Experimental Results on Two-Photon Physics from LEP

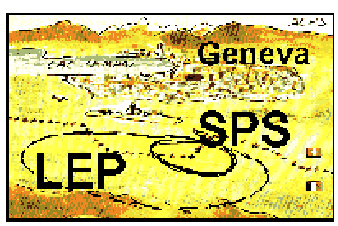
Richard Nisius (CERN) May, 31 ’99

- Introduction

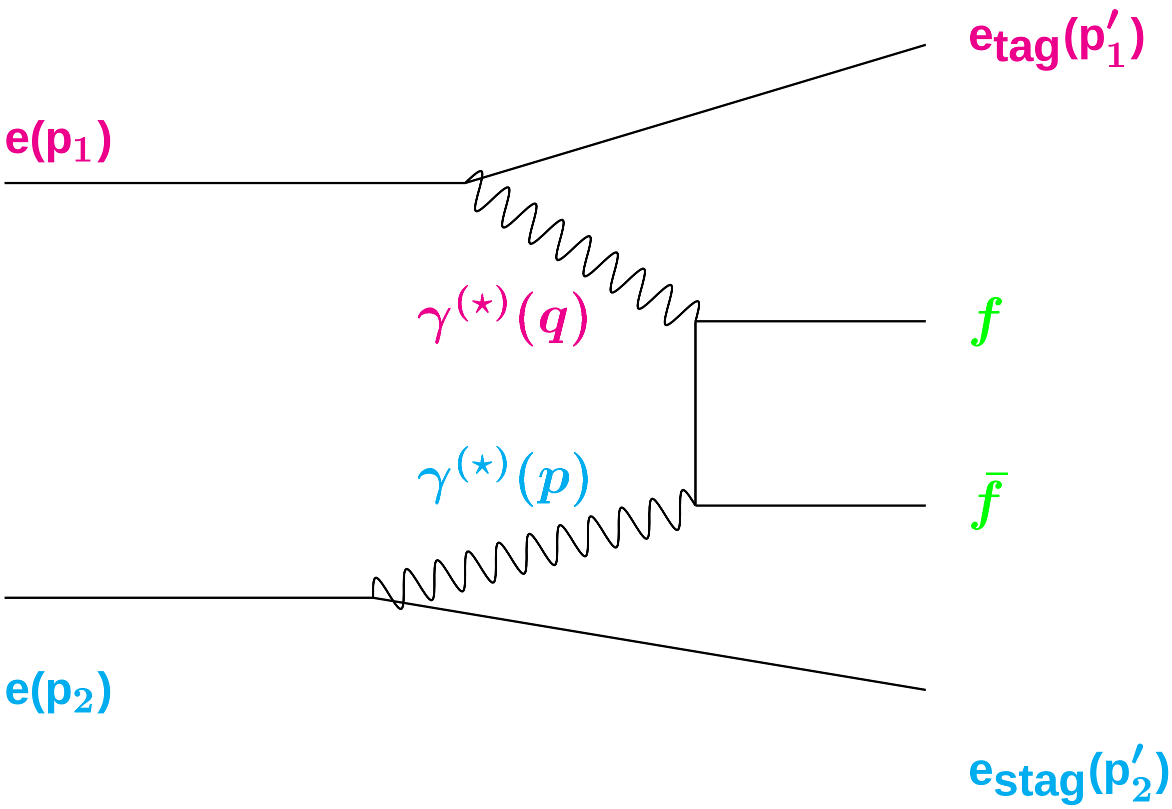
1. The structure of quasi-real photons

2. The structure of virtual photons

- Conclusions



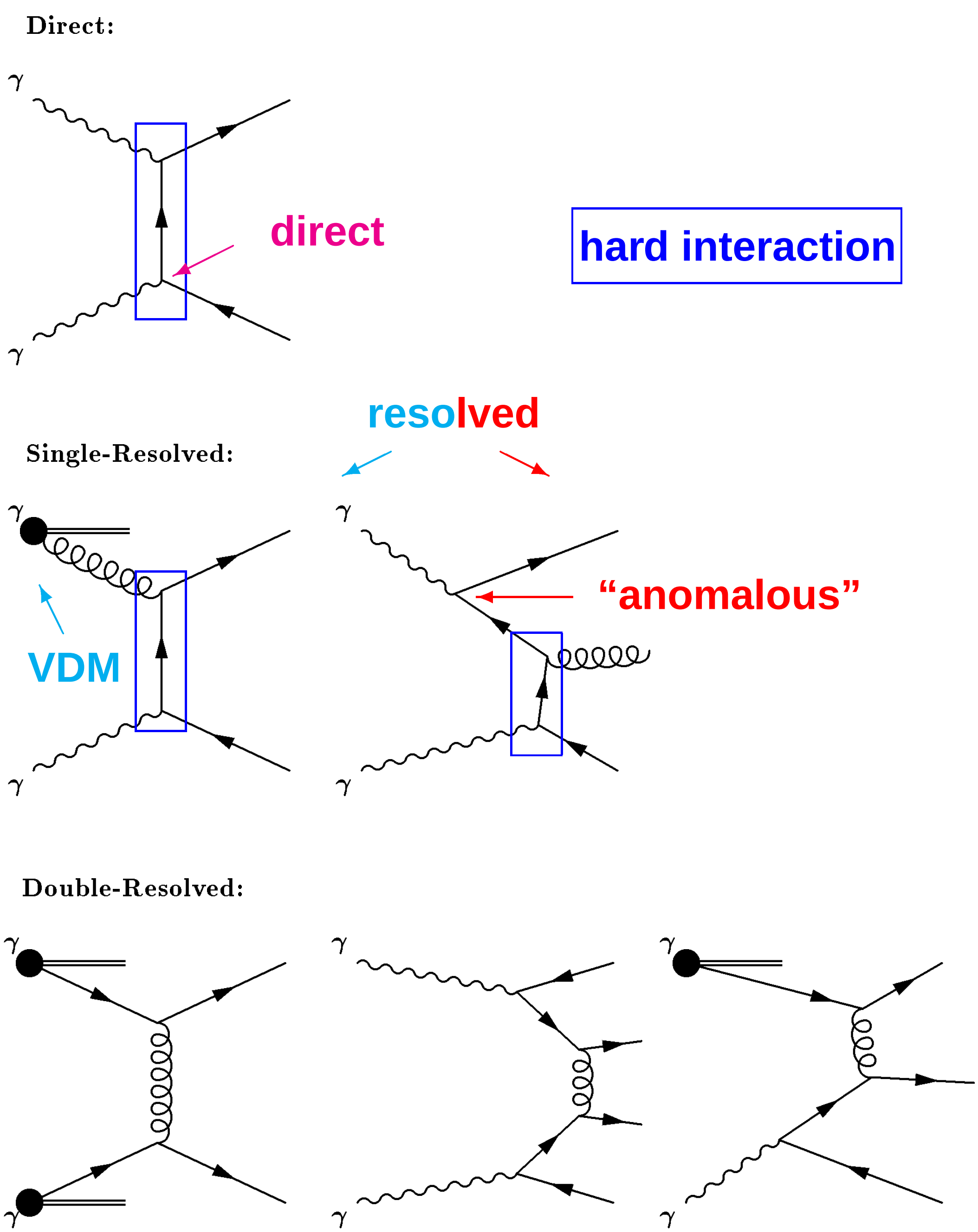
The reaction $\mathrm{ee} \to \mathrm{ee f\bar{f}}$



$$\mathrm{d}^6\sigma = \frac{\mathrm{d}^3 p'_1 \mathrm{d}^3 p'_2}{E'_1 E'_2} \frac{\alpha^2}{16\pi^4 q^2 p^2} \left[\frac{(q\cdot p)^2 - q^2 p^2}{(p_1\cdot p_2)^2 - m_\mathrm{e}^2 m_\mathrm{e}^2}\right]^{1/2} \cdot$$
$$\Big(4\rho_1^{++}\rho_2^{++}\sigma_{\mathrm{TT}} + 2\rho_1^{++}\rho_2^{00}\sigma_{\mathrm{TL}}$$
$$+2\rho_1^{00}\rho_2^{++}\sigma_{\mathrm{LT}} + \rho_1^{00}\rho_2^{00}\sigma_{\mathrm{LL}} +$$
$$2|\rho_1^{+-}\rho_2^{+-}|\tau_{\mathrm{TT}}\cos 2\bar{\phi} - 8|\rho_1^{+0}\rho_2^{+0}|\tau_{\mathrm{TL}}\cos\bar{\phi}\Big)$$

$$Q^2 = 2\,E_\mathrm{b}\,E_{\mathrm{tag}}\,(1-\cos\theta_{\mathrm{tag}})$$
$$P^2 = 2\,E_\mathrm{b}\,E_{\mathrm{stag}}\,(1-\cos\theta_{\mathrm{stag}})$$
$$x = \frac{Q^2}{Q^2 + W^2 + P^2}$$

Leading order diagrams



Monte Carlo models

PYTHIA and PHOJET

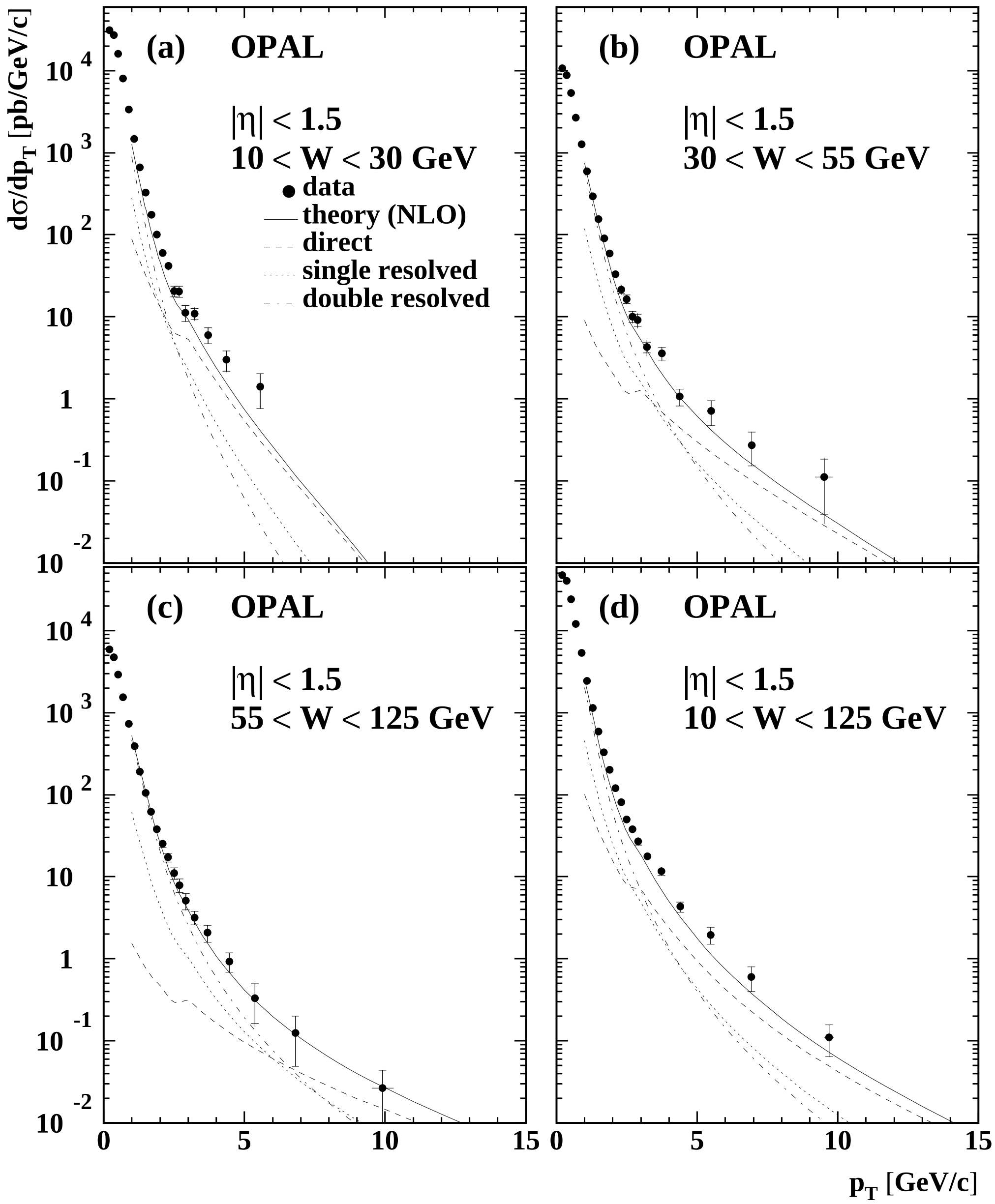
Monte Carlo ingredients:

1. Leading order (LO) QCD matrix elements
2. Hard and soft processes
3. Total cross sections from Regge models
4. Initial state parton radiation
5. Fragmentation based on JETSET
6. Multiple interactions

NLO calculations

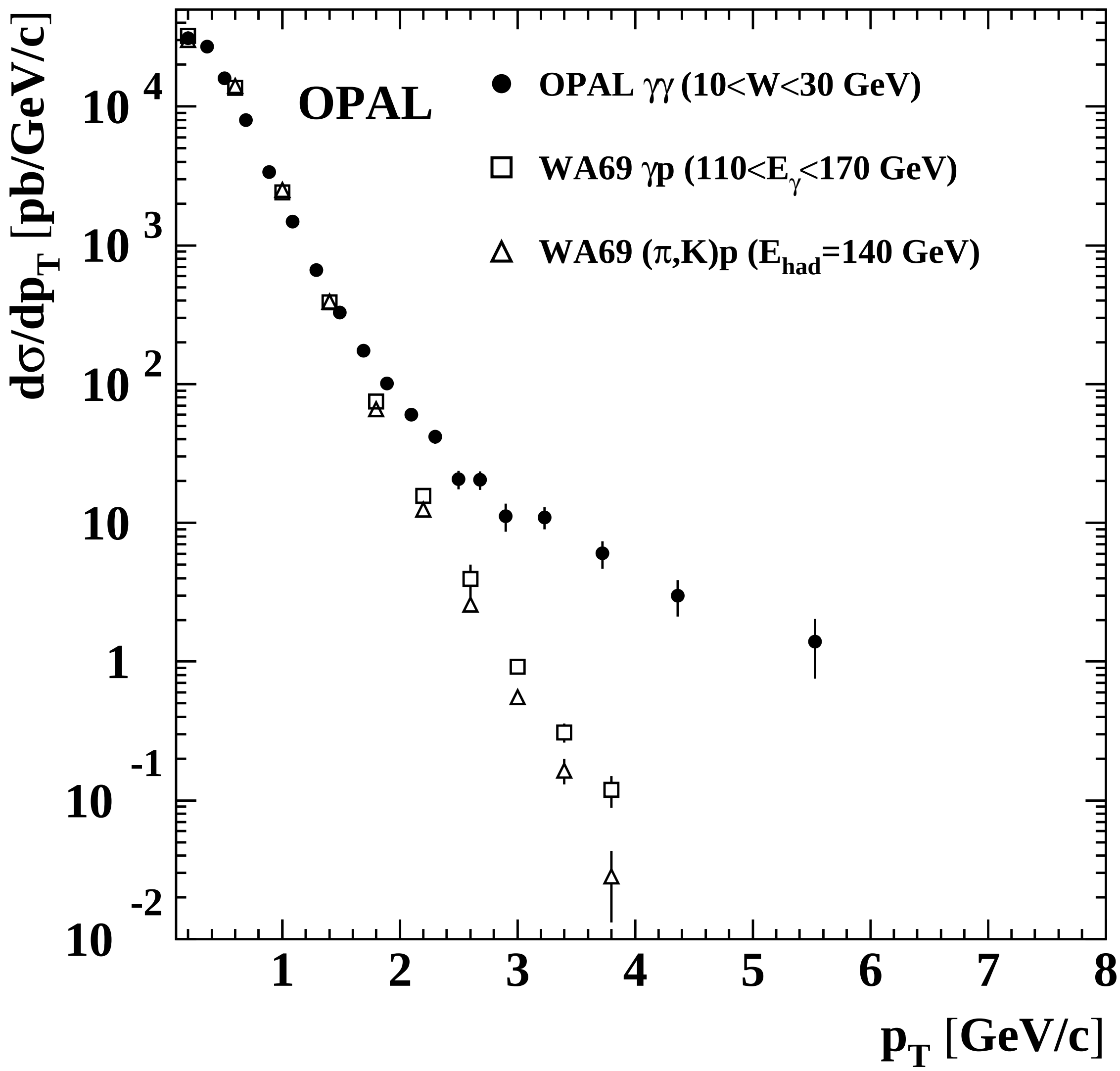
- NLO particle spectra by J. Binnewies, B.A.. Kniehl and G. Kramer
- NLO jet cross-sections by M. Klasen, T. Kleinwort and G. Kramer

Inclusive charged hadron production



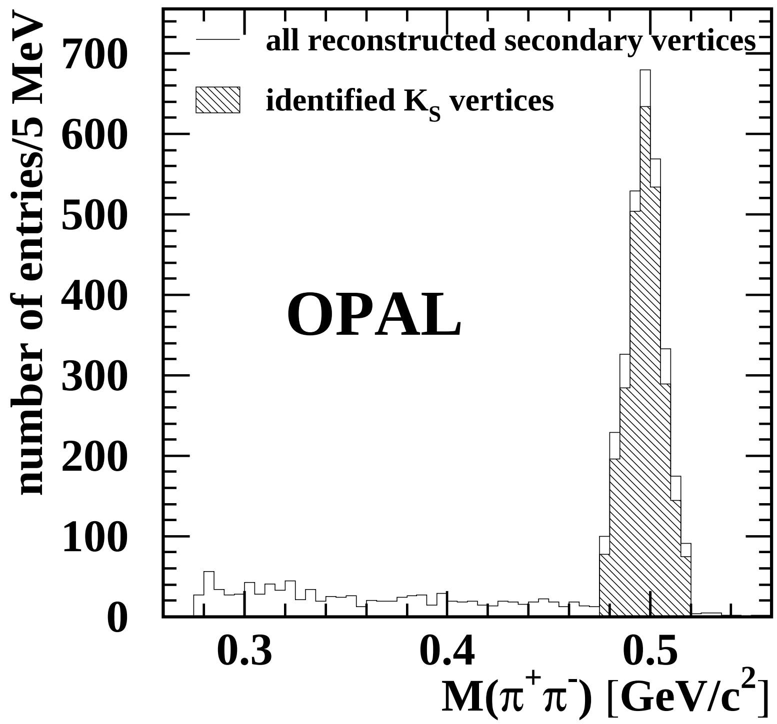
The NLO QCD calculation agrees well with the data.

Comparison to γp and hp data



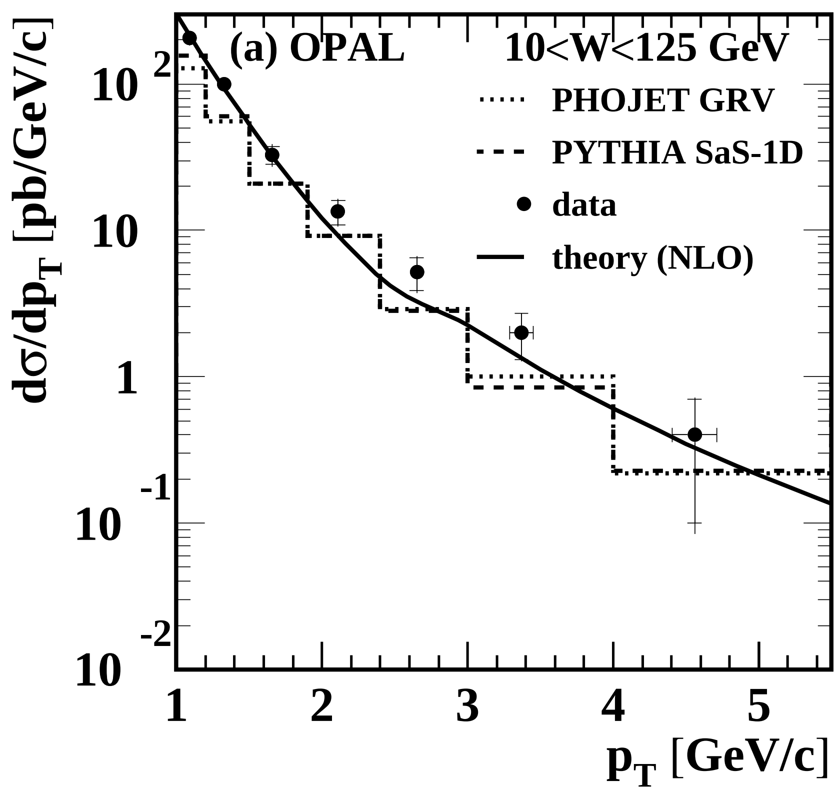
The hard component due to the pointlike coupling of the photon is clearly seen in the data.

Production of K_S^0 mesons

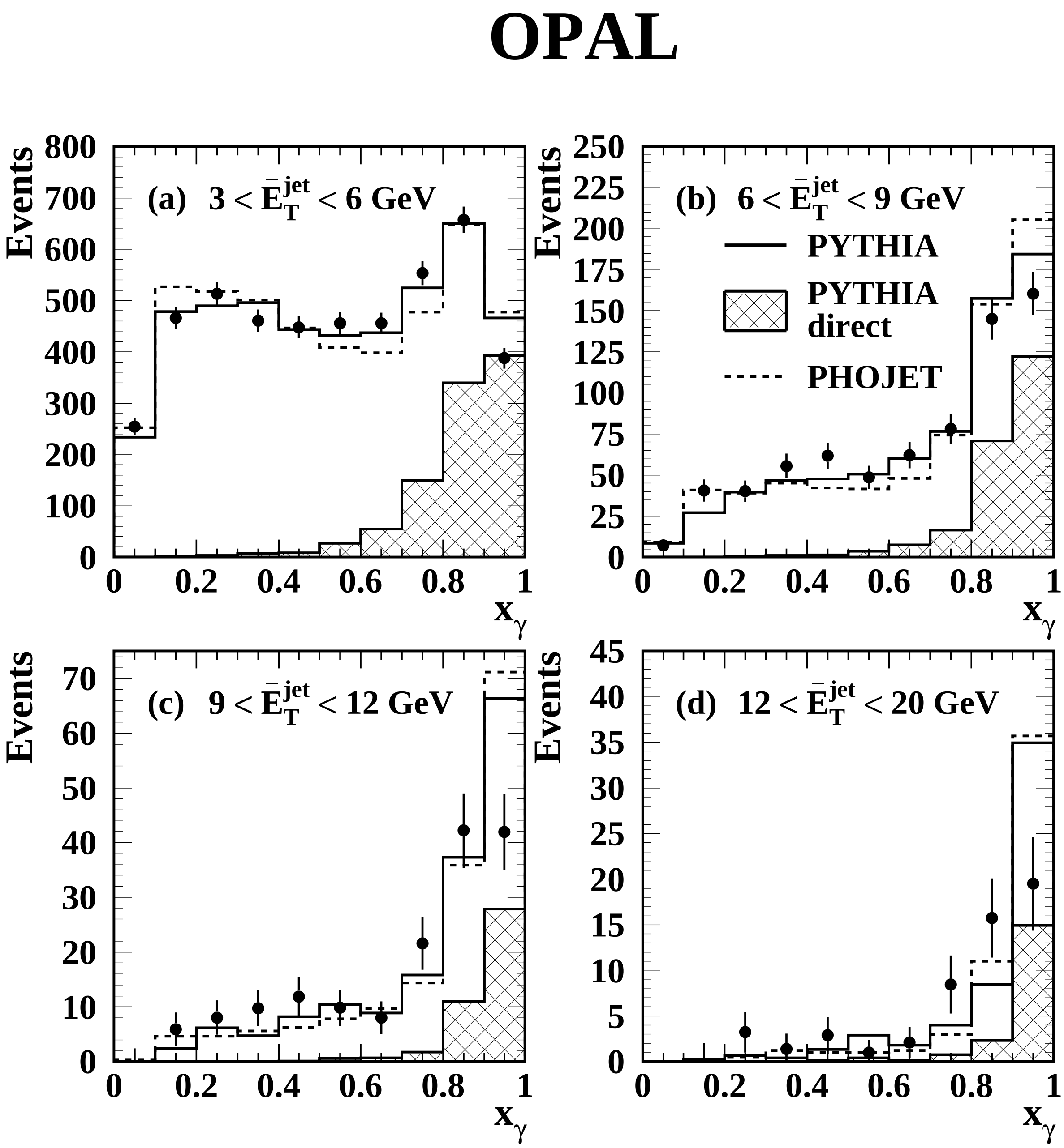


$eff = 35.5\%$

$pur = 95.5\%$

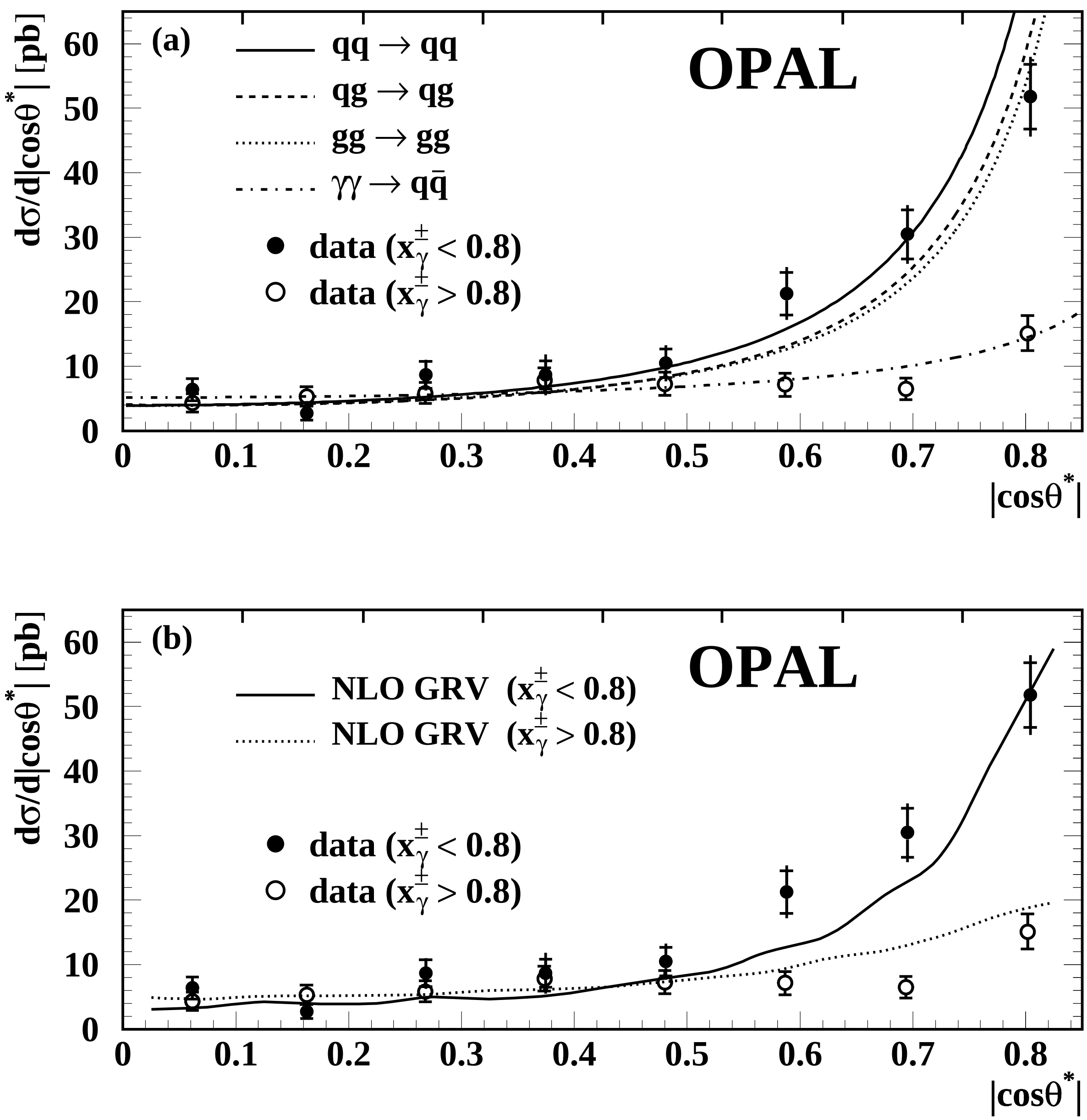


Event classes for direct events



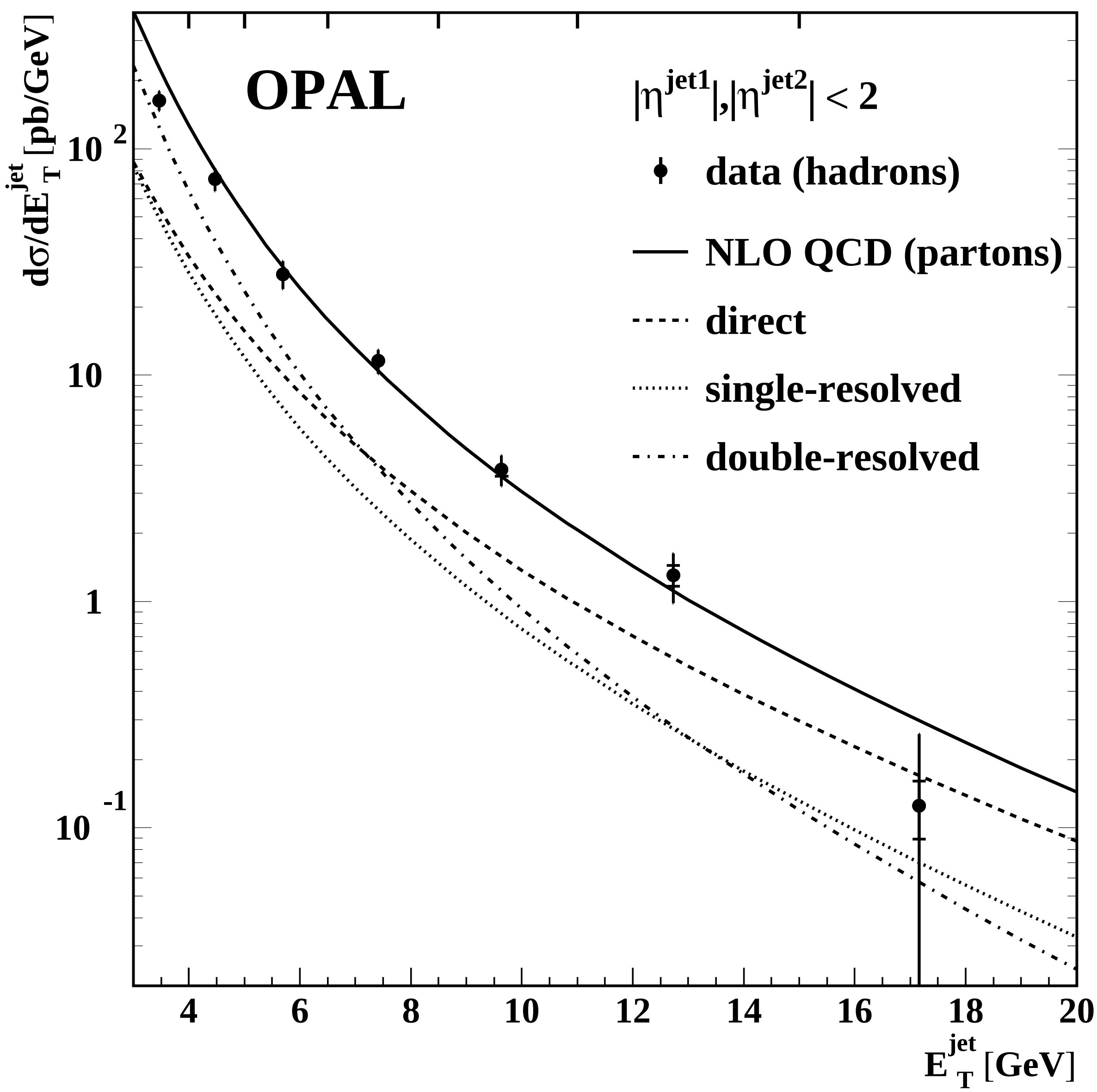
A clear separation between direct and resolved events can be made

The angular dependencies of different processes



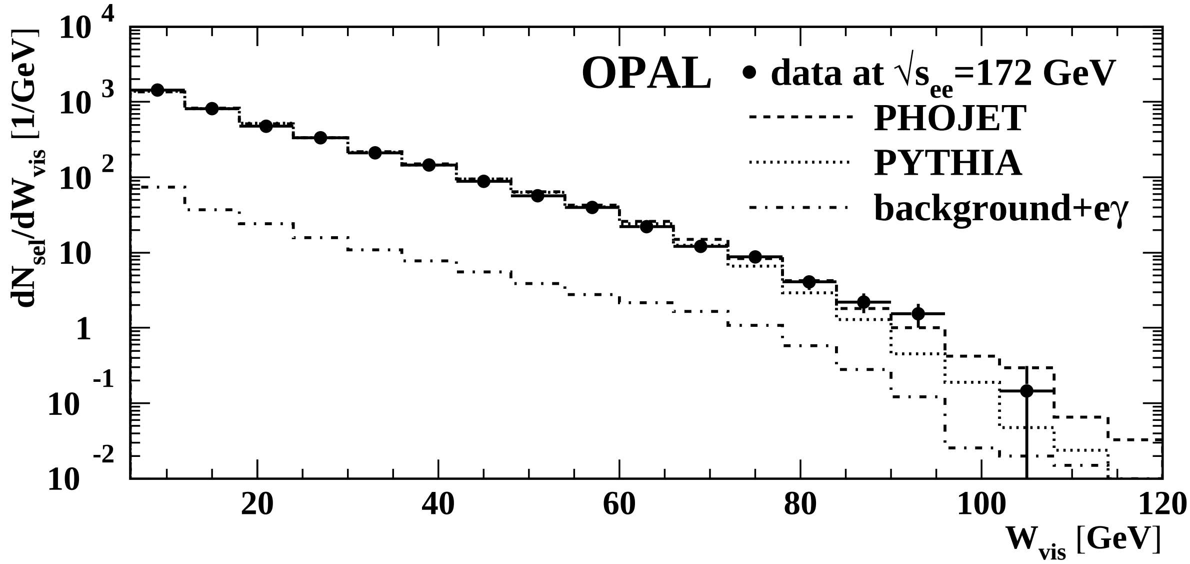
The angular dependencies of the different processes can be clearly disentangled

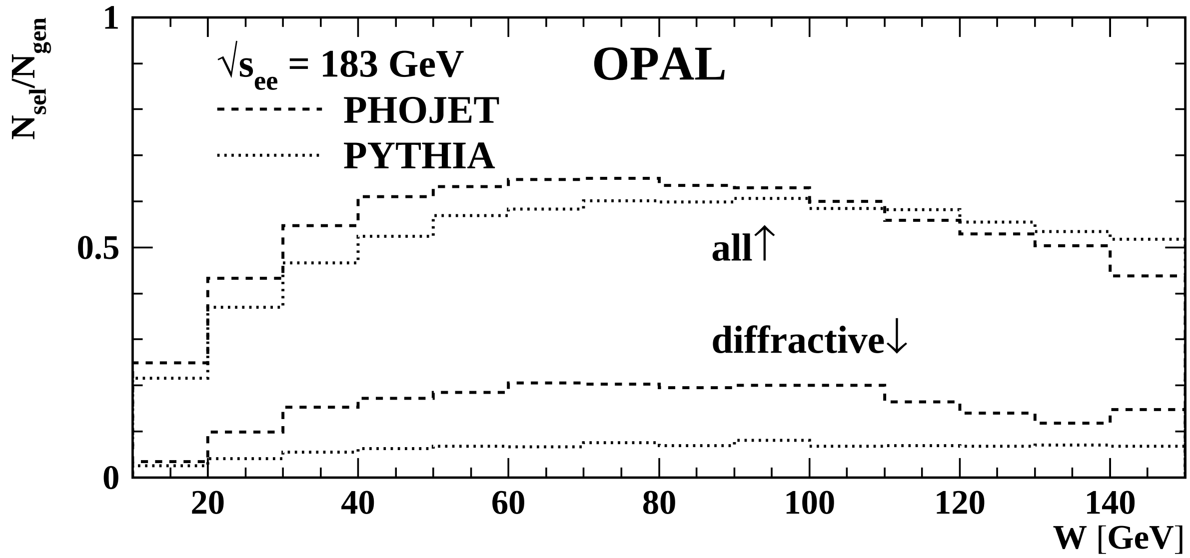
Jet cross-sections as a function of E_T



The NLO calculation is in fair agreement with the data

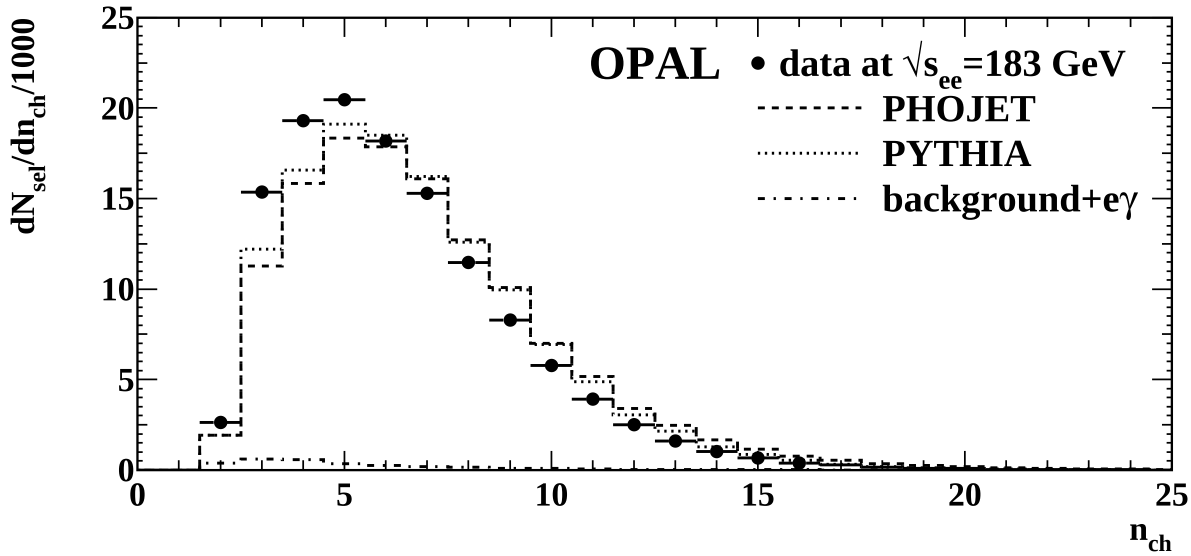
The W distributions for anti-tagged events

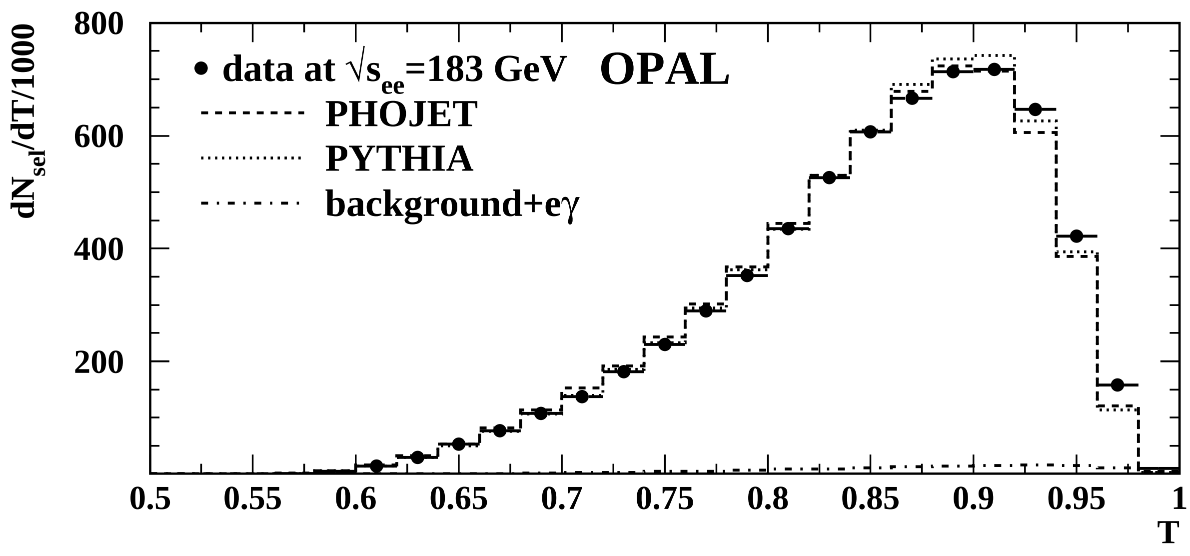




The acceptance for diffractive and elastic events is very different for the Phojet and Pythia models

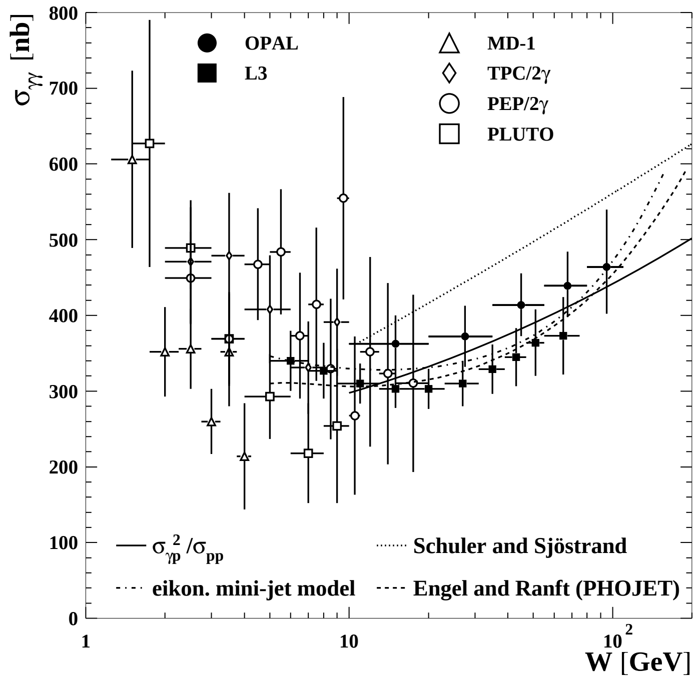
Some global quantities for anti-tagged events

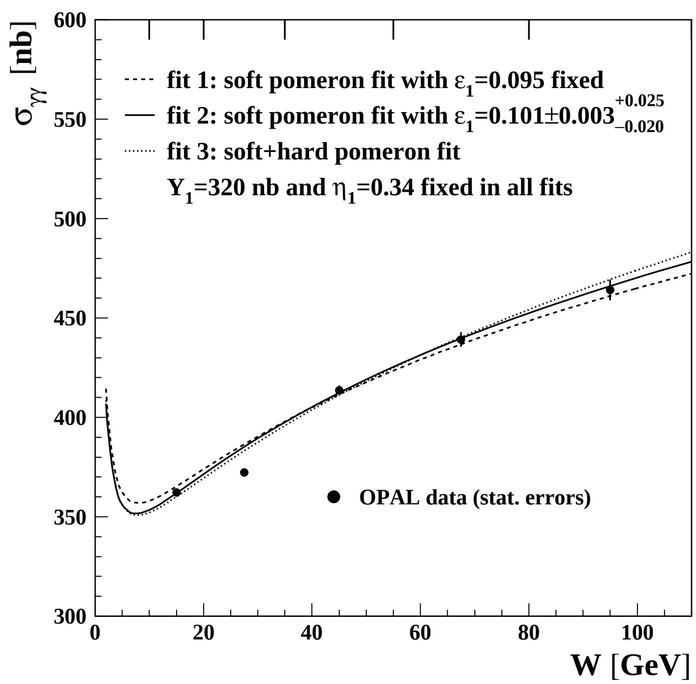




The low multiplicity region is most problematic

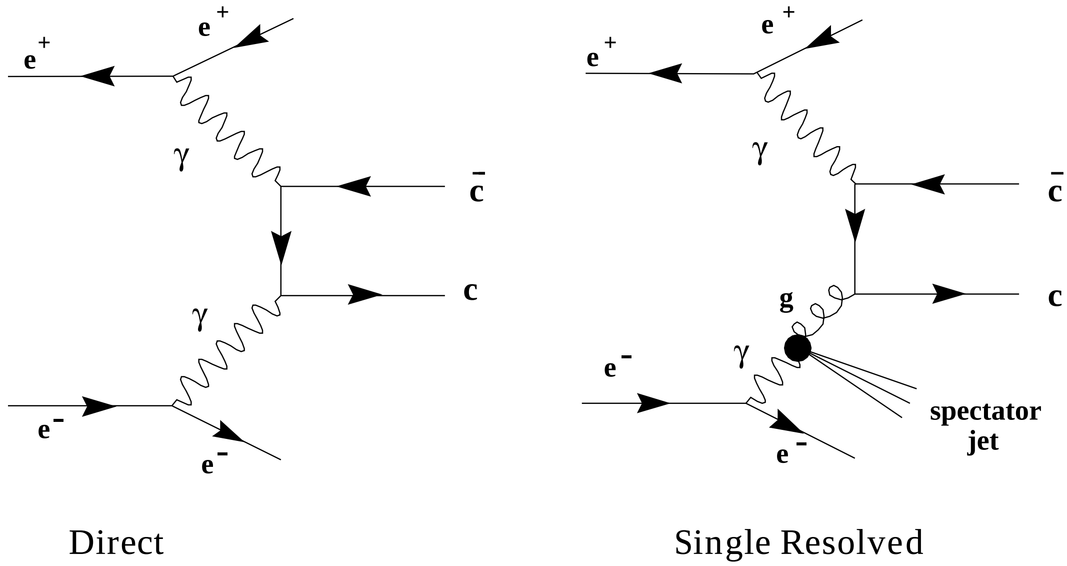
The total hadronic cross-section

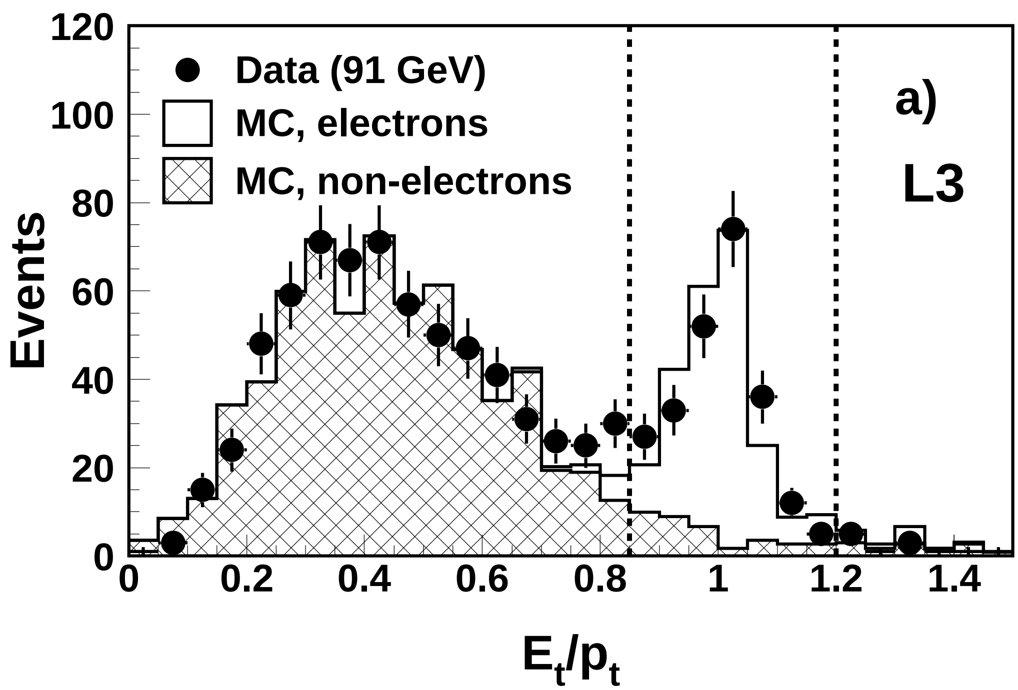




A clear rise of the total cross-section is observed in the data

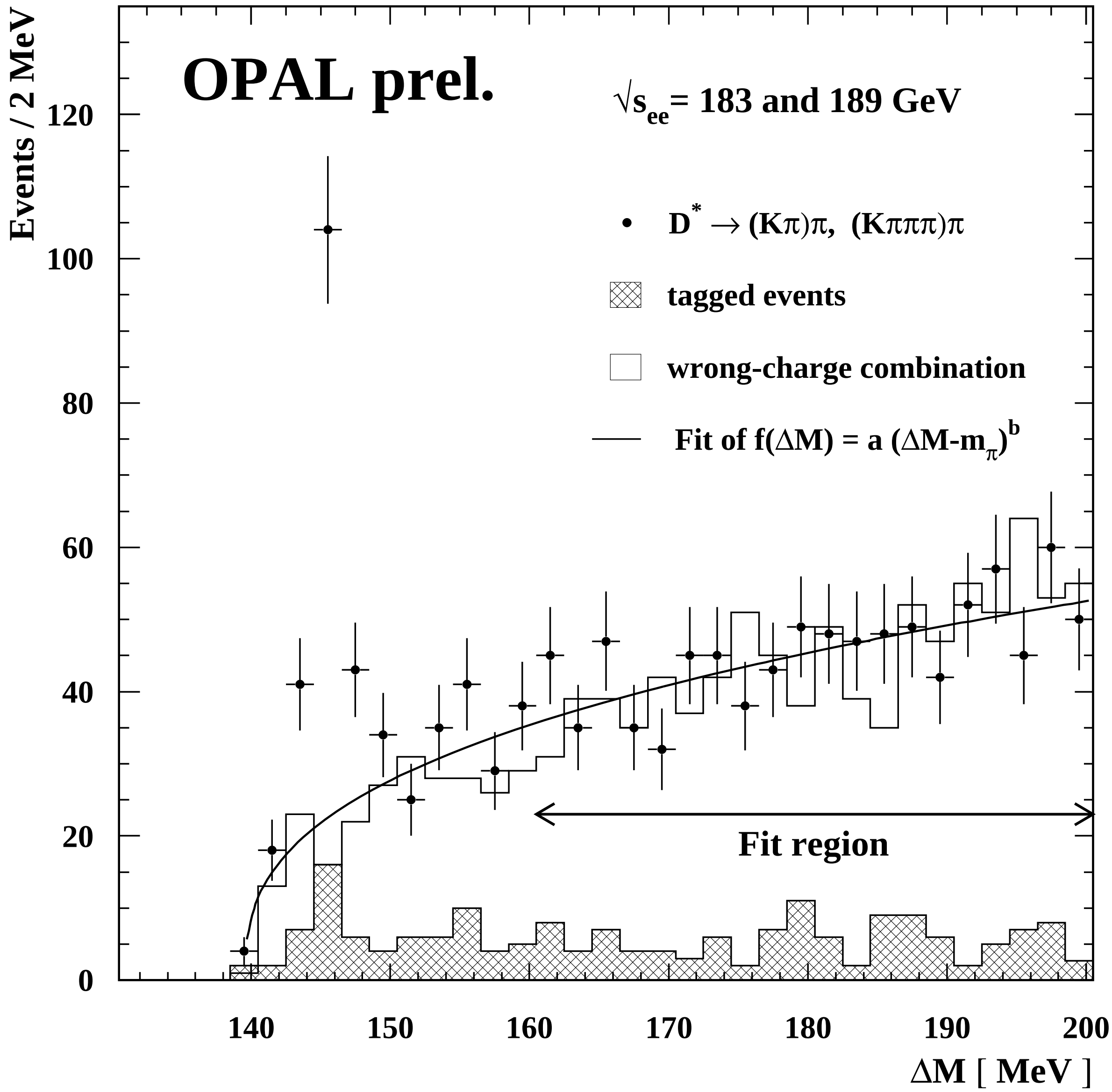
Inclusive charm production





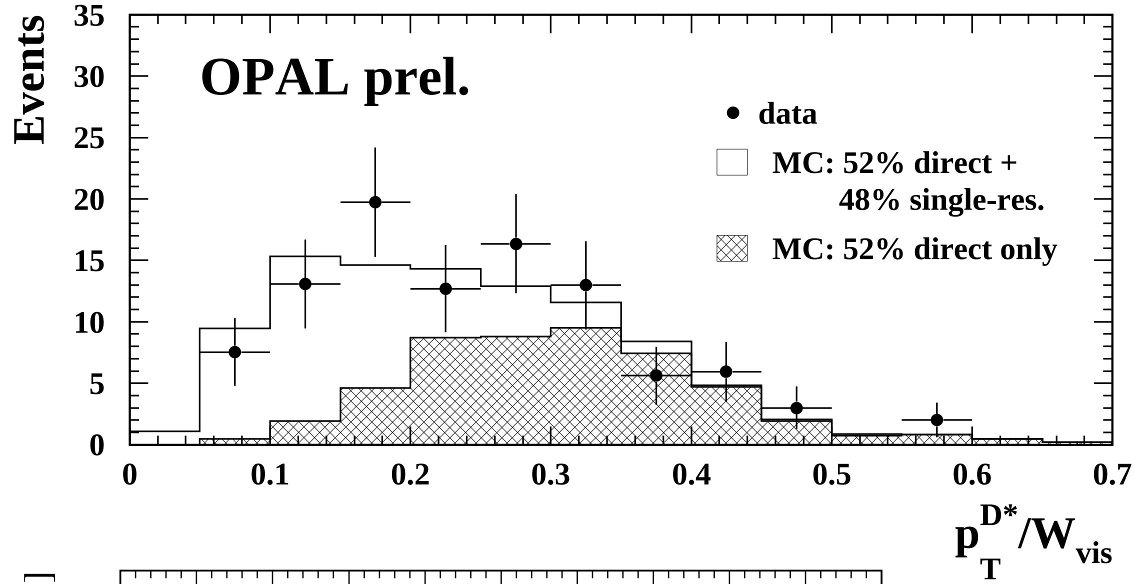
A clear electron signal of the semileptonic charm decays is observed

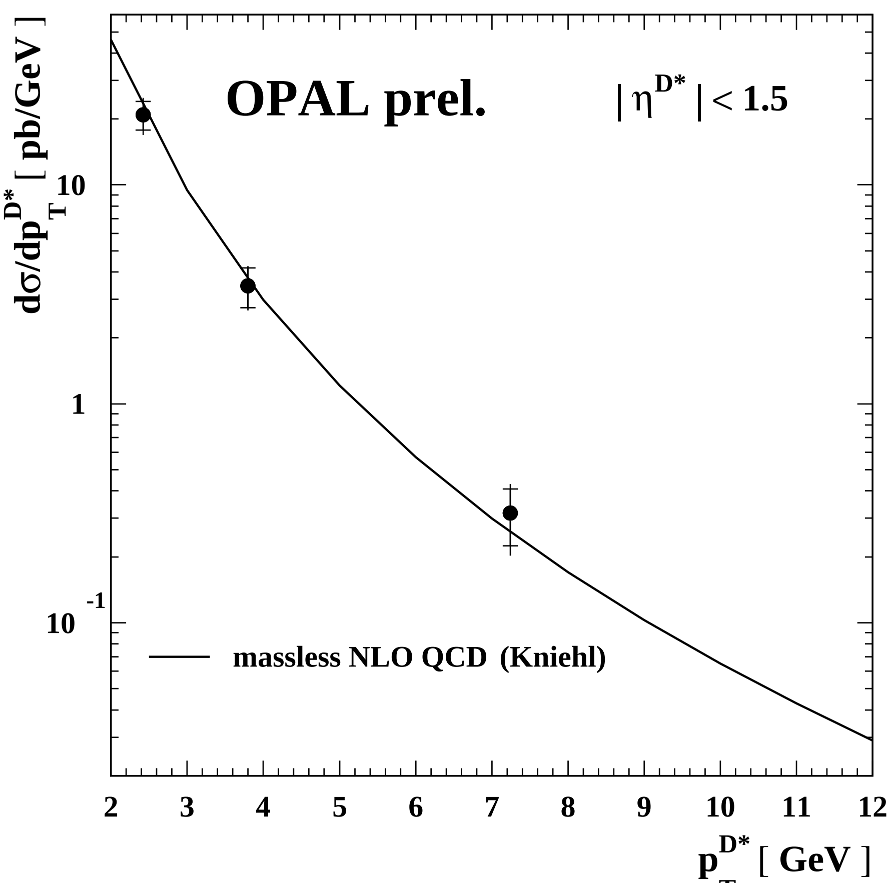
The D* candidates



A clear signal in the $\Delta(M) = M(D^\star) - M(D^0)$ mass spectrum is seen for anti-tagged and tagged events

$D^\star$ production for anti-tagged events

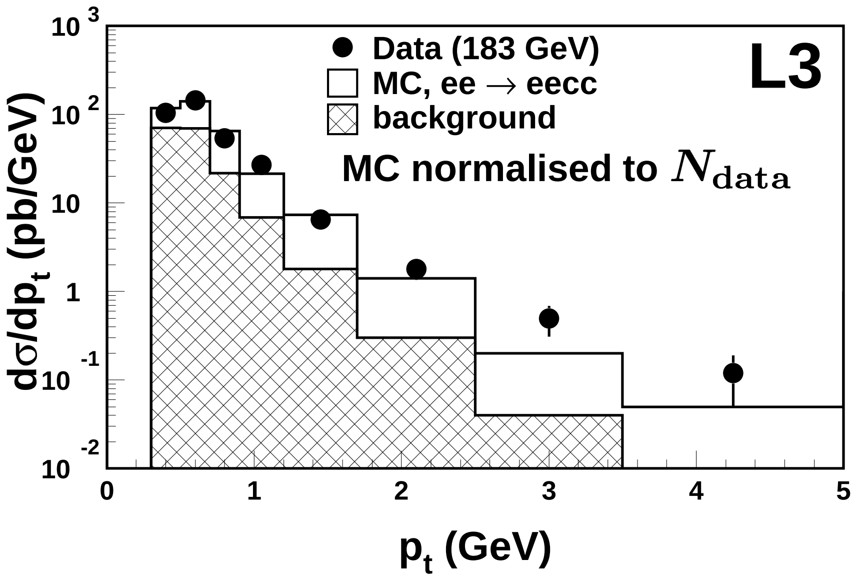


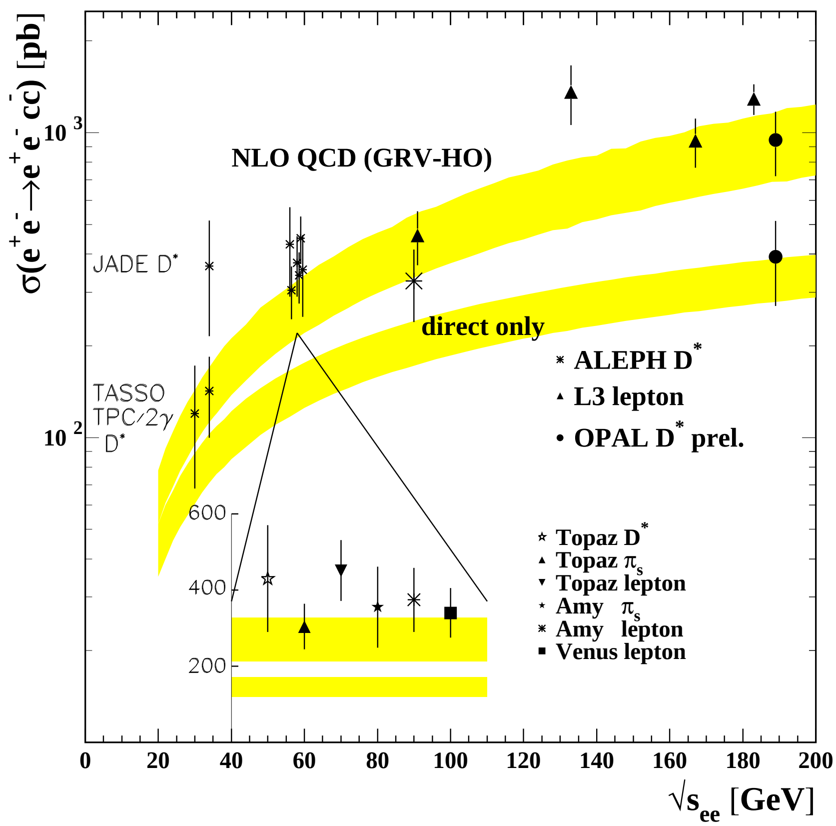


About 50% are resolved events

The NLO QCD calculation agrees well with the data.

The inclusive charm cross-section





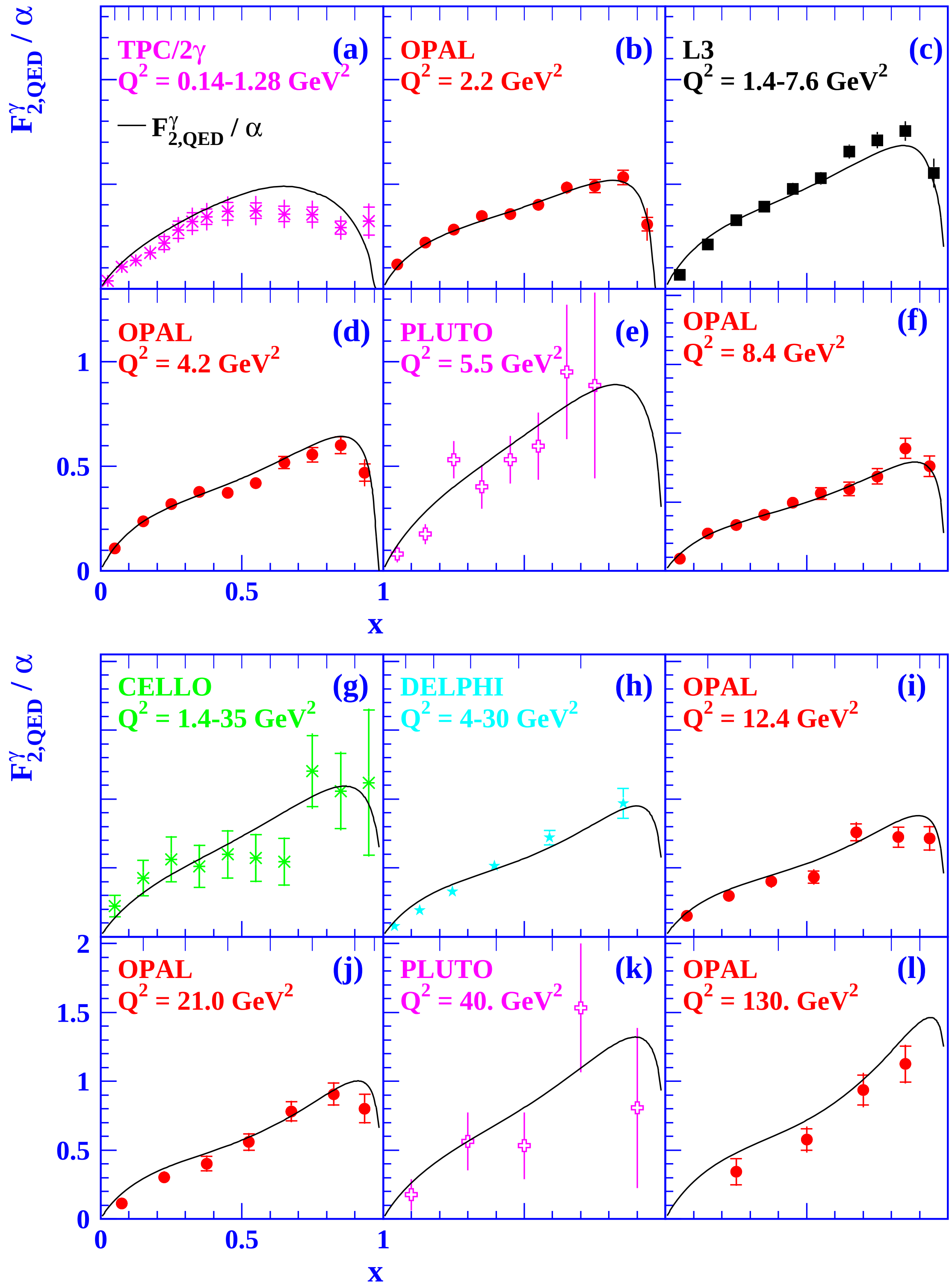
The direct charm production alone is insufficient to describe the data

The formalism for deep inelastic electron-photon scattering

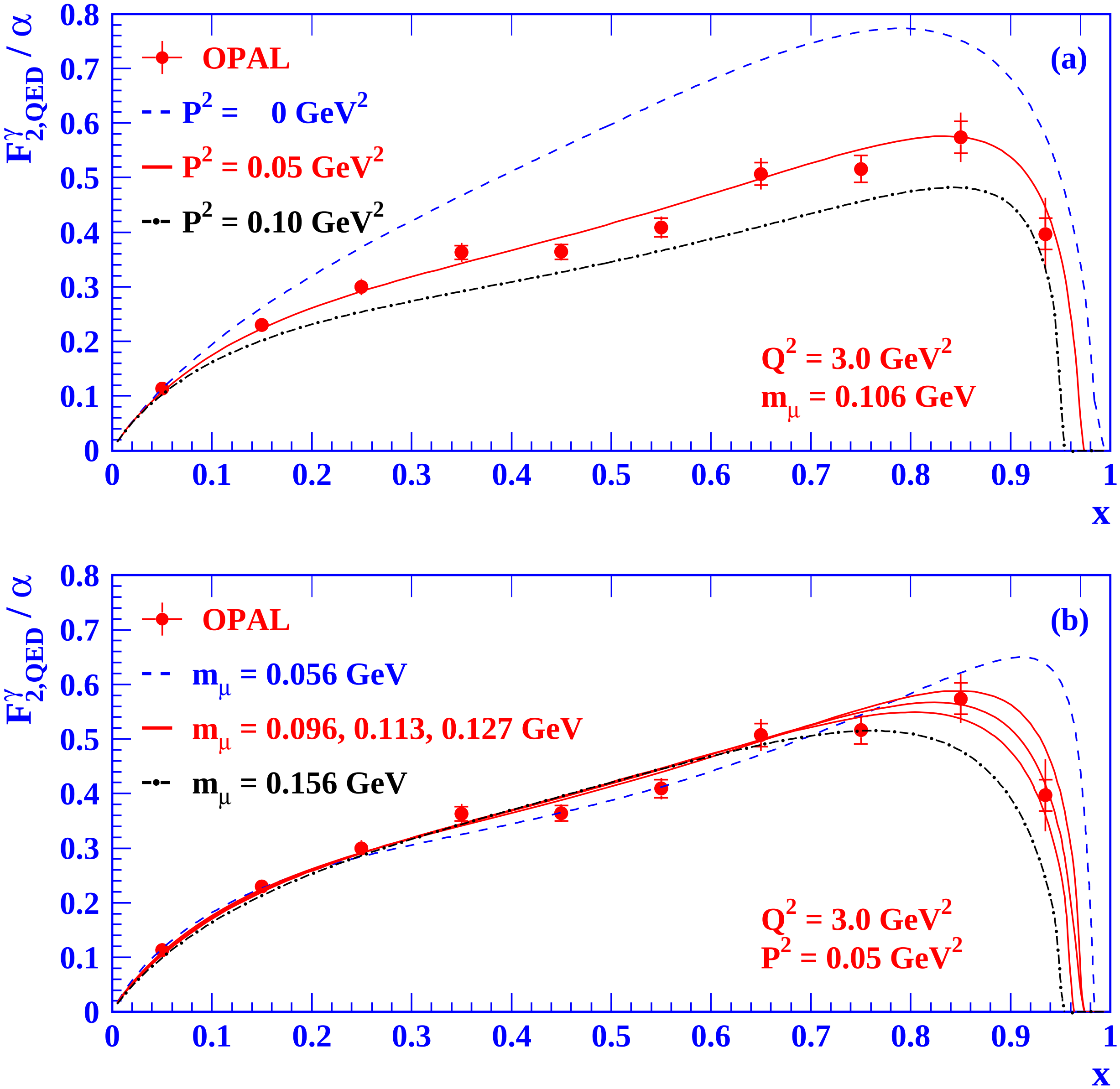
$$
\begin{aligned}
2xF_1^\gamma &= \frac{-q^2}{4\pi^2\alpha}\frac{\sqrt{(q\cdot p)^2-q^2p^2}}{q\cdot p}\left(\sigma_{\rm TT}(x,q^2,p^2)-\frac{1}{2}\sigma_{\rm TL}(x,q^2,p^2)\right)\\
F_2^\gamma &= \frac{-q^2}{4\pi^2\alpha}\frac{q\cdot p}{\sqrt{(q\cdot p)^2-q^2p^2}}\left(\sigma_{\rm TT}(x,q^2,p^2)+\sigma_{\rm LT}(x,q^2,p^2)\right.\\
&\qquad \left.-\frac{1}{2}\sigma_{\rm LL}(x,q^2,p^2)-\frac{1}{2}\sigma_{\rm TL}(x,q^2,p^2)\right)\\
F_{\rm L}^\gamma &= F_2^\gamma-2xF_1^\gamma
\end{aligned}
$$

$$
\begin{aligned}
\frac{{\rm d}^4\sigma_{\rm ee\to eef\bar{f}}}{{\rm d}x\,{\rm d}Q^2\,{\rm d}\tilde{z}\,{\rm d}P^2} &= \frac{{\rm d}^2N_\gamma}{{\rm d}\tilde{z}{\rm d}P^2}\cdot\frac{2\pi\alpha^2}{x\,Q^4}\cdot\left[\left(1+(1-y)^2\right)F_2^\gamma(x,Q^2,P^2)\right.\\
&\qquad \left.-y^2F_{\rm L}^\gamma(x,Q^2,P^2)\right]
\end{aligned}
$$

The world data on $F_{2,\mathrm{QED}}^{\gamma}$



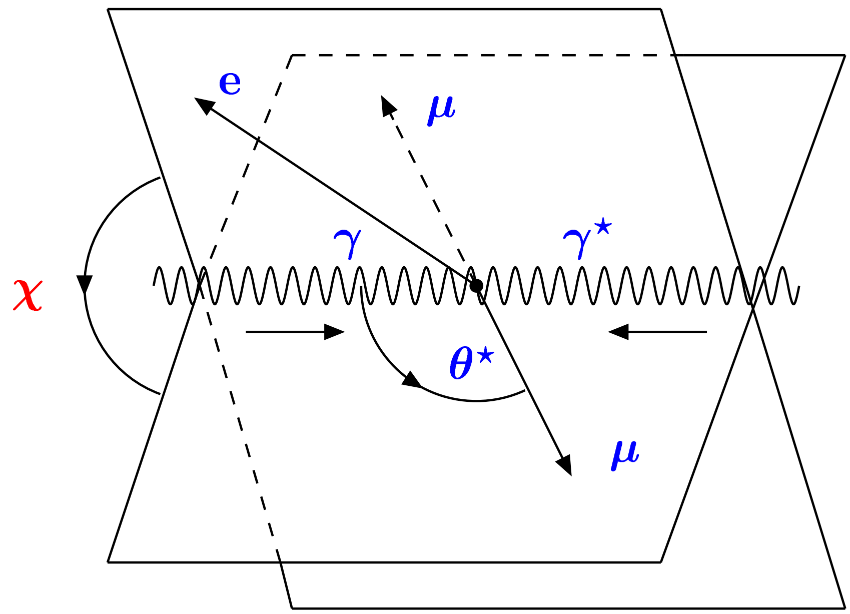
The dependence of F_2^γ on P^2 and m_μ



The P^2 dependence is clearly observed in the data.

The muon mass can be determined to about $\pm15\%$.

Azimuthal Correlations



$$\mathbf{e}\gamma \to \mathbf{e}\mu\mu$$

$$d\sigma \quad \propto \quad 1 - \rho(y) F_A^\gamma / F_2^\gamma \cos\chi + \frac{1}{2}\epsilon(y) F_B^\gamma / F_2^\gamma \cos 2\chi$$

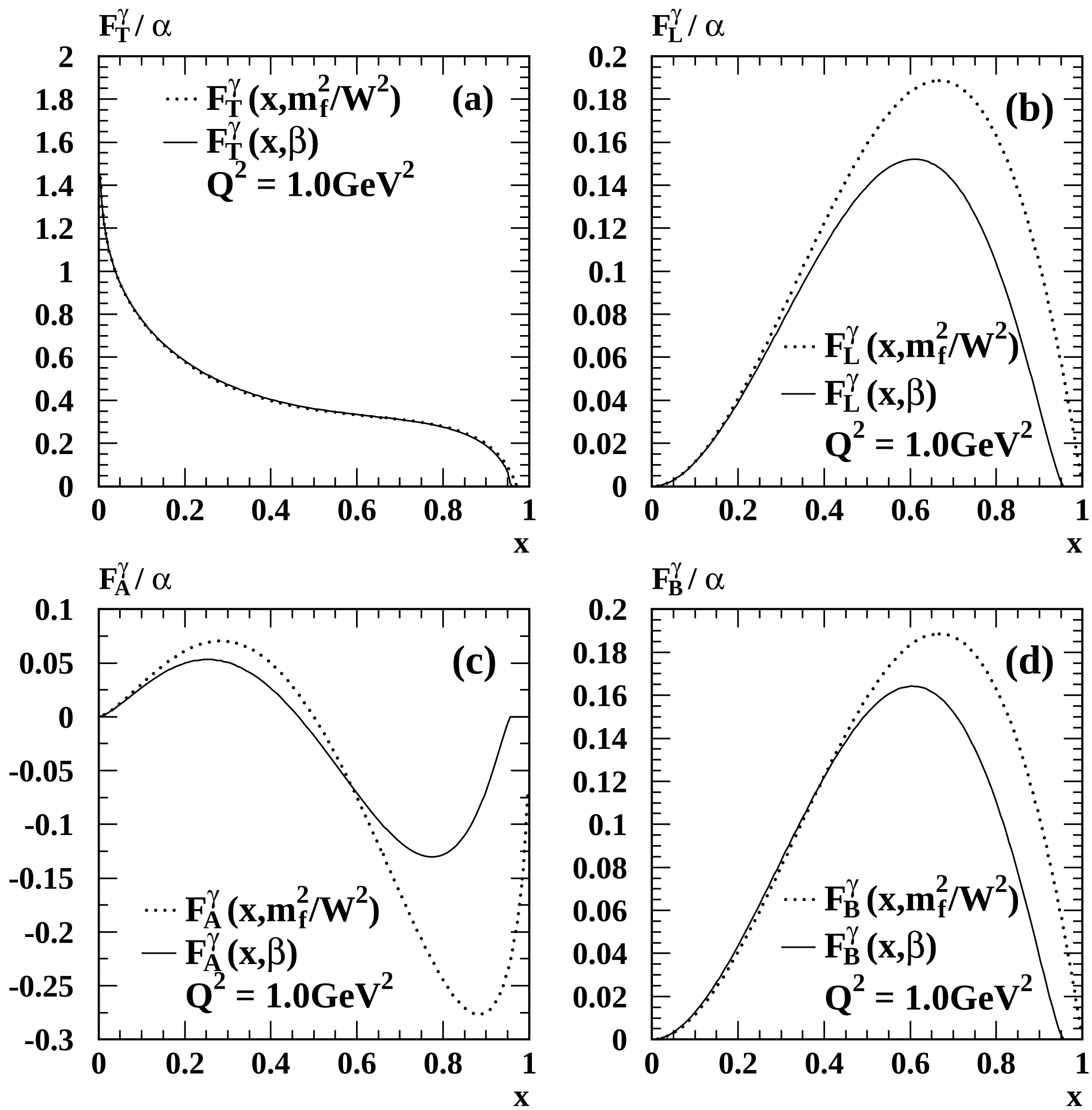
$$\epsilon(y) = \frac{2(1-y)}{1+(1-y)^2} \approx 1, \;\; \rho(y) = \frac{(2-y)\sqrt{1-y}}{1+(1-y)^2} \approx 1$$

The χ dependence gives access to other structure functions besides F_2^γ.

The functional form of F_A^γ and F_B^γ

$$
\begin{aligned}
F_A^\gamma(x,\beta) &= \frac{4\alpha}{\pi} x\sqrt{x(1-x)}\,(1-2x)\left\{\beta\left[1+(1-\beta^2)\frac{1-x}{1-2x}\right]\right.\\
&\left.+\frac{3x-2}{1-2x}\sqrt{1-\beta^2}\arccos\left(\sqrt{1-\beta^2}\right)\right\}\\
F_B^\gamma(x,\beta) &= \frac{4\alpha}{\pi} x^2(1-x)\left\{\beta\left[1-(1-\beta^2)\frac{1-x}{2x}\right]\right.\\
&\left.+\frac{1}{2}(1-\beta^2)\left[\frac{1-2x}{x}-\frac{1-x}{2x}(1-\beta^2)\right]\log\left(\frac{1+\beta}{1-\beta}\right)\right\}\\
F_2^\gamma(x,\beta) &= \frac{\alpha}{\pi} x\left\{\left[x^2+(1-x)^2\right]\log\left(\frac{1+\beta}{1-\beta}\right)-\beta+8\beta x(1-x)\right.\\
&-\beta(1-\beta^2)(1-x)^2\\
&\left.+(1-\beta^2)(1-x)\left[\frac{1}{2}(1-x)(1+\beta^2)-2x\right]\log\left(\frac{1+\beta}{1-\beta}\right)\right\}\\
\beta &= \sqrt{1-\frac{4m_\mu^2}{W^2}}\,, \qquad \text{(leading log } \beta\to 1\text{)}
\end{aligned}
$$

The improvement of the leading log approximation

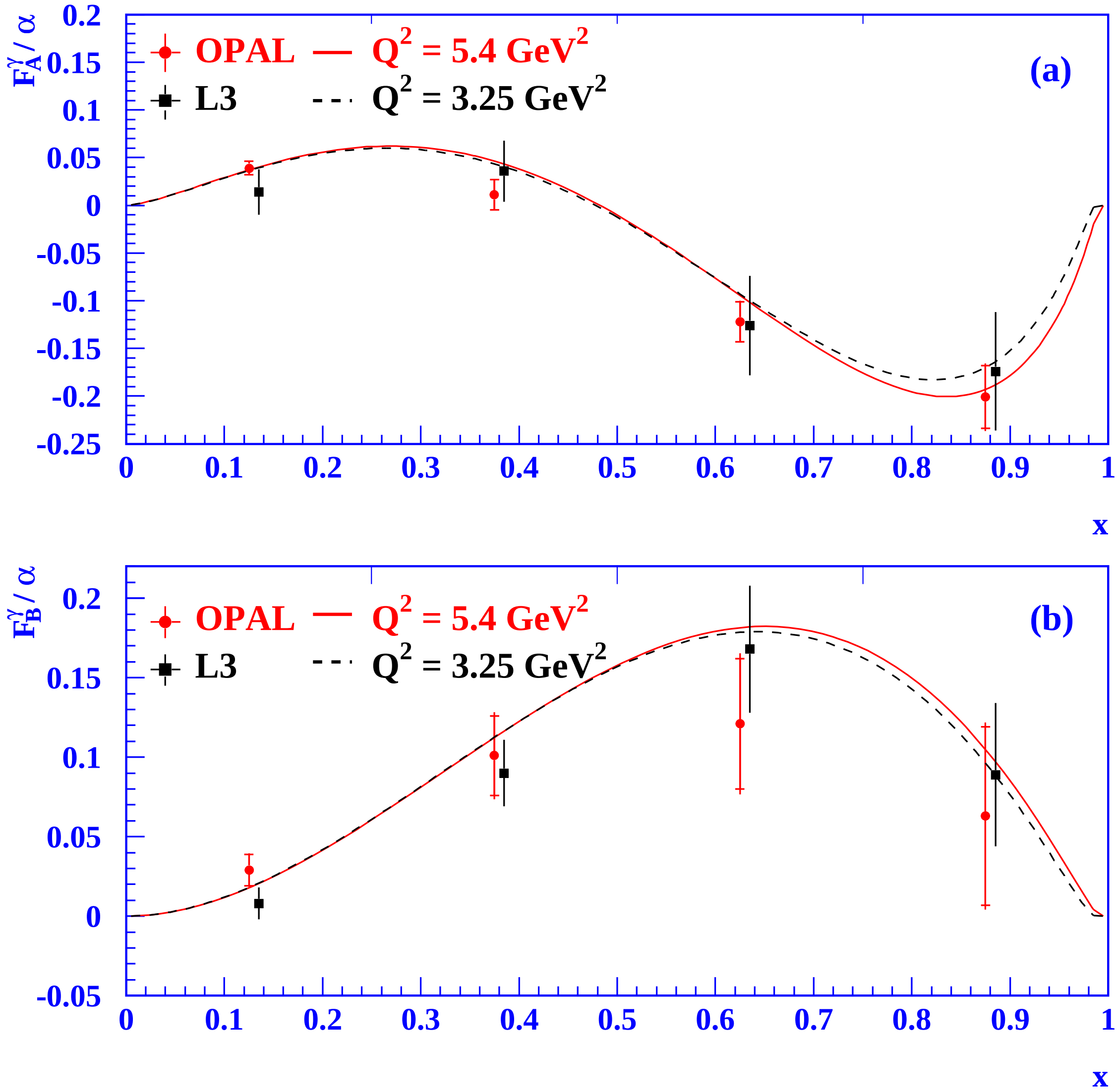


The structure function $F^\gamma_{\mathrm{A,QED}}$ and $F^\gamma_{\mathrm{B,QED}}$ receive seizable corrections at low values of Q^2

R. Nisius, M.H. Seymour, Phys.Lett. B452 (1999), 409-413

The structure functions

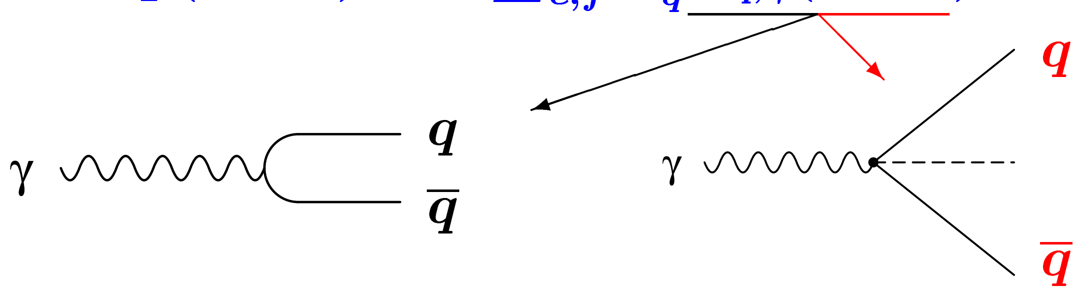
F_A^γ and F_B^γ



First measurement that goes further than measuring the differential cross-section.

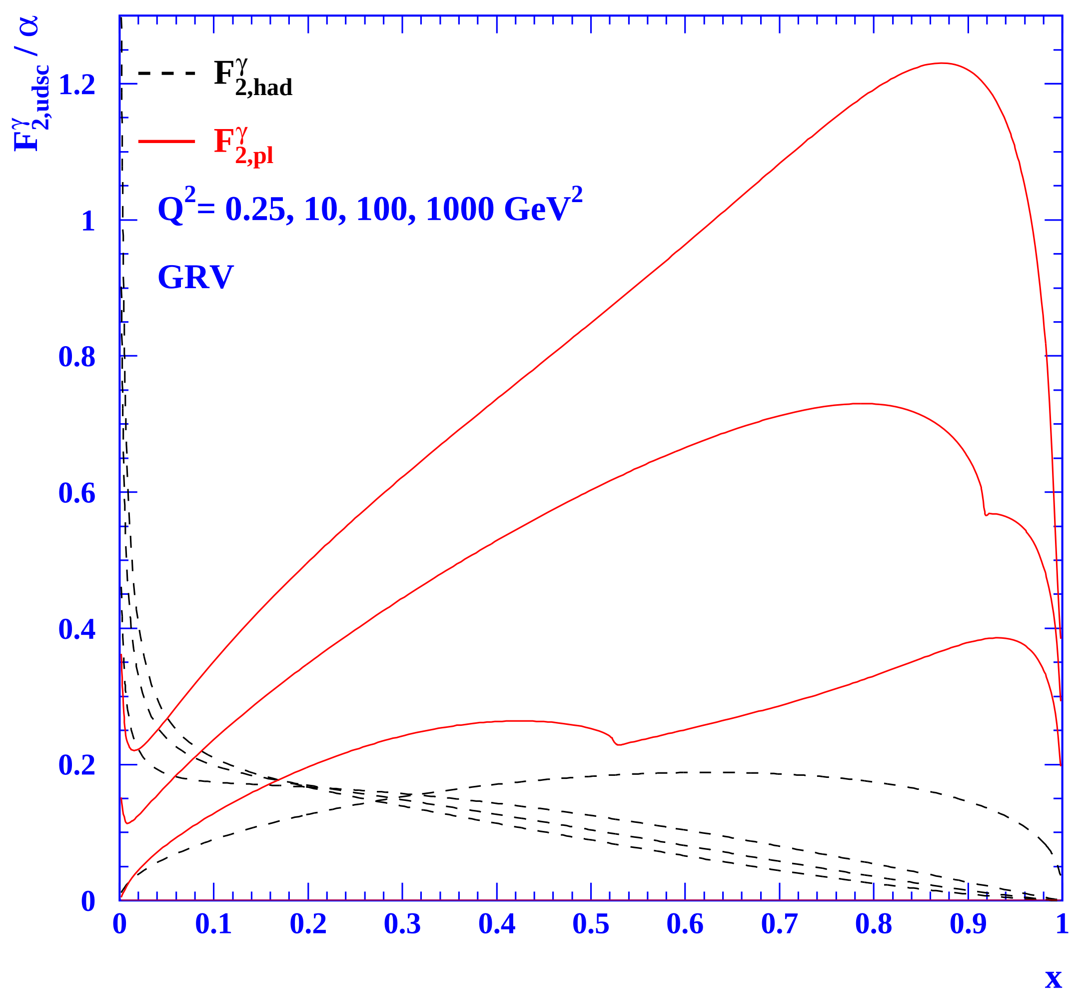
The contributions to $F_2^\gamma(x, Q^2)$

$$F_2^\gamma(x,Q^2) = x \sum_{c,f} e_q^2 \, f_{q,\gamma}(x,Q^2)$$

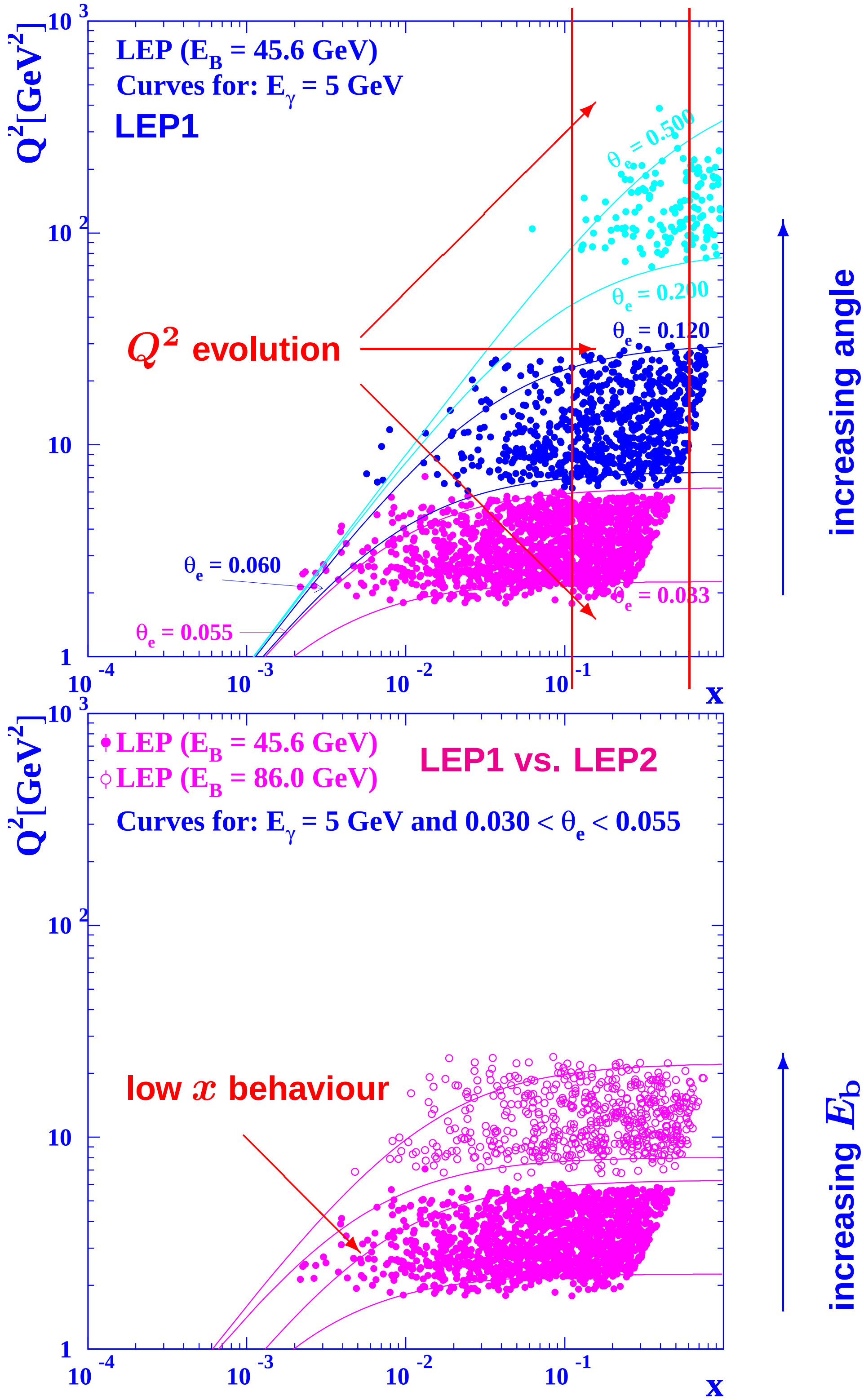


hadronic, VDM, "small x"
ρ, ω, ϕ, *non–perturbative*

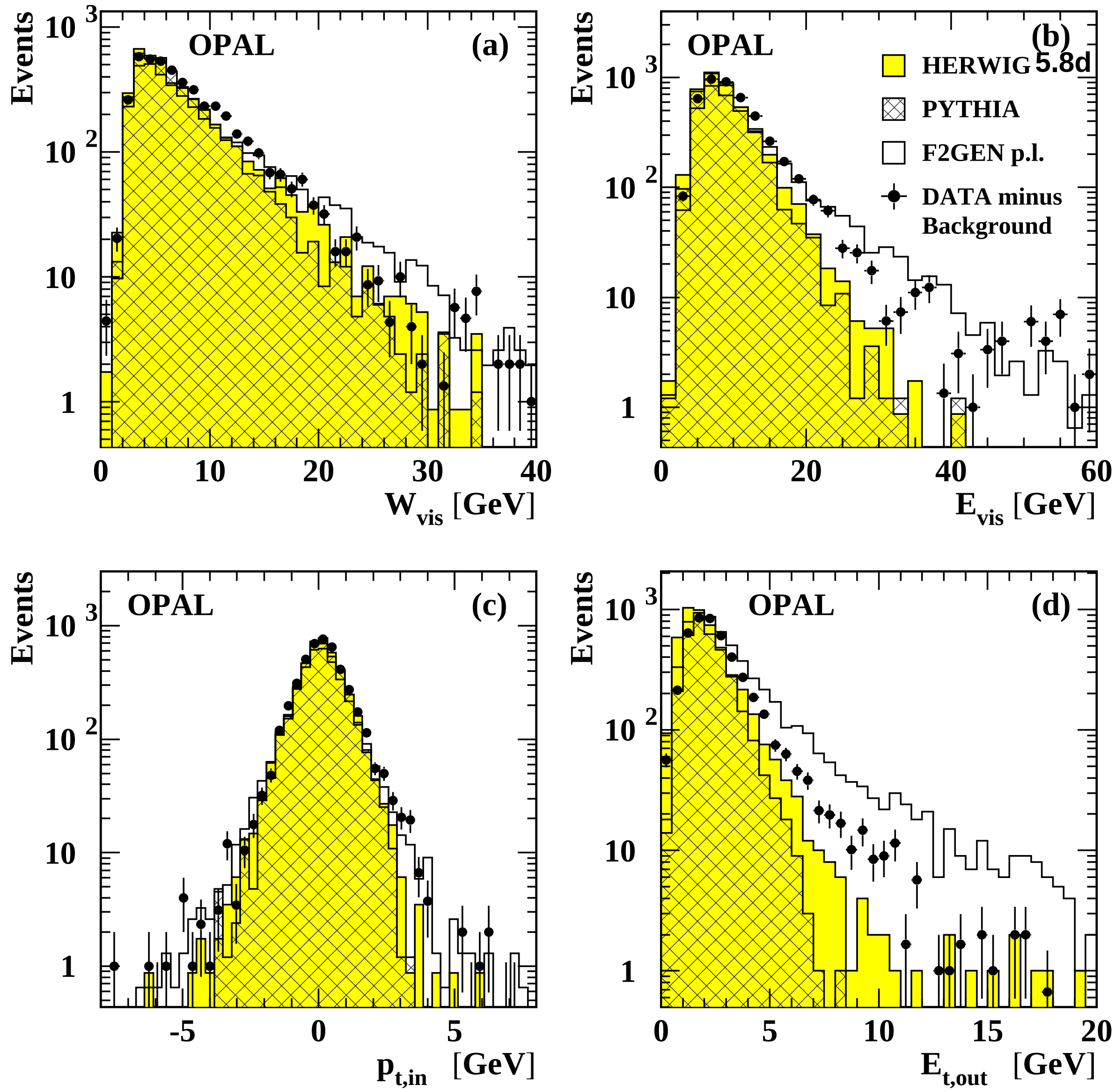
pointlike, "large x"
perturbative



The $x - Q^2$ plane

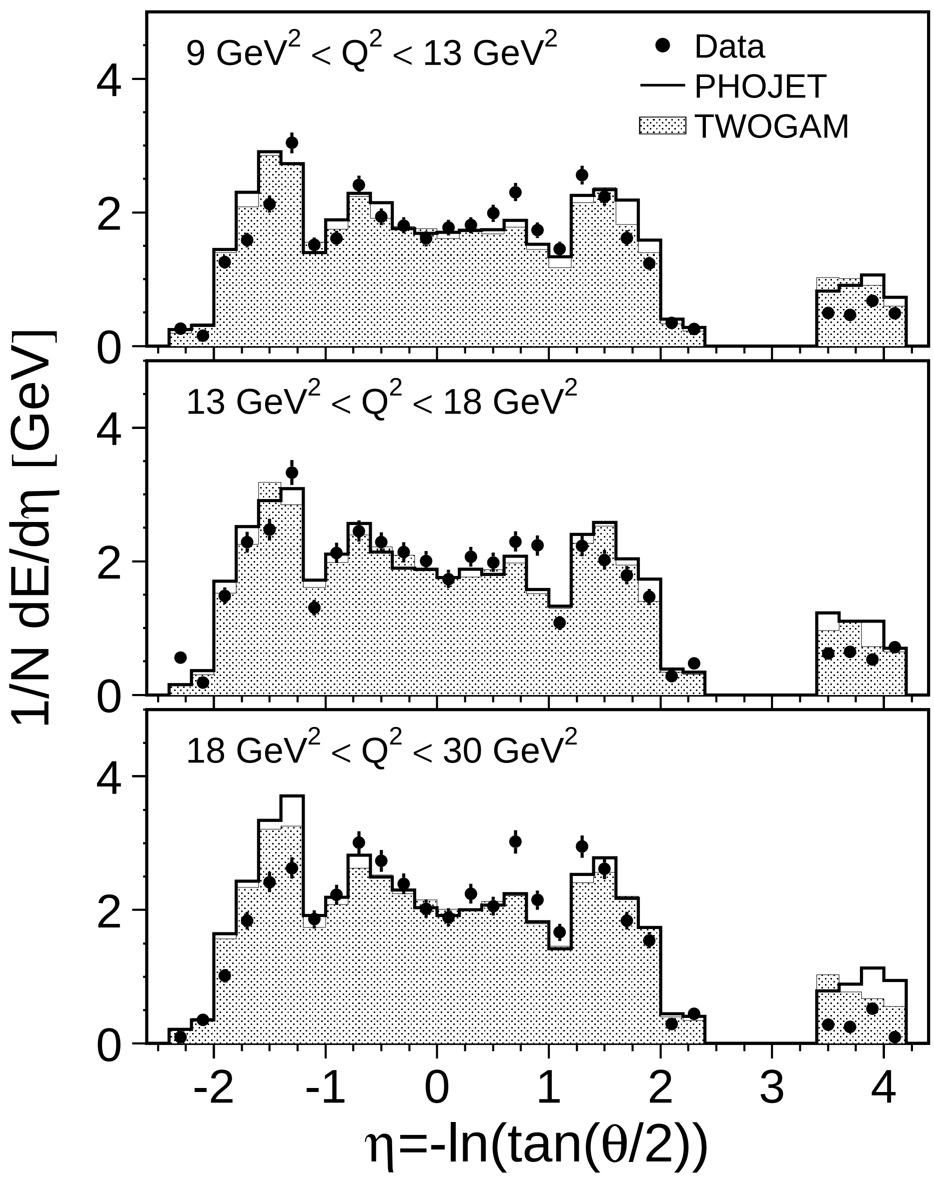


The description of the hadronic final state



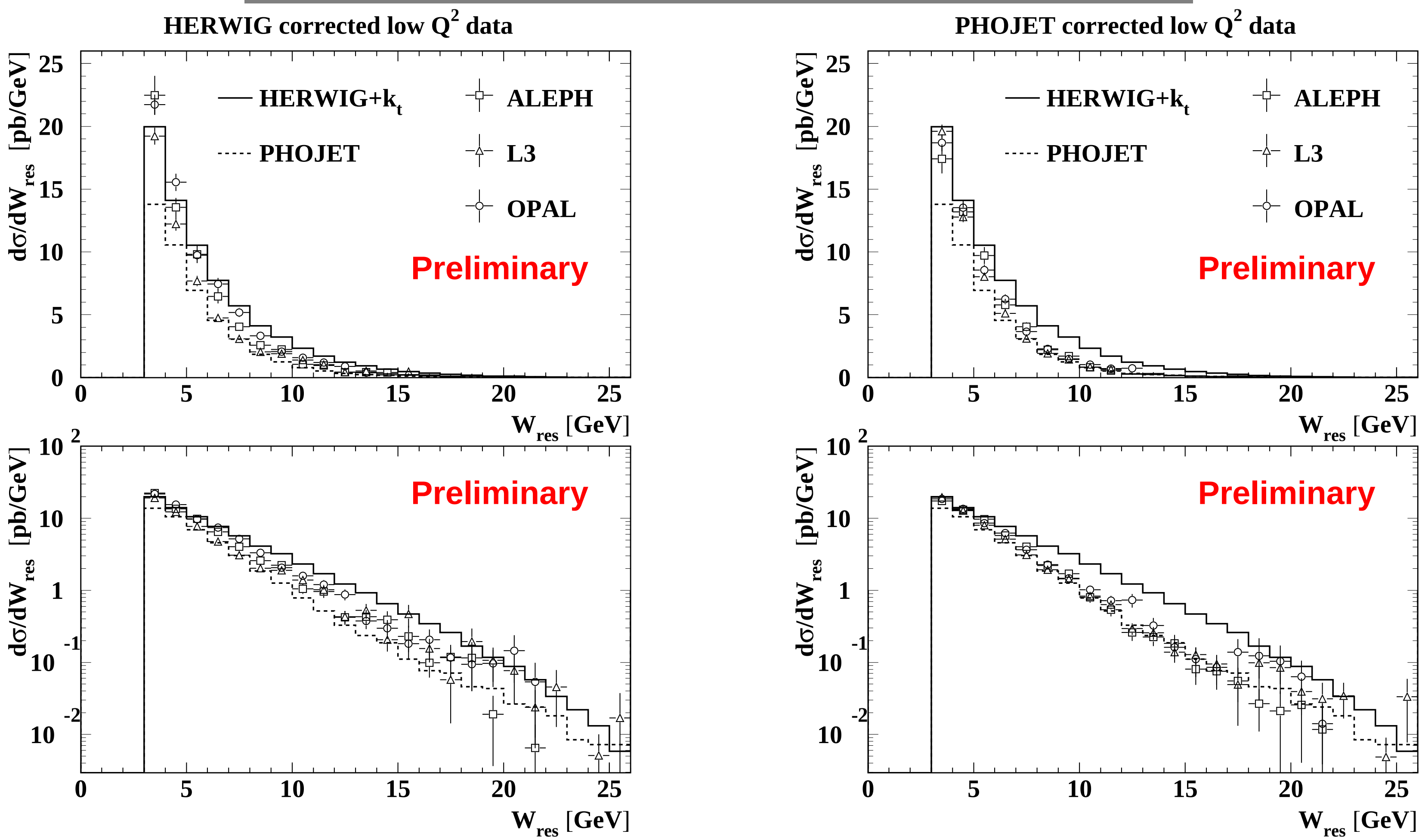
There are significant differences between the data and the Monte Carlo predictions (OPAL '96)

The hadronic energy flow



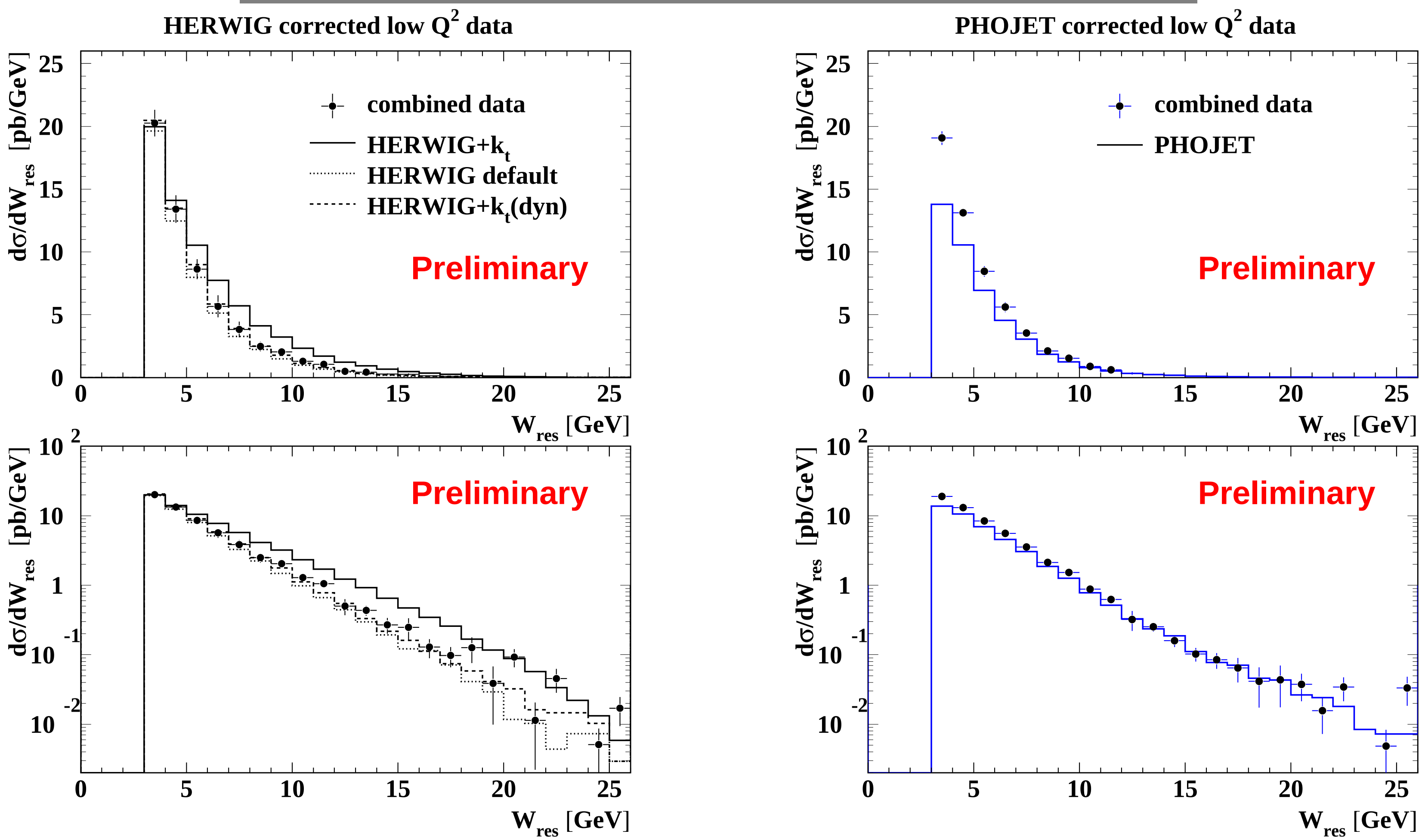
The hadronic energy flow is not well described by all available Monte Carlo models (L3 ’98)

Comparison to corrected LEP data



In general the data are closer to each other than the differences to the Monte Carlo models (LEP Two-Photon WG '99)

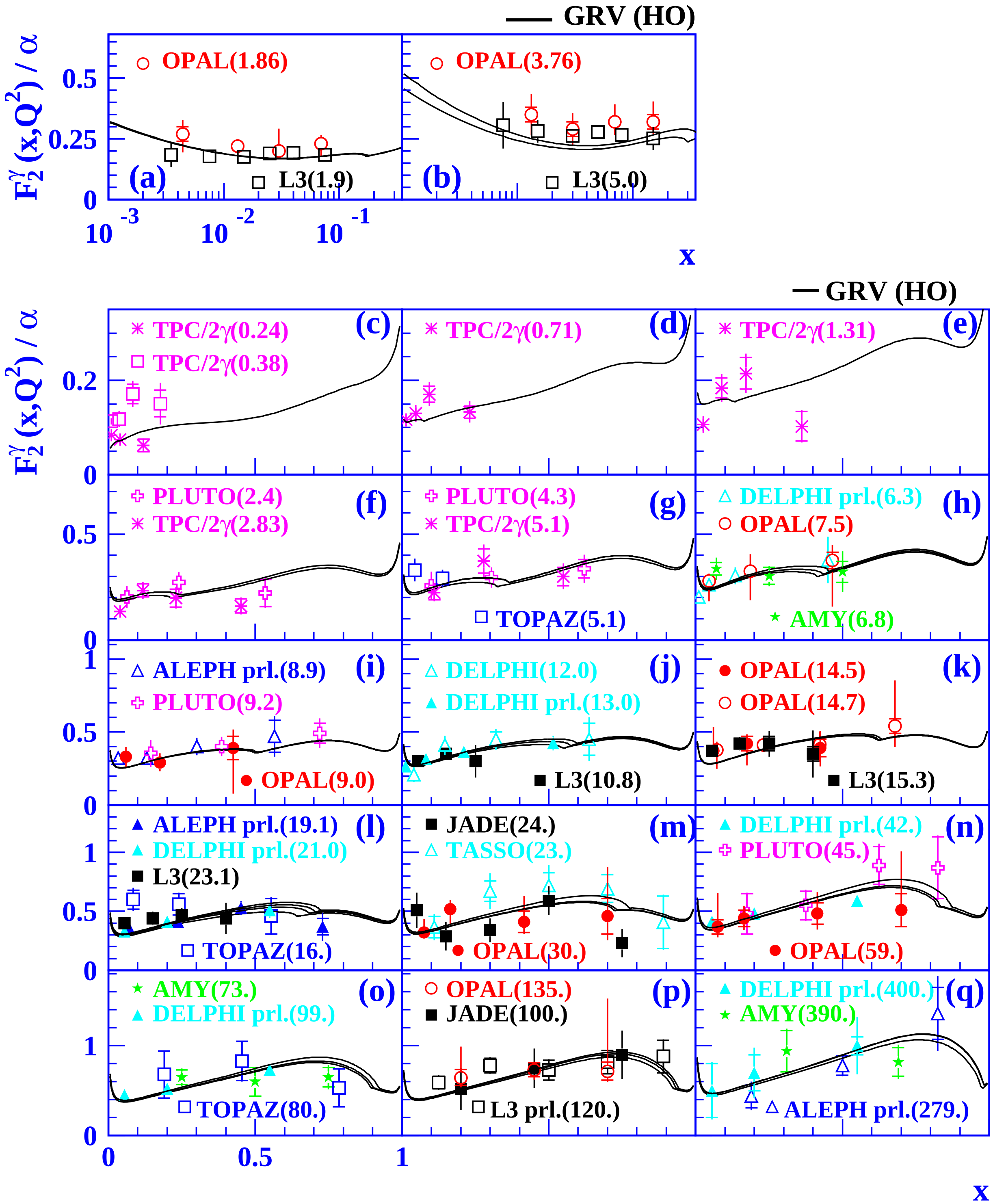
Comparison to LEP combined data



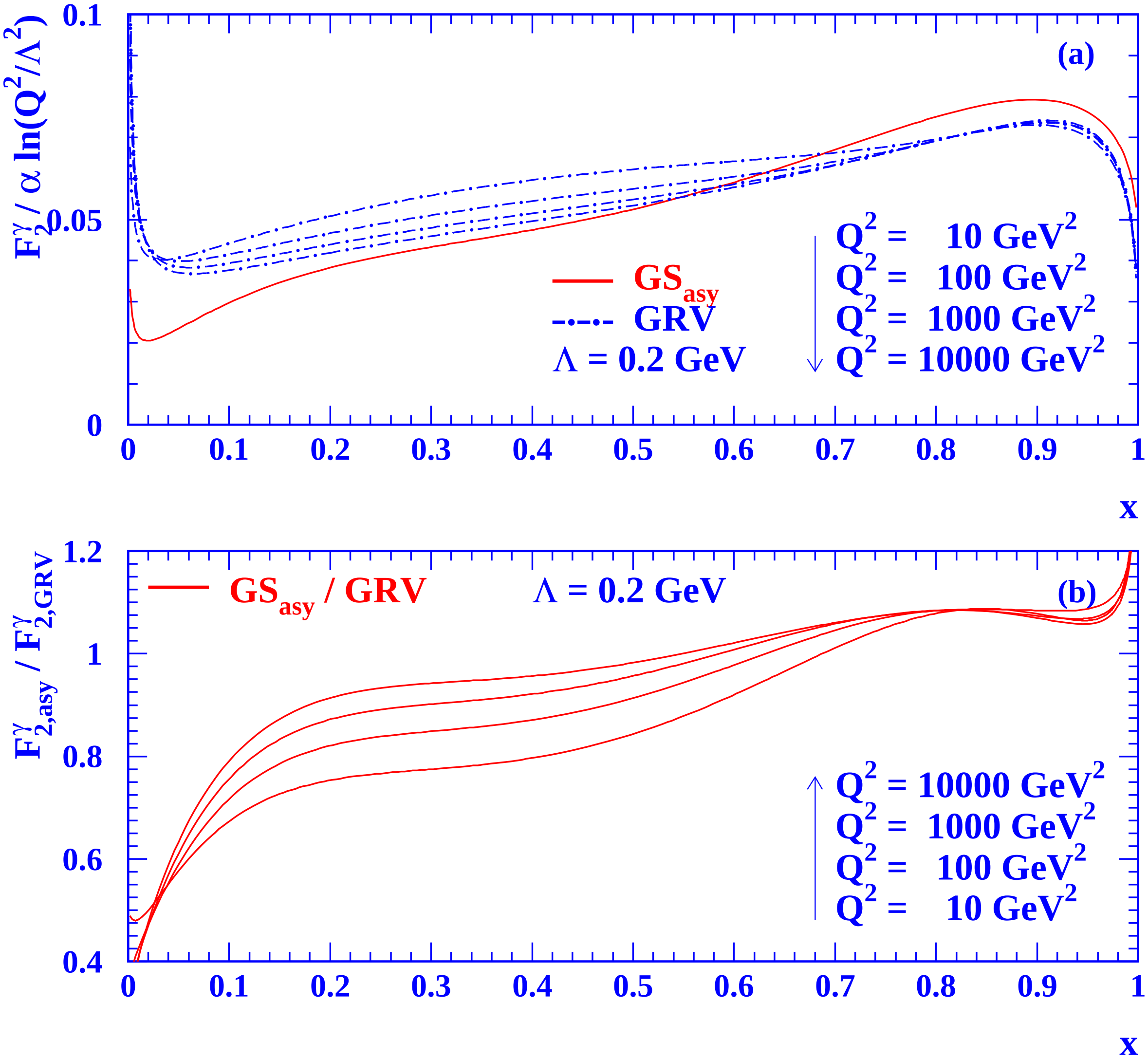
The combined data are a valuable input to constrain the Monte Carlo models

(LEP Two-Photon WG '99)

The world data on F_2^γ

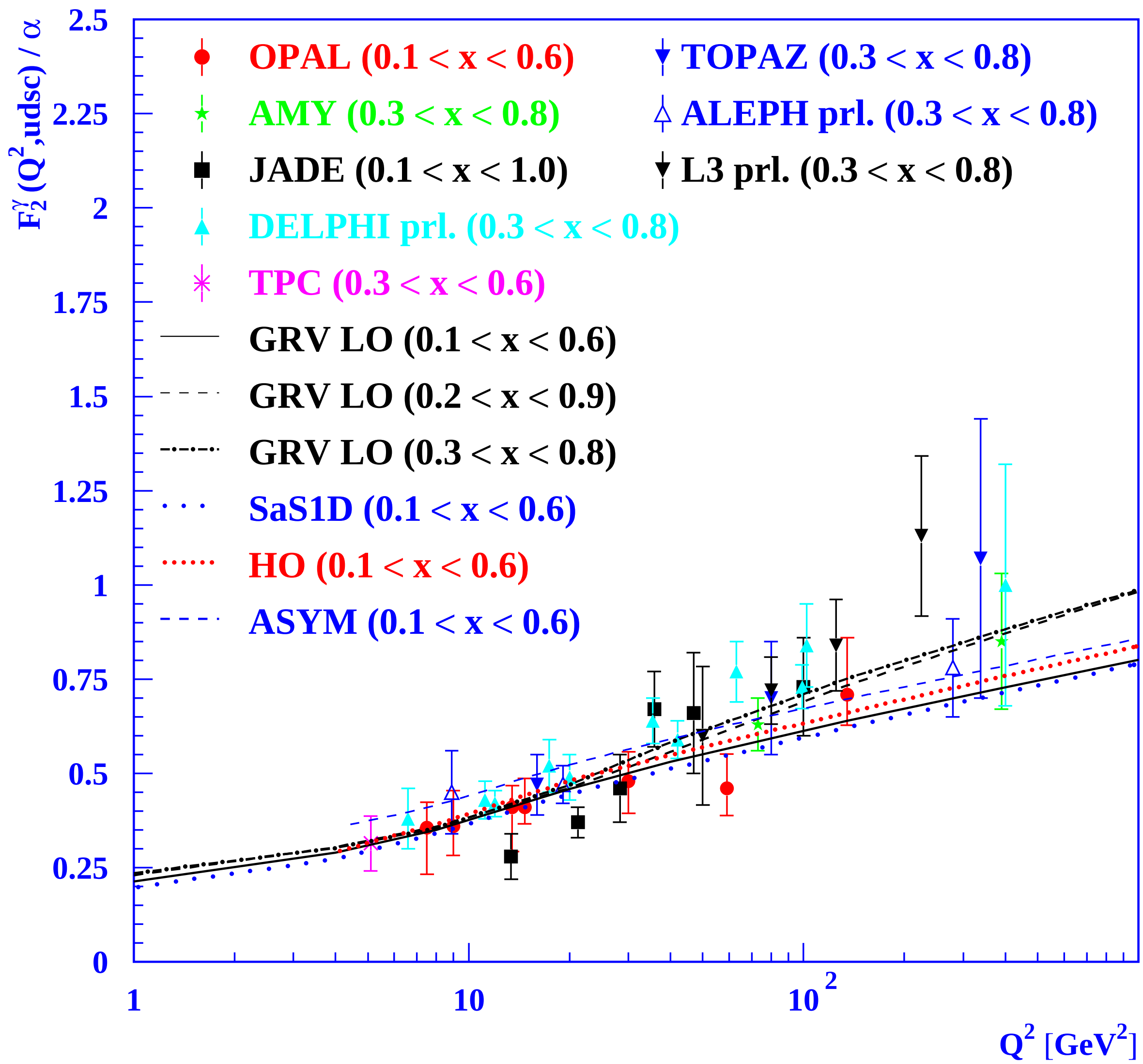


The x dependence of F_2^γ (GRV) and F_2^γ (asy)



The structure function F_2^γ is to 90% perturbative at large x

Measurements of the Q^2 evolution of F_2^γ for $\mathrm{n_f} = 4$

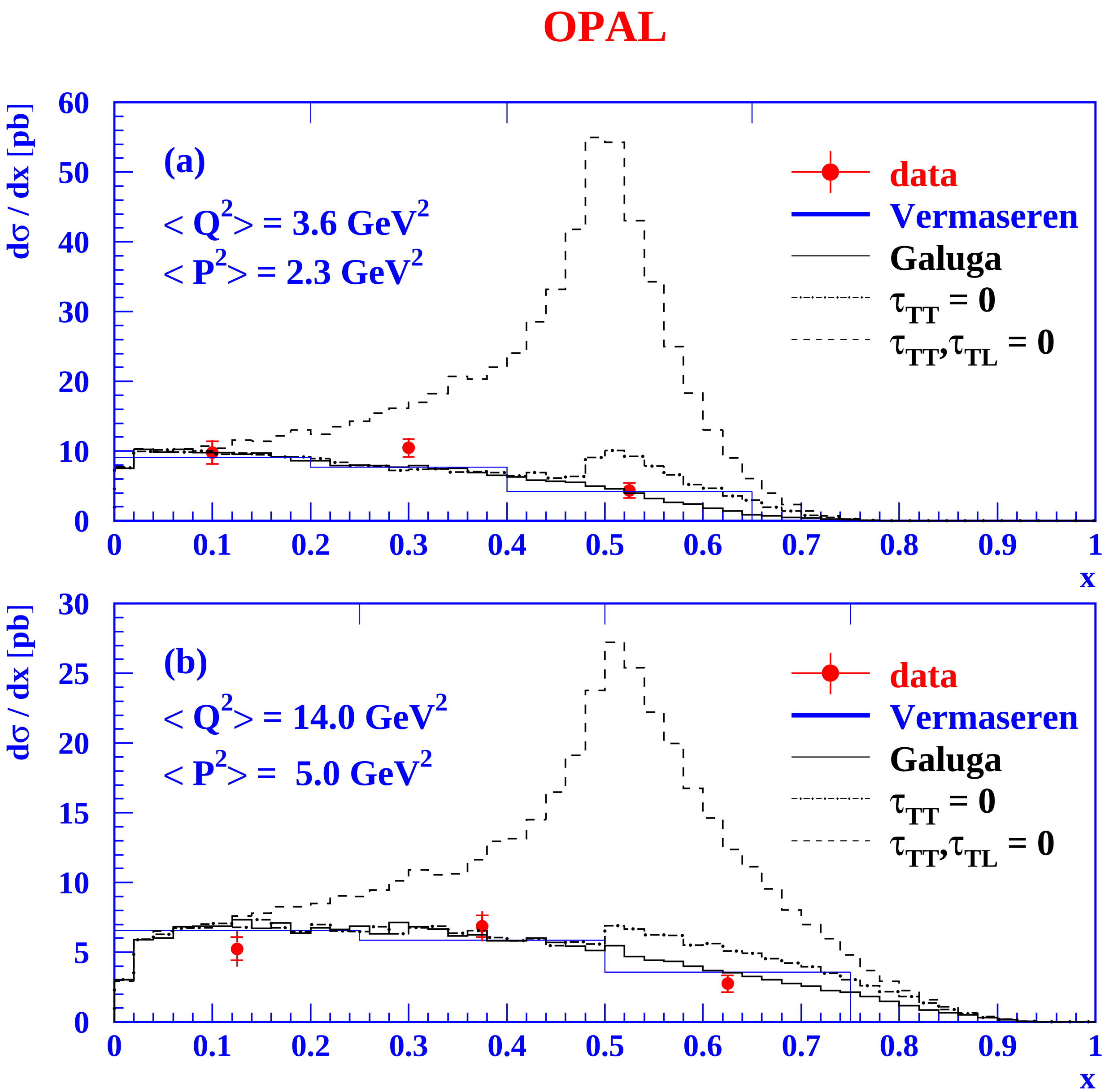


A clear rise consistent with $\log Q^2$ is seen in the data

The double tag limit: $Q^2, P^2 \gg m_{\mathrm{e}}^2, \frac{\rho_{\mathrm{i}}^{00}}{2\rho_{\mathrm{i}}^{++}} \to 1$

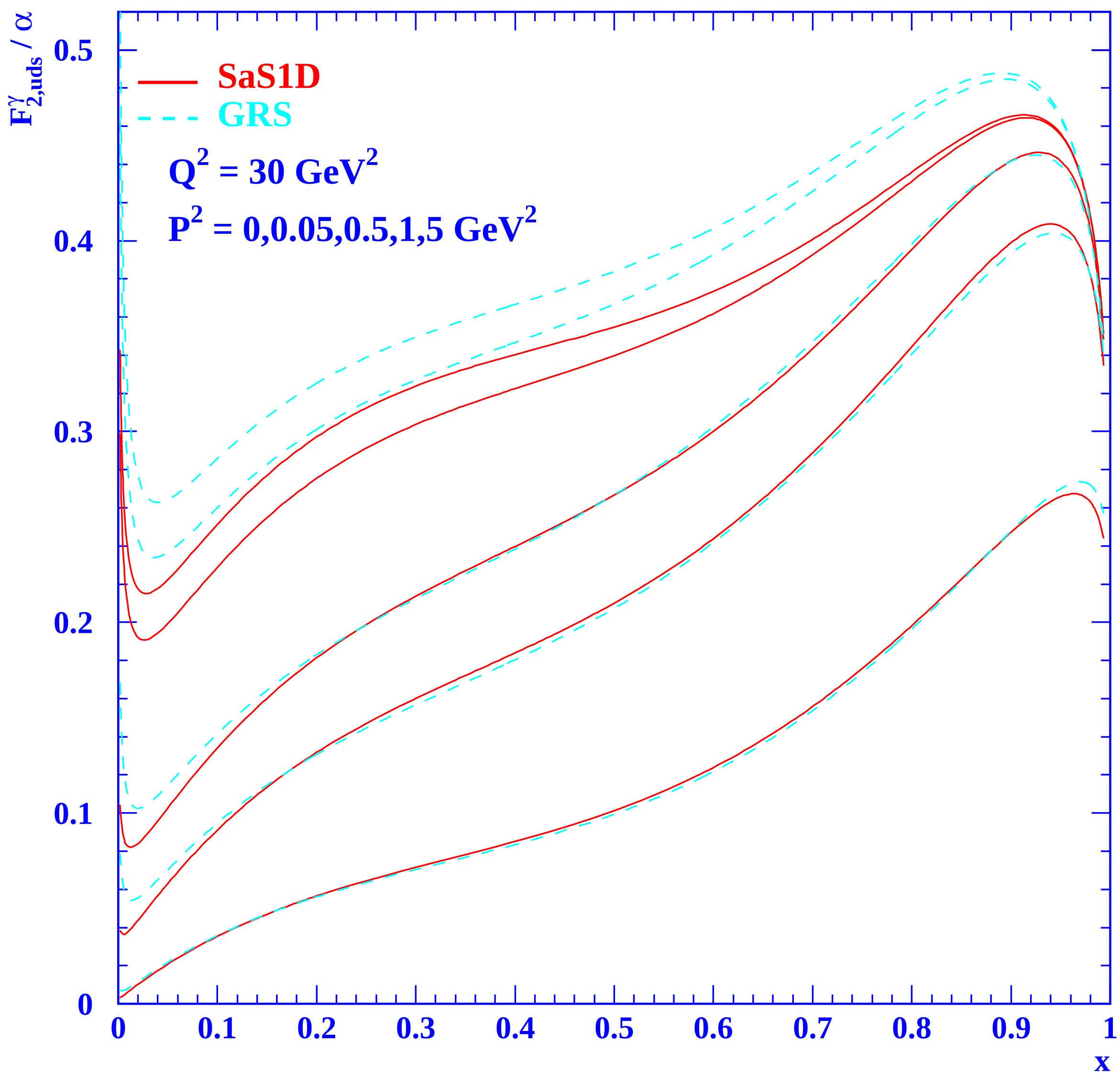
$$\begin{aligned} \mathrm{d}^6\sigma &= \frac{\mathrm{d}^3\mathrm{p}_1'\mathrm{d}^3\mathrm{p}_2'}{E_1' E_2'} \frac{\alpha^2}{16\pi^4 q^2 p^2} \left[\frac{(q\cdot p)^2 - q^2p^2}{(p_1\cdot p_2)^2 - m_{\mathrm{e}}^2 m_{\mathrm{e}}^2}\right]^{1/2} 4\rho_1^{++}\rho_2^{++} \cdot \\ &\quad \left(\sigma_{\mathrm{TT}} + \sigma_{\mathrm{TL}} + \sigma_{\mathrm{LT}} + \sigma_{\mathrm{LL}} + \frac{1}{2}\tau_{\mathrm{TT}}\cos 2\bar{\phi} - 4\tau_{\mathrm{TL}}\cos\bar{\phi}\right) \end{aligned}$$

The cross-section for double tags



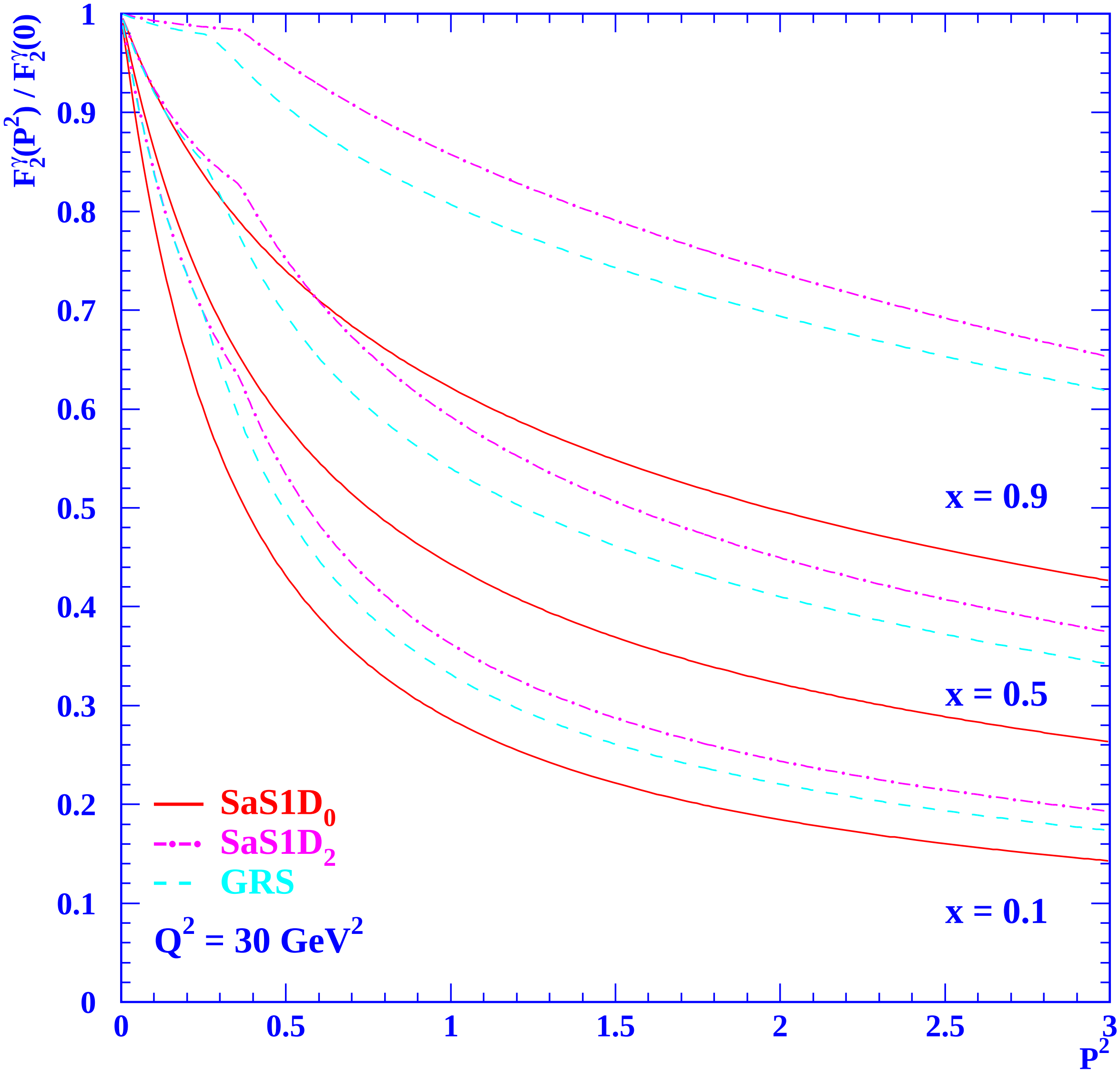
QED agrees well with the data and the presence of the interference terms is clearly seen for the first time.

F_2^{γ} for virtual photons



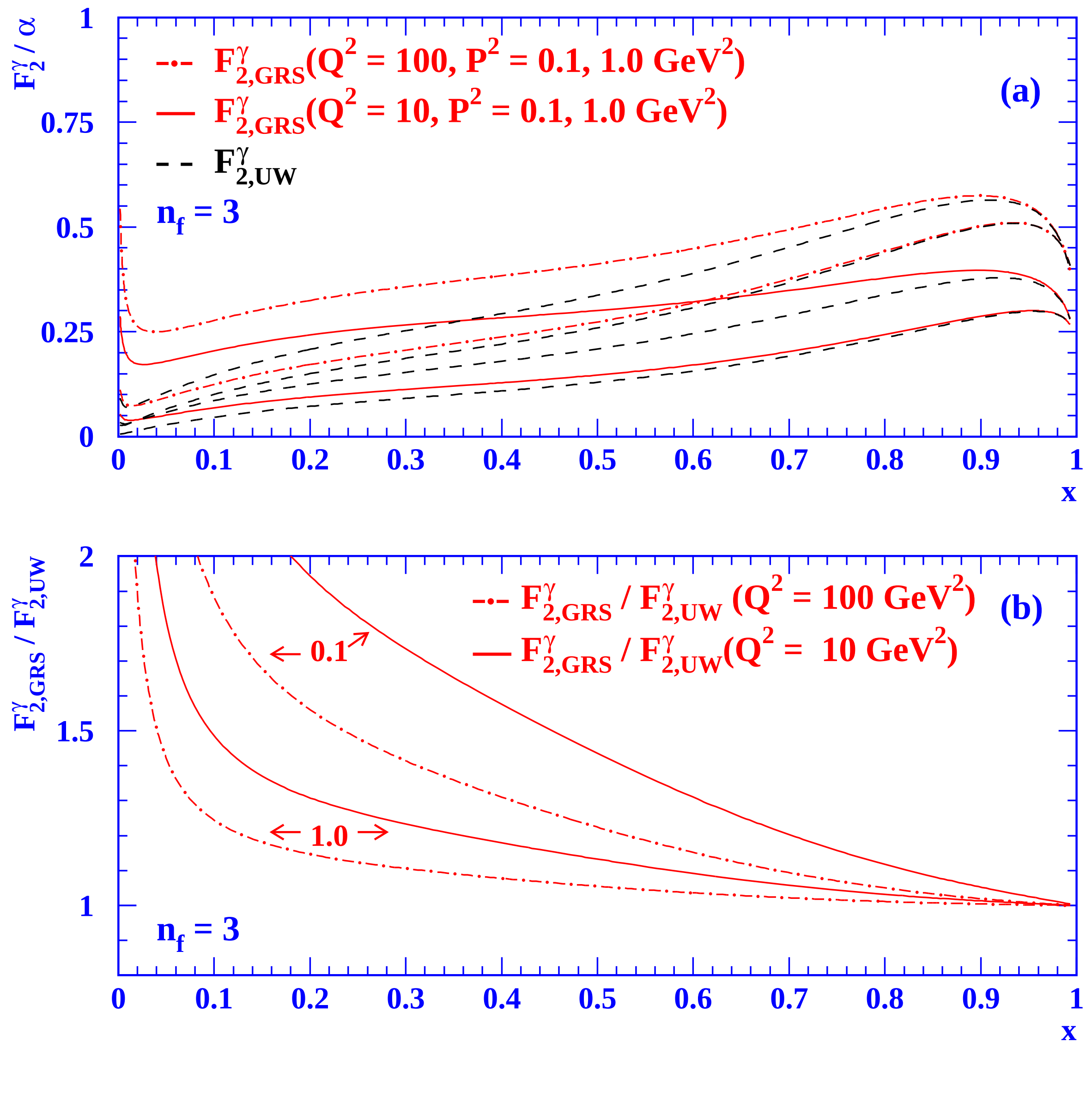
The absolute predictions agree for $P^2 > 0.5\ \mathrm{GeV}^2$, when using SaS1D ($IP2 = 2$)

F_2^γ as a function of P^2



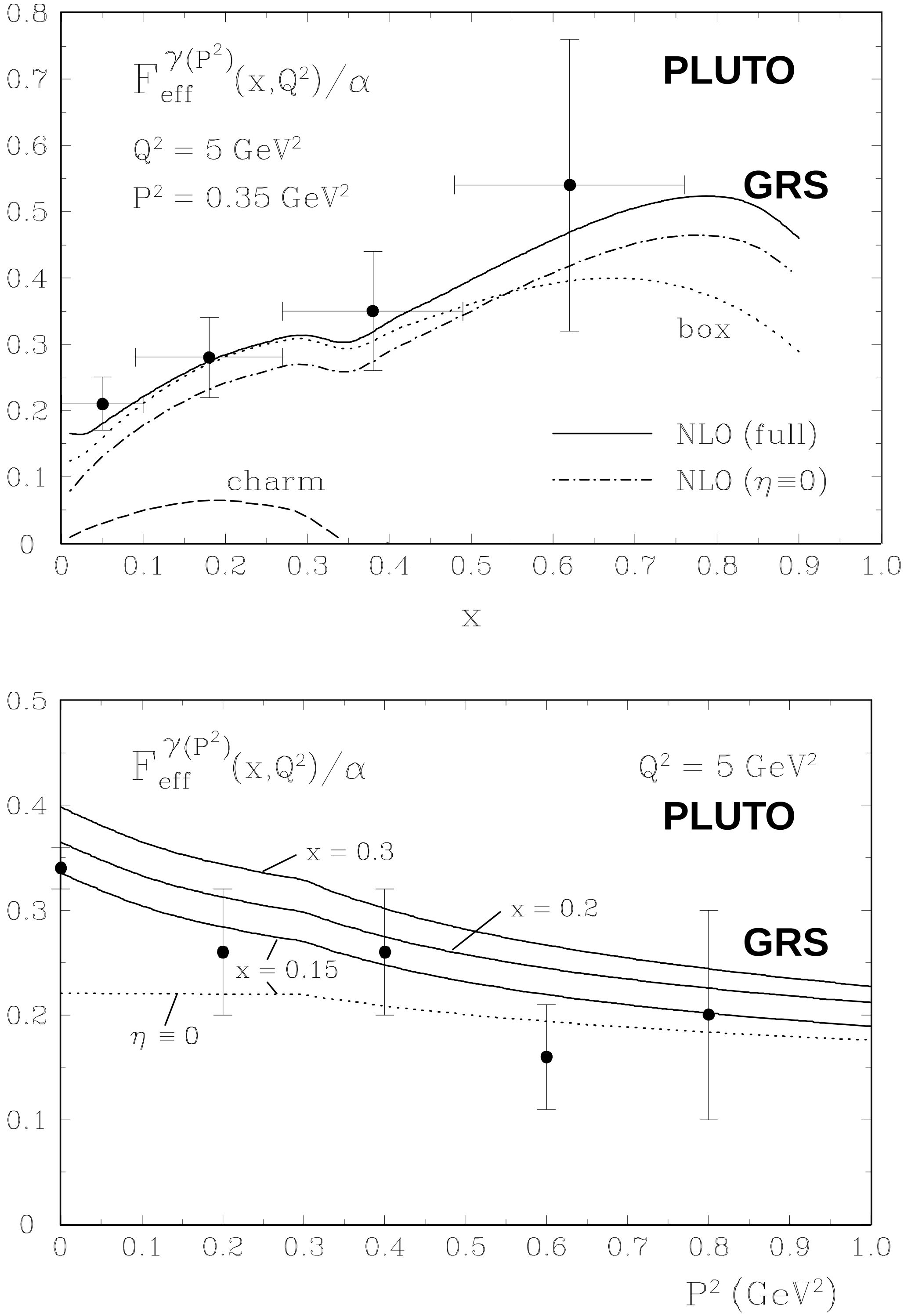
The suppression strongly depends on the assumptions made for the supression in SaS (IP2) and on x

The x dependence of $F_2^\gamma\,(P^2)$(GRS) and $F_2^\gamma\,(P^2)$(pl)

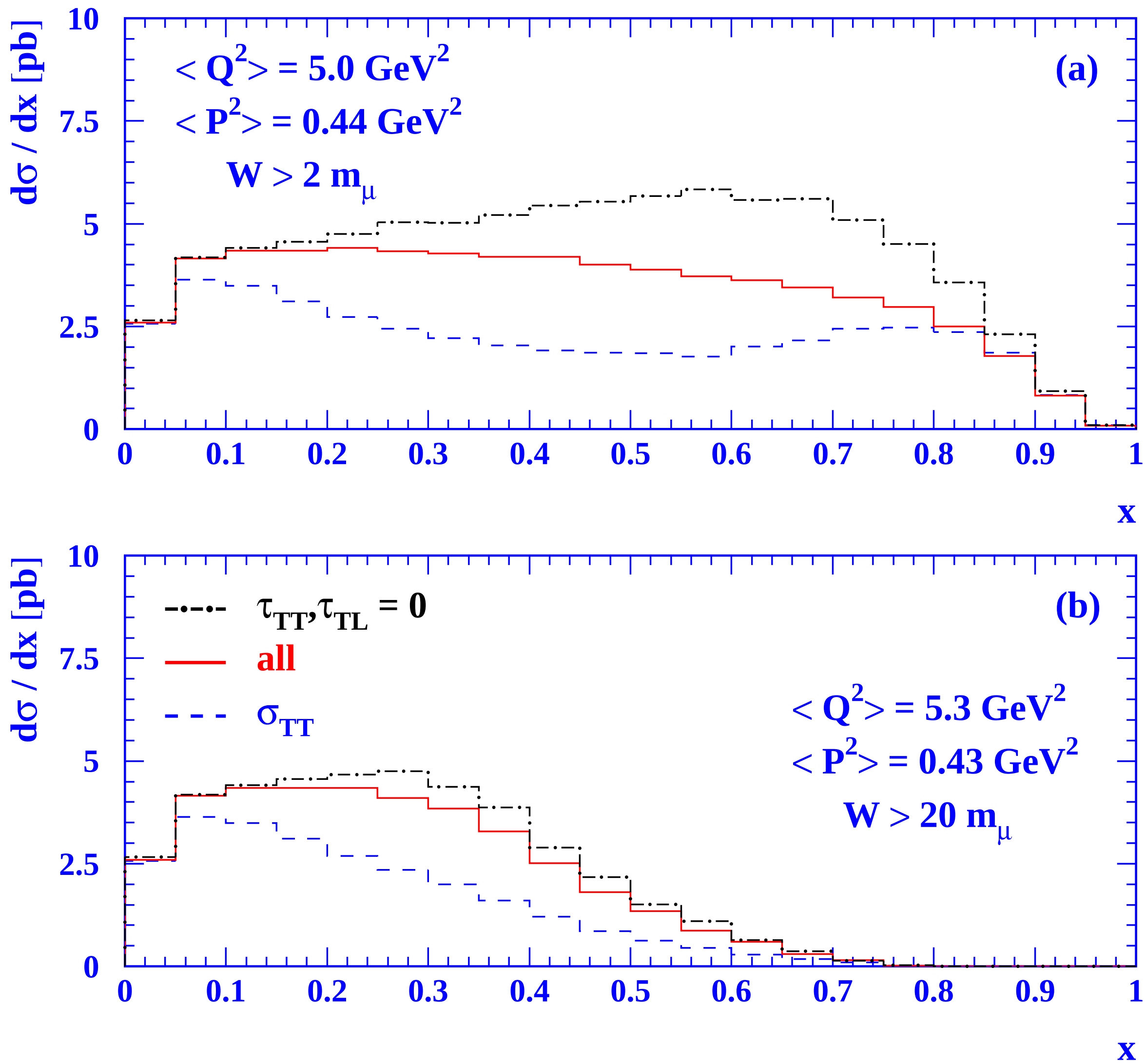


The non perturbative part is a 10% correction for $x > 0.3$, $Q^2 = 100\ \mathrm{GeV}^2$ and $P^2 = 1\ \mathrm{GeV}^2$

The Measurement of $F_{\rm eff}^{\gamma}$

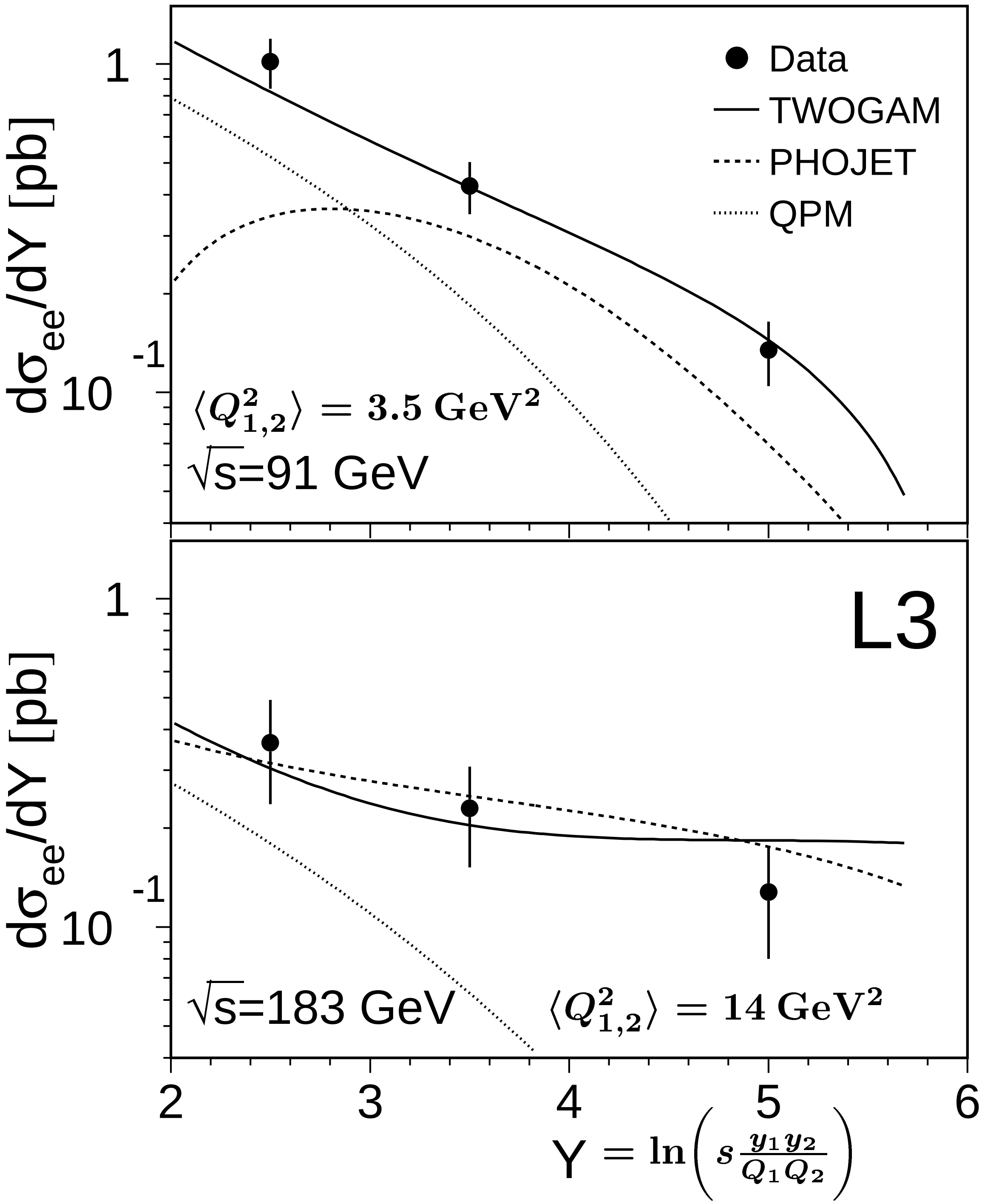


$d\sigma/dx$ for two virtual photons

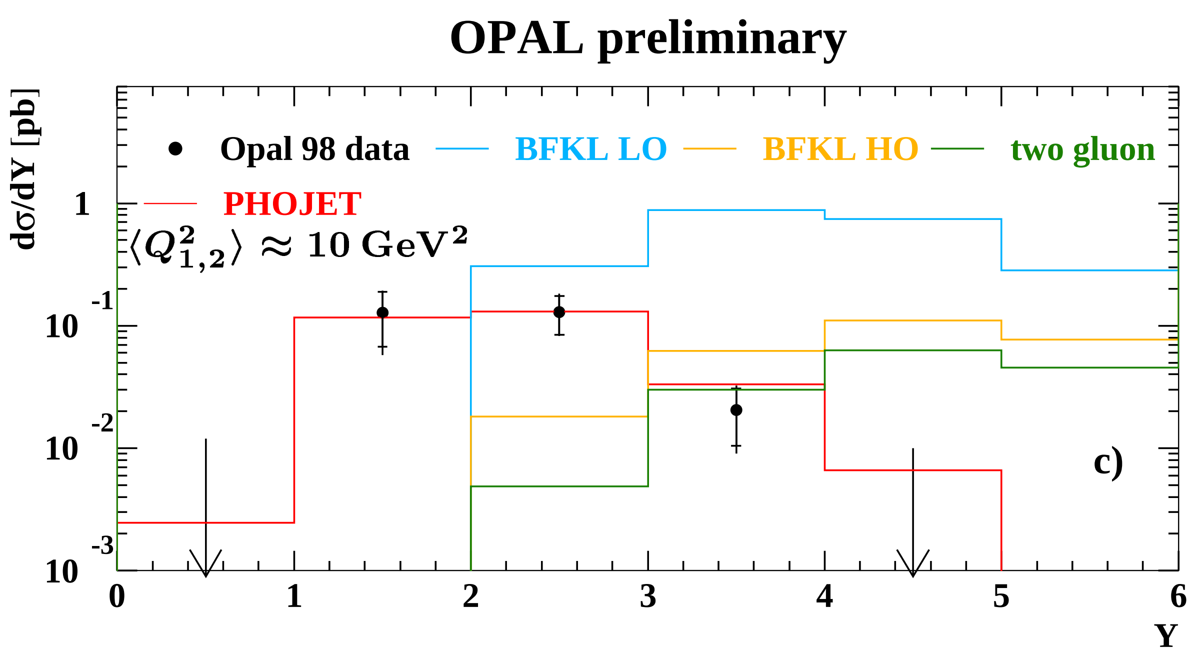


The cross-sections for longitudinal photons, σ_{LT} and σ_{TL}, and the interference terms, τ_{TL} and τ_{TT} can be important.

Cross-section for $ee \to ee$ hadrons



Comparison to BFKL



Cross-section corrected to:

$E_e > E$, $34 < \theta_e < 55$ mrad and $W > 5$ GeV

Cross-section integrated for $2 < Y < 6$ in [pb]				
E	OPAL	Phojet	2-gluon	BFKL LO / HO
65	$0.15 \pm 0.05 {}^{+0.03}_{-0.02}$	0.17	0.14	2.2 / 0.26
33	$0.21 \pm 0.06 {}^{+0.04}_{-0.02}$	0.25	0.24	5.7 / 0.50

BFKL is not favoured by the data

Conclusions and ...

1. Two photon physics is a very active field of research at LEP.
2. Particle production and jet cross sections for anti-tagged events are well described by NLO calculations, and the total hadronic cross-section is found to rise with W.
3. The production cross-section for charm quarks has been measured in anti-tagged events, and is satisfactorily described by NLO calculations. The contributions from direct and resolved charm production are of equal importance. The charm quark production was also observed for tagged events.
4. The QED structure of quasi-real and virtual photons is well understood.
5. The logarithmic rise of the hadronic structure function F_2^γ is clearly seen in the data, and the low-x behaviour of F_2^γ is intensively studied.
6. First results on the hadronic structure of virtual photons have been derived and BFKL predictions are not favoured.

... Outlook

1. There is much more work to be done to get a more complete understanding of the hadronic structure of the photon, especially for virtual photons.
2. Many more measurements are expected exploring the full luminosity of the LEP2 programme.

Slides: http://home.cern.ch/~nisius