Introduction to the Structure of real and virtual Photons

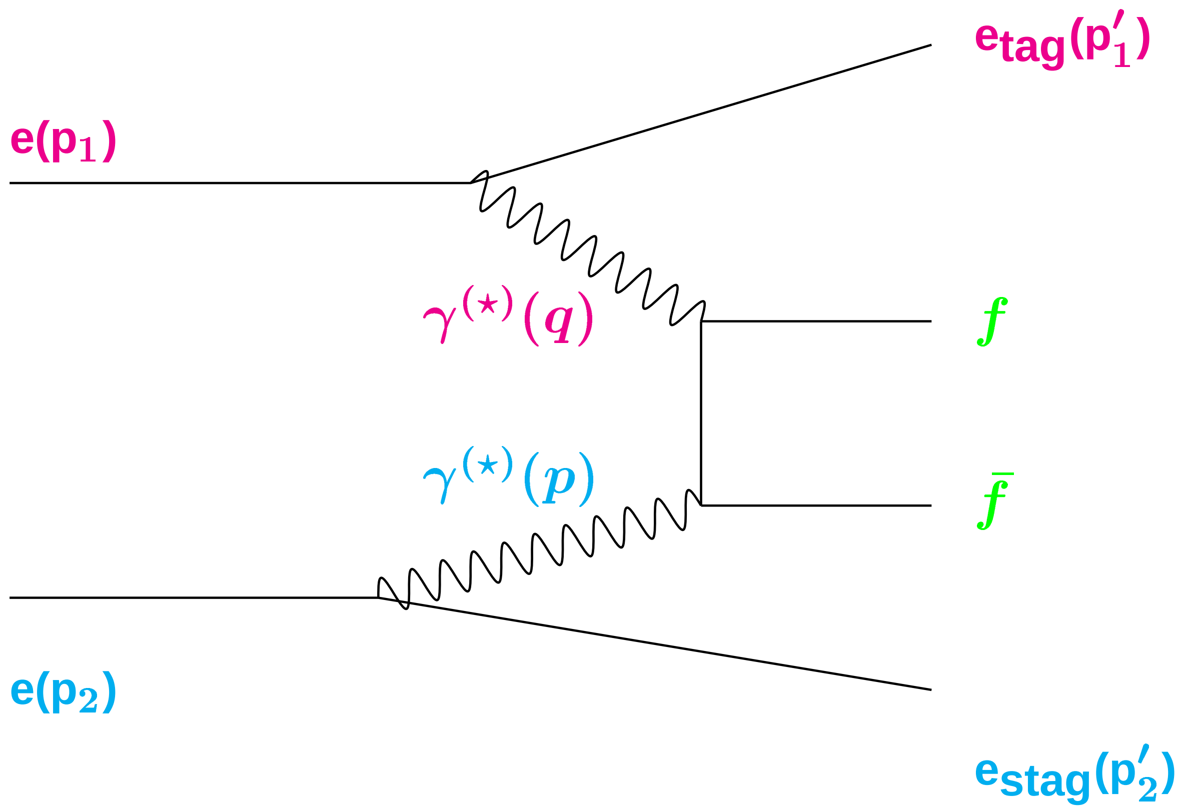
Richard Nisius (CERN) Freiburg, May, 23 ’99

- Introduction

1. The QED structure
2. The hadronic structure

- Conclusions

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



$$\mathrm{d}^6\sigma = \frac{\mathrm{d}^3 p_1' \mathrm{d}^3 p_2'}{E_1' E_2'} \frac{\alpha^2}{16\pi^4 q^2 p^2} \left[\frac{(q \cdot p)^2 - q^2 p^2}{(p_1 \cdot p_2)^2 - m_\mathrm{e}^2 m_\mathrm{e}^2} \right]^{1/2} \cdot$$

$$\Big(4\rho_1^{++}\rho_2^{++}\sigma_{\mathrm{TT}} + 2\rho_1^{++}\rho_2^{00}\sigma_{\mathrm{TL}}$$

$$+ 2\rho_1^{00}\rho_2^{++}\sigma_{\mathrm{LT}} + \rho_1^{00}\rho_2^{00}\sigma_{\mathrm{LL}} +$$

$$2|\rho_1^{+-}\rho_2^{+-}|\tau_{\mathrm{TT}} \cos 2\bar{\phi} - 8|\rho_1^{+0}\rho_2^{+0}|\tau_{\mathrm{TL}} \cos\bar{\phi} \Big)$$

$$Q^2 = 2\, E_\mathrm{b}\, E_{\mathrm{tag}}\, (1 - \cos\theta_{\mathrm{tag}})$$

$$P^2 = 2\, E_\mathrm{b}\, E_{\mathrm{stag}}\, (1 - \cos\theta_{\mathrm{stag}})$$

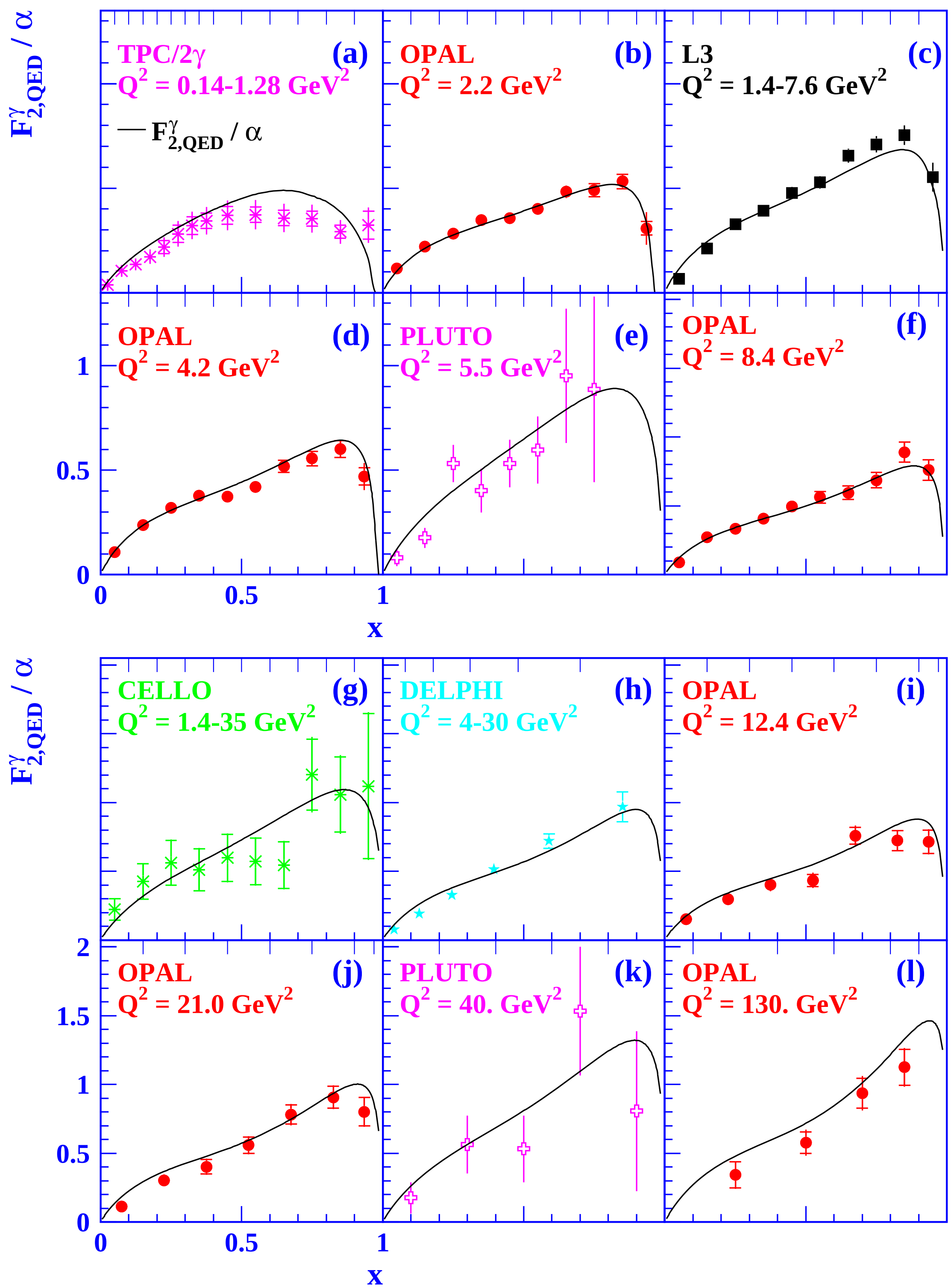
$$x = \frac{Q^2}{Q^2 + W^2 + P^2}$$

The formalism for deep inelastic electron-photon scattering

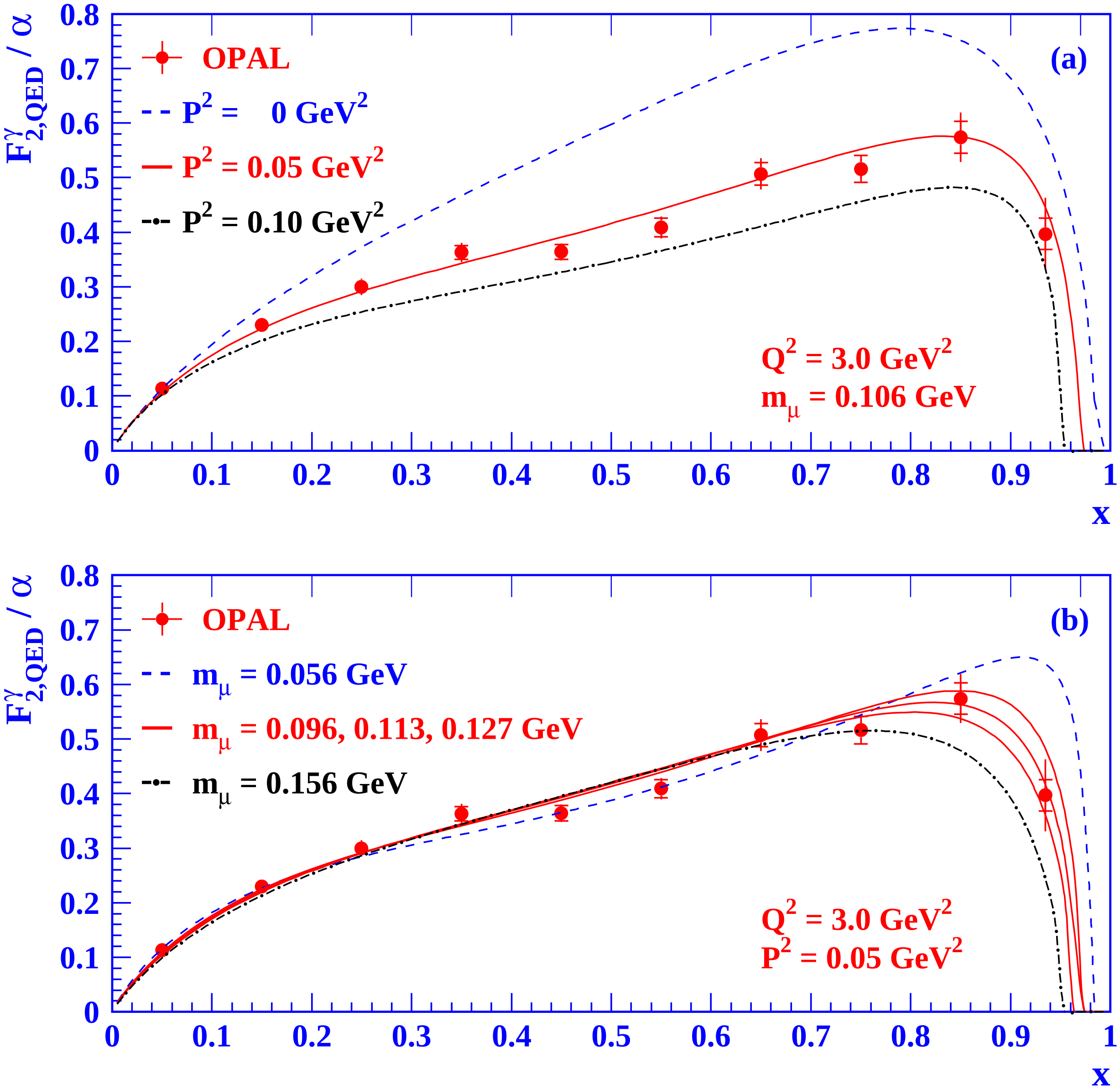
$$
\begin{aligned}
2xF_1^\gamma &= \frac{-q^2}{4\pi^2\alpha}\frac{\sqrt{(q\cdot p)^2-q^2p^2}}{q\cdot p}\left(\sigma_{\mathrm{TT}}(x,q^2,p^2)-\frac{1}{2}\sigma_{\mathrm{TL}}(x,q^2,p^2)\right)\\
F_2^\gamma &= \frac{-q^2}{4\pi^2\alpha}\,\frac{q\cdot p}{\sqrt{(q\cdot p)^2-q^2p^2}}\left(\sigma_{\mathrm{TT}}(x,q^2,p^2)+\sigma_{\mathrm{LT}}(x,q^2,p^2)\right.\\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

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

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

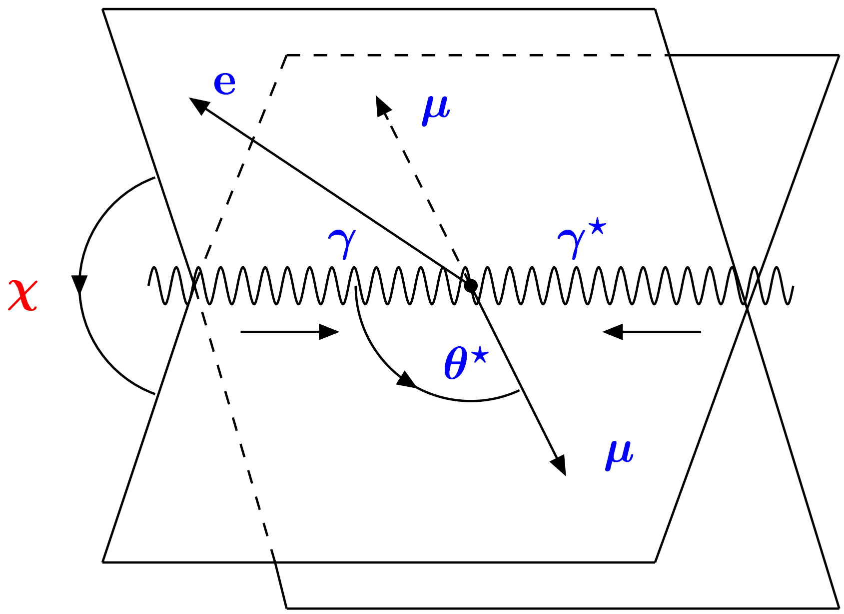


The dependence of F_2^γ on P^2 and m_μ



The P^2 dependence is clearly observed in the data.
The muon mass can be determined to about $\pm$15%.

Azimuthal Correlations



$$\boxed{\mathrm{e}\gamma \to \mathrm{e}\mu\mu}$$

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

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

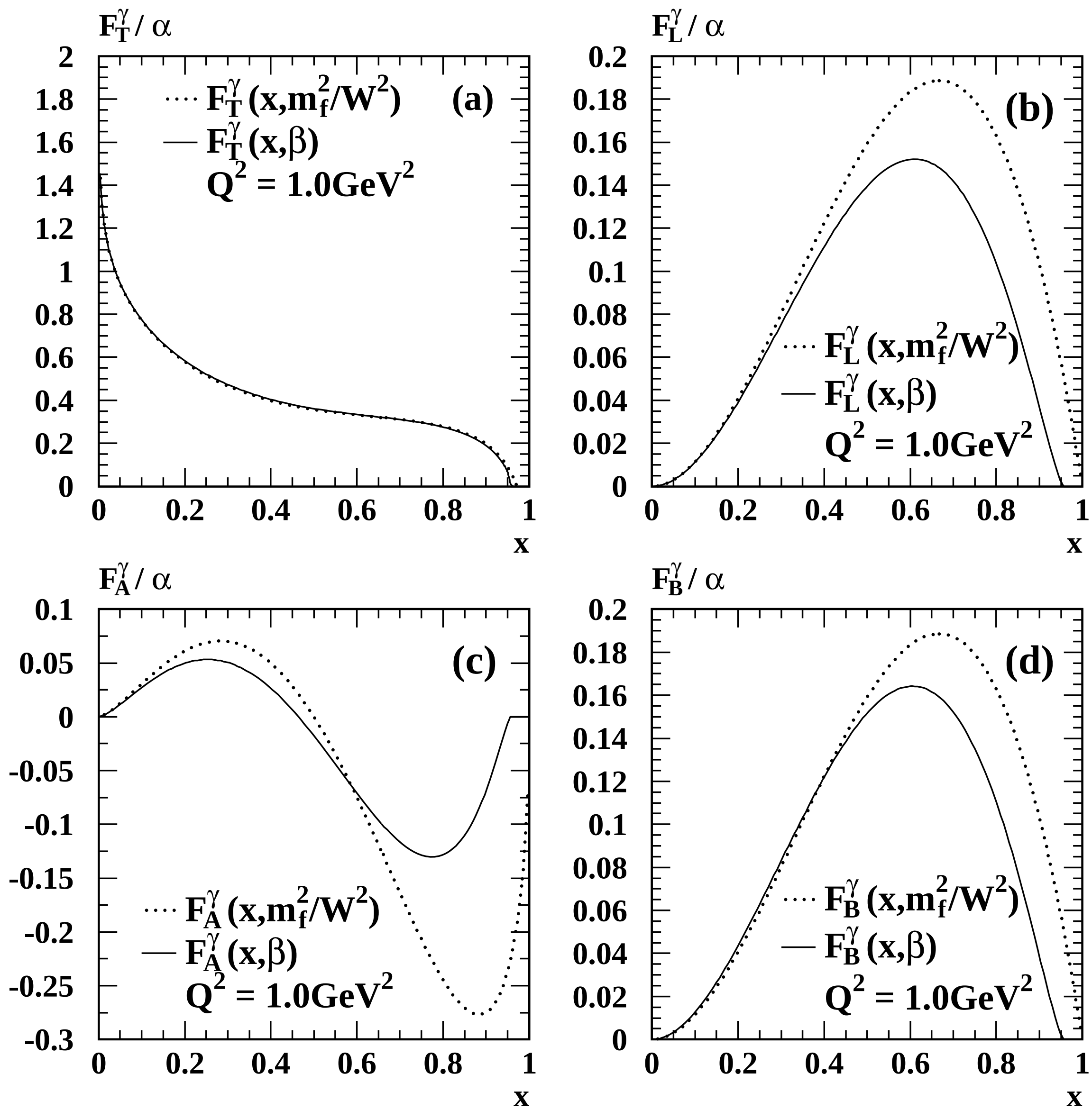
The χ dependence gives access to other structure functions besides F_2^γ.

The functional form of F_A^γ and F_B^γ

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

(leading log $\beta \to 1$)

The improvement of the leading log approximation

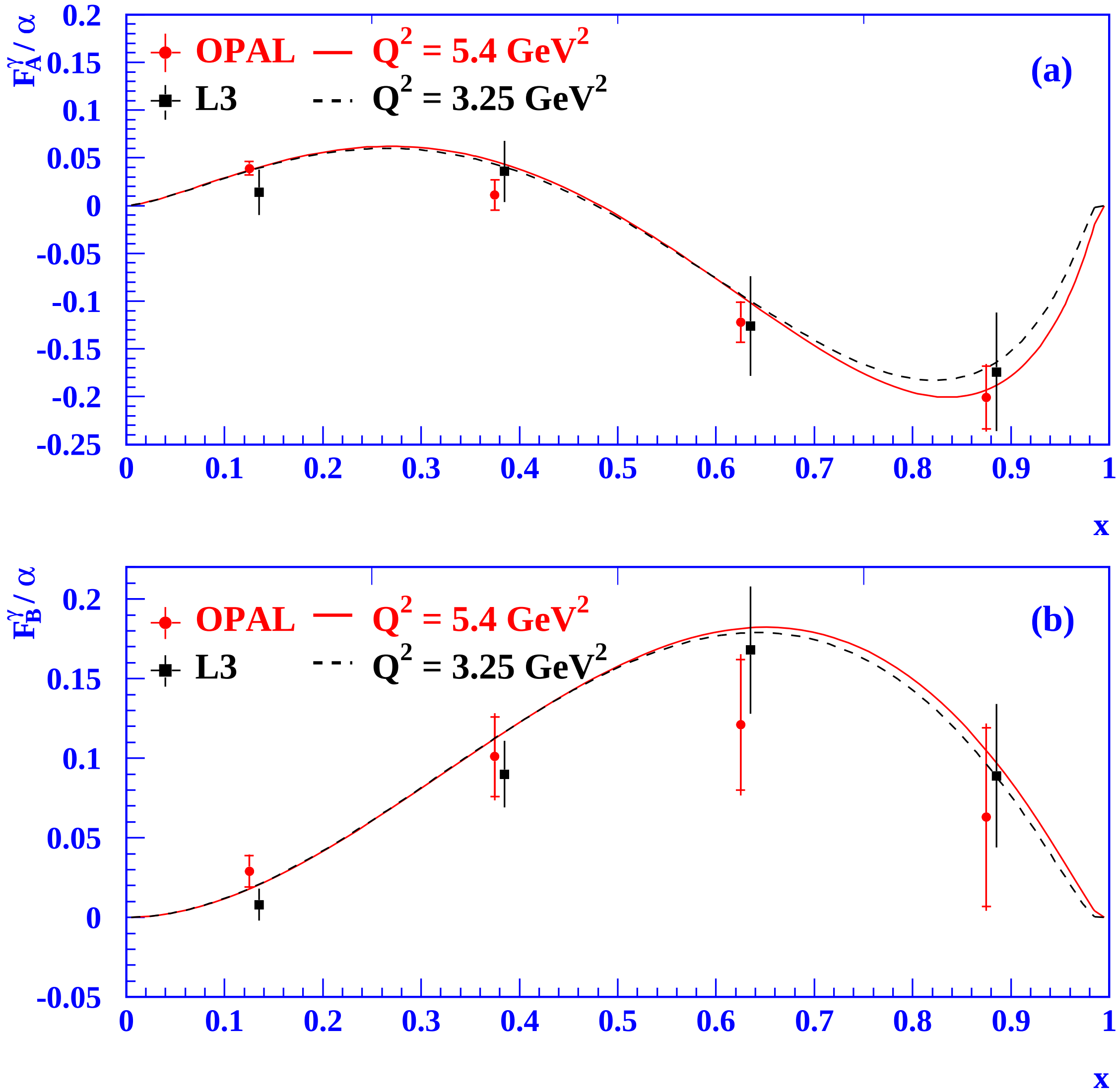


The structure function $F^\gamma_{\mathrm{A,QED}}$ and $F^\gamma_{\mathrm{B,QED}}$ receive seizable corrections at low values of Q^2

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

The structure functions

F_A^γ and F_B^γ

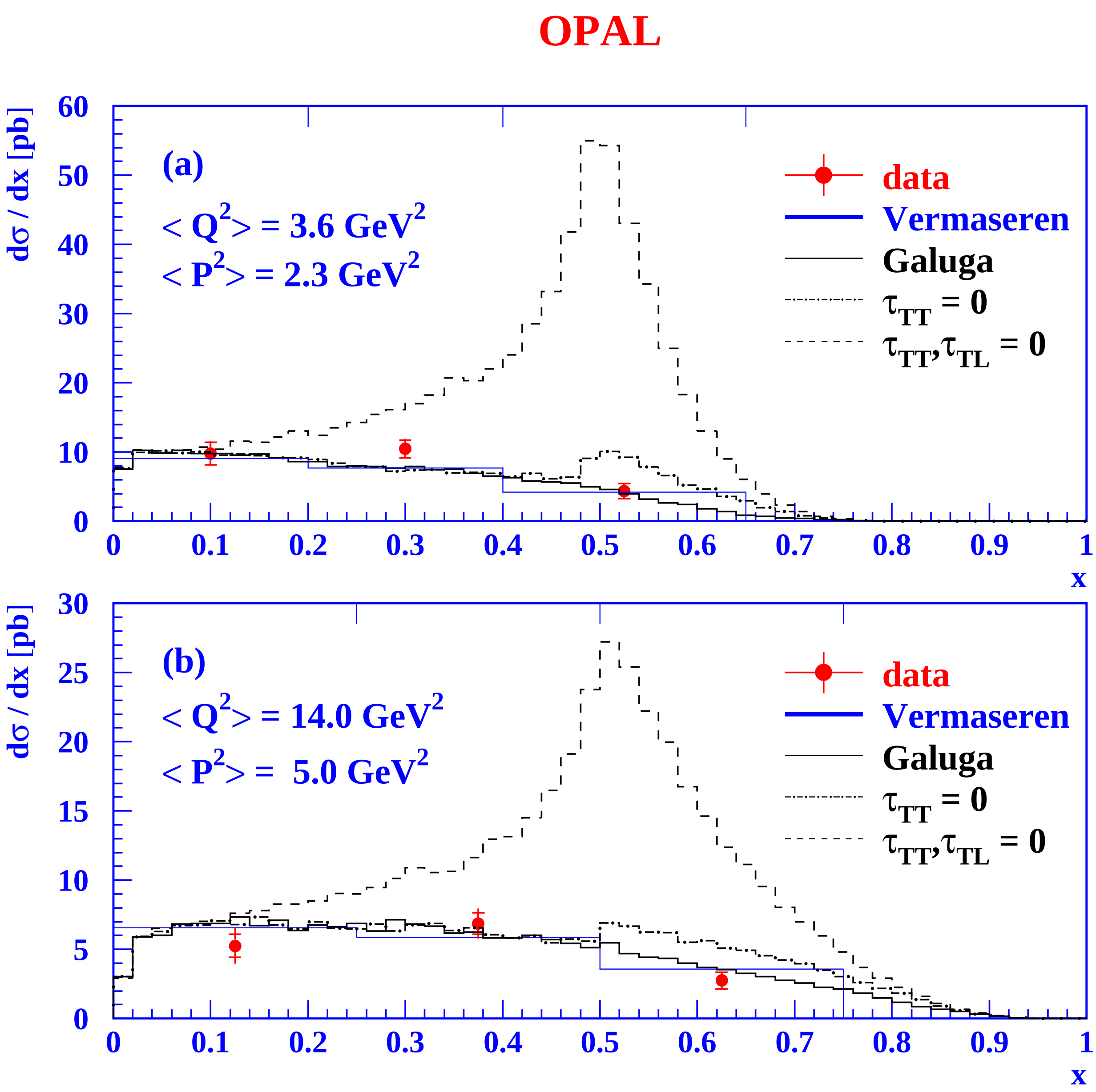


First measurement that goes further than measuring the differential cross-section.

The double tag limit: $Q^2, P^2 \gg m_e^2, \frac{\rho_i^{00}}{2\rho_i^{++}} \to 1$

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

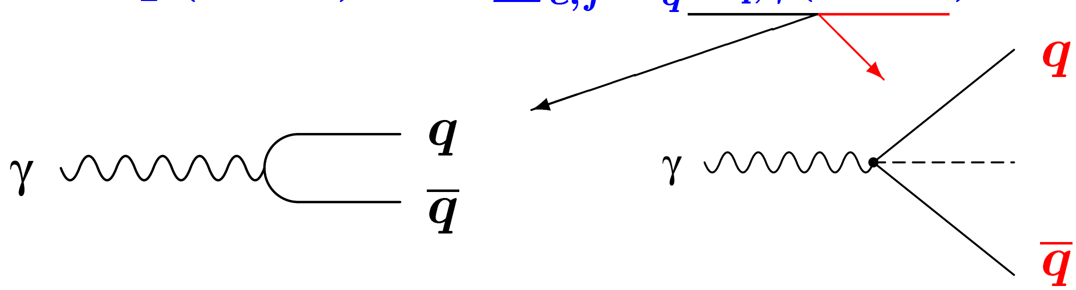
The cross-section for double tags



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

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

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

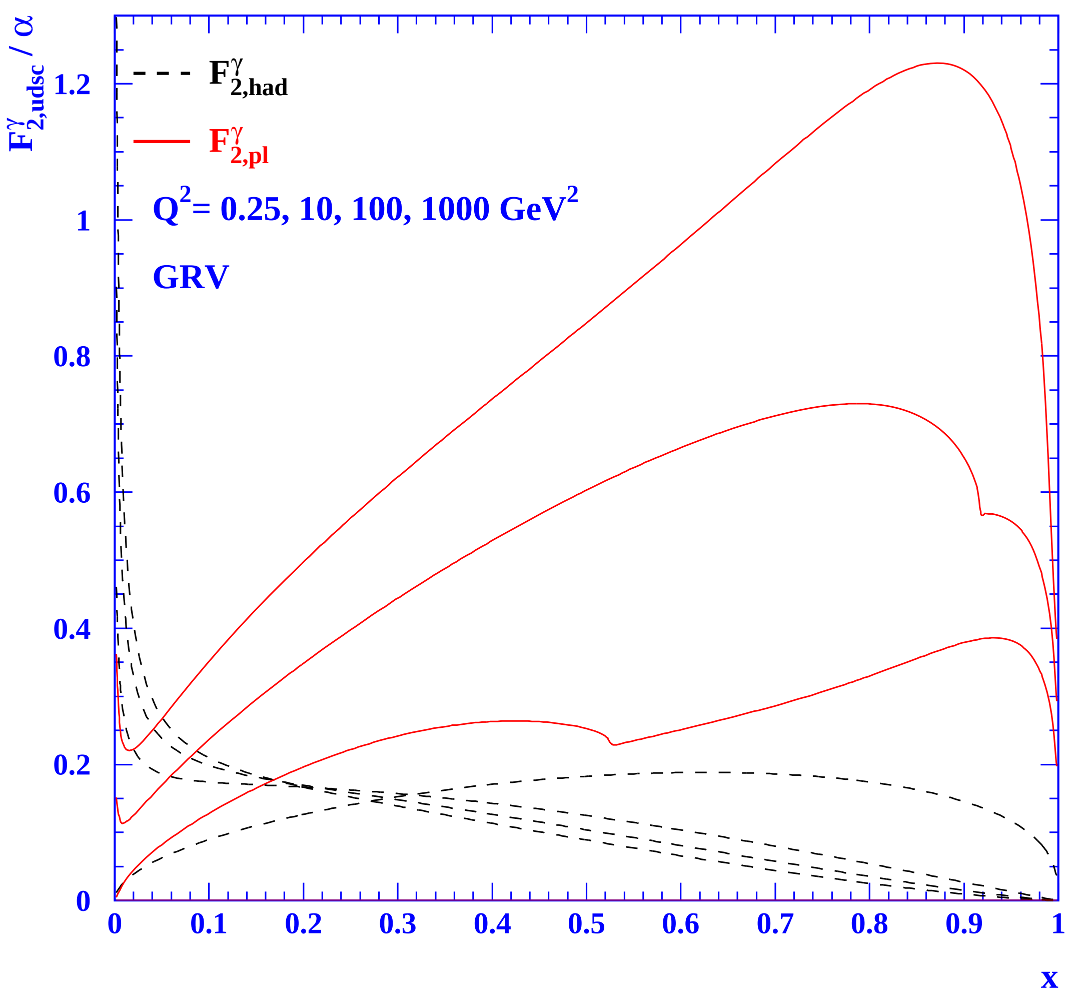


hadronic, VDM, "small x"

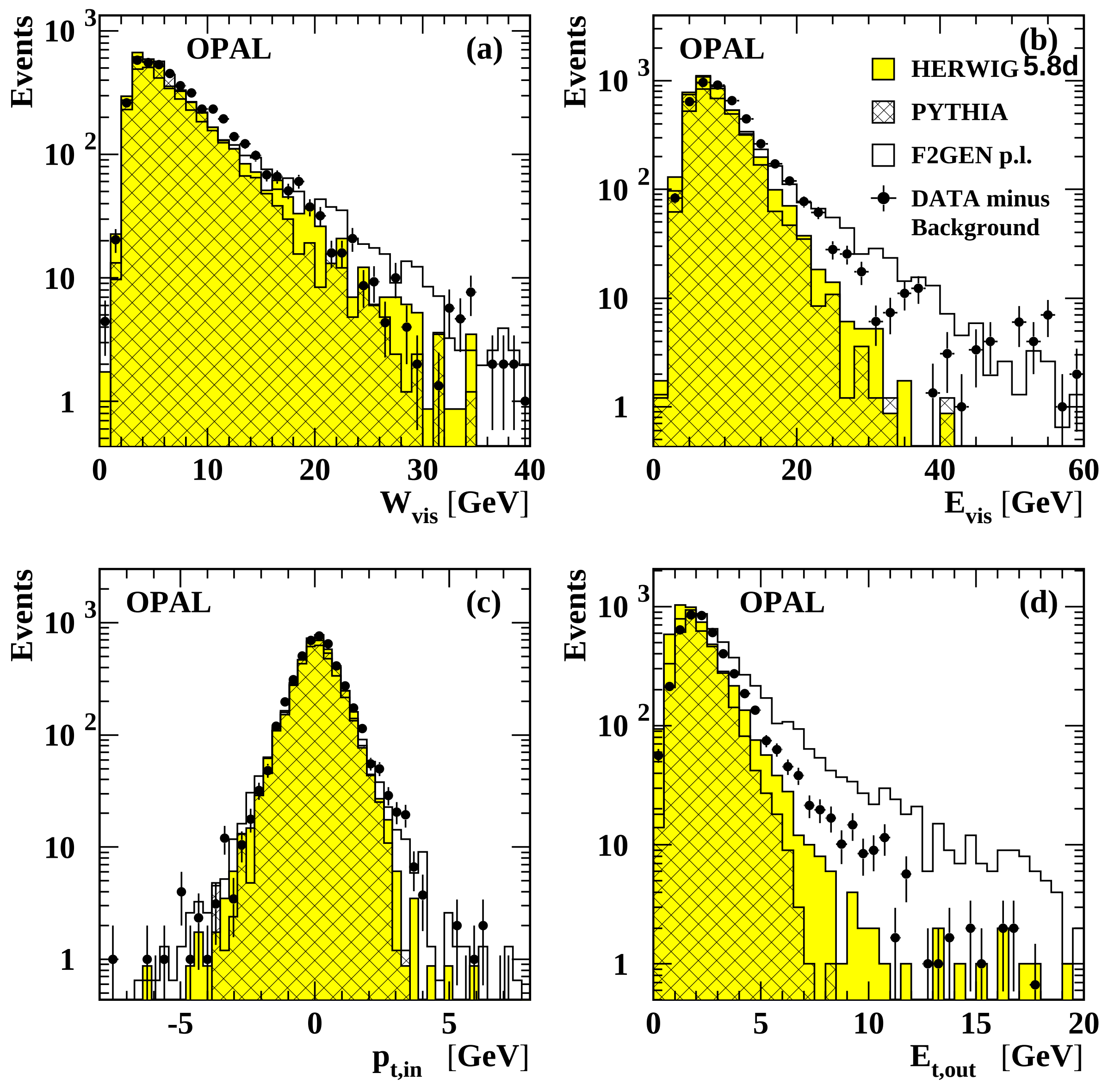
ρ, ω, ϕ, *non–perturbative*

pointlike, "large x"

perturbative

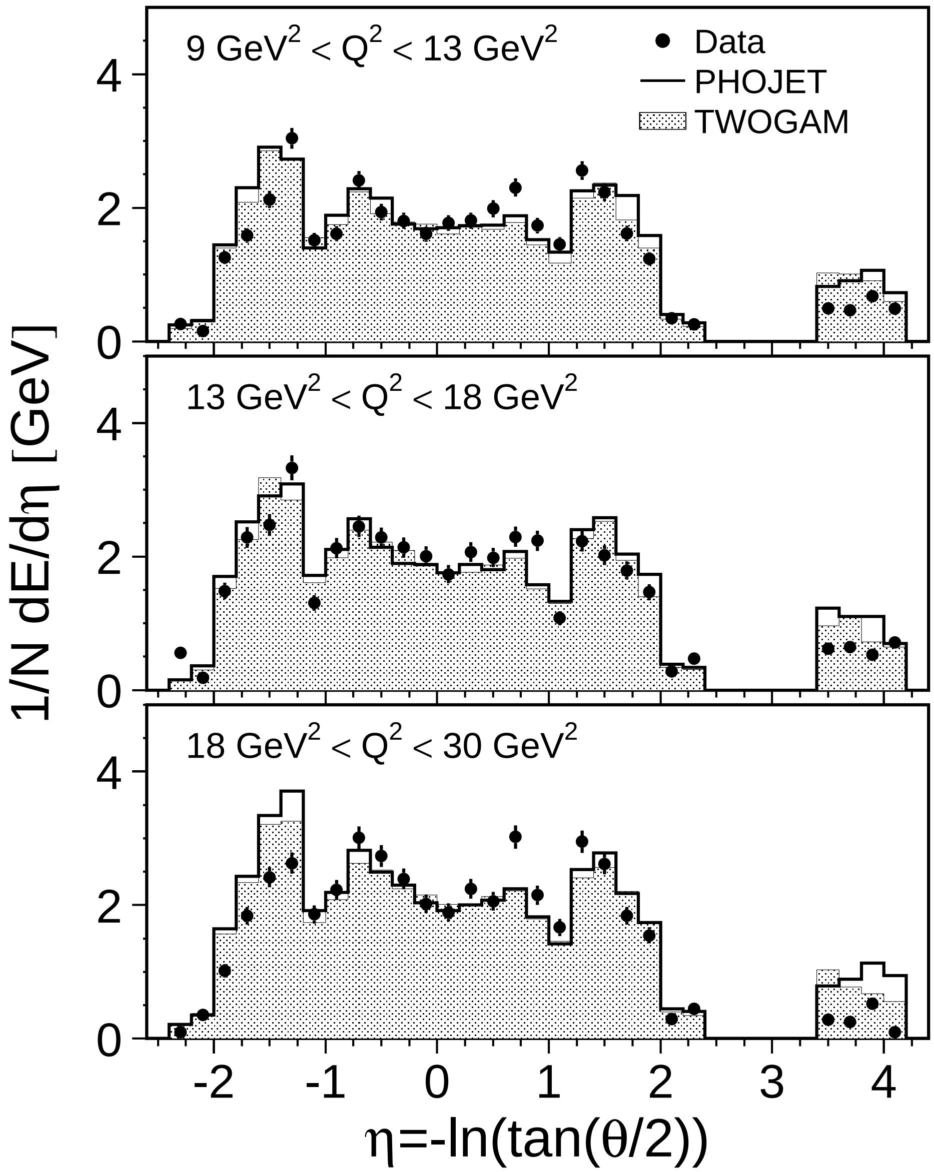


The description of the hadronic final state



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

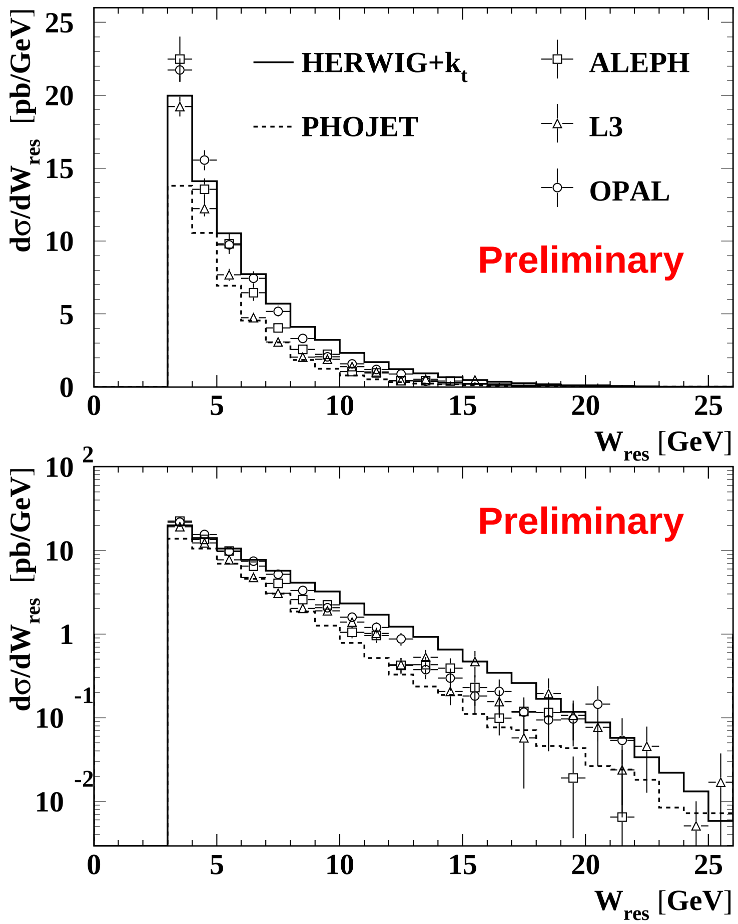
The hadronic energy flow



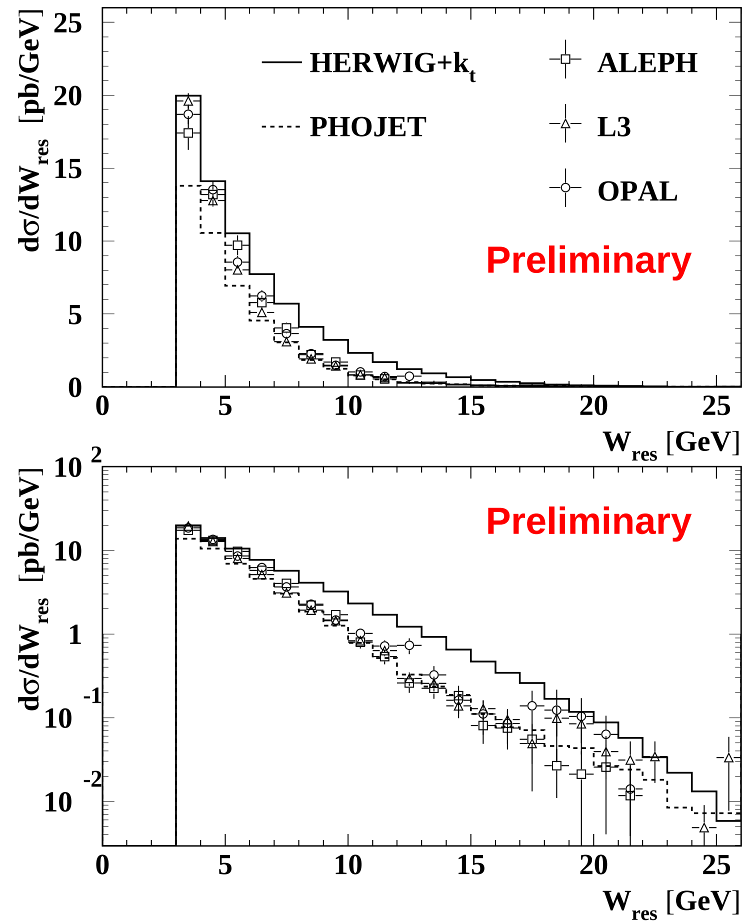
The hadronic energy flow is not well described by all available Monte Carlo models (L3 '98)

Comparison to corrected LEP data

HERWIG corrected low Q^2 data

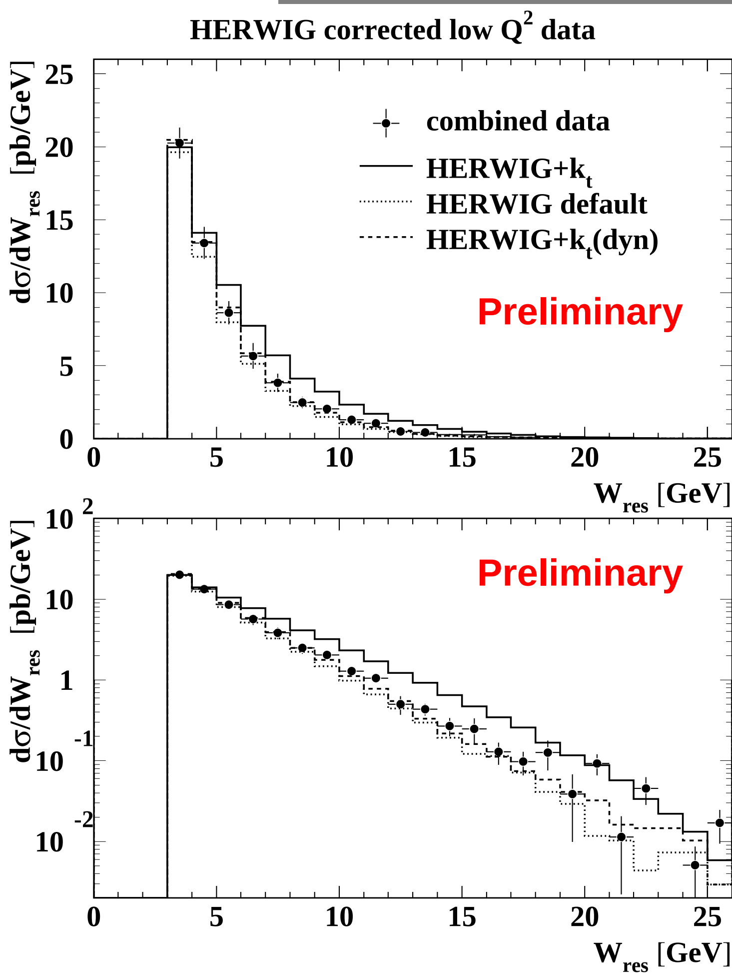


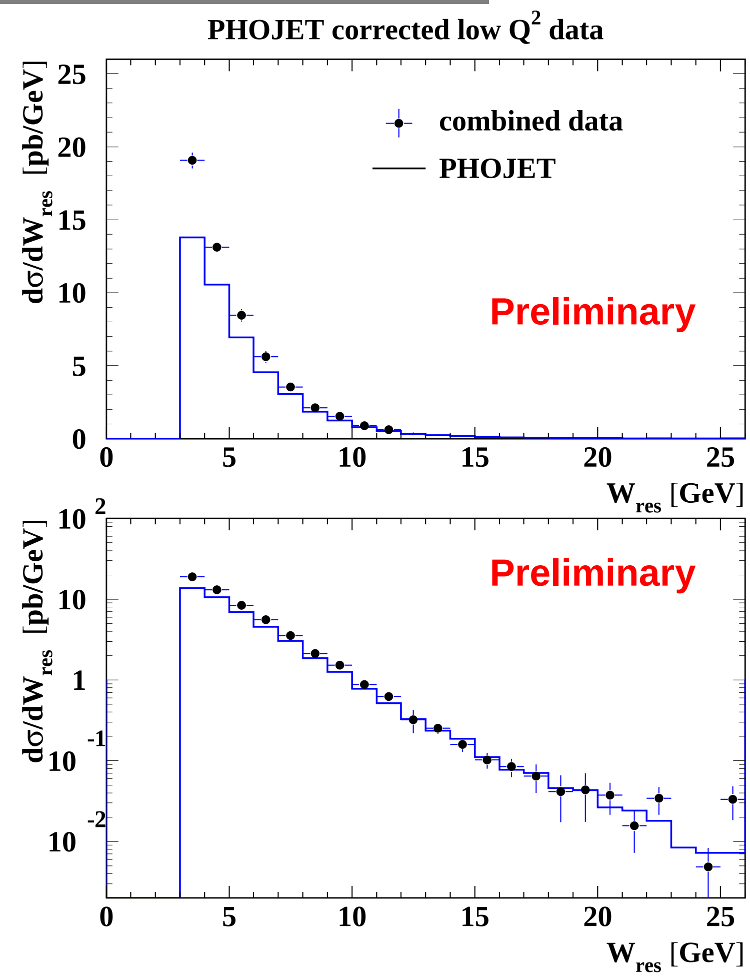
PHOJET corrected low Q^2 data



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

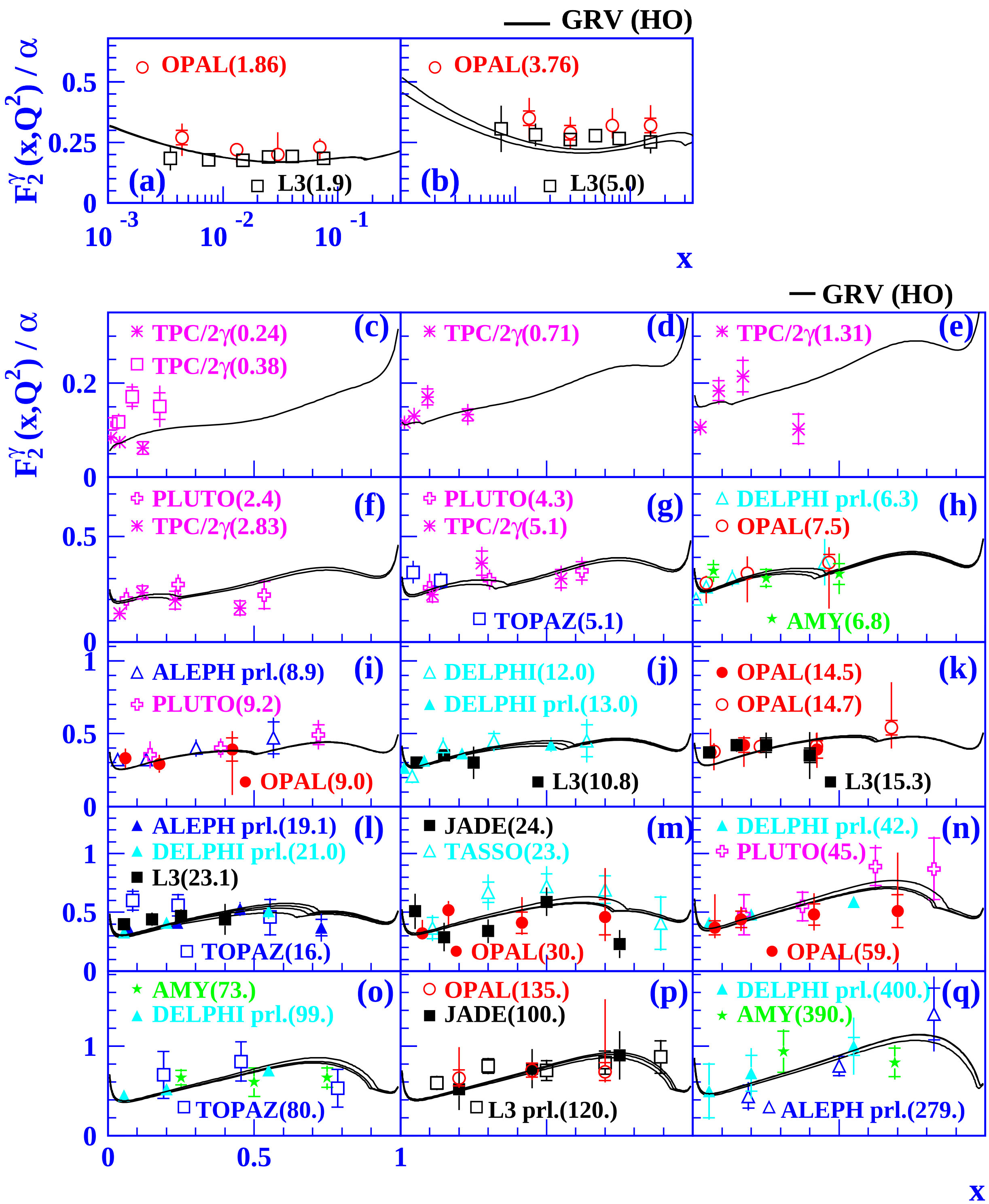




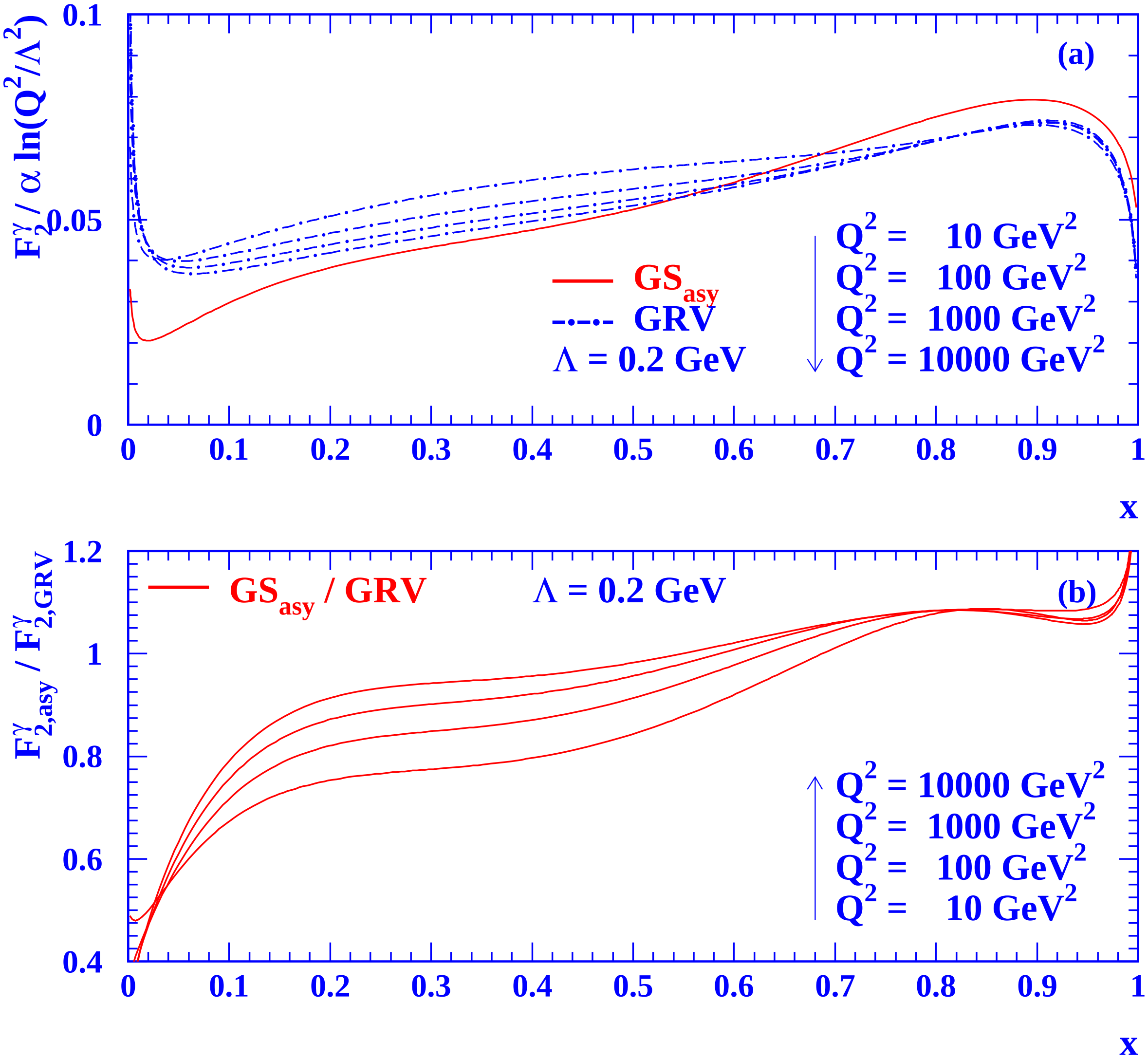
The combined data are a valuable input to constrain the Monte Carlo models

(LEP Two-Photon WG '99)

The world data on F_2^γ

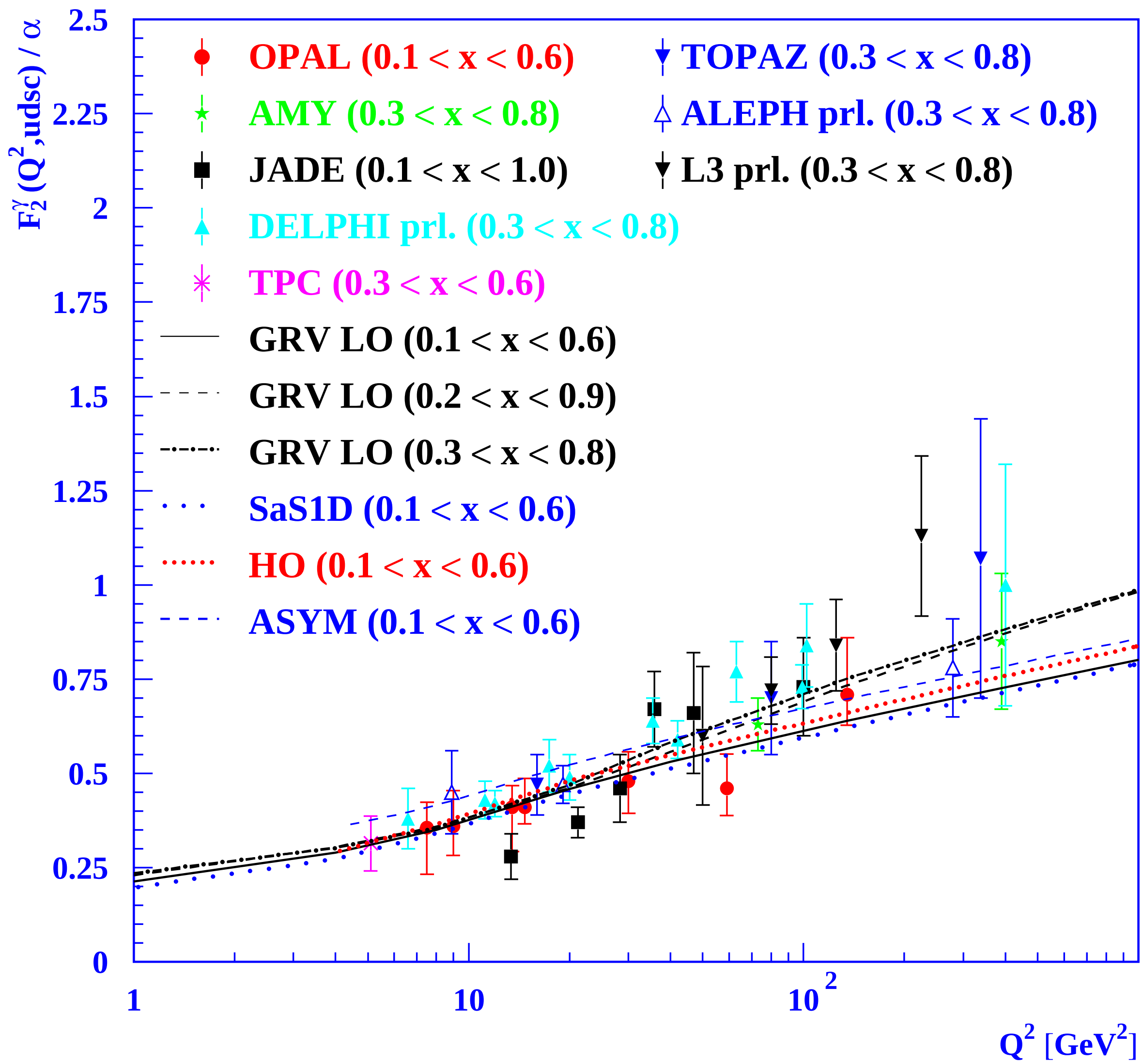


The x dependence of F_2^γ (GRV) and F_2^γ (asy)



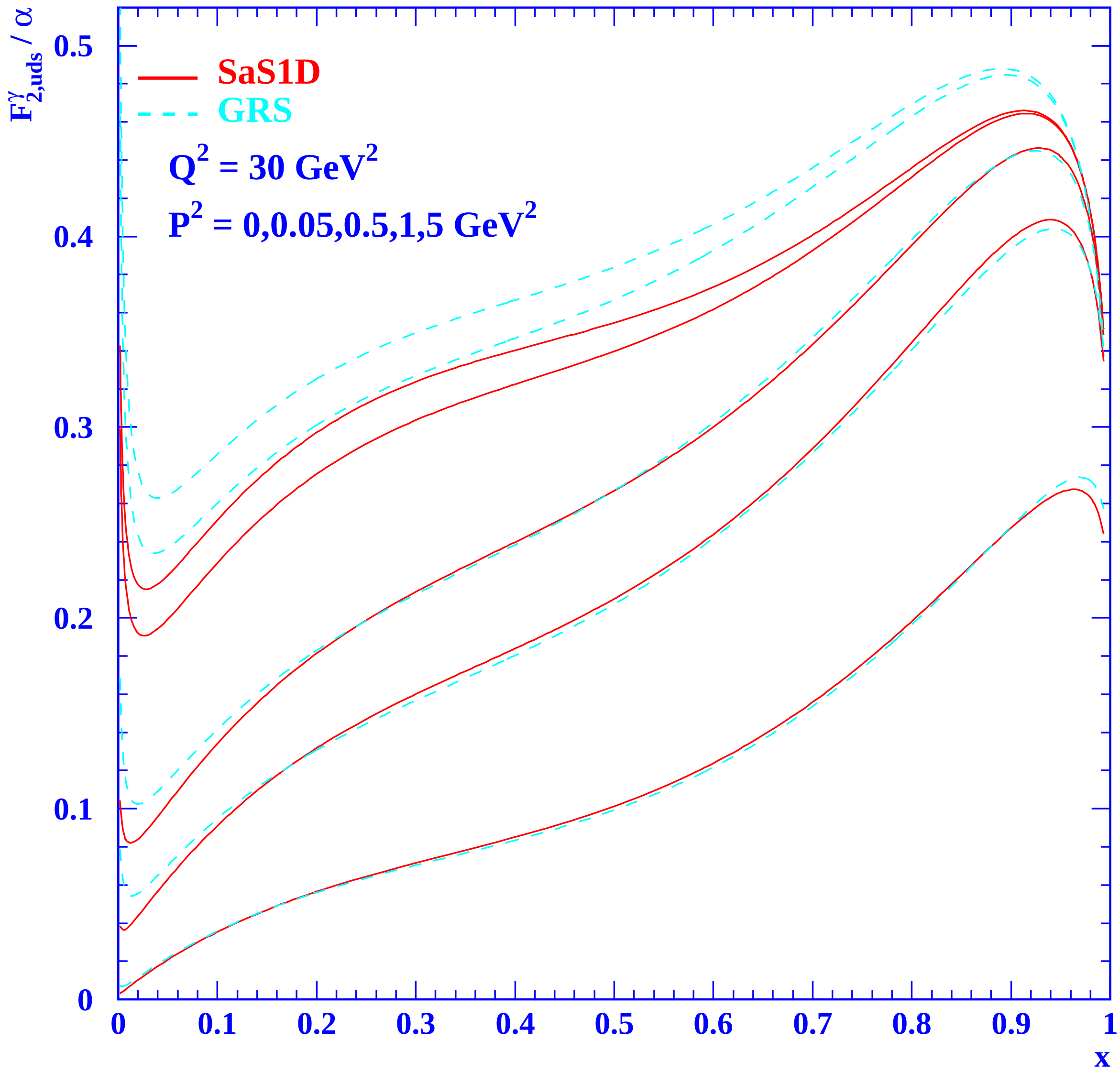
The structure function F_2^γ is to 90% perturbative at large x

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



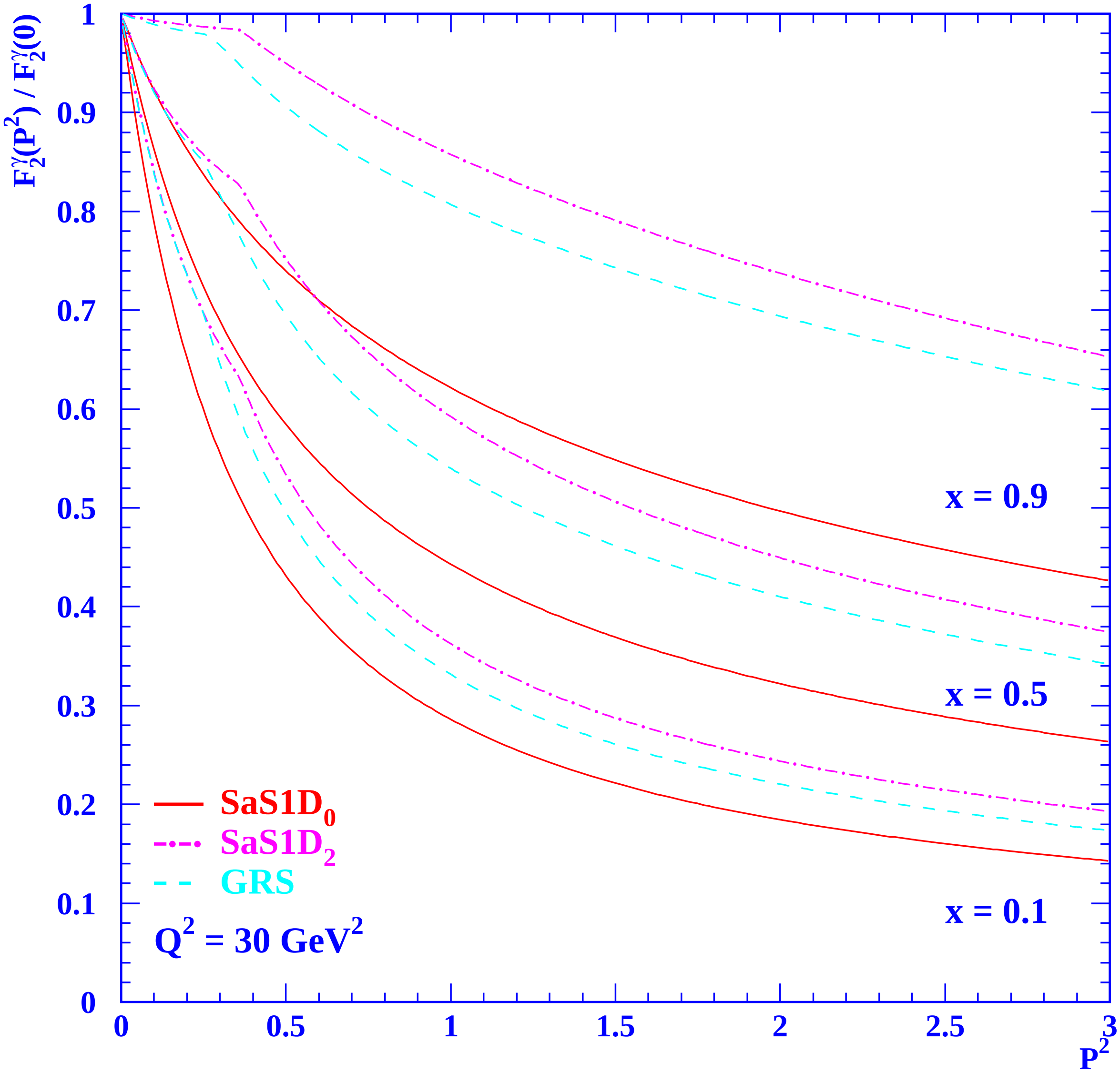
A clear rise consistent with $\log Q^2$ is seen in the data

F_2^γ for virtual photons



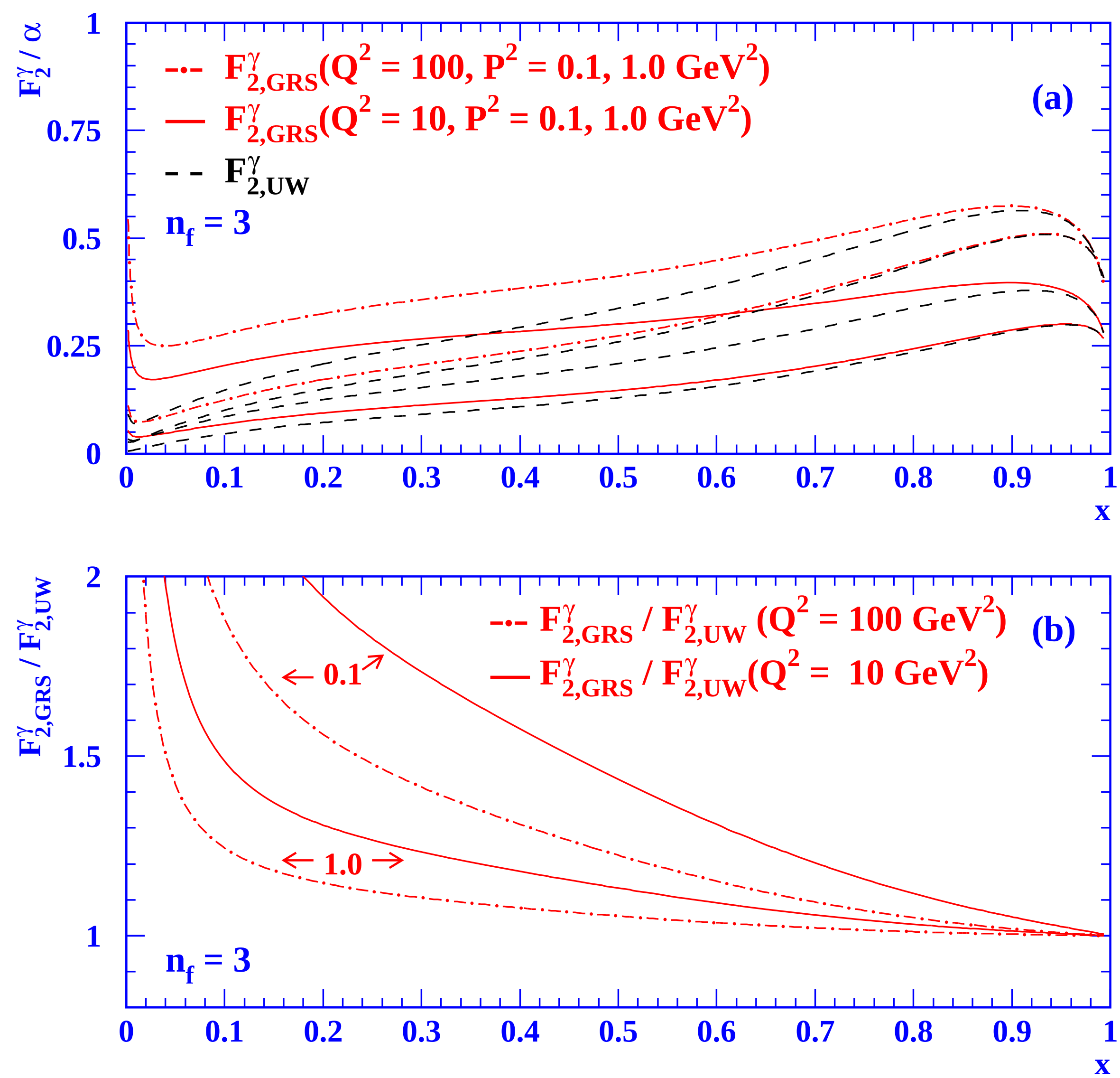
The absolute predictions agree for $P^2 > 0.5\ \mathrm{GeV}^2$, when using SaS1D ($IP2 = 2$)

F_2^γ as a function of P^2



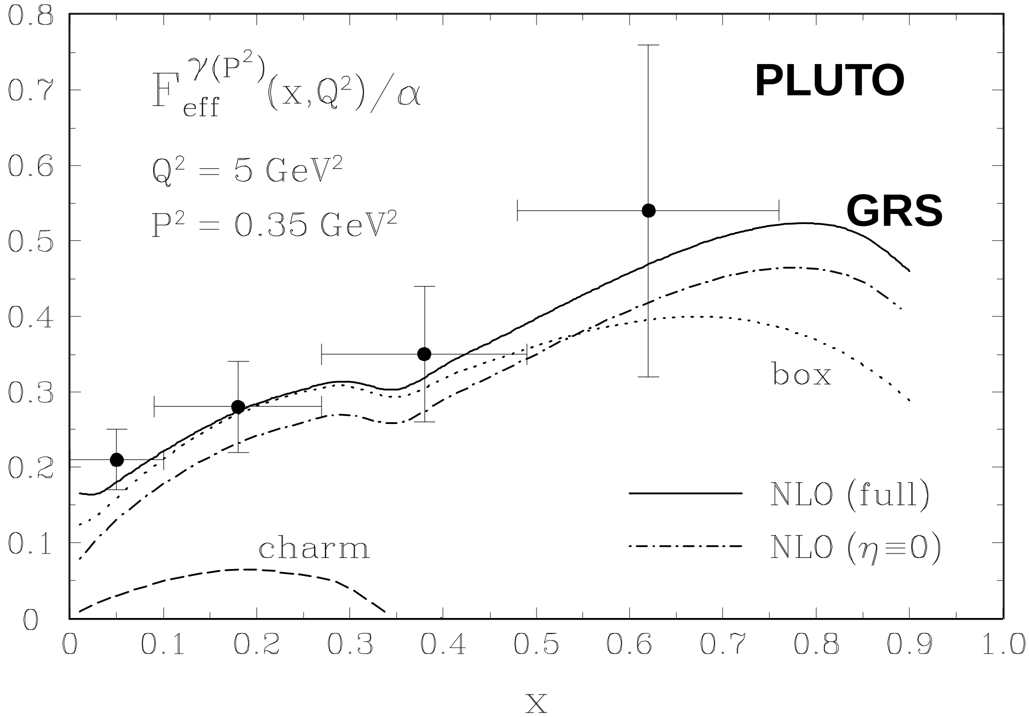
The suppression strongly depends on the assumptions made for the supression in SaS (IP2) and on x

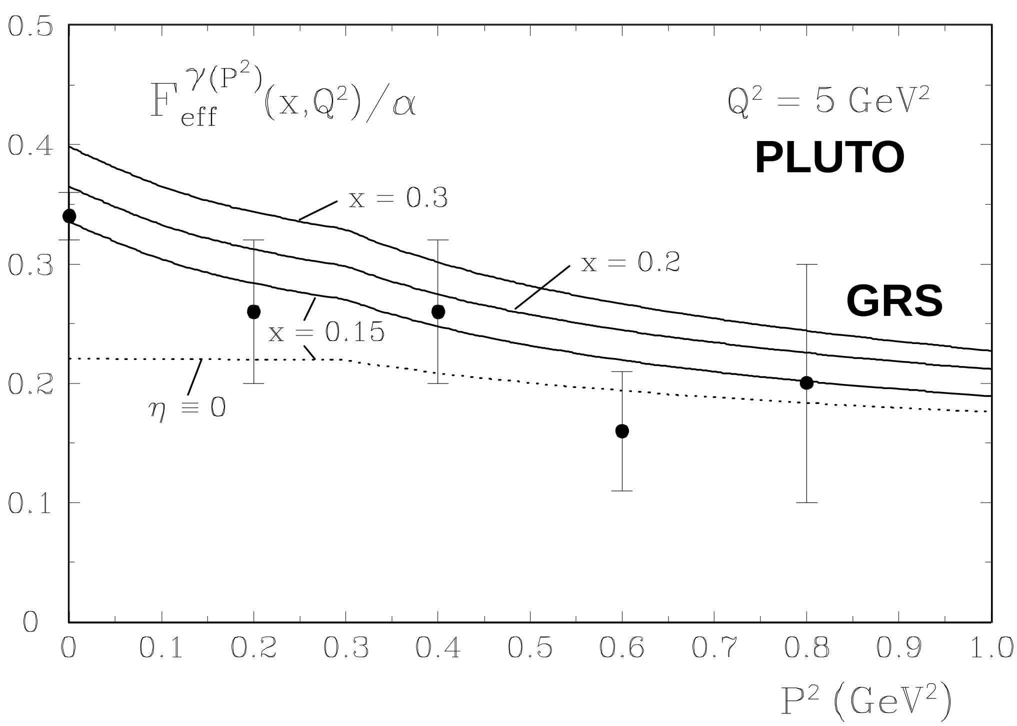
The x dependence of $F_2^\gamma\,(P^2)$(GRS) and $F_2^\gamma\,(P^2)$(pl)



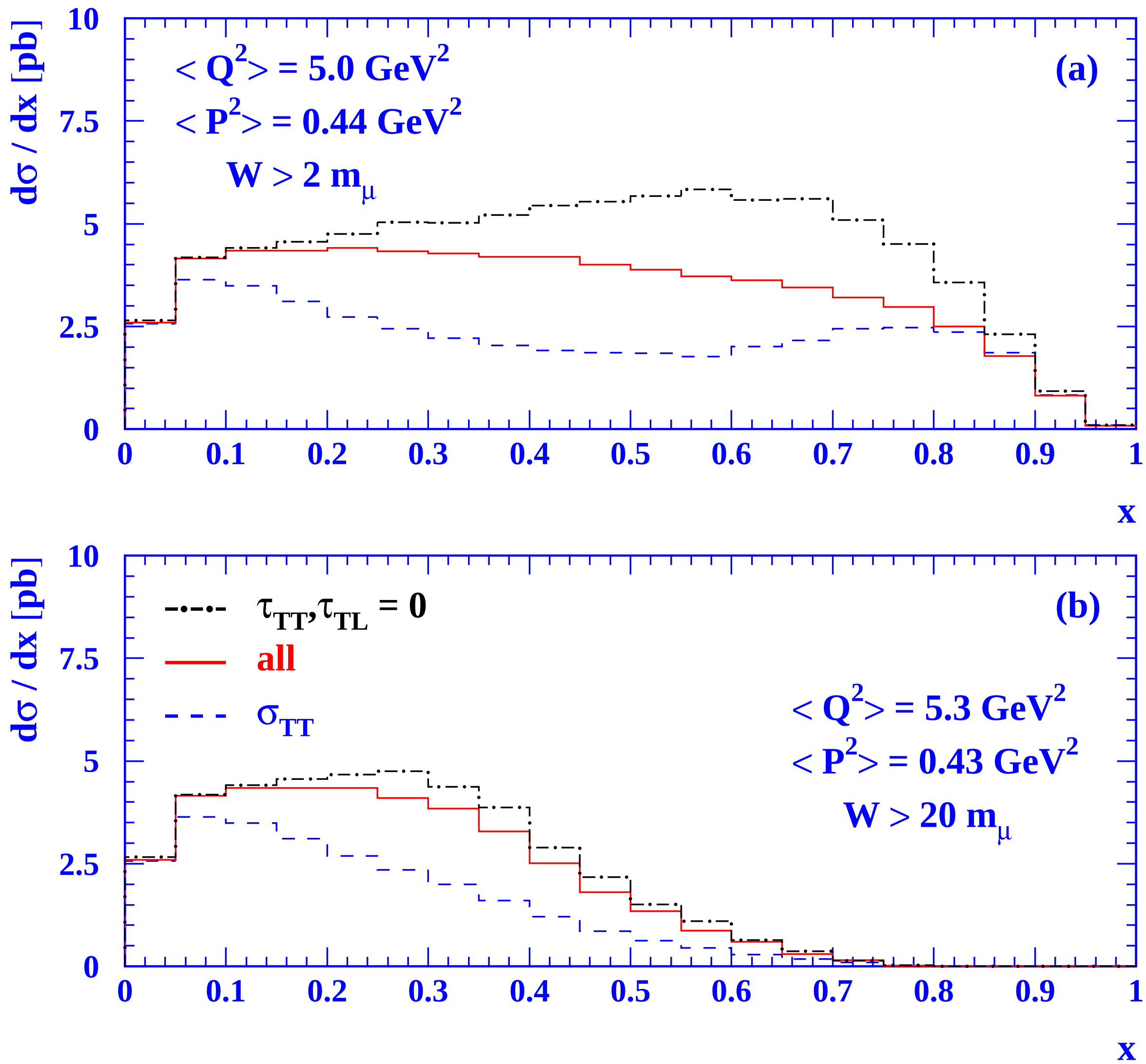
The non perturbative part is a 10% correction for $x > 0.3$, $Q^2 = 100\ \mathrm{GeV}^2$ and $P^2 = 1\ \mathrm{GeV}^2$

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



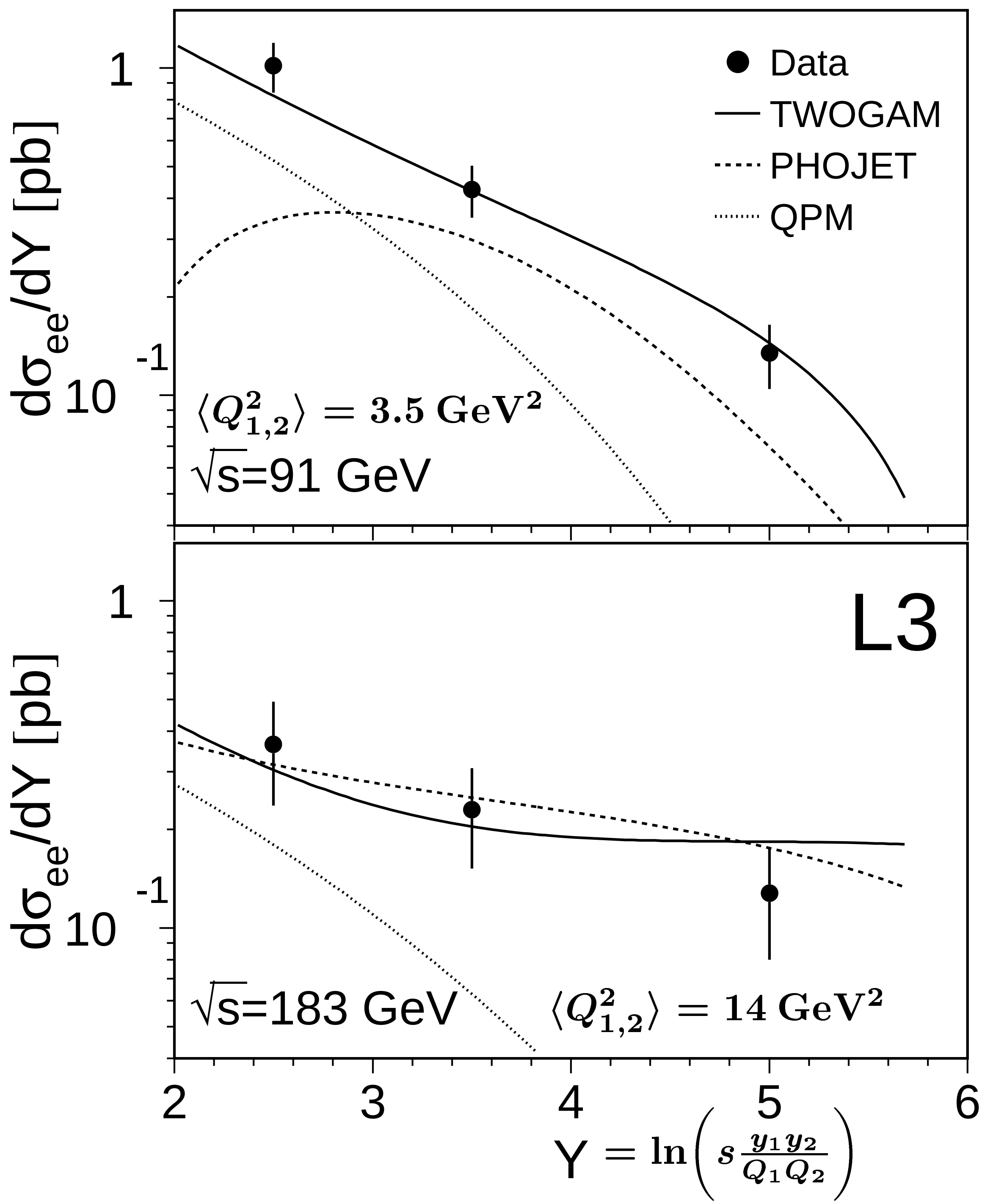


$d\sigma/dx$ for two virtual photons



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 $\rightarrow$ ee hadrons



Conclusions

1. QED is in good shape and sucessfully describes:
   (a) $F_{2,\mathrm{QED}}^{\gamma}$ in the large kinematical range of $1.5 < Q^2 < 400\ \mathrm{GeV}^2$ including the effect of the small virtuality of the quasi-real photon P^2.
   (b) The structure functions F_{A}^{γ} and F_{B}^{γ}.
   (c) The differential cross section $\mathrm{d}\sigma/\mathrm{d}x$ for $1.5 < P^2, Q^2 < 20, 30\ \mathrm{GeV}^2$.
2. The hadronic structure is a field of active research:
   (a) Accurately describing the hadronic final state is non-trivial.
   (b) The logarithmic rise of F_2^{γ} is clearly seen.
   (c) The low-x behaviour of F_2^{γ} is intensively studied.
   (d) The information on the structure of virtual photons is still very limited.

Let us enjoy a session with interesting new results and developments.

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