Two Photon Physics at LEP

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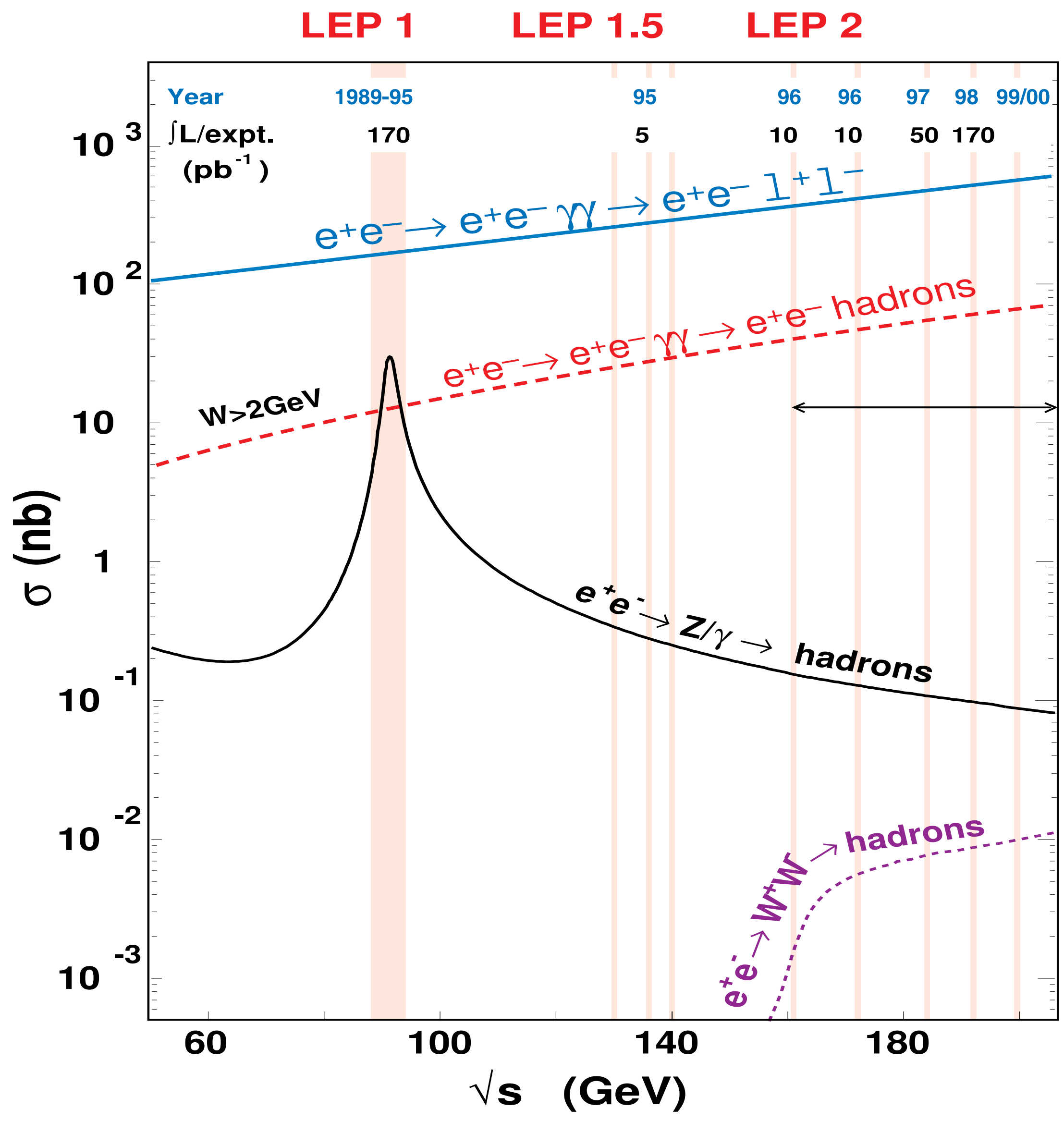
Physics In Collisions
Ann Arbor, Michigan

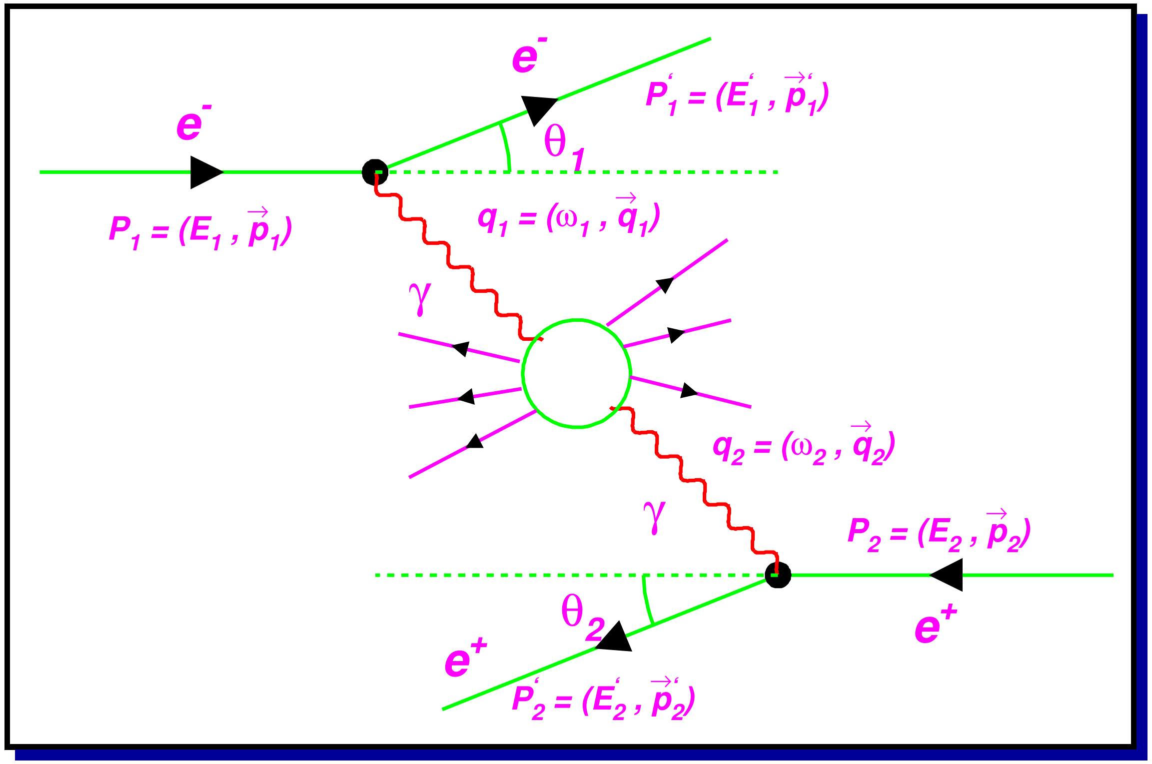
Introduction



- 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)

Photon Photon Collision



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

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

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

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

Photon Photon Collision

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

Photon Photon Collision

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

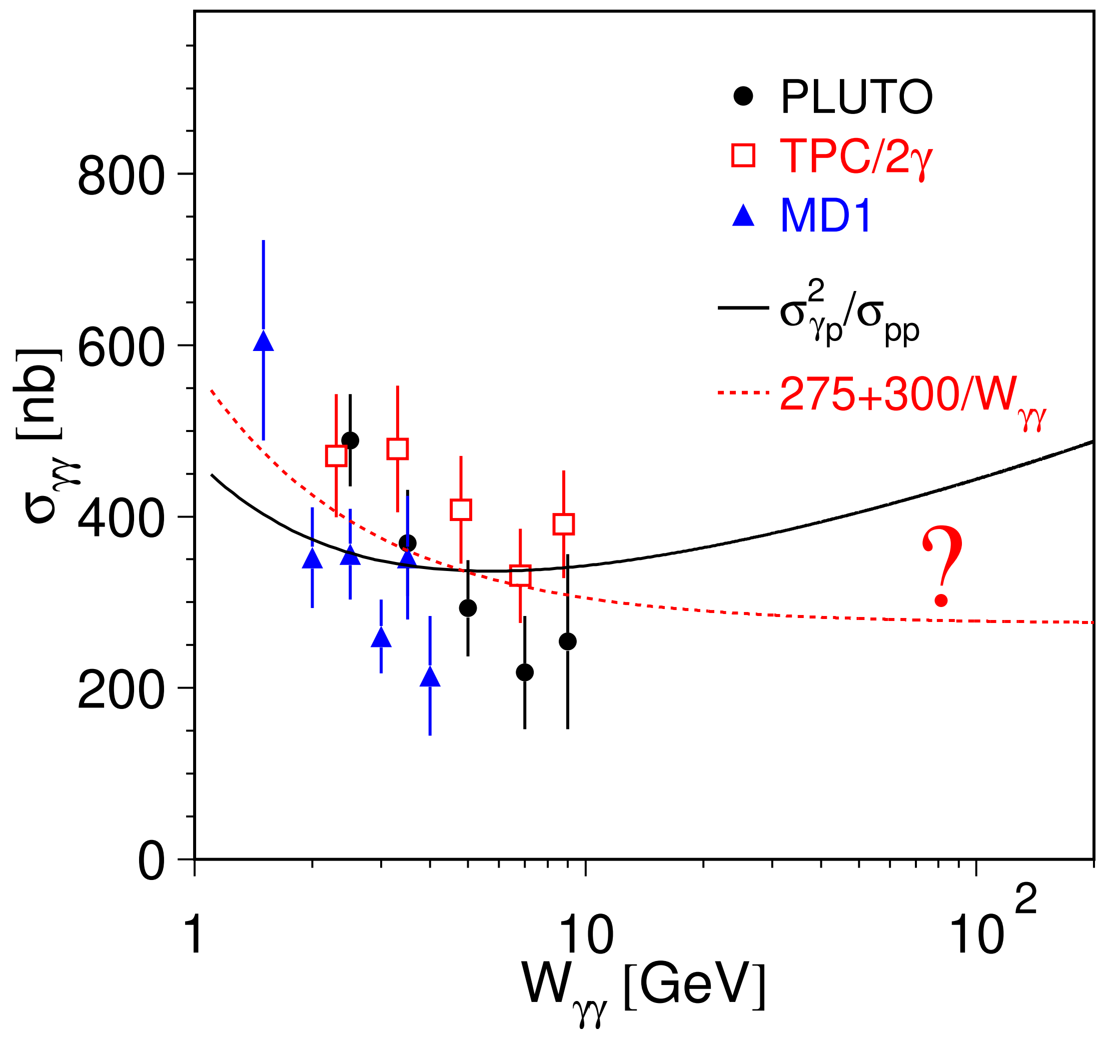
❒ We can study :

➩ Cross-section of $\gamma^*\gamma^*$ collision ➔ BFKL Pomeron

➩ Virtual photon structure function

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

The measurements before LEP :

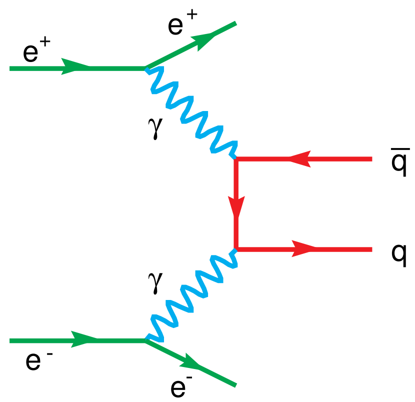


- Limited by beam energy ➜ $W_{\gamma\gamma} < 10$ GeV.
- Wide spread in the measurements.
- Does $\sigma_{\gamma\gamma}$ increase at high energy ?
- At LEP, $5 \text{ GeV} < W_{\gamma\gamma} < 145 \text{ GeV}$ has been measured.

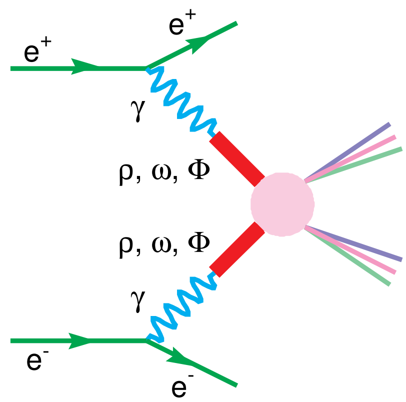
Total $\sigma_{\gamma\gamma}$: Physics

The diagrams contributing to :

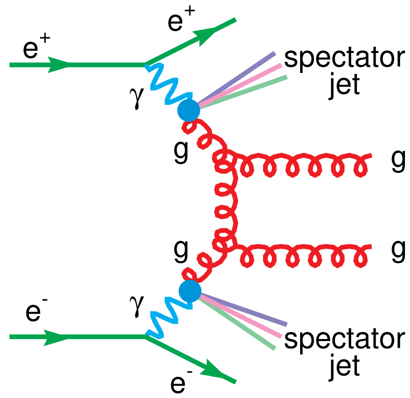
$$e^+e^- \rightarrow e^+e^-\gamma\gamma \rightarrow e^+e^-\mathrm{hadrons}$$



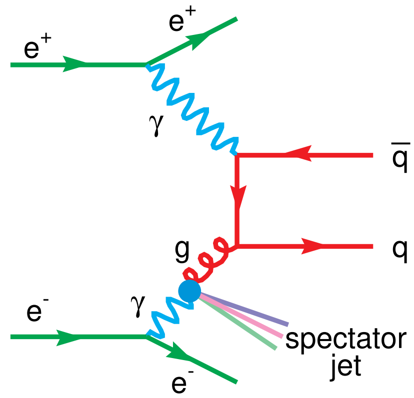
Direct



VDM



Double Resolved



Single Resolved

➩ The VDM process is dominant.

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

- Data :

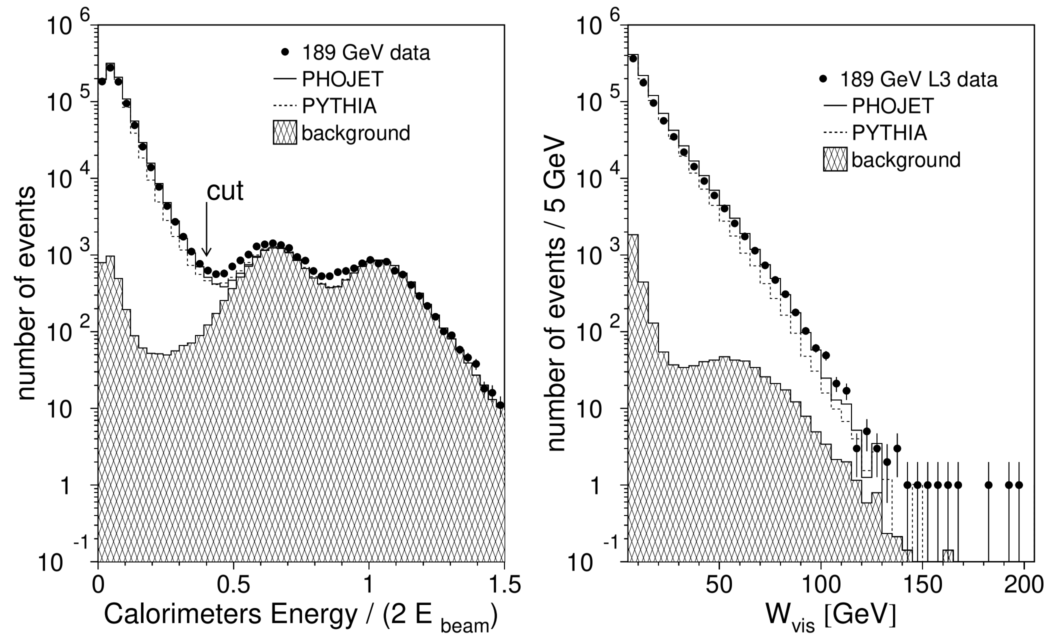
L3 :		91 GeV,	140. pb^{-1}
	130 - 140	GeV,	4.98 pb^{-1}
		161 GeV,	10.4 pb^{-1}
	183	GeV,	51.9 pb^{-1}
	189	GeV,	171.8 pb^{-1}
OPAL:	$161 - 172$	GeV,	19.9 pb^{-1}
	183	GeV,	54.4 pb^{-1}

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

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

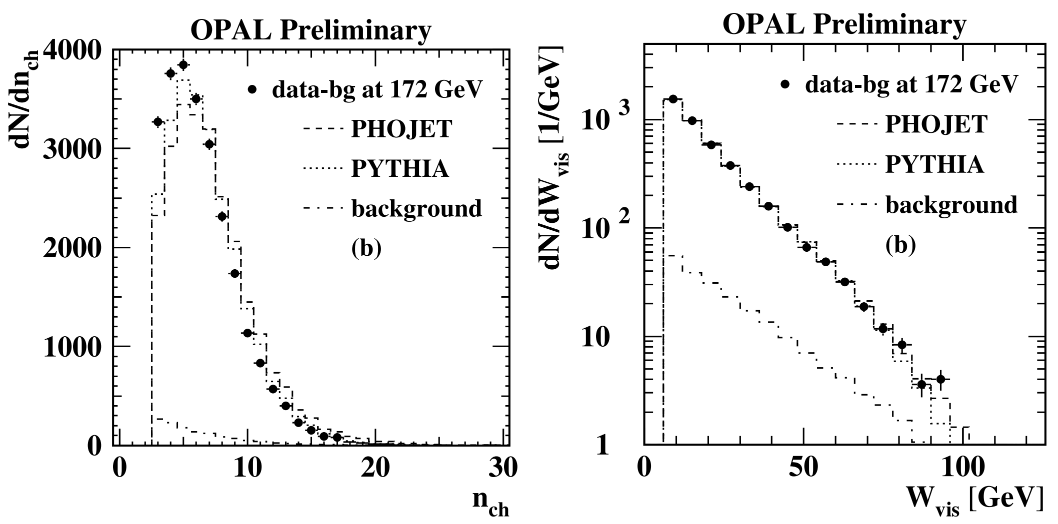
Total $\sigma_{\gamma\gamma}$: MC Comparison

L3 preliminary



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

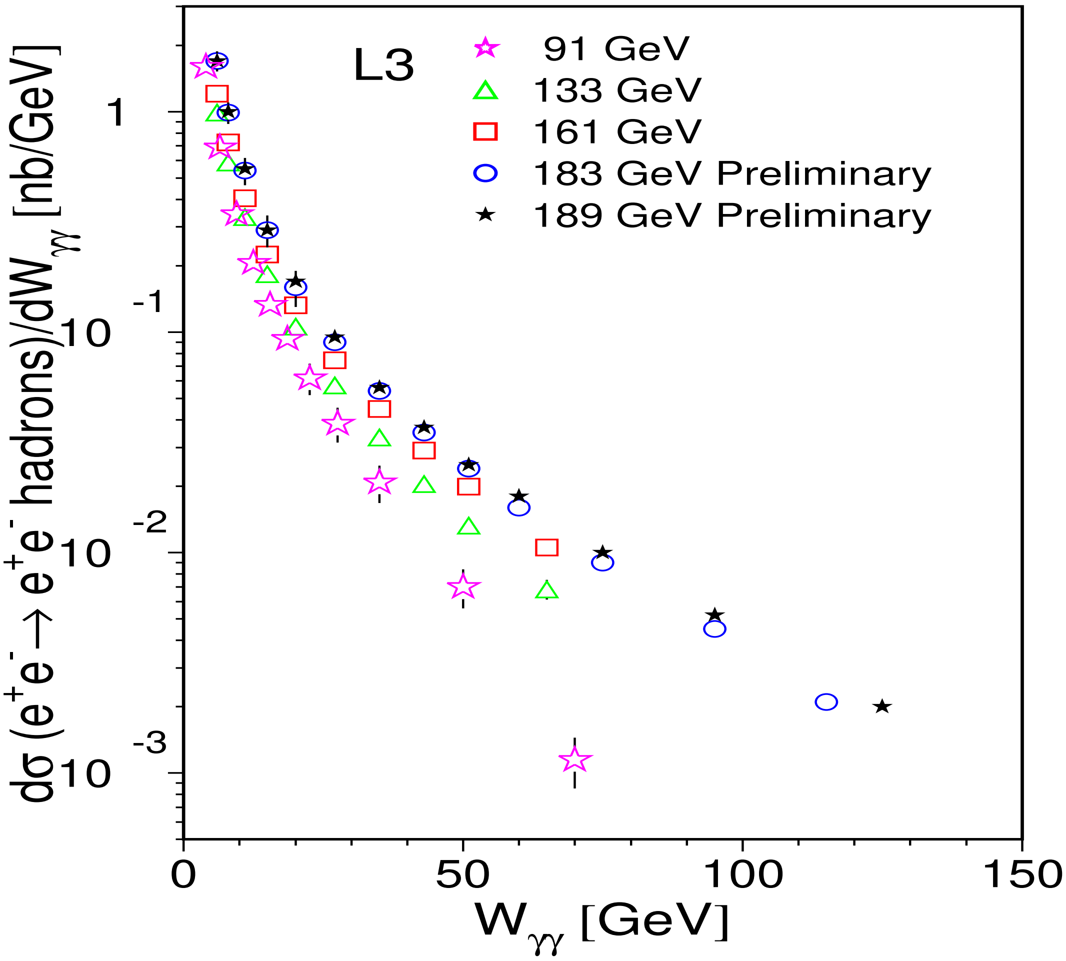
OPAL preliminary



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

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

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



✻ 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 $d\sigma_{ee}$

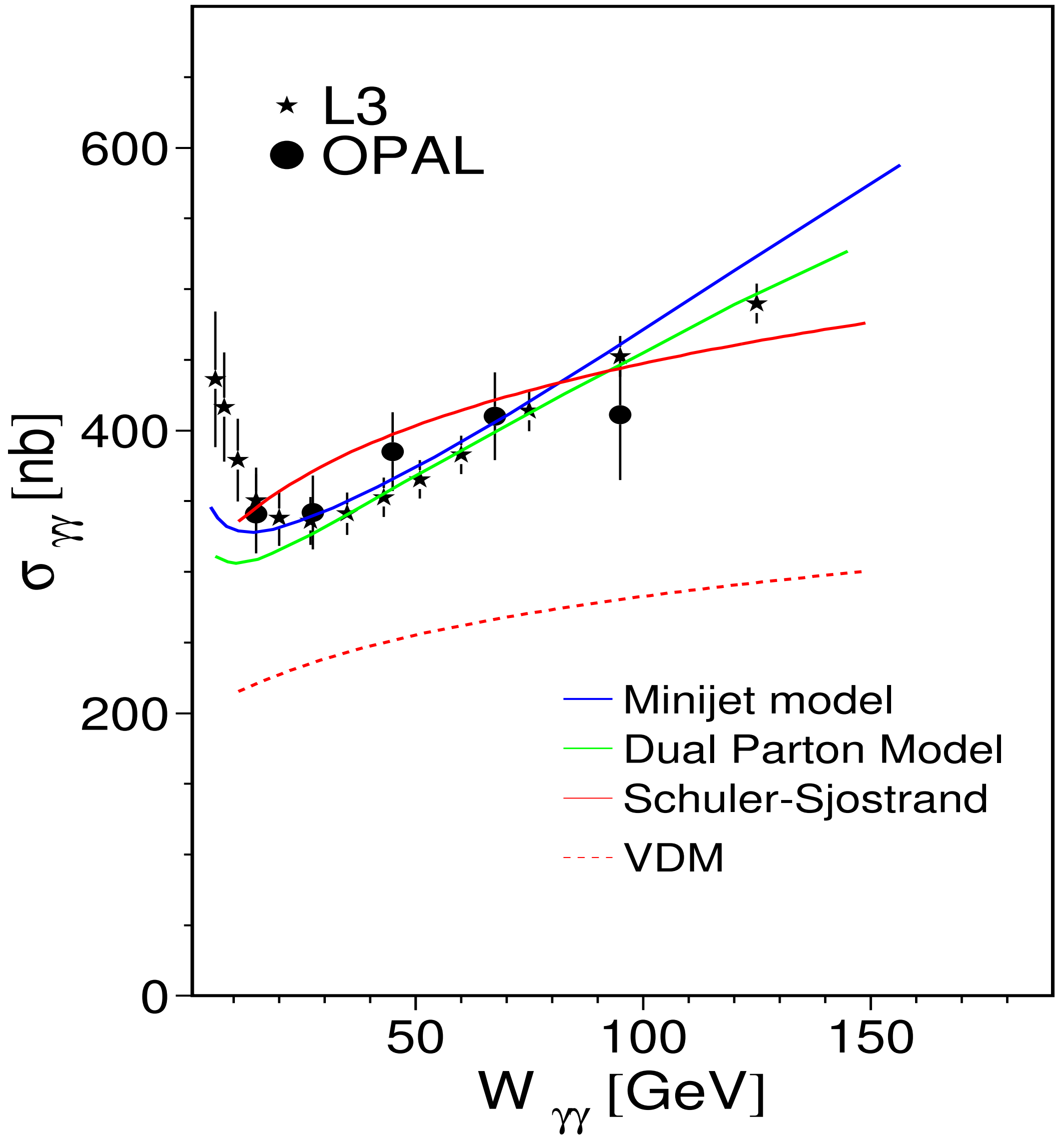
$$\frac{d\sigma_{ee}}{d(W^2_{\gamma\gamma}/s)} = \int \frac{dQ^2}{Q^2}\frac{dP^2}{P^2} \sum_{a,b=T,S} \mathcal{L}_{ab}\sigma^{\gamma\gamma}_{ab}(W_{\gamma\gamma}, P^2, Q^2)$$

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

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

L3 Coll., PLB 408(1997)147

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

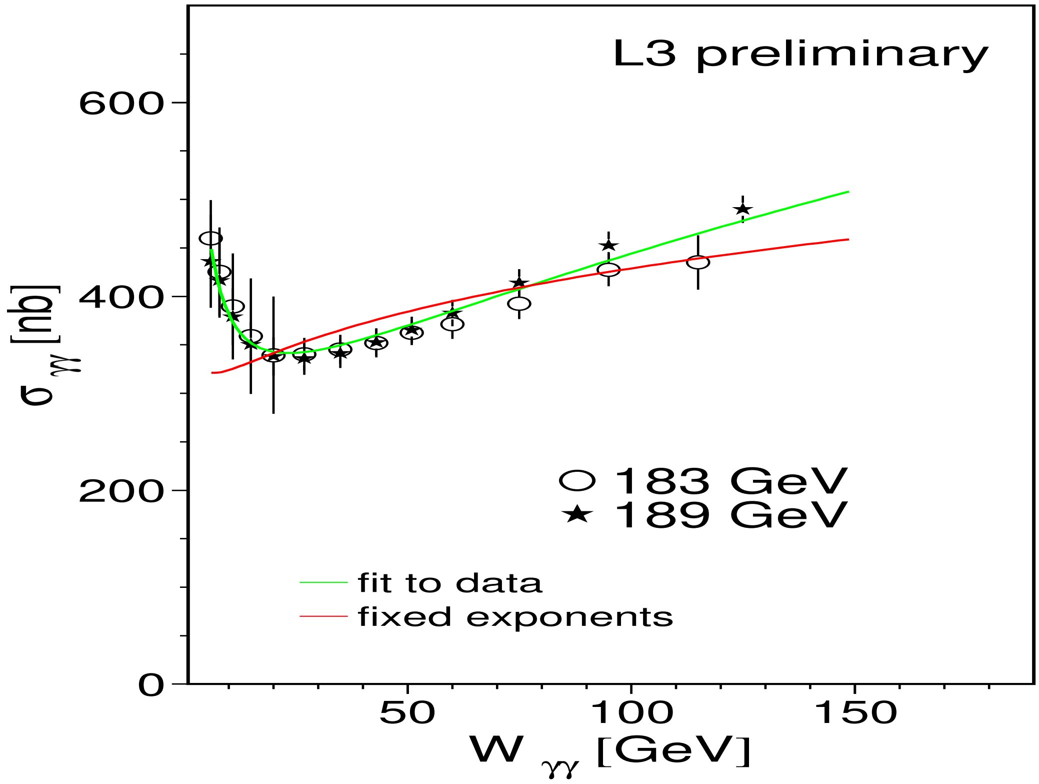
Total $\sigma_{\gamma\gamma}$: DL fit

❒ 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

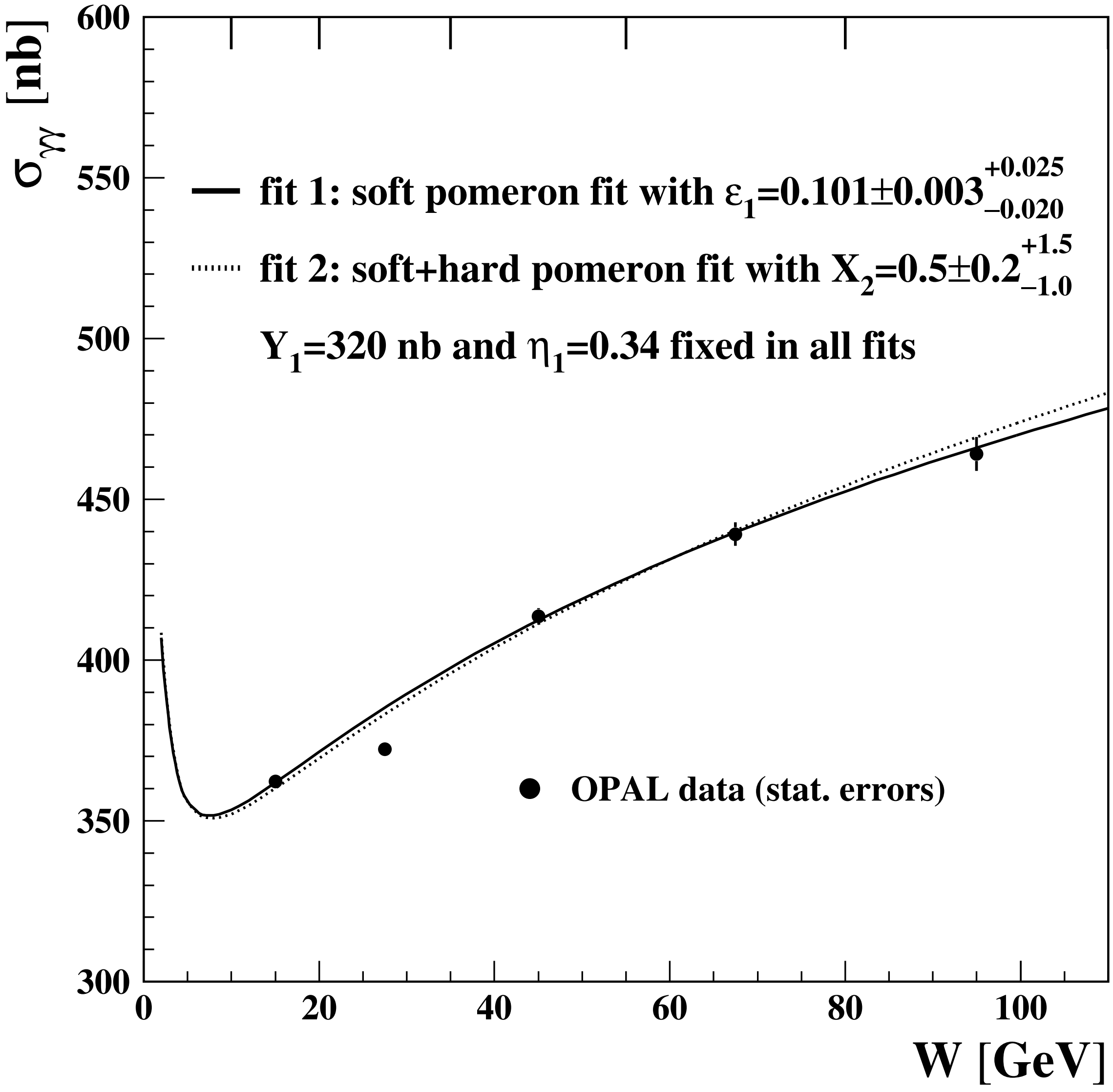
	ε	χ^2	CL
Universal ε	0.095 fixed	62	3.4×10^{-5}
Free ε !7σ higher!	0.22 ± 0.02	9.3	99.5%

Contribution from another Pomeron?! [a]

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

Total $\sigma_{\gamma\gamma}$: OPAL Data

Different Regge Parameterisations:

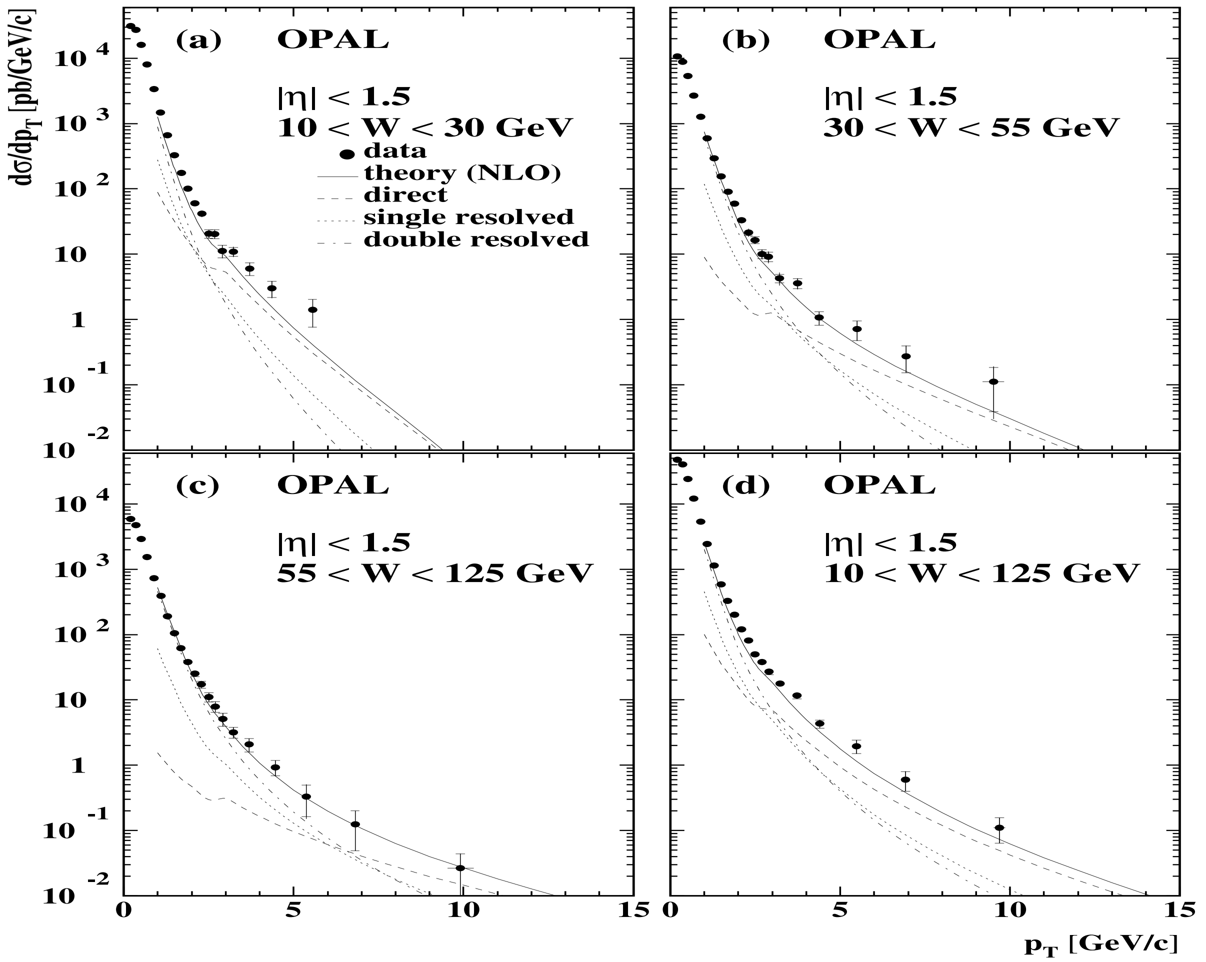


B and η is fixed

	ε	χ^2/ndf
fit1	0.095 fixed	137/3
fit2	0.101 ± 0.03	130/3

Inclusive particles $d\sigma/dp_T$

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



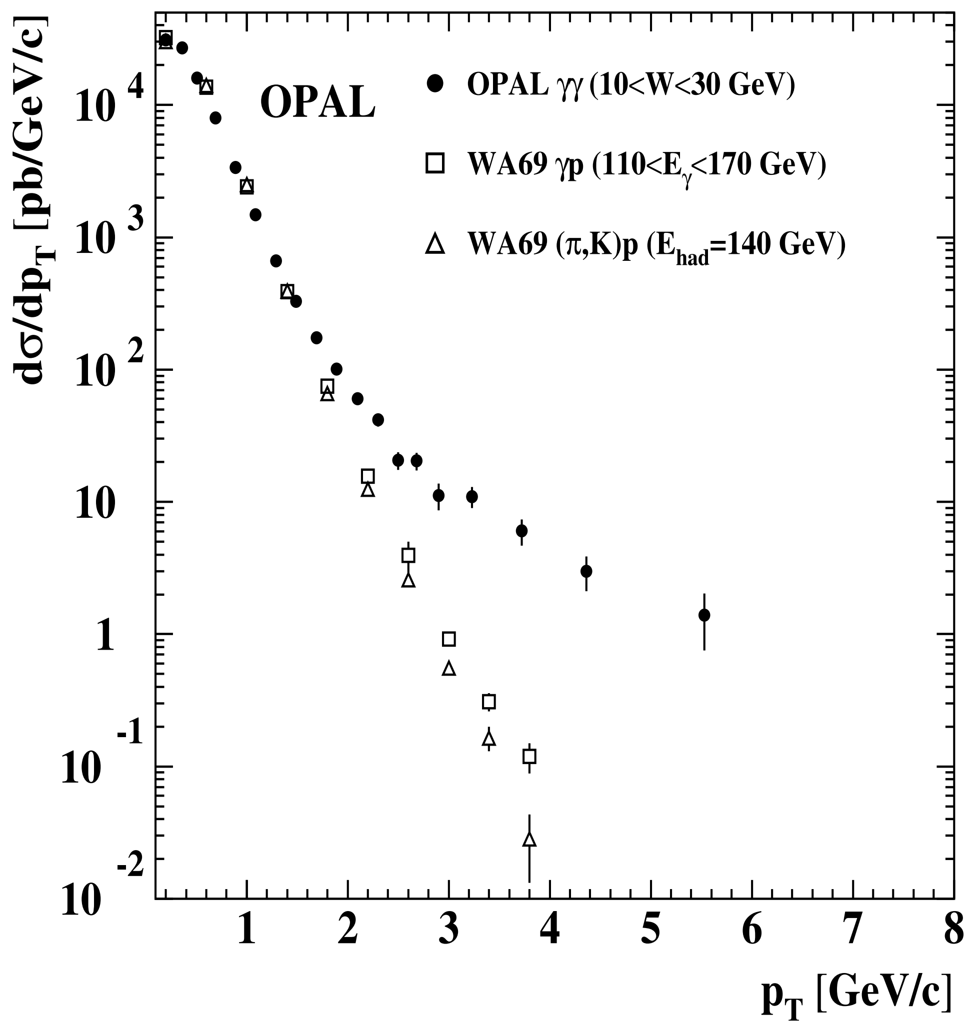
- NLO calculation by Binnewies, Kniehl and Kramer. (Phys. Rev. D53, 6110, 1996)
- The direct component is dominant at high p_T.
- For low $W_{\gamma\gamma}$, the NLO calculations lie below the data.
- For high $W_{\gamma\gamma}$, the agreement is good.

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

Inclusive particles $d\sigma/dp_T$

- Compare to γp and $(\pi, K)p$ interactions.

- The γp and $(\pi, K)p$ are normalised to the low p_T region.

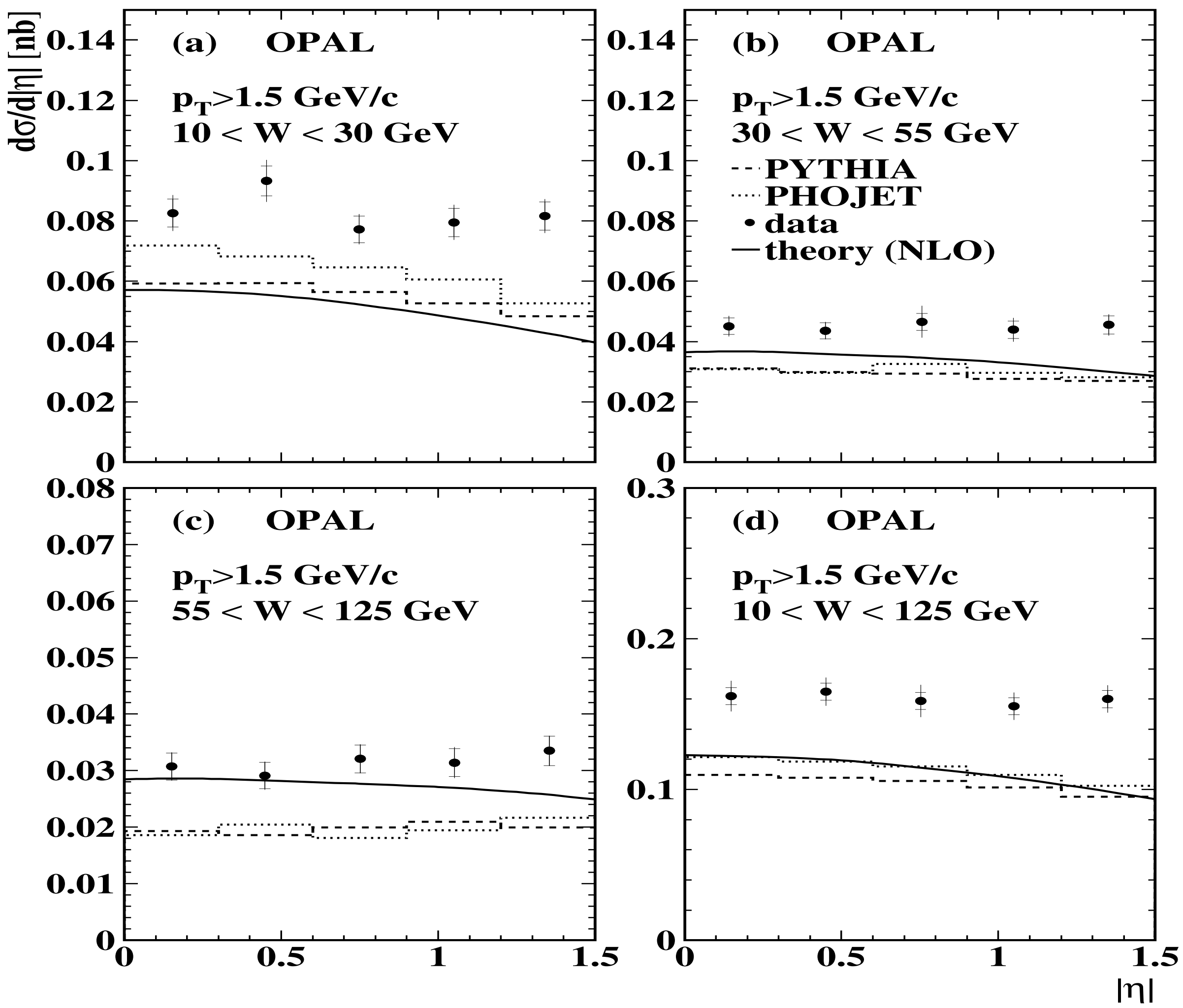


⇨ The $\gamma\gamma$ interaction is much harder because of the direct component.

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

Inclusive particles $d\sigma/d\eta$

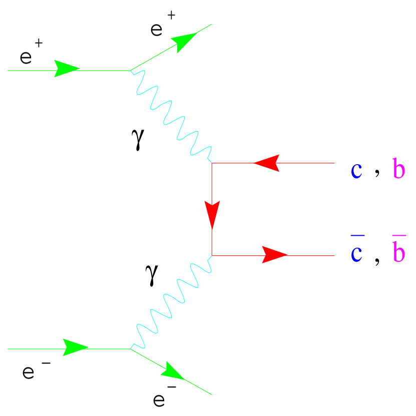
Inclusive charged particle production $d\sigma/d\eta$ for $|p_T| > 1.5$ GeV



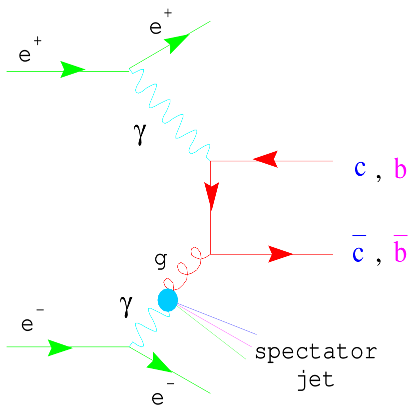
- ⇨ Monte Carlos and NLO calculation lie below the data for $W < 55$ GeV.
- ⇨ NLO calculation agrees better for $55 \text{ GeV} < W < 125$ GeV.

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.

❑ <u>Charm identification :</u>

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

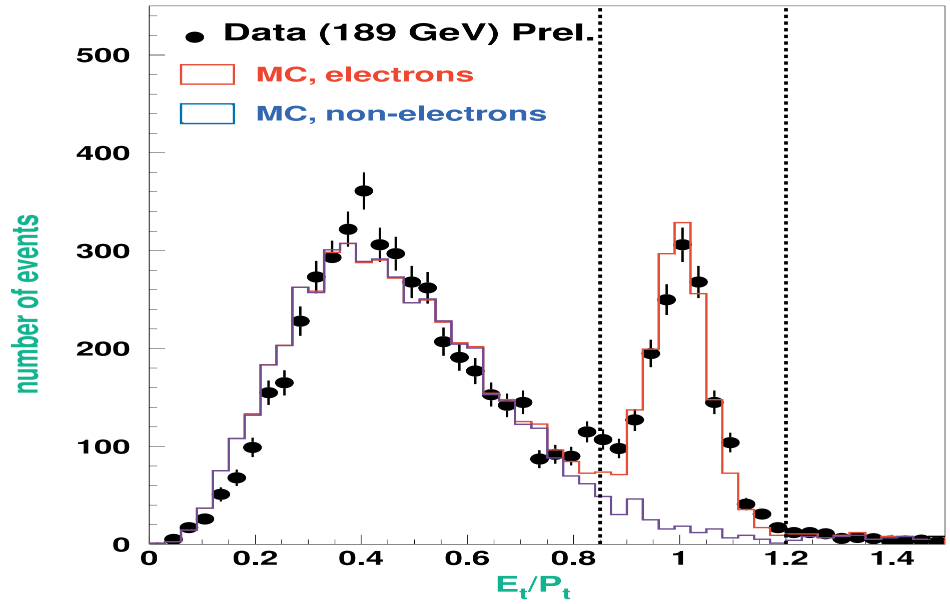
❑ Data :

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}

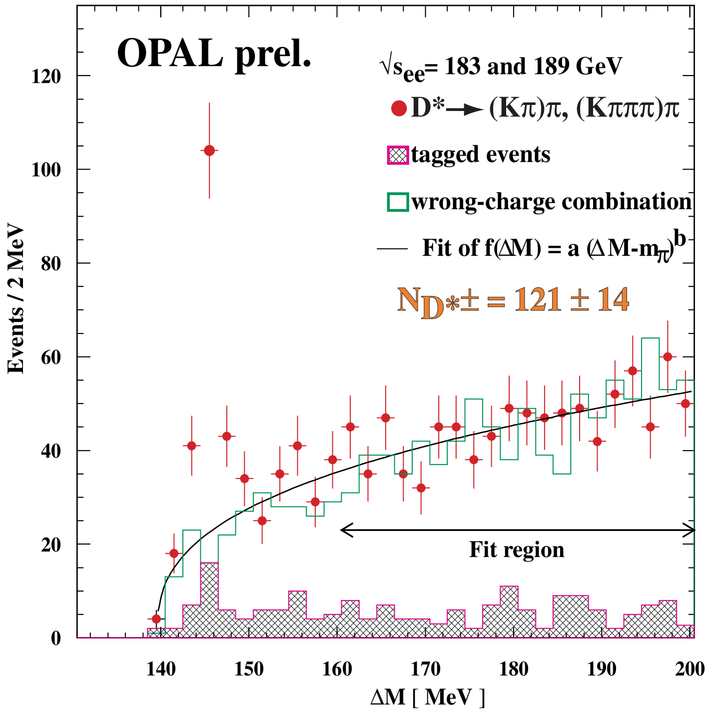
⋆ Preliminary

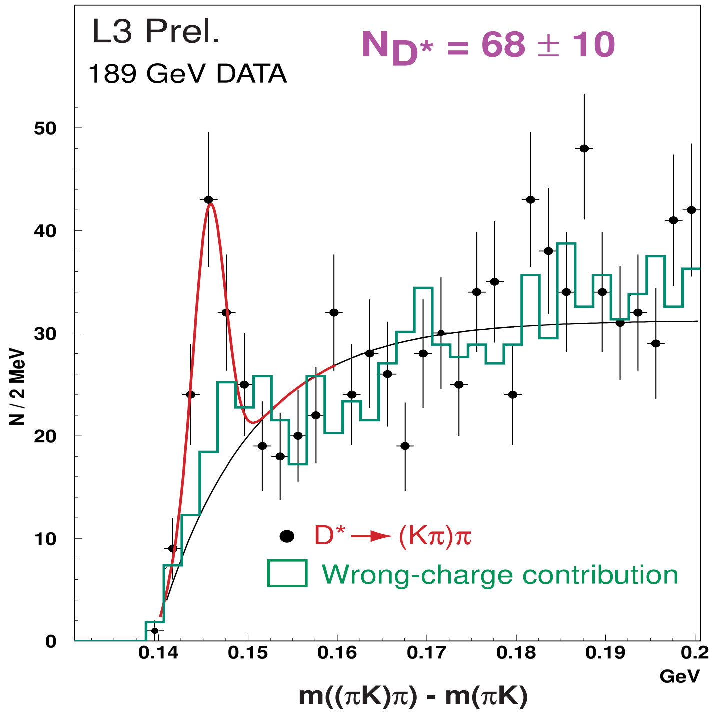
Inclusive Charm Production

❐ Electron Identification:

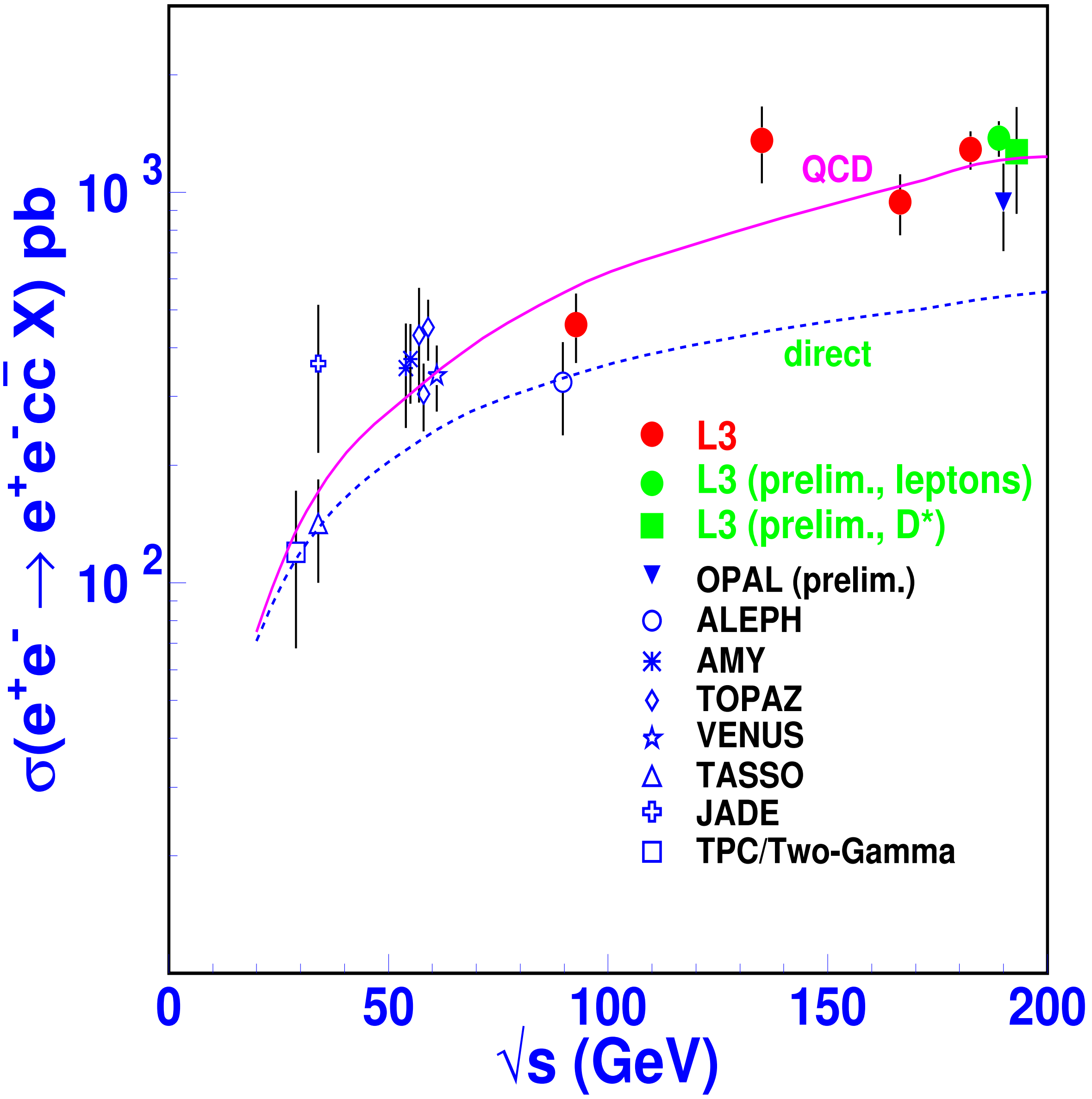


❐ $D^{*\pm} \to D^0 \pi_s^\pm,\ D^0 \to K^\pm\pi^\pm, D^0 \to K^\pm\pi^\pm\pi^\pm\pi^\pm$





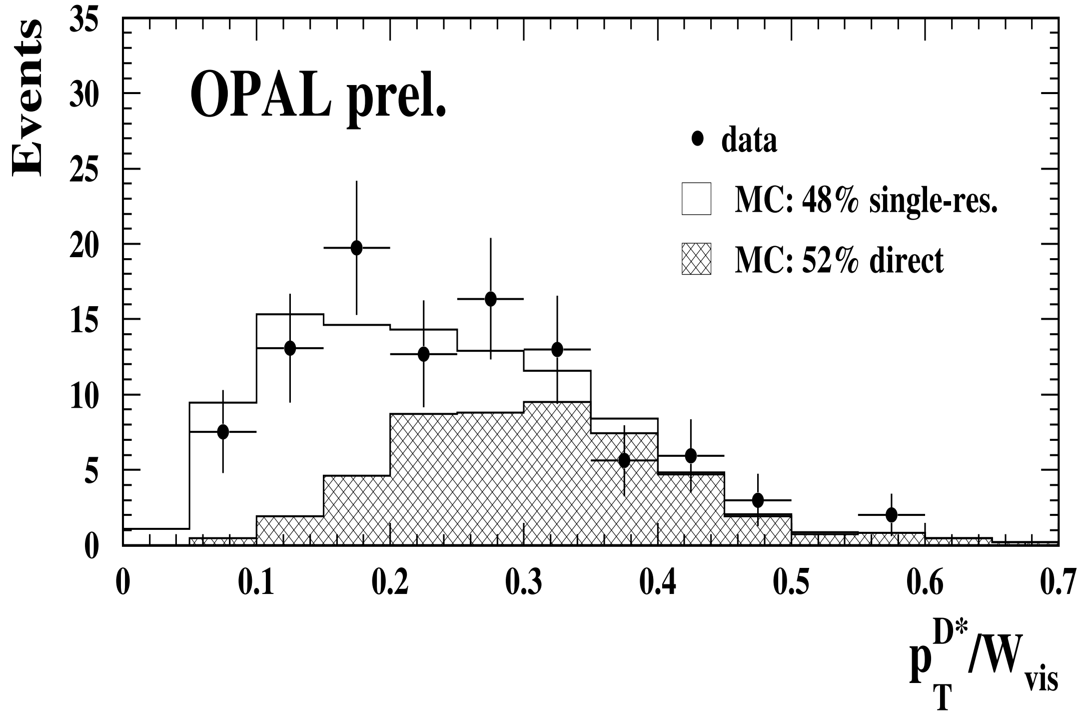
Inclusive Charm Production

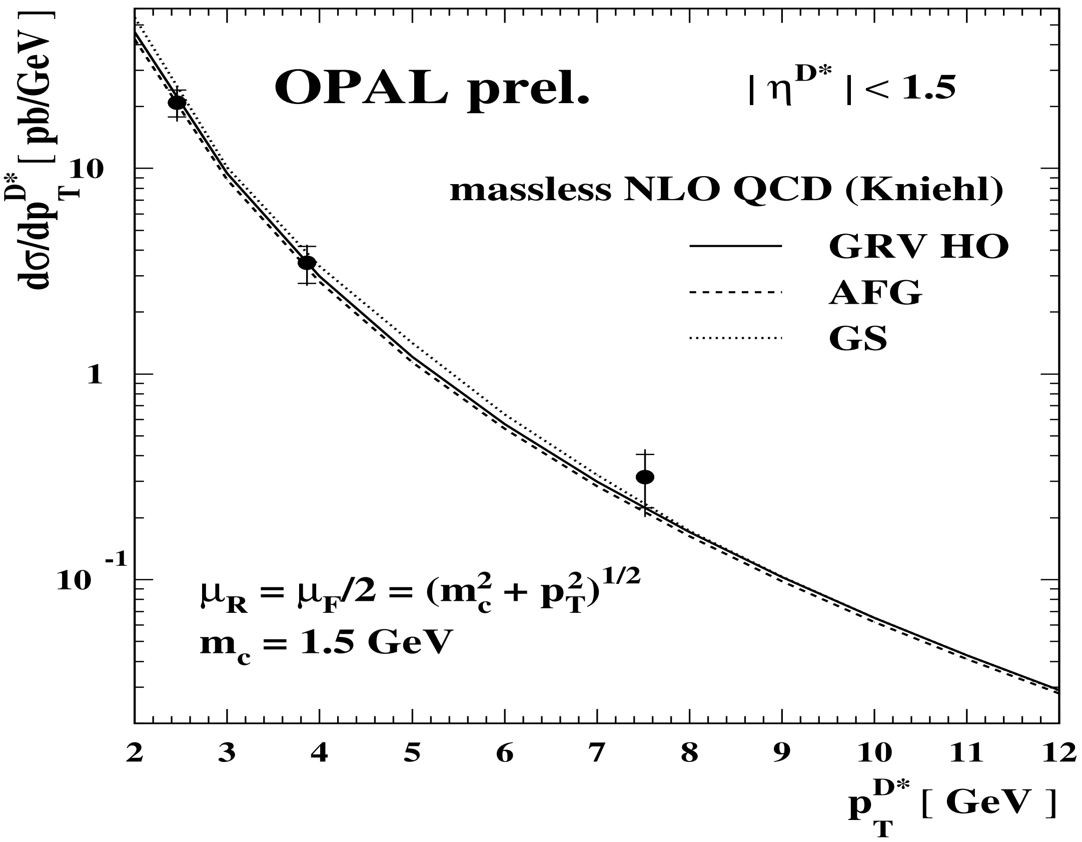


- QCD calculation by Drees, Krämer, Zunft and Zerwas. (Phys. Lett. B306, 371, 1993)
- $\sigma(\mathrm{e^+e^-} \to \mathrm{e^+e^-}c\bar{c}\mathrm{X})$ increases with the beam energy.
- The direct process is insufficient to describe the data. ➜ The resolved processes are necessary

D^* Production

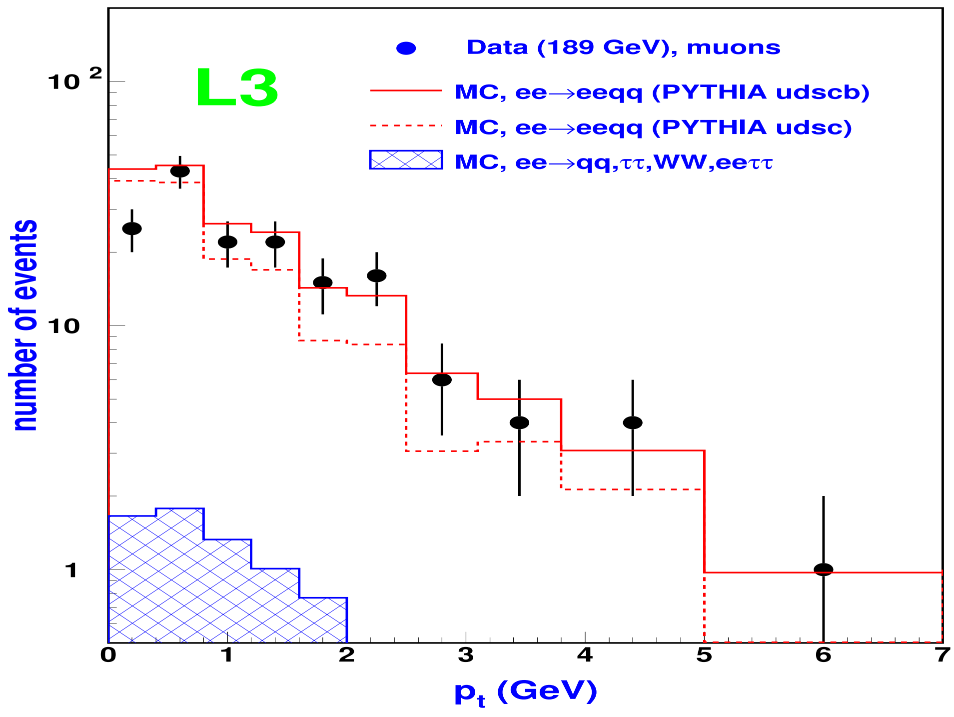
- ❐ Data: $\sqrt{s} = 183\text{-}189$ GeV
- ❐ Separation of Direct and Resolved processes



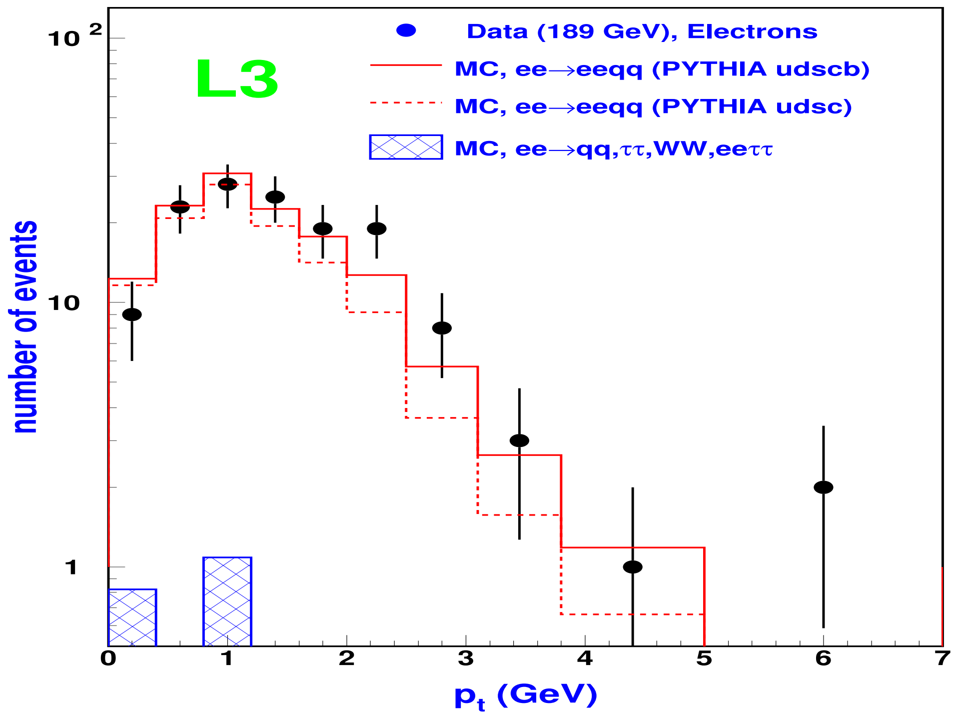


Search for Beauty: L3 Data

p_t with respect to the nearest jet



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



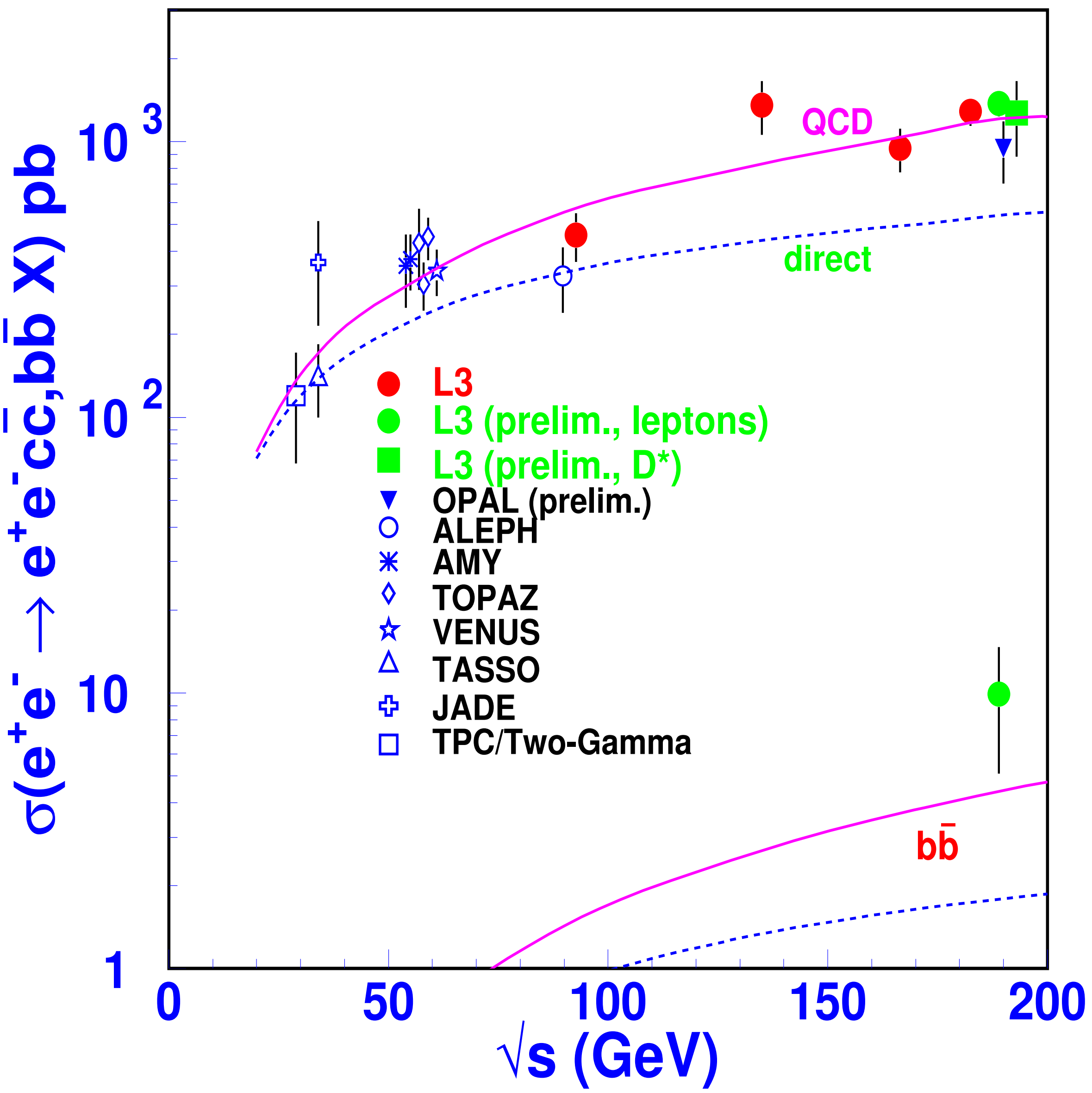
$P_t^e > 1$ GeV
$N_{ev}^e = 96$
$\varepsilon_b^e = 1.6\%$
$\Pi_b^e = 28\%$

Leptons from bottom decays have higher p_t.

Beauty Production

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

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



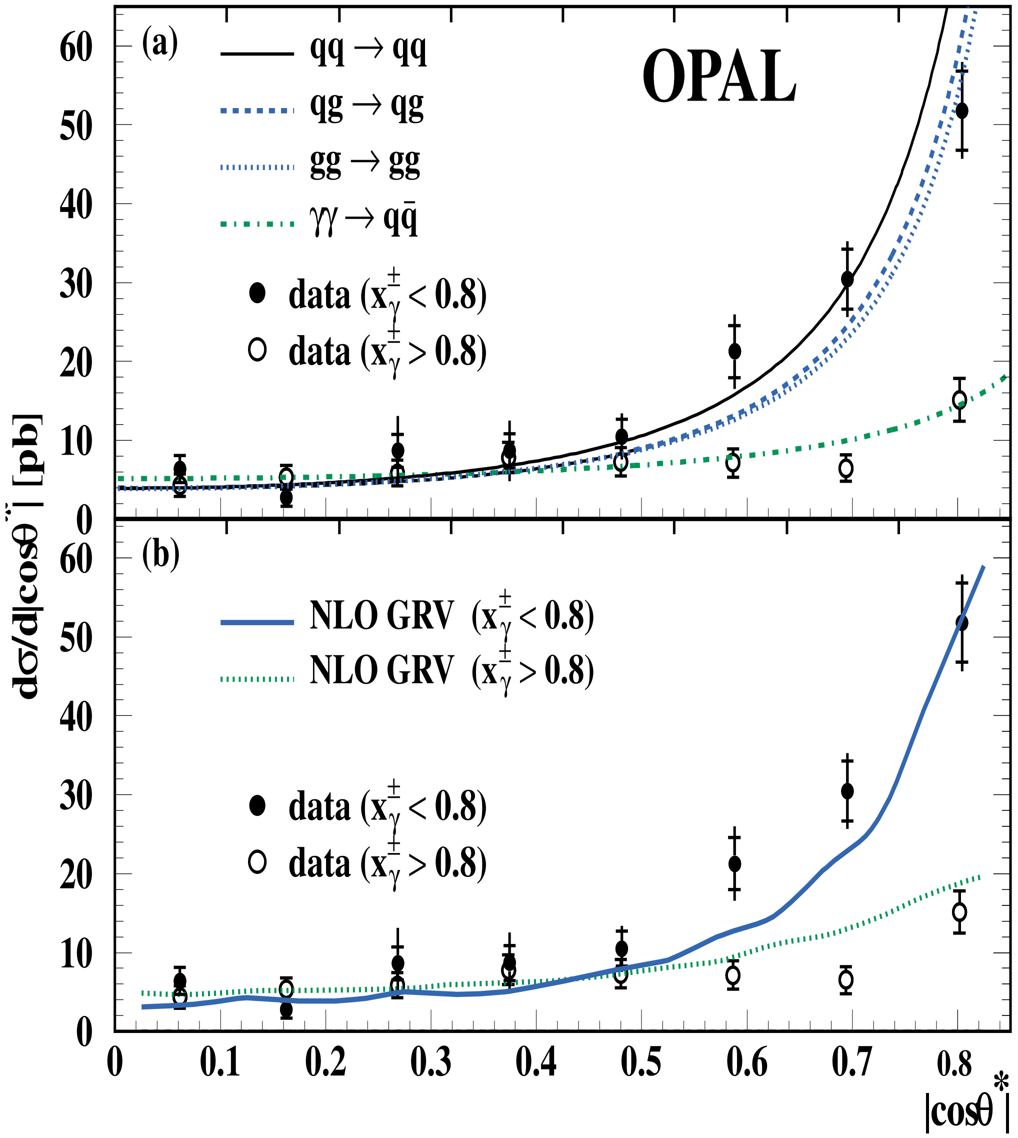
- Theory prediction from M. Drees,M. Krämer,J. Junft and P.M. Zerwas,PL **B306** 371 (1993); $m_c = 1.3$ GeV, $m_b = 5.0$ GeV.

DiJet Production

❒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



- $x_\gamma^\pm < 0.8$ 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

Exclusive Hadronic States

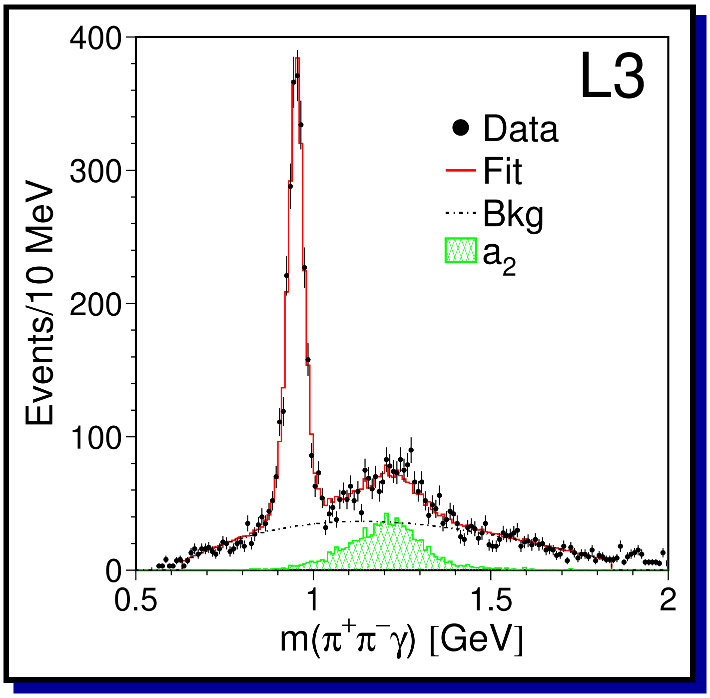
- Structure of hadron and its constituents
- Singlet-Octet mixing of $q\bar{q}$ mesons.
- $\Gamma_{\gamma\gamma}$ of heavy quark allows measurement of α_s
- QCD predicts the existence of Glueballs
- Possible Existence of Four Quark States

❒ Many Exclusive channels

Resonance	Final state	J^{PC}	$\Gamma_{\gamma\gamma}$(keV)	
η' (958)	$\pi^+\pi^-\gamma$	0^{-+}	$4.17 \pm 0.10 \pm 0.27$	✔
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^{++}	$0.09 \pm 0.02 \pm 0.02/(BR)$	✔
η_c (2980)	9 Channels	0^{-+}	$8.0 \pm 2.3 \pm 2.4$	✔
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

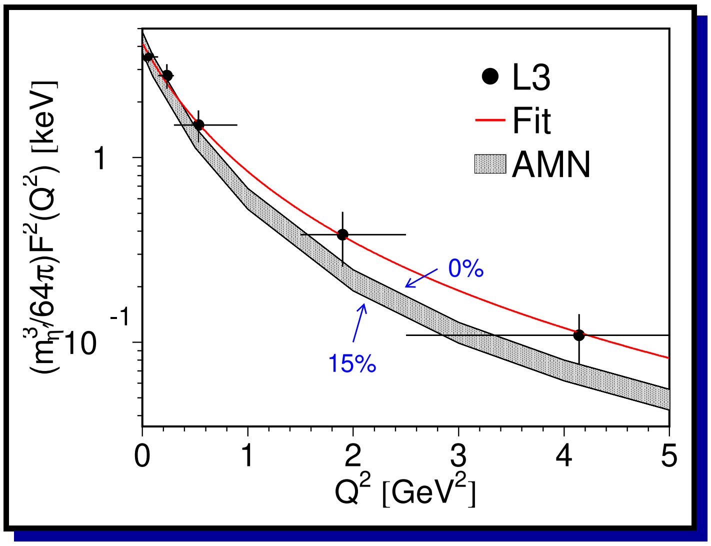
❒ η' **Form Factor**

➠ $\sum p_T^2 = Q^2$

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

Λ_{fit} = 900±51 MeV

Consistent with VDM



➠ Anisovich *etal.* Phys. Rev. D55(1997) 2918.

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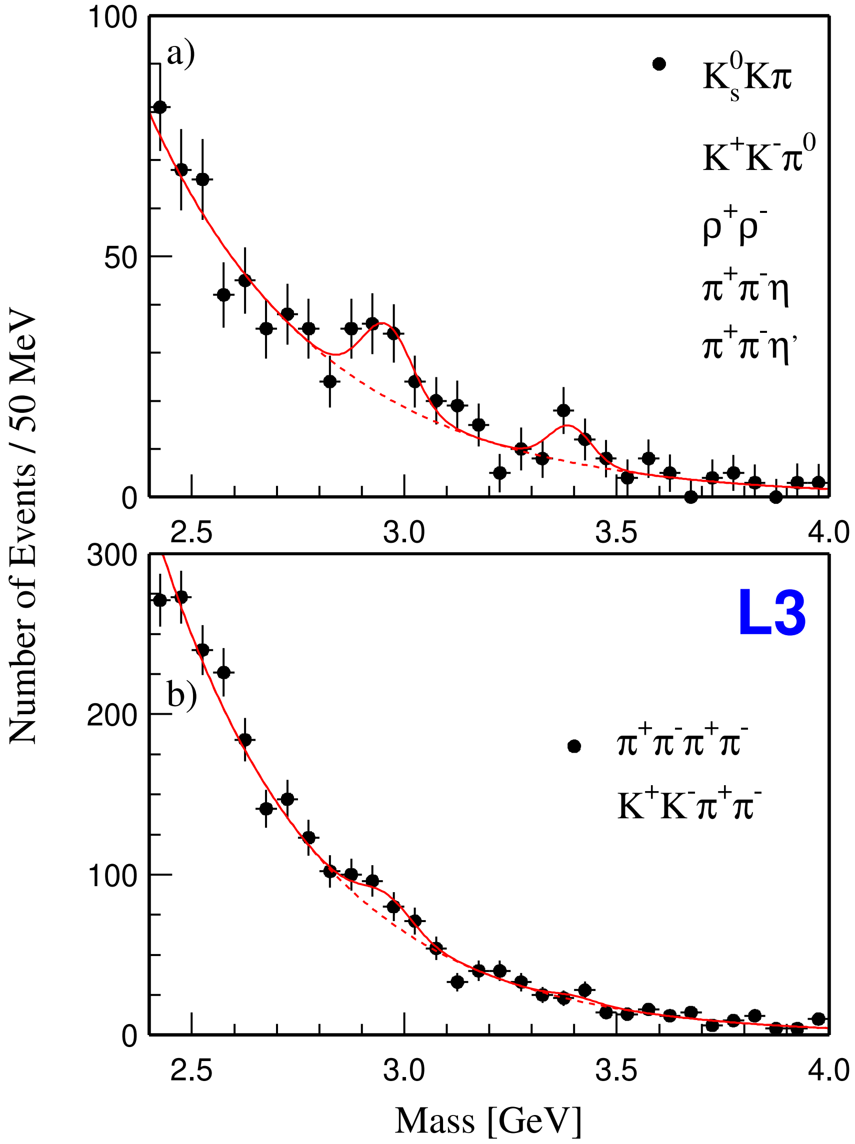
η_c(2980) Decay Channels



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]

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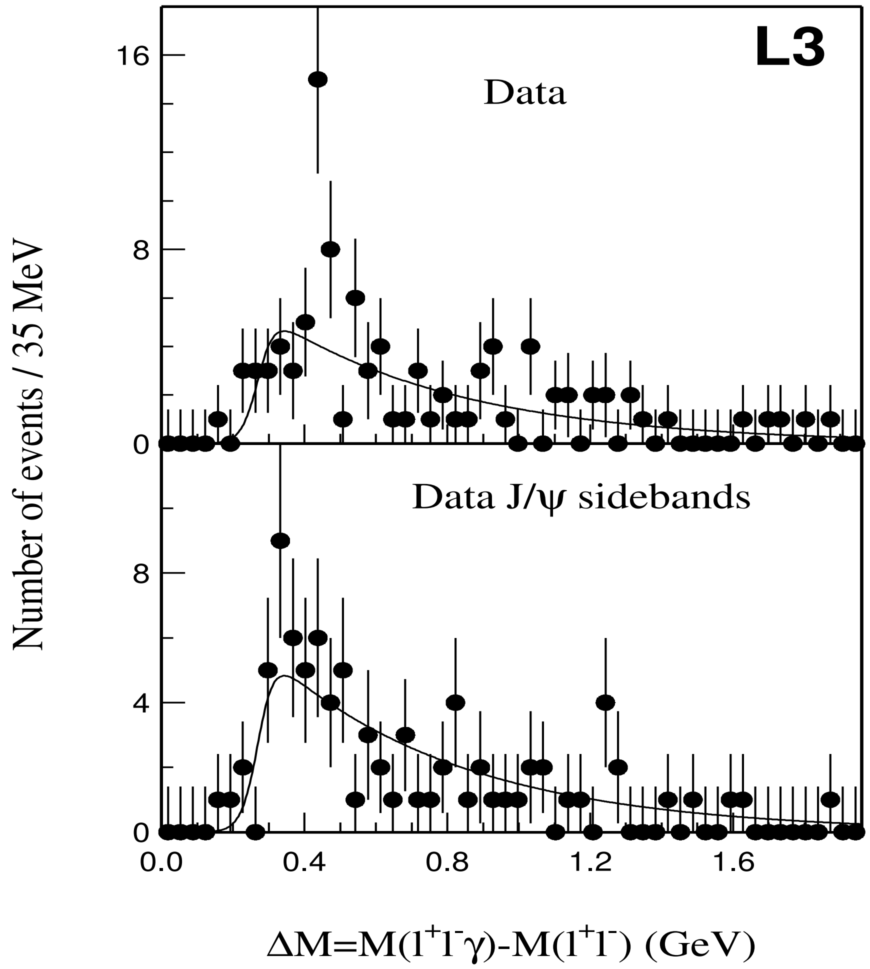
[a] **CERN-EP/99-072**

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



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

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

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

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

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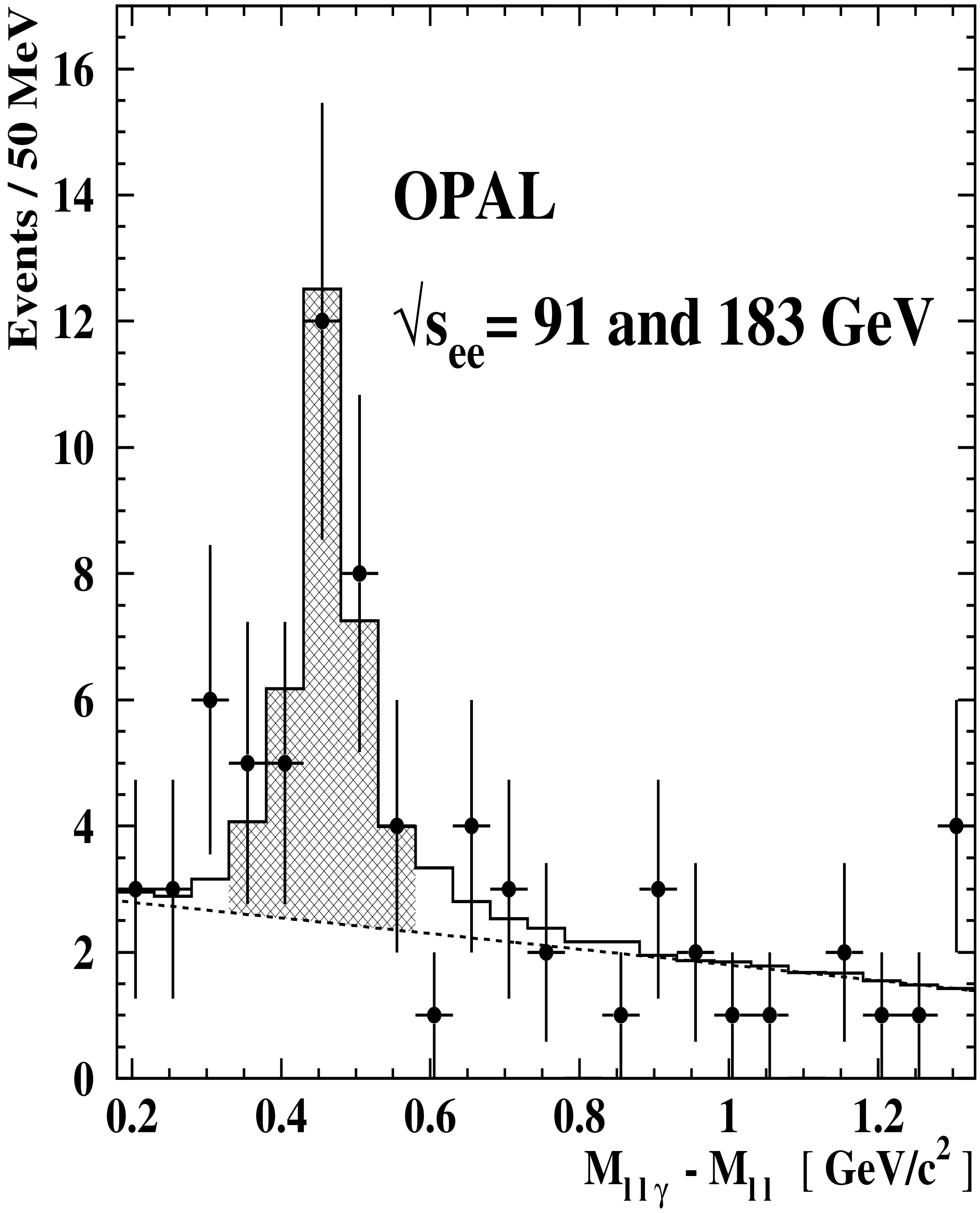
$\chi_{c2}(3555) \rightarrow \mathbf{J}/\psi + \gamma$

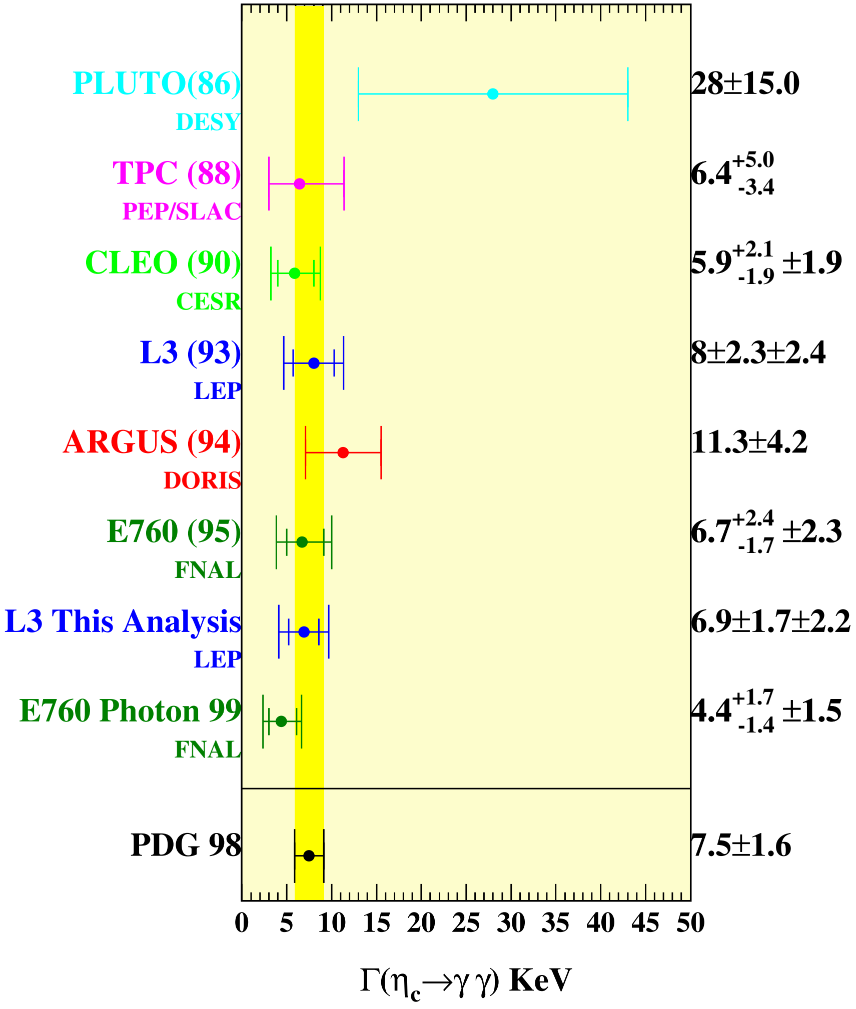


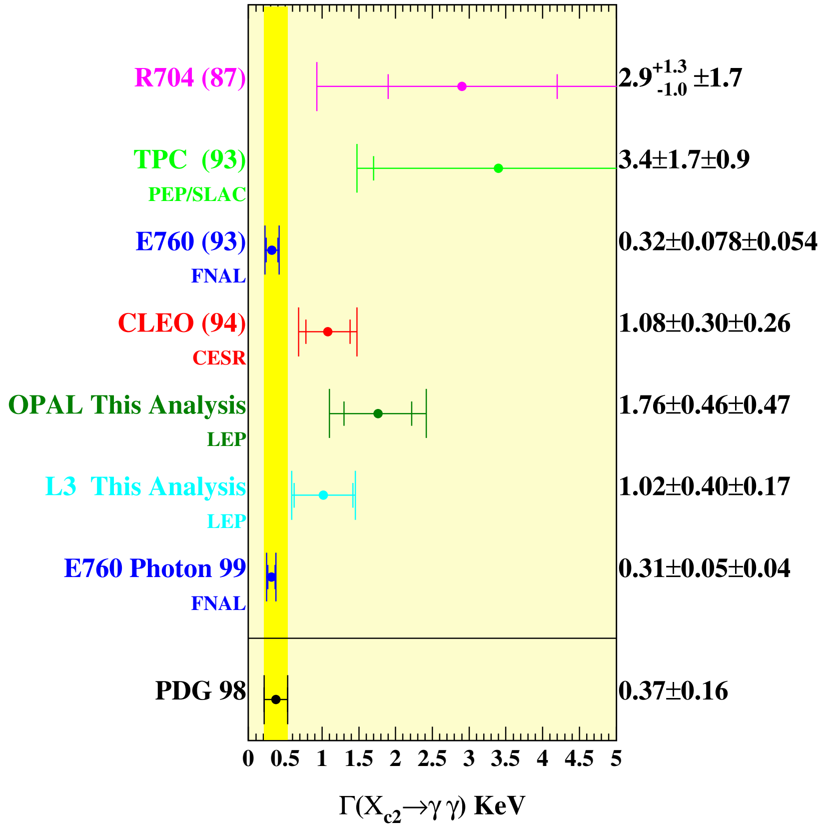
34 signal events above a background of 12
for L_{ee}=167 pb^{-1} at $\sqrt{s}$= 91 GeV
and L_{ee}=55 pb^{-1} at $\sqrt{s}$= 183 GeV

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

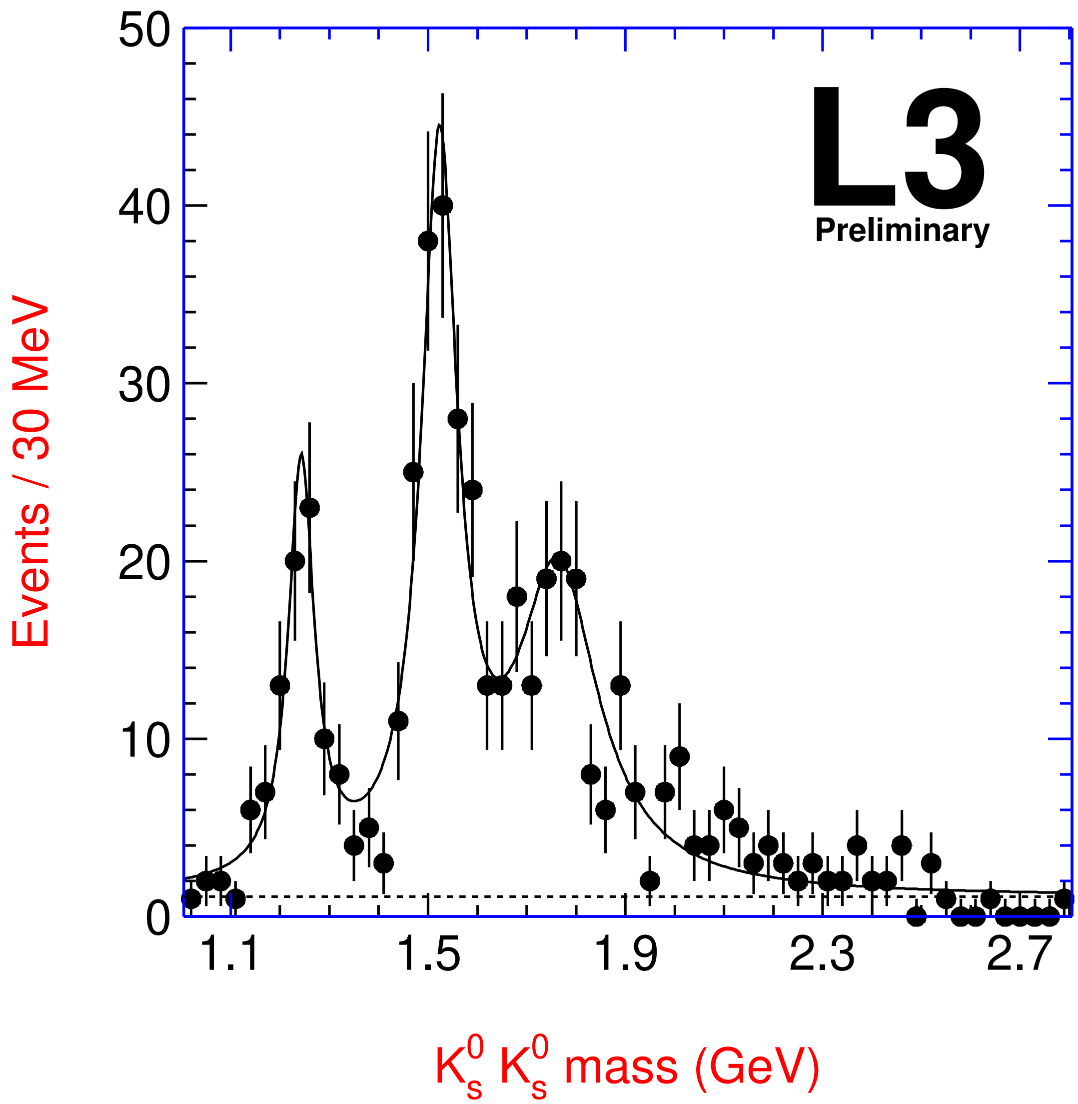
OPAL Coll., PLB 439 (1998) 197

Comparison with Previous measurements





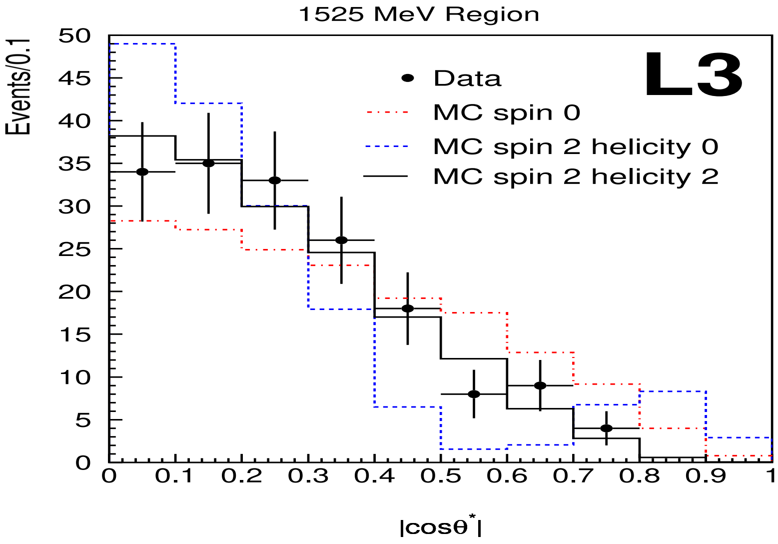
The $K^0_s K^0_s$



	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

The $f_2'(1525)$



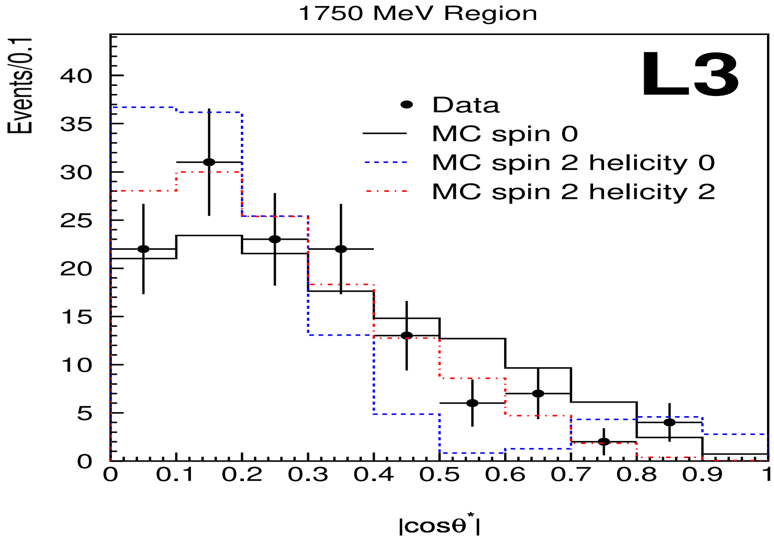
	$\chi^2/7$ d.o.f.
J=0, λ=0	25.2
J=2, λ=2	4.2
J=2, λ=0	28.5

Helicity 2 dominates !

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

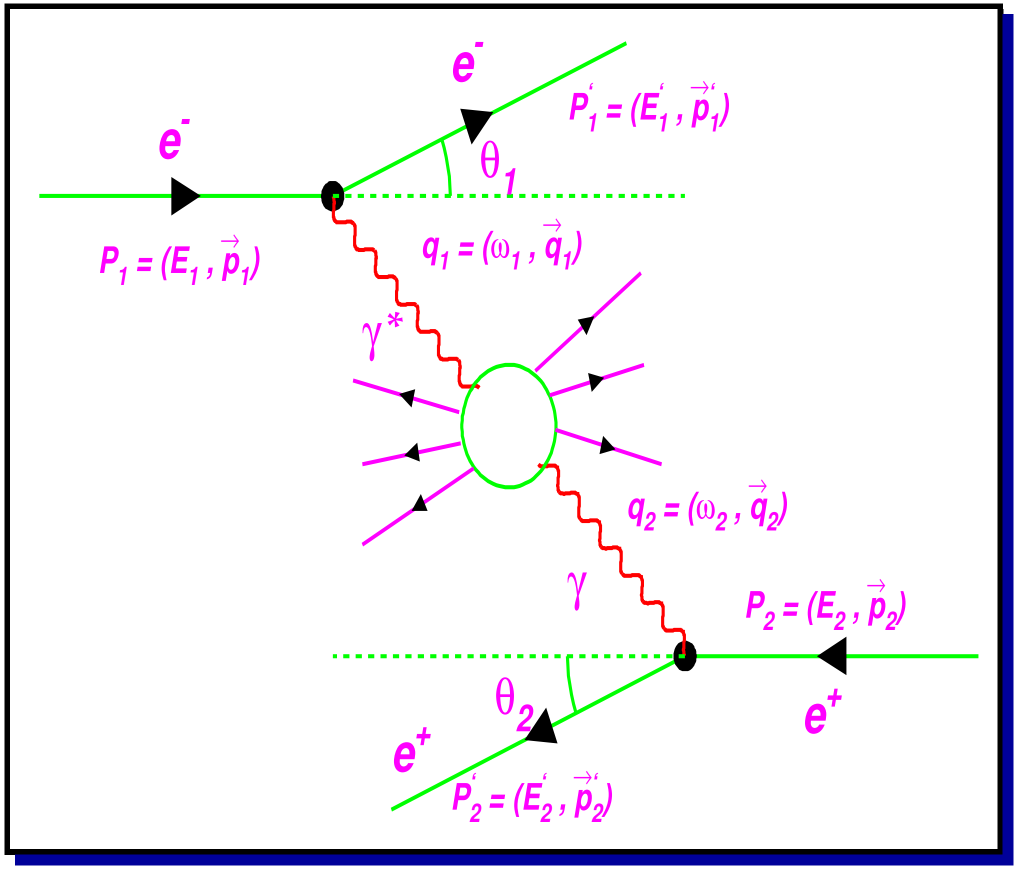
The 1750 MeV Region

- $f_2'(1525)$ 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

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

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

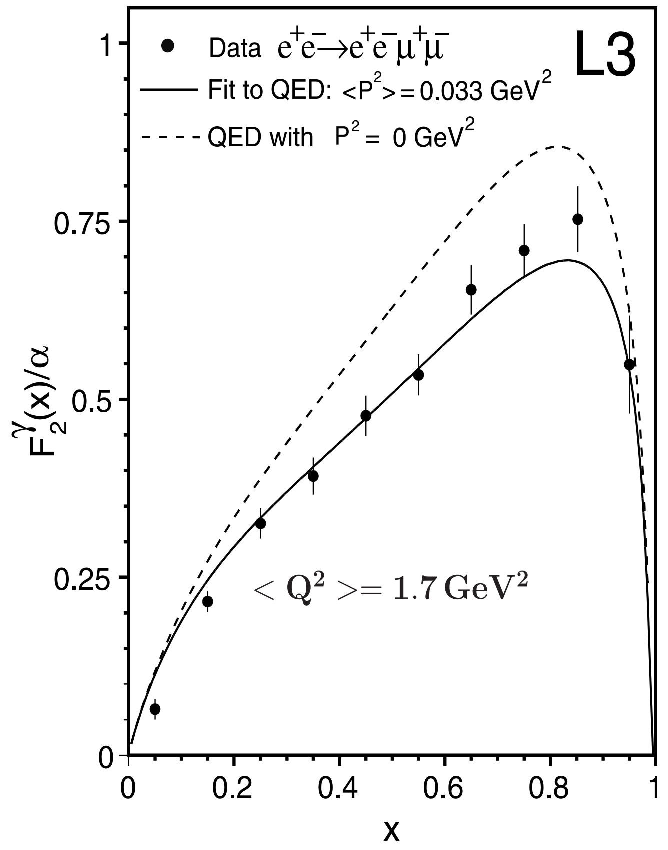
$$y \simeq 1 - \frac{E_1}{E_{beam}} \cos^2\frac{\theta_1}{2}$$

❒ Cross Section

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

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

Measurements of $F_{2,QED}^{\gamma}$: $e^+e^- \to e^+e^-\mu^+\mu^-$



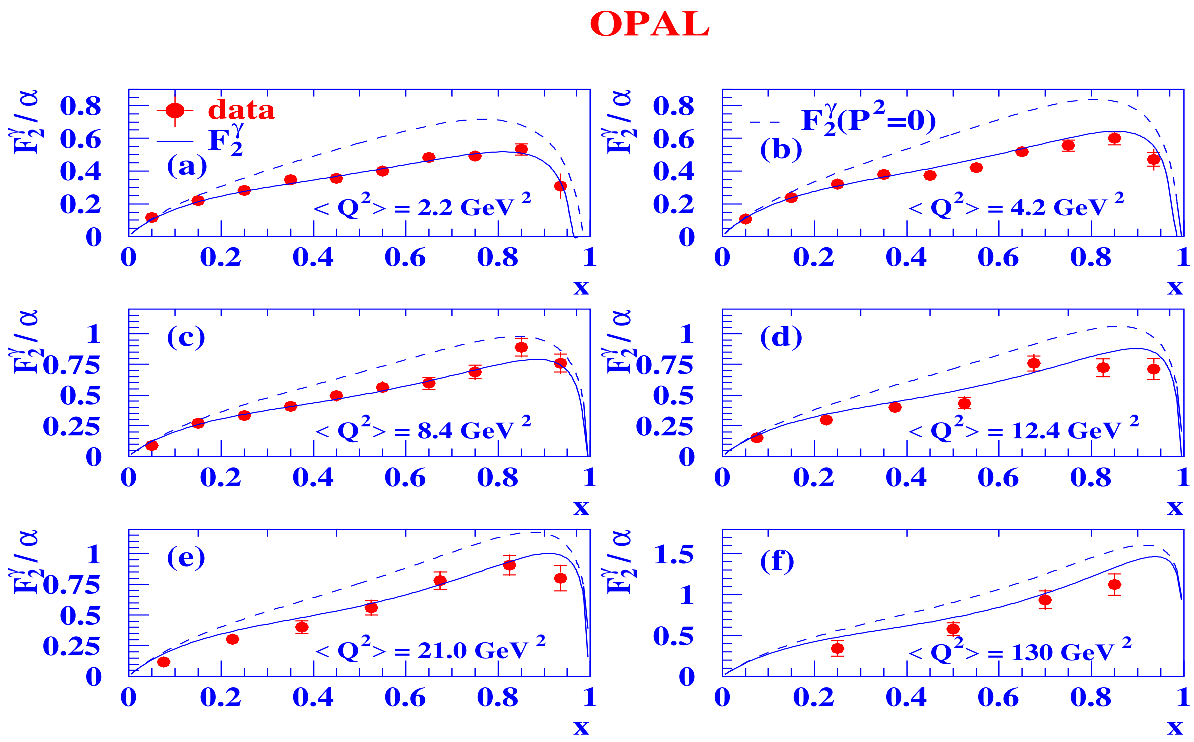
$< P^2 >= 0.033 \pm 0.005$ GeV^2

Non-zero target photon virtuality

$< P^2 >_{MC} = 0.034$ GeV^2

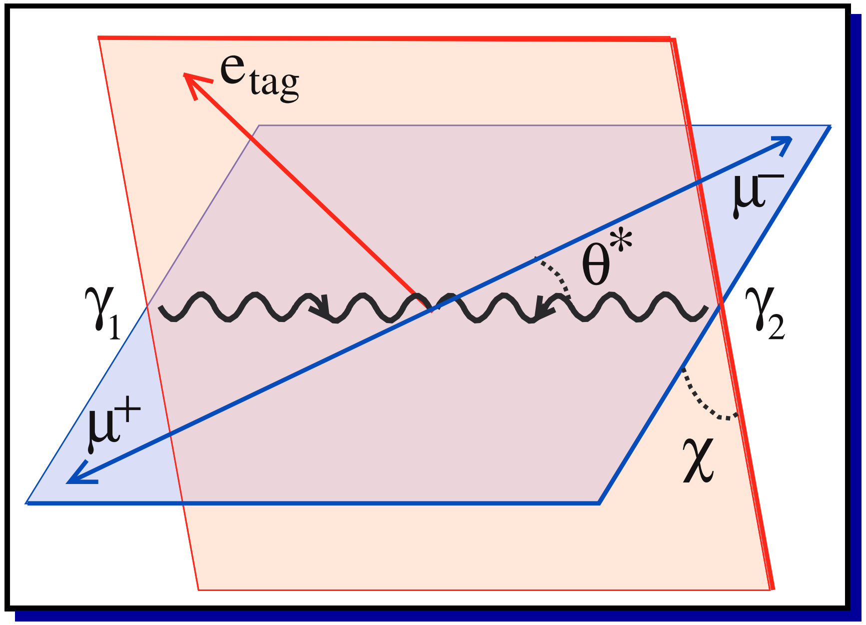
incl. radiative corrections

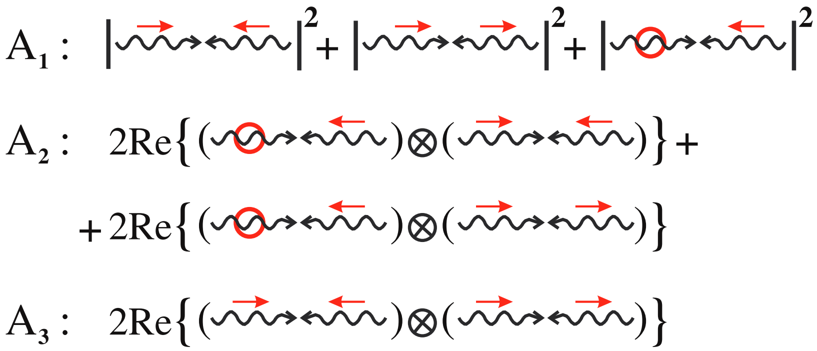
L3 Collab., PLB 438 (1998) 363
OPAL Coll., CERN-EP-99-010



$< P^2 >= 0.05$ GeV^2 $Prob(\chi^2) \sim 0.07 - 0.79$

Azimuthal Correlations





$$\frac{d^4\sigma}{dx\,dy\,dz\,d\chi} = \frac{2\pi\alpha^2}{Q^2}\,\frac{1+(1-y)^2}{xy} A_1(x,z) + A_2(x,z)\cos\chi + A_3(x,z)\cos 2\chi]$$

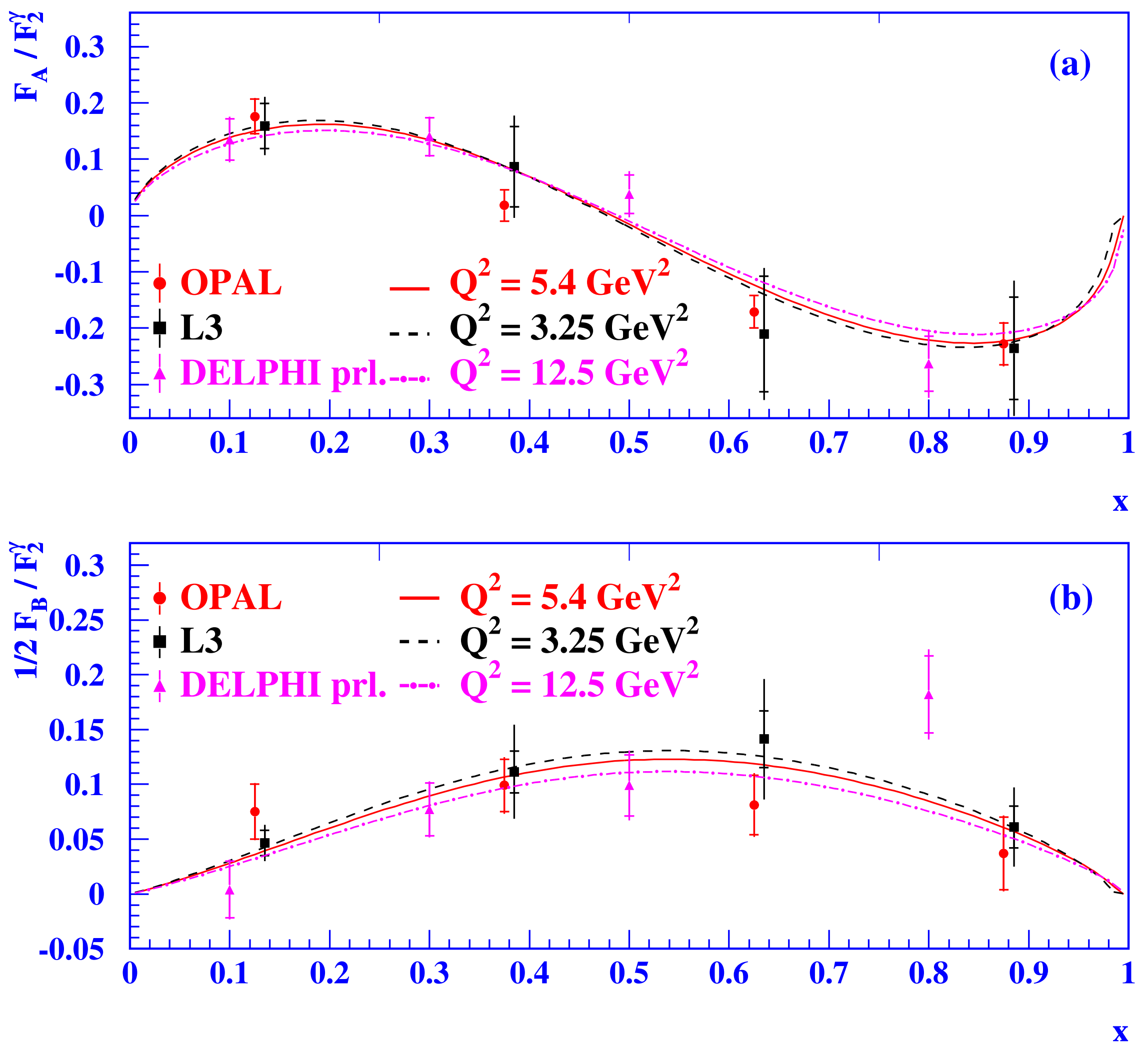
$A_1 \propto F_2^{\gamma}$ ➠ Sum of all photon helicity states

$A_2 \propto F_A$ ➠ Interference of longitudinal-transverse photons

$A_3 \propto F_B$ ➠ Interference of two transverse photons

F_A^γ and F_B^γ

❑ F_B and F_A measurement at DELPHI, L3 and OPAL



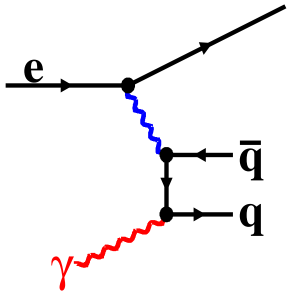
➠ Non-zero F_A^γ is seen ➜ $F_L^\gamma \neq 0$

➠ Consistent with QED prediction

Hadronic F_2^γ : $e^+e^- \longrightarrow e^+e^-$hadrons

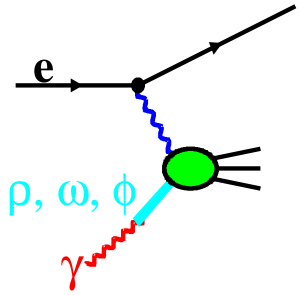
$$F_2^\gamma = F_2^{PL} + F_2^{hadr}$$

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

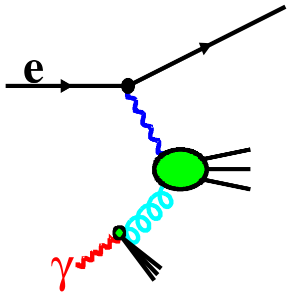


➜ QPM

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

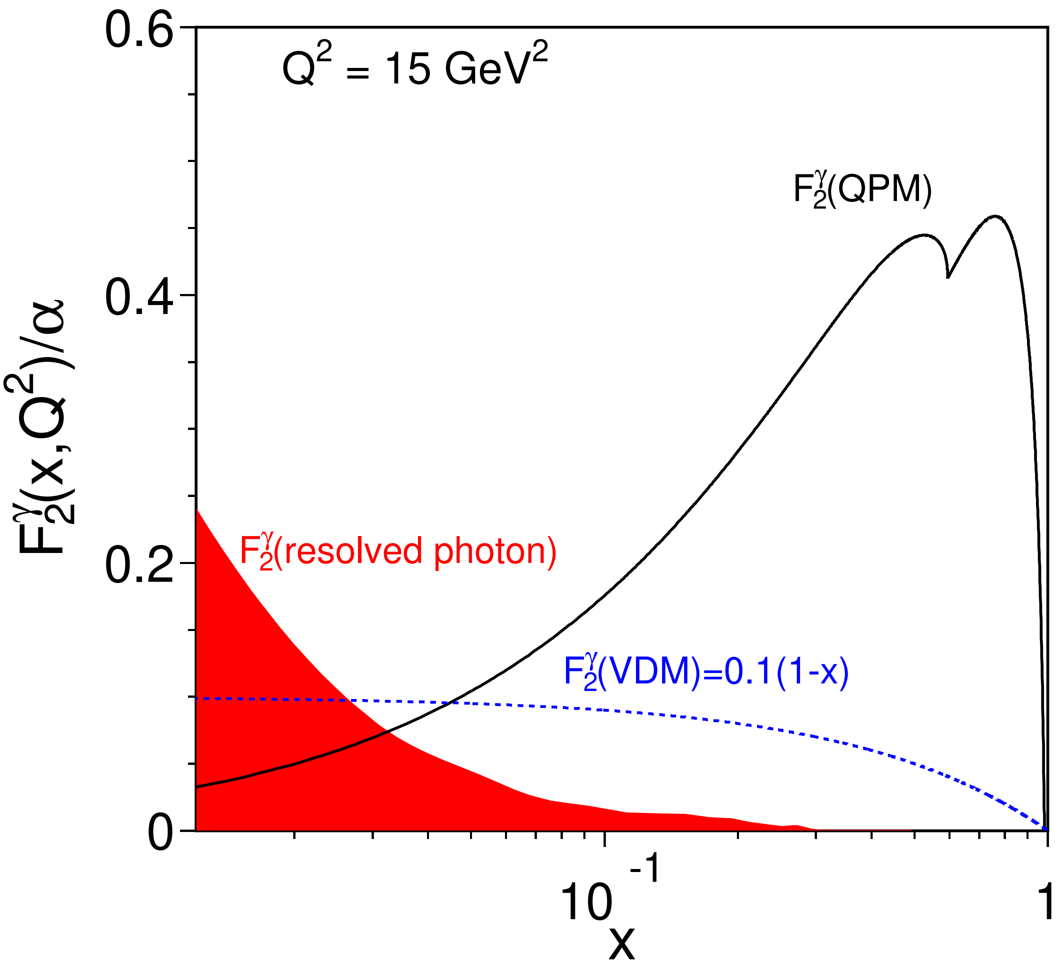


➜ VDM, non-perturbative QCD



➜ Resolved γ, perturbative QCD

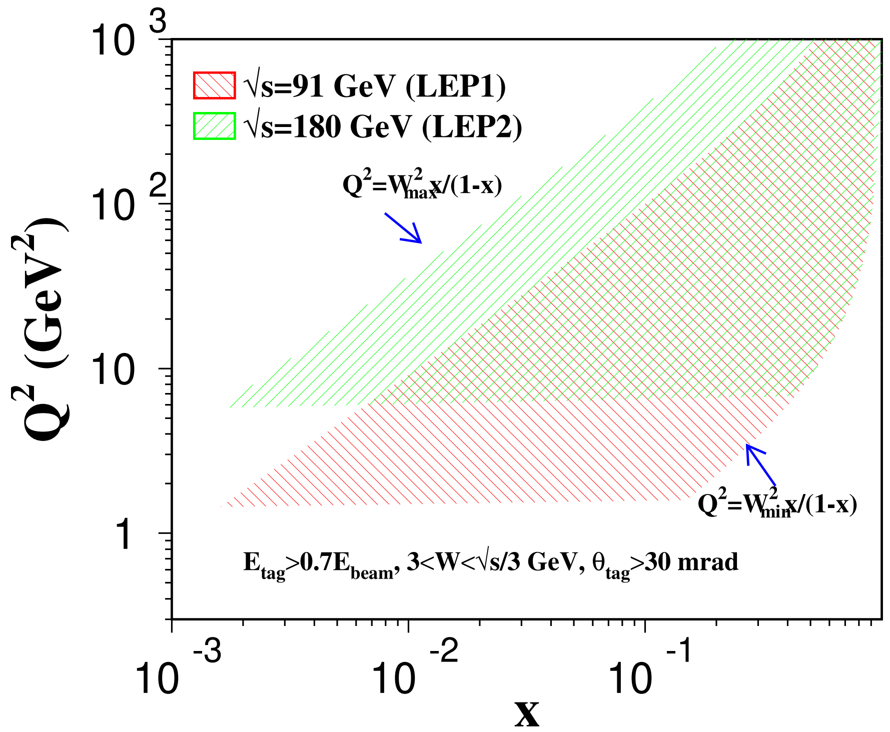
F_2^γ: Components



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

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

F_2^γ: Kinematic region



Exp	$\sqrt{s}$	θ_{tag}	Q^2	x
	GeV	mrad	GeV^2	
ALEPH	91	65-150	6 - 44	0.005 - 0.90
ALEPH	91	318-927	35 - 3000	0.03 - 0.97
ALEPH	183*	35-155	7 - 200	0.003 - 0.97
DELPHI	91	43-135	4 - 30	0.005 - 0.977
DELPHI	161,172,183,189	42-610	10 - 1000	0.01 - 0.8
L3	91	26-66	1.2- 9	0.002 - 0.2
L3	91*	200-600	40 - 500	0.05 - 0.98
L3	183	30-66	9 - 30	0.01 - 0.3
OPAL	91	27-55	1.1- 6.6	0.0025 - 0.2
OPAL	161,172	33-120	6 - 100	0.02 - 0.6
OPAL	91*,189*	25-60	1.5- 30	0.001 - 0.32

- The Q^2 ranges from $1\ \mathrm{GeV}^2$ to $3000\ \mathrm{GeV}^2$
- The x ranges down to 0.001 GeV^2 at low Q^2

⋆ Preliminary

$F^{\gamma}{}_2$: Monte Carlo

Monte Carlo Programs :

- $F^{\gamma}_{2,QED}$, $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$:

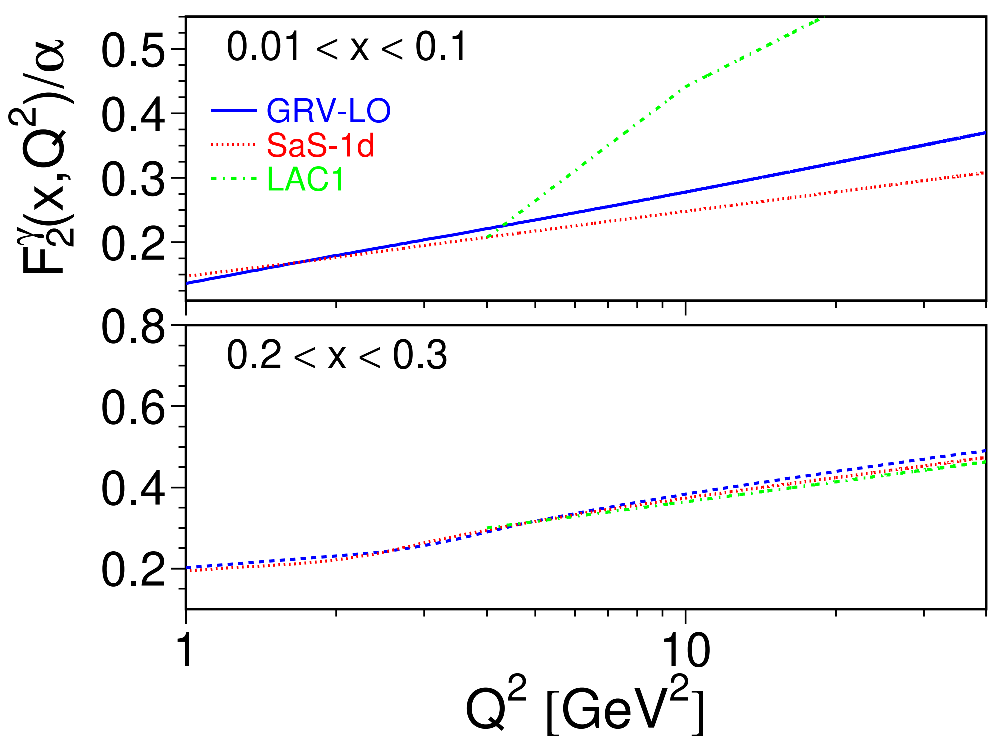
JAMVG, J.A.M. Vermaseren (Nucl. Phys. B229 347 (1983))
DIAG36, Berends, Daverveldt and Kleiss (CPC 40, 285 (1986)
RADCOR, Berends, Daverveldt and Kleiss (CPC 40, 271 (1986)

- $F^{\gamma}_{2,QCD}$, $e^+e^- \rightarrow e^+e^-\mathrm{hadrons}$:

TWOGAM, Nova, Olshevski and Todorov (Delphi Note 90-35)
PHOJET, Engel and Ranft (Phys. Rev. D54, 4244, (1995))
HERWIG, Marchesini et al. (CPC 67, 465, (1992))
PYTHIA, Sjöstrand and Schuler (CPC 82, 74, (1994))

$F^{\gamma}_{2,QCD}$: Parametrisations

- GRV-LO/HO, Glück, Reya and Vogt (1992) evolution starts at a low Q_0^2 ($= 0.25$ GeV^2)
- SaS-1d, Schuler and Sjöstrand (1995, 1996) evolution starts at a low Q_0^2 ($= 0.36$ GeV^2)
- LAC, Abramovicz, Charchula and Levy (1991) evolution starts at a high Q_0^2 ($= 4$ GeV^2)

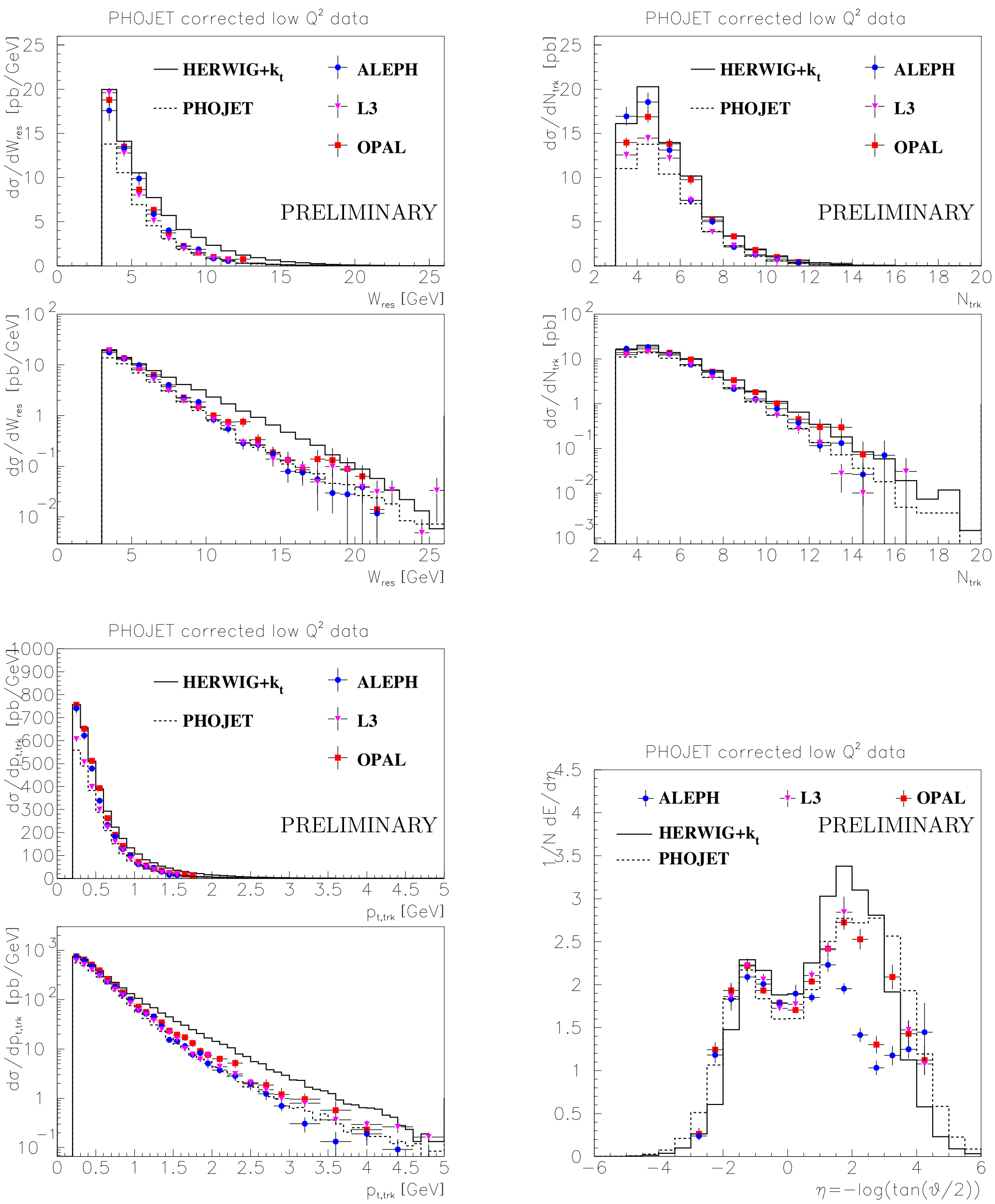


⇨ The effect of $P^2 \neq 0$ is not taken into account, it would reduce the predictions.

$F_{2,QCD}^{\gamma}$: Lep $\gamma\gamma$ Working Group

➜ Perform identical analysis in all Experiments

➜ Compare distributions inside the detector acceptance



⇨ Good agreement between Experiments

⇨ Need Improved Monte Carlo

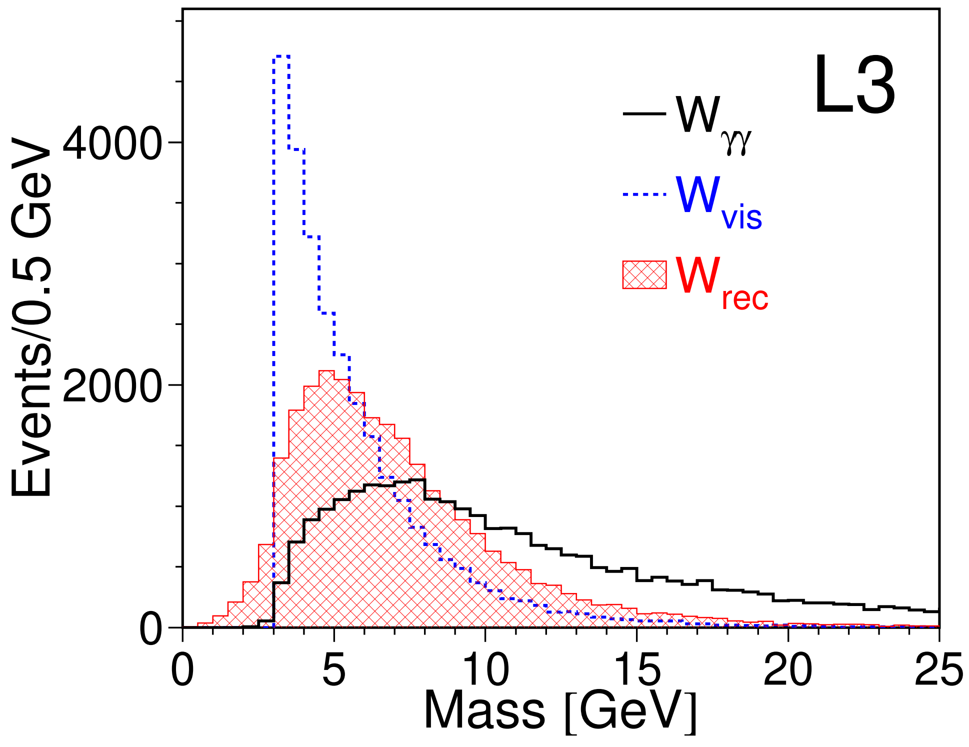
$\mathbf{F}^{\gamma}_{\mathbf{2,QCD}}$: $\boldsymbol{W_{vis}}$

Extract $\mathrm{F}^{\gamma}_{2,\mathrm{QCD}}$ from differential cross-section.

- Due to detector acceptance and efficiency ⇨ $W_{vis} < W_{\gamma\gamma}$ ➜ Unfolding
- Improve W_{vis} ➜ Use kinematics of e_{tag}

$$W^2_{rec} = (p_+^{e_{in}} - p_+^{e_{tag}})(\textstyle\sum_i p_-^i) - |p_t^{e_{tag}}|^2$$
$$p_\pm = E \pm p_z$$

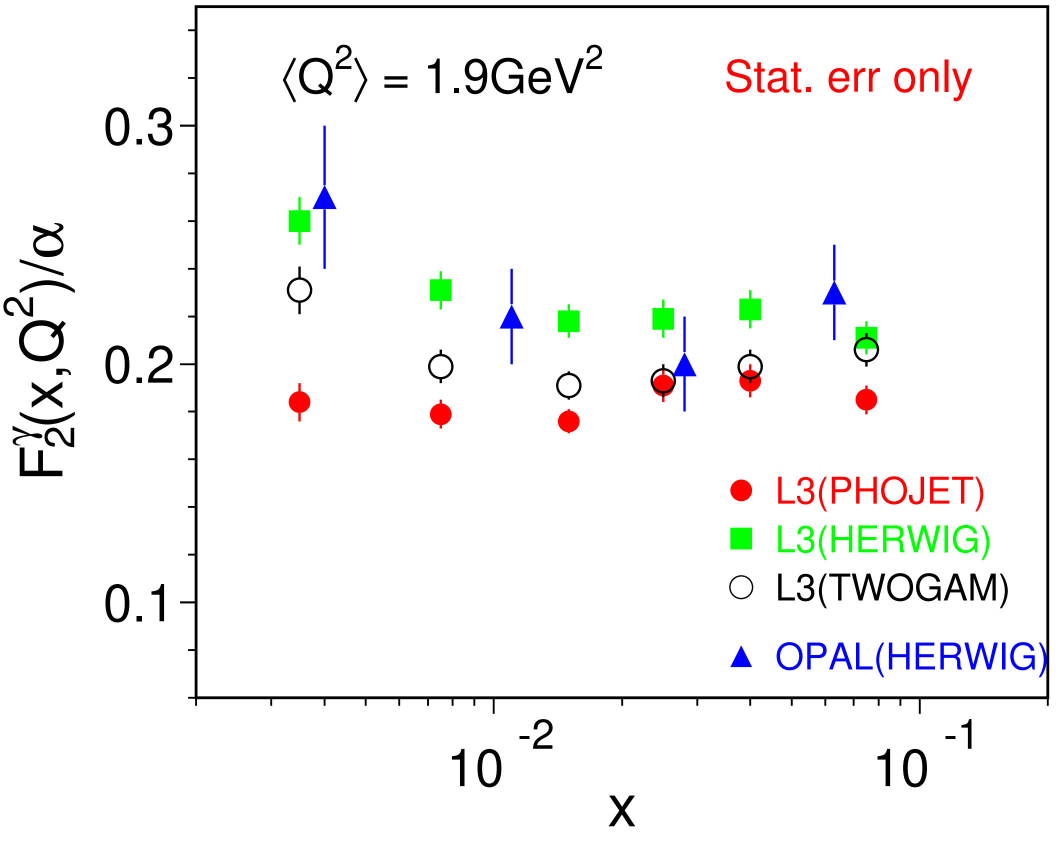
* Physics at LEP2, CERN 96-01, Vol.2, 201.



- Use Unfolding for x_{rec} ➜ x.

$F^{\gamma}_{2,\mathrm{QCD}}$: Modelling Dependence

- Unfold the data with different Monte Carlos.
- The OPAL results are obtained with HERWIG.

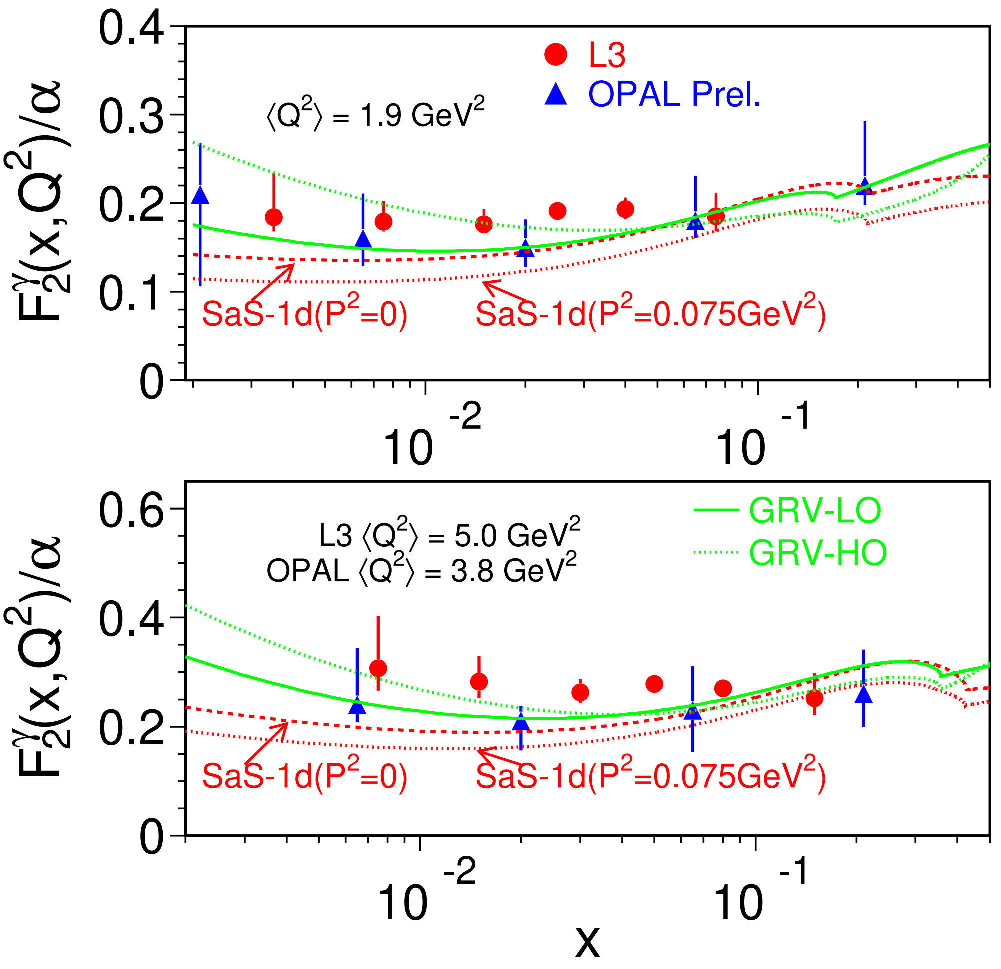


⇨ L3 and OPAL agree if they use the same MC

⇨ The discrepancy (10% - 30%) is larger at low x.

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

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



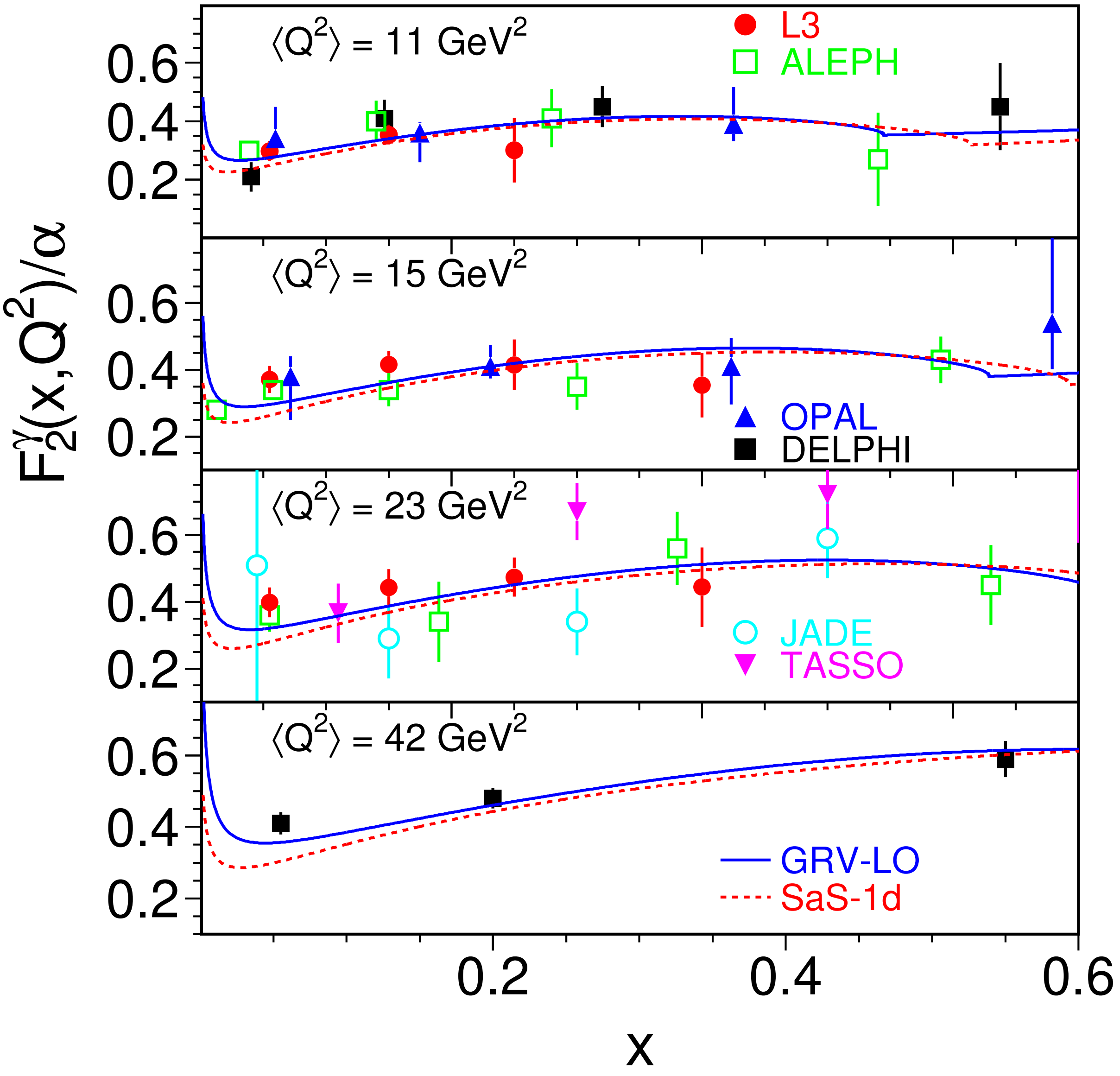
➪ SaS-1d lies below the data

➪ The effect of $< P^2 > \neq 0$ decreases SaS-1d by $\sim 15\%$ ➜ Since $< P^2 >$ depends on the unkown mixture F_2^{PL} and F_2^{hadr} no correction is applied to the data

➪ GRV better at the low x and is for $< P^2 >= 0$

$F^{\gamma}_{2,\mathrm{QCD}}$: Medium Q^2

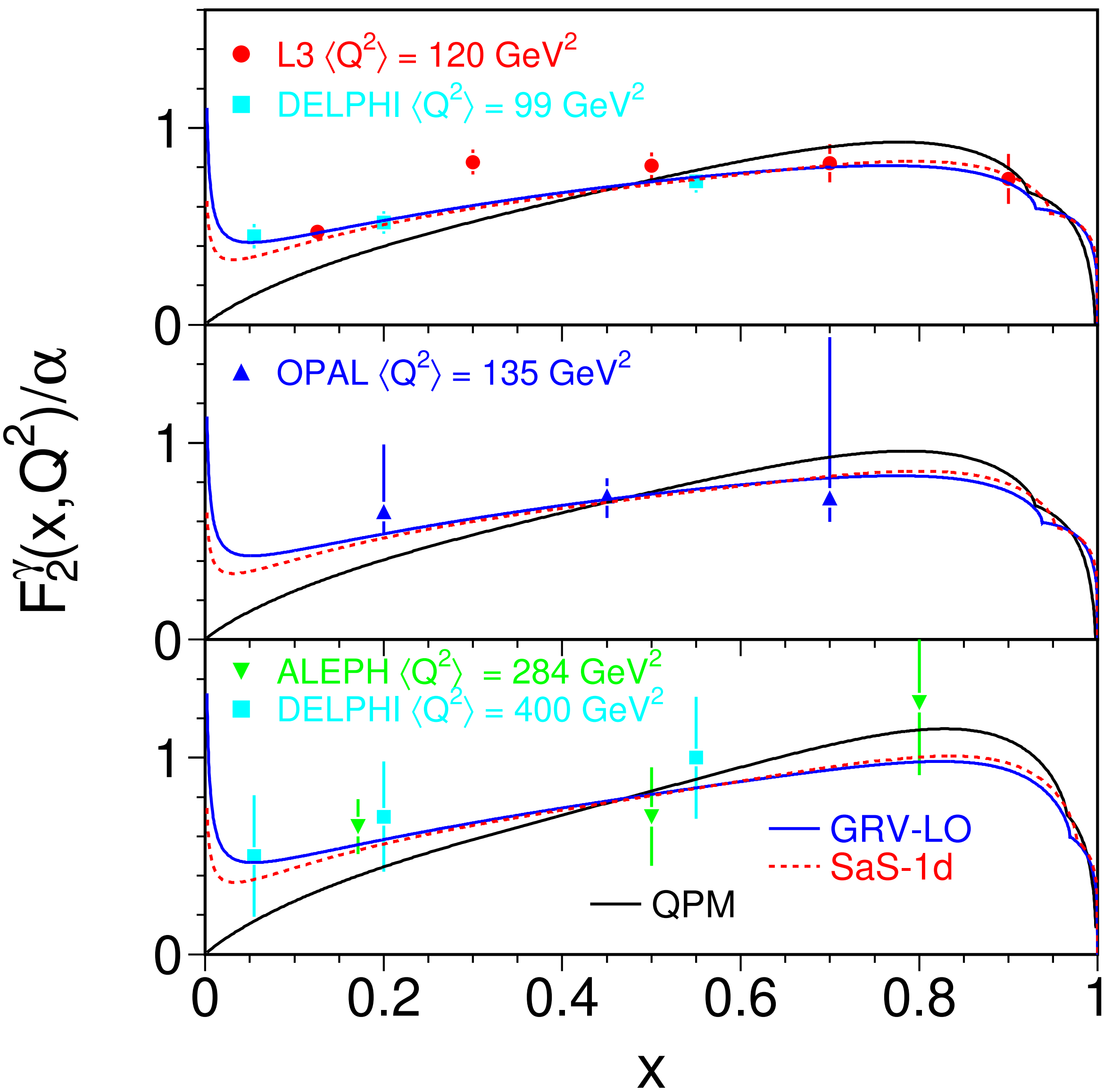
- The measured $F^{\gamma}_{2,\mathrm{QCD}}$ at medium Q^2



- Small modelling dependence
- GRV and SAS are in good agreement with data
- The measurement of F^{γ}_{2} at LEP has improved with respect to PETRA.

$F^{\gamma}_{2,\mathrm{QCD}}$: High Q^2

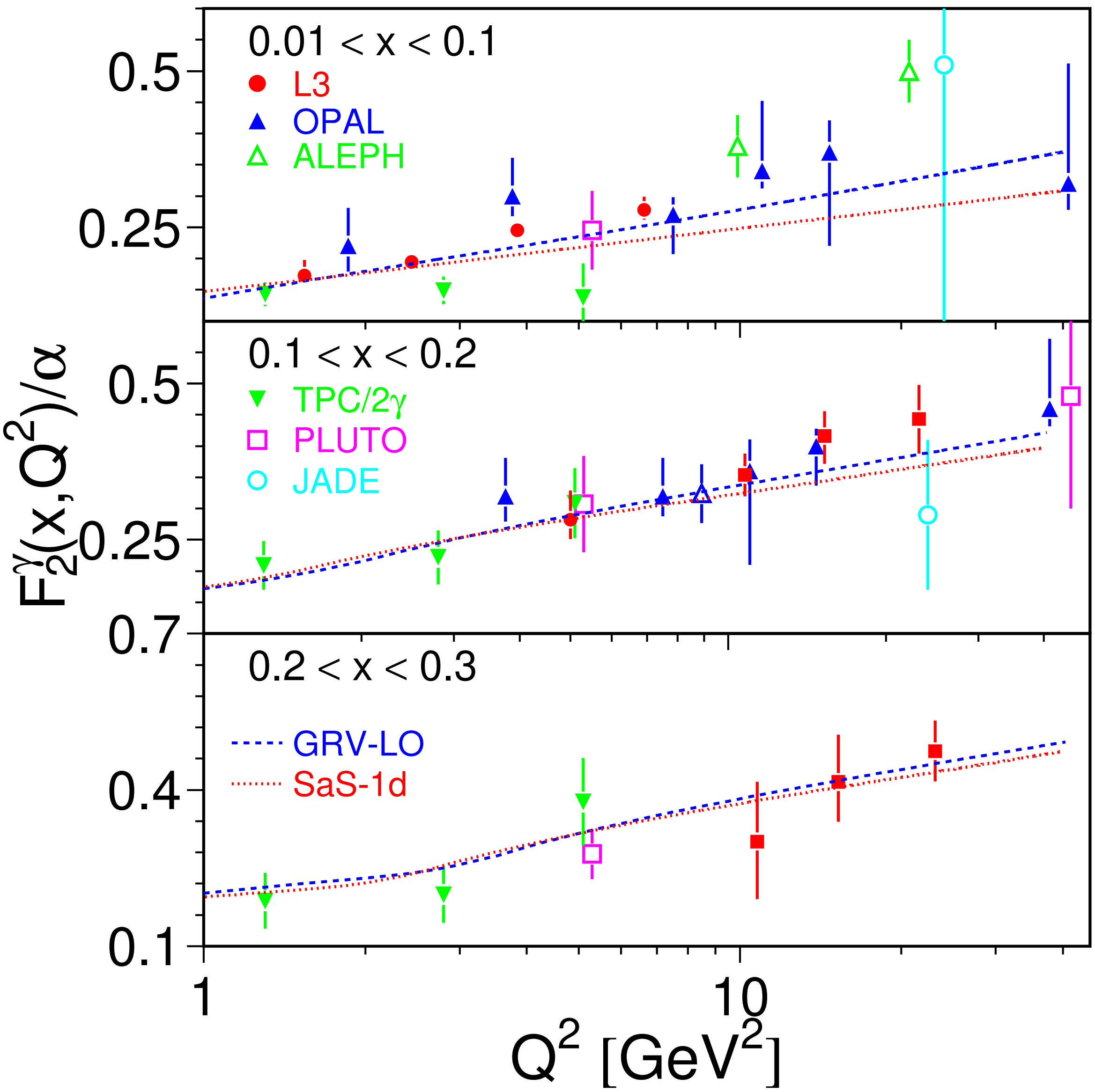
- The measured $F^{\gamma}_{2,\mathrm{QCD}}$ at high Q^2



- 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

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

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

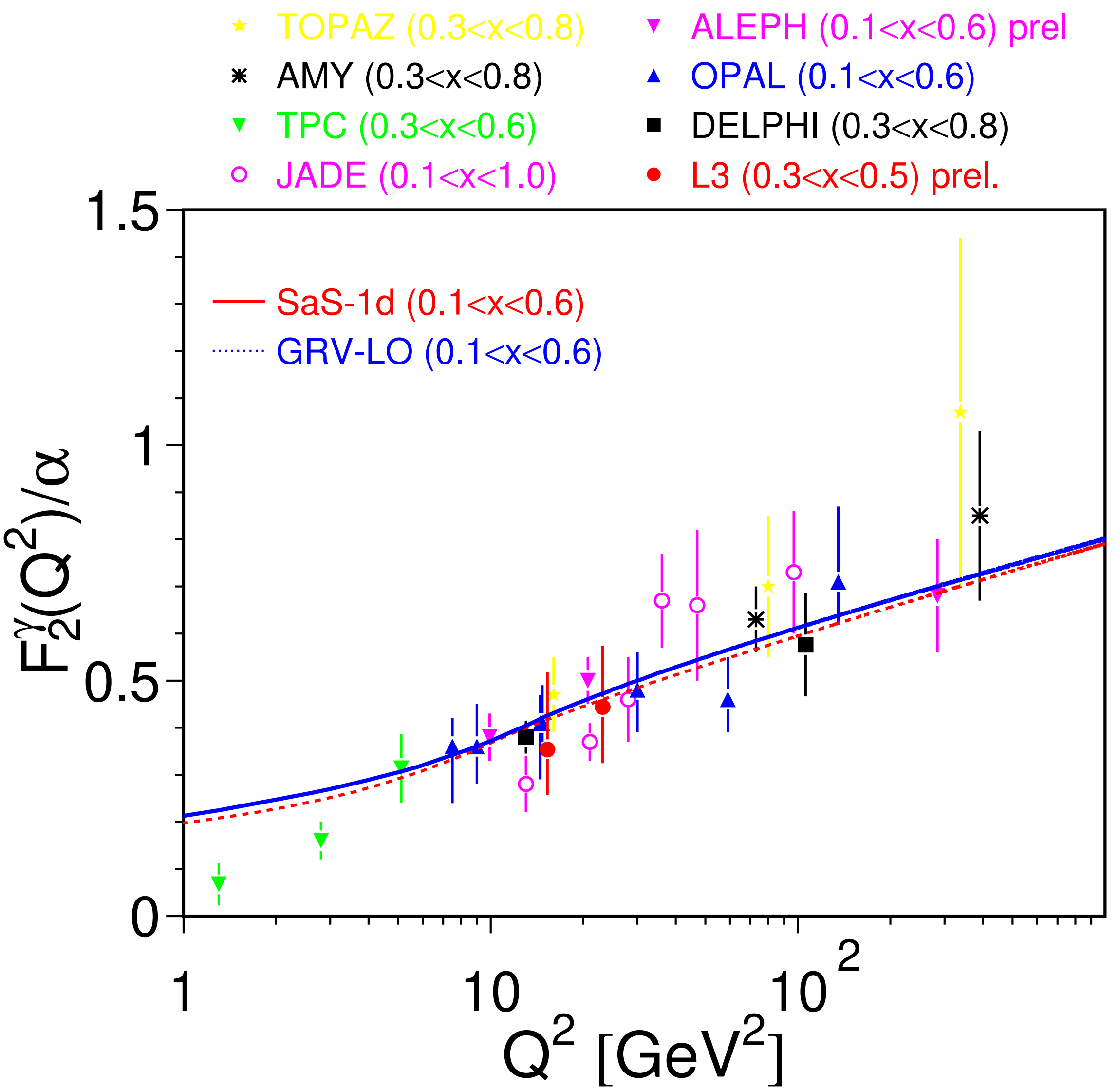


➩ $\ln Q^2$ evolution well established

➩ Improvement on the models at low X is needed

$F^{\gamma}_{2,QCD}$: Q^2 Evolution

- The measured F^{γ}_2 as a function of $\ln Q^2$ at high x.



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

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

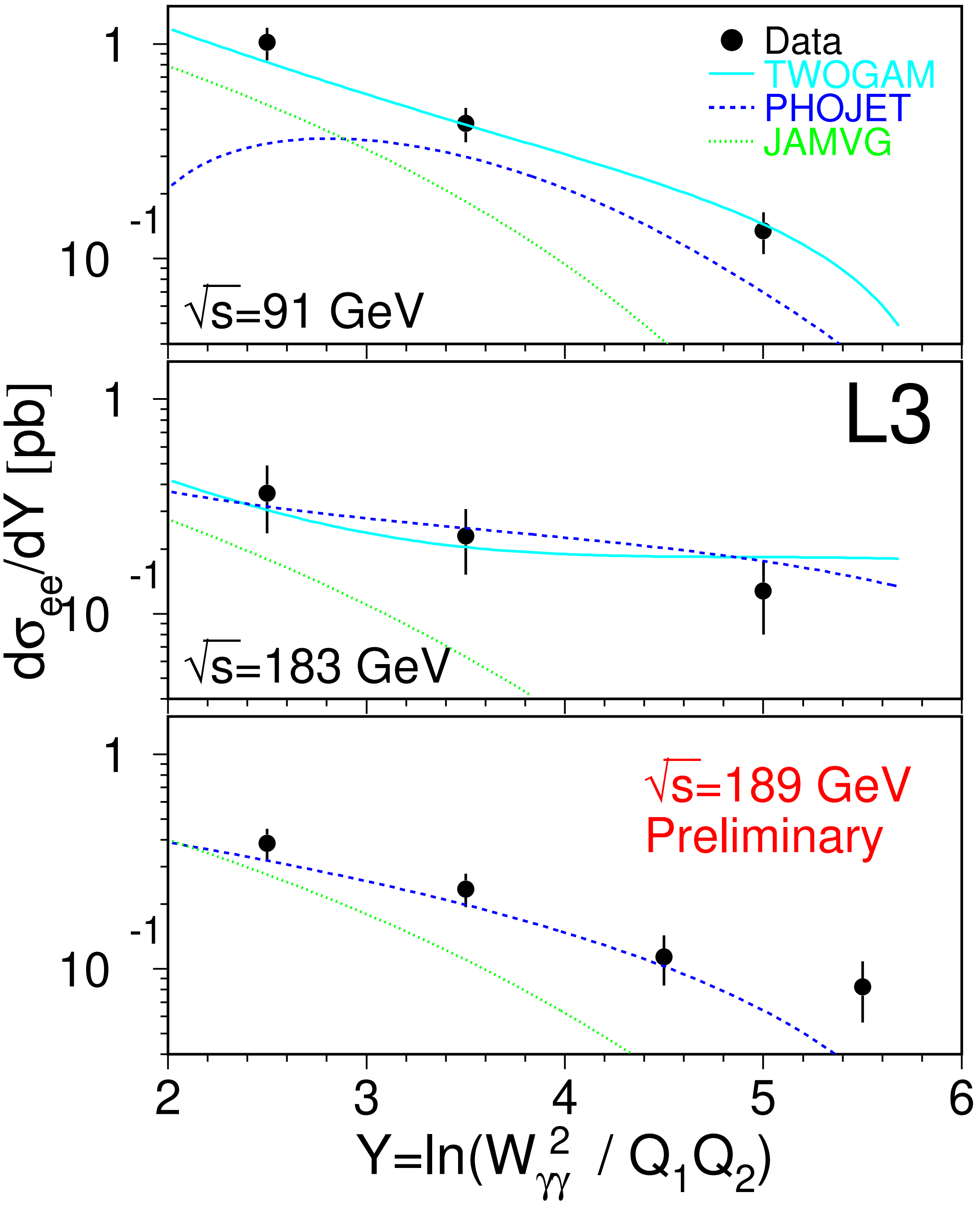
$\sqrt{s}$	91 GeV	183 GeV	189 GeV
$W_{\gamma\gamma}$	2 - 3 GeV	5 - 70 GeV	5 - 75 GeV
Q^2	1 - 9 GeV^2	2 - 35 GeV^2	3 - 37 GeV^2
$< Q^2 >$	3.5 GeV^2	14 GeV^2	14.5 GeV^2

Events	137	34	108
Bkg	12	4	14

→ OPAL: 44 Events

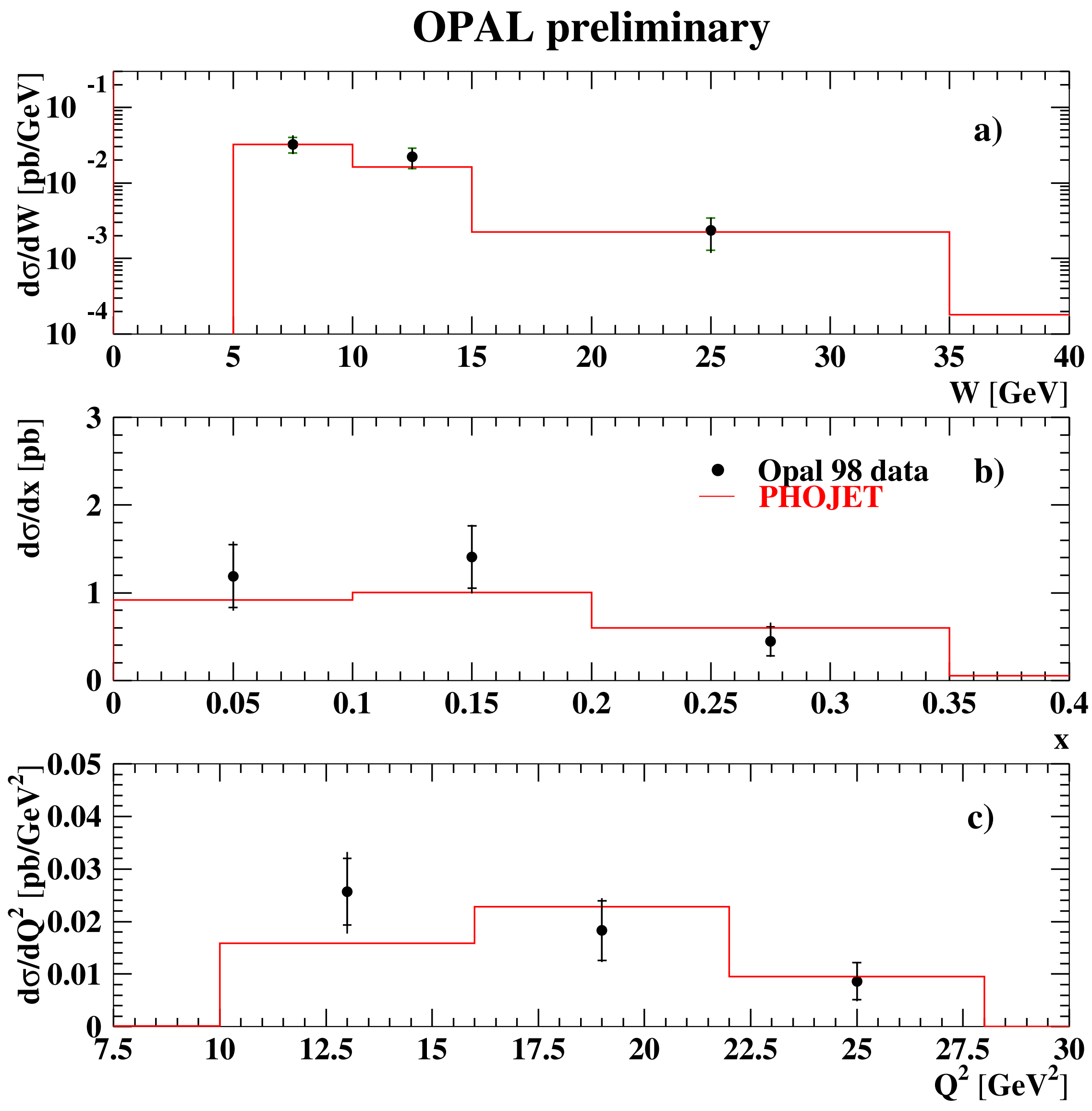
- The backgrounds come from $e^+e^- \rightarrow e^+e^-\tau^+\tau^-$ and single tagged events.
- Typical efficiencies for L3 at 189 GeV:
  PHOJET: 64.8 ± 2.7 %
  JAMVG: 64.3 ± 3.0 %
- Results are insensitive to MC corrections

σ_{ee} : Results

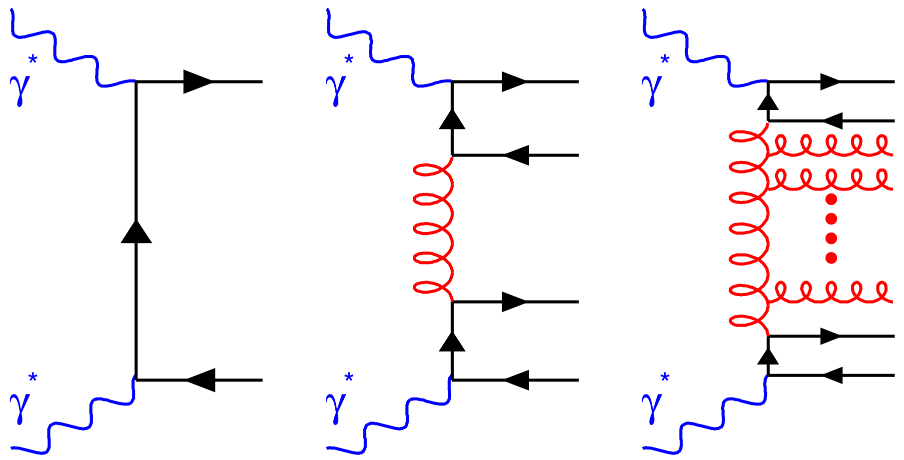


Direct process (JAMVG) is insufficient
but
PHOJET and TWOGAM agree quite well

σ_{ee} : Results



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

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

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

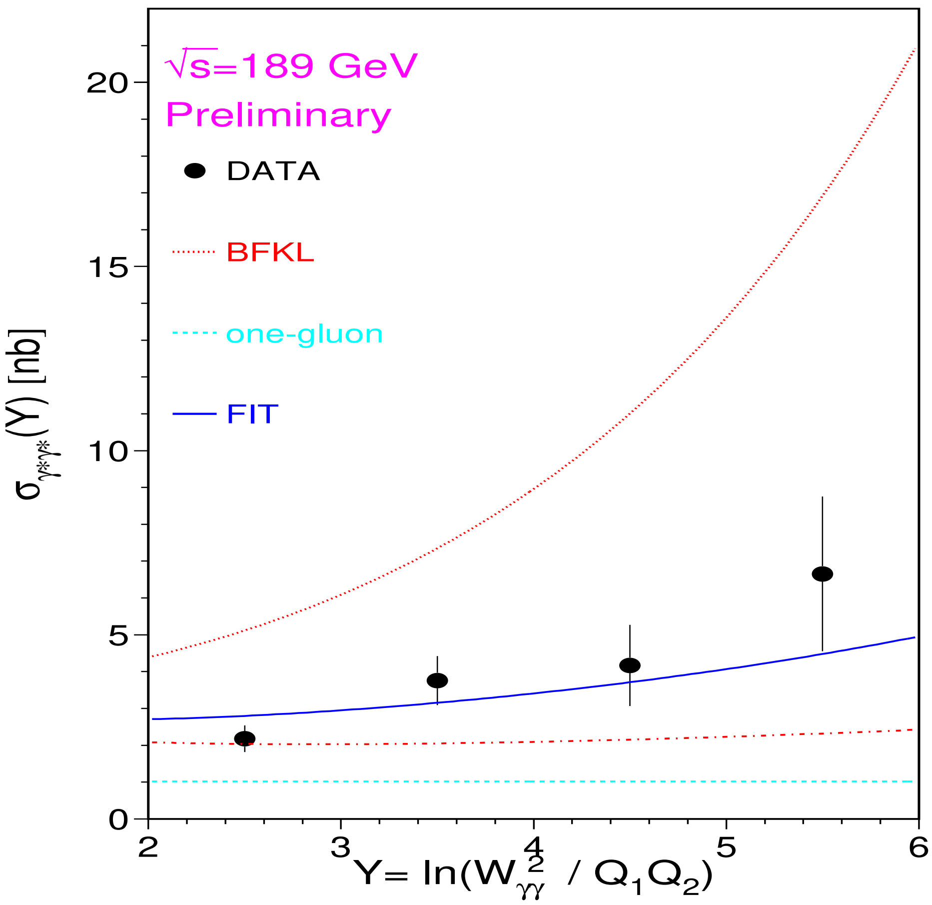
Using $N_c = 3$, $\alpha_s = 0.2$ ➜ $\alpha_P - 1 \simeq 0.53$
(> 0.095 "soft Pomeron")

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

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

After subtraction of the direct part :

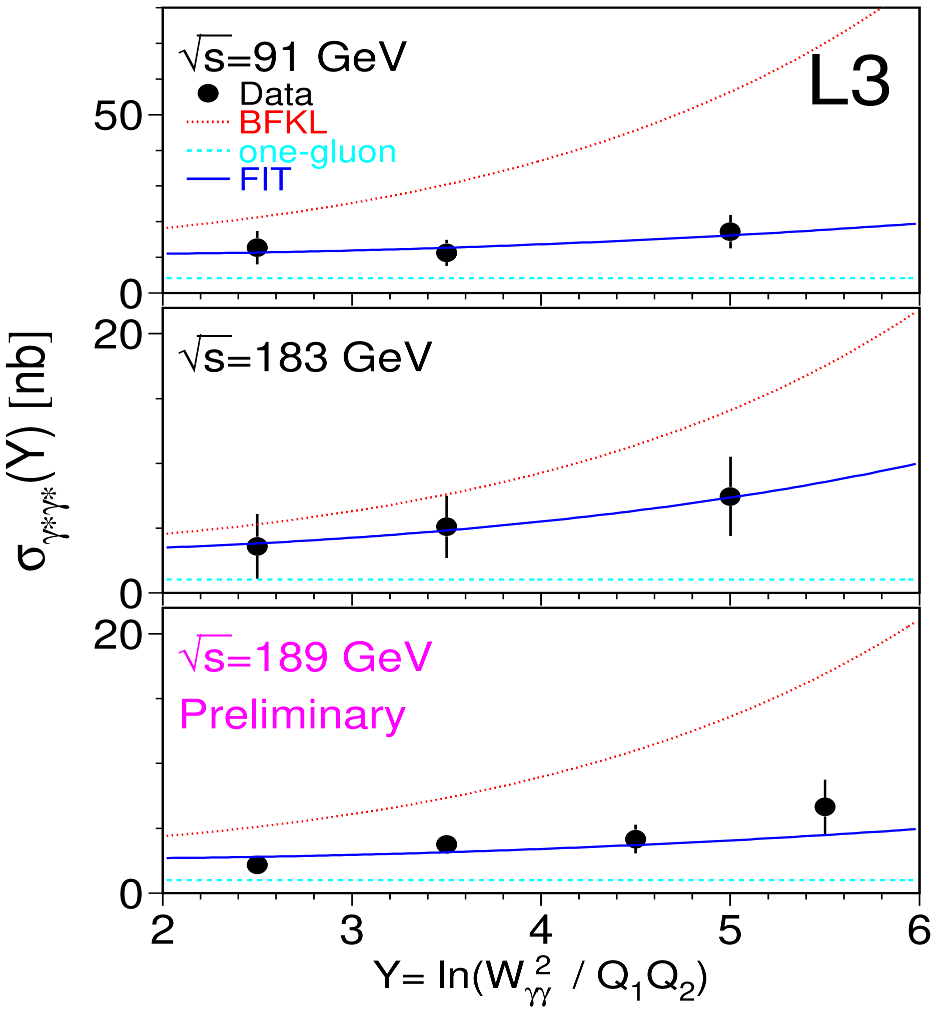
$\sigma_{ee} = L_{TT} \otimes \sigma_{\gamma^*\gamma^*}$



- 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:

$$\alpha_P - 1 = 0.29 \pm 0.032 \quad < 0.53 \text{ (LO)}$$
$$> 0.175 \text{ (NLO) !}$$

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



combined fit:

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

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

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

Conclusions

LEP will run until year 2000 ➜ more data are coming !

Even more precise results are foreseen !

Theory and Monte Carlo must improve!!