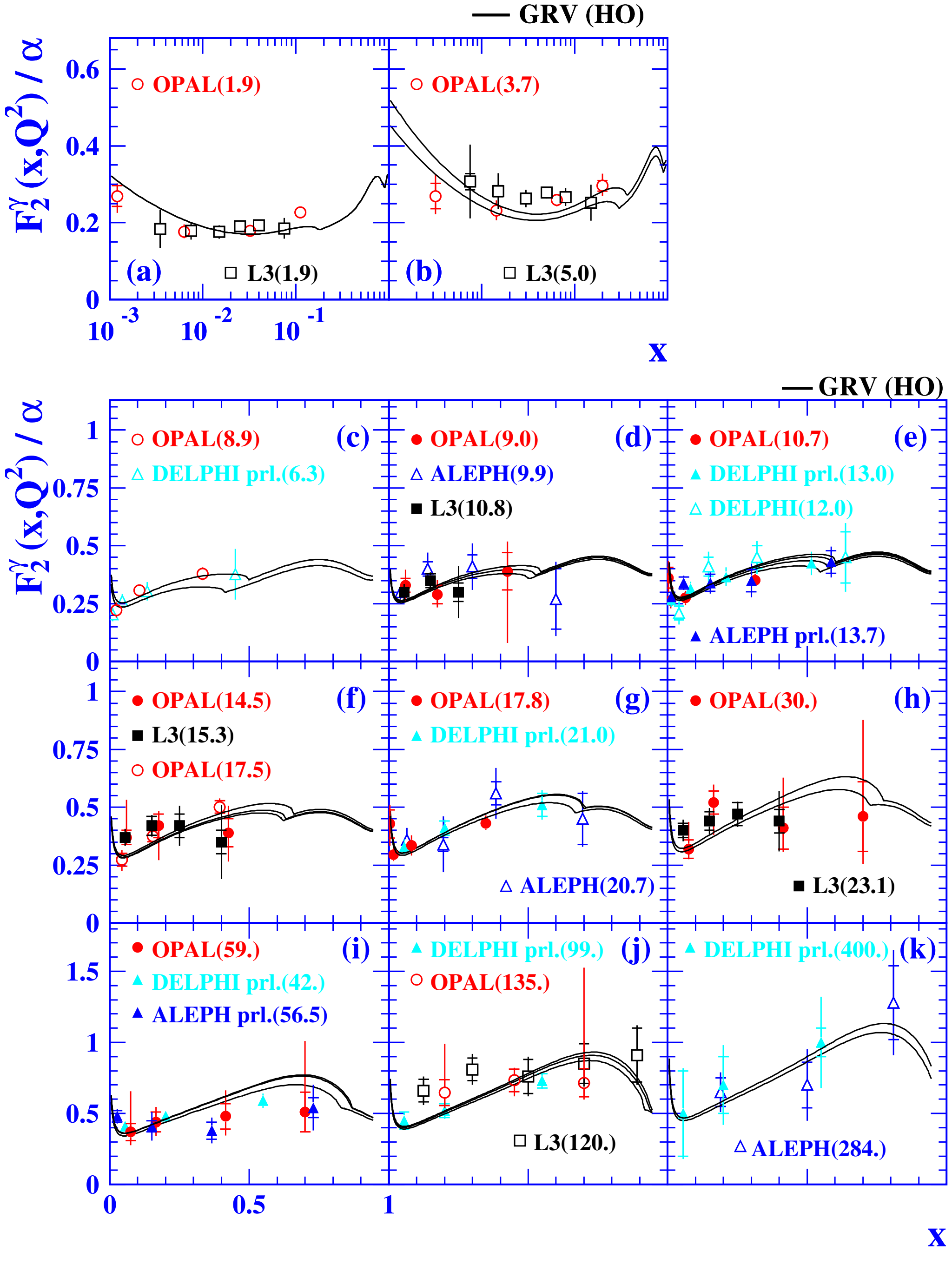
➜ Perform identical analysis in all Experiments

➜ Compare distributions inside the detector acceptance



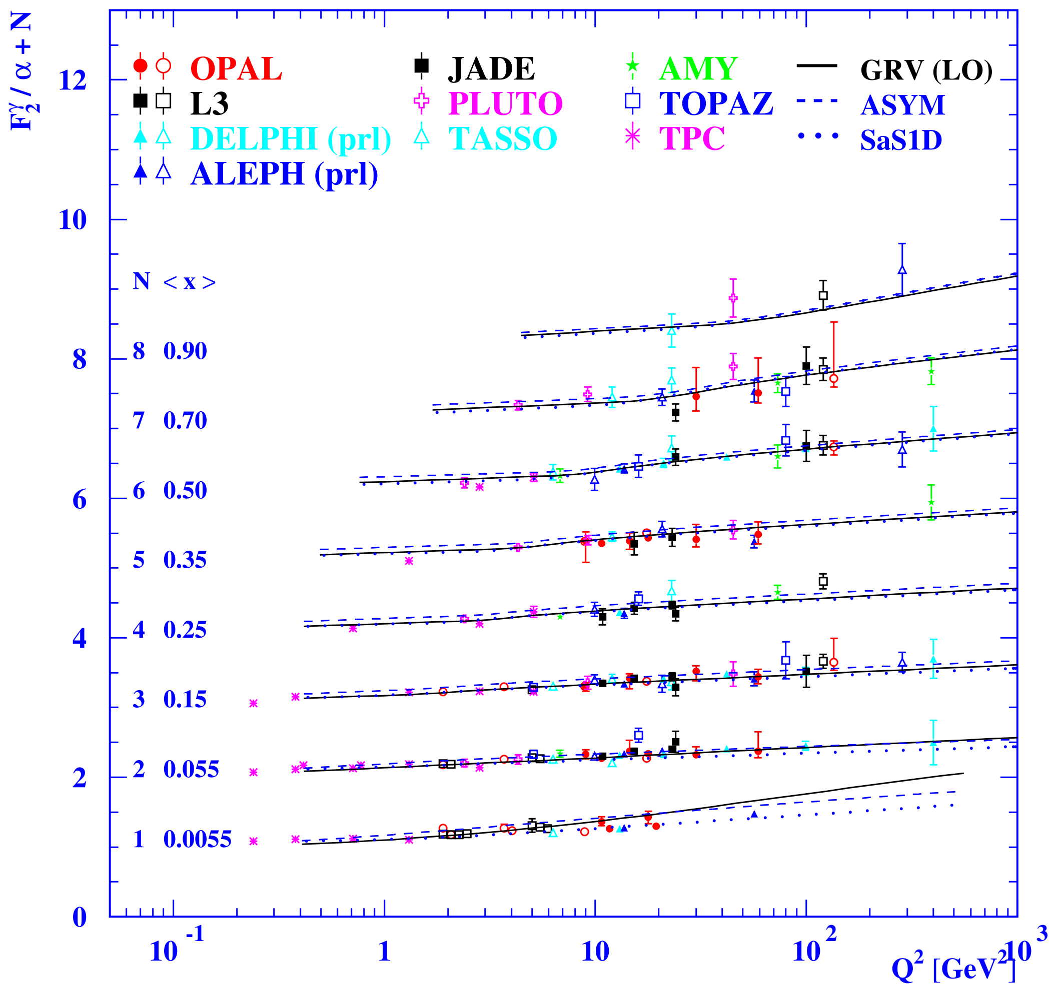
⇨ Smaller differences between experiments than differences between models

LEP F_2^{had}:



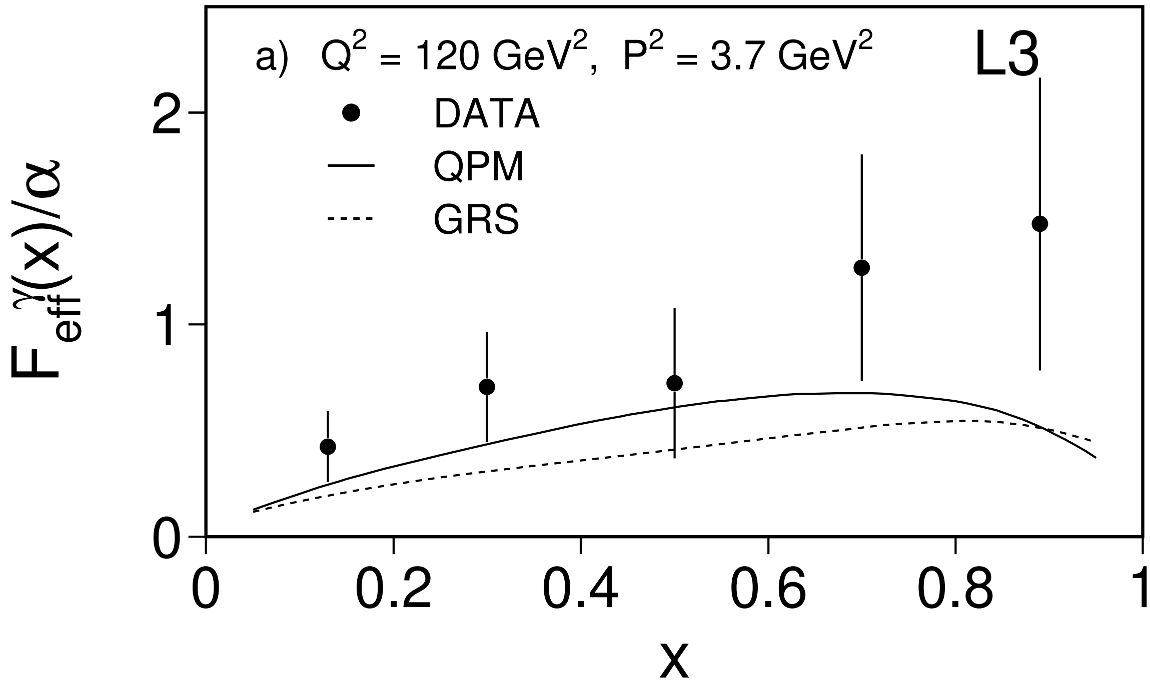
GRV (HO)
$F_2^\gamma(x,Q^2)/\alpha$
OPAL(1.9)
L3(1.9)
(a)
OPAL(3.7)
L3(5.0)
(b)
x
OPAL(8.9)
DELPHI prl.(6.3)
(c)
OPAL(9.0)
ALEPH(9.9)
L3(10.8)
(d)
OPAL(10.7)
DELPHI prl.(13.0)
DELPHI(12.0)
ALEPH prl.(13.7)
(e)
OPAL(14.5)
L3(15.3)
OPAL(17.5)
(f)
OPAL(17.8)
DELPHI prl.(21.0)
ALEPH(20.7)
(g)
OPAL(30.)
L3(23.1)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

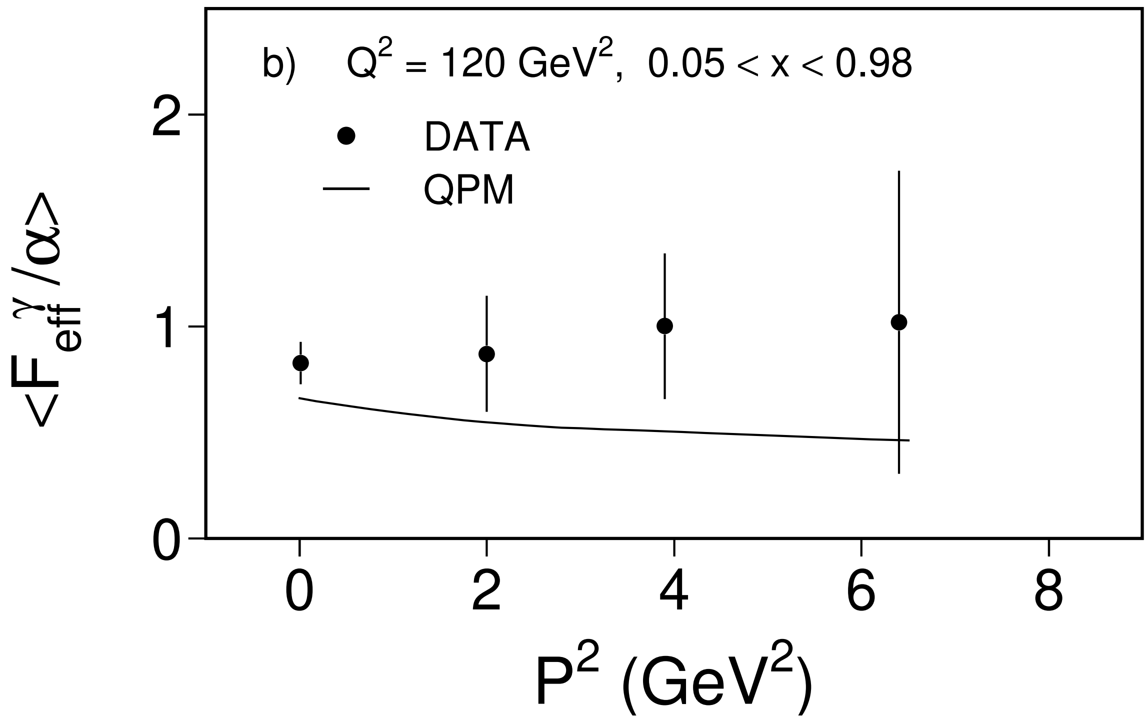
F_2^{had} evolution with Q^2:



❑ ln Q^2 evolution agrees well with QCD

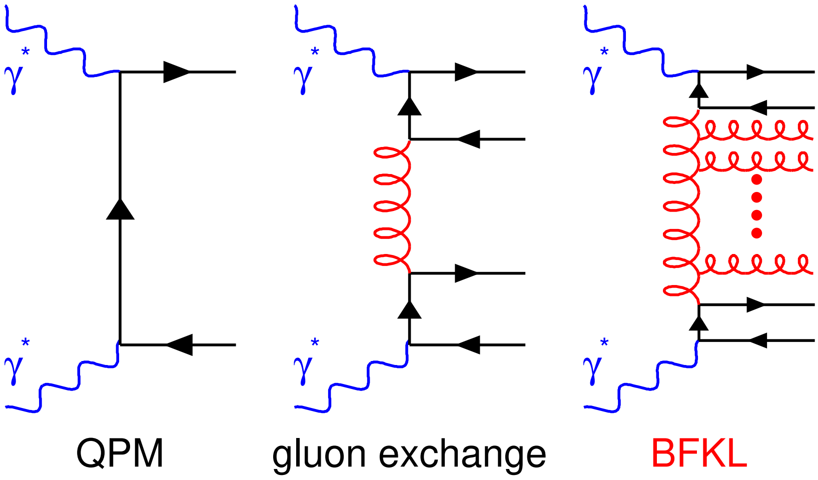
$F^{\gamma}_{\text{effective}}$ in double-tag events by L3:





❑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 :**

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

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

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

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

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

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

❑ Selected :

137 events at 91 GeV ($\langle Q^2 \rangle = 3.5$ GeV^2)

34 events at 183 GeV ($\langle Q^2 \rangle = 14$ GeV^2)

489 events at 189-208 GeV ($\langle Q^2 \rangle = 15$ GeV^2)

OPAL :

Preliminary:

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

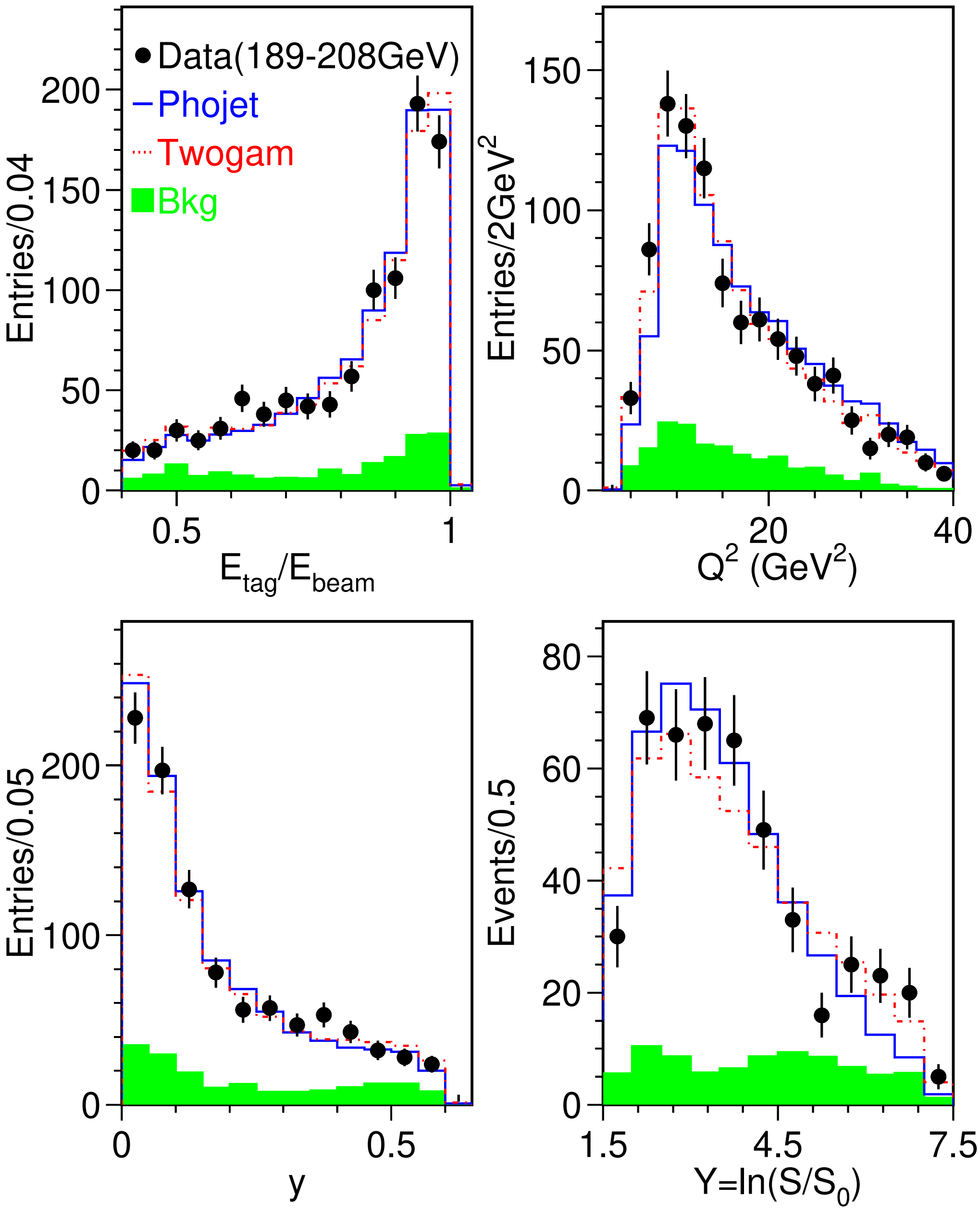
➜ $E_{tag} > 0.4 \cdot E_{beam}$, 34 mrad $< \theta_{tag} <$ 55 mrad

➜ $W_{\gamma\gamma}$ calculated from hadrons

❑ Selected :

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

L3: Data/MC comparison



Monte Carlo used :

➜ PHOJET

➜ TWOGAM (v.2.04) - radiative corrections

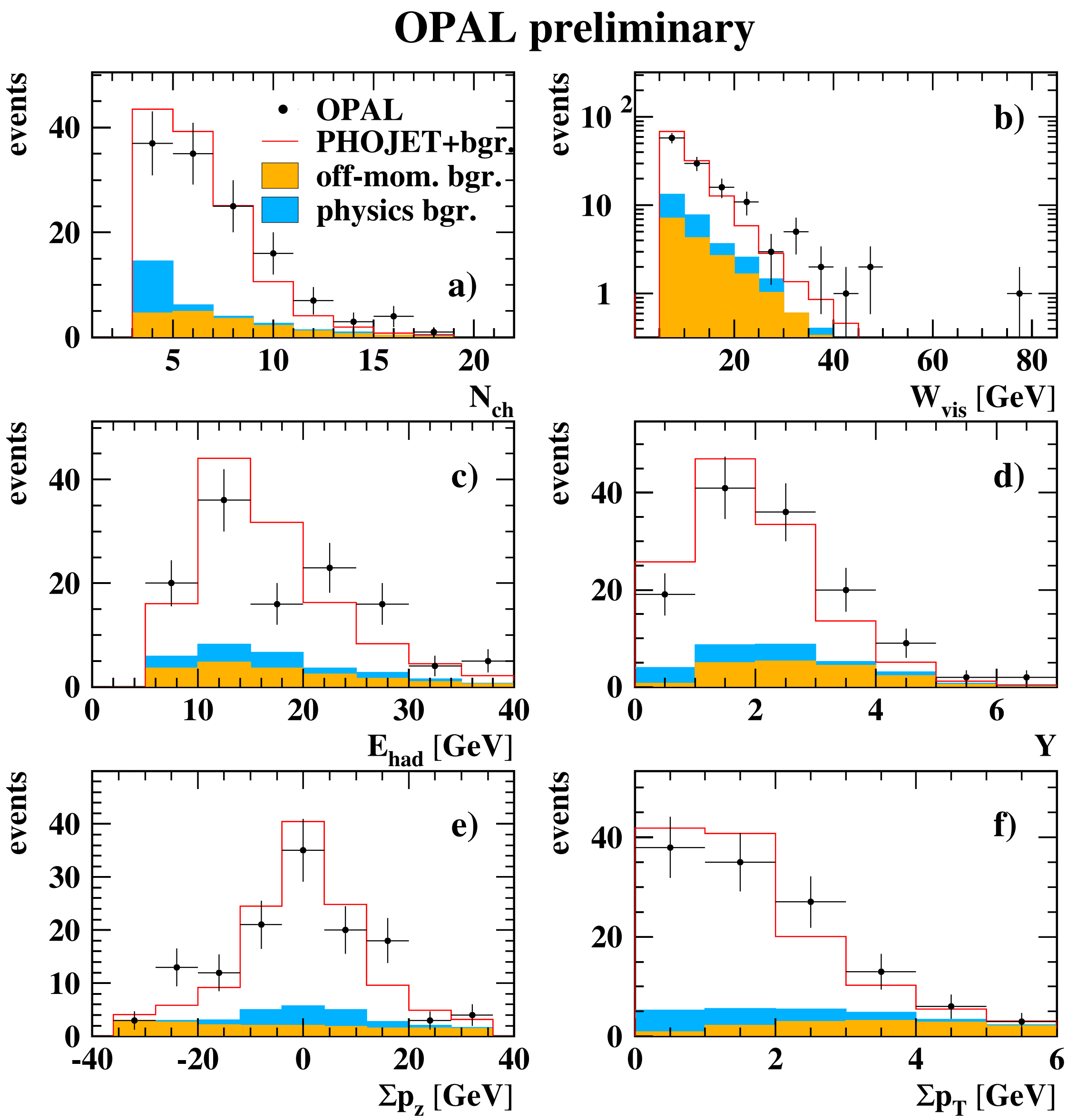
S. Nova, A. Olshevski, T. Todorov (CERN 96-01 (1996), vol.2)

➜ QPM contribution :

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

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

OPAL: Data/MC comparison



Monte Carlo used :

➜ PHOJET, PYTHIA

➜ GALUGA - QPM contribution

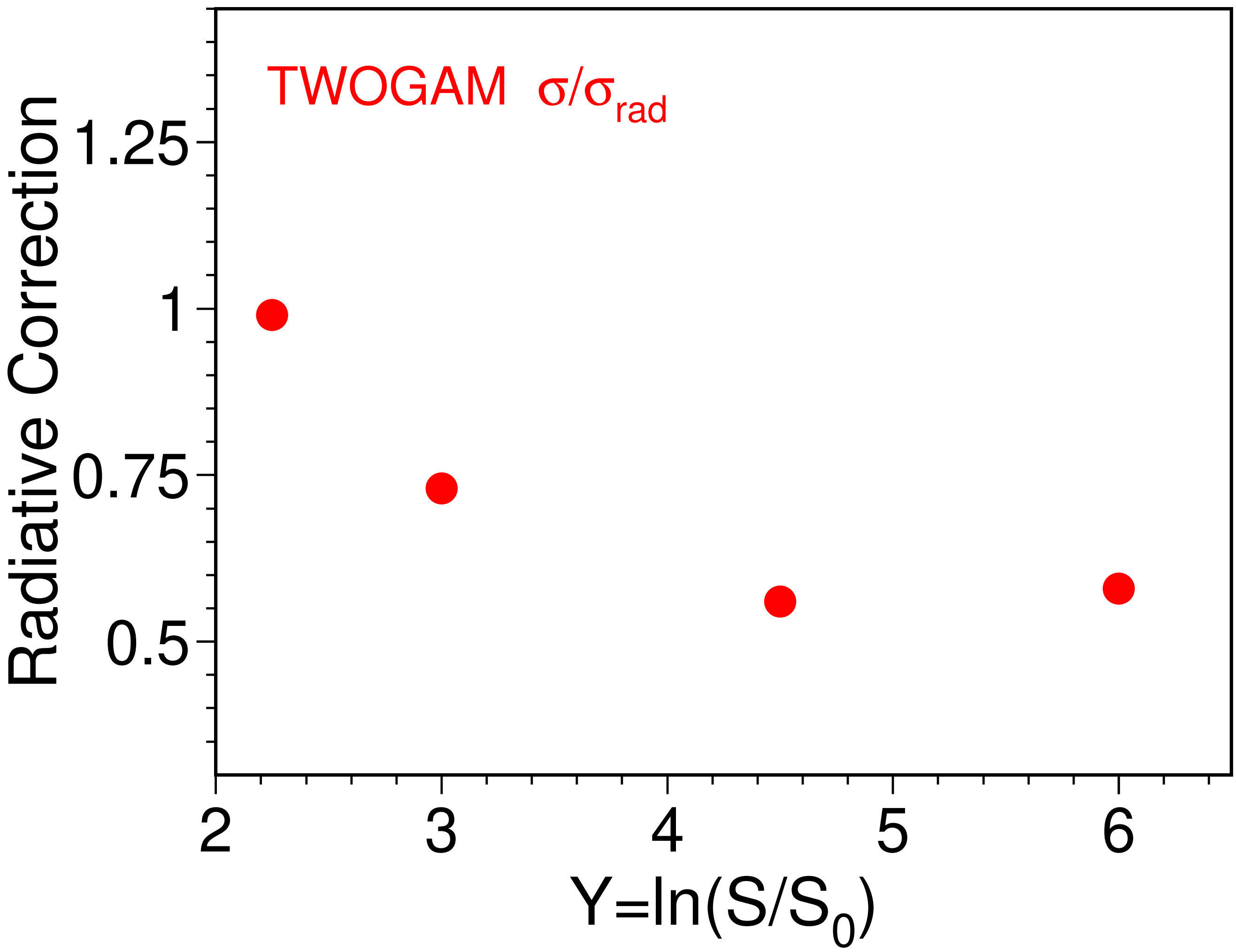
➜ BDK - estimation of radiative corrections

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

Importance of Radiative Corrections

L3 : $W_{\gamma\gamma}$ is calculated from e^+e^-

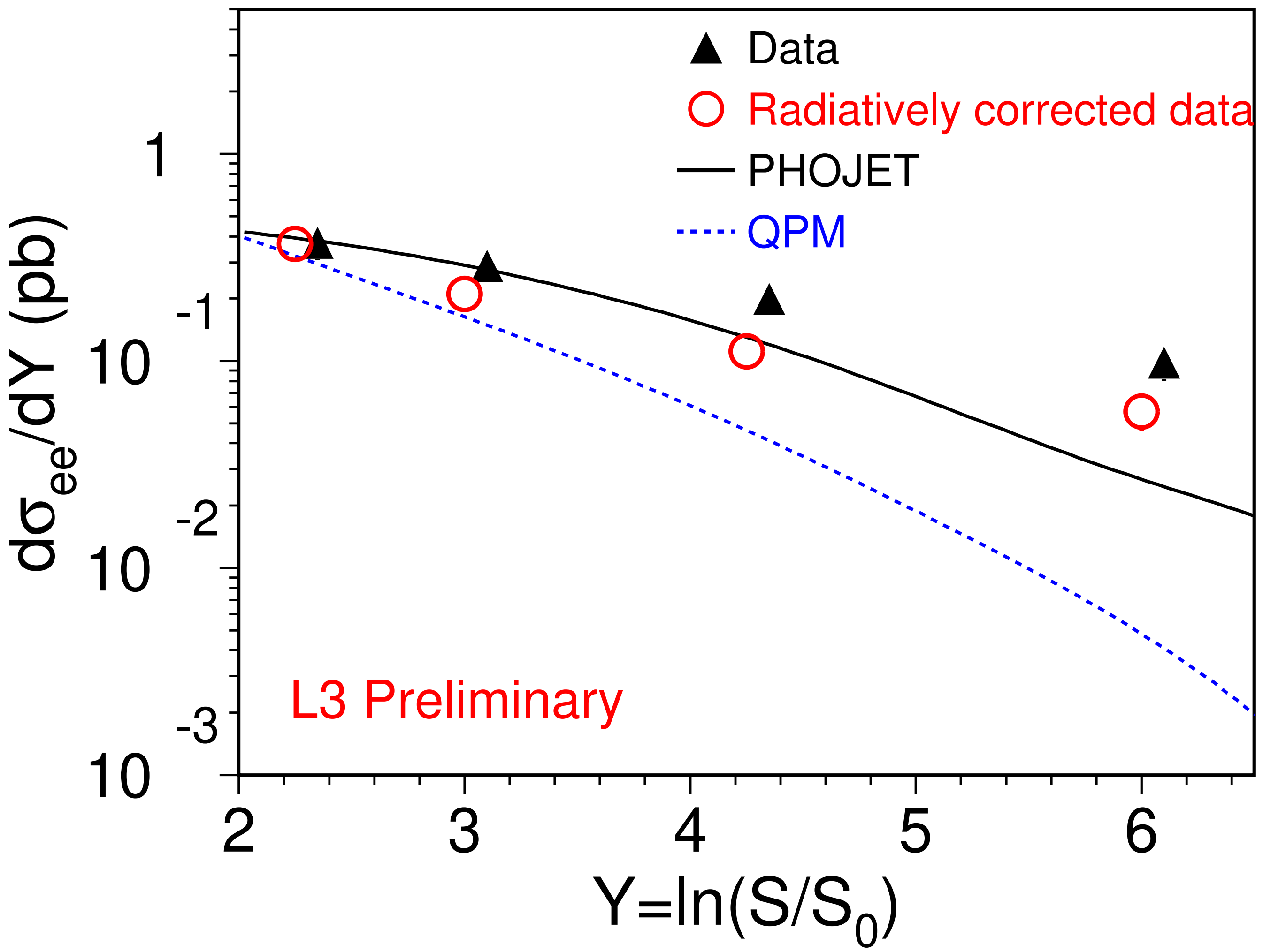
Radiative corrections in kinematical range
$E_{tag} > 30$ GeV, 30 mrad $< \theta_{tag} <$ 66 mrad



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 the data

➜ Data in excess at $Y > 5$

➜ BFKL ?

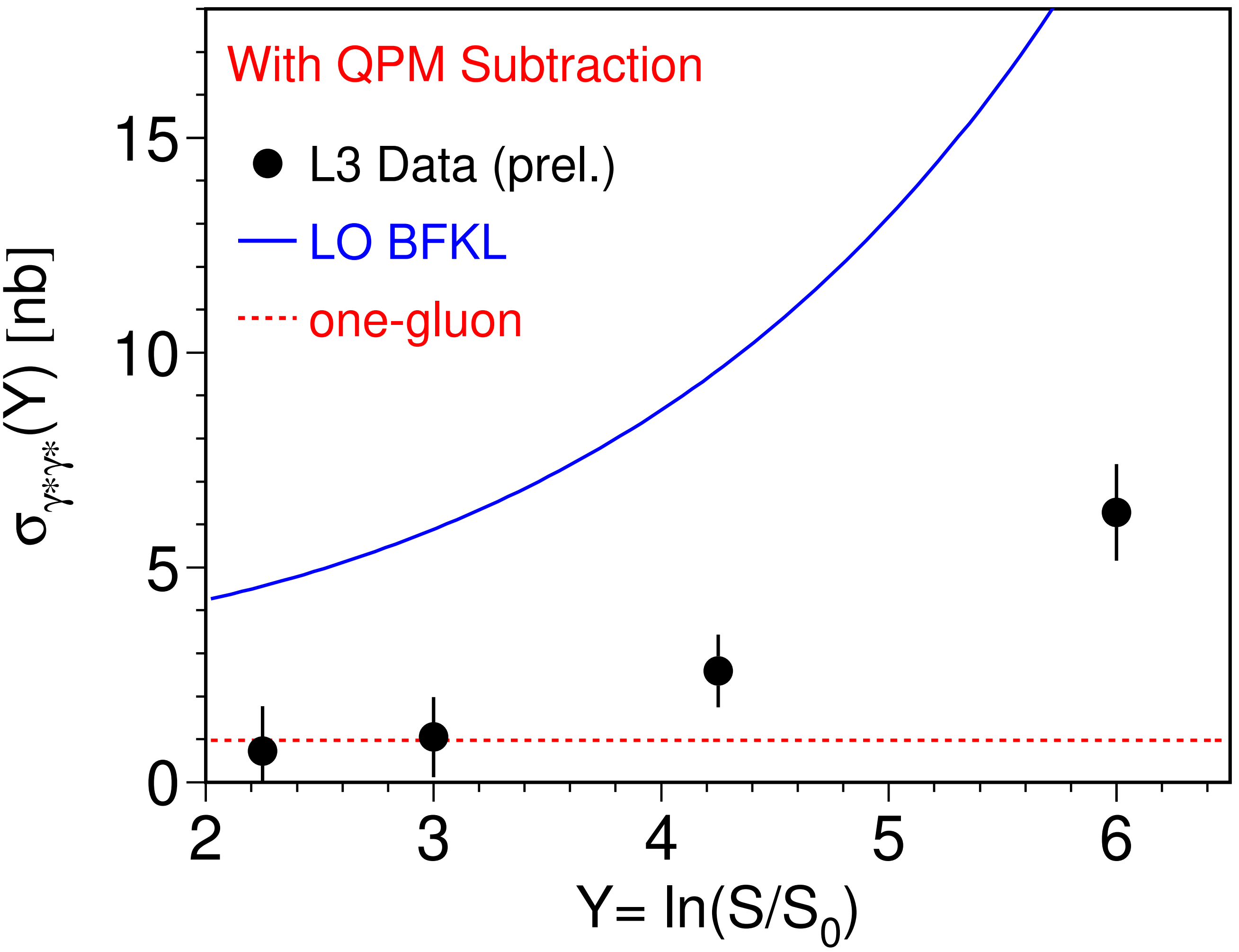
Double Tag: $\sigma_{\gamma^*\gamma^*}$ (L3)

➤ **L3 :**

❑ $\sigma_{ee} = \mathcal{L}_{TT} \times \sigma_{\gamma^*\gamma^*}$

❑ **Subtract the QPM contribution.**

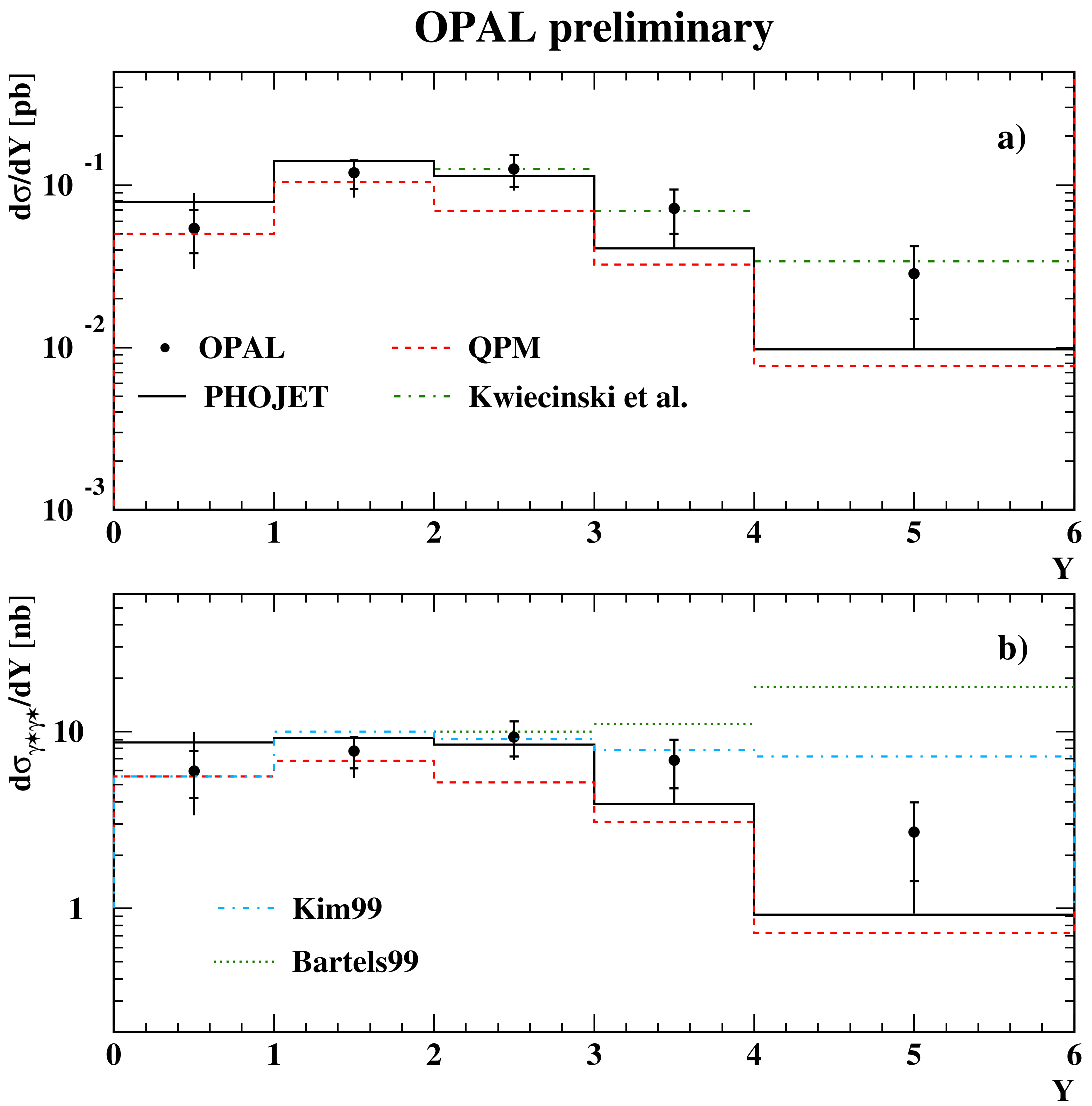
189 - 208 GeV



- **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: OPAL

➤ OPAL :

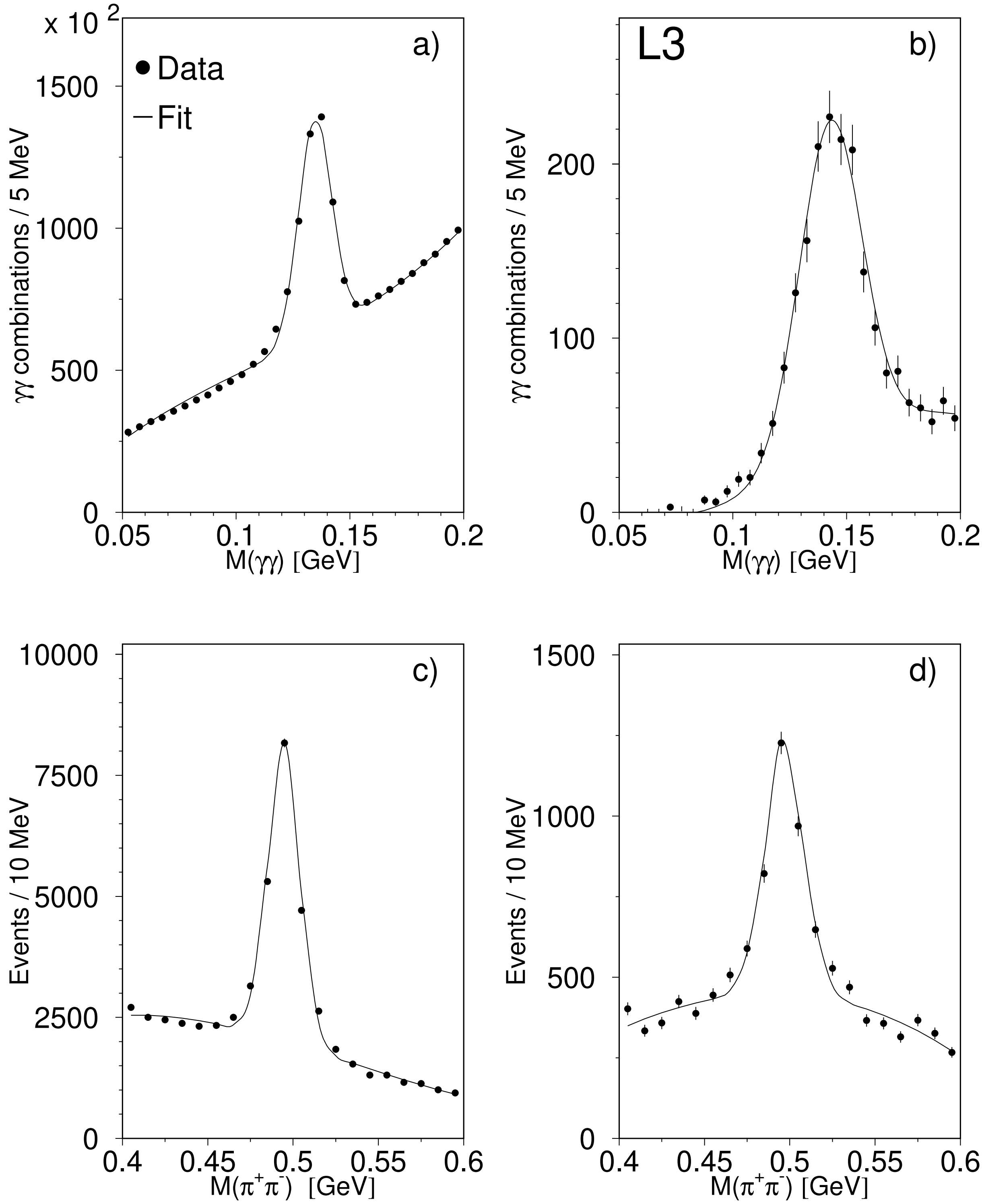


J. Kwiecinski, L. Motyka, Phys. Lett. B462 (1999) 203.
Kim99: S.J. Brodsky, V.S. Fadin, V.T. Kim, L.N. Lipatov,
G.B. Pivovarov, JETP Lett. 70 (1999) 155.
V.T. Kim, private communication.
Bartels99: J. Bartels, C. Ewerz, R. Staritzbichler, hep-ph/0004029.

Consistent with L3 ➜ excess at large Y.

Inclusive single hadron production

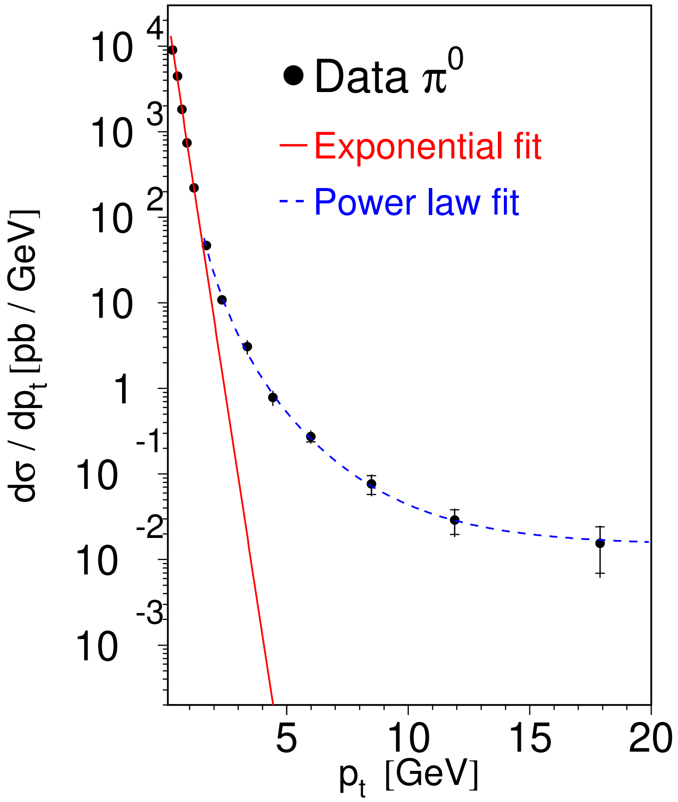
For each p_t and $|\eta|$ bin:

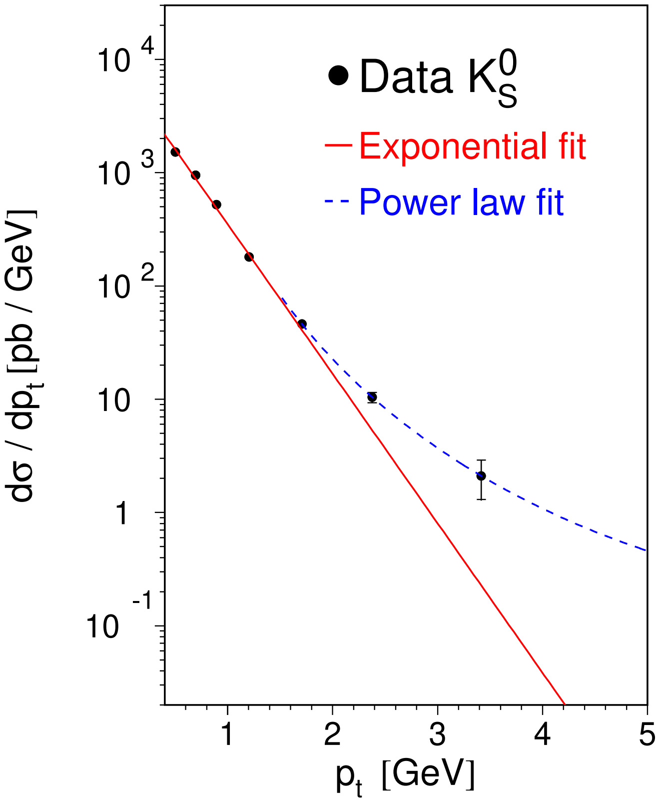


⇨ well identified π_0 and K_S^0

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

➤ **L3 Preliminary:**





Exponential $A.e^{-p_t/B}$: $B = \langle p_t \rangle =$ 234 ± 11 MeV for π^0

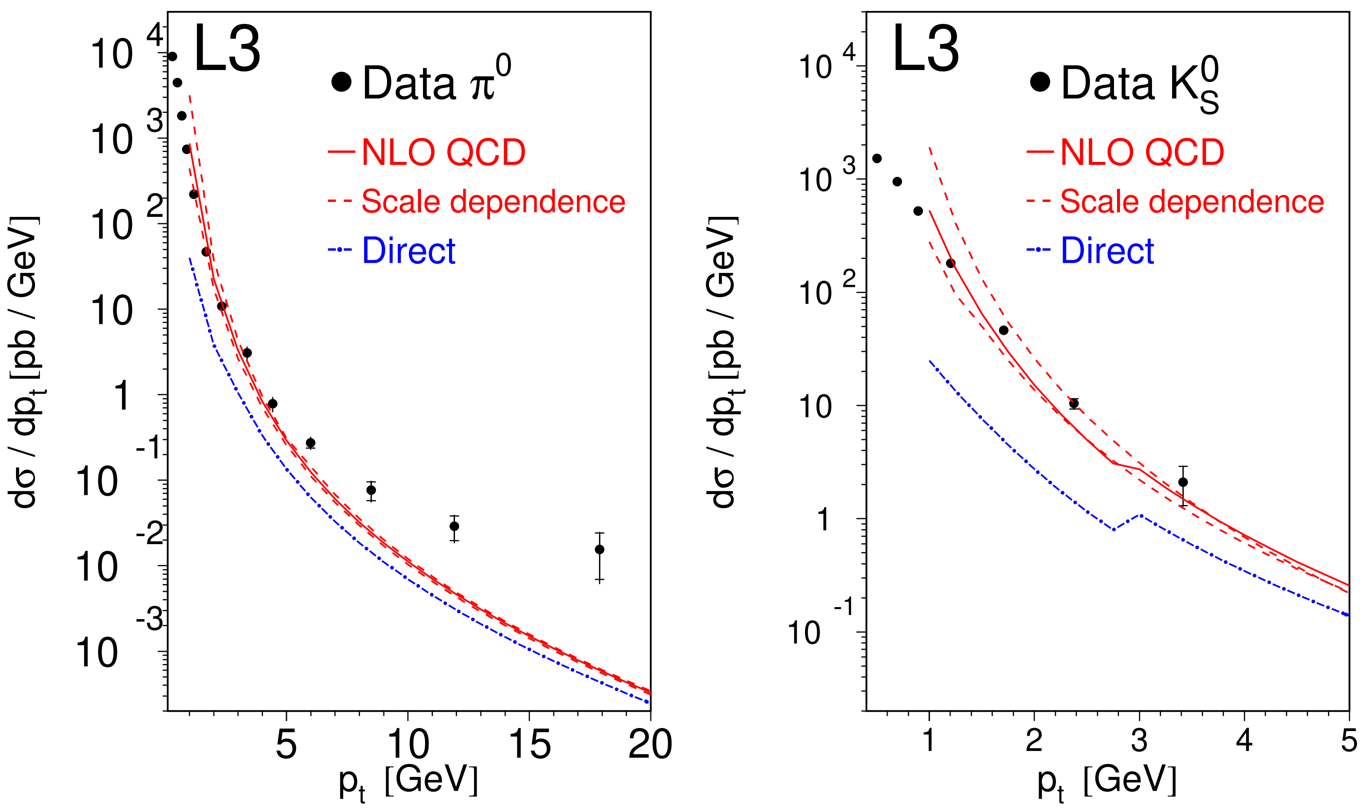
329 ± 4 MeV for K^0_S

Power law $A.p_t^{-B}$: B= 4.12 ± 0.17 MeV for π^0

4.52 ± 1.22 MeV for K^0_S

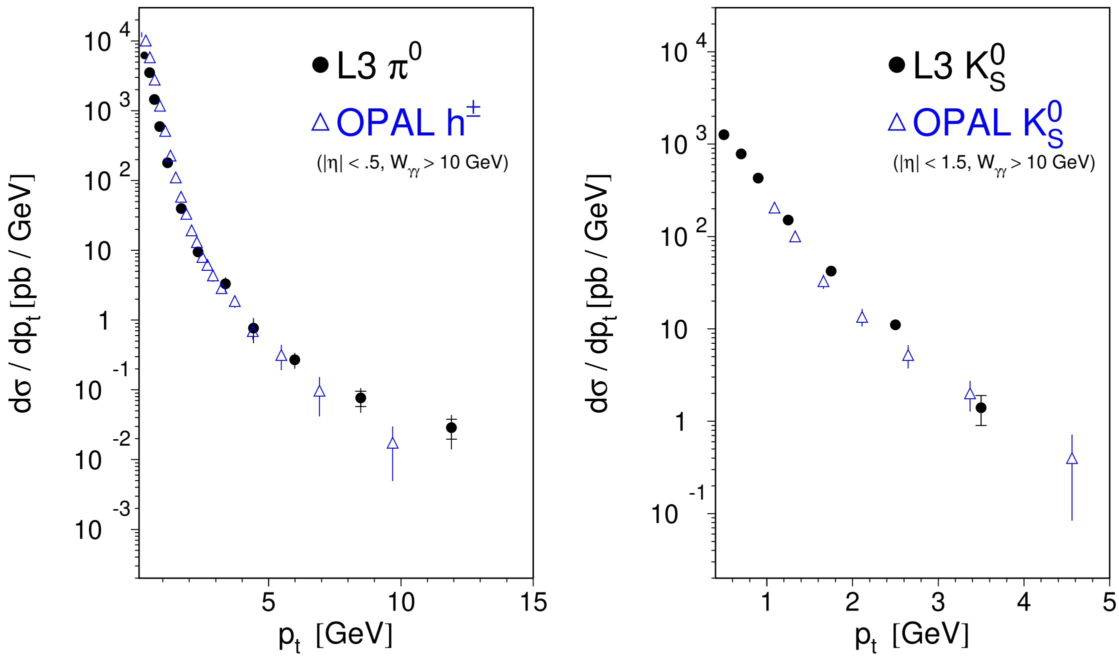
$\frac{d\sigma}{dp_t}$: comparison with NLO QCD

➤ **L3 Preliminary:**



⇨ **excess in π_0 data for $p_t > 5\ GeV$**

Comparison with OPAL:

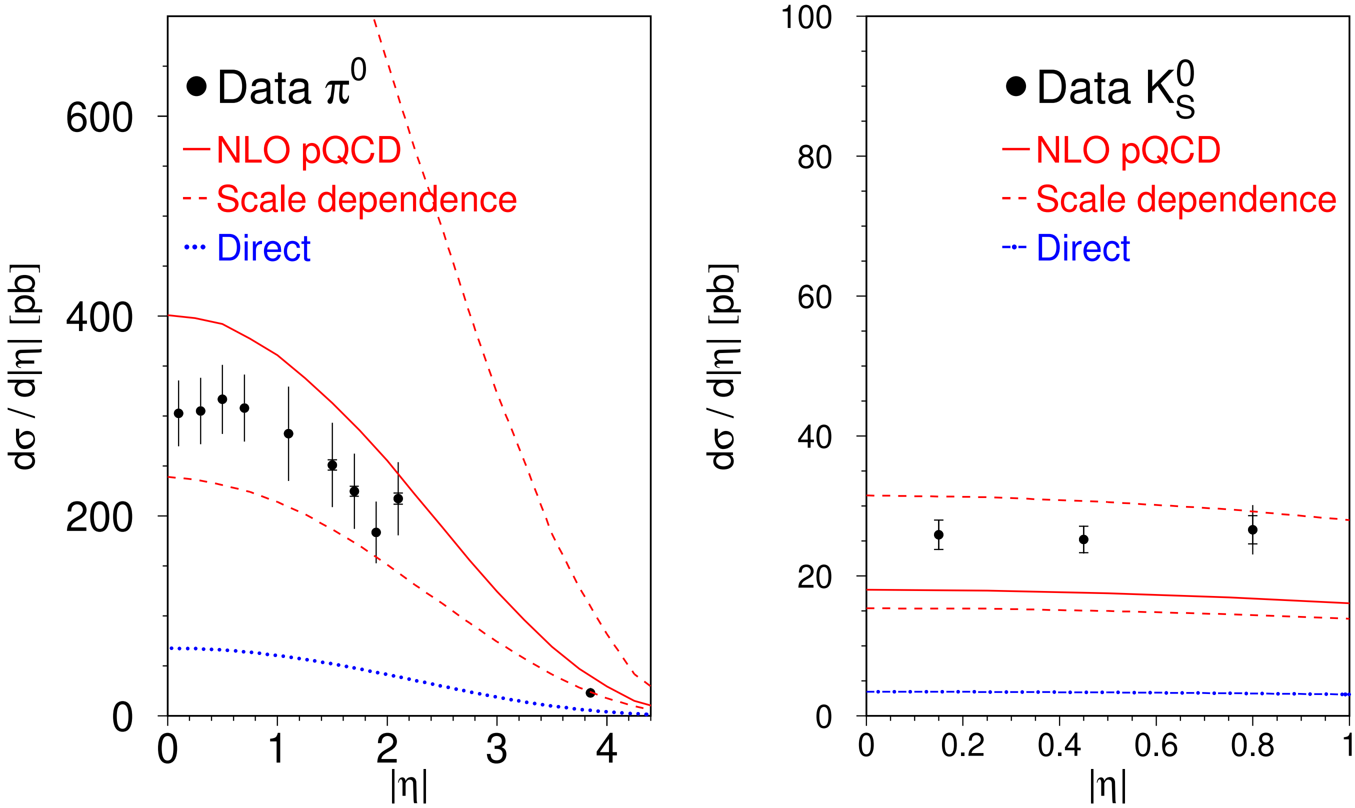


⇨ **good agreement between experiments**

$\frac{d\sigma}{d|\eta|}$: comparison with NLO QCD

➤ **L3 Preliminary:**

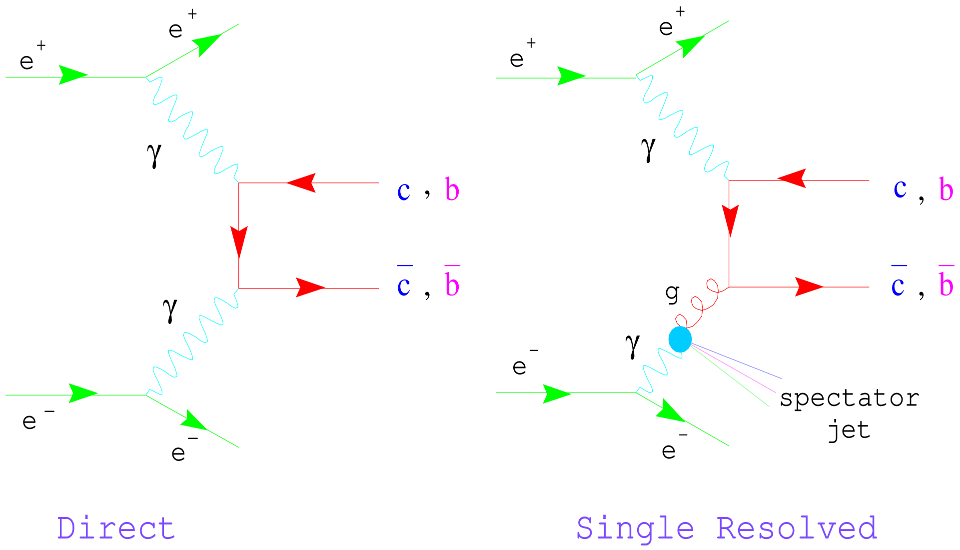
$p_t > 1$ GeV $\qquad$ $p_t > 1.5$ GeV



⇨ the pseudo-rapidity shape is well reproduced

Inclusive Charm and Beauty Production

Motivation :



- Test of the perturbative QCD
  - ⇨ Direct Process depends on $m_c(m_b)$ and α_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 - 202 GeV, $\mathcal{L} = 575$ pb^{-1}

PLB453 (1999) 83; PLB503 (201) 10.

OPAL * : 183 - 202 GeV, $\mathcal{L} = 428$ pb^{-1}

CERN-EP/99-157.

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

DELPHI* : 161 - 204 GeV, $\mathcal{L} = 458$ 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

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

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

D^{*+} tag

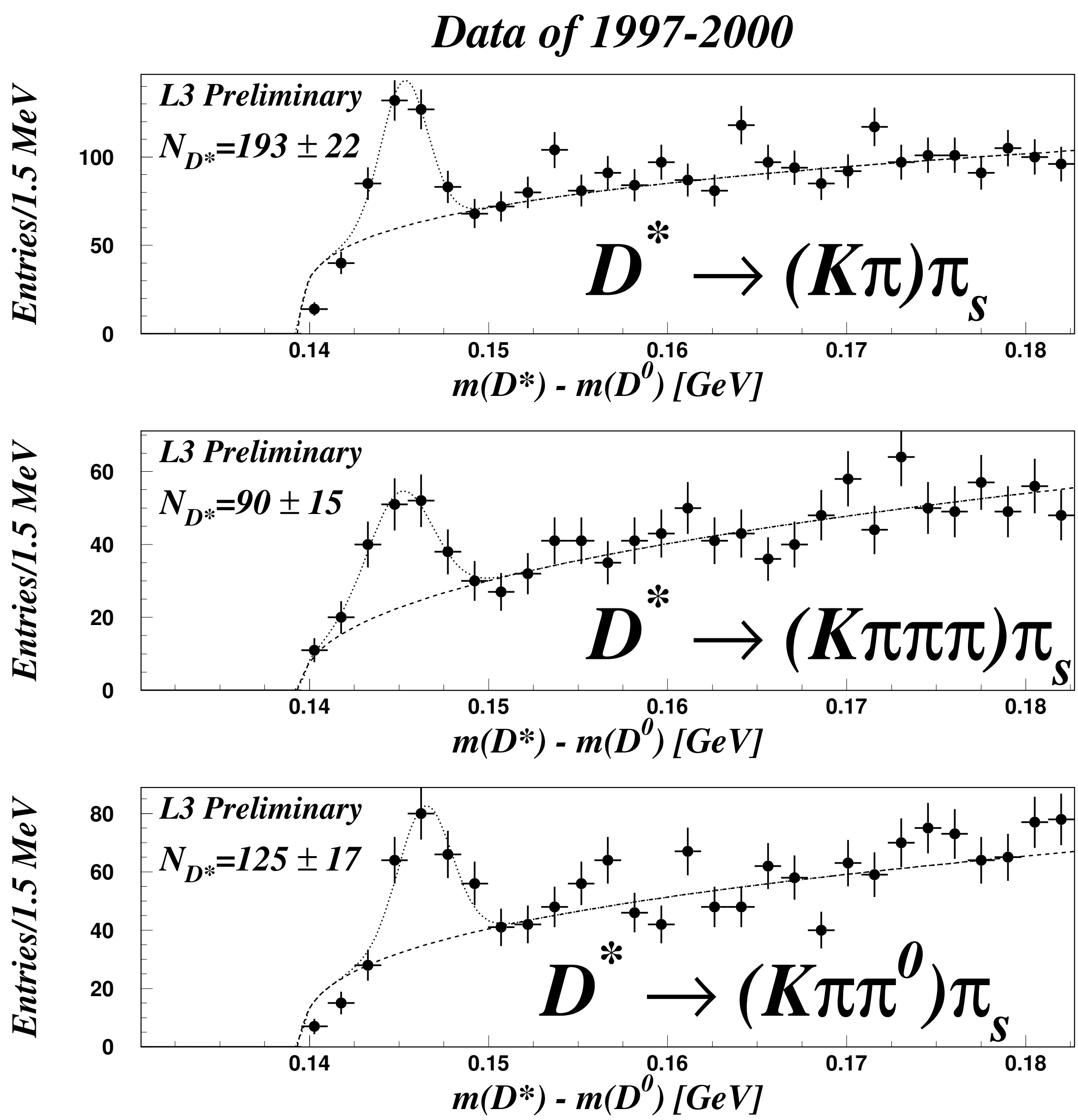
DELPHI: D^{*+} tag

Bottom identification :

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

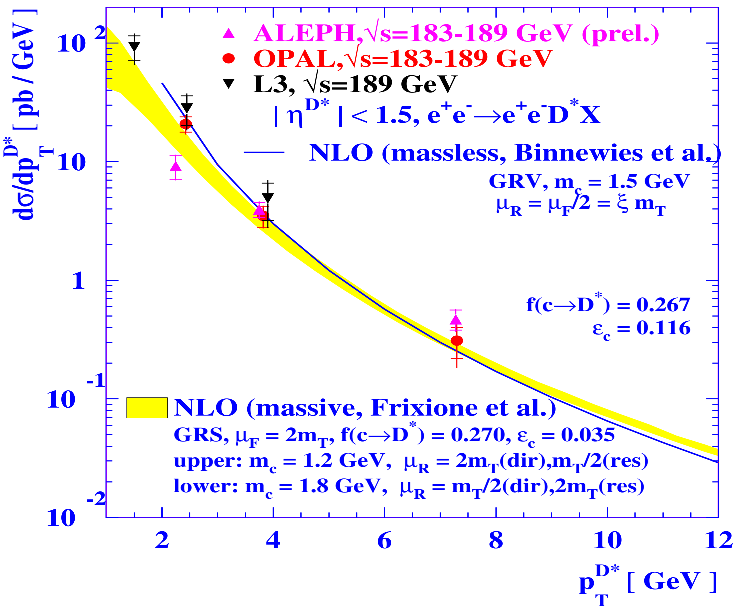
OPAL : lepton tag ($c \rightarrow l^{\pm}$X , $l^{\pm} \equiv \mu^{\pm}$)

D* Production :

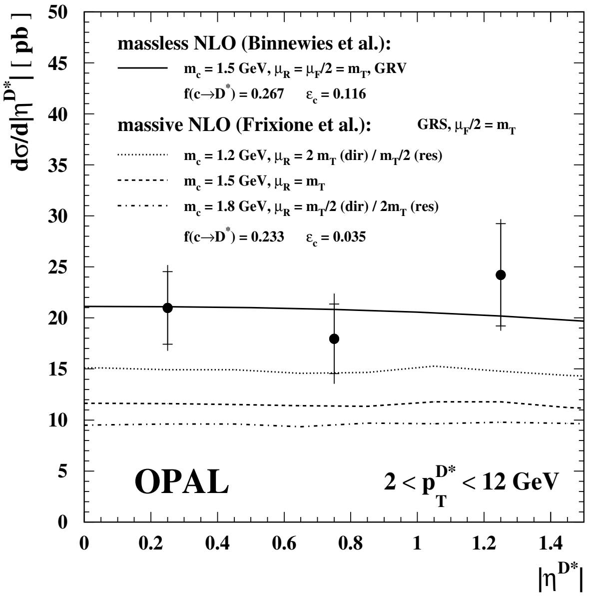


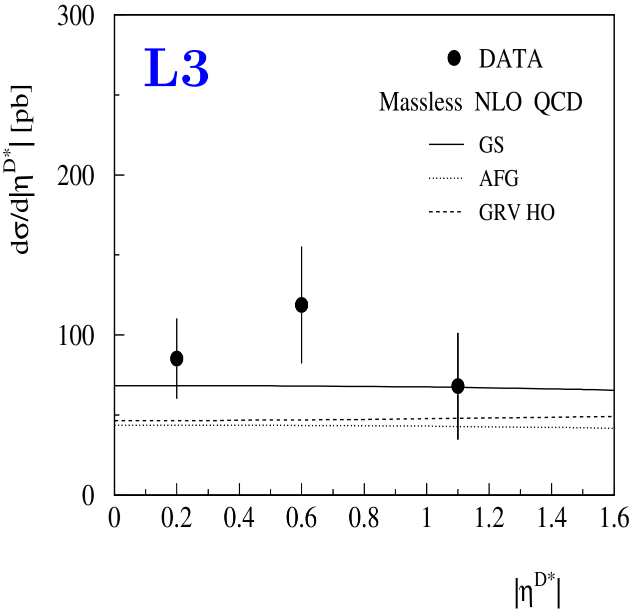
D* Production : Differential cross-sections

❒ $\frac{d\sigma}{dp_t}$:

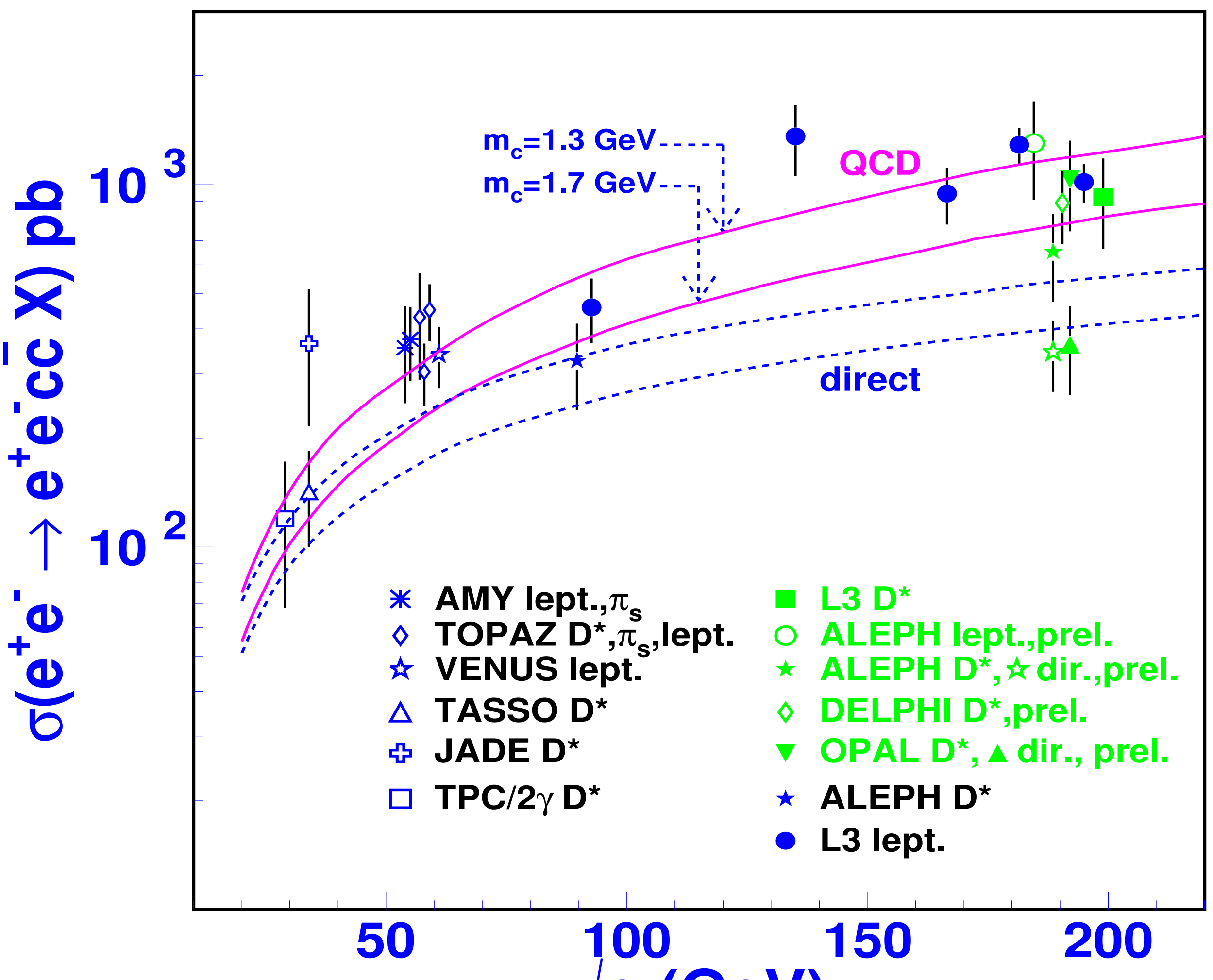


❒ $\frac{d\sigma}{d|\eta|}$::





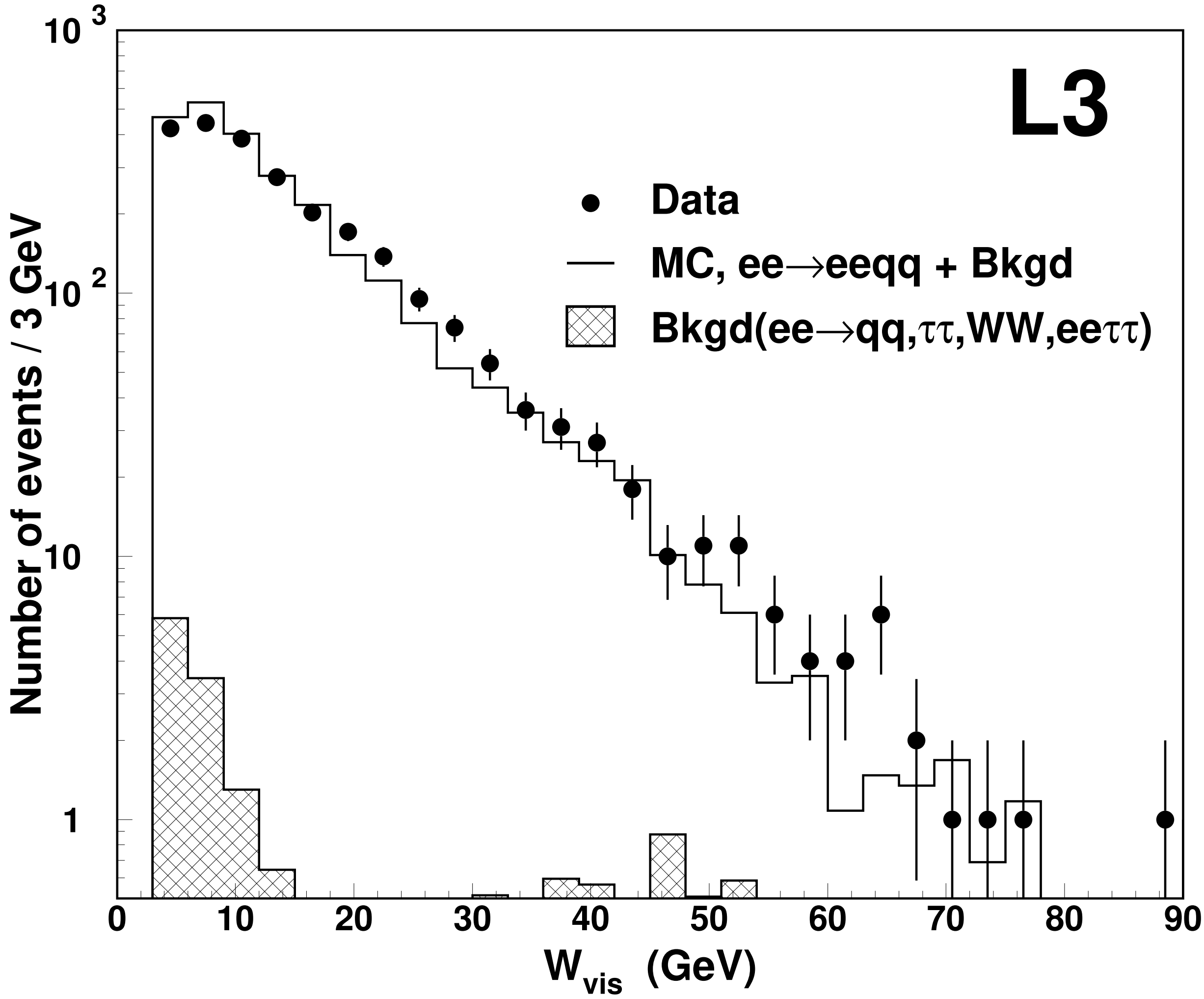
Charm production in $\gamma\gamma$ collisions



- 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.

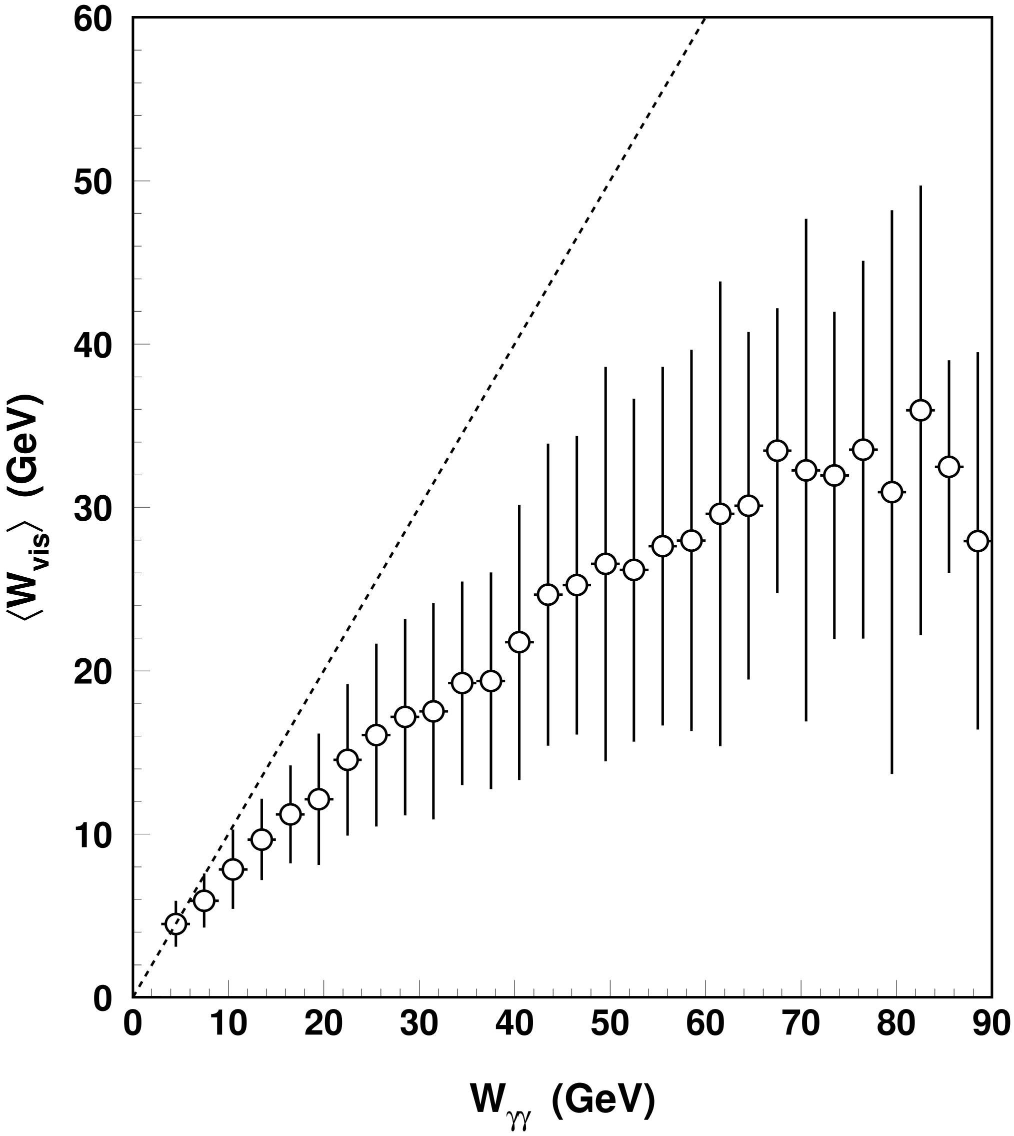
$\sigma(\gamma\gamma \to c\bar{c})$ vs $W_{\gamma\gamma}$



- Data are in excess of MC for high visible mass

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

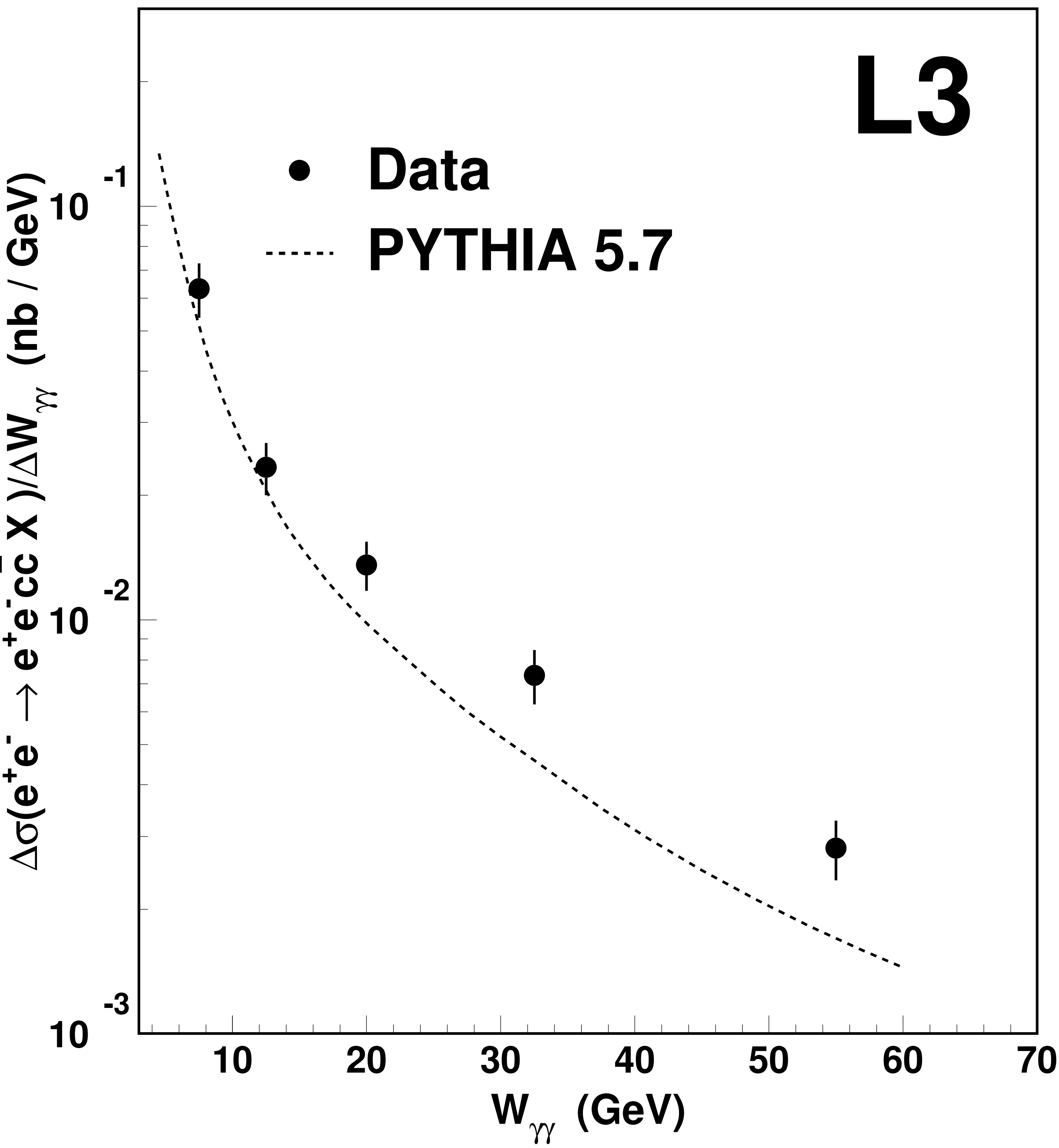
- Unfolding corrects for acceptance (missing energy) and detector resolution



❑ unfolding with Bayes (G. D'Agostini, NIM A362(1995) 487)

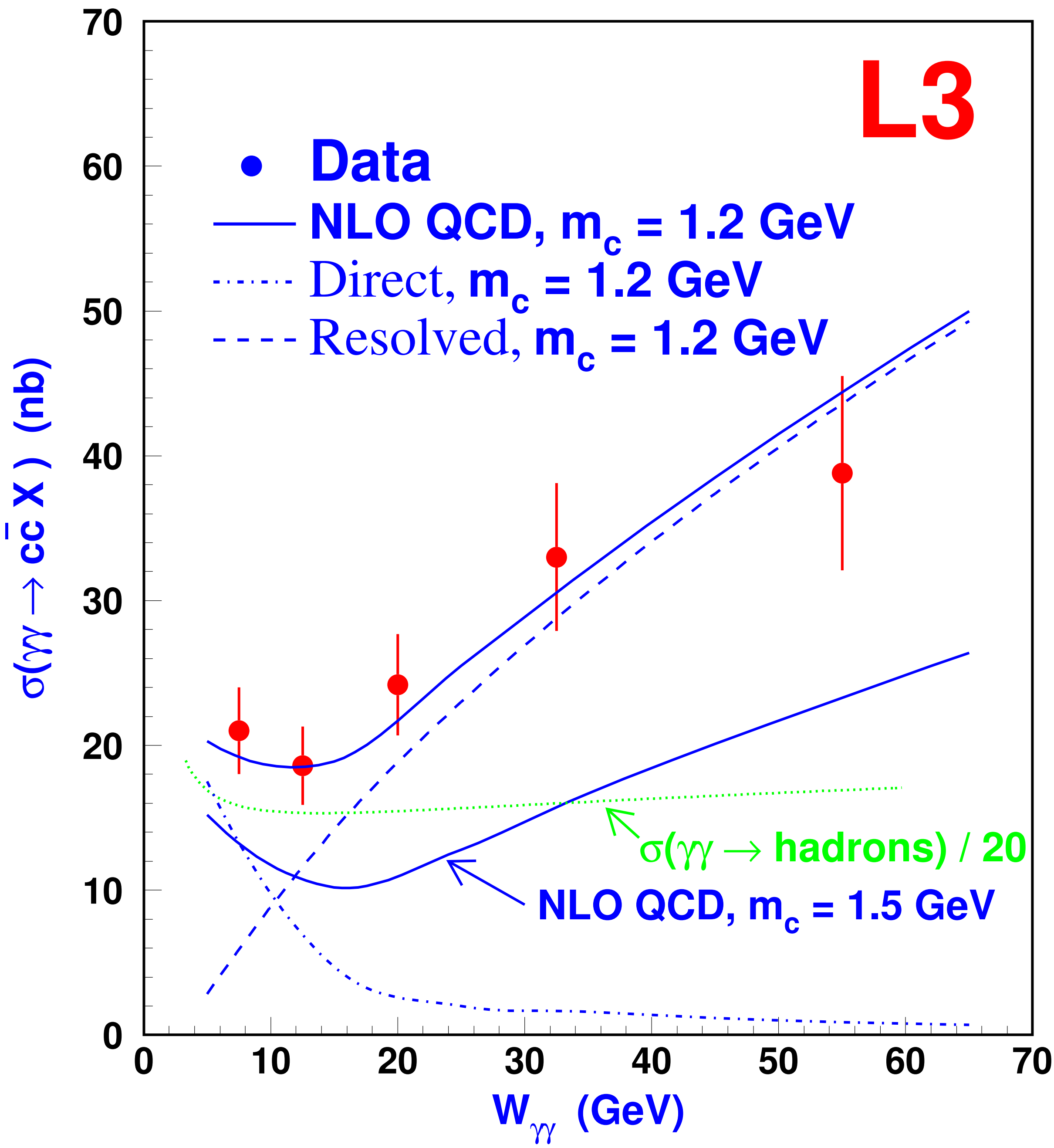
❑ $\sigma_{ee} = \mathcal{L}_{\gamma\gamma} \otimes \sigma_{\gamma\gamma}$

$\sigma(ee \rightarrow eec\bar{c}X)$ vs $W_{\gamma\gamma}$:



- harder than LO MC prediction

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



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

$\sigma(\gamma\gamma \to c\bar{c})$: DL fit

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

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

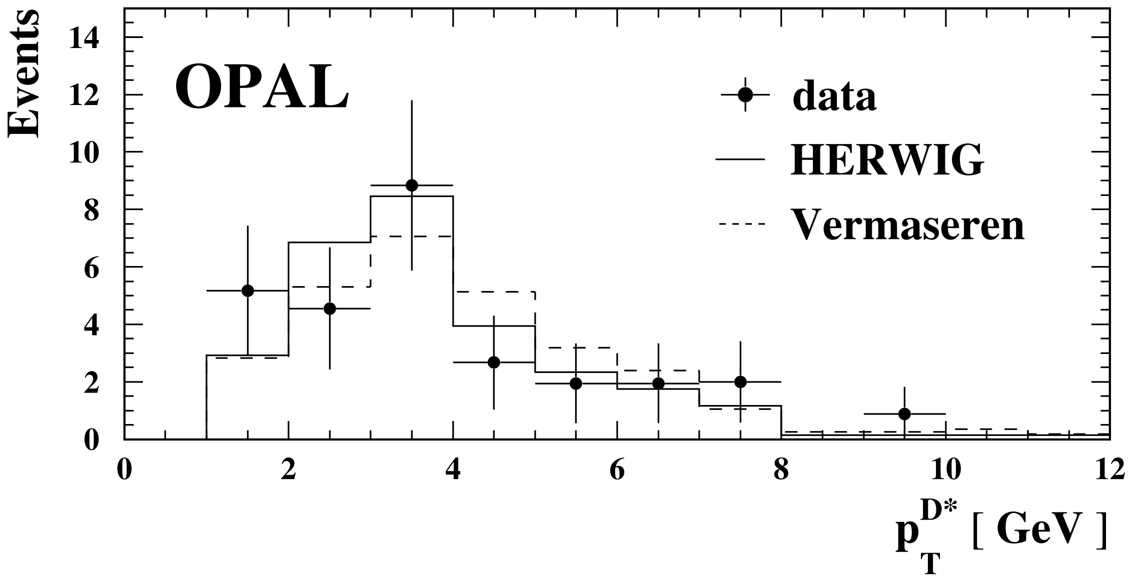
- **Universal fit** (PDG 2000):
  $\varepsilon = 0.093 \pm 0.002,\ \eta = 0.358 \pm 0.015,\ A, B$ free

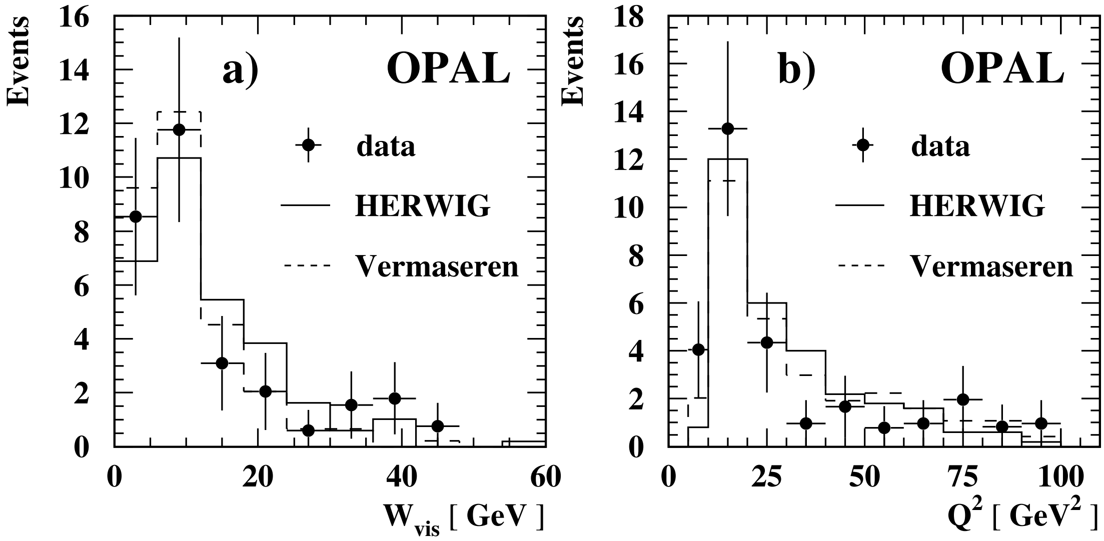
- **L3 fit for $\sigma(\gamma\gamma \to q\bar{q})$, $\eta = 0.358$ fixed, A,B free**
  $\varepsilon = 0.225 \pm 0.021$ $\quad 5 < \mathrm{W}_{\gamma\gamma} < 185\mathrm{GeV}$

- **L3 fit for $\sigma(\gamma\gamma \to c\bar{c})$, $\eta = 0.358$ fixed, A,B free**
  $\varepsilon = 0.40 \pm 0.08$ $\quad 5 < \mathrm{W}_{\gamma\gamma} < 70\mathrm{GeV}$

Charm structure function

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

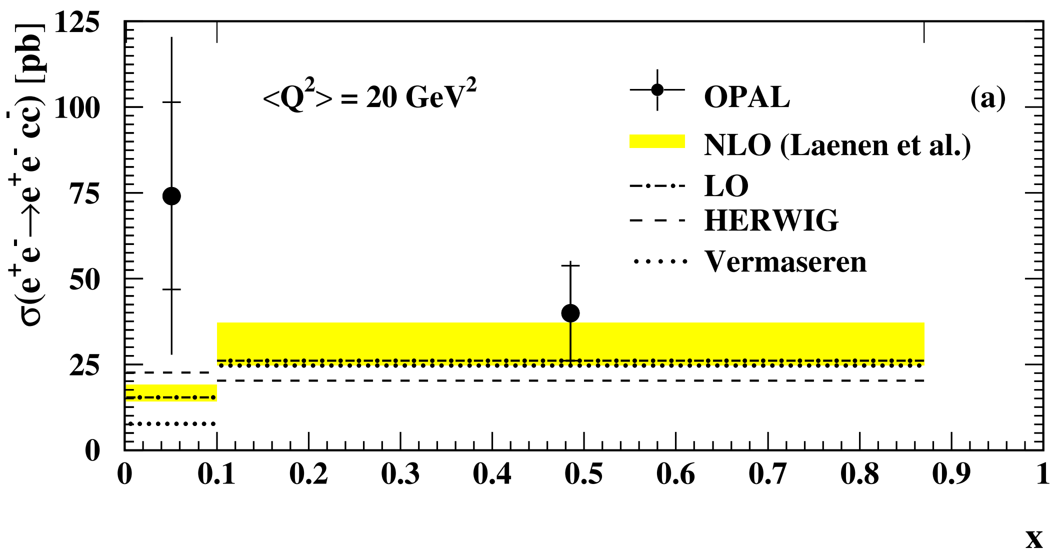


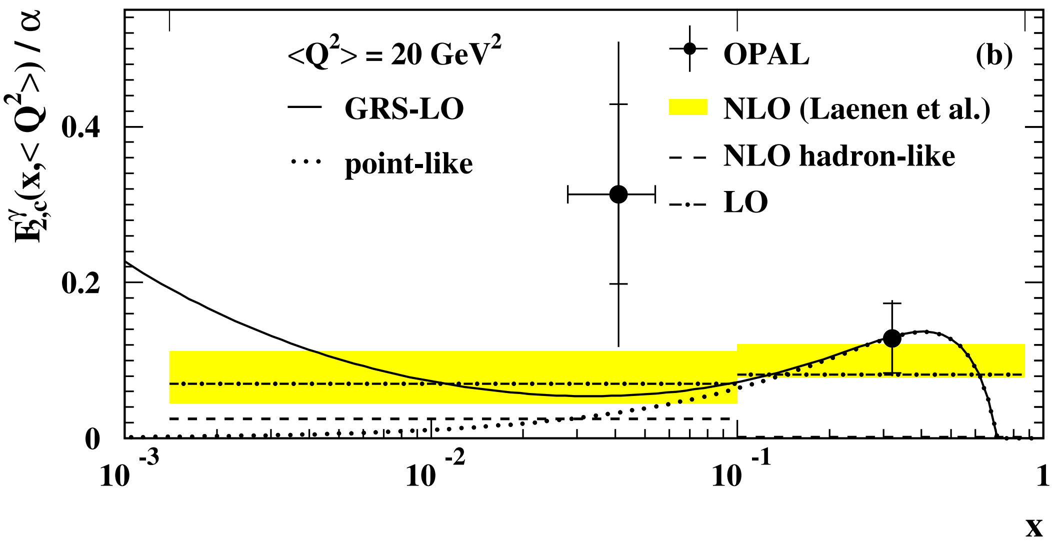


- Both HERWIG and Vermaseren MC describe the shape of the data

Charm structure function:

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

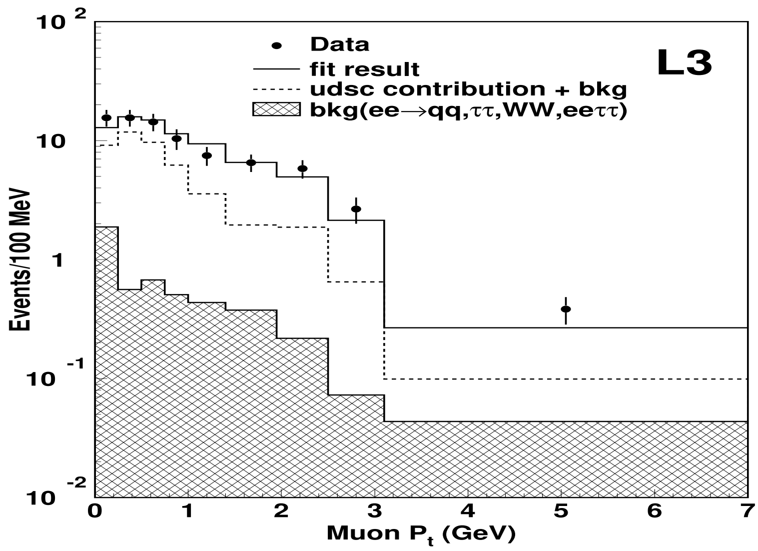




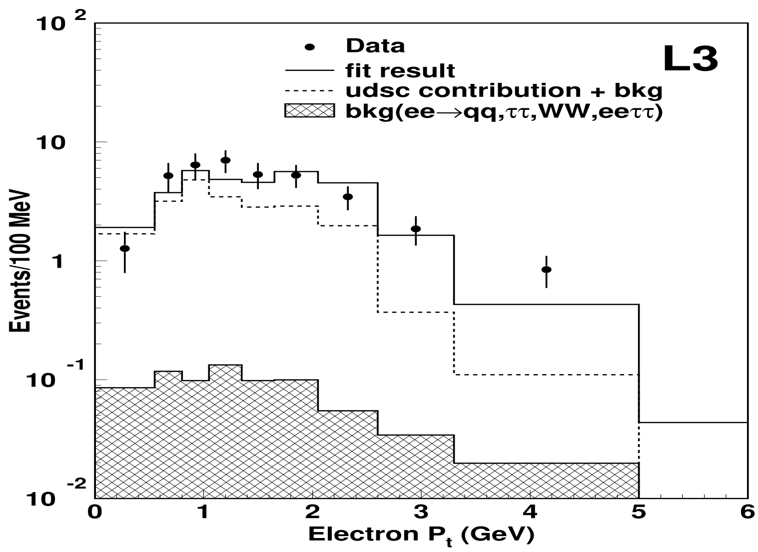
- **Hadron-like component of $F_{2,c}^{\gamma}$ is needed**

Search for Beauty: L3 Data

p_t with respect to the nearest jet



$P^{\mu} > 2.0$ GeV
$N^{\mu}_{ev} = 269$
$\varepsilon^{\mu}_{b} = 2.2\%$
$\Pi^{\mu}_{b} = 51.6\% \pm 9.8\%$

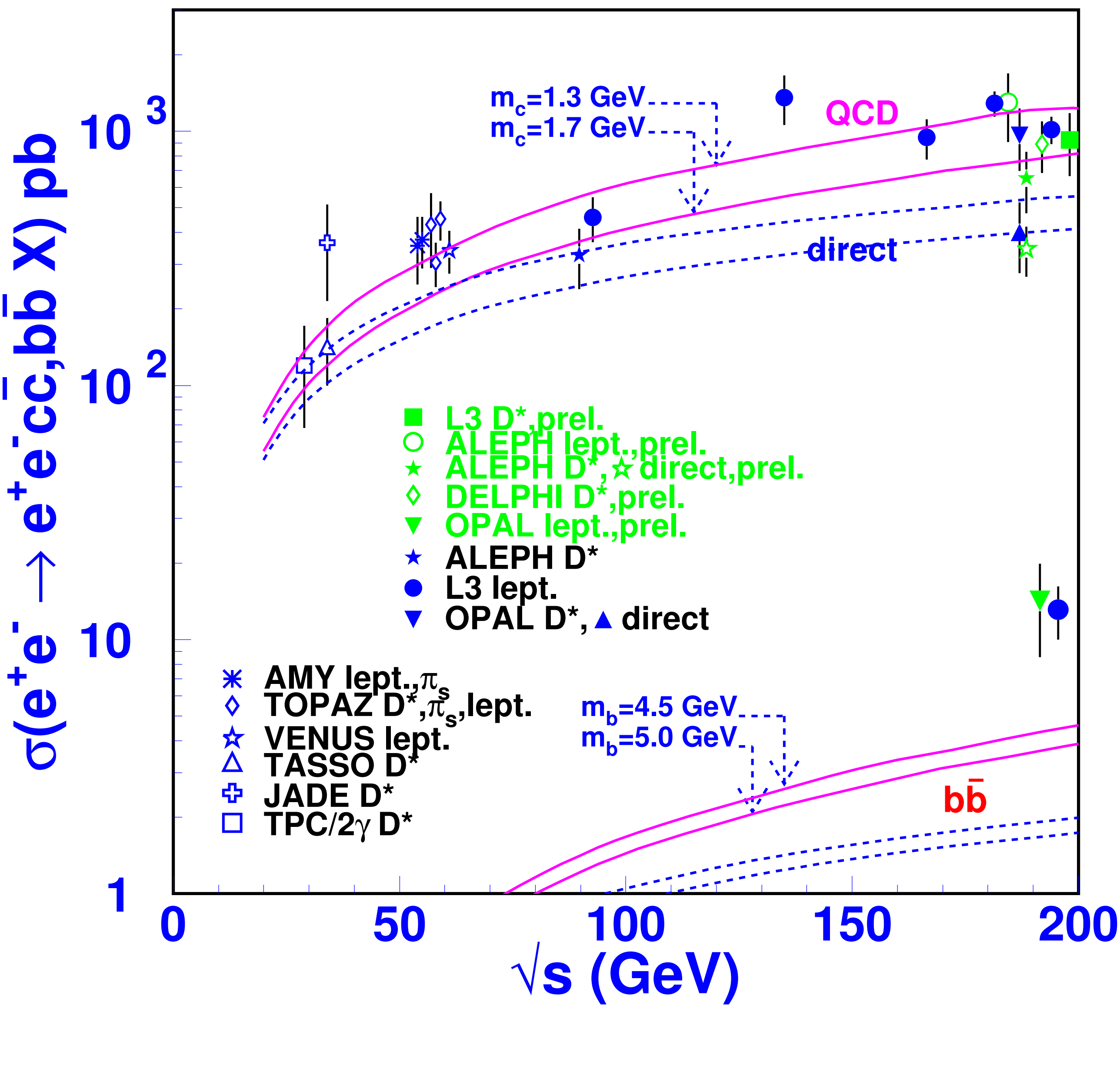


$P^{e} > 2.0$ GeV
$N^{e}_{ev} = 137$
$\varepsilon^{e}_{b} = 1.25\%$
$\Pi^{e}_{b} = 42.3\% \pm 11.4\%$

Leptons from bottom decays have higher p_t.

Muons:	$\sigma_{b\bar{b}} = 14.9 \pm 2.8(st) \pm 2.6$ pb
Electrons:	$\sigma_{b\bar{b}} = 10.9 \pm 2.9(st) \pm 2.0$ pb
Combined (L3):	$\sigma_{b\bar{b}} = 13.1 \pm 2.0(st) \pm 2.4$ pb
Muons (OPAL prl.):	$\sigma_{b\bar{b}} = 14.2 \pm 2.5(st) \pm 5.0$ pb

Charm and beauty in $\gamma\gamma$ collisions

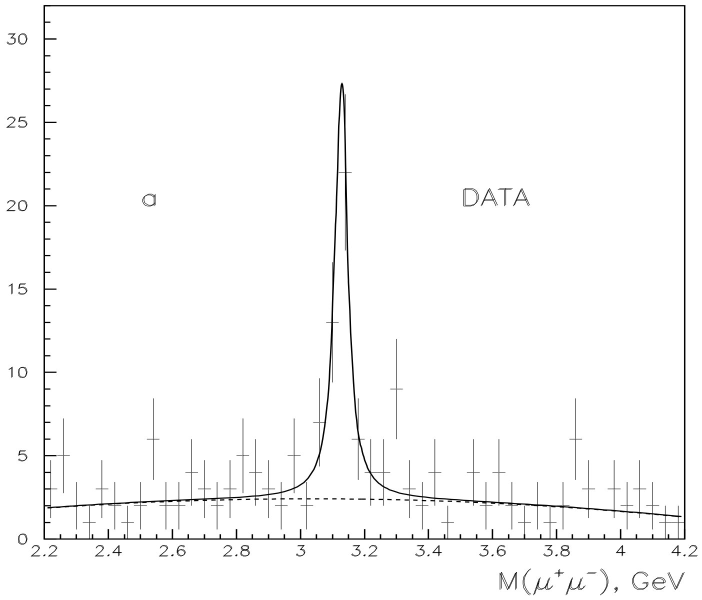


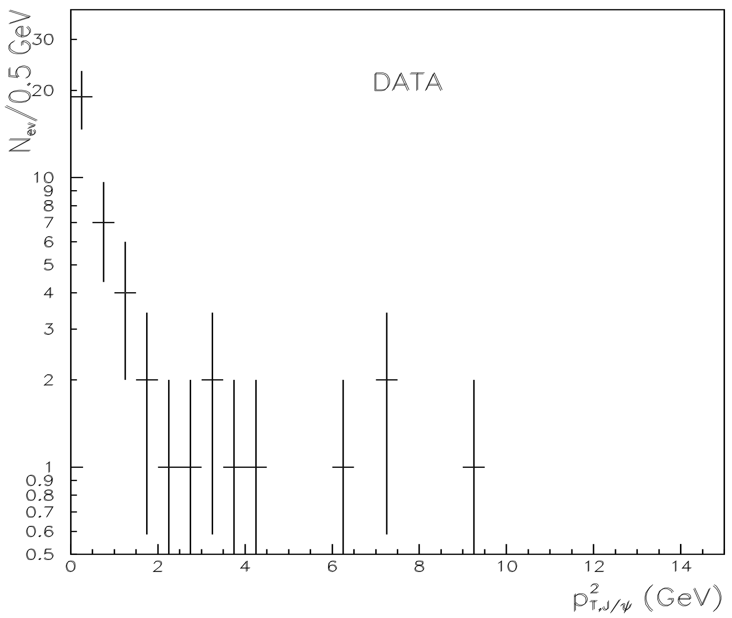
$b\bar{b}$ in excess of the QCD prediction by a factor three !

Inclusive J/ψ production:

DELPHI : 161 - 204 GeV, $\mathcal{L} = 673\ \mathrm{pb}^{-1}$

Very Preliminary





- $N(J/\psi \rightarrow \mu^+\mu^-) = 47 \pm 6.8$

Summary

❑ Hadronic cross sections

➩ $\sigma_{\gamma\gamma}$ increases at high energies

➩ Pomeron slope value is larger than PDG value

➩ More work on ρ^0 is needed

➩ High-p_t π^0: NLO QCD prediction is too low

➩ The F_2^{had} (F_2^c) needs resolved processes at low x

➩ There is no striking growth of F_2^{γ} at low x

➩ Virtual photons cross section at LEP has been measured. Inconsistent with LO BFKL prediction

➩ Charm production is in agreement with QCD prediction, ➜ $\gamma g \to c\bar{c}$ is important

➩ Pomeron slope value for charm production $\epsilon = 0.40 \pm 0.08$ is larger than PDG value ➜ as expected by QCD

➩ Beauty production is in disagreement with QCD prediction, about 4 standard deviations higher than expected !