Two Photon Collisions at LEP : $e^+e^- \longrightarrow e^+e^- hadrons$

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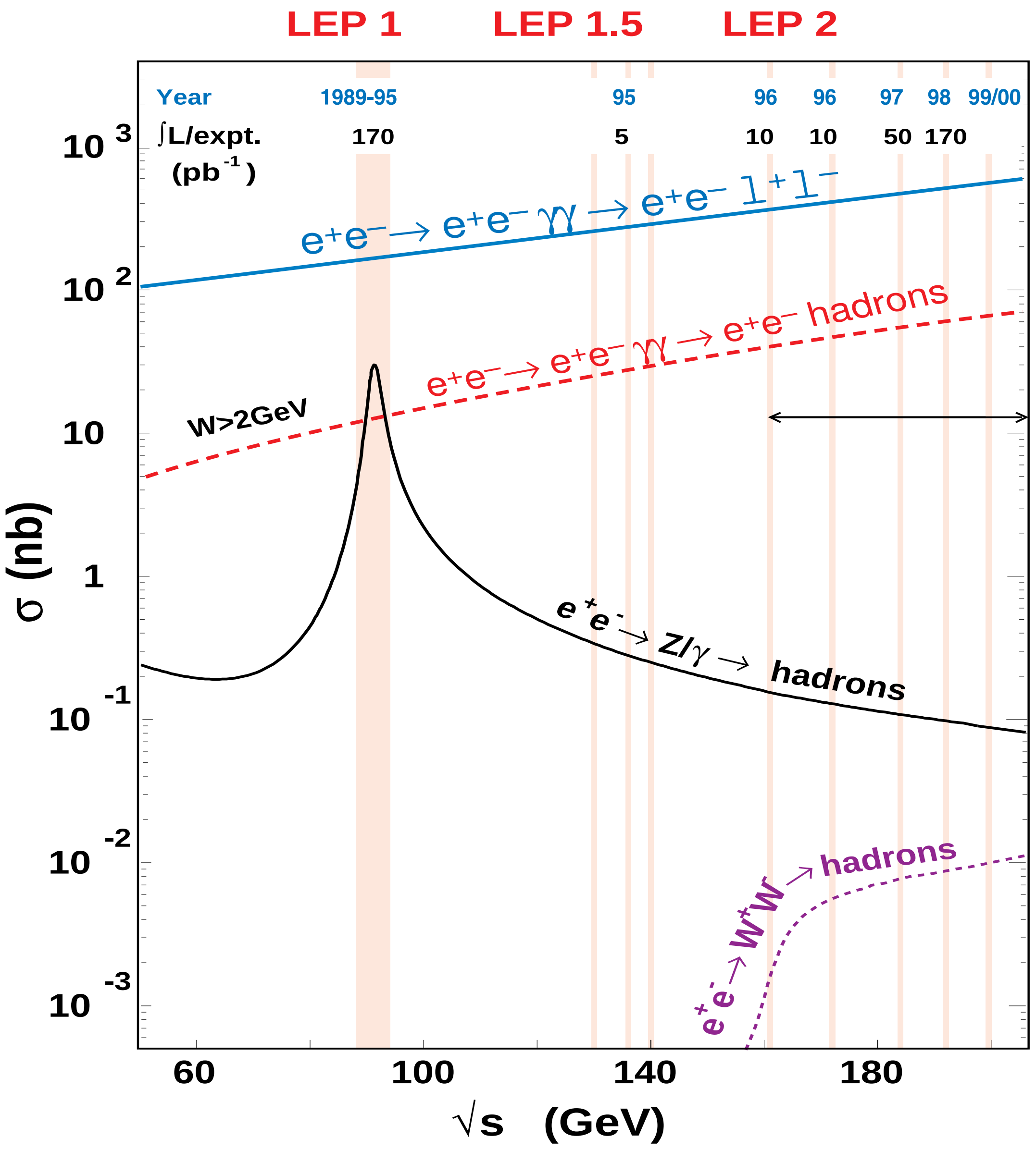
- Introduction
- Two-photon total cross-sections
- Diffractive ρ^0 production
- Single particle and Dijet production
- Inclusive Charm production
- Cross-section of $\gamma^*\gamma^*$ collision ➔ BFKL Pomeron
- Resonances
- Conclusions

Introduction



- ❒ The dominant interaction at LEP2 is the Two-photon processes.
- ❒ LEP2 is the best place to study two-photon physics (high cross-section, low background)

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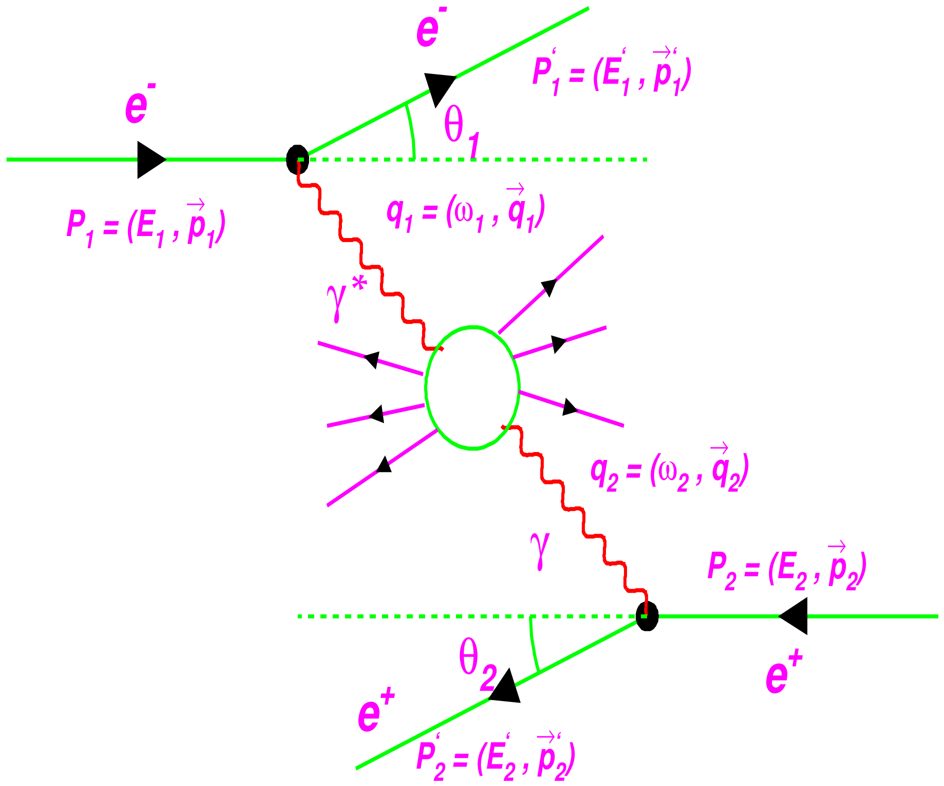
Two Photon kinematics



$$Q^2 = -q_1^2 = 2E_1E_1'(1-\cos\theta_1)$$
$$P^2 = -q_2^2$$
$$W_{vis}^2 = (\sum_h E_h)^2 - (\sum_h \vec{p}_h)^2 \leq W_{\gamma\gamma}^2$$

h = particle measured in the detector

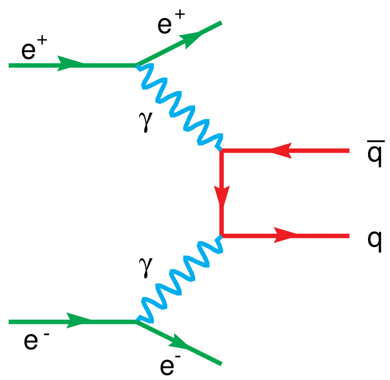
Depending on the detection of scatterd $e^{\pm}$

- Untagged events $Q^2 \simeq 0, P^2 \simeq 0$
- Single tag events $Q^2 > P^2 \simeq 0$
- Double tag events $Q^2 \simeq P^2 > 0$

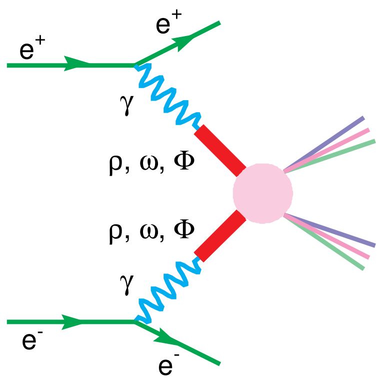
Two Photon Physics

The diagrams contributing to :

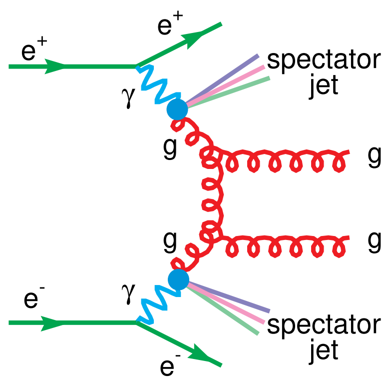
$$e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-\text{hadrons}$$



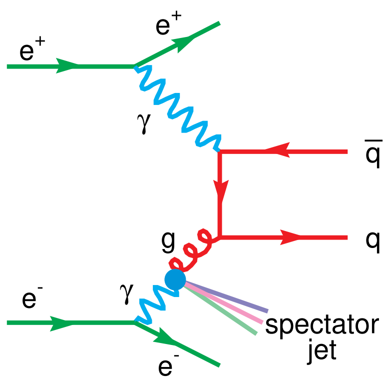
Direct



VDM



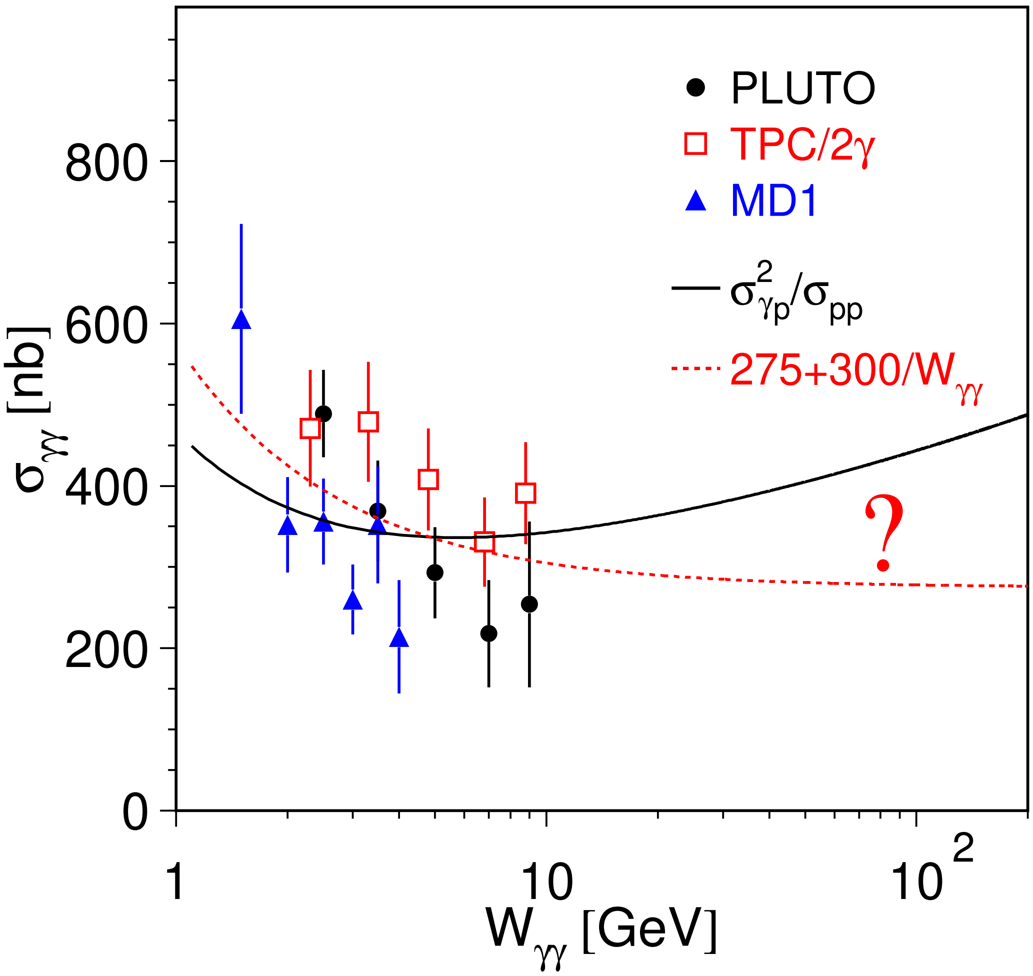
Double Resolved



Single Resolved

Total $\sigma_{\gamma\gamma}$: Motivation

The measurements before LEP :



- Limited by beam energy ➜ $W_{\gamma\gamma} < 10$ GeV.
- Wide spread in the measurements.
- Does $\sigma_{\gamma\gamma}$ increase at high energy ?
- At LEP, 5 GeV $< W_{\gamma\gamma} < 145$ GeV has been measured.

Total $\sigma_{\gamma\gamma}$: Analysis

- Data :

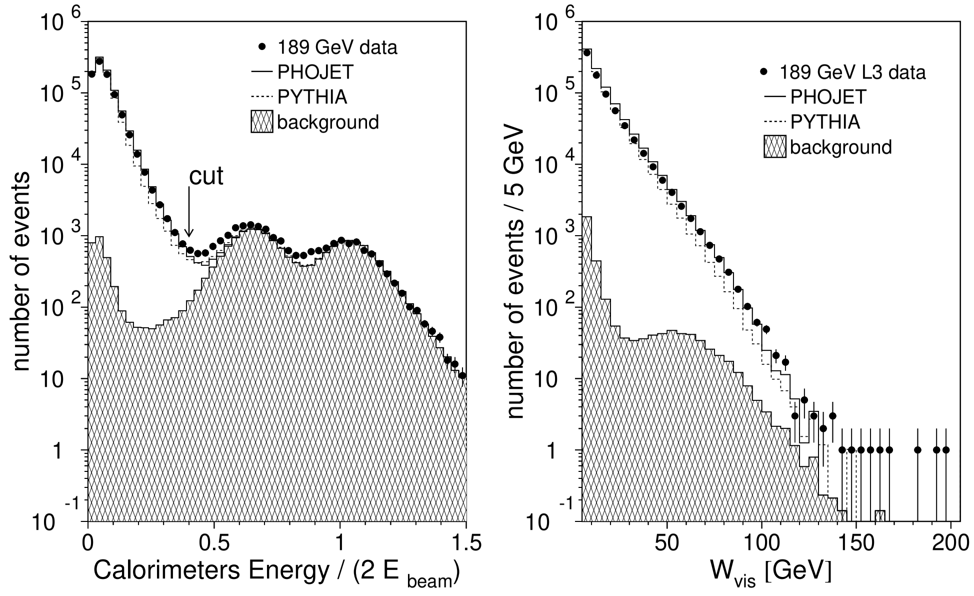
L3 :	91 GeV,	140. pb^{-1}
	130 - 140 GeV,	4.98 pb^{-1}
	161 GeV,	10.4 pb^{-1}
	$183\ GeV$,	$51.9\ pb^{-1}$
	$189\ GeV$,	$171.8\ pb^{-1}$
OPAL:	$161\ GeV$,	$9.9\ pb^{-1}$
	$172\ GeV$,	$10.0\ pb^{-1}$
	$183\ GeV$,	$54.4\ pb^{-1}$

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

- Due to detector effect → $W_{vis} < W_{\gamma\gamma}$
  - ➥ Use unfolding for $W_{vis} \rightarrow W_{\gamma\gamma}$
  - ➥ Need Monte Carlo which reproduce well the data

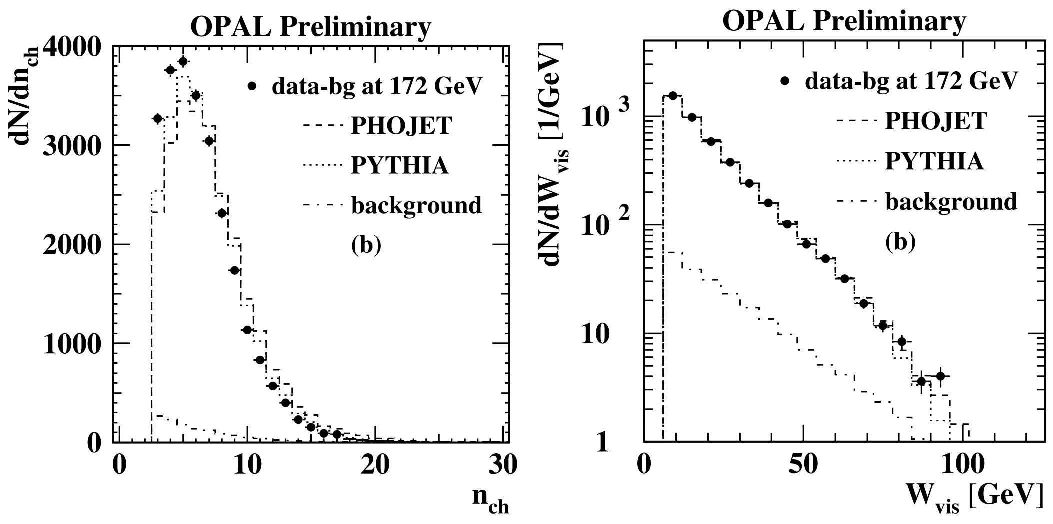
Total $\sigma_{\gamma\gamma}$: MC Comparison

L3 preliminary



- The backgrounds : $e^+e^- \rightarrow e^+e^-\tau^+\tau^-$ and $e^+e^- \rightarrow hadrons$ are small.

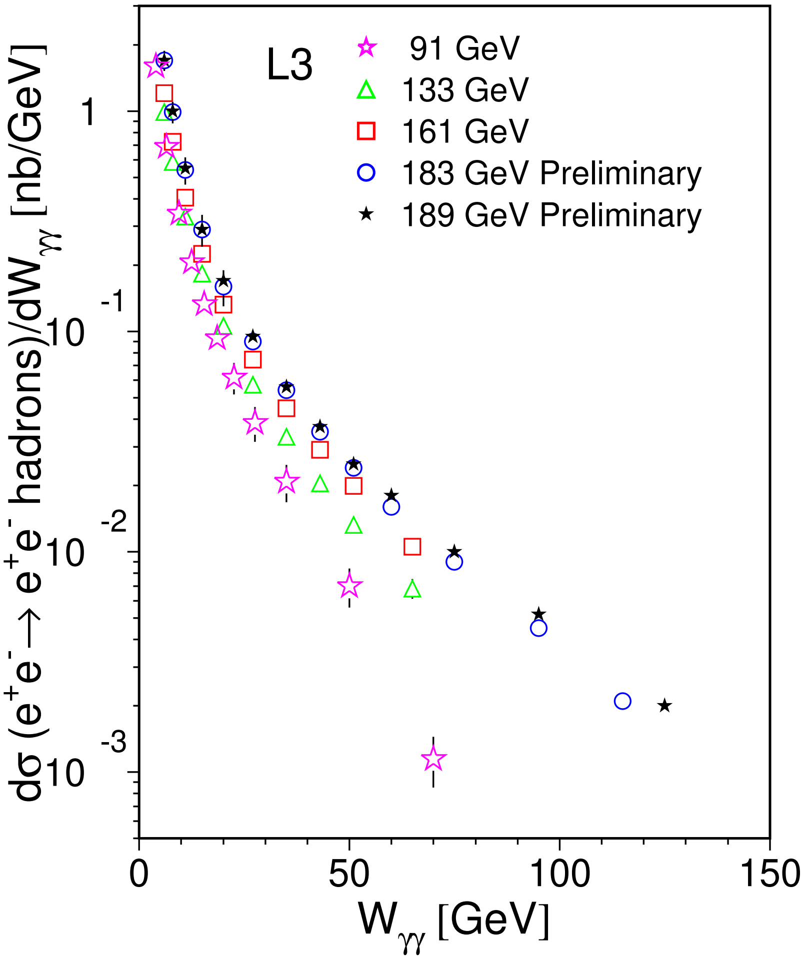
OPAL preliminary



- Satisfactory (not perfect! $\sim 20 - 30\%$) agreement with both PYTHIA and PHOJET.

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

❑ $d\sigma(e^+e^- \to e^+e^-\text{hadrons})$



✻ Effect of the $\gamma\gamma$ luminosity function

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

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

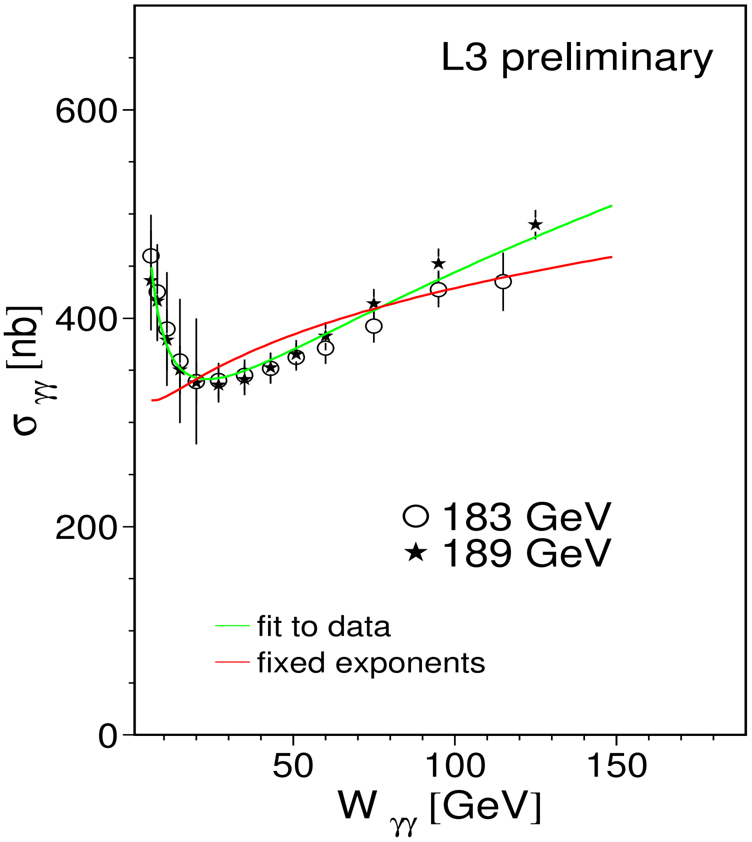
❑ Extract $\sigma_{\gamma\gamma}$ from $d\sigma_{ee}$

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

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

*T and S are Transverse and Scalar photon helicity indices.

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



Data unfolded with Phojet

- 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 1998):

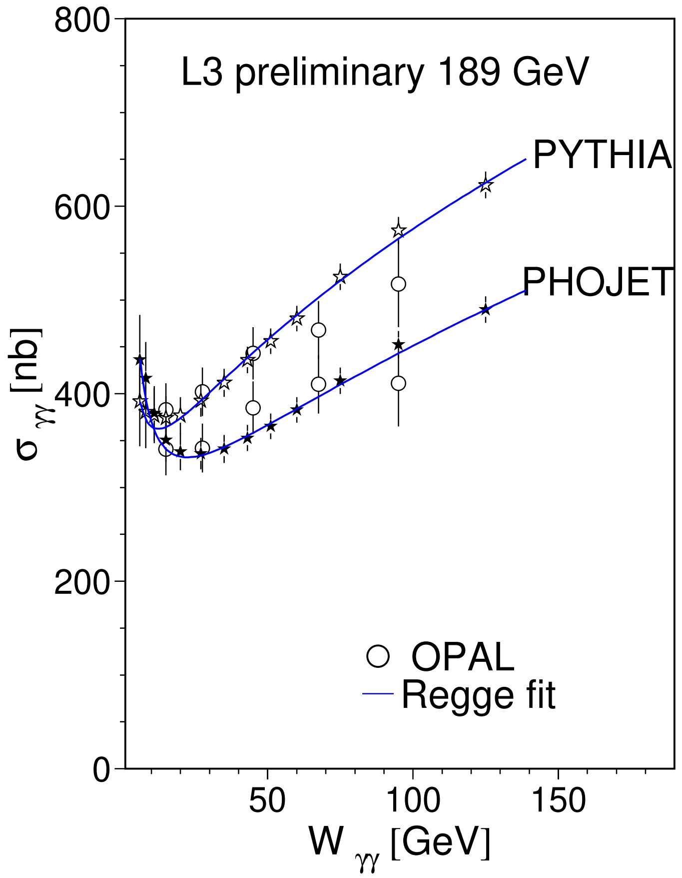
  $\varepsilon = 0.095 \pm 0.002, \ \eta = 0.34 \pm 0.02, \ A, B$ free

- Fit to 183–189 GeV data (26 points)

  with correlation matrix, $\eta = 0.34$ fixed, A,B free

	ε	χ^2	CL
Universal ε	0.095 fixed	62	3.4×10^{-5}
Free ε !7σ higher!	0.22 ± 0.02	9.3	99.5%

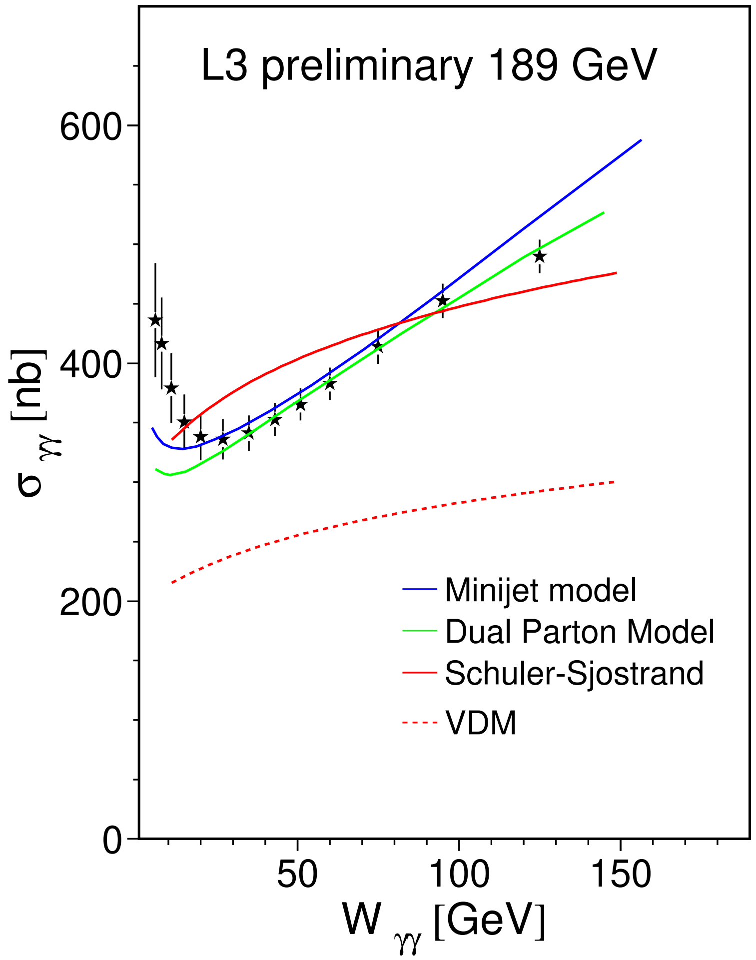
Total $\sigma_{\gamma\gamma}$: Results



Statistic and detector related systematic errors only

- L3 and OPAL are compatible if the same generator is used.
- Both OPAL and L3 show clear rising behaviour with increasing energy. ⇨ Independent of MC
- The uncertainty on absolute values is $\sim 20\%$. ⇨ Due to the MC model dependence.

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



Data unfolded with Phojet

Minijet: Godbole and Pancheri (hep-ph/9903331)

DPM (Phojet): R. Engel private communication

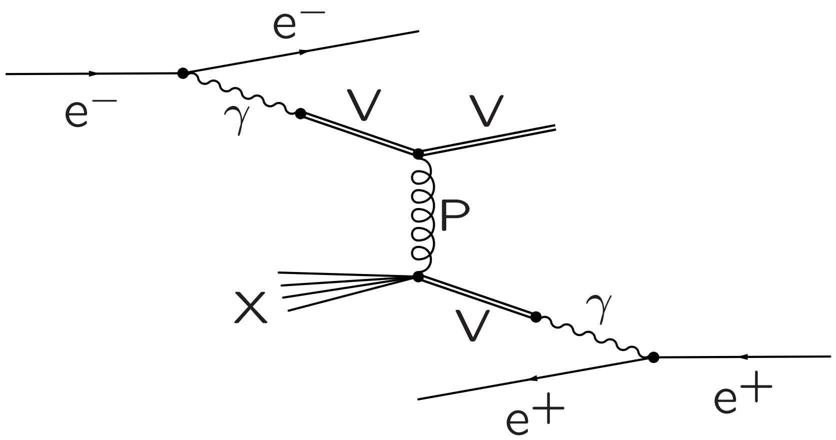
SaS (Pythia): Z. Phys. **C 73** (1997) 677

- Predictions for $W_{\gamma\gamma} > 10 - 20$ GeV
- The data are well reproduced by models wich include QCD effects
- Also explained by ("hard Pomeron") :

  Donnachie,Dosch,Rueter hep-ph/9810206

Diffractive Vector Meson Production

- Quasi-elastic:
  $\gamma\gamma \rightarrow \mathrm{VV}$ $\mathrm{V} = \rho^0,\ \omega^0,\ \phi,\ \ldots$
- Single diffractive dissociation:
  $\gamma\gamma \rightarrow \mathrm{VX}$



- Forward peaked angular distribution
- Low multiplicity

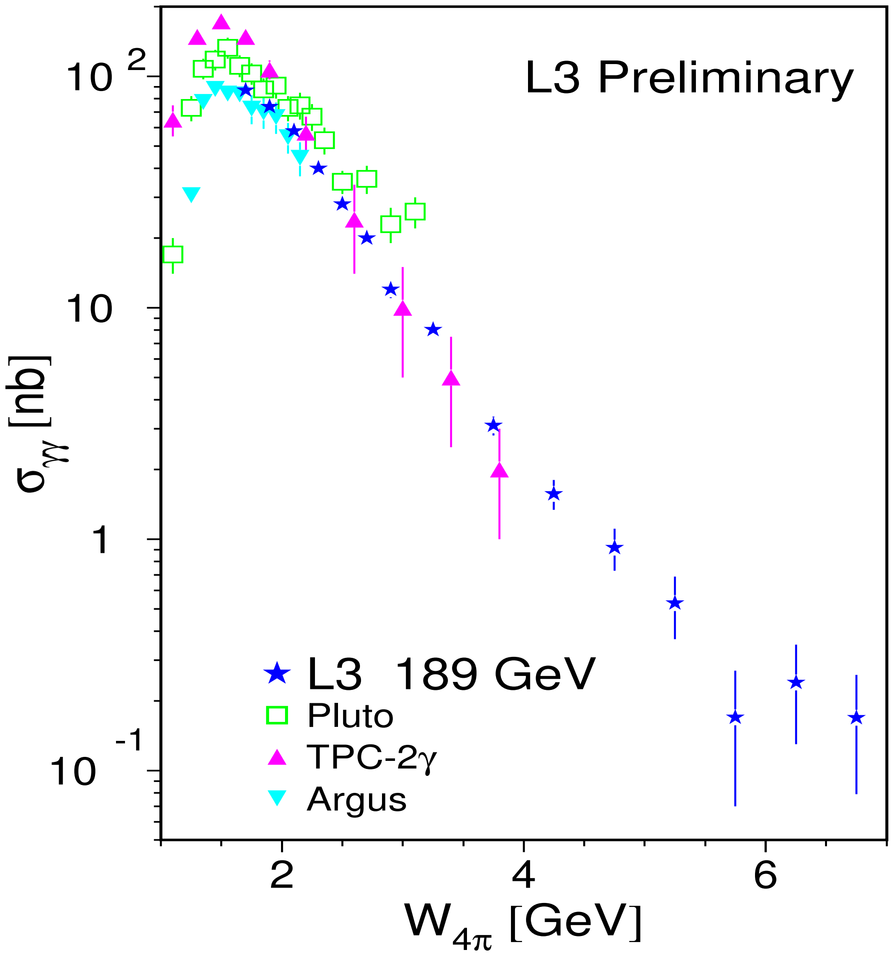
⇒ Small acceptance in detector

- Rapidity gap between ρ^0 and rest of event
- Transverse ρ^0 polarization

$\gamma\gamma \to 4\pi$ **at** $\sqrt{s} = 189$ **GeV**

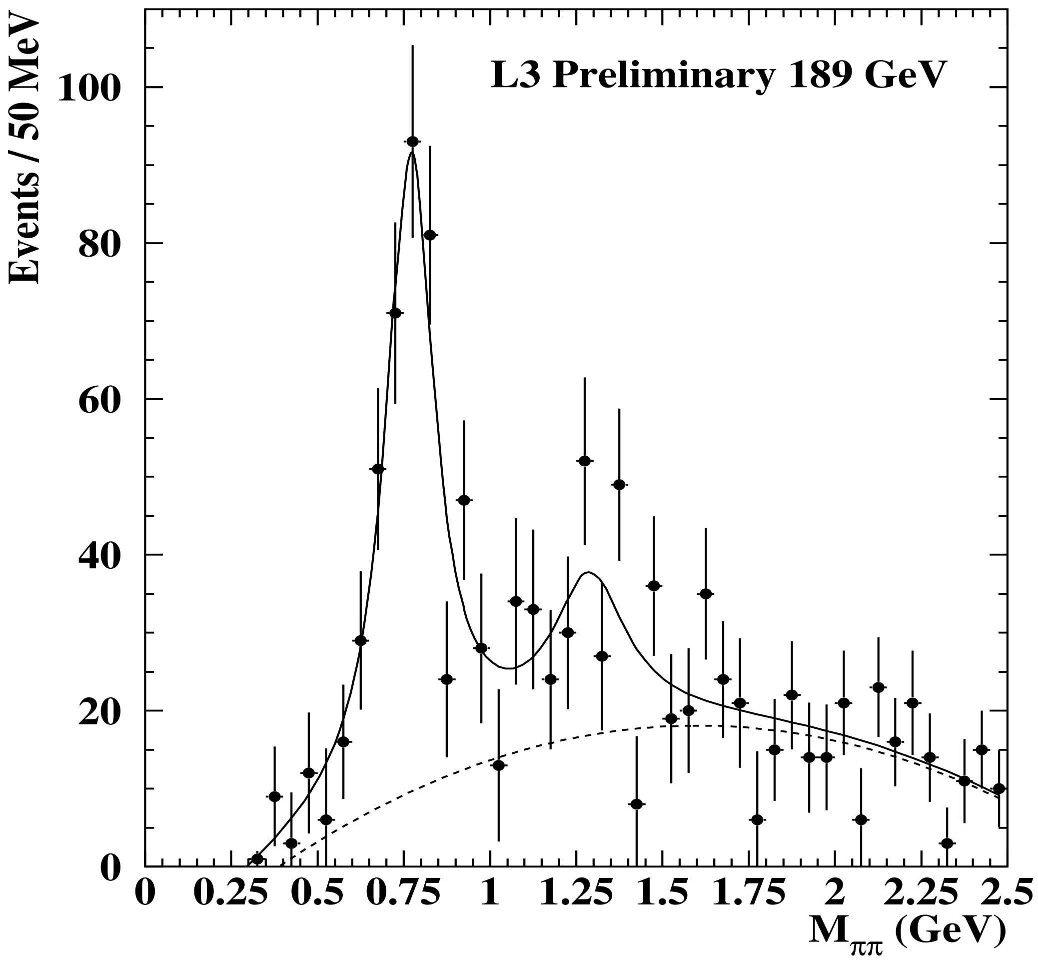
$e^+e^- \to e^+e^-\pi^+\pi^-\pi^+\pi^-$ (exclusive, $Q^2 < 0.05$ GeV^2)

- ❑ Charge balance
- ❑ $(\sum \vec{P}_T)^2 < 0.05$ GeV^2



- ❑ Statistical errors only
- ❑ Luminosity function by G. Schuler
- ❑ Data corrected with $\rho^0\rho^0$ phase-space MC
- ❑ Angular distribution study to be performed
- ❑ Good agreement with previous measuements

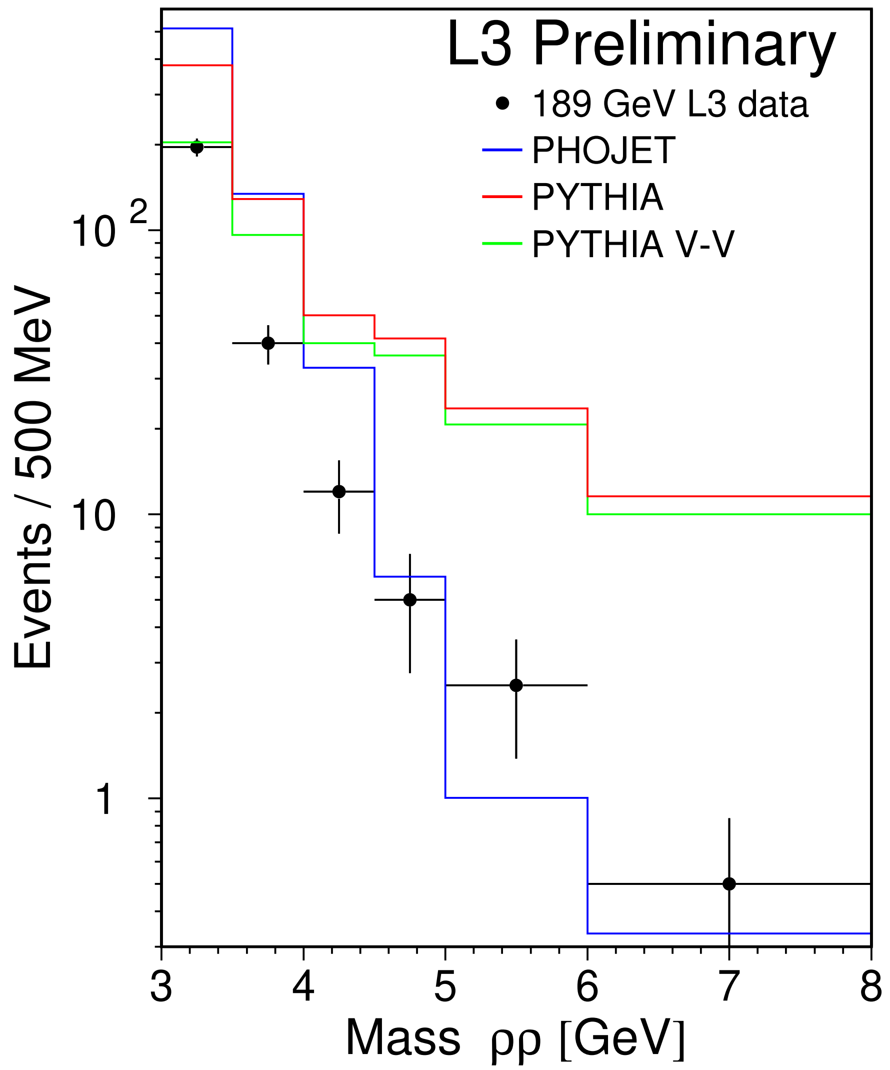
ρ^0 mass (4 entries/event) $W_{\gamma\gamma} > 3$ GeV



	Area	M (MeV)	Γ (MeV)
Fitted ρ^0	460 ± 47	768 ± 7	170 ± 20
PDG'98		768 ± 1	151 ± 2
Fitted f_2	187 ± 89	1288 ± 22	258 ± 135
PDG'98		1275 ± 1	186 ± 3

f_2 present: not only diffractive

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

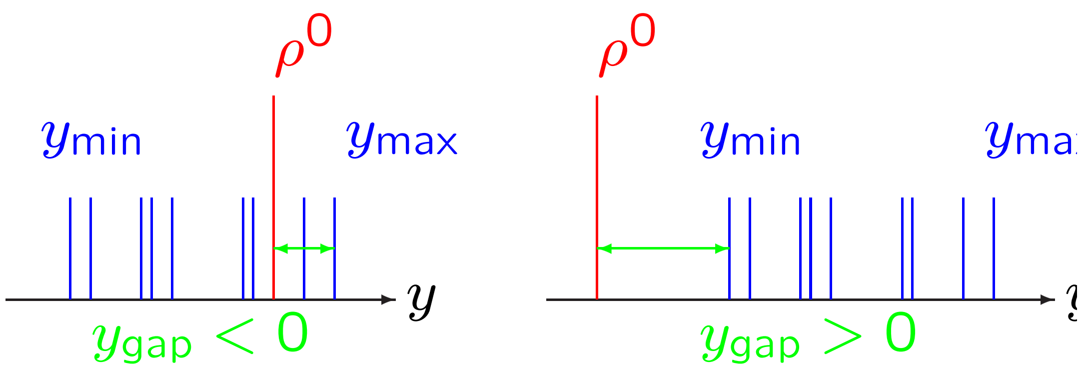


MC normalized to data luminosity statistical errors only

- ❏ 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 $\gamma\gamma \to \rho^0 X$ at 183 GeV

- $W_{\text{vis}} > 2$ GeV
- $P_T > 1$ GeV
- $|\cos(\theta)| < 0.8$
- ρ^0 rapidity gap $y_{\text{gap}} > 0$

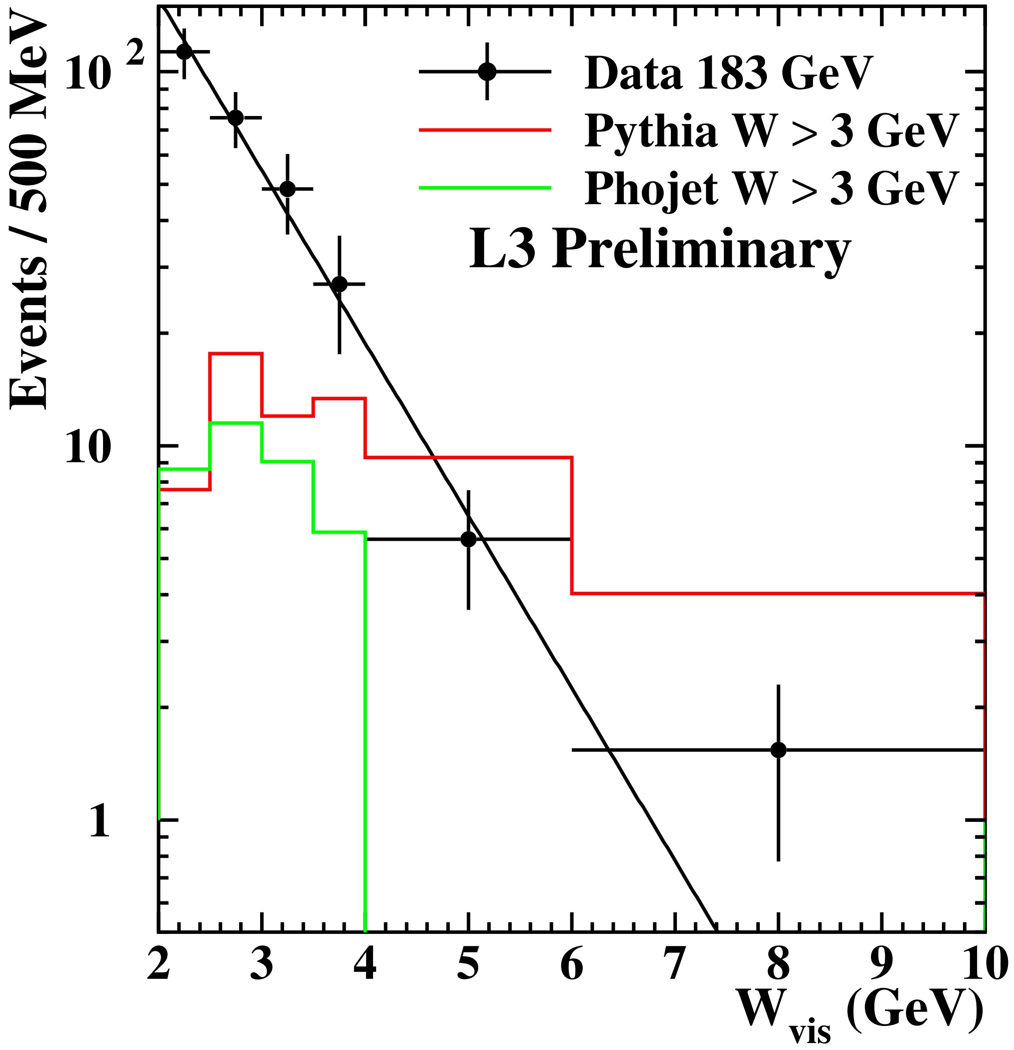


$\sqrt{s} = 183$ GeV, $\mathcal{L} = 47.9\ \text{pb}^{-1}$

Events after background subtraction:

	$W_{\text{vis}} > 3$ GeV	$W_{\text{vis}} > 5$ GeV
Data	77.1±23.9	34.3±6.8
Pythia	108.7±12.5	74.3±8.0
Pythia VV	82.6± 6.8	35.6±2.3
Phojet	6.2± 5.9	—

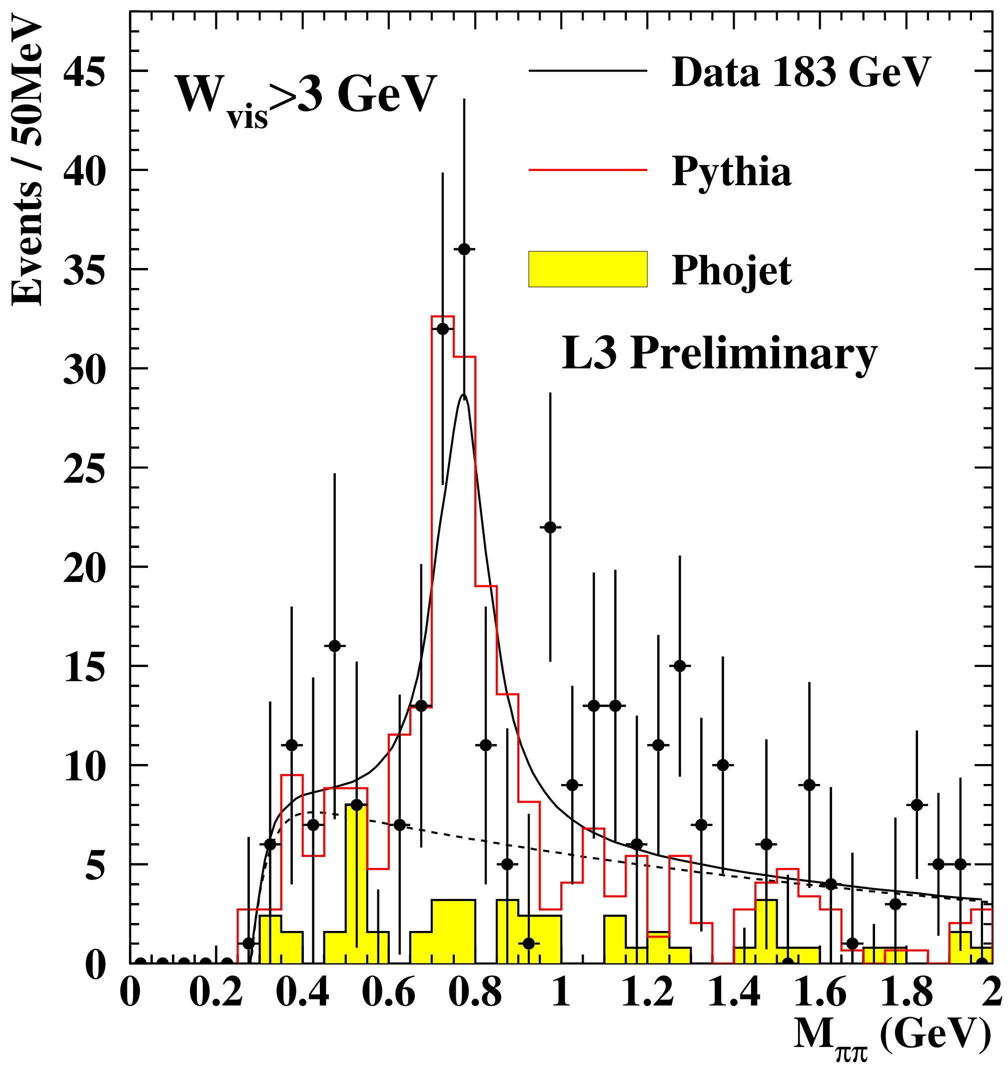
Inclusive ρ^0 production: W_{vis}



MC normalized to data luminosity

Bad correspondence in this region:
Pythia too flat
Phojet too steep

Inclusive ρ^0 mass

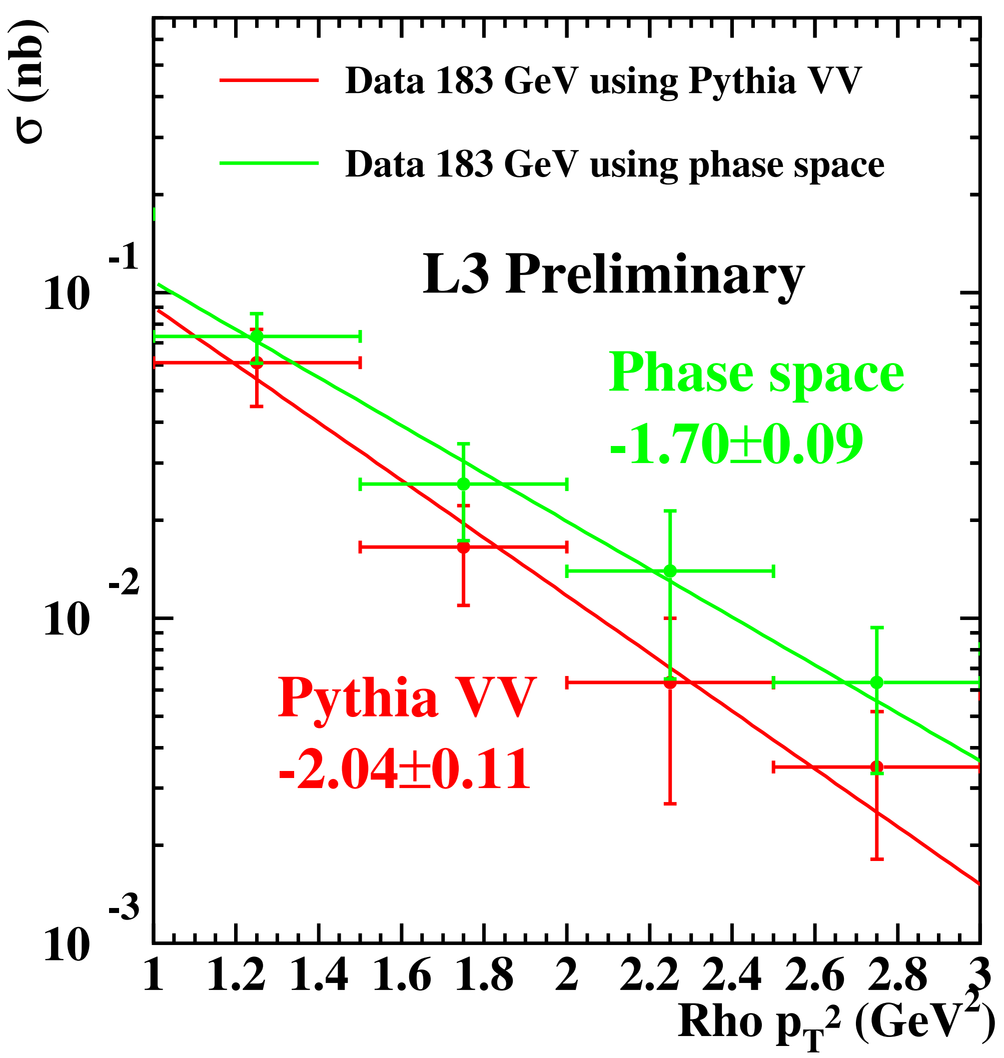


MC normalized to data luminosity
Wrong charge background subtracted

This mass distribution is fitted with BW+bkg. (fixed $M_{\rho^0} = 770$ MeV, Γ_{ρ^0}=150 MeV)
in bins of P_T^2, etc.

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

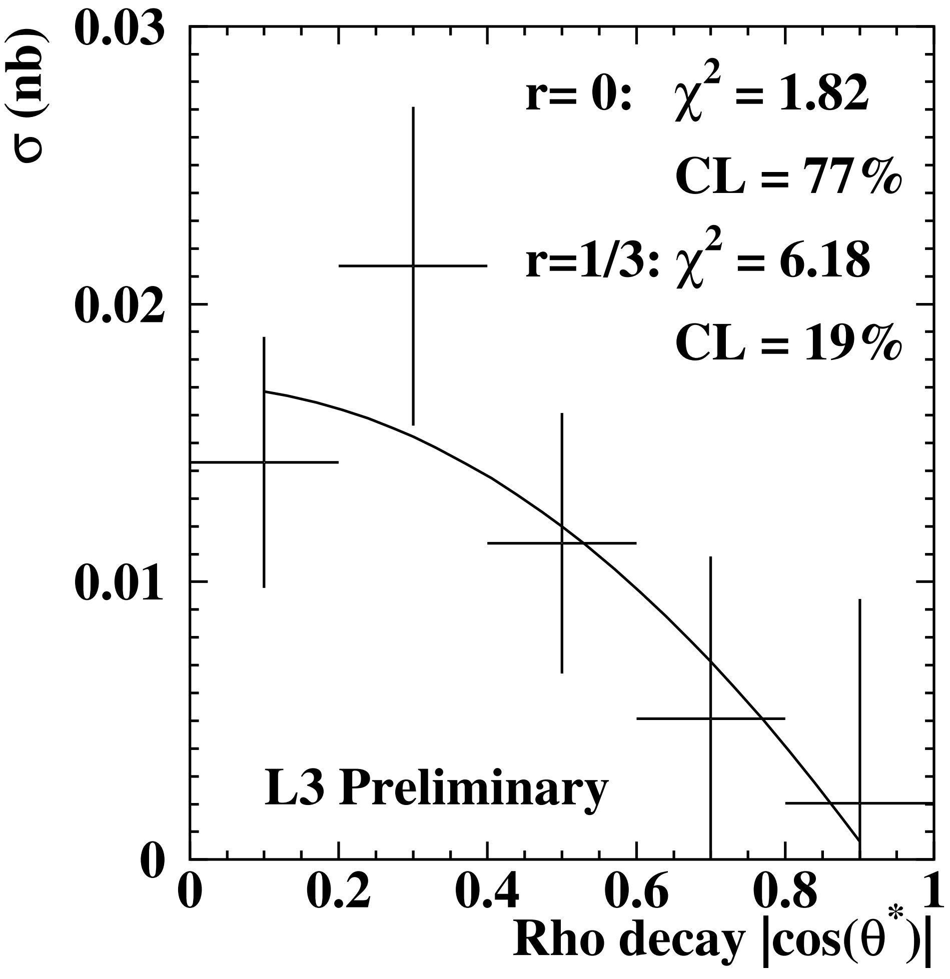
ρ^0 polarization

π^+ momentum in ρ^0 rest frame

ρ^0 momentum in visible $\gamma\gamma$ frame r: fraction of longitudinal polarization.

$0 \leq r \leq 1$,

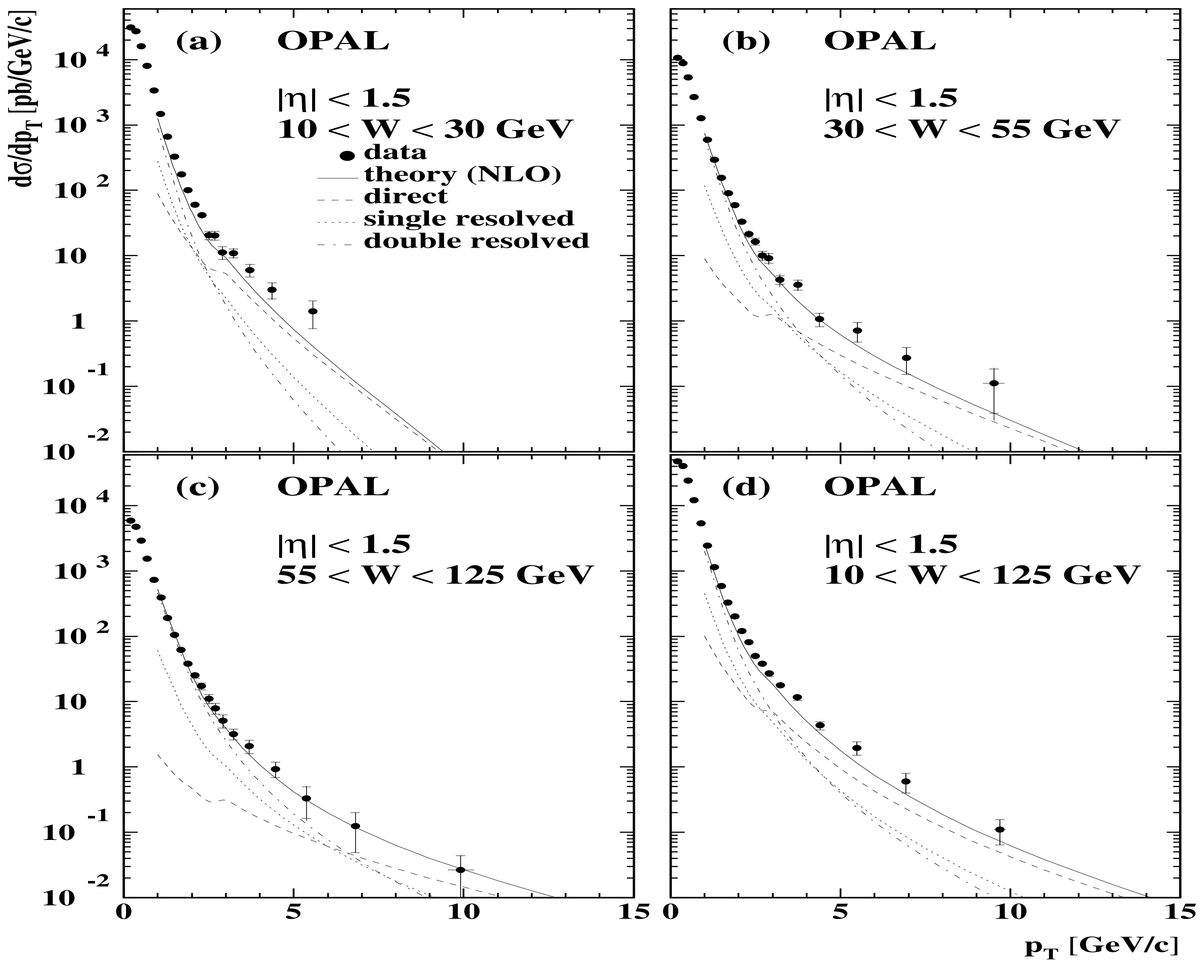
transverse:	$r = 0$	$1 - \cos^2\theta^*$
unpolarized:	$r = 1/3$	const.
longitudinal:	$r = 1$	$\cos^2\theta^*$



Consistent with purely transverse polarization

Inclusive particles $d\sigma/dp_T$

Inclusive charged hadron production[a] for $|\eta| < 1.5$

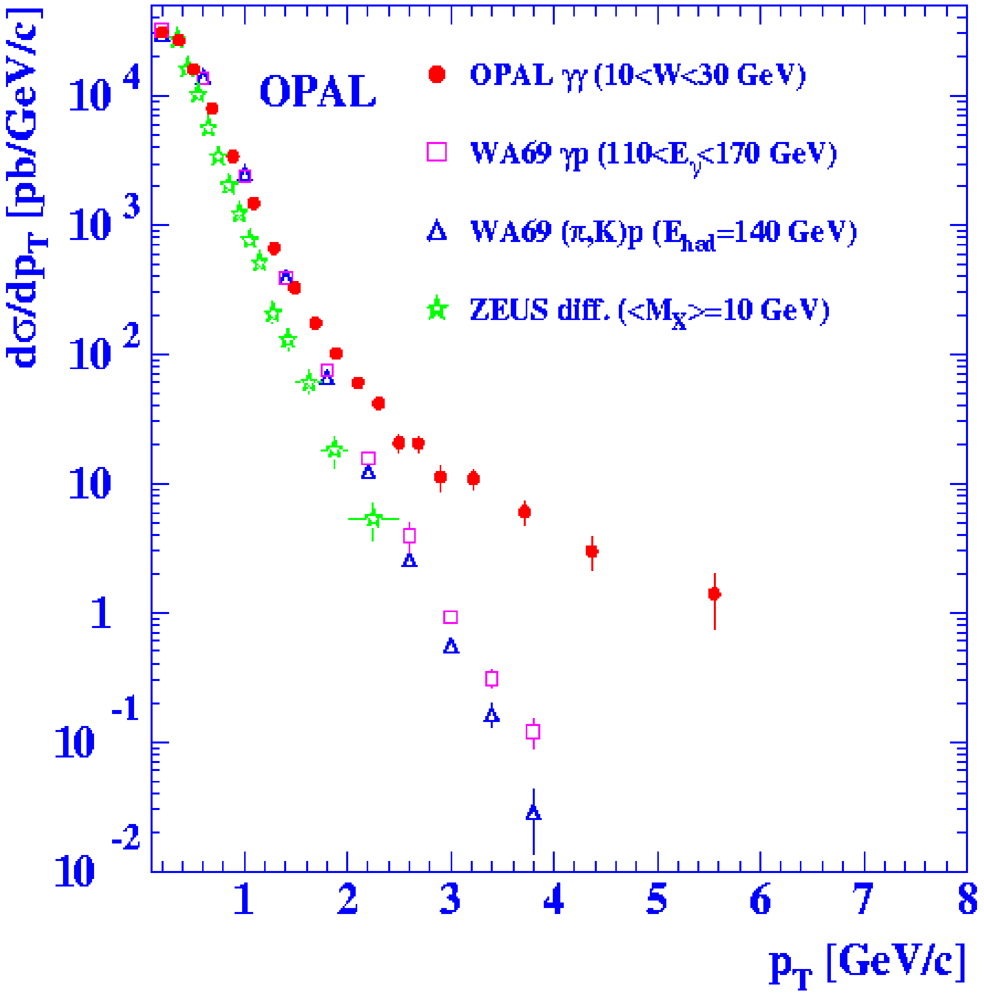


- NLO calculation by Binnewies, Kniehl and Kramer. (Phys. Rev. D53, 6110, 1996)
- The direct component is dominant at high p_T.
- For low $W_{\gamma\gamma}$, the NLO calculations lie below the data.
- For high $W_{\gamma\gamma}$, the agreement is good.

[a] OPAL Coll., Eur. Phys. J. C6 (1999) 253

Inclusive particles $\mathrm{d}\sigma/\mathrm{dp_T}$

- Compare to $\gamma\mathrm{p}$ and $(\pi,\mathrm{K})\mathrm{p}$ interactions, normalised to $\gamma\gamma$ data at low p_T region.

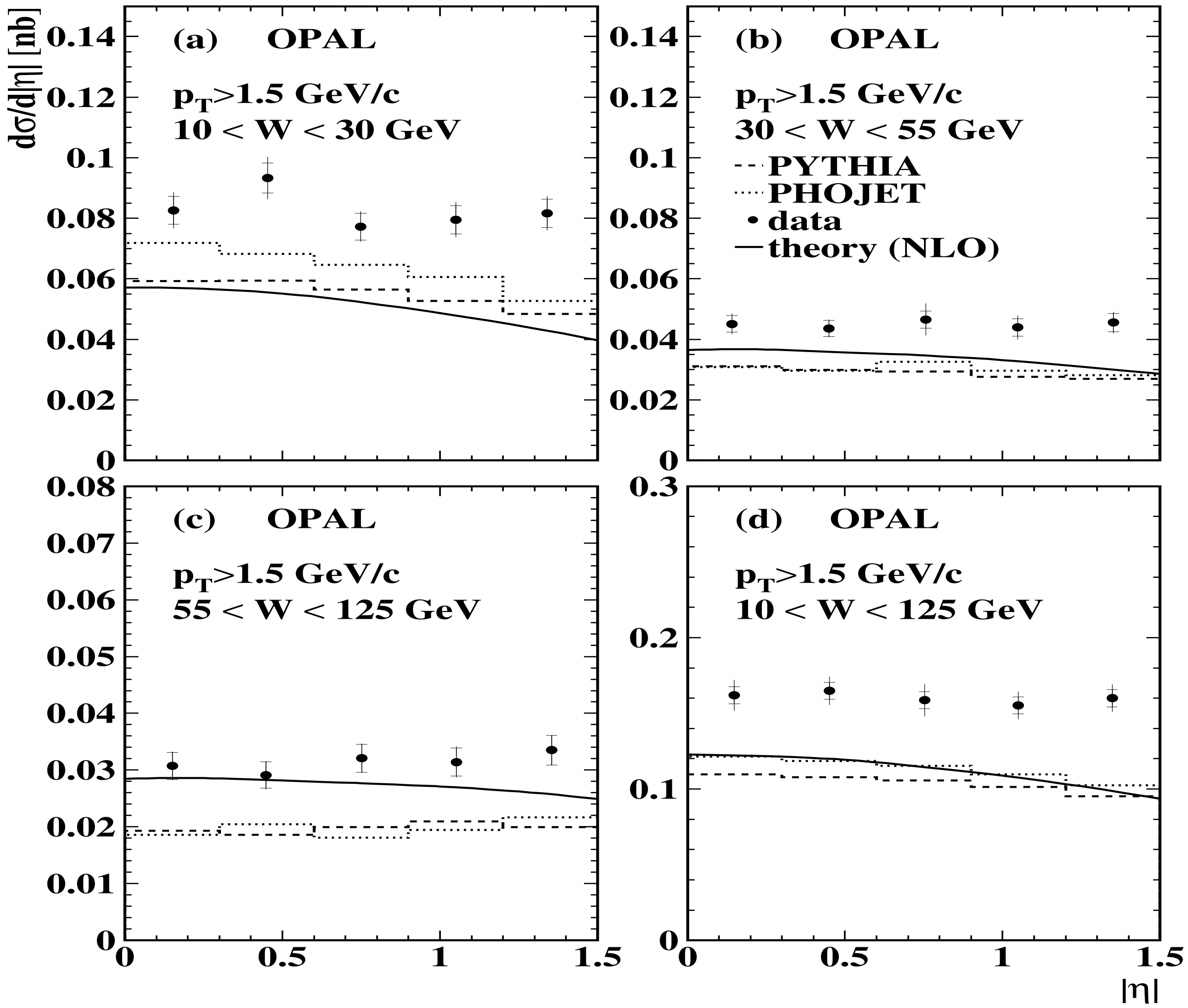


⇨ The $\gamma\gamma$ interaction is much harder because of the direct component.

WA69 : OMEGA Coll., Z. Phys. C43(1989) 63

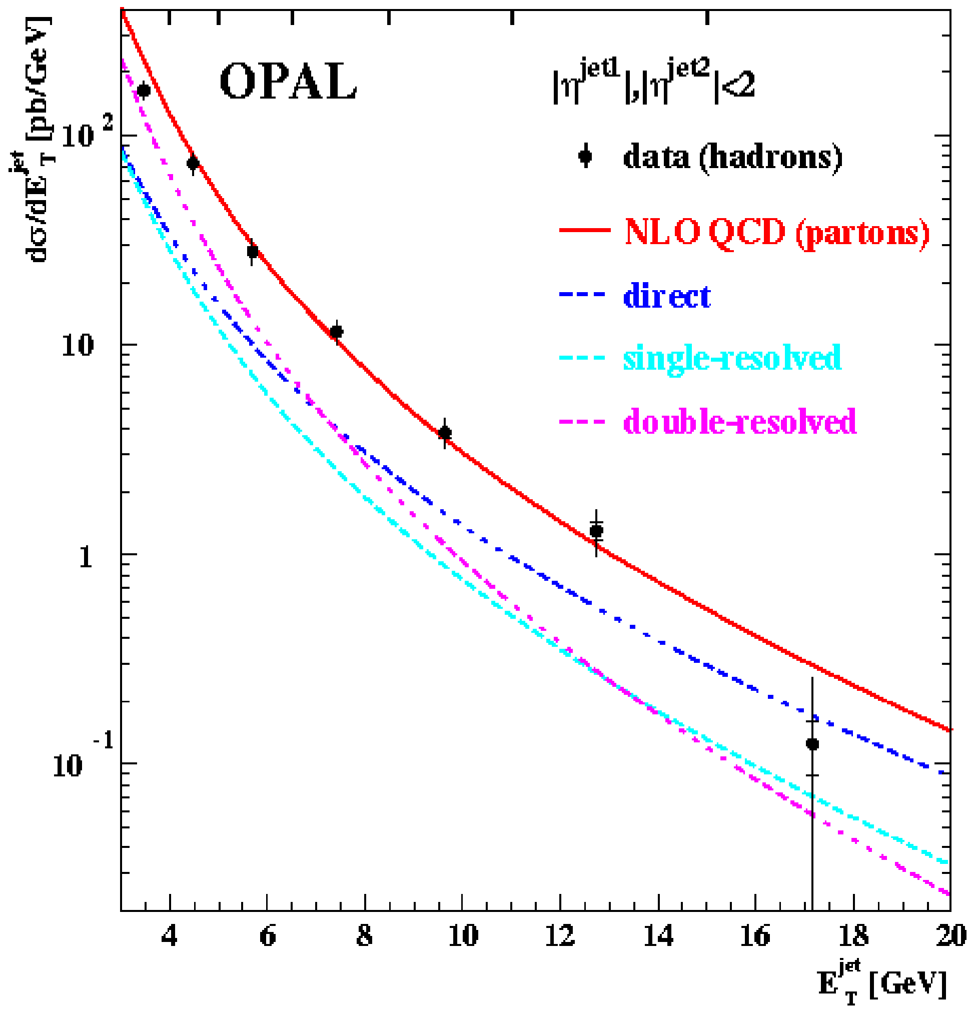
Inclusive particles $d\sigma/d\eta$

Inclusive charged particle production $d\sigma/d\eta$ for $|p_T| > 1.5$ GeV



- ➪ Monte Carlos and NLO calculation lie below the data for $W < 55$ GeV.
- ➪ NLO calculation agrees better for $55 \text{ GeV} < W < 125$ GeV.

DiJet Production



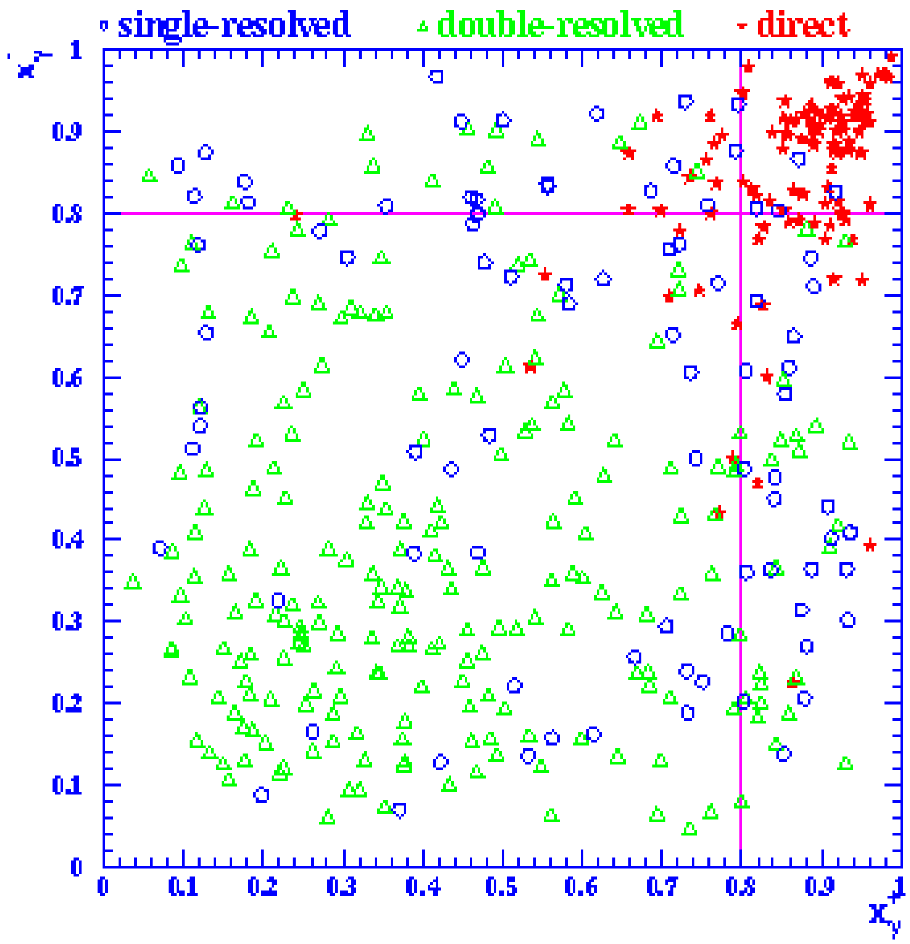
- ❒ NLO calculation by Klasen, Kleinwort, Kramer.
- ❒ The three processes are needed!

DiJet Production : OPAL

❐Separation of Direct and Resolved processes

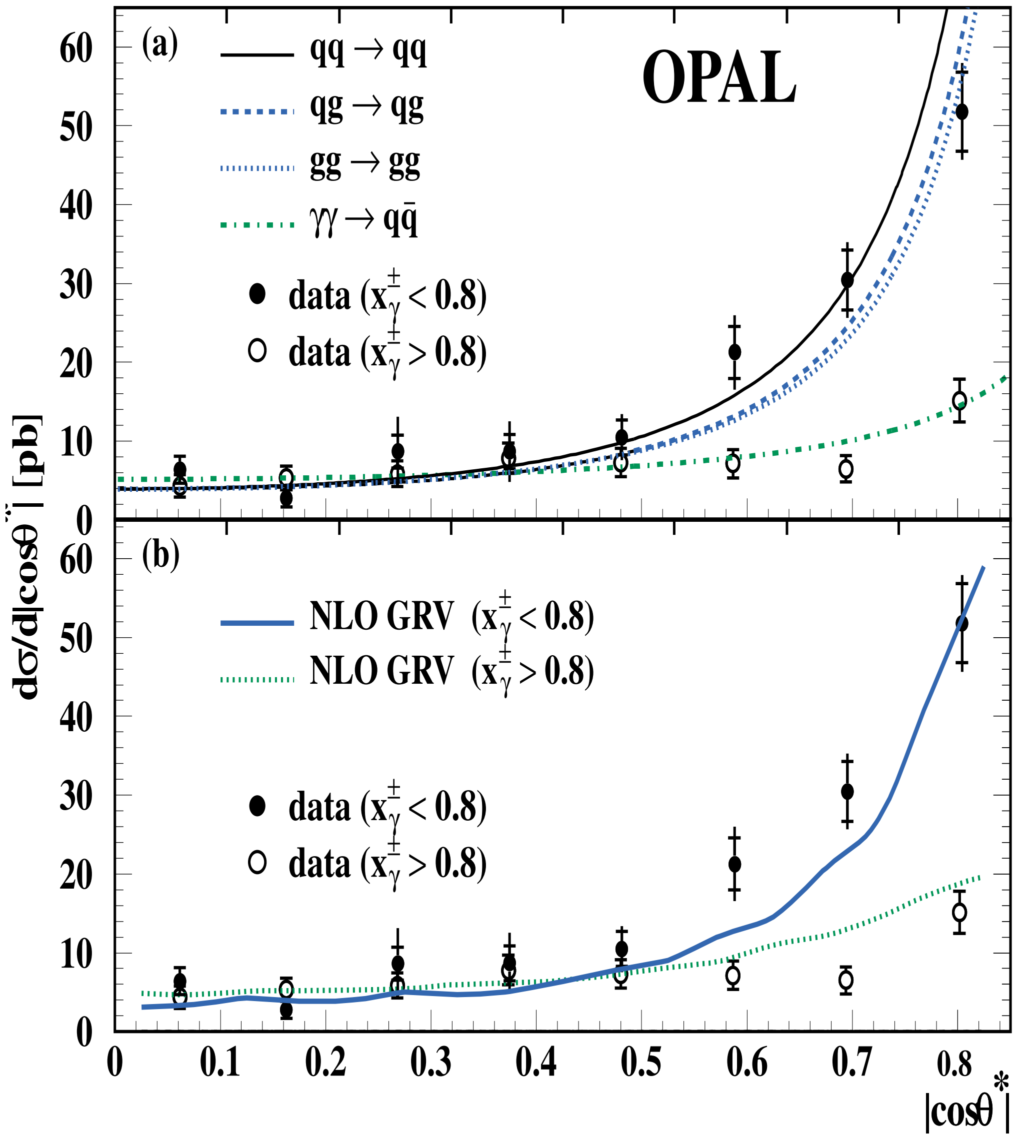
$$x_\gamma^{\pm} = \frac{\sum_{\text{jets}=1,2}(E \pm p_z)}{\sum_{\text{hadrons}}(E \pm p_z)}$$

$x_\gamma^{\pm}$: Fraction of photon momentum in hard process



DiJet Production

❒ Data: $\sqrt{s}$ = 161-172 GeV and 183-189 GeV

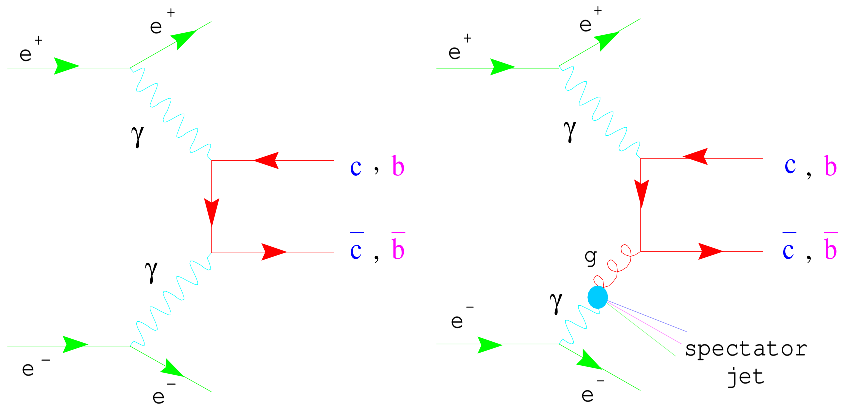


- $x_\gamma^\pm < 0.8$ Resolved (Gluon Exchange) $\propto (1 - |cos\theta^*|)^{-2}$
- $x_\gamma^\pm > 0.8$ Direct (Quark Exchange) $\propto (1 - |cos\theta^*|)^{-1}$

Sensitive to the spin of the Exchanged Particle

Inclusive Charm and Beauty Production

- Motivation :



Direct — Single Resolved

➪ The cross-section is calculable by pQCD because of heavy $m_{c,b}$. ➜ good test of pQCD

➪ Provide information about gluon content of the photon.

- <u>Charm identification :</u>

ALEPH : D^{*+} tag ($c \rightarrow D^{*+}X$)

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

D^{*+} tag

OPAL : D^{*+} tag

- Data :

ALEPH : 91 GeV, $\mathcal{L} = 73$ pb^{-1}

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

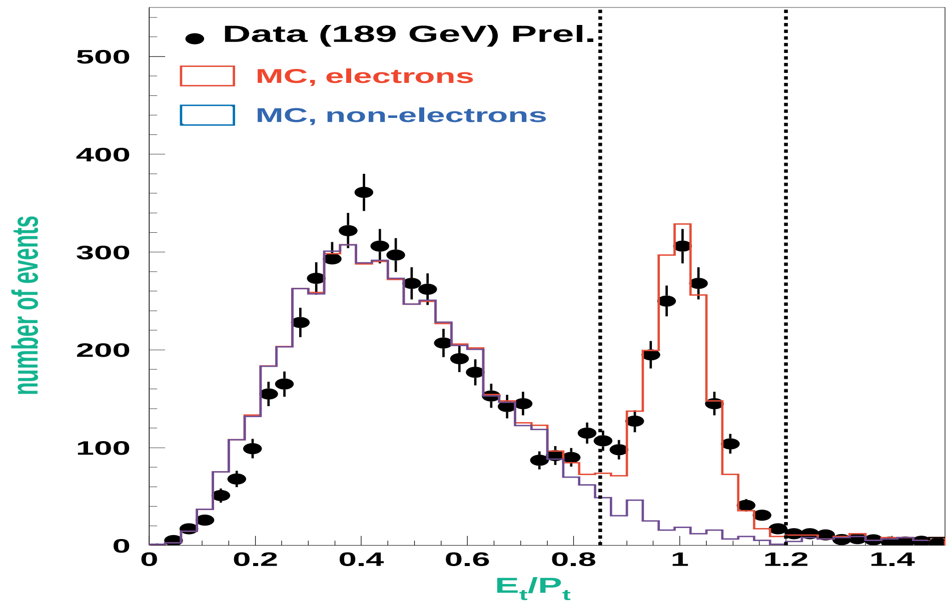
L3* : 189 GeV, $\mathcal{L} = 176$ pb^{-1}

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

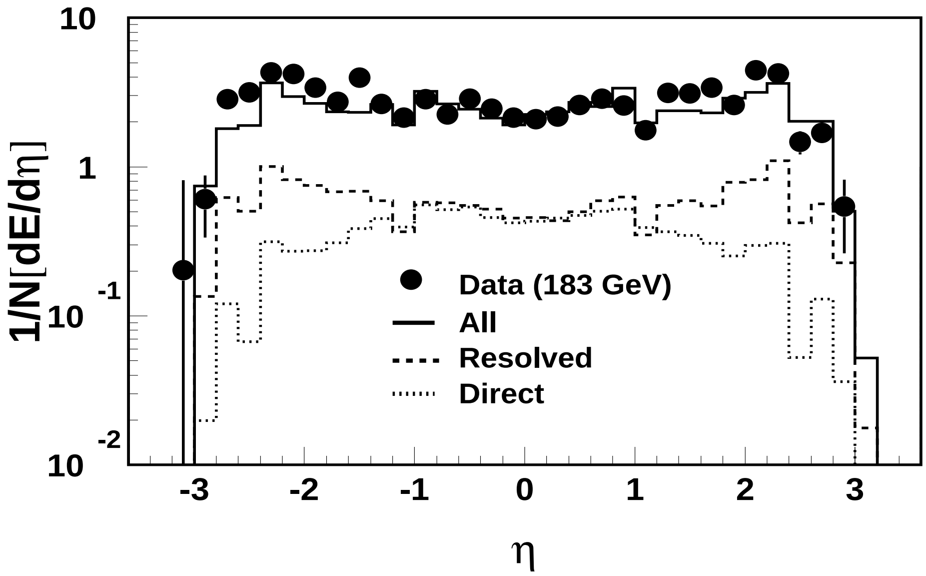
⋆ Preliminary

Inclusive Charm Production : L3

❒ Electron Identification:



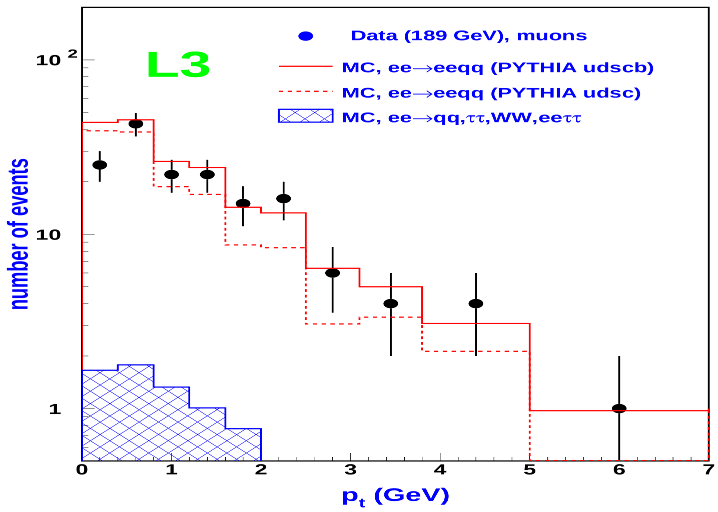
❒ Comparison with Pythia:



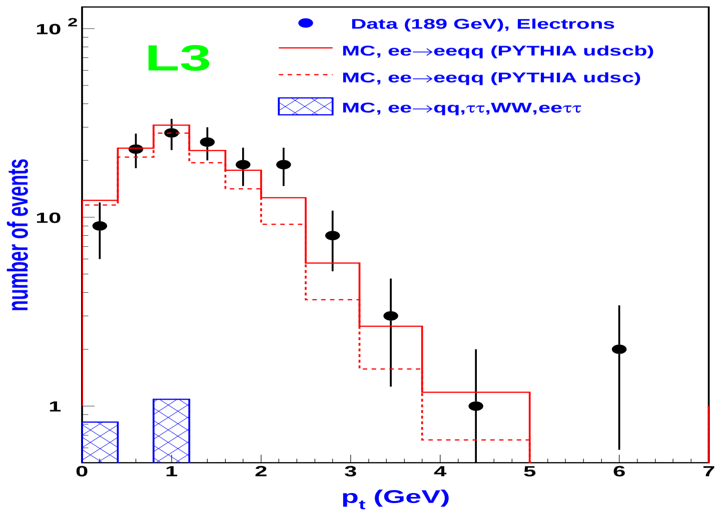
The Resolved Contribution is Needed

Search for Beauty: L3 Data

p_t with respect to the nearest jet



$P_t^{\mu} > 1.5$ GeV
$N_{ev}^{\mu} = 49$
$\varepsilon_b^{\mu} = 0.9\%$
$\Pi_b^{\mu} = 34\%$



$P_t^{e} > 1$ GeV
$N_{ev}^{e} = 96$
$\varepsilon_b^{e} = 1.6\%$
$\Pi_b^{e} = 28\%$

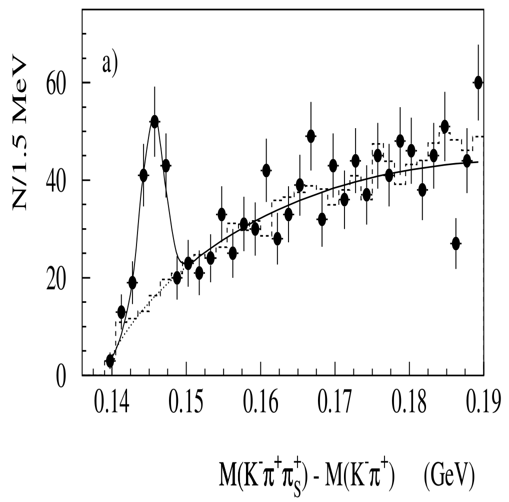
Leptons from bottom decays have higher p_t.

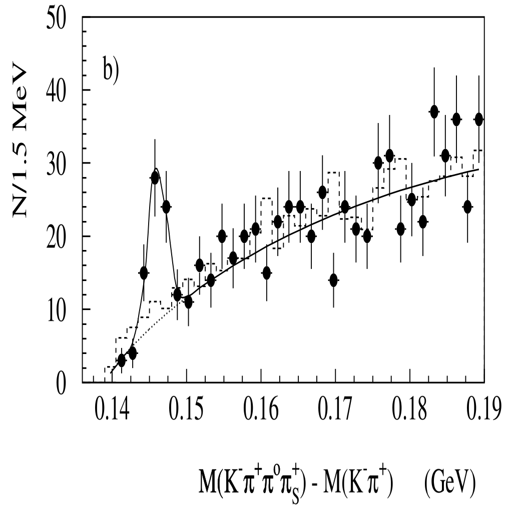
Muons:	$\sigma_{b\bar{b}} = 10.3 \pm 4.6(\text{stat}) \pm 3.3(\text{syst})$ pb
Electrons:	$\sigma_{b\bar{b}} = 9.6 \pm 3.6(\text{stat}) \pm 4.1(\text{syst})$ pb
Combined:	$\sigma_{b\bar{b}} = 9.9 \pm 2.9(\text{stat}) \pm 3.8(\text{syst})$ pb

D* Production : L3

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

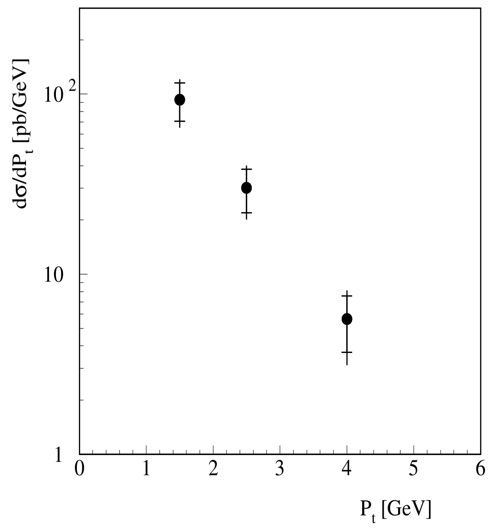
  $D^0 \to \mathrm{K}^-\pi^+, \mathrm{D}^0 \to \mathrm{K}^-\pi^+\pi^0$

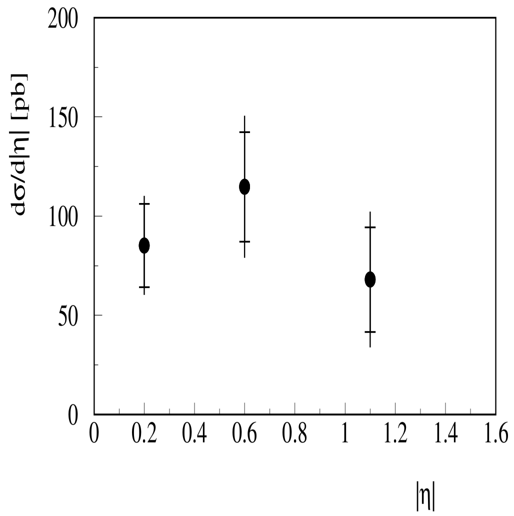




Nevents $= 102 \pm 17$ Nevents $= 42 \pm 11$

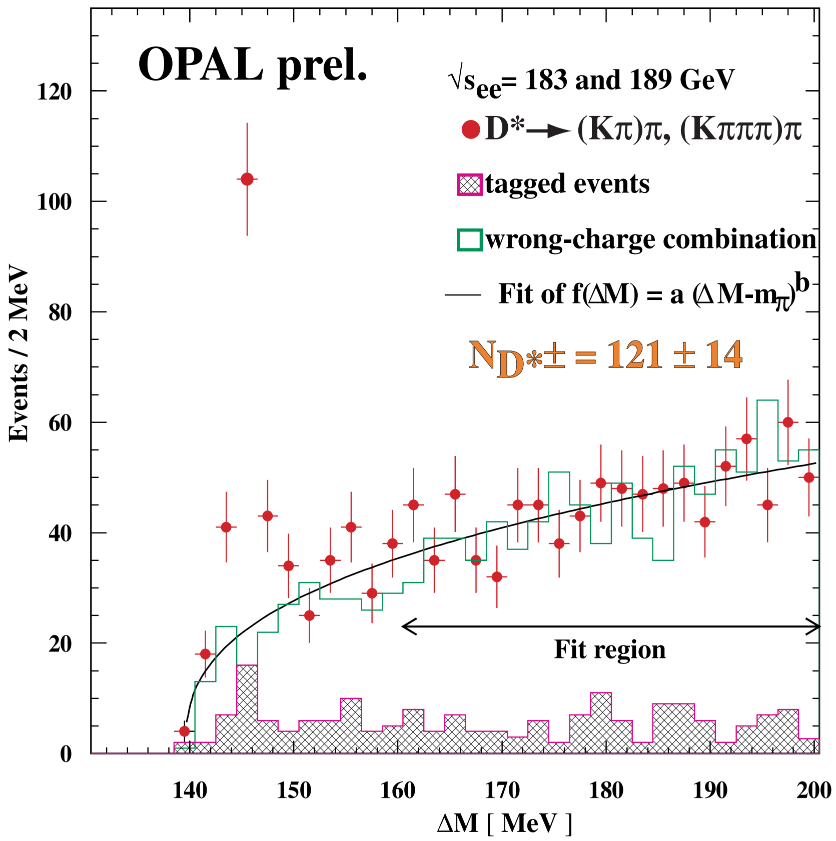
- Differential cross-sections:





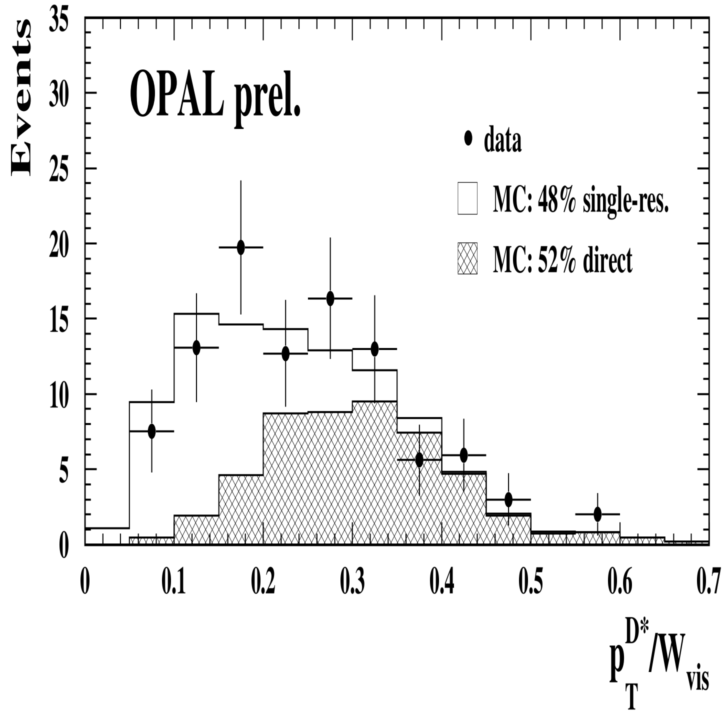
D^* Production : OPAL

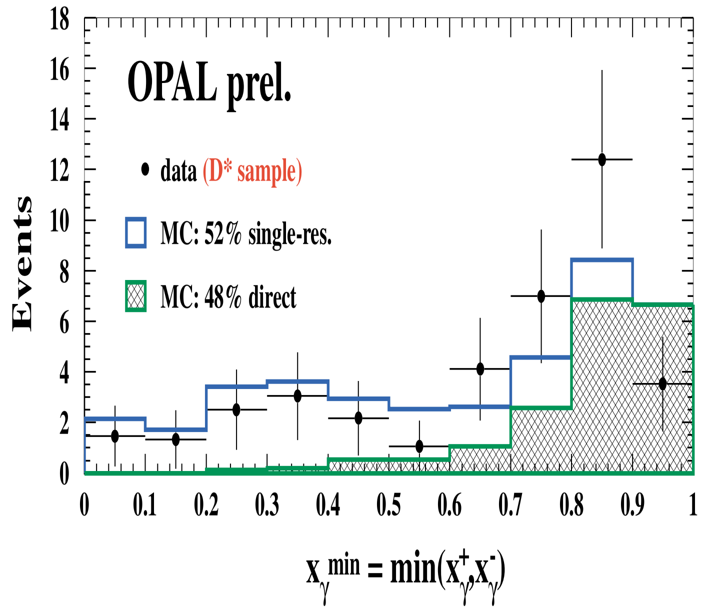
- Data: $\sqrt{s}$ = 183-189 GeV
- $D^{*\pm} \rightarrow D^0 \pi_s^\pm$,
  $D^0 \rightarrow K^- \pi^+, D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$



D^* Production : OPAL

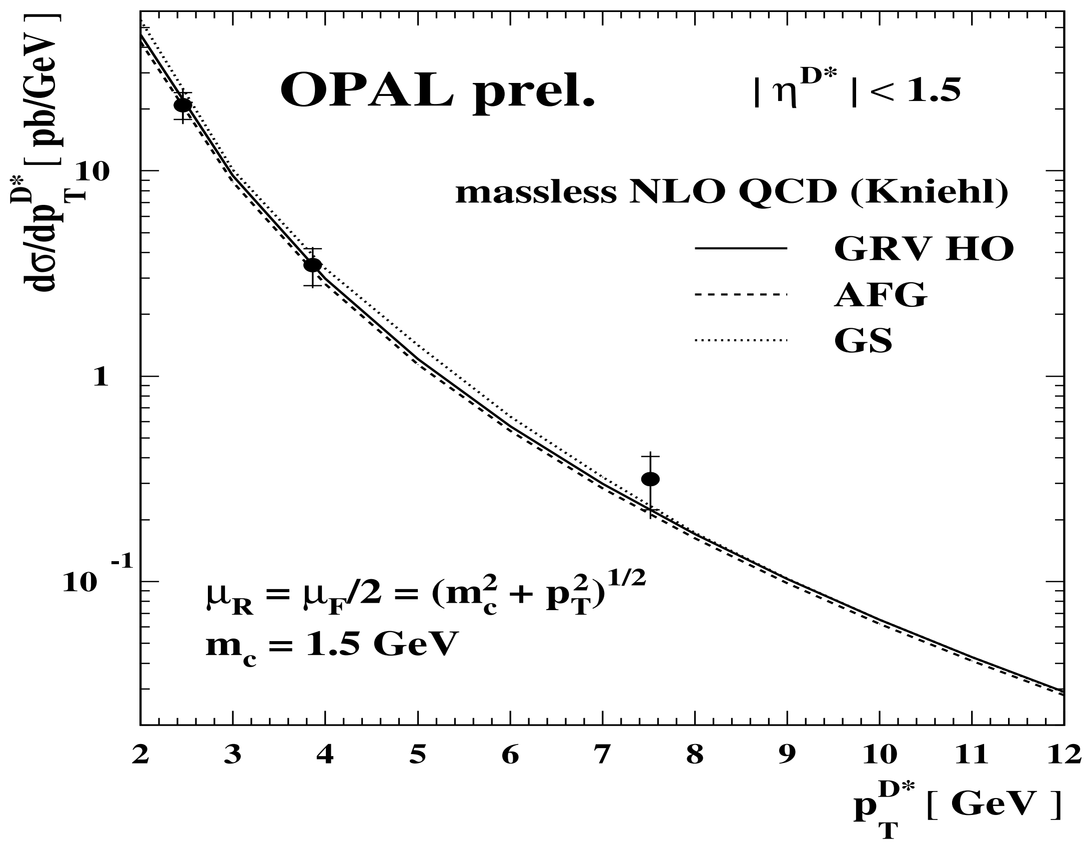
❒Separation of Direct and Resolved processes





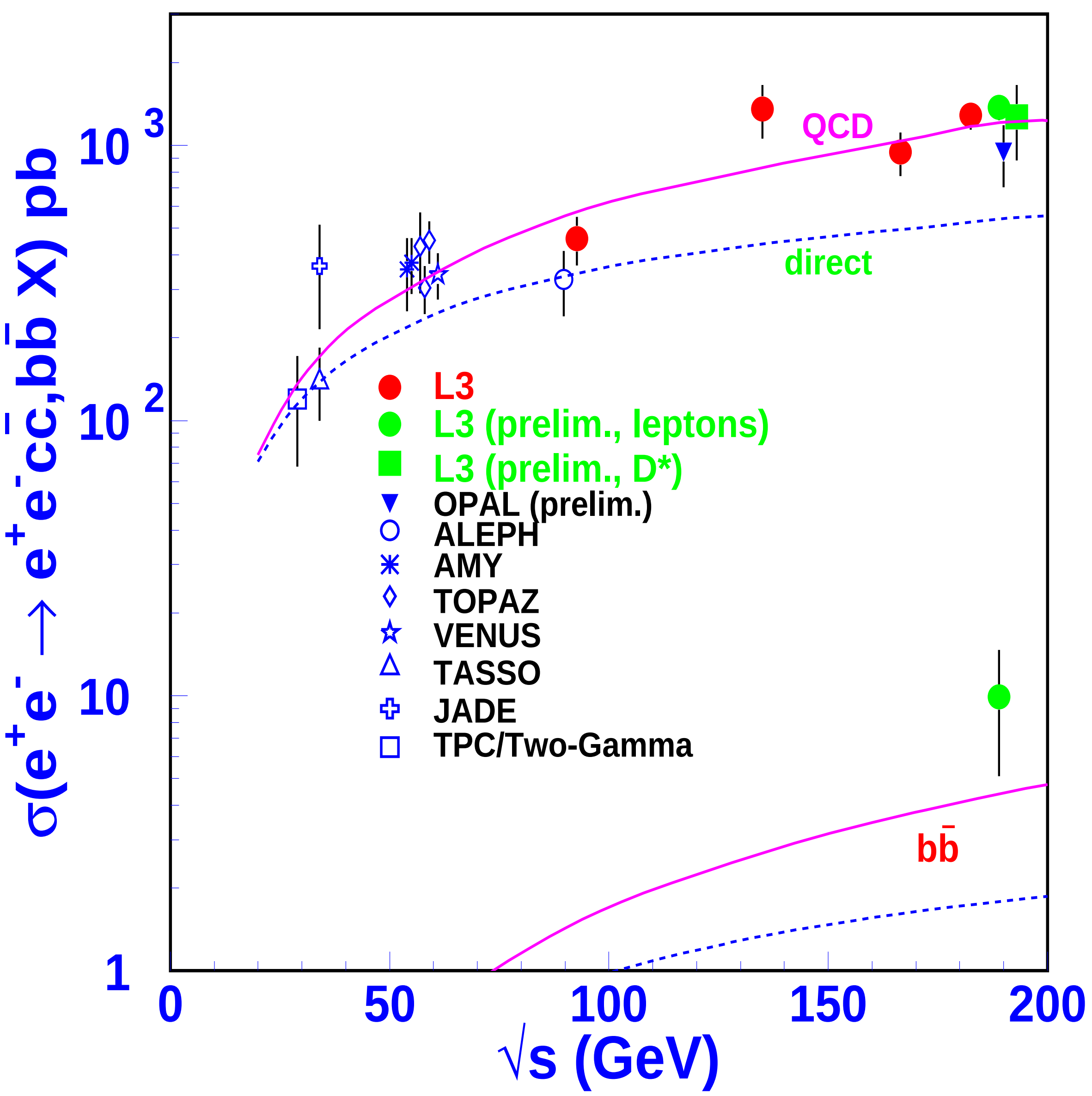
D^* Production : OPAL

Differential cross-section



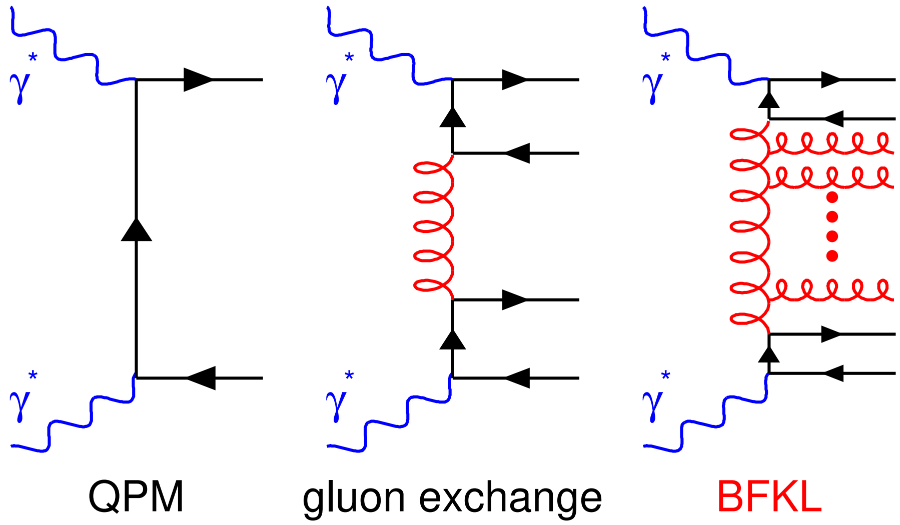
- ⇨ Massless calculation is better than massive
- ⇨ Weak dependence on the photon structure function parametrisations
- ⇨ Weak dependence on the scale

Total Cross Sections



- QCD calculation by Drees, Krämer, Junft and Zerwas, PL **B306** 371 (1993); $m_c = 1.3$ GeV, $m_b = 5.0$ GeV.
- $\sigma(\mathrm{e^+e^-} \to \mathrm{e^+e^-}c\bar{c}\mathrm{X})$ increases with $\sqrt{s}$.
- The direct process is insufficient to describe the data. ➜
  evidence of a gluon component in the photon

Double tag events : $\gamma^*\gamma^*$



- BFKL Kuraev, Lipatov, Fadin (Sov. Phys. JETP 45 (1977)); Balitski, Lipatov (Sov. J. Nucl. Phys. 28 (1978)
- The BFKL diagram is predicted to be dominant in $\gamma^*\gamma^*$ collisions for $Y = \ln\left(\frac{s}{s_0}\right) = \ln\left(\frac{W^2_{\gamma^*\gamma^*}}{Q_1 Q_2}\right) >> 1$
  Bartels, De Roeck, Lotter (Phys.Lett.B389 (1996))
  Brodsky, Hautmann, Soper (Phys.Rev.D56 (1997))
- In Leading order approximation :

  $\sigma_{\gamma^*\gamma^*} = \sigma_0(Q^2, Y)\left(\frac{s}{s_0}\right)^{\alpha_P - 1} \qquad \alpha_P - 1 = 4\ln 2\frac{N_c\alpha_s}{\pi}$

  Using $N_c = 3$, $\alpha_s = 0.2$ ➜ $\alpha_P - 1 \simeq 0.53$
- Next to leading order calculations by Brodsky, Fadin,Kim,Lipatov, Pivarov (hep-ph/9901229) give $\alpha_P - 1 \leq 0.175$

$\gamma^*\gamma^*$: Analysis

- Data :

L3 Prel. :	189 GeV,	176. pb^{-1}
already published:	183 GeV,	51.9 pb^{-1}
(L3 coll., CERN-EP/98-205)	91 GeV,	140. pb^{-1}
OPAL Prel.:	189 GeV	169. pb^{-1}

→ OPAL: 44 Events $< Q^2 >= 17$ GeV^2

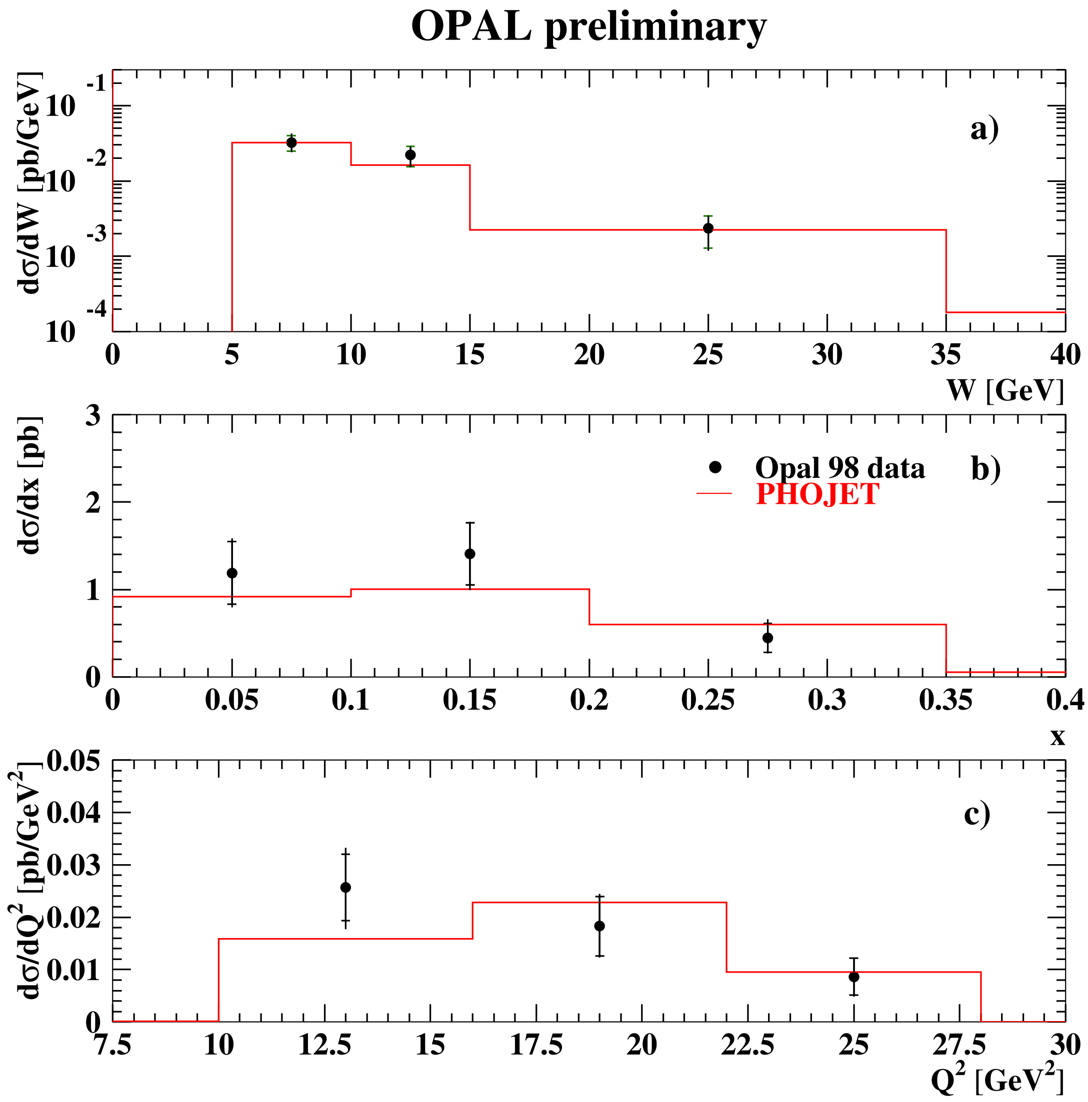
→ L3:

$\sqrt{s}$	91 GeV	183 GeV	189 GeV
$W_{\gamma\gamma}$	2 - 3 GeV	5 - 70 GeV	5 - 75 GeV
Q^2	1 - 9 GeV^2	2 - 35 GeV^2	3 - 37 GeV^2
$< Q^2 >$	3.5 GeV^2	14 GeV^2	14.5 GeV^2

Events	137	34	108
Bkg	12	4	14

- The backgrounds come from $e^+e^- \to e^+e^-\tau^+\tau^-$ and single tagged events.
- Typical efficiencies for L3 at 189 GeV:
  PHOJET: 64.8 ± 2.7 %
  JAMVG: 64.3 ± 3.0 %
- Results are insensitive to MC corrections

$\sigma(e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-hadrons)$



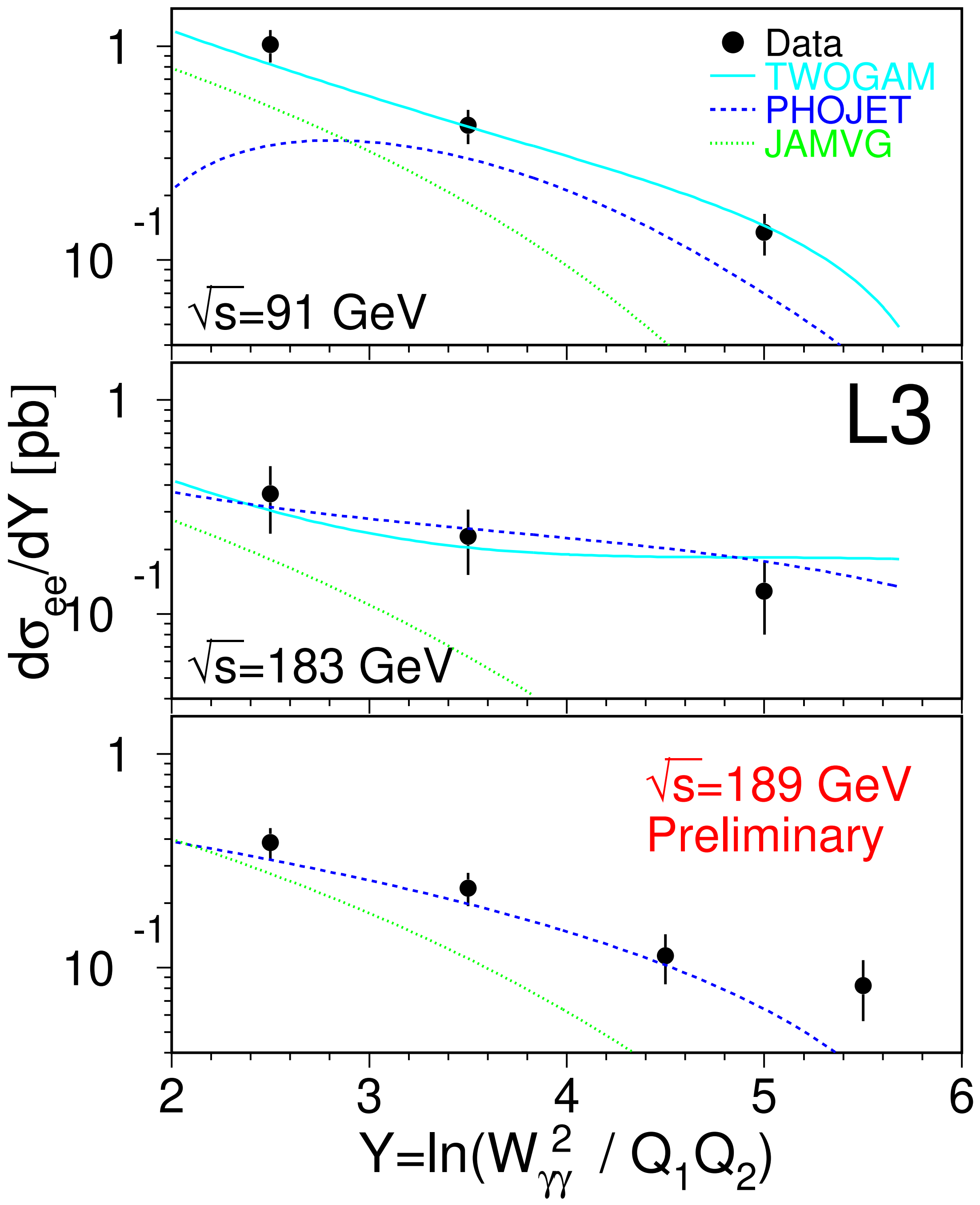
Cross section $\sigma_{\gamma^*\gamma^*}$

for $2 < Y < 6$, $E_e > 33$ GeV, $34 < \theta_e < 55$ mrad, $W_{\gamma\gamma} > 5$ GeV

- $\sigma_{\gamma^*\gamma^*} = [0.21 \pm 0.06(stat) \pm 0.03(syst)]$ pb
- PHOJET= 0.25 pb (one-gluon= 0.24 pb)
- BFKL LO= 5.7 pb HO= 0.5 pb

BFKL is not favoured by the data

$\sigma(e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^- hadrons)$



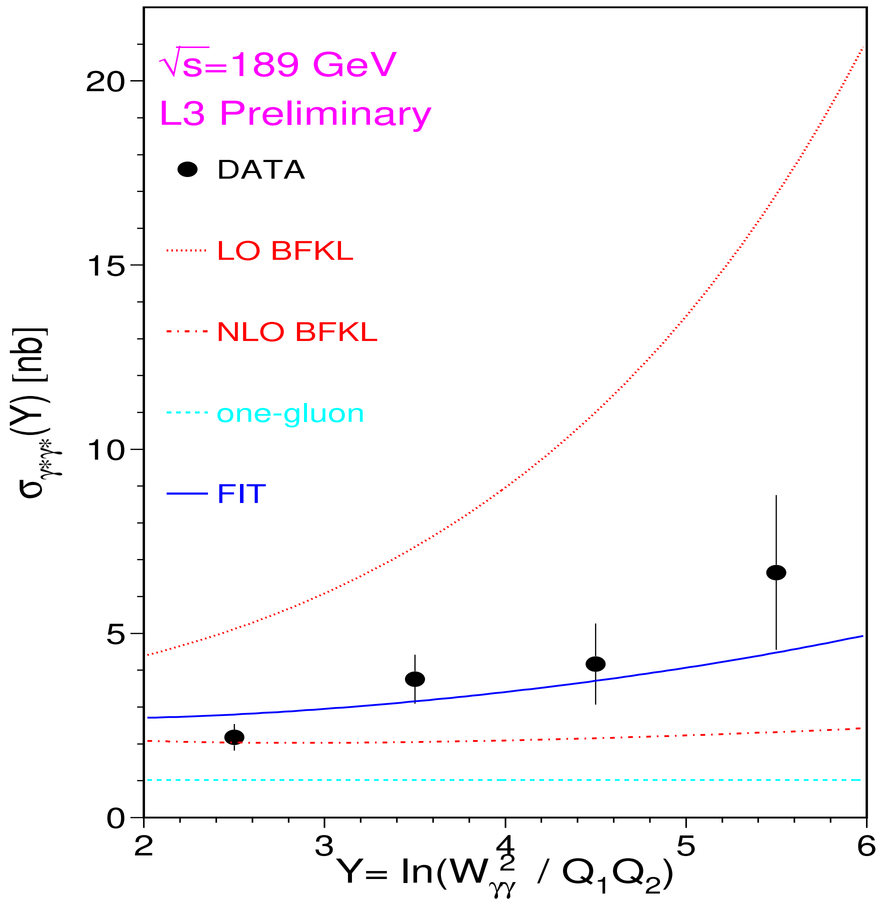
Direct process (JAMVG) is insufficient
but
PHOJET and TWOGAM agree quite well

M.N.Kienzle-Focacci
Geneva University

$\sigma_{\gamma^*\gamma^*}$: Test of BFKL

After subtraction of the direct part :

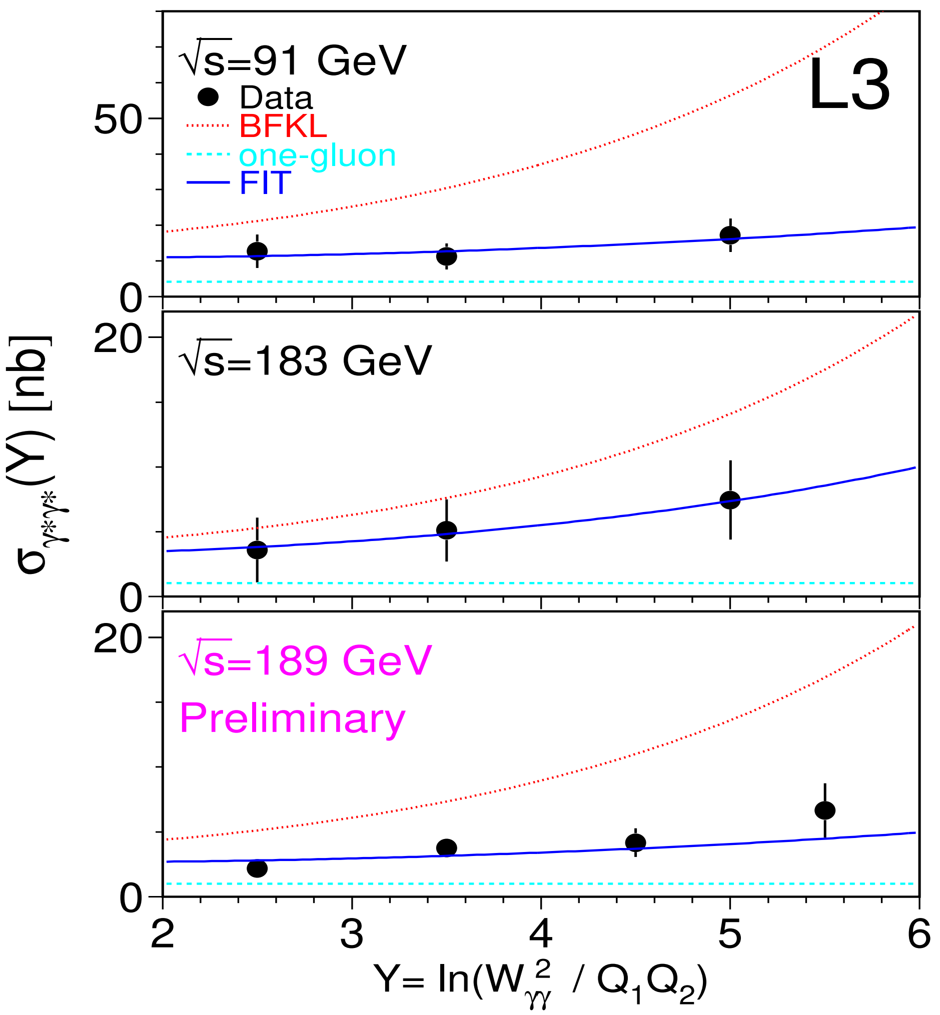
$\sigma_{\rm ee} = L_{TT} \otimes \sigma_{\gamma^*\gamma^*}$



- The measured cross-section is lower than the LO BFKL prediction, and higher than the NLO
- Fit to the data, leaving α_P as a free parameter:

$$\alpha_P - 1 = 0.29 \pm 0.032 \qquad \begin{array}{l} < 0.53 \text{ (LO)} \\ > 0.175 \text{ (NLO) !} \end{array}$$

$\sigma_{\gamma^*\gamma^*}$: Test of BFKL



combined fit:

$$\alpha_P - 1 = 0.29 \pm 0.025$$

$$\chi^2/d.o.f. = 7/10 \qquad C.L. = 72.5\%$$

$$\chi^2_{LO-BFKL}/d.o.f. = 263/10$$
$$\chi^2_{NLO-BFKL}/d.o.f. = 21/10$$

Exclusive Hadronic States

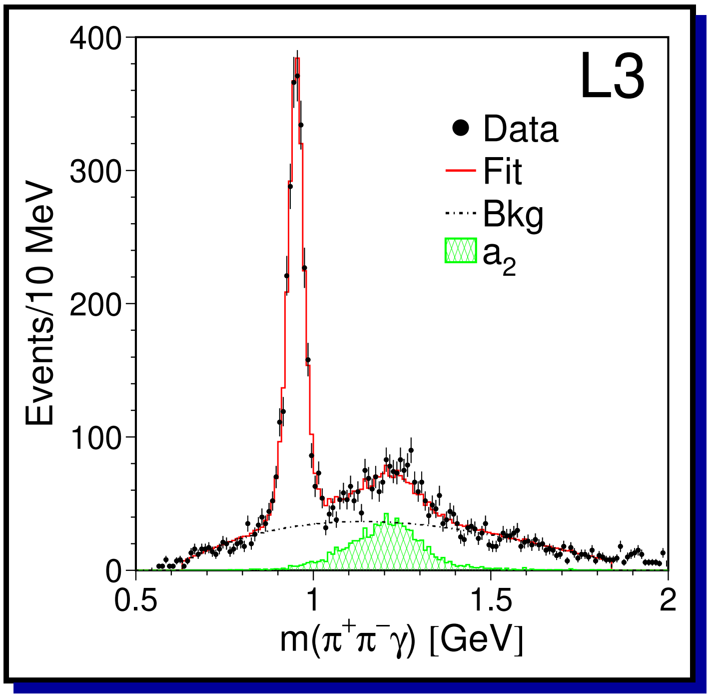
- Structure of hadron and its constituents
- Singlet-Octet mixing of $q\bar{q}$ mesons.
- $\Gamma_{\gamma\gamma}$ of heavy quark allows measurement of α_s
- QCD predicts the existence of Glueballs
- Possible Existence of Four Quark States

❒ Many Resonances studied by L3

Resonance	Final state	J^{PC}	$\Gamma_{\gamma\gamma}$(keV)
η' (958)	$\pi^+\pi^-\gamma$	0^{-+}	$4.17 \pm 0.10 \pm 0.27$
η (1440)	$K^\pm K^0_s \pi^\mp$	0^{-+}	$0.166 \pm 0.052/(BR)$
X (1450)	$K^\pm K^0_s \pi^\mp$	1^{++}	
a_2 (1320)	$\pi^+\pi^-\pi^0$	2^{++}	$0.98 \pm 0.05 \pm 0.09$
a_2' (1750)	$\pi^+\pi^-\pi^0$	2^{++}	$0.29 \pm 0.04 \pm 0.02/(BR)$
f_2' (1525)	$K^0_s K^0_s$	2^{++}	$0.09 \pm 0.02 \pm 0.02/(BR)$
X (1750)	$K^0_s K^0_s$	$0^{++}, 2^{++}?$	
η_c (2980)	9 Channels	0^{-+}	$6.9 \pm 1.7 \pm 2.2$
χ_{c2}(3555)	$J/\psi\gamma$	2^{++}	$0.97 \pm 0.40 \pm 0.36$

$$\eta' \rightarrow \pi^+\pi^-\gamma$$

❐ $\int \mathcal{L}\, dt = 129$ pb^{-1} @ LEP I



$N_{\eta'}$=2123 ± 53

$M_{\eta'}$=958 ± 1 MeV
σ =24 ± 1 MeV

$\Gamma_{\gamma\gamma} = (4.17 \pm 0.10 \pm 0.21)$ keV

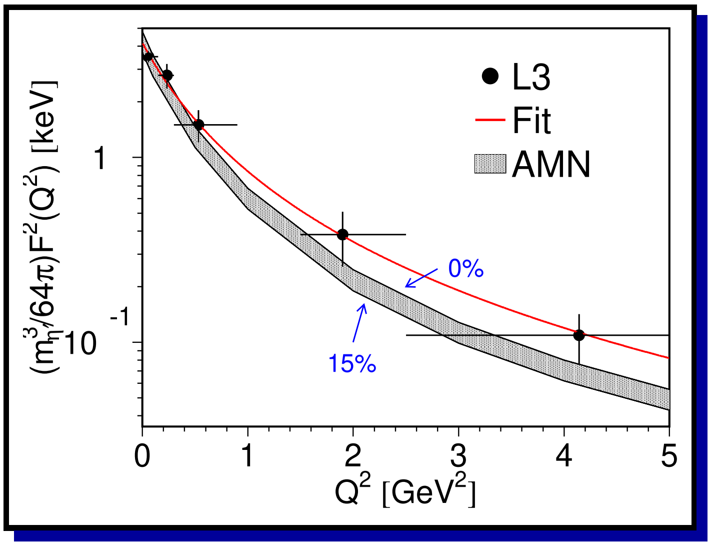
❐ η' **Form Factor**

➠ $\sum p_T^2 = Q^2$

$F^2(Q^2) = \left(\frac{1}{1+Q^2/\Lambda^2}\right)^2$

Λ_{fit} = 900±51 MeV

Consistent with VDM

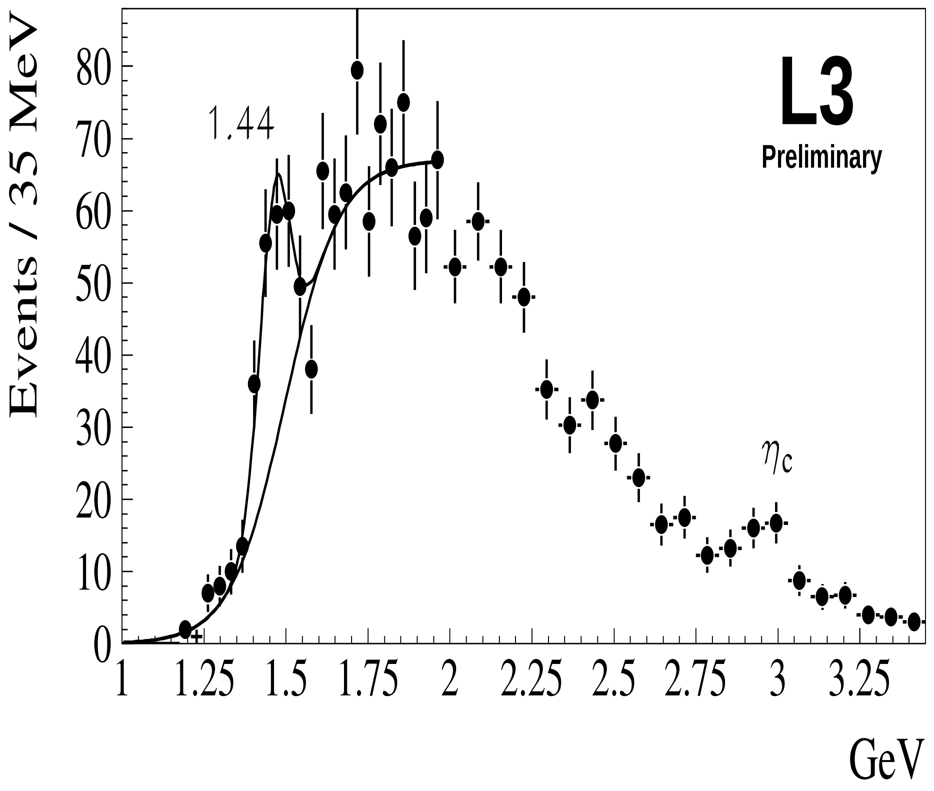


➠ Anisovich *et al.* Phys. Rev. D55(1997) 2918.

L3 Collab., PLB 418 (1998) 399

The $K^0_s K^\pm \pi^\mp$

- $\int \mathcal{L}\, dt = 250$ pb^{-1} @ LEP II

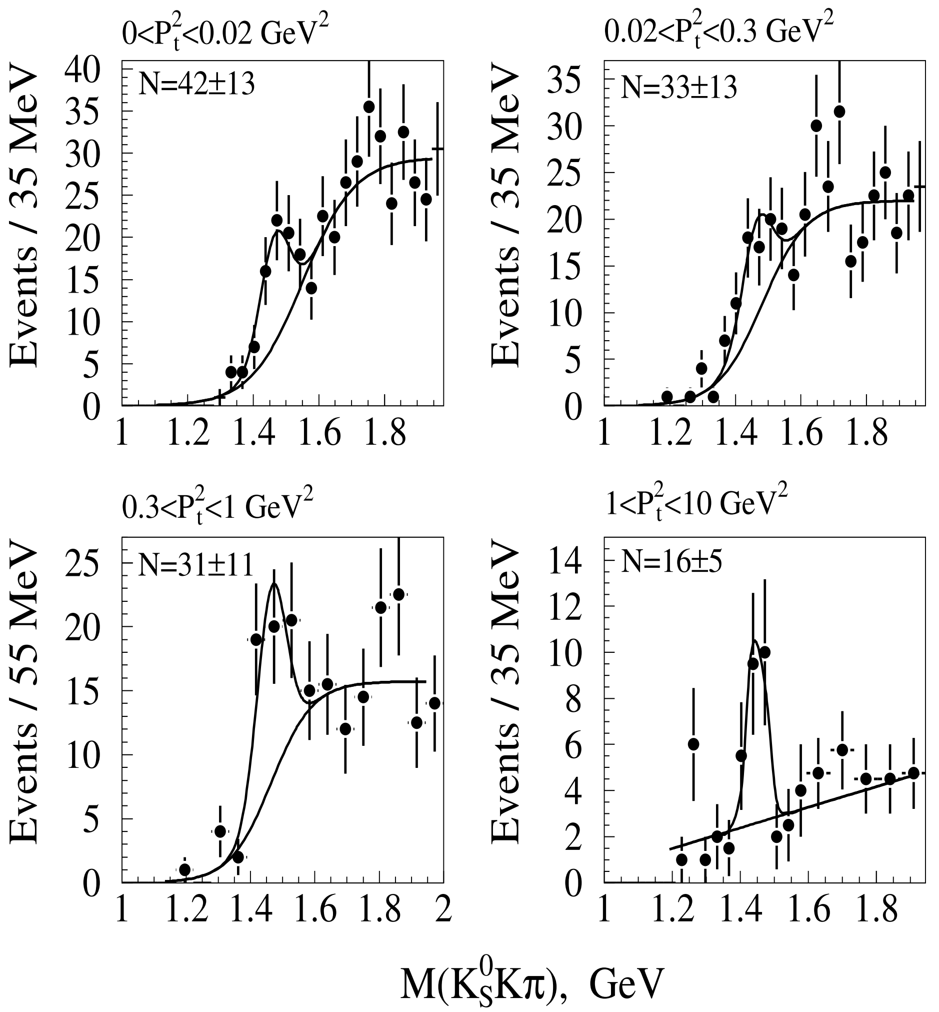


- Mass = 1465 ± 31 MeV
- σ = 45 ± 5 MeV

  resolution $\sigma = 24$ MeV
- Nevents = 119 ± 22

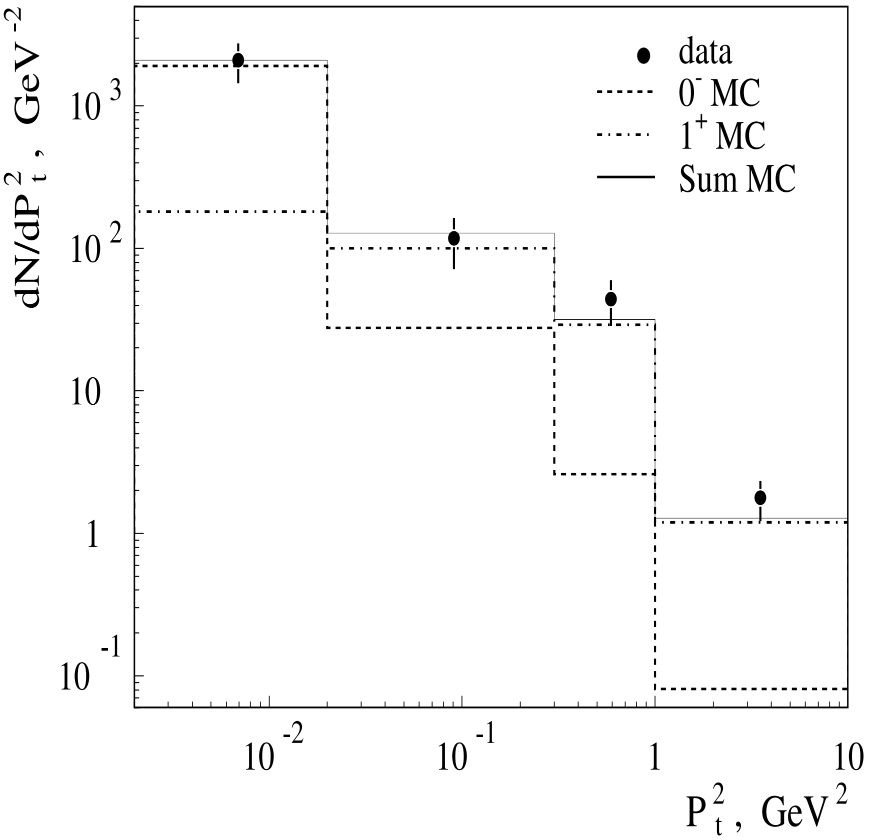
The $K_s^0 K^\pm \pi^\mp$

- The evolution of the peak : $\sum p_T^2 = Q^2$



- Peak formed by quasi-real photons (low Q^2)
- Peak formed by highly virtual photons (high Q^2)

The $K^0_s K^{\pm}\pi^{\mp}$

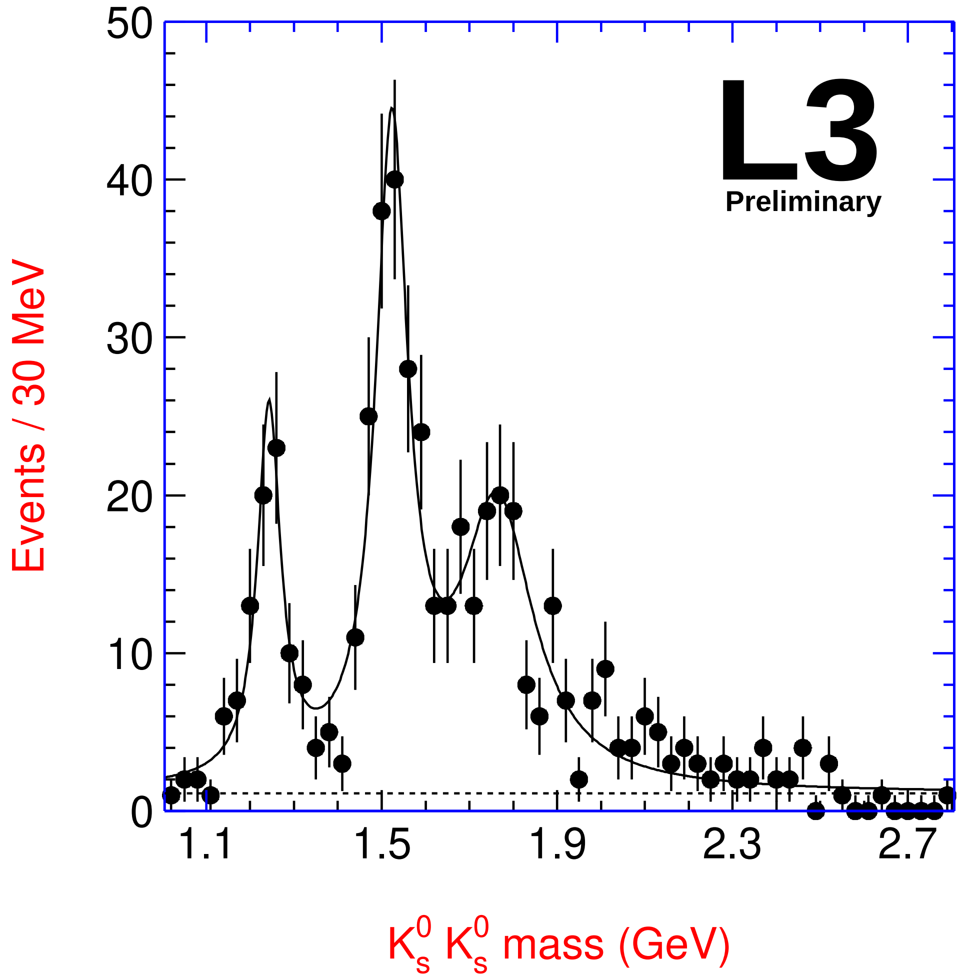


- The peak is not a pure J^P state :
  Prob $(0^-) < 1\%$, Prob $(1^+) < 1\%$
- $J^P = 0^-$ $\eta(1440)$ Nevents $= 49 \pm 1$

  ➠ $\Gamma_{\gamma\gamma} \times Br(\eta \to K^0_s K^{\pm}\pi^{\mp}) = (166 \pm 52)$ eV

  ➠ Stickiness $= 9.5 \pm 3.0$ Not a gluonium!!
- $J^P = 1^+$ f_1 Nevents $= 63 \pm 6$

The $K_s^0 K_s^0$

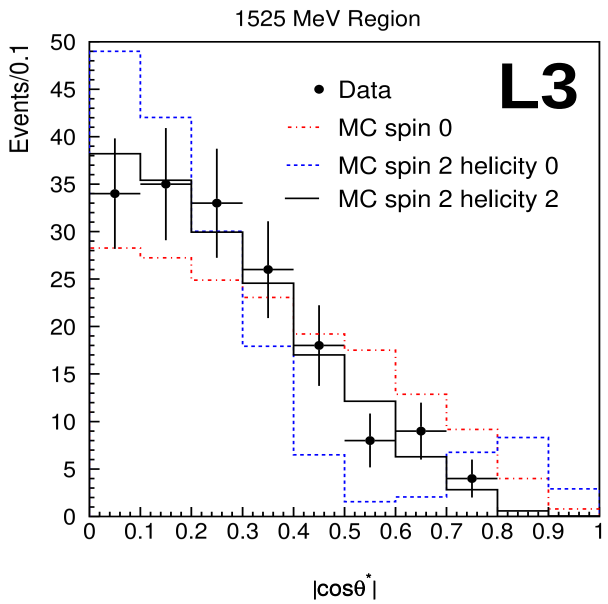


	f_2-a_2	$f_2'(1525)$	X(1750)
Mass (MeV)	—	1523±8	1765±22
Width (MeV)	—	89±37	200±50
Events	75±15	184±27	171±26

- $f_2 - a_2$ destructive interference
- Clear $f_2'(1525)$ signal
- Clear enhancement around 1750 MeV
- No signal in the $\xi(2230)$ region ➠ gluonium ?

The $f_2'(1525)$ and the 1750 MeV Region

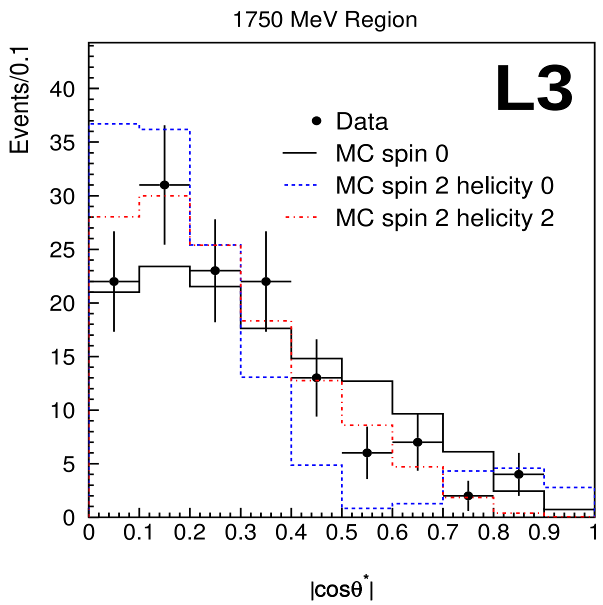
- $f_2'(1525)$: Helicity 2 dominates !



	$\chi^2/7$ d.o.f.
J=0, λ=0	25.2
J=2, λ=2	4.2
J=2, λ=0	28.5

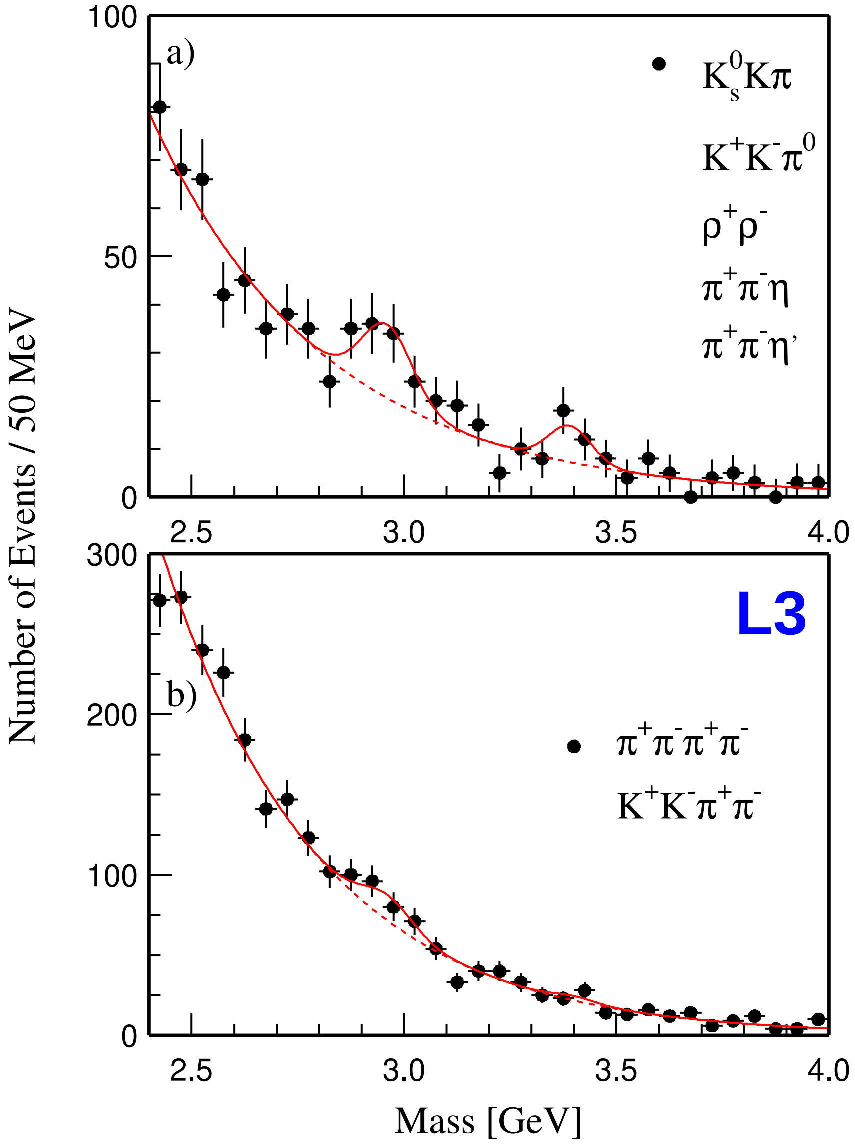
$$\Gamma_{\gamma\gamma}(f_2') \times Br(f_2' \to K\bar{K}) = (0.085 \pm 0.03)\text{keV}$$

- $f_2'(1750)$ radial recurrence?
  $f_2''(1740)$, $f_2'''(1820)$ (OGE-SRM prediction)
- 0^{++} $s\bar{s}$ state ? (C.Amsler and F.E.Close)



	$\chi^2/8$ d.o.f.
J=0, λ=0	17.9
J=2, λ=2	7.2
J=2, λ=0	26.3

η_c(2980) Decay Channels

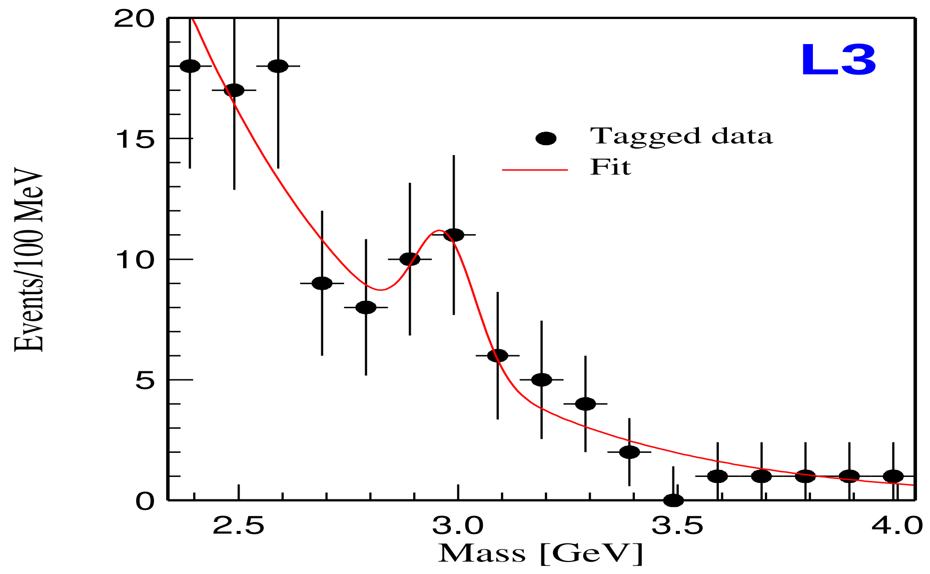


76 signal events above a background of 14
for L_{ee}=140.2 pb^{-1} at $\sqrt{s}$= 91 GeV
and L_{ee}=52.4 pb^{-1} at $\sqrt{s}$= 183 GeV

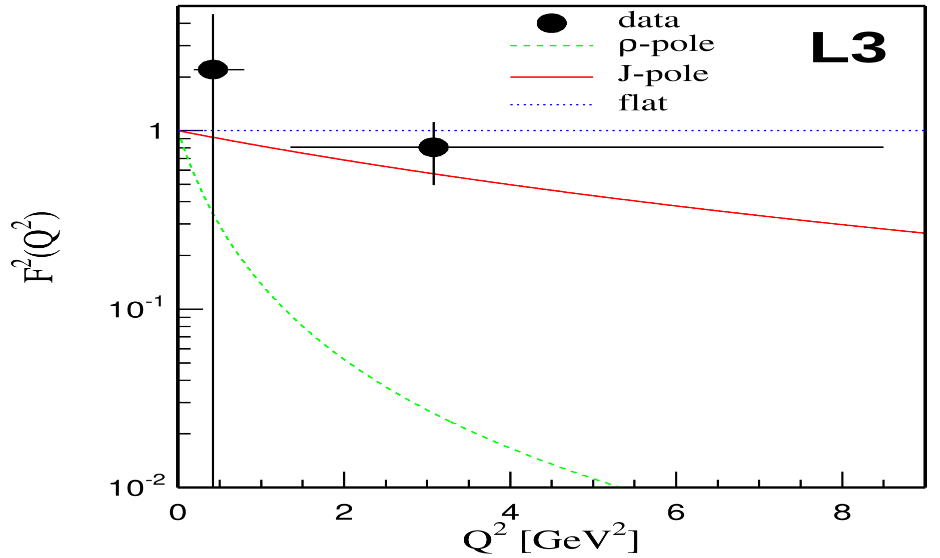
$\Gamma_{\gamma\gamma}(\eta_c) = 6.9 \pm 1.7(\text{stat}) \pm 0.8(\text{sys}) \pm 2.0(\text{BR})$ keV [a]

[a] CERN-EP/99-072

η_c(2980) Form factor



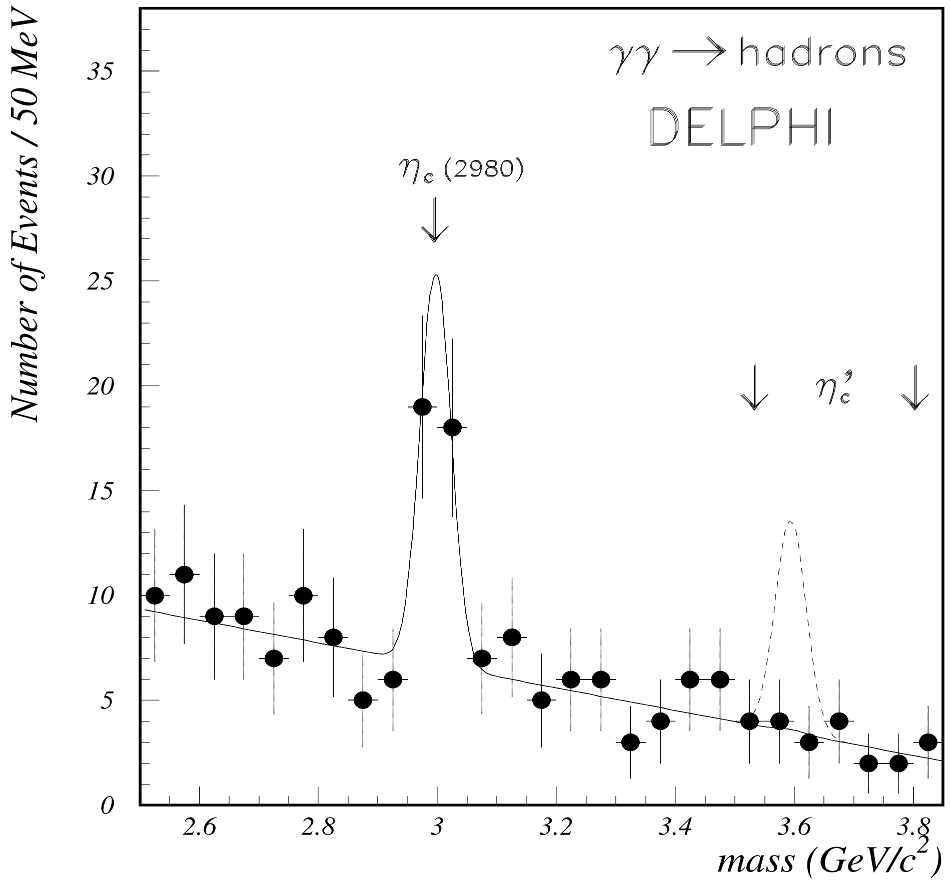
- Tagged events : $8.3^{+5.5}_{-4.9}$



- Prob (J/ψ - pole) $\simeq 10\times$ Prob (ρ - pole)

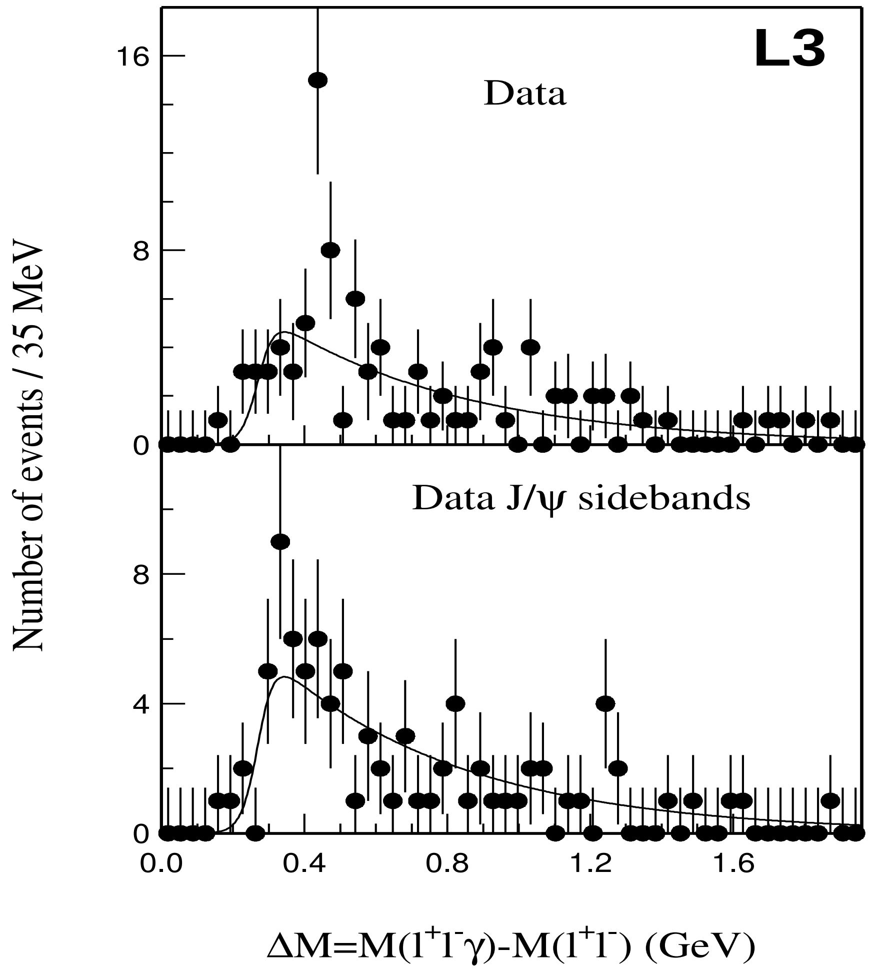
$\eta_c'(3590)$

- Crystall Ball : Mass(η_c') $= 3594 \pm 5$ MeV
  first radial exitation of η_c ?
- Barnes, Browder, Tuan (PL B385(1996) 391)
  $\Gamma_{\gamma\gamma}(\eta_c') \simeq 0.75 \times \Gamma_{\gamma\gamma}(\eta_c)$



- DELPHI : $\Gamma_{\gamma\gamma}(\eta_c') < 0.34 \times \Gamma_{\gamma\gamma}(\eta_c)$ at 90 % CL
- L3 : $\Gamma_{\gamma\gamma}(\eta_c') < 2.0$ KeV
  $\Gamma_{\gamma\gamma}(\eta_c') \simeq 0.29 \times \Gamma_{\gamma\gamma}(\eta_c)$ at 95 % CL

$\chi_{c2}(3555) \to J/\psi + \gamma$



14 signal events above a background of 5.5
for L_{ee}=140.2 pb^{-1} at $\sqrt{s}$= 91 GeV
and L_{ee}=52.4 pb^{-1} at $\sqrt{s}$= 183 GeV

$$\Gamma_{\gamma\gamma}(\chi_{c2}) = 1.02 \pm 0.40(\text{stat}) \pm 0.17(\text{sys}) \quad \text{keV}$$

$$\frac{\Gamma_{gg}(\chi_{c2})}{\Gamma_{\gamma\gamma}(\chi_{c2})} = \frac{9\alpha_s^2(m_c)}{8\alpha^2}\left(\frac{1-2.2\alpha_s/\pi}{1-16\alpha_s/3\pi}\right).$$

$$\boldsymbol{\alpha_s(m_c) = 0.21 \pm 0.05.}$$

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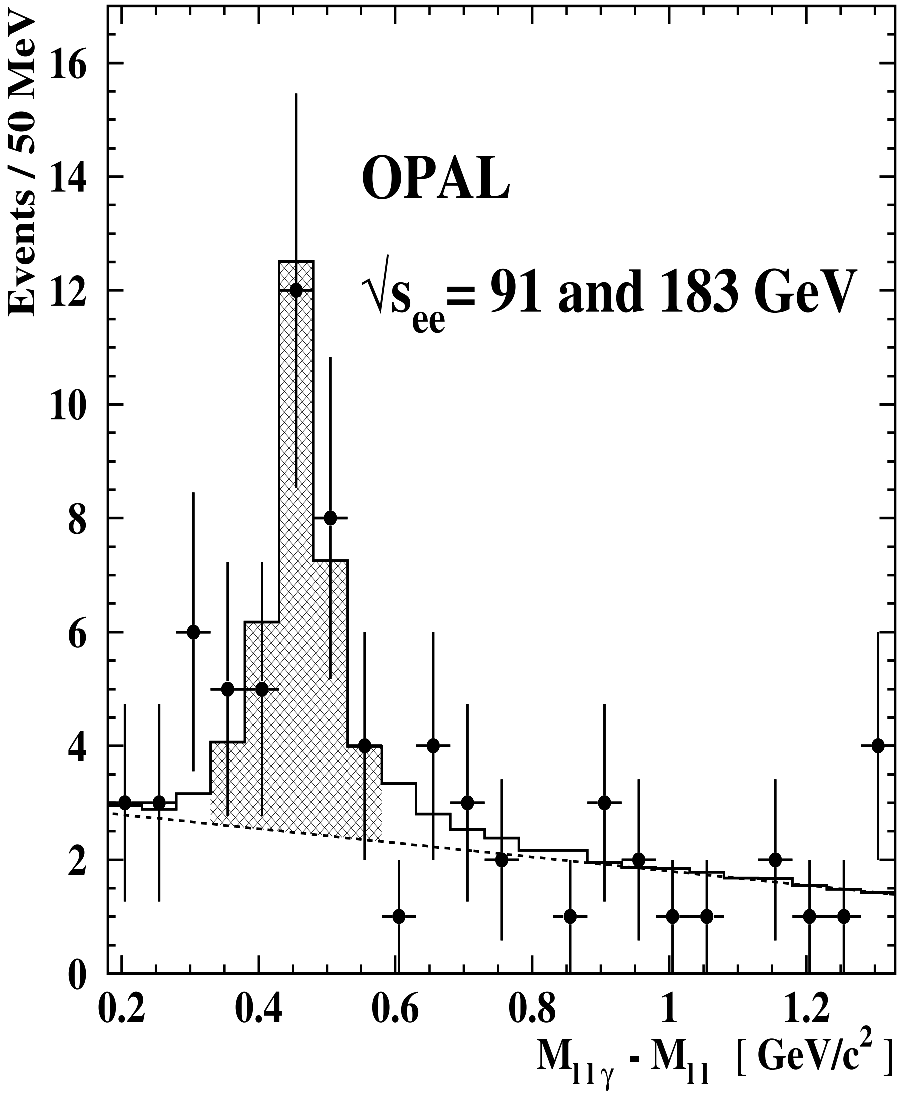
$\chi_{c2}(3555) \to J/\psi + \gamma$



34 signal events above a background of 12
for L$_{ee}$=167 pb^{-1} at $\sqrt{s}$= 91 GeV
and L$_{ee}$=55 pb^{-1} at $\sqrt{s}$= 183 GeV

$$\Gamma_{\gamma\gamma}(\chi_{c2}) = 1.76 \pm 0.47(\mathrm{stat}) \pm 0.40(\mathrm{sys}) \ \ \mathrm{keV}$$

OPAL Coll., PLB 439 (1998) 197

Conclusions

- Two-photon collisions is a rich field of physics at LEP
- LEP will run until the year 2000
  - ➜ more data are coming
  - ➜ even more precise results are foreseen

Our understanding of this physics is grawing fast

To match the good data precision
we need to improve
the models and the Monte Carlos!