Two Photon Physics at LEP

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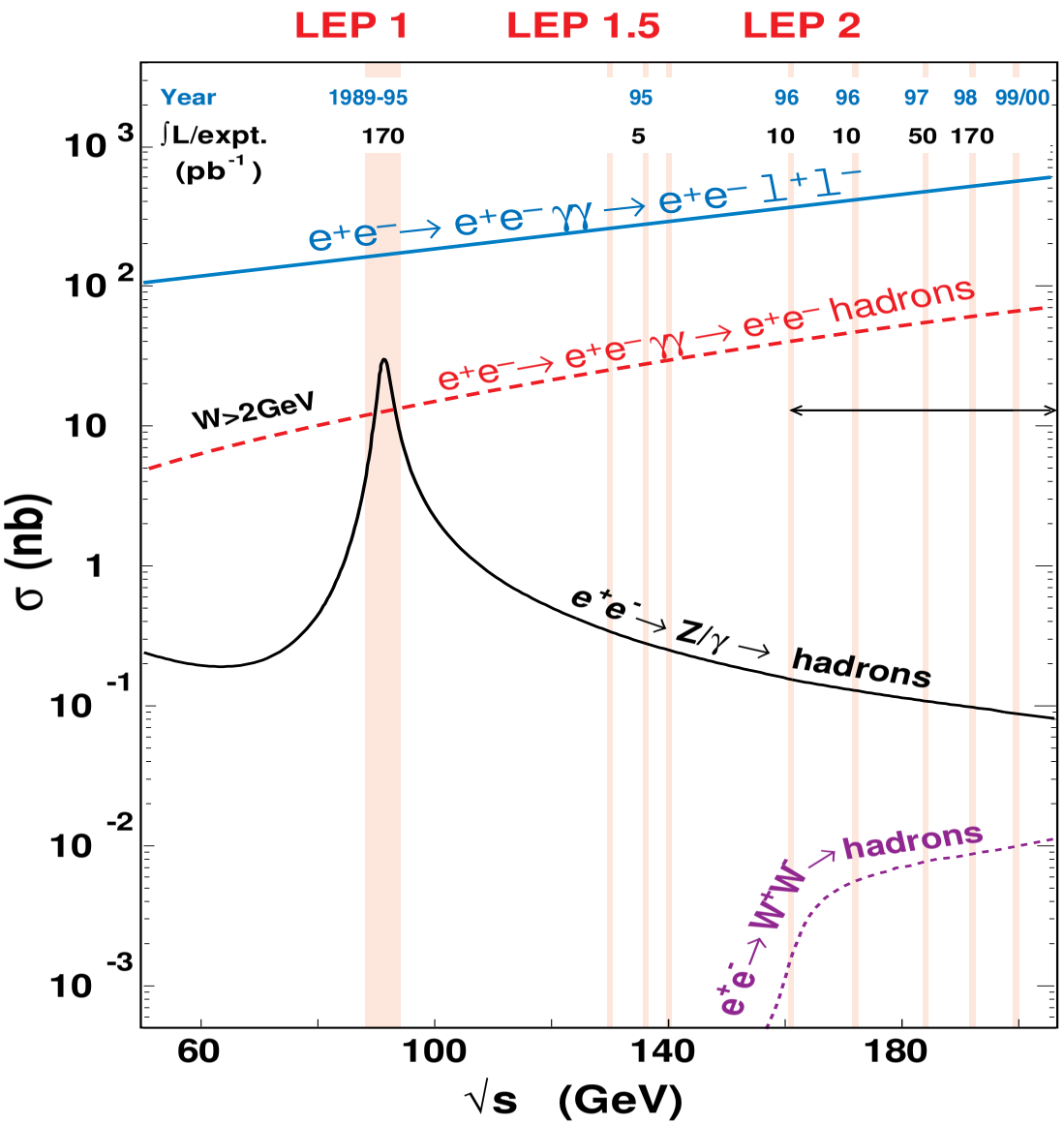
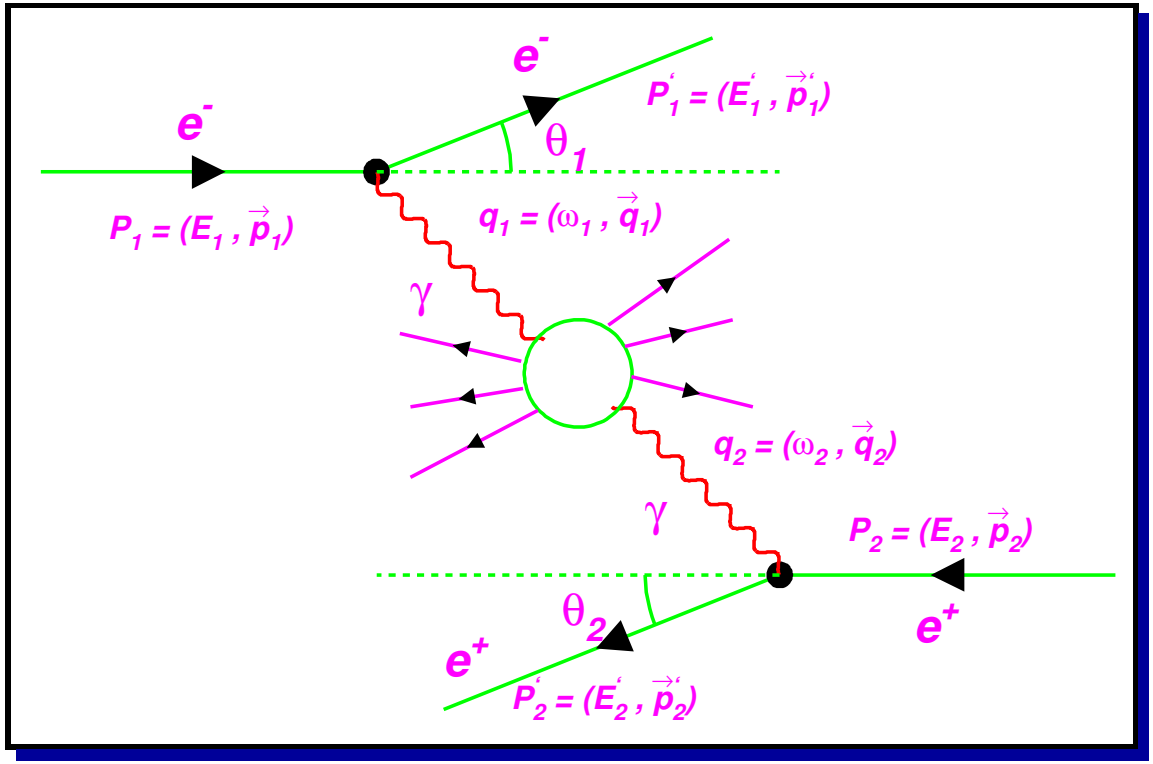
Introduction



- The dominant process at LEP2 is the Two-photon interaction.

- LEP2 is the best place to study two-photon physics (high cross-section, low background)

Photon Photon Collisions



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

$$P^2 = -q_2^2 = 2E_2E_2'(1-\cos\theta_2)$$

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

- The final state can be :
  1. Lepton pairs
  2. A single resonant state
  3. A non-resonant hadronic state

Photon Photon Collisions

The two-photon events can be classified as:

1. Non-tagged events ($Q^2 \sim P^2 \sim 0$)

❒ Both scattered $e^{\pm}$ are lost in the beam pipe.

➪ Both photons are quasi-real.

❒ We can study :

➪ σ_{tot} of $\gamma\gamma$ collisions

➪ Inclusive Charm and Beauty production

➪ Single particle and Dijet production

➪ Resonances

2. Single-tagged events ($Q^2 >> P^2 \sim 0$)

❒ Only one scattered electron is detected.

➪ One photon is highly virtual and the other is quasi-real.

➪ Q^2 is well measured.

❒ We can study :

➪ Photon structure functions

➪ The photon-meson transition form factor

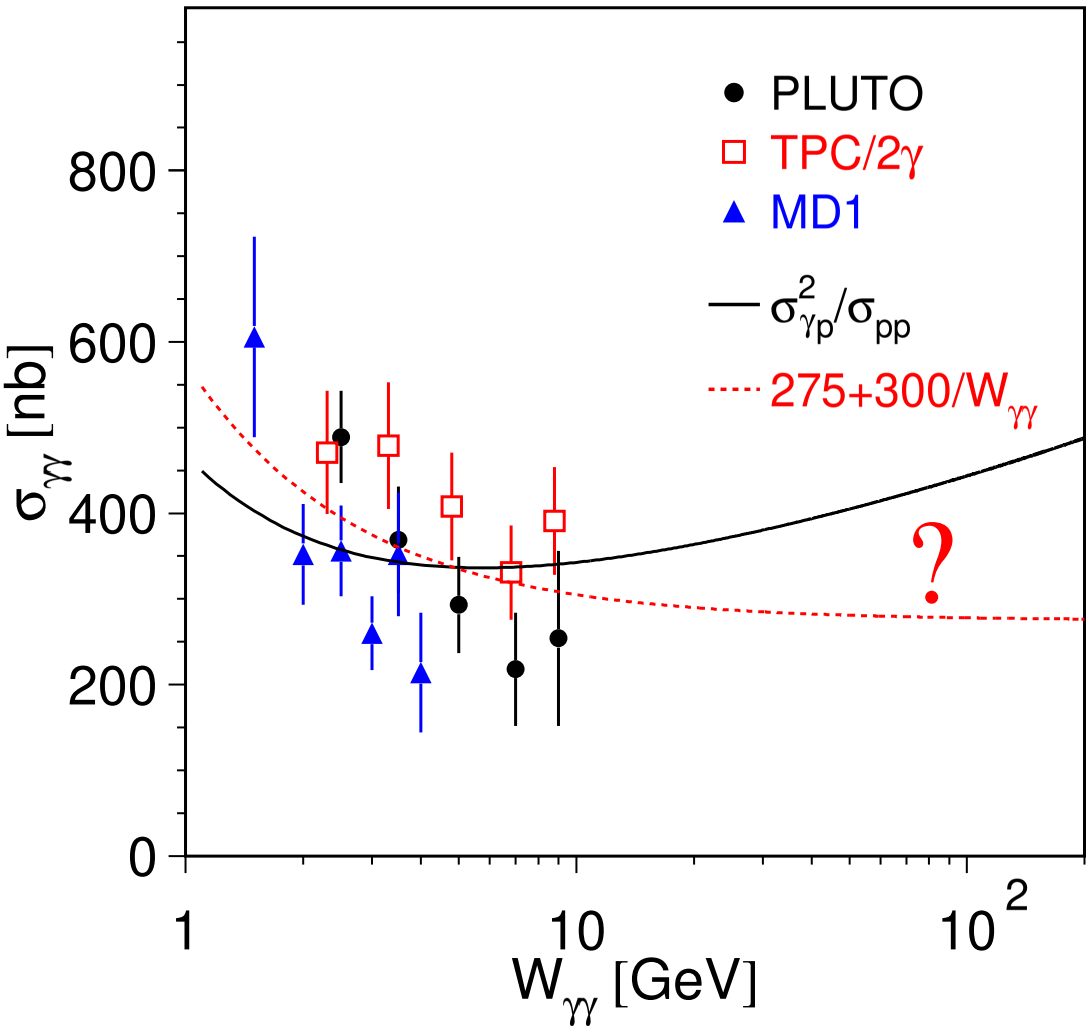
3. Double-tagged events

- Both scattered electrons are detected.
  - Q^2 and P^2 are well measured.
  - $W_{\gamma\gamma}$ can be measured directly → No unfolding

- We can study :
  - Cross-section of $\gamma^*\gamma^*$ collision → BFKL Pomeron
  - Virtual photon structure function

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

The measurements before LEP :

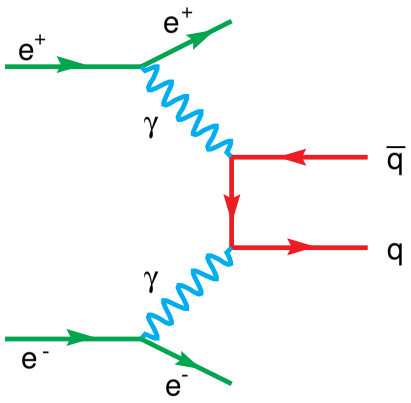


- Limited by beam energy ➜ $W_{\gamma\gamma} < 10$ GeV.
- Wide spread in the measurements.
- Does $\sigma_{\gamma\gamma}$ increase at high energy ?
- At LEP, $5 \text{ GeV} < W_{\gamma\gamma} < 145 \text{ GeV}$ has been measured.

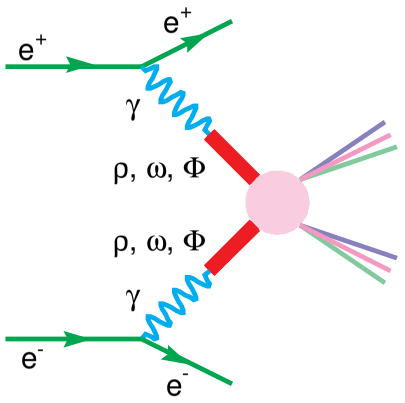
Total $\sigma_{\gamma\gamma}$: Physics

The diagrams contributing to :

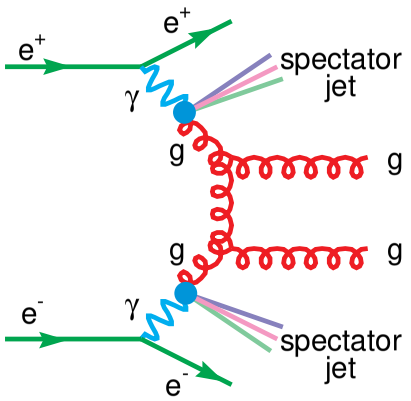
$$e^+e^- \to e^+e^-\gamma\gamma \to e^+e^-\text{hadrons}$$



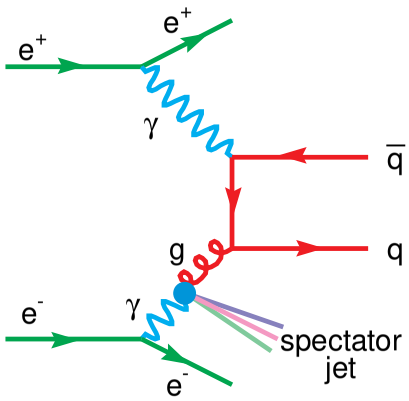
Direct



VDM



Double Resolved



Single Resolved

⇨ The VDM process is dominant.

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

- Data :

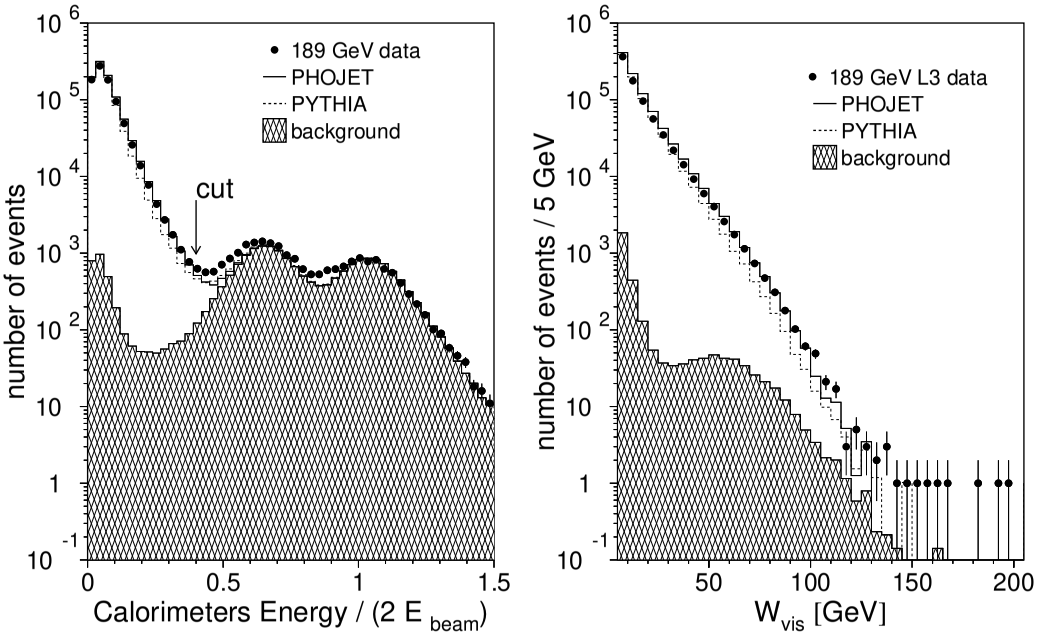
L3 :	91 GeV,	140. pb^{-1}
	130 - 140 GeV,	4.98 pb^{-1}
	161 GeV,	10.4 pb^{-1}
	183 GeV,	51.9 pb^{-1}
	189 GeV,	171.8 pb^{-1}
OPAL:	161 – 172 GeV,	19.9 pb^{-1}
	183 GeV,	54.4 pb^{-1}

- Due to detector effect ➜ $W_{vis} < W_{\gamma\gamma}$
  - Use unfolding for W_{vis} ➜ $W_{\gamma\gamma}$
  - Need good Monte Carlo

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

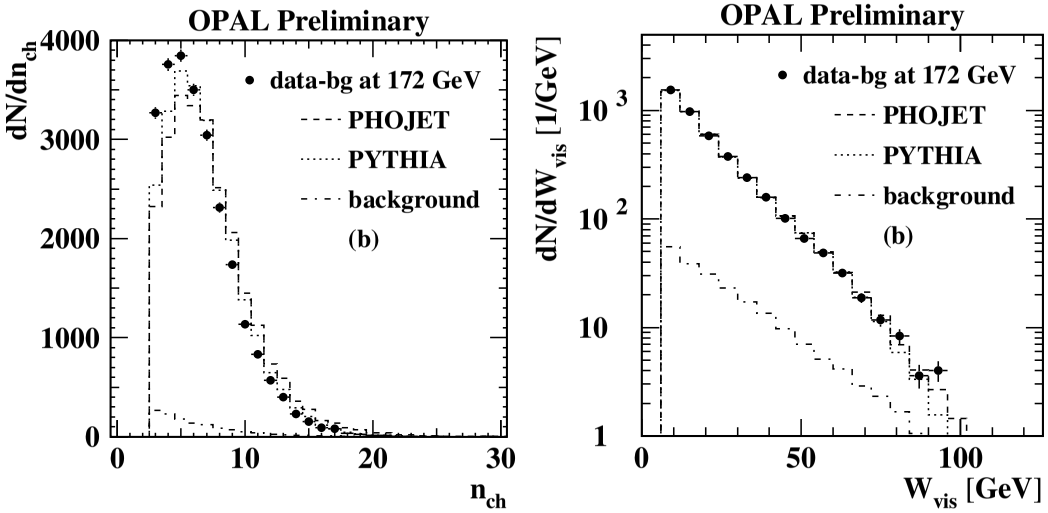
Total $\sigma_{\gamma\gamma}$: MC Comparison

L3 preliminary



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

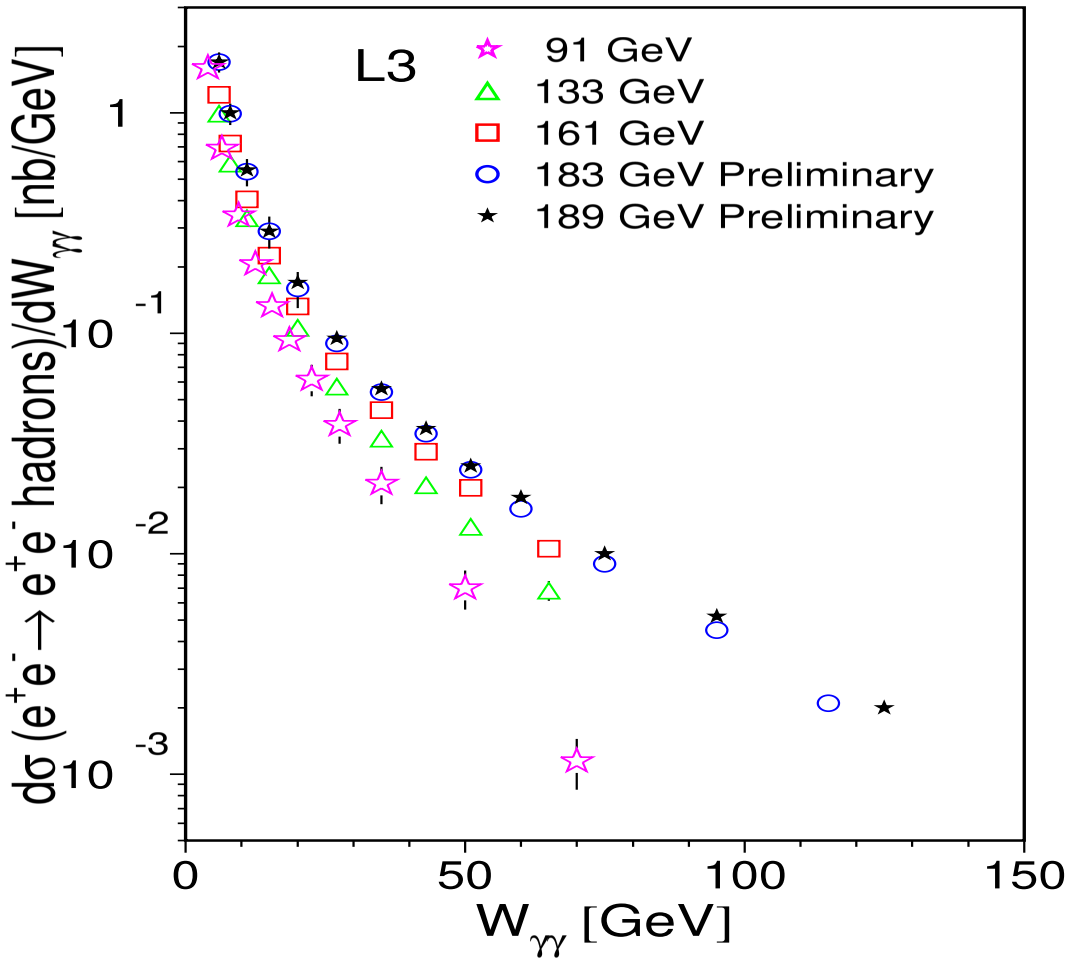
OPAL preliminary



- Satisfactory (not perfect!) agreement with both PYTHIA and PHOJET.

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

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



✻ 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.

L3 Coll., PLB 408(1997)147

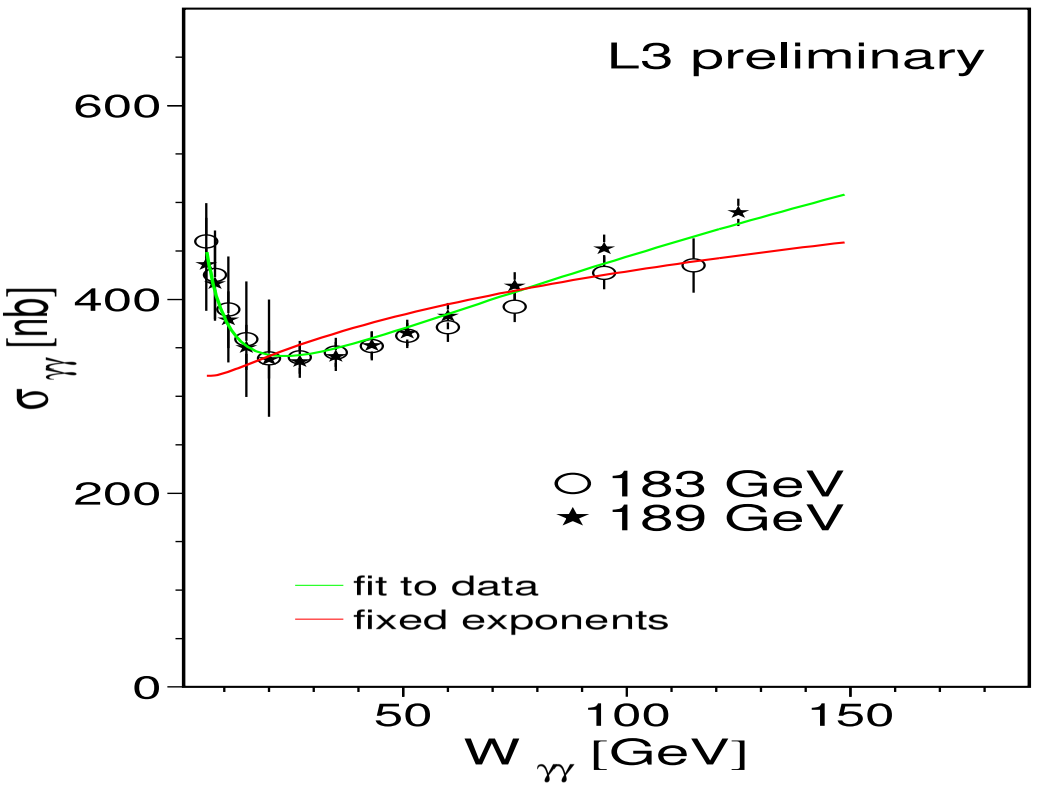
Total $\sigma_{\gamma\gamma}$: DL fit

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

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

- Using the 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)

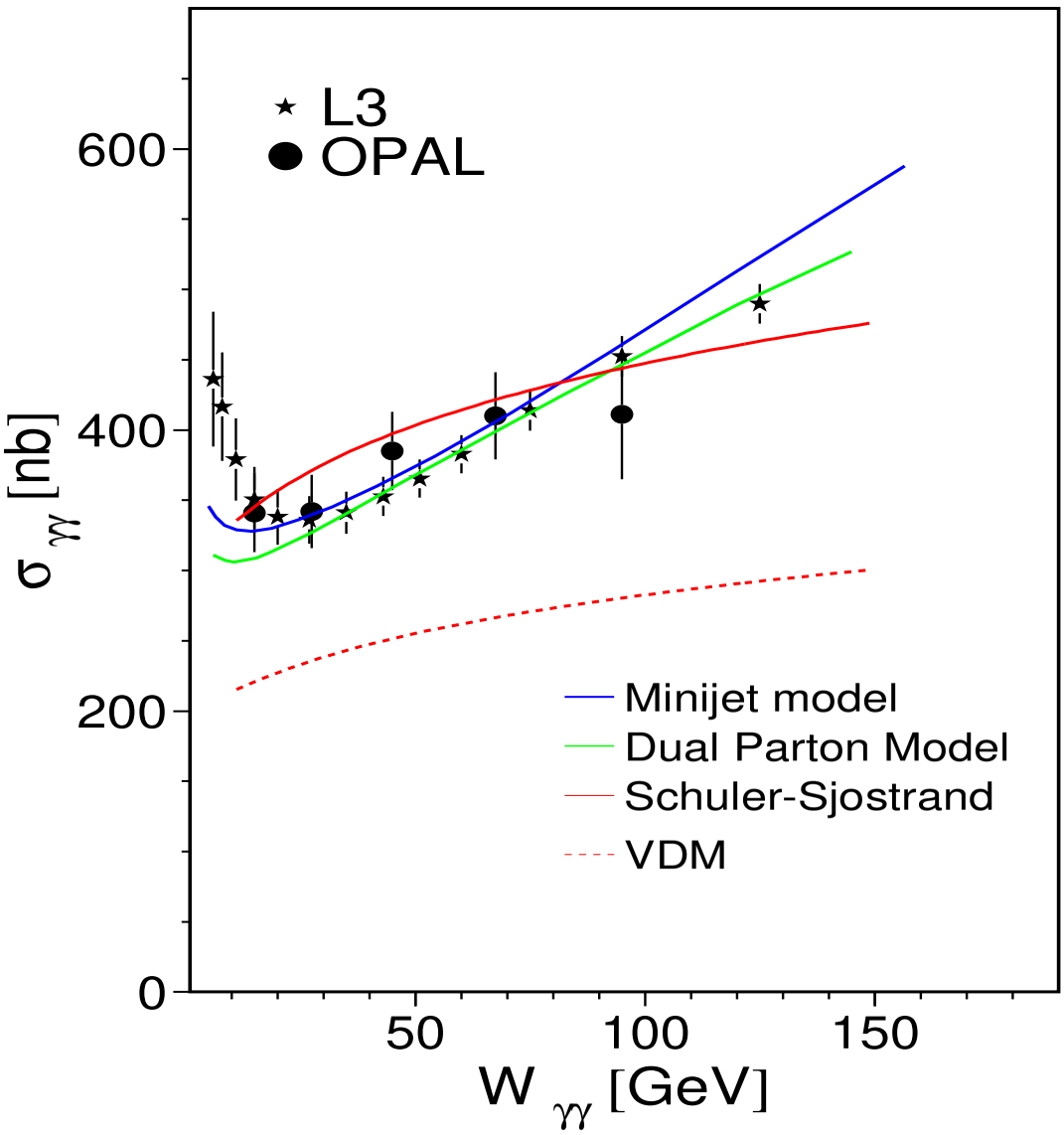
with correlation matrix, $\eta = 0.34$ fixed, A,B free

	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%

Contribution from another Pomeron?! [a]

[a] A.Donnachie,Dosch and Rueter, hep-ph/9810206.

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



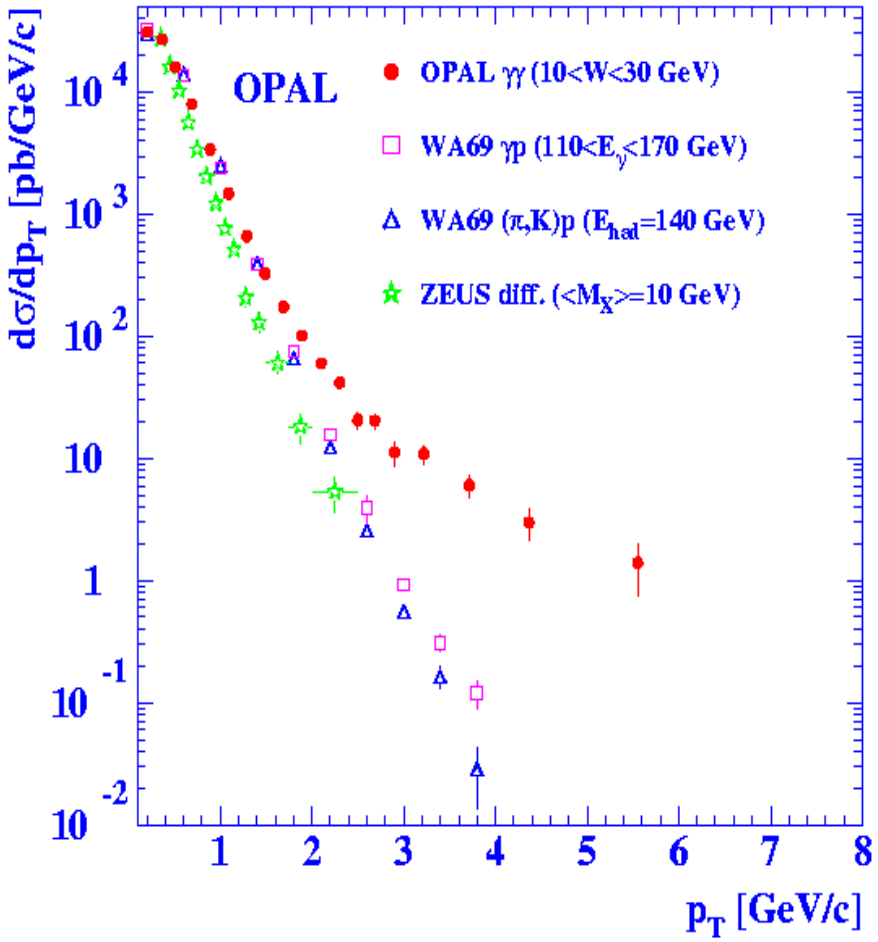
Data unfolded with PHOJET

- Both OPAL and L3 show clear rising behaviour with increasing energy as expected by QCD Models
- The uncertainty on absolute values is large ($\sim 20\%$). ⇨ Due to the MC model dependence.

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

❑ Compare to $\gamma\mathrm{p}$ and $(\pi, \mathrm{K})\mathrm{p}$ interactions.

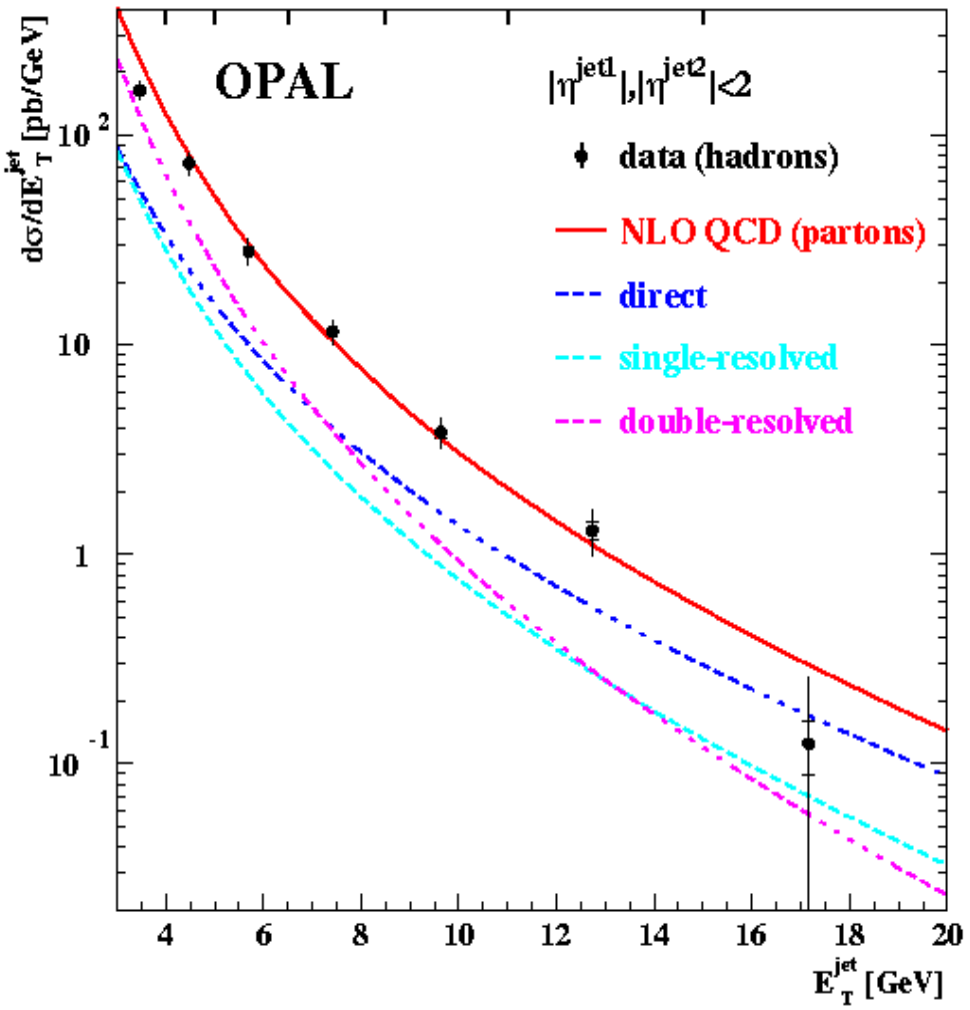
❑ The $\gamma\mathrm{p}$ and $(\pi, \mathrm{K})\mathrm{p}$ are normalised to the low p_T region.



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

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

DiJet Production



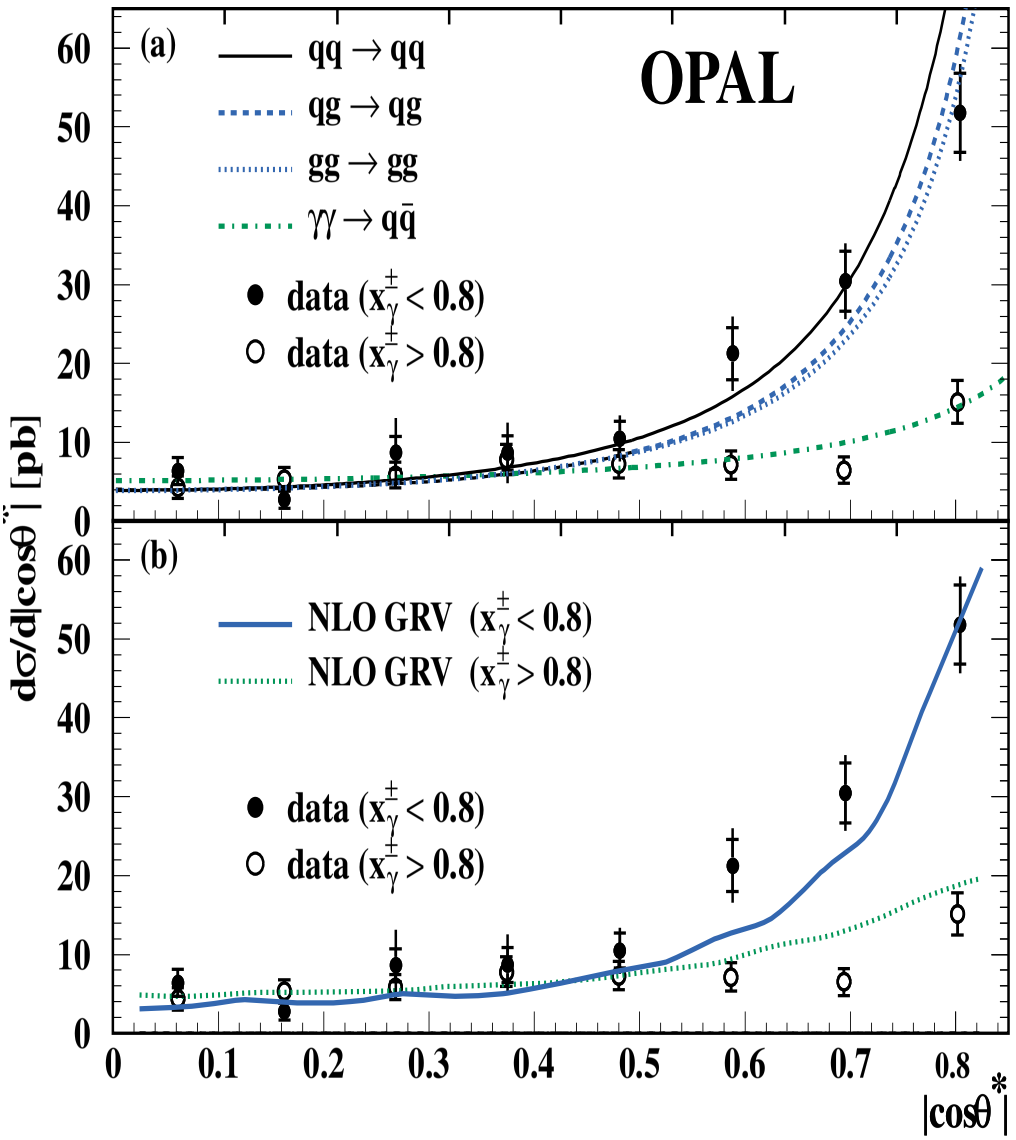
- NLO calculation by Klasen, Kleinwort, Kramer.
- The three processes are needed!

DiJet Production

❒Separation of Direct and Resolved processes

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

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



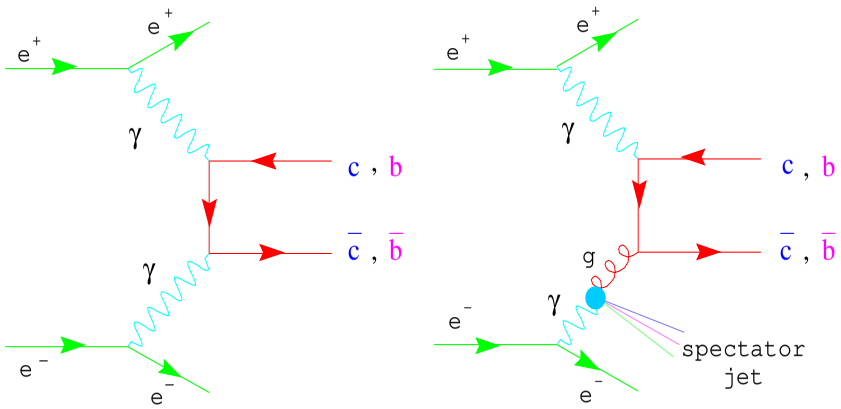
➠ $x_\gamma^\pm < 0.8$ Resolved (Gluon Exchange) $\propto (1 - |cos\theta^*|)^{-2}$

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

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 photon.

❑ Charm identification :

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

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

OPAL : D^{*+} tag

❑ Data :

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

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

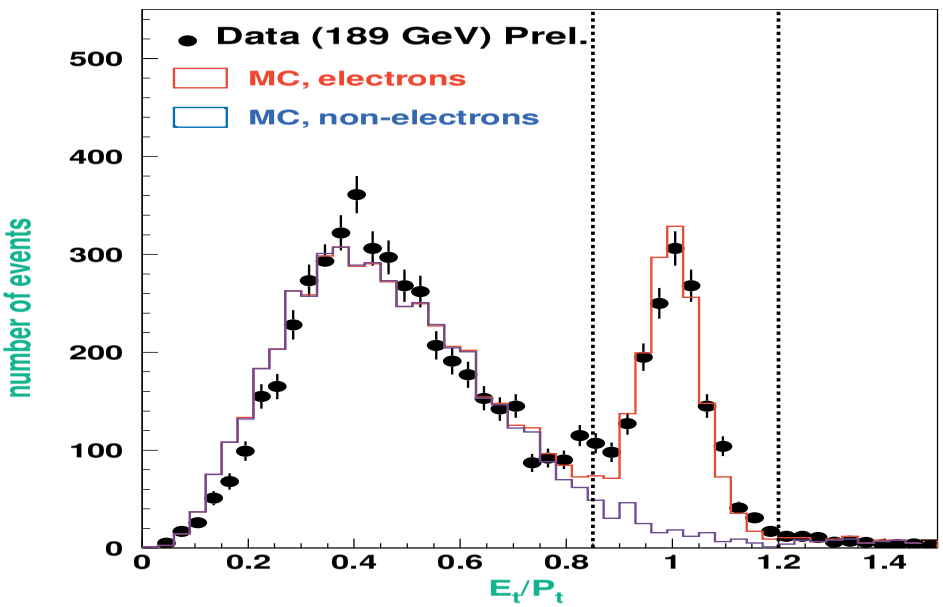
L3* : 189 GeV, $\mathcal{L} = 176$ pb^{-1}

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

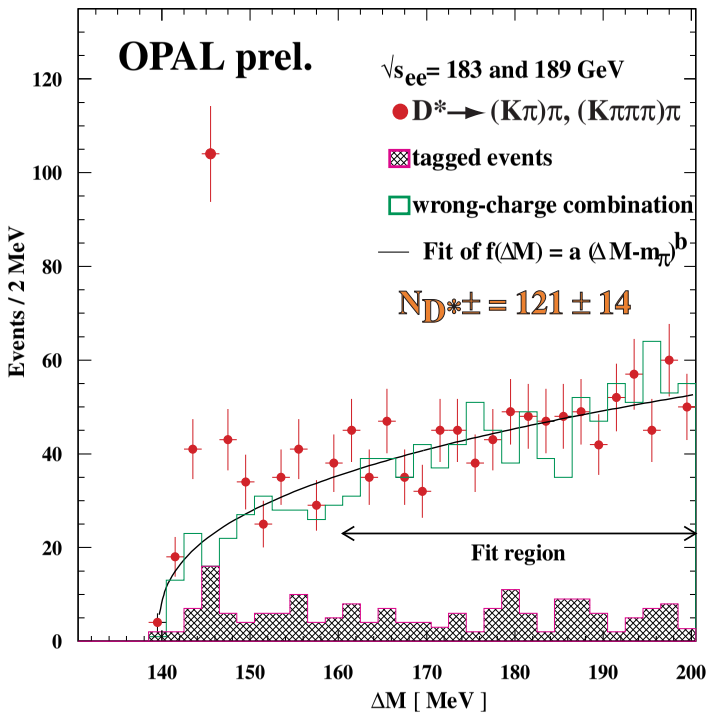
$\star$ Preliminary

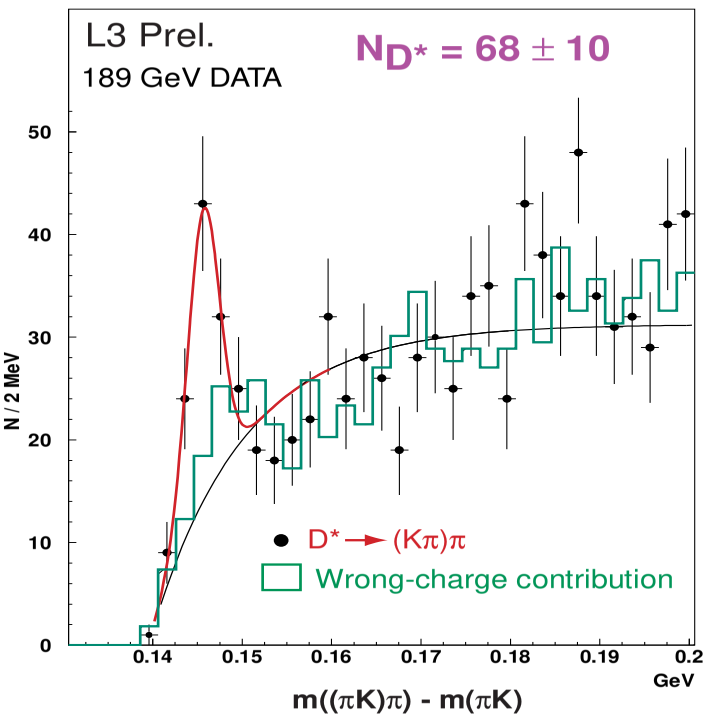
Inclusive Charm Production

❒ Leptonic Tag:

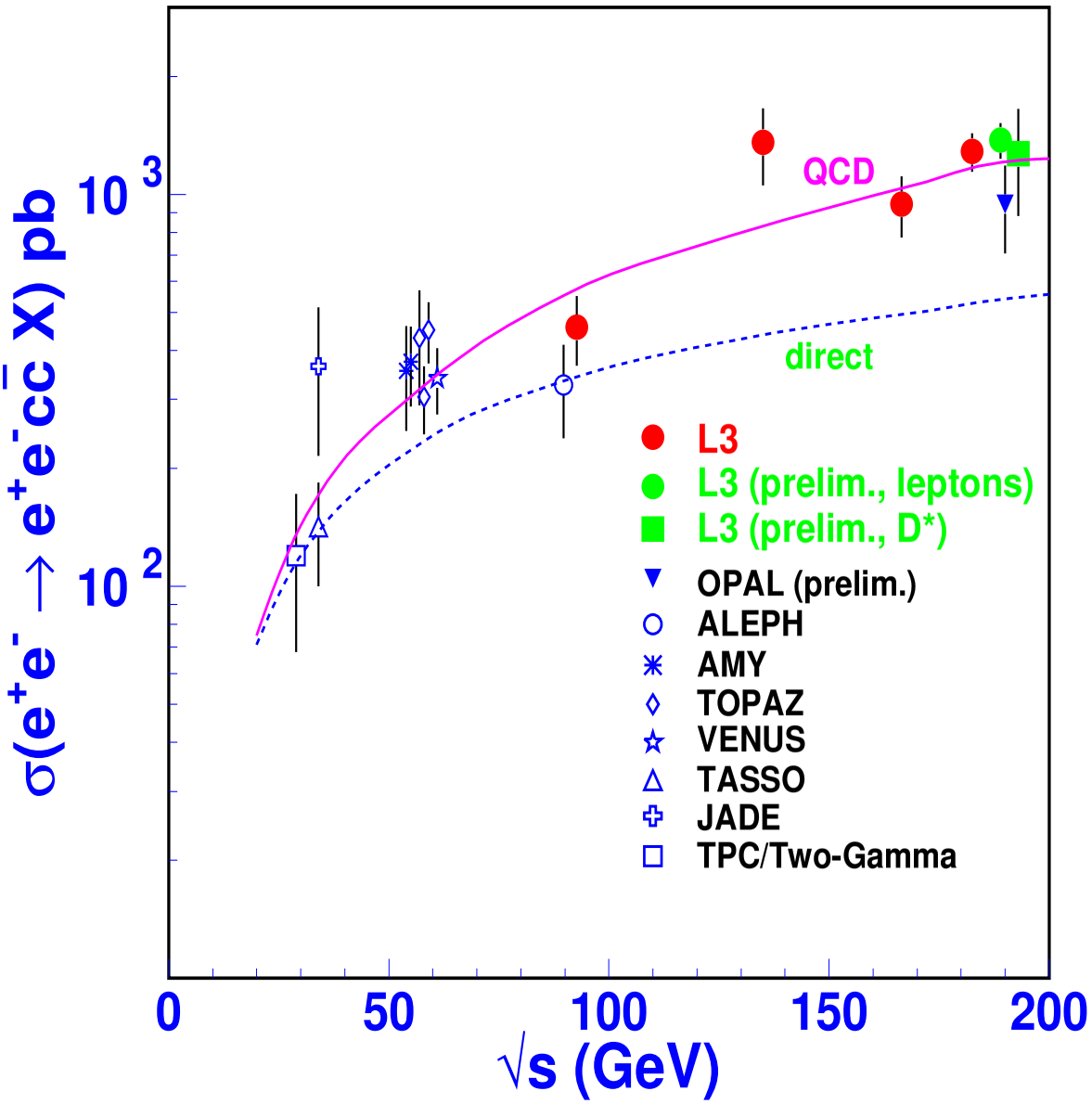


❒ $D^{*\pm} \to D^0\pi_s^{\pm}$, $D^0 \to K^{\pm}\pi^{\pm}$, $D^0 \to K^{\pm}\pi^{\pm}\pi^{\pm}\pi^{\pm}$





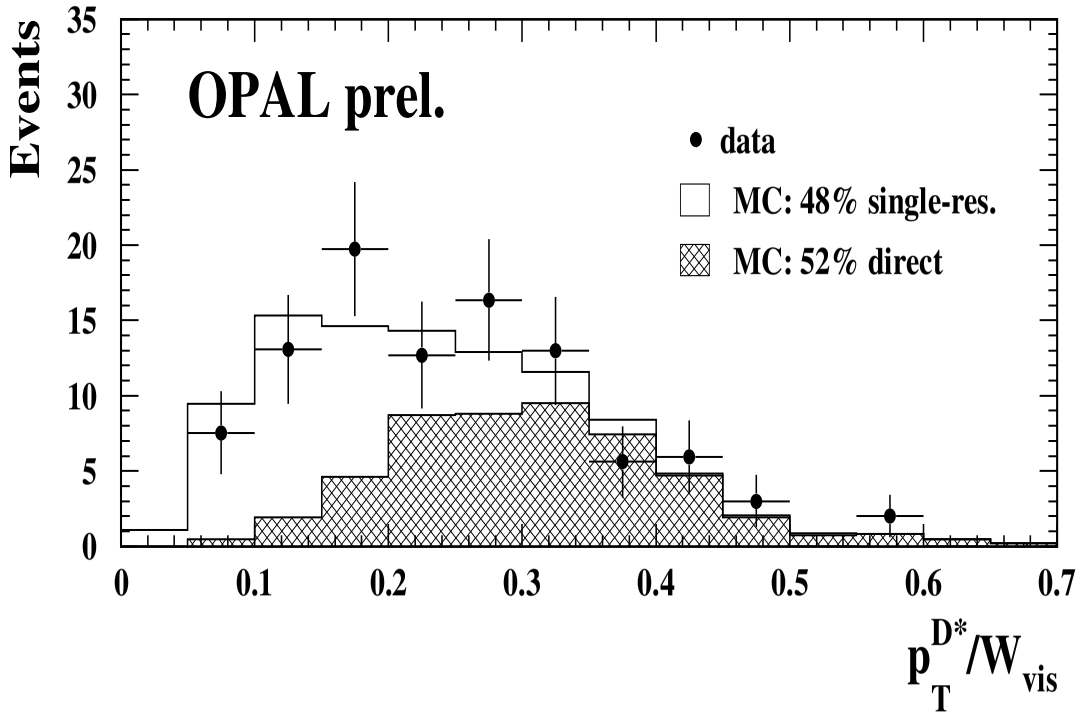
Inclusive Charm Production

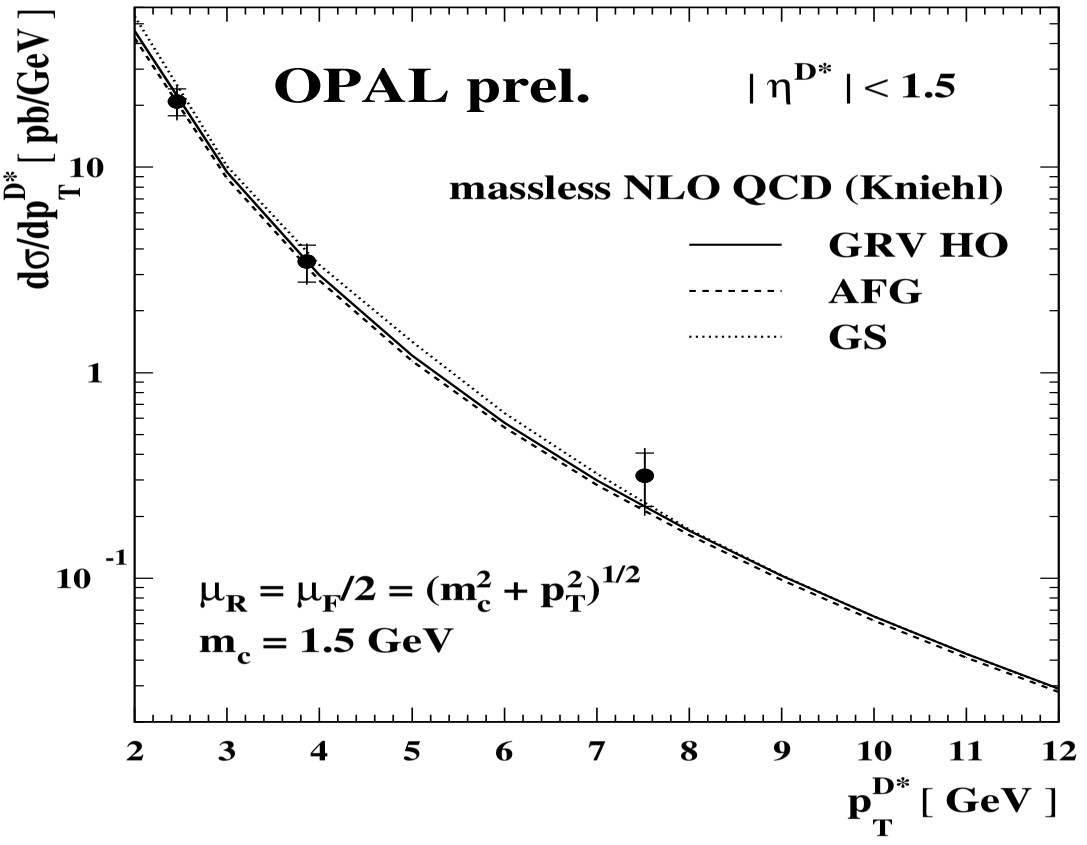


- QCD calculation by Drees, Krämer, Zunft and Zerwas. (Phys. Lett. B306, 371, 1993)
- $\sigma(e^+e^- \to e^+e^- c\bar{c}X)$ increases with the beam energy.
- The direct process is insufficient to describe the data. ➜ The resolved processes are necessary

D^* Production

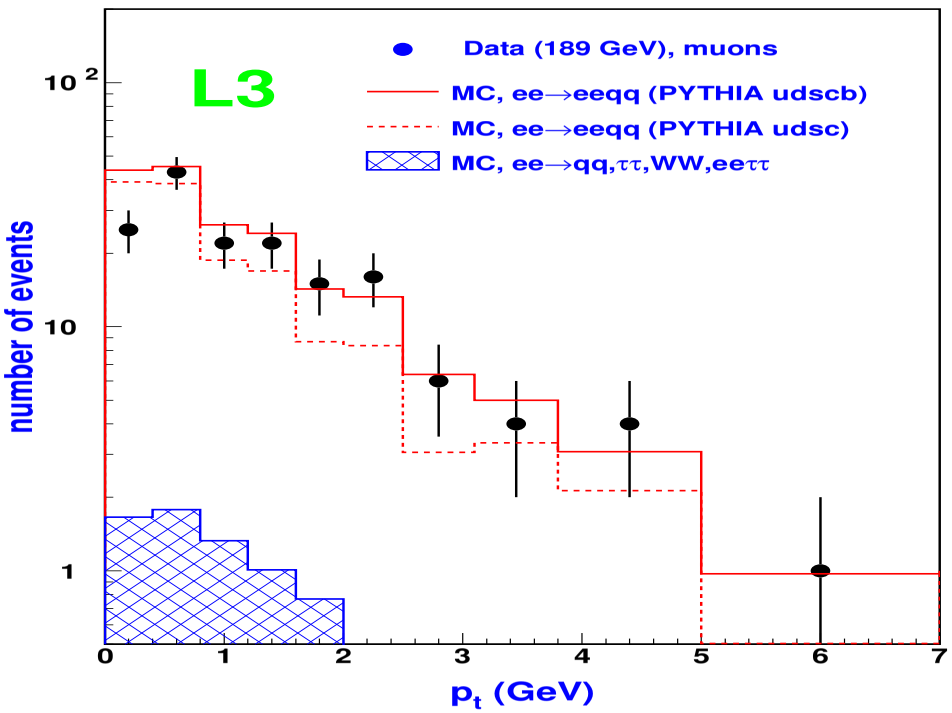
- Data: $\sqrt{s}$ = 183-189 GeV
- Separation of Direct and Resolved processes



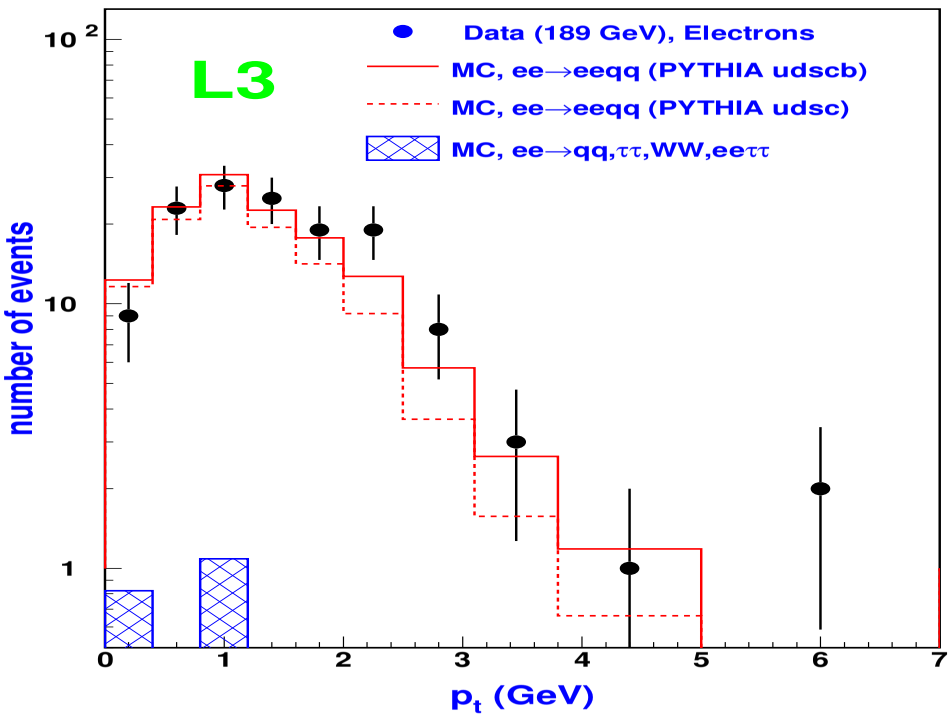


Search for Beauty: L3 Data

p_t with respect to the nearest jet



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



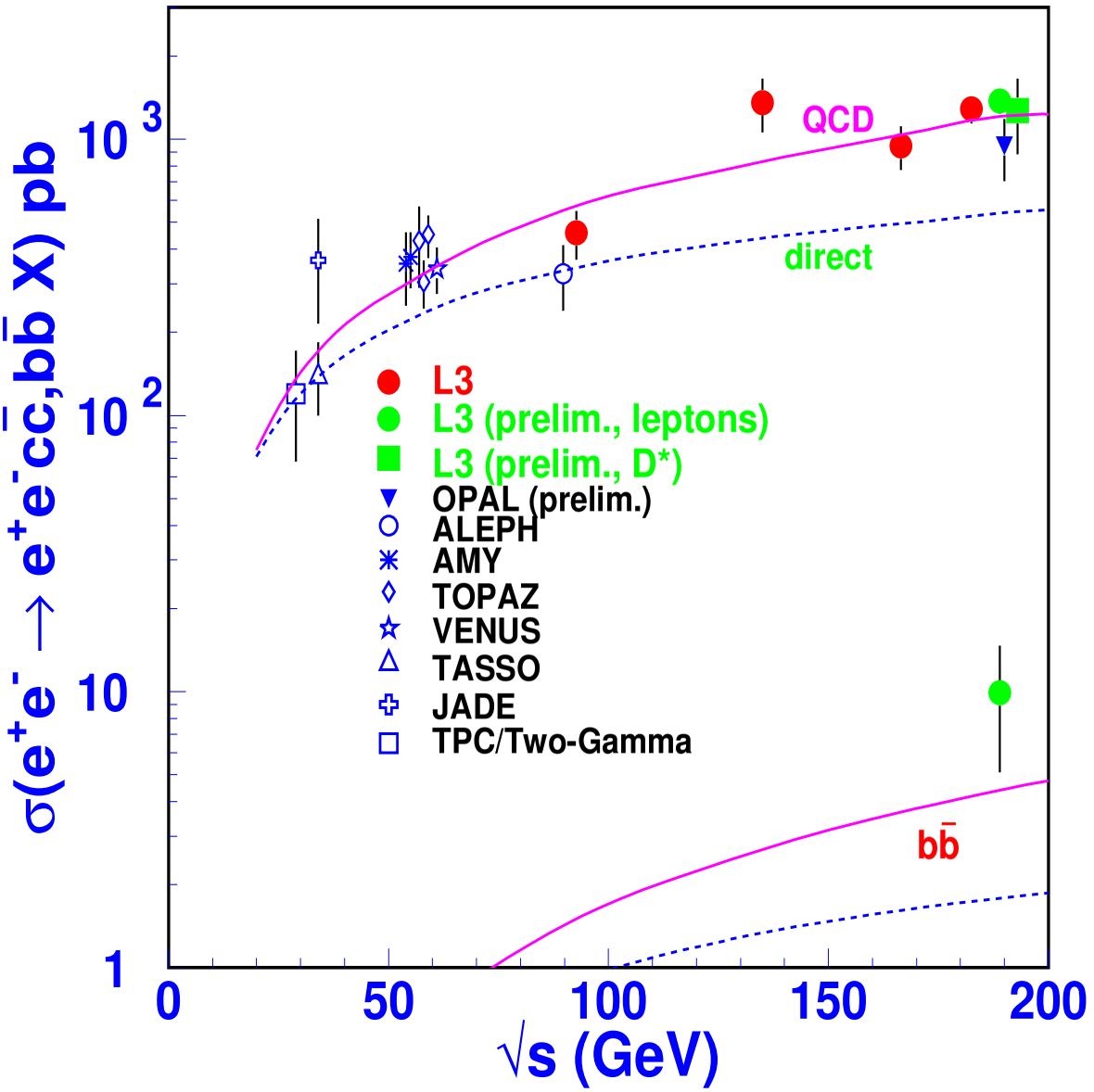
$P_t^{e} > 1$ GeV
$N_{ev}^{e} = 96$
$\varepsilon_b^{e} = 1.6\%$
$\Pi_b^{e} = 28\%$

Leptons from bottom decays have higher p_t.

Beauty Production

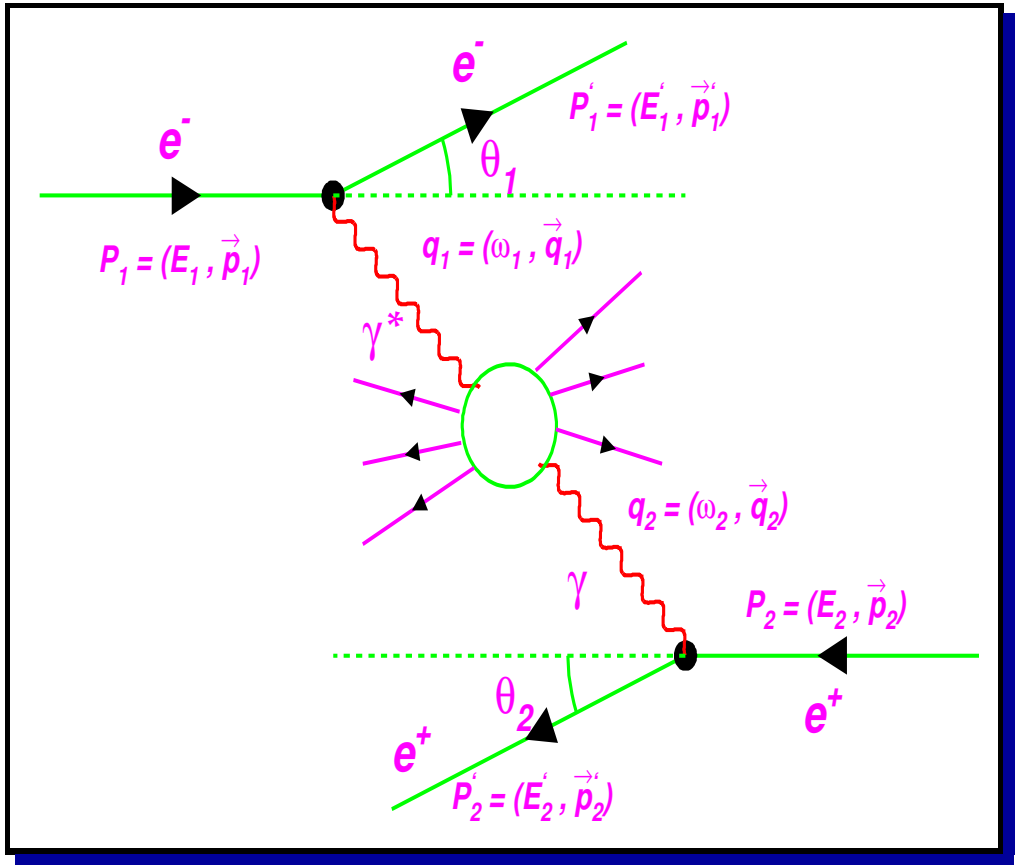
Preliminary measurement at $\sqrt{s} = 189$ GeV

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



- Theory prediction from
  M. Drees,M. Krämer,J. Junft and P.M. Zerwas,PL **B306** 371 (1993); $m_c = 1.3$ GeV, $m_b = 5.0$ GeV.

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

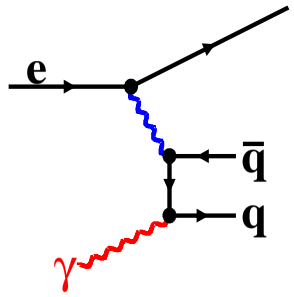
$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4}\frac{1}{x}\left\{1+(1-y)^2F_2^\gamma(x,Q^2) - \frac{y^2}{2}F_L^\gamma(x,Q^2)\right\}$$

➠ Leptonic and Hadronic $F_2^\gamma(x,Q^2)$

Hadronic F_2 : $e^+e \rightarrow e^+e$ hadrons

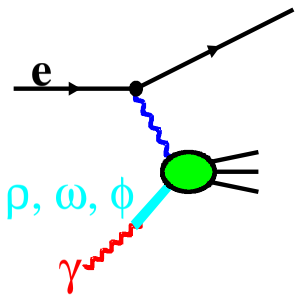
$$F_2^\gamma = F_2^{PL} + F_2^{hadr}$$

- F_2^{PL} : peaks at large x, must include $c\bar{c}$

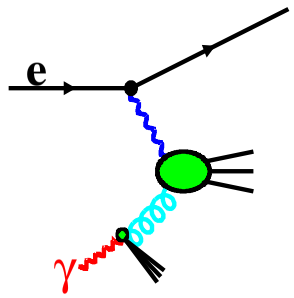


➜ QPM

- F_2^{hadr} : main part at small x

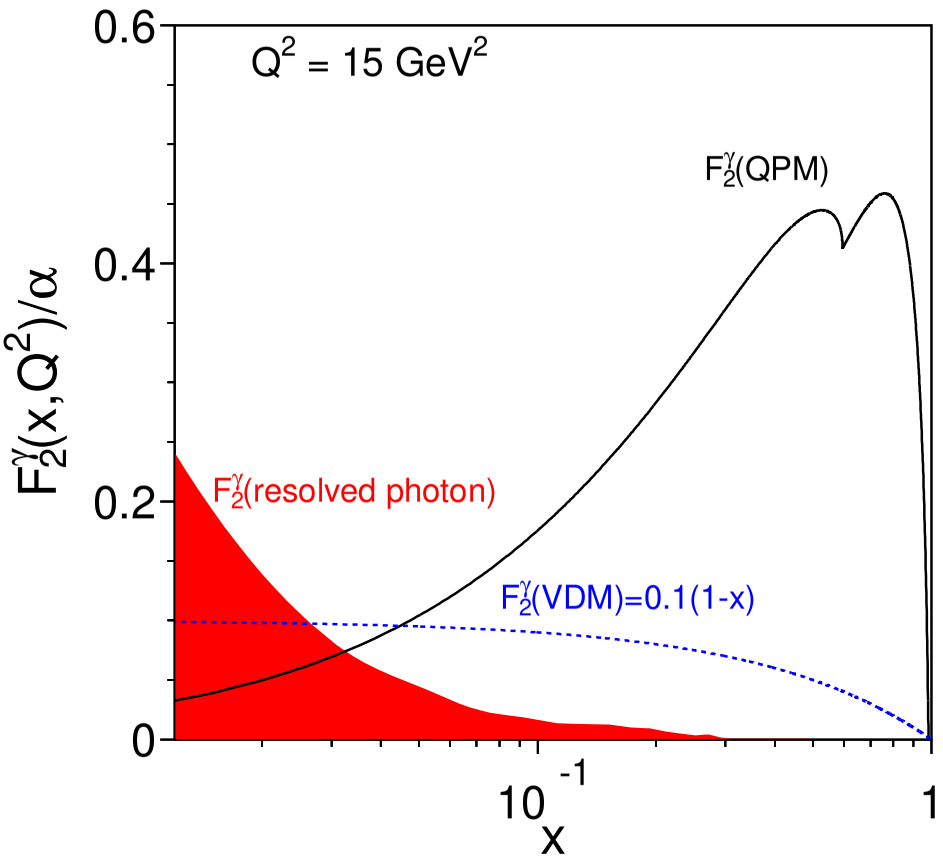


➜ VDM, non-perturbative QCD



➜ Resolved γ, perturbative QCD

F_2: Components



- At high x ➜ Quark constituents are dominant.
- At low x ➜ Gluon constituents are dominant.

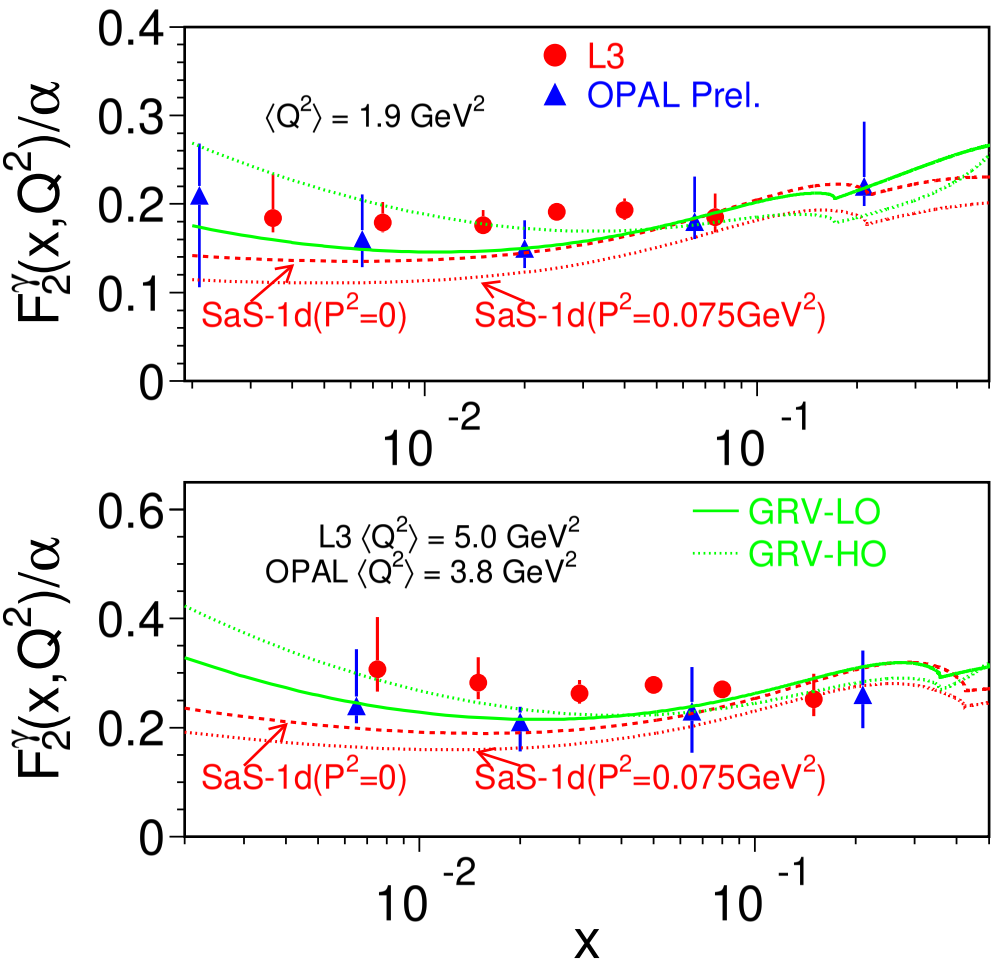
⇨ The low x region is sensitive to the gluon density.

At LEP:

- The Q^2 ranges from 1 GeV^2 to 3000 GeV^2
- The x ranges down to 0.001 GeV^2 at low Q^2

$F_{2,QCD}$:Low Q^2

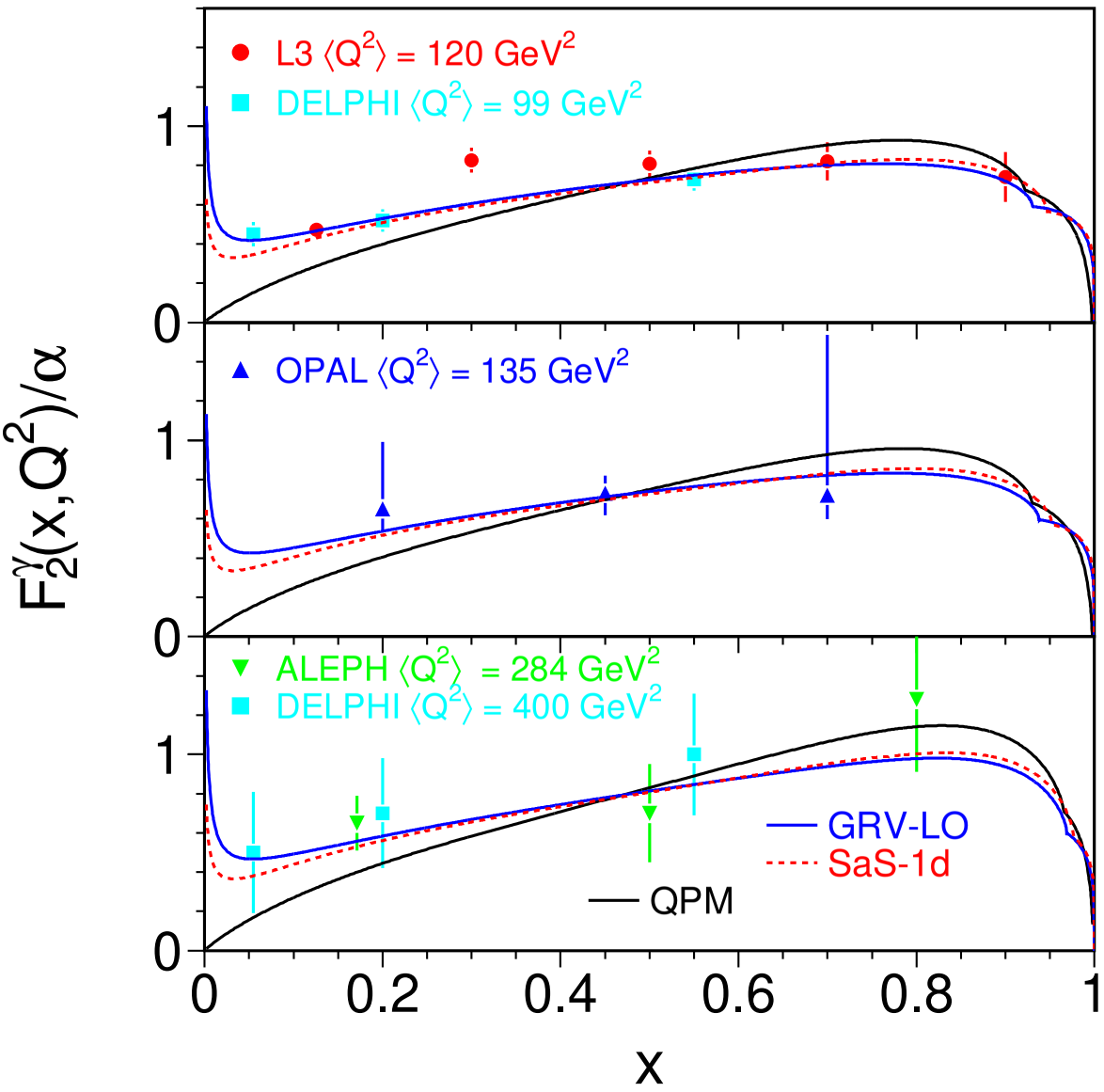
- The measured F_2^γ at low Q^2 ➜ access to low x.



- ⇨ SaS-1d lies below the data
- ⇨ The effect of $< P^2 > \neq 0$ decreases SaS-1d by $\sim 15\%$ ➜ Since $< P^2 >$ depends on the unkown mixture $F_2^{\rm PL}$ and F_2^{hadr} no correction is applied to the data
- ⇨ GRV better at the low x and is for $< P^2 > = 0$

$\mathrm{F_{2,QCD}}$: High Q^2

- The measured $\mathrm{F}^{\gamma}_{2,\mathrm{QCD}}$ at high Q^2

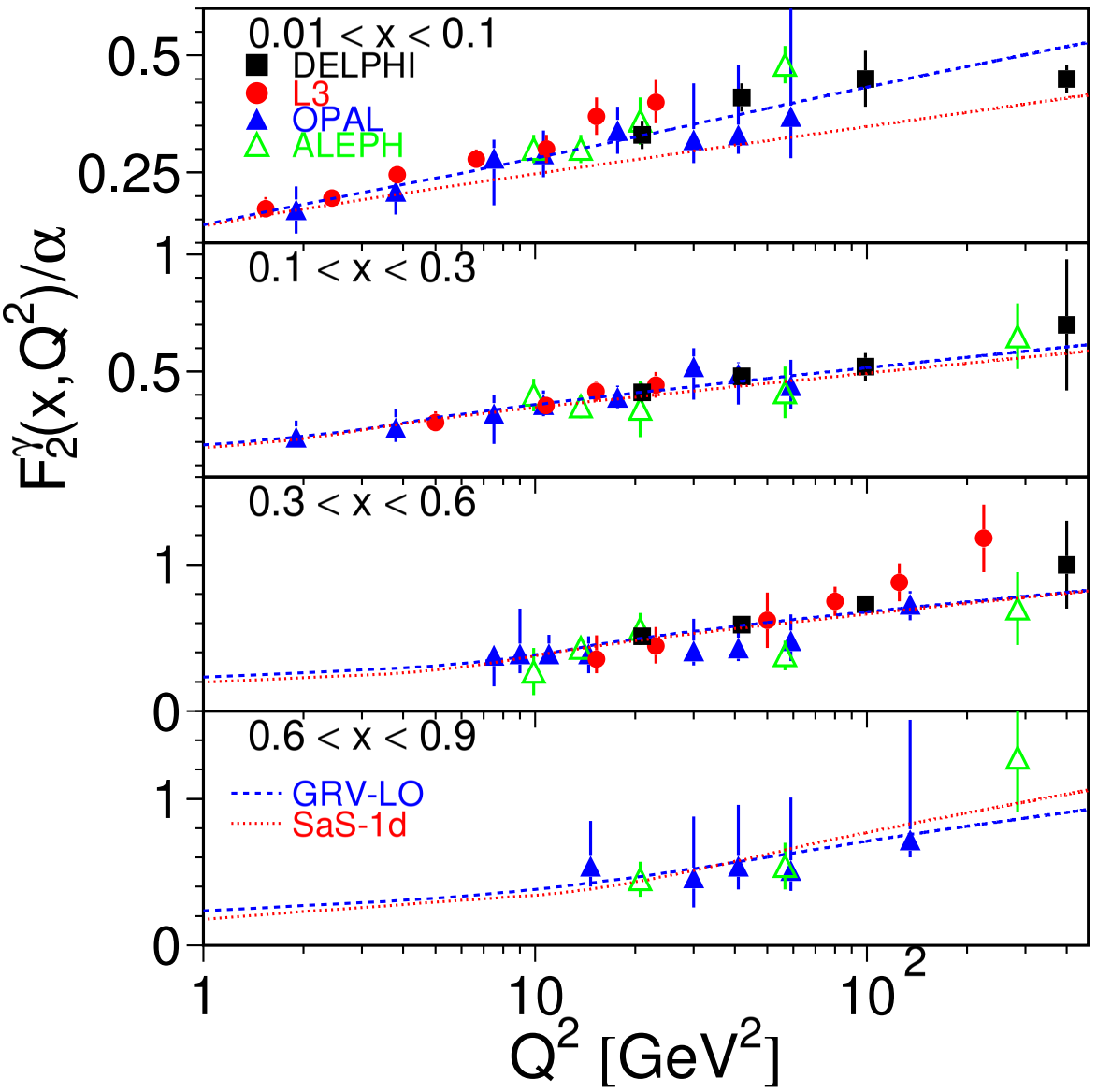


⇨ The QPM model is insufficient to describe the data for $x < 0.3$. ➜ need the resolved processes.

⇨ GRV-LO and SaS-1d agree with the data well

$\mathrm{F_{2,QCD}}$: Q^2 Evolution

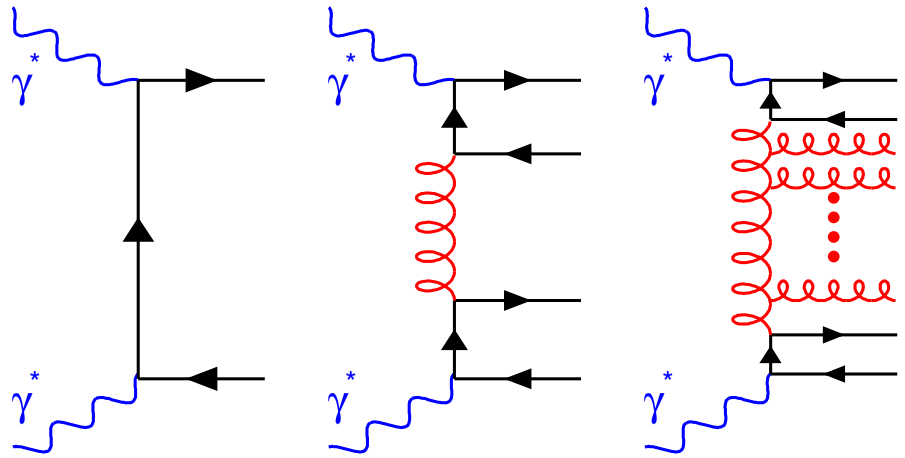
- The measured $\mathrm{F}^{\gamma}_{2,\mathrm{QCD}}$ as a function of $\ln Q^2$



⇨ $\ln Q^2$ evolution well established

⇨ Improvement on the models at low X is needed

$\sigma_{\gamma^*\gamma^*}$ (Double-tagged events)



- J. Bartels et al. (Phys. lett. B389 742, 1996) and S.J. Brodsky et al. (Phys. Rev. D56 6957, 1997) pointed out that the BFKL Pomeron can be investigated in $\gamma^*\gamma^*$ collisions.

  ⇨ The BFKL diagram is predicted to be dominant at high Q^2 and high $W_{\gamma^*\gamma^*}$ for $\ln(\frac{W_{\gamma^*\gamma^*}}{Q^2}) >> 1$

- In Leading order approximation :

$$\sigma_{\gamma^*\gamma^*} = \sigma_0(Q^2, Y)\,(\tfrac{s}{s_0})^{\alpha_P - 1} = \sigma_0(Q^2, Y)\, e^{Y.(\alpha_P - 1)}$$

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

Using $N_c = 3$, $\alpha_s = 0.2$ ➜ $\alpha_P - 1 \simeq 0.53$
$(> 0.095$ "soft Pomeron")

- Next to leading order calculations by S.J. Brodsky et al. (hep-ph/9901229) give $\alpha_P - 1 \leq 0.175$

$\sigma_{\gamma^*\gamma^*}$: 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}

→ L3:

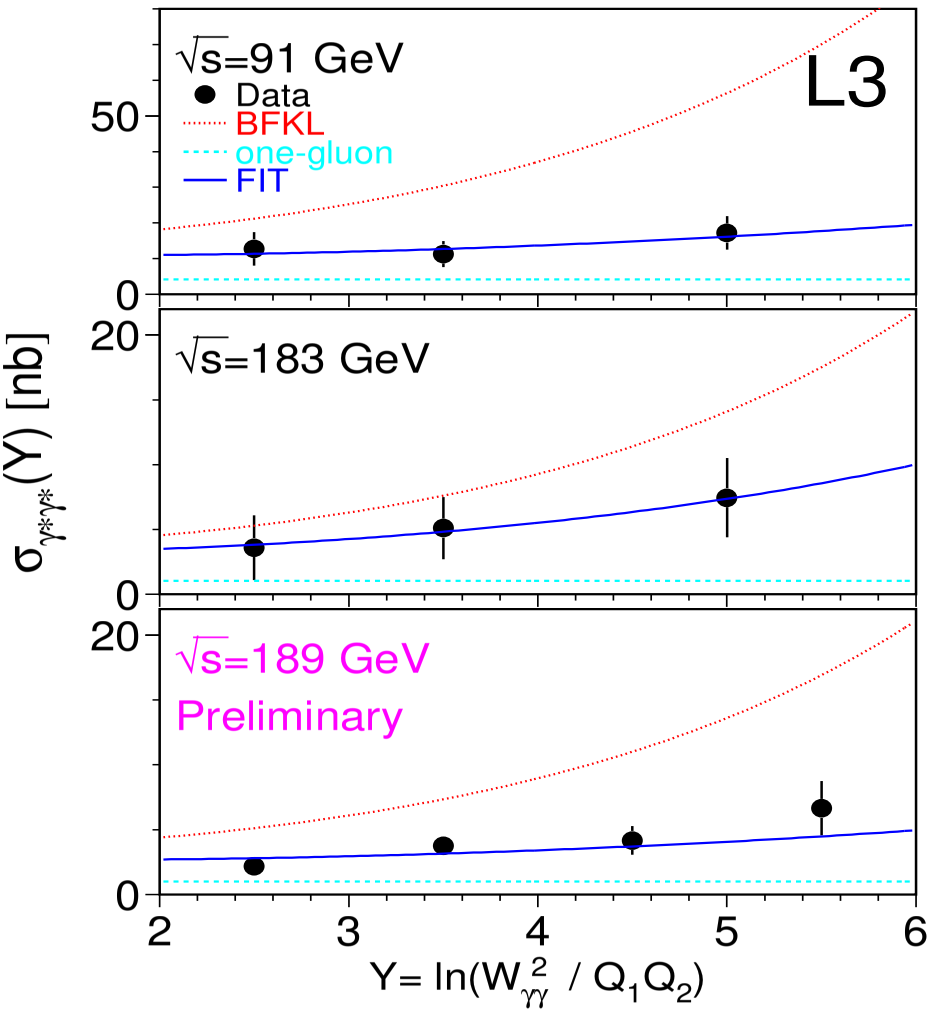
$\sqrt{s}$	91 GeV	183 GeV	189 GeV
$W_{\gamma\gamma}$	2 - 3 GeV	5 - 70 GeV	5 - 75 GeV
Q^2	1 - 9 GeV^2	2 - 35 GeV^2	3 - 37 GeV^2
$< Q^2 >$	3.5 GeV^2	14 GeV^2	14.5 GeV^2

Events	137	34	108
Bkg	12	4	14

→ OPAL: 44 Events

- 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

$\sigma_{\gamma^*\gamma^*}$: Results



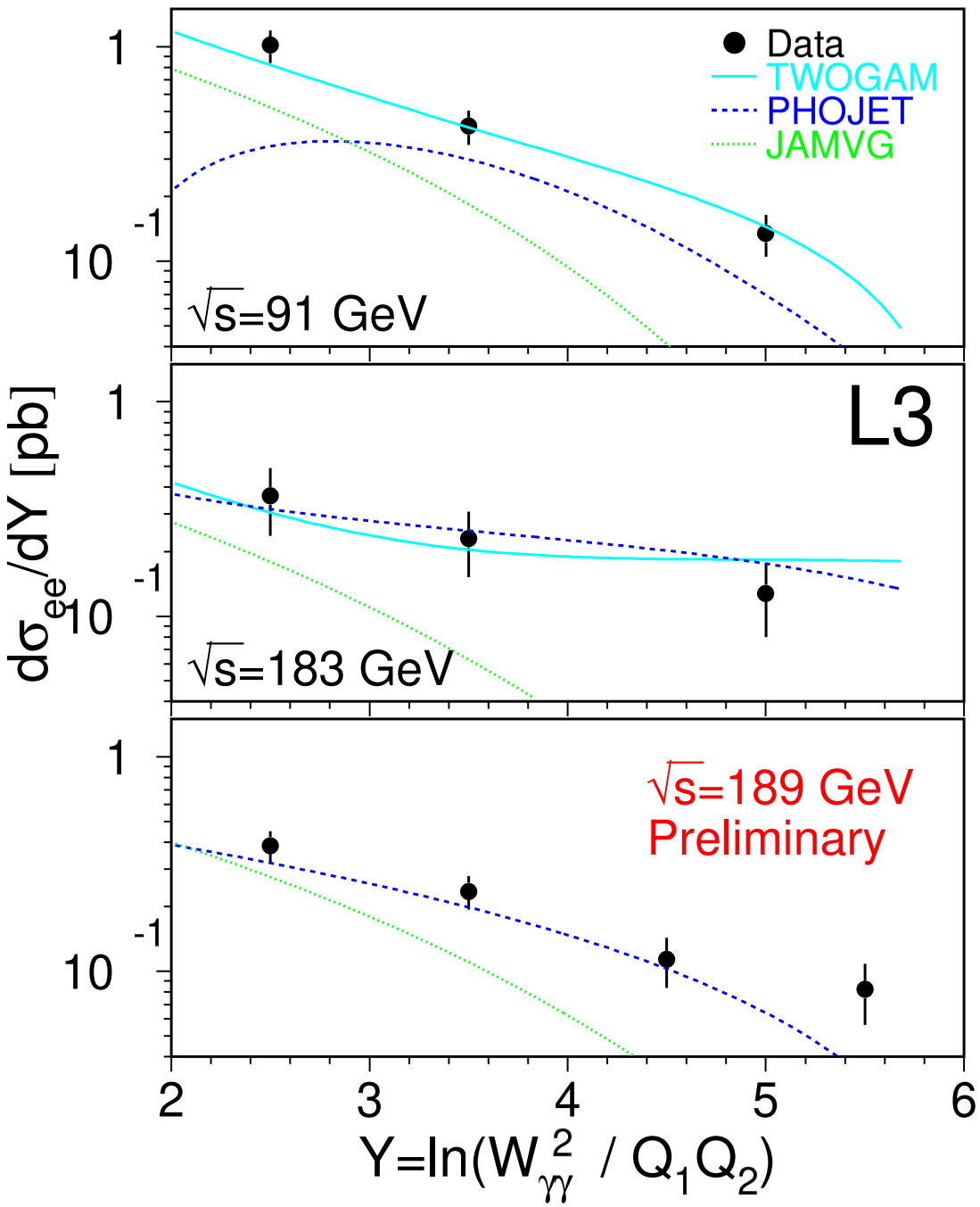
combined fit:

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

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

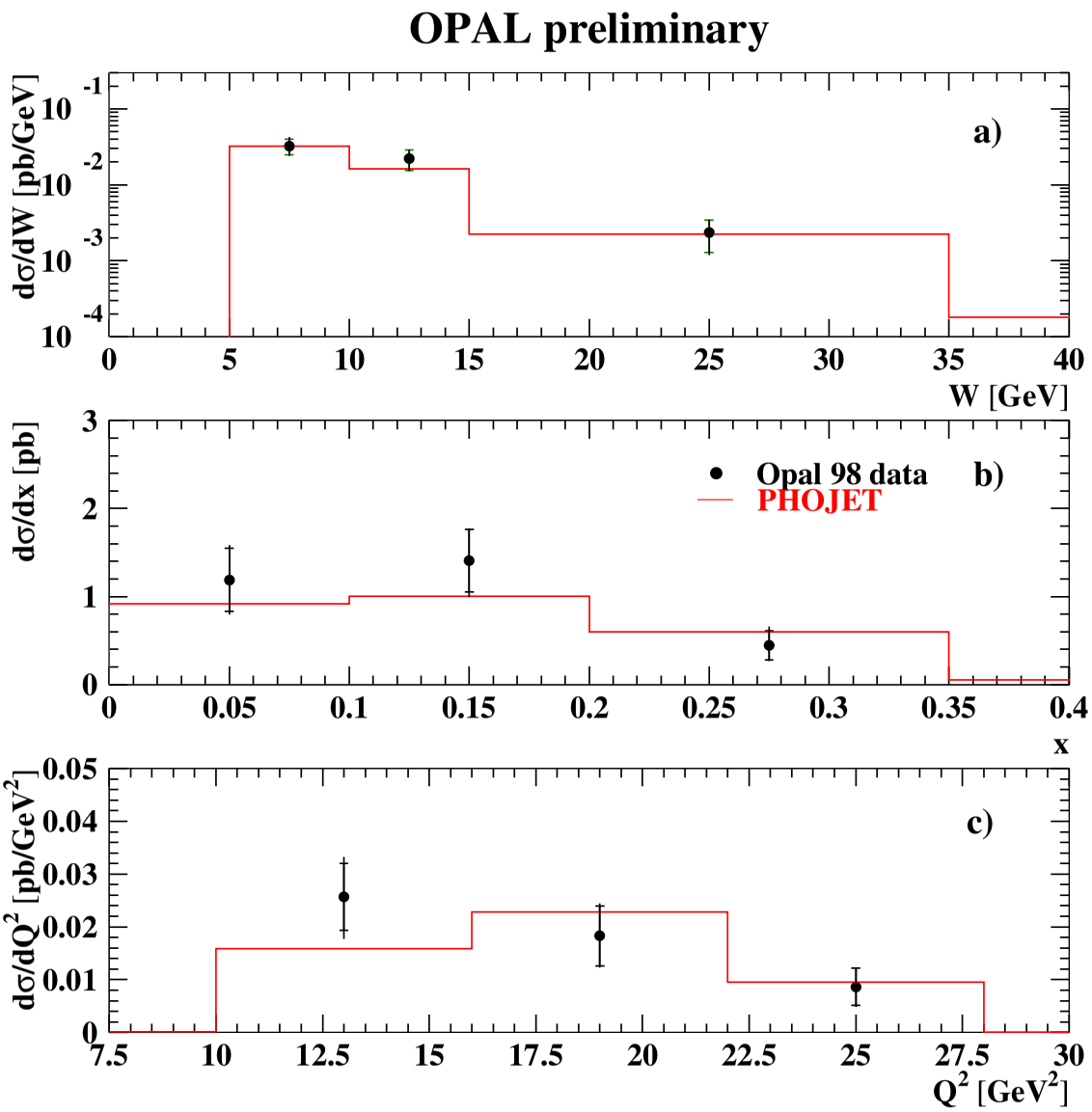
$$\chi^2_{LO-BFKL}/d.o.f. = 263/9 \qquad \chi^2_{NLO-BFKL}/d.o.f. = 21/9$$

σ_{ee} : Results



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

σ_{ee} : Results



Conclusions

⇨ Two-photon collisions are a rich field of physics at LEP; our understanding of these processes is more and more growing

⇨ LEP will run until the year 2000

➜ more data are coming

➜ even more precise results are foreseen

To match the good data precision

we need to improve

models and Monte Carlo!