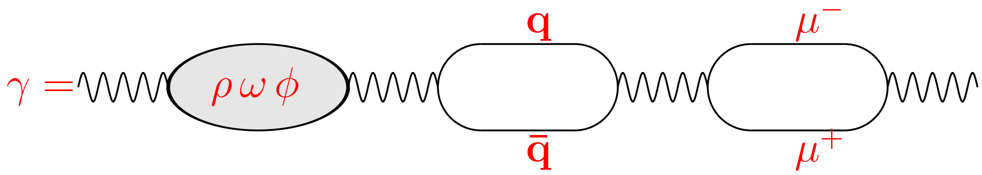
The Structure of the



Richard Nisius (CERN) CERN, 11.04.00

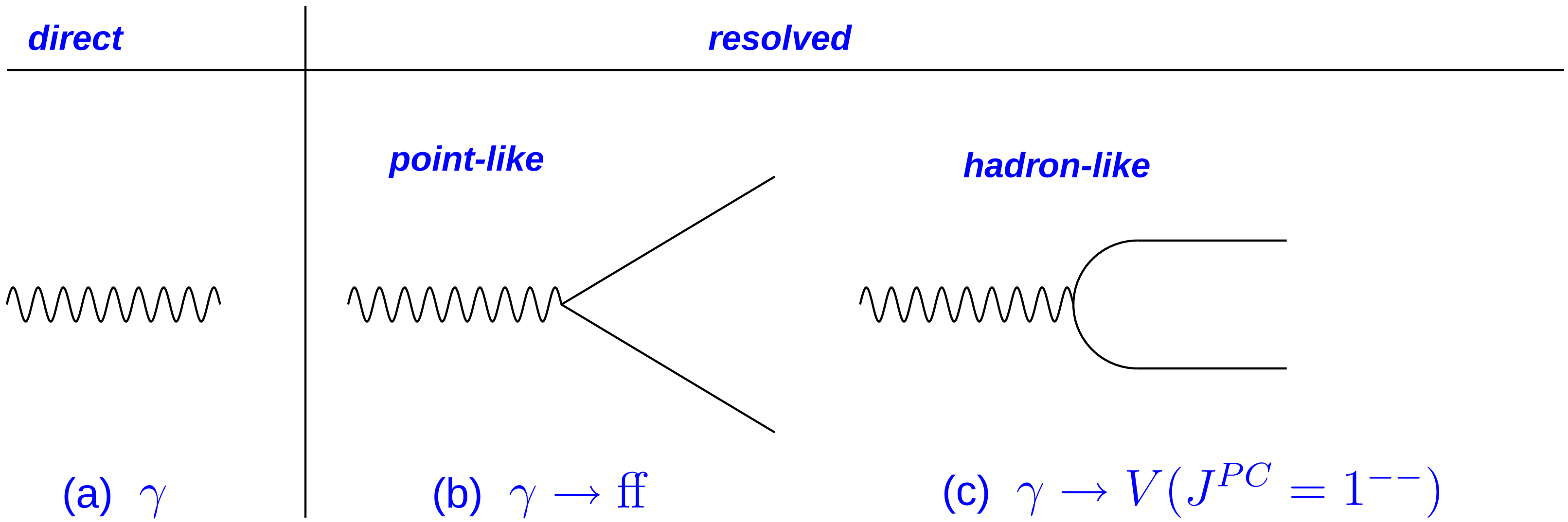
- Introduction

1. Electron-Photon DIS
    1. Quasi-Real Photons
    2. Virtual Photons
3. Results from Other Reactions
    1. Photon-Photon Scattering
    2. Results from HERA

- Conclusions

More Information:
http://home.cern.ch/nisius, and R. Nisius, hepex/9912049

Why do we talk about Photon Structure?



(a) γ

(b) $\gamma \rightarrow \mathrm{f\bar{f}}$

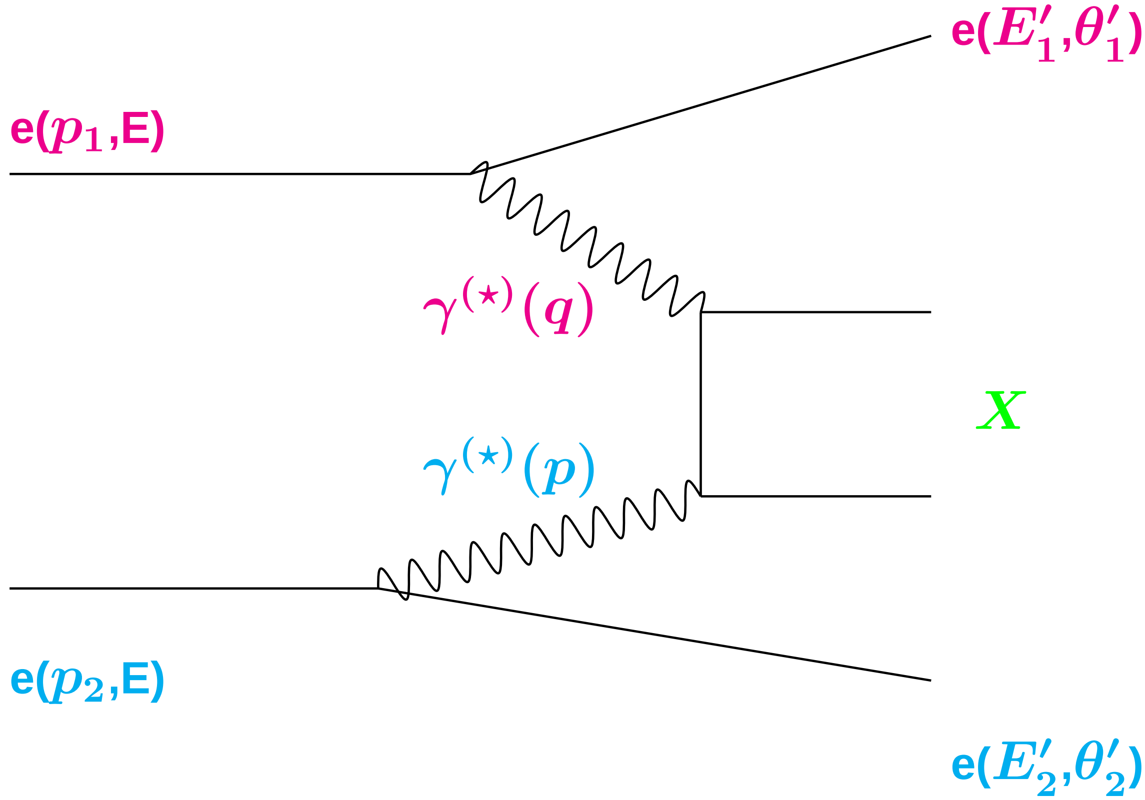
(c) $\gamma \rightarrow V(J^{PC} = 1^{--})$

In (a) the whole photon interacts $\Rightarrow$ NO structure

The fluctuations (b,c) exist due to the uncertainty principle $\Rightarrow$ Photon 'Structure'

The typical lifetime of the fluctuations increases with the photon energy and decreases with the photon virtuality

The reaction e e $\longrightarrow$ e e X



$$\begin{aligned}
d^6\sigma &= \frac{d^3p_1' d^3p_2'}{E_1' E_2'} \frac{\alpha^2}{16\pi^4 Q^2 P^2} \left[\frac{(q\cdot p)^2 - Q^2P^2}{(p_1\cdot p_2)^2 - m_e^2 m_e^2}\right]^{1/2} \\
&\Big(4\rho_1^{++}\rho_2^{++}\sigma_{TT} + 2\rho_1^{++}\rho_2^{00}\sigma_{TL} \\
&+ 2\rho_1^{00}\rho_2^{++}\sigma_{LT} + \rho_1^{00}\rho_2^{00}\sigma_{LL} + \\
&2|\rho_1^{+-}\rho_2^{+-}|\tau_{TT}\cos 2\bar{\phi} - 8|\rho_1^{+0}\rho_2^{+0}|\tau_{TL}\cos\bar{\phi}\Big) \\
Q^2 &= -q^2 = 2\,E\,E_1'\,(1-\cos\theta_1') \\
P^2 &= -p^2 = 2\,E\,E_2'\,(1-\cos\theta_2') \\
x &= \frac{Q^2}{Q^2 + W^2 + P^2}
\end{aligned}$$

The limit of deep inelastic electron-photon scattering

Using:

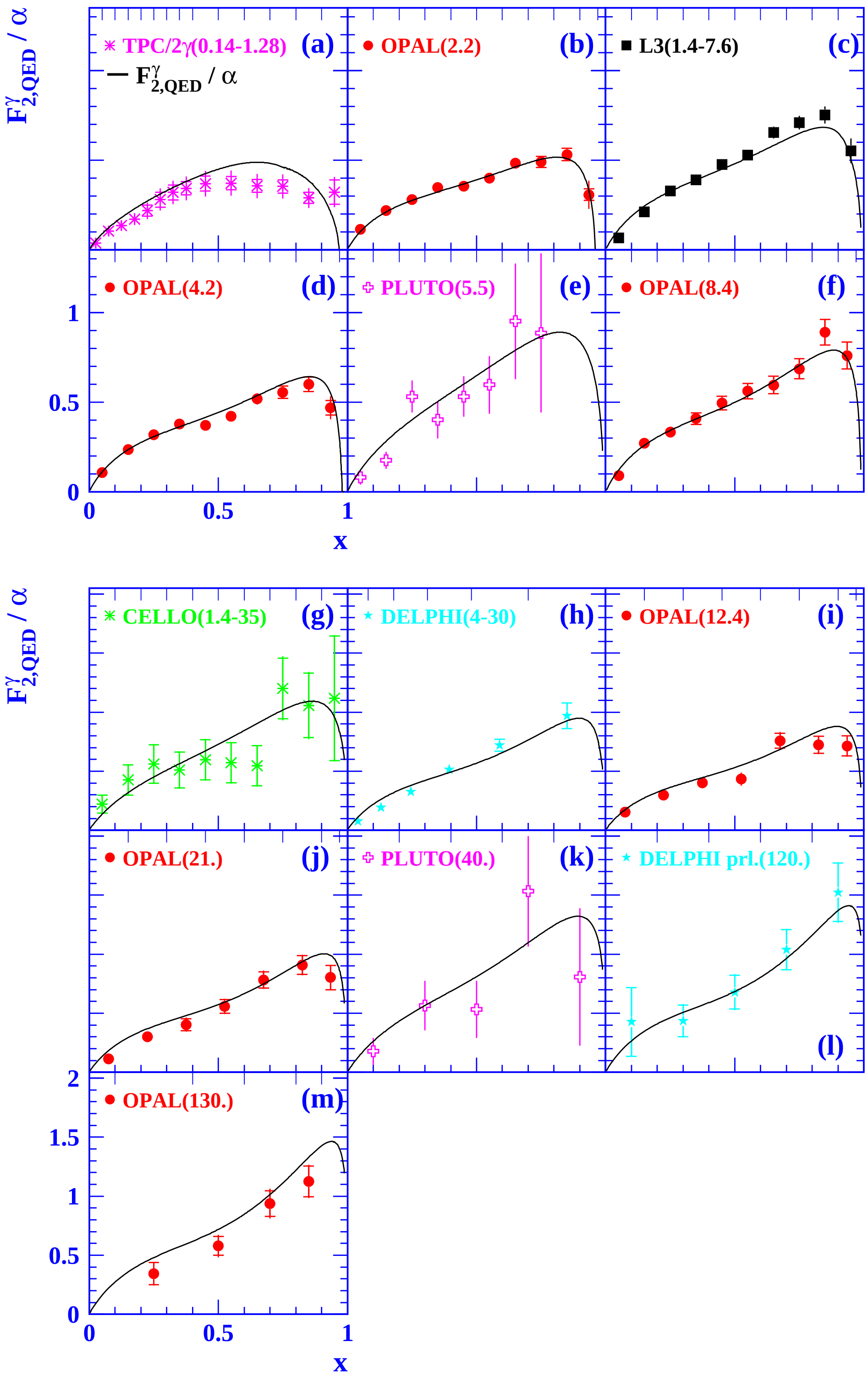
$$\begin{aligned} 2xF_T^\gamma &= \frac{Q^2}{4\pi^2\alpha}\,\sigma_{TT}(x,Q^2) \\ F_L^\gamma &= \frac{Q^2}{4\pi^2\alpha}\,\sigma_{LT}(x,Q^2) \\ F_2^\gamma &= 2xF_T^\gamma + F_L^\gamma \end{aligned}$$

and the limit $(p\cdot q)^2 - Q^2P^2 \approx (p\cdot q)^2$ the cross section reduces to:

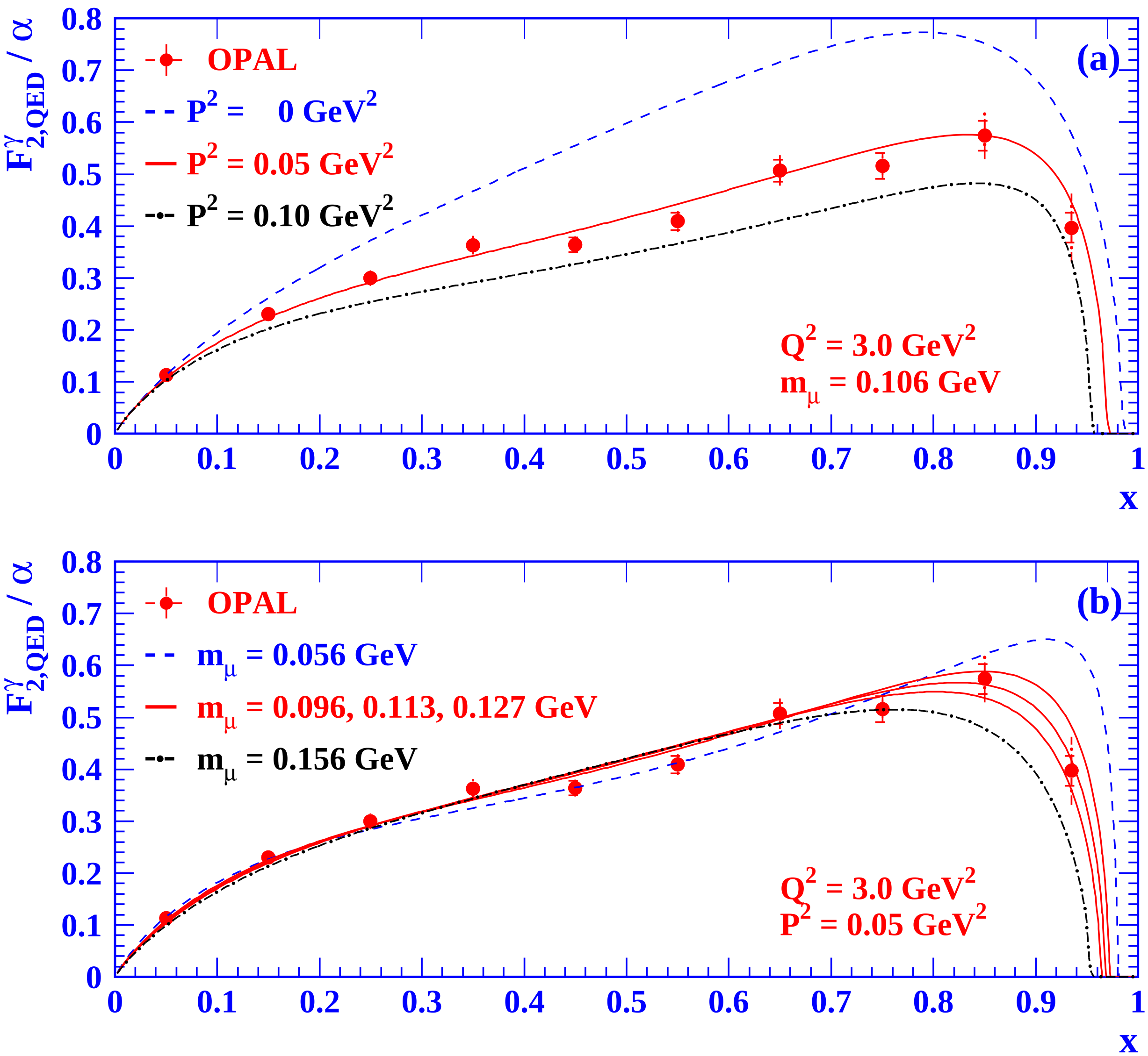
$$\frac{d^4\sigma}{dx\,dQ^2\,dz\,dP^2} = \frac{d^2N_\gamma^T}{dz dP^2}\cdot\frac{2\pi\alpha^2}{x\,Q^4}\cdot\left[1+(1-y)^2\right]\cdot \underbrace{\left[2xF_T^\gamma(x,Q^2) + \frac{2(1-y)}{1+(1-y)^2}F_L^\gamma(x,Q^2)\right]}_{\to F_2^\gamma \text{ for } y\ll 1}$$

with:
$$\frac{d^2N_\gamma^T}{dz dP^2} = \frac{\alpha}{2\pi}\left[\frac{1+(1-z)^2}{z}\frac{1}{P^2} - \frac{2\,m_e^2\,z}{P^4}\right]$$

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

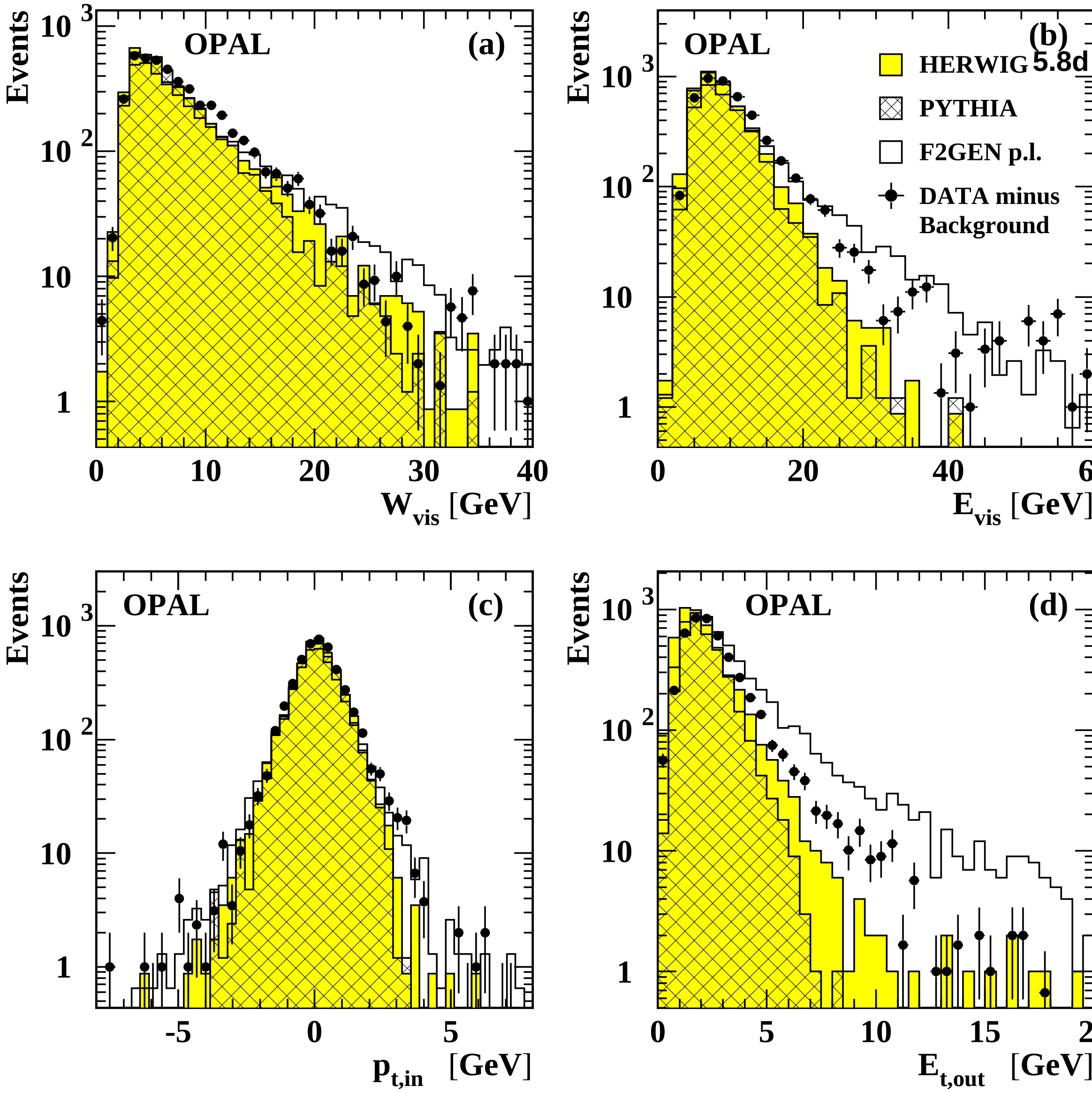


The dependence of $F_{2,\mathrm{QED}}^{\gamma}$ on P^2 and m_μ



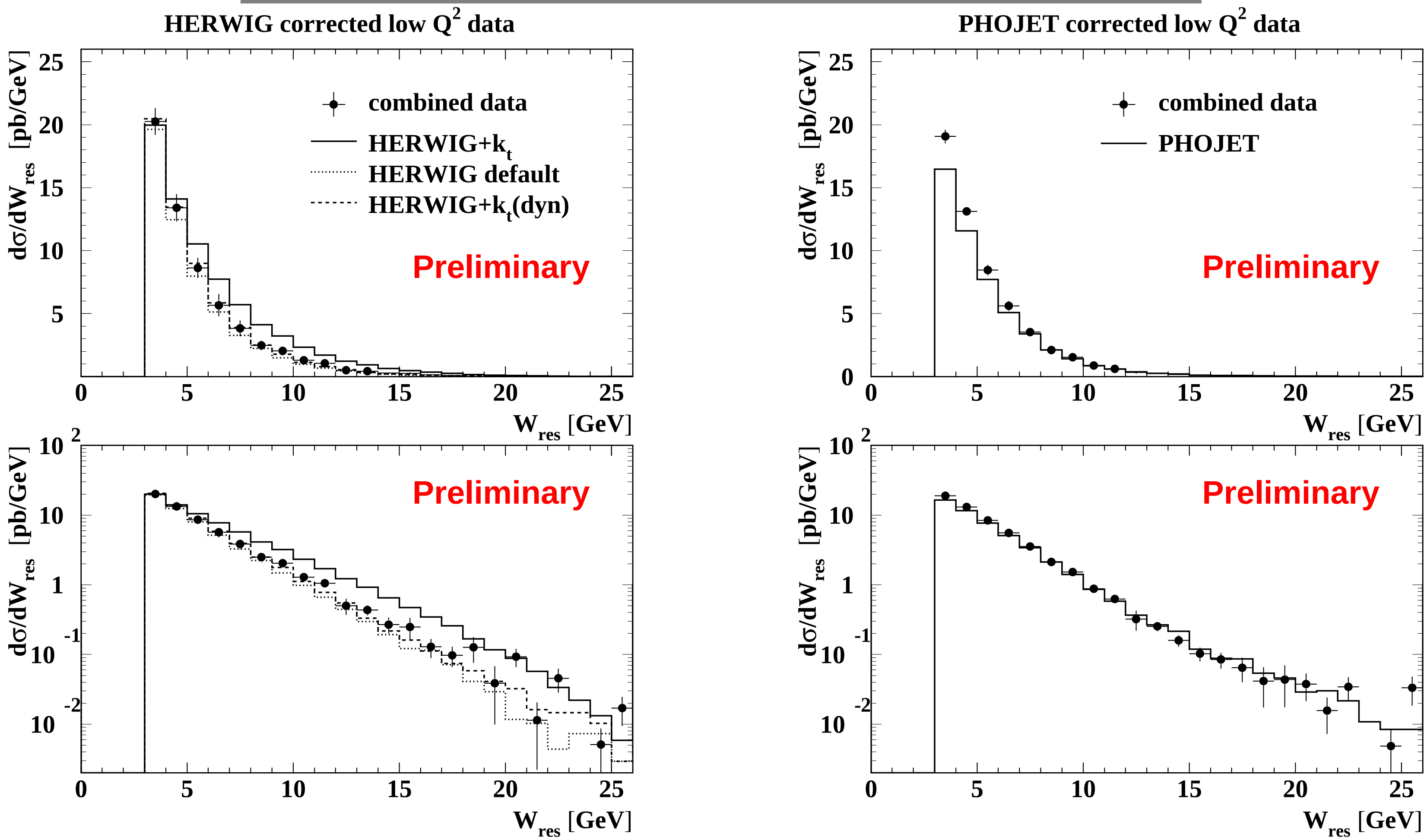
The P^2 dependence is clearly observed in the data.
The muon mass can be determined to about $\pm 15\%$.

The description of the hadronic final state



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

Comparison to LEP combined data

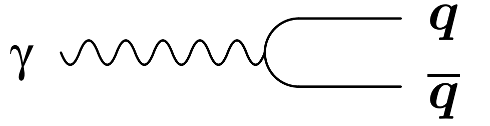


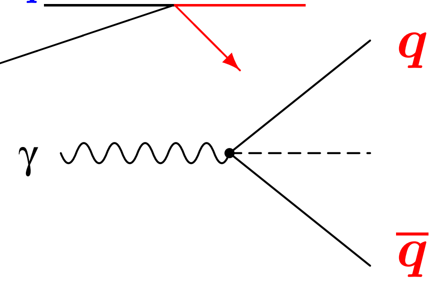
The combined data are a valuable input to constrain the Monte Carlo models

(LEP Two-Photon WG '99)

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

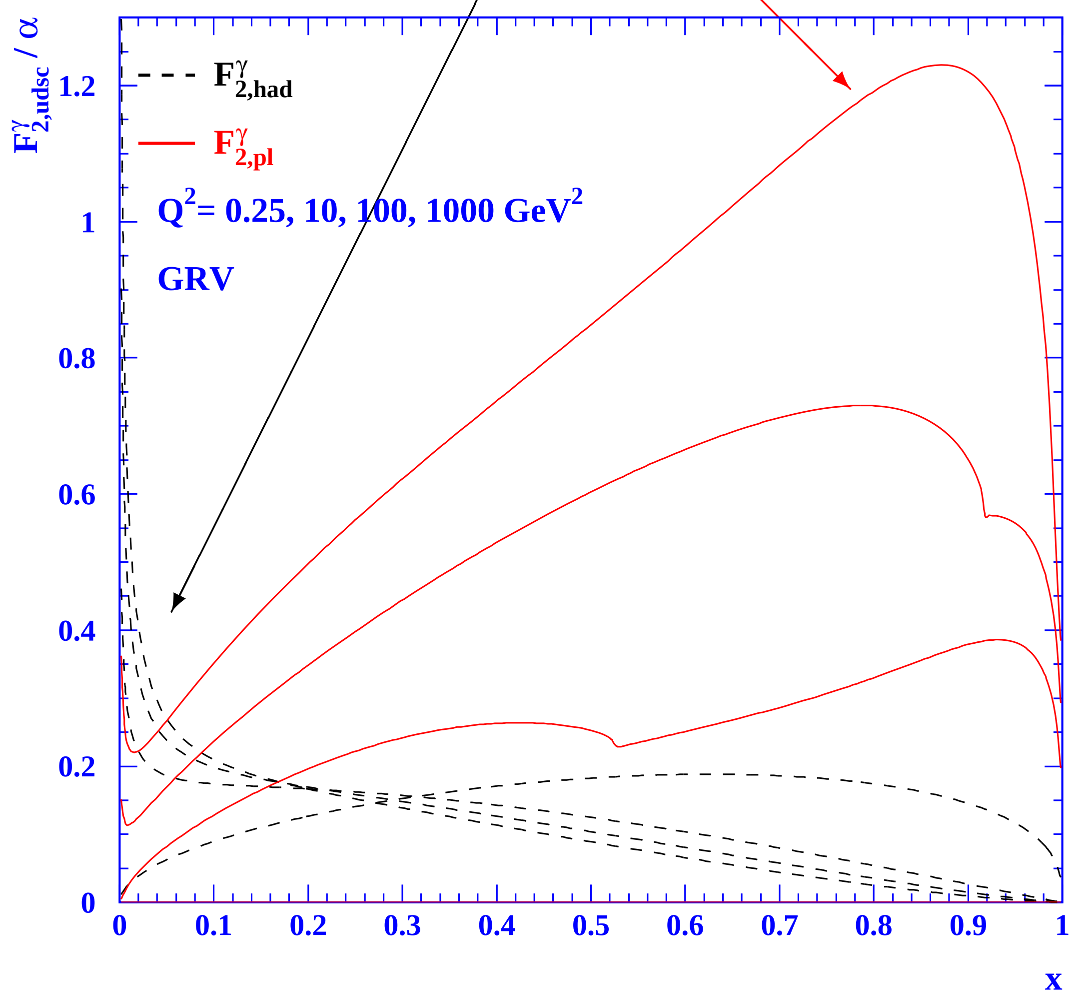
$$F_2^\gamma(x,Q^2) = x\sum_{c,f} e_q^2\, f_{q,\gamma}(x,Q^2)$$



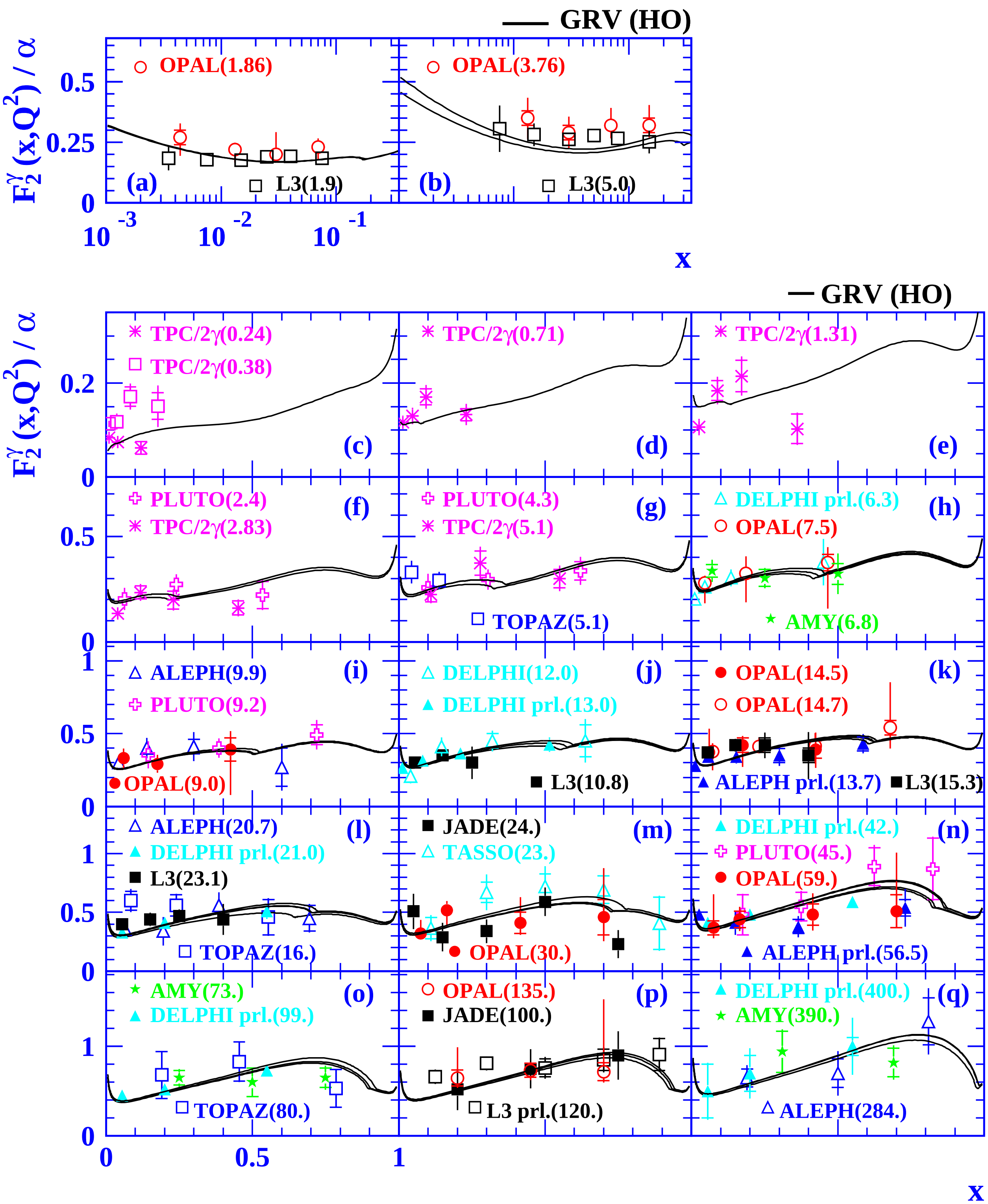


hadron-like, *non–perturbative*
e.g. VMD(ρ,ω,ϕ), **low-**x

point-like, *perturbative*
high-x

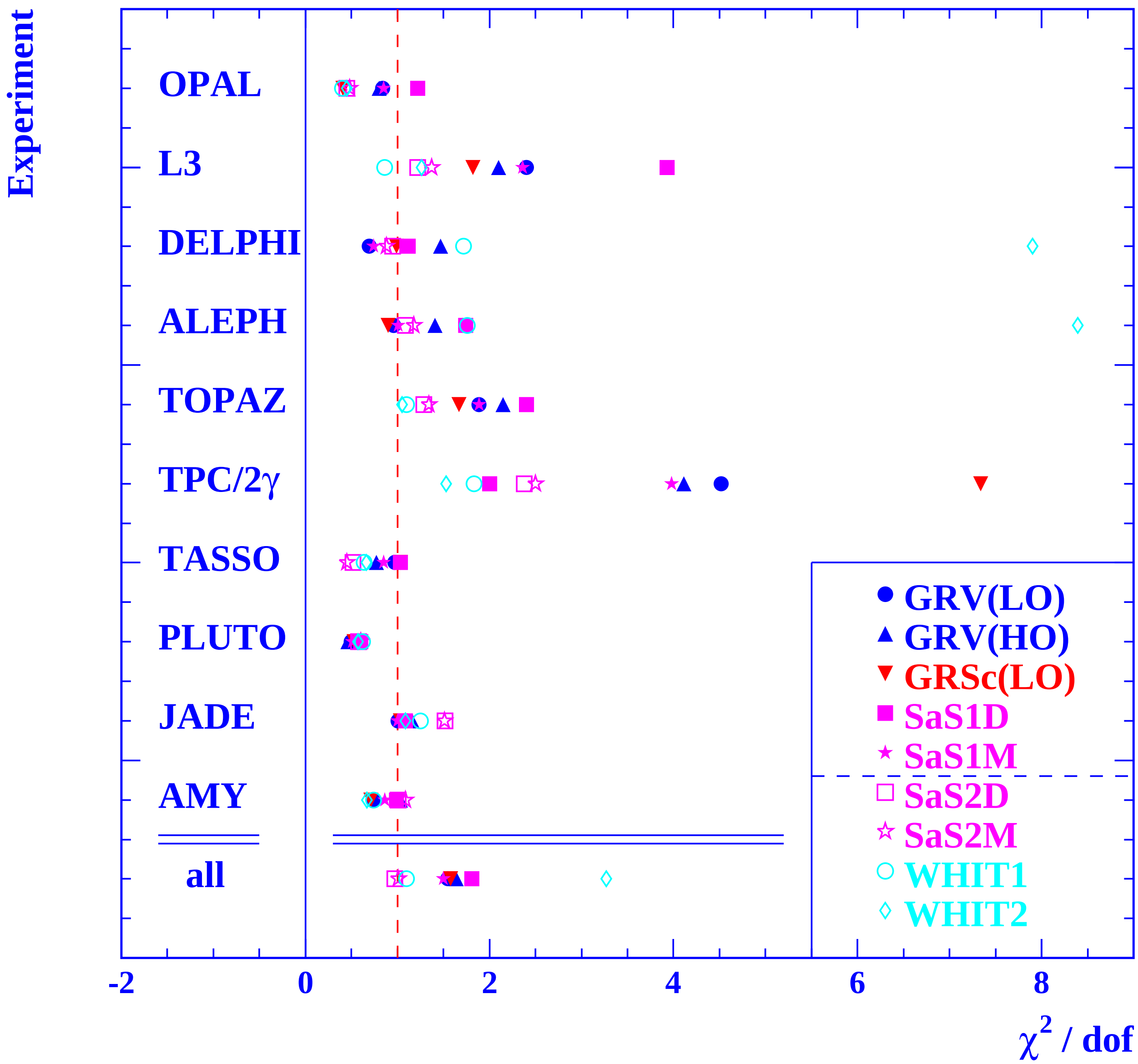


The world data on F_2^γ



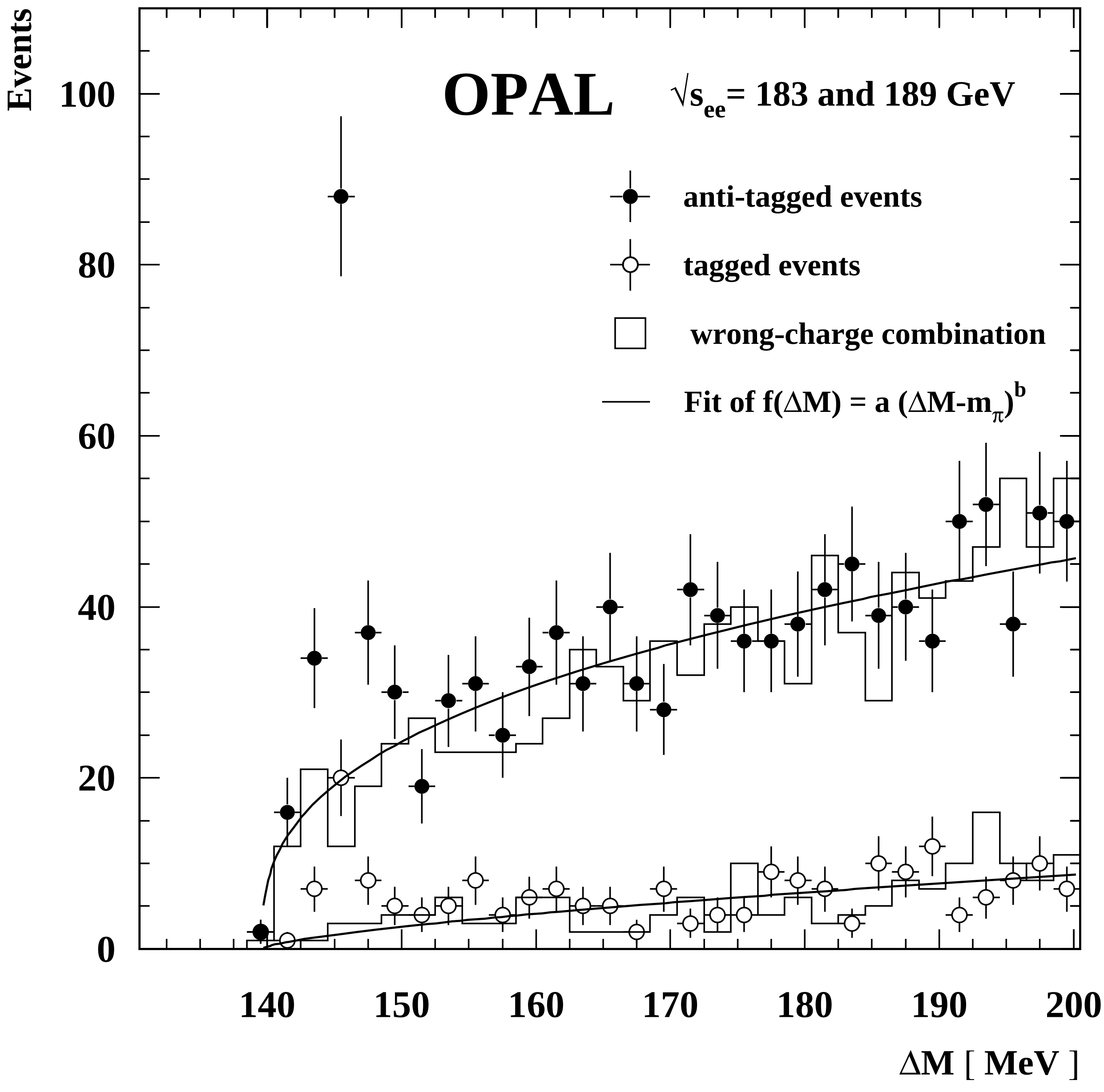
Data description by existing pdf's

$$\chi^2 = \sum_{i=1}^{\mathrm{dof}} \left(\frac{F_{2,i}^{\gamma} - \langle F_2^{\gamma}(x, \langle Q^2 \rangle, 0) \rangle}{\sigma_i} \right)^2$$



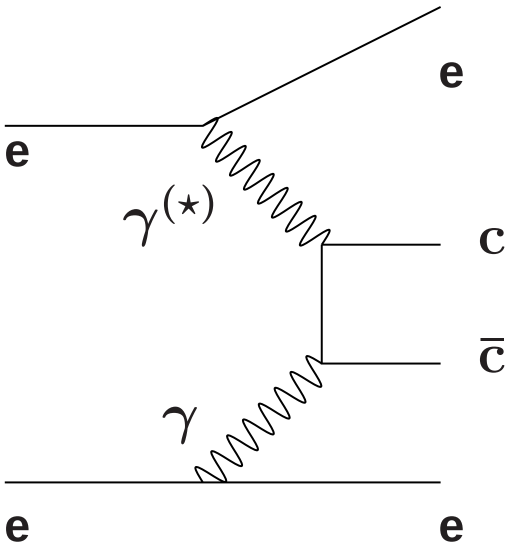
Most of the data can be accounted for by existing pdf's, but...

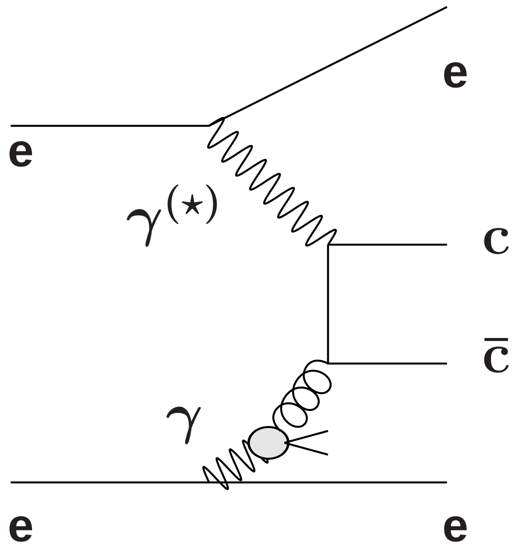
Charm production tagged by $D^{\star}$s



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

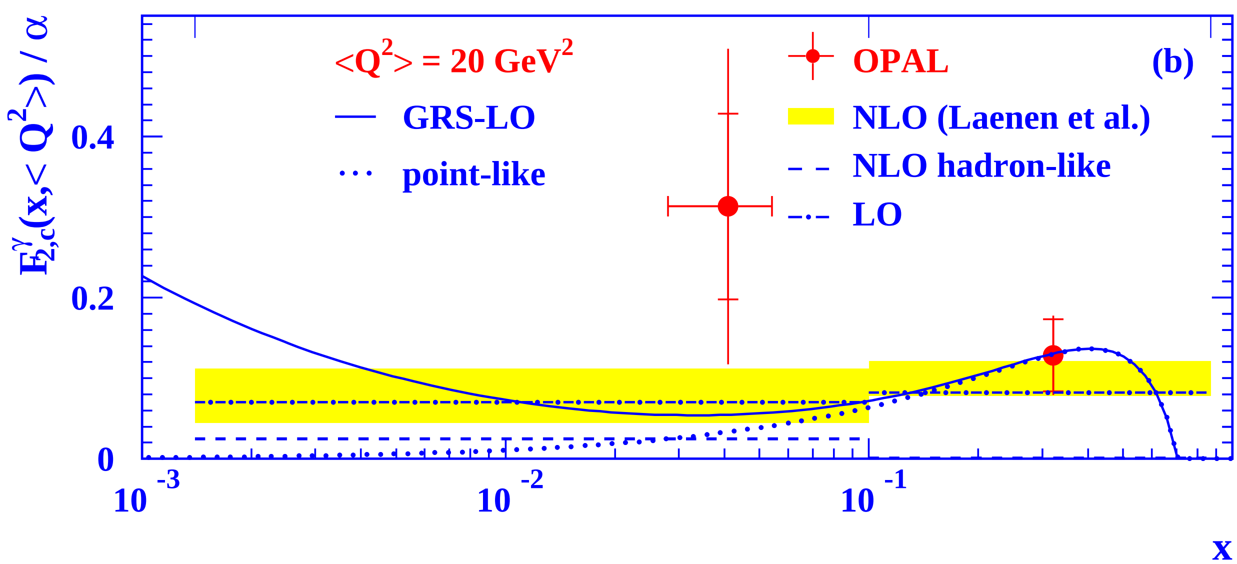
The first measurement of $F_{2,c}^{\gamma}$



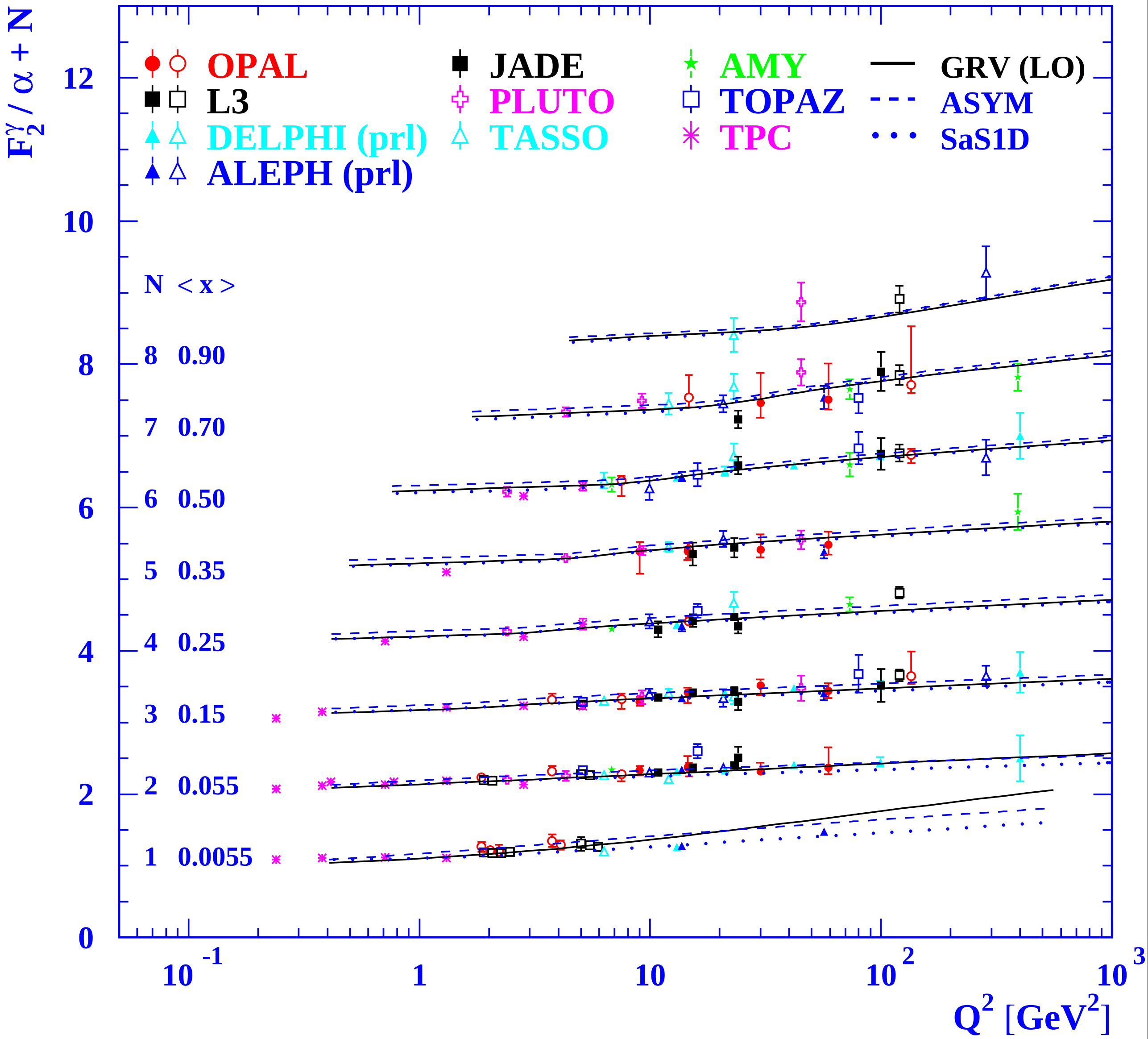


point-like, purely perturbative QCD prediction, dominates at **high-x**

hadron-like, depends on f_g^{γ}, dominates at **low-x**

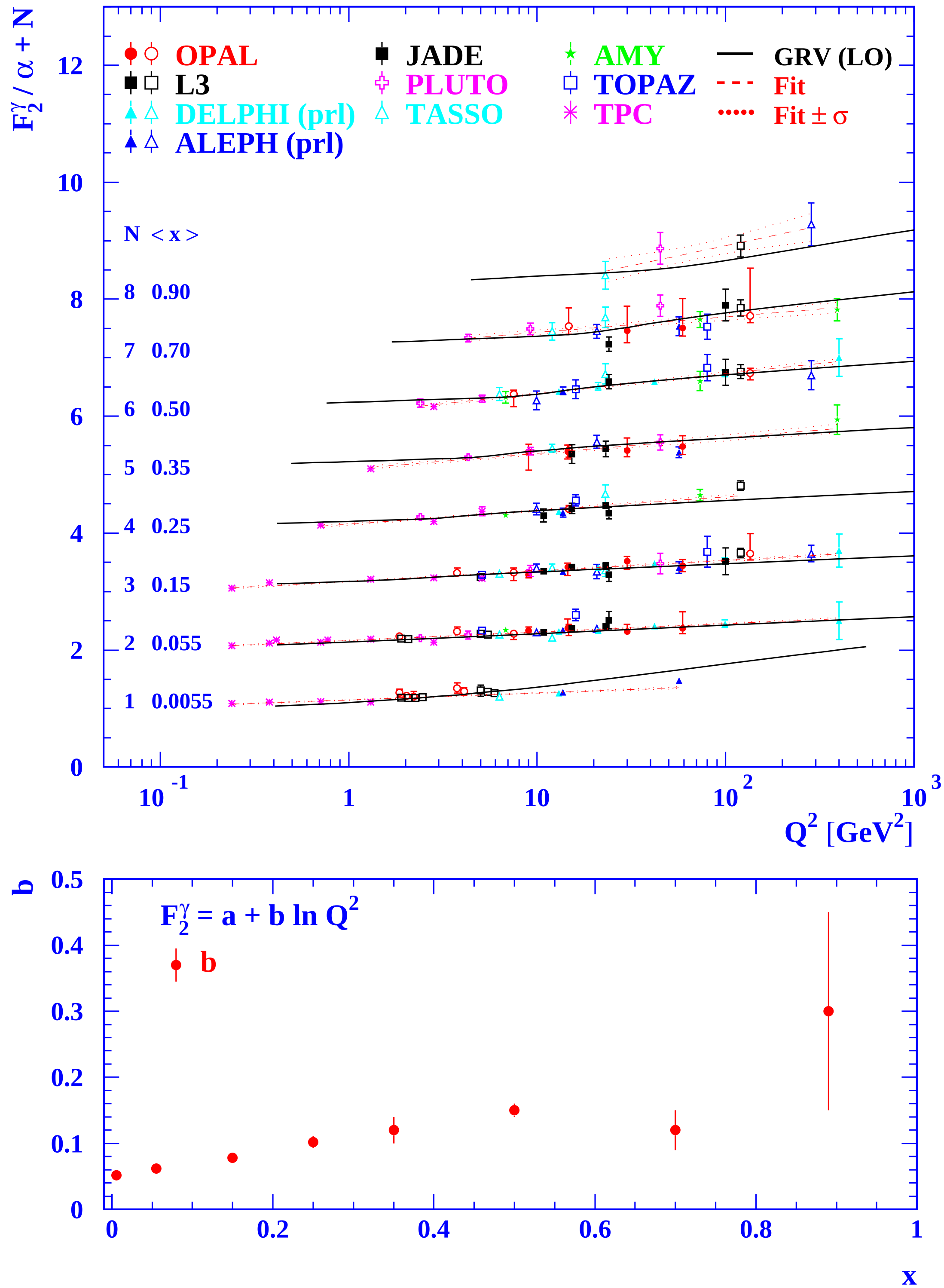


The Q^2 evolution of F_2^γ for $\mathrm{n_f} = 4$



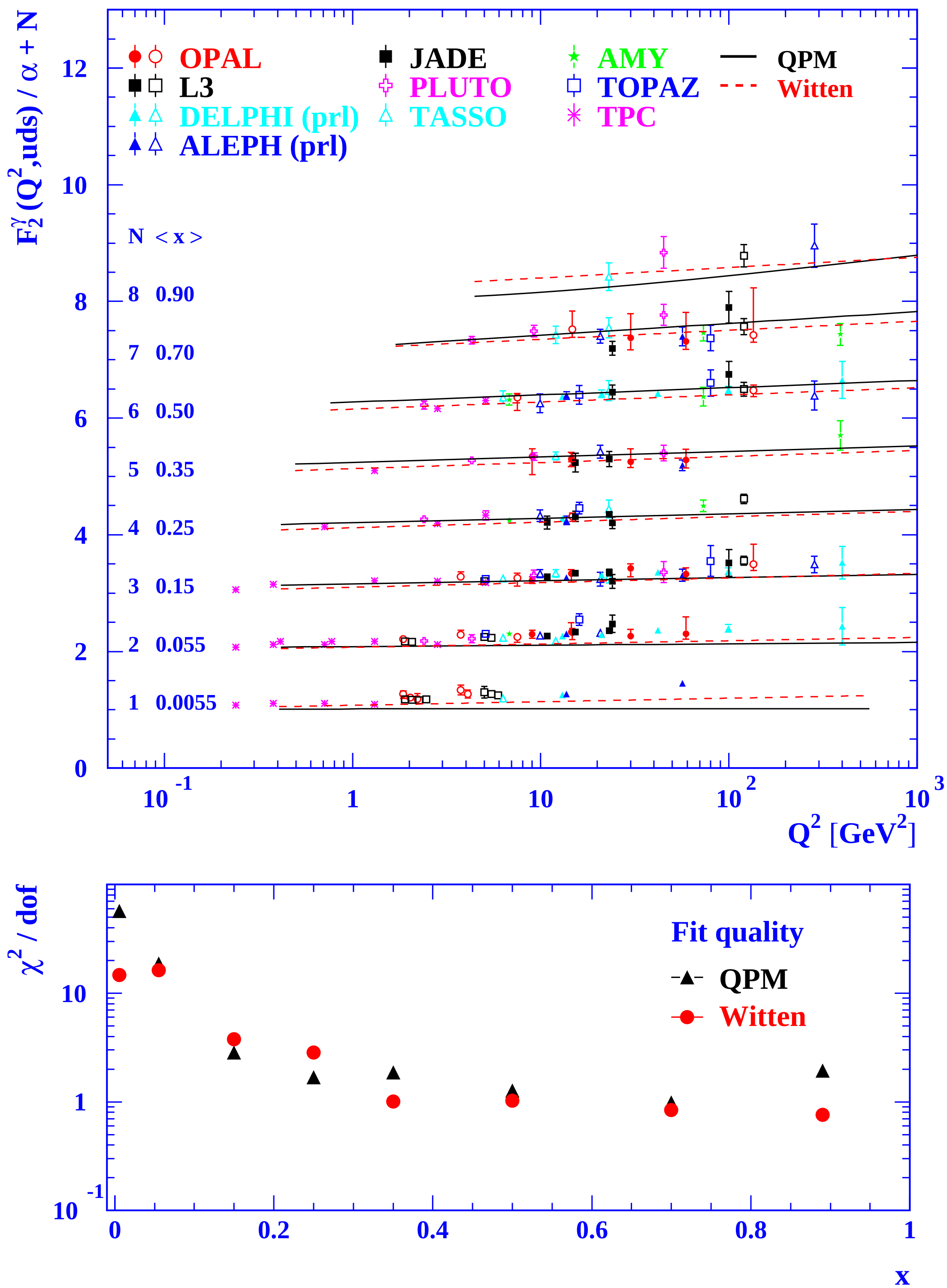
The general trend of the data is followed by the parametrisations.

Q^2 evolution compared to linear fits

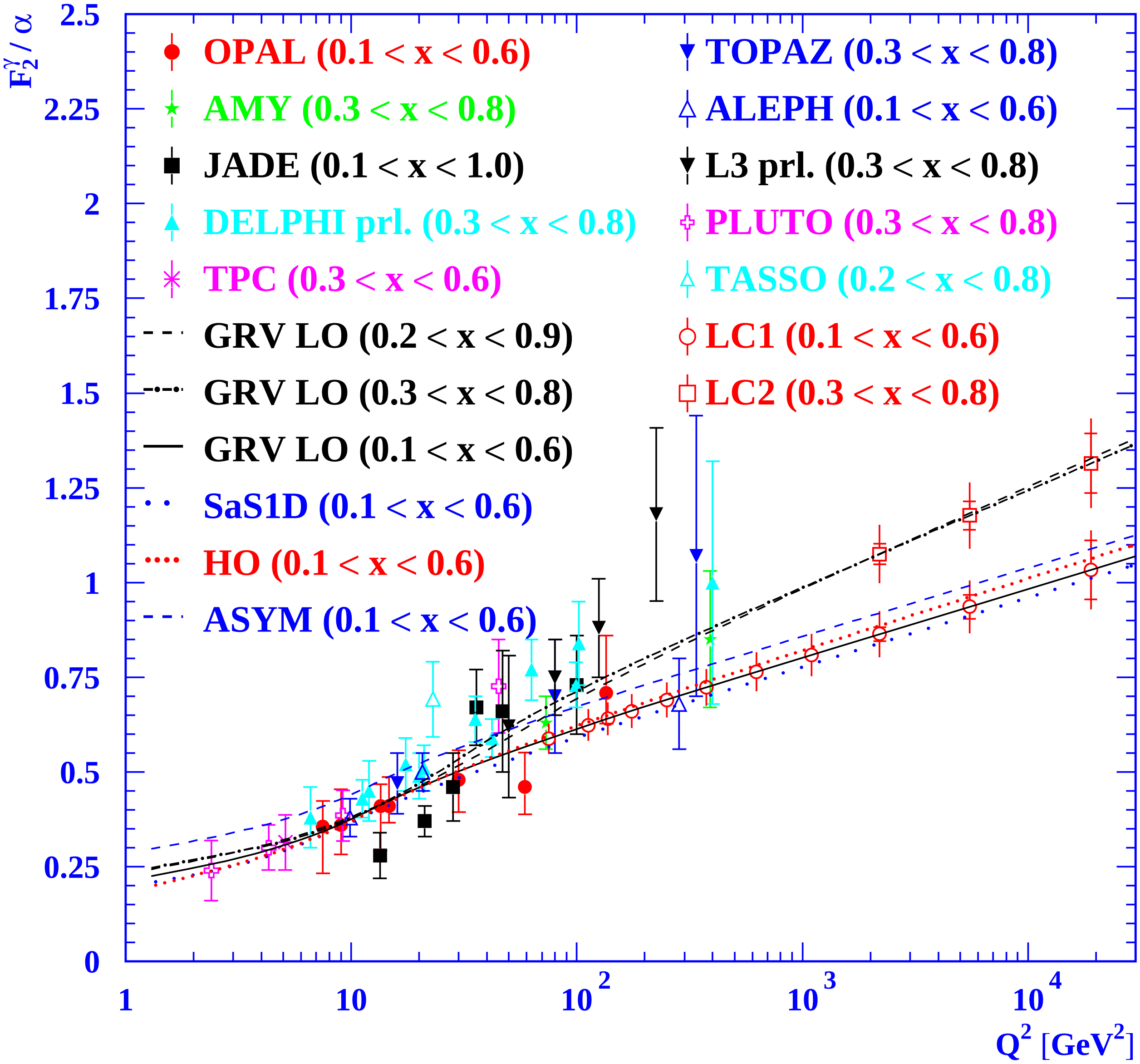


An increasing slope as a function of x is observed.

Q^2 evolution after charm subtraction

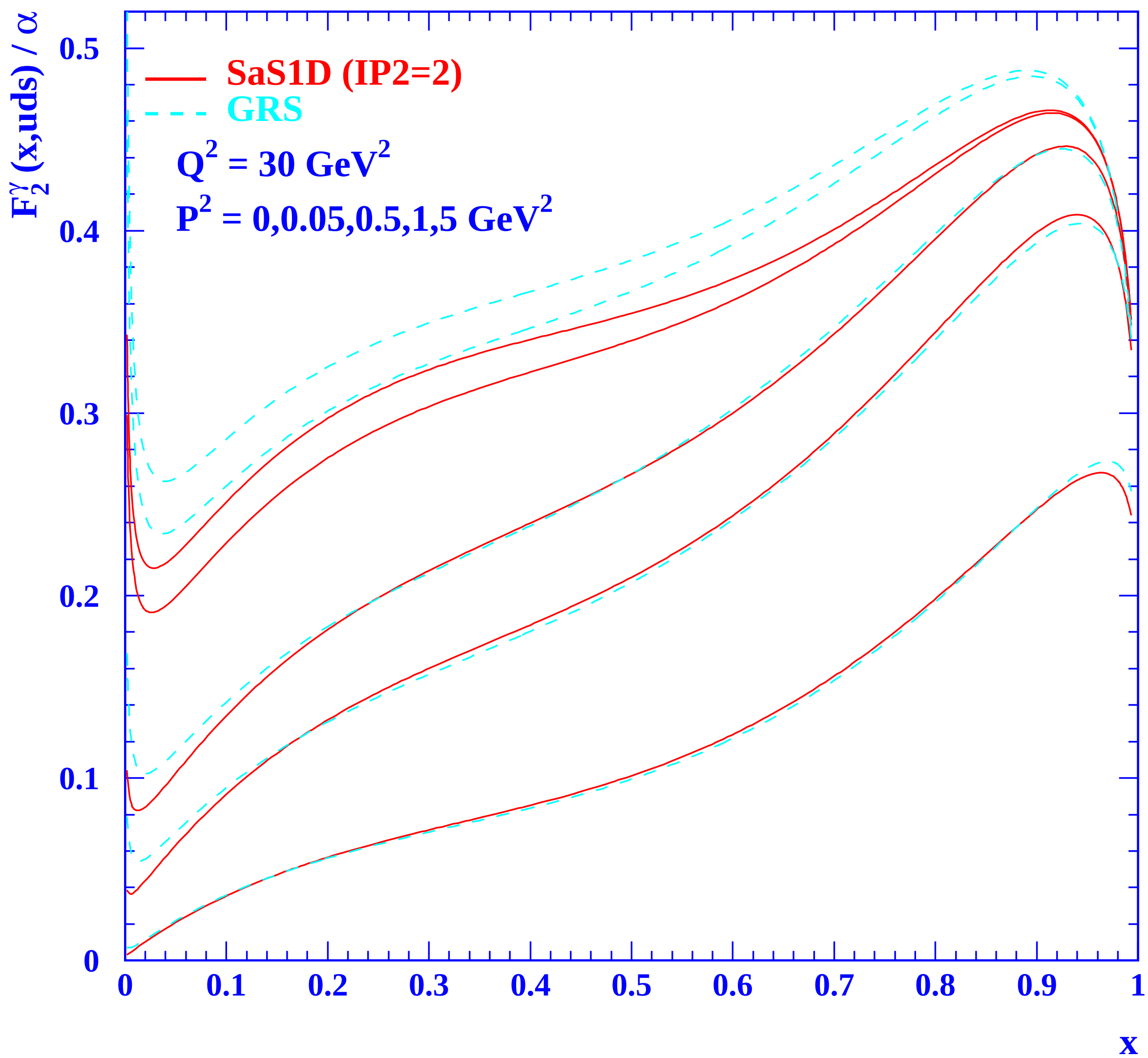


The future of the F_2^{γ} measurements



The Linear Collider (LC) will play an important role in testing this fundamental prediction of perturbative QCD.

F_2^γ for virtual photons

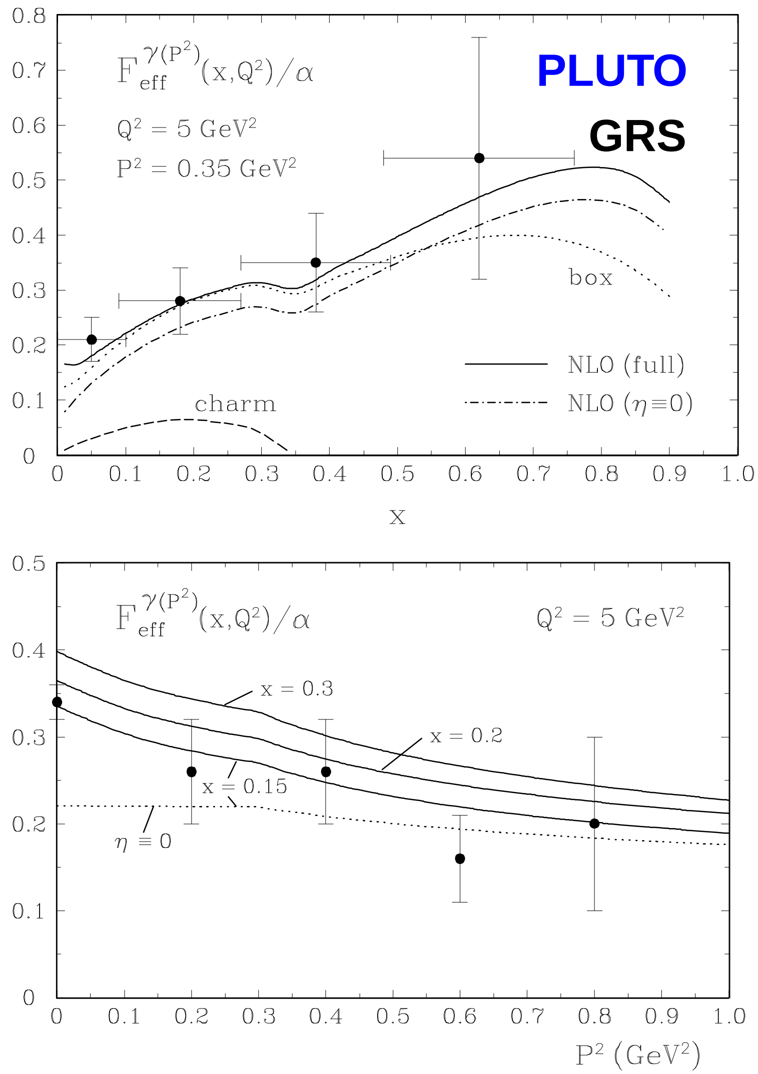


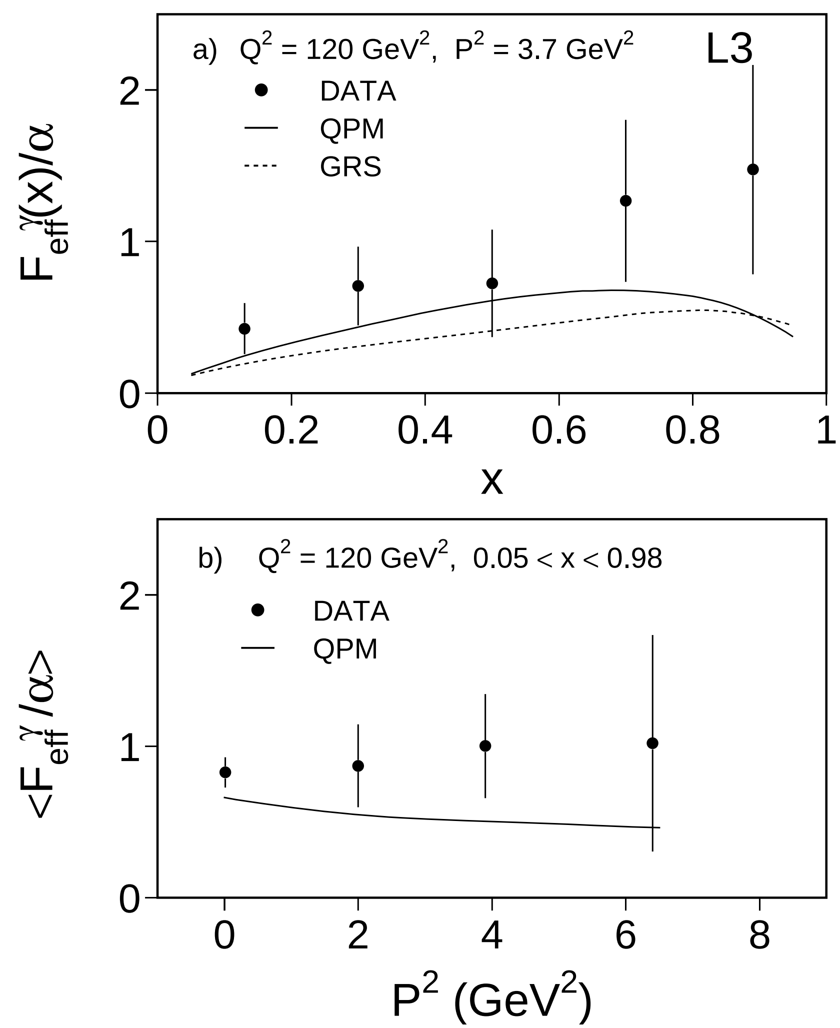
The absolute predictions agree for $P^2 > 0.5\ \mathrm{GeV}^2$, when using SaS1D ($IP2 = 2$)

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

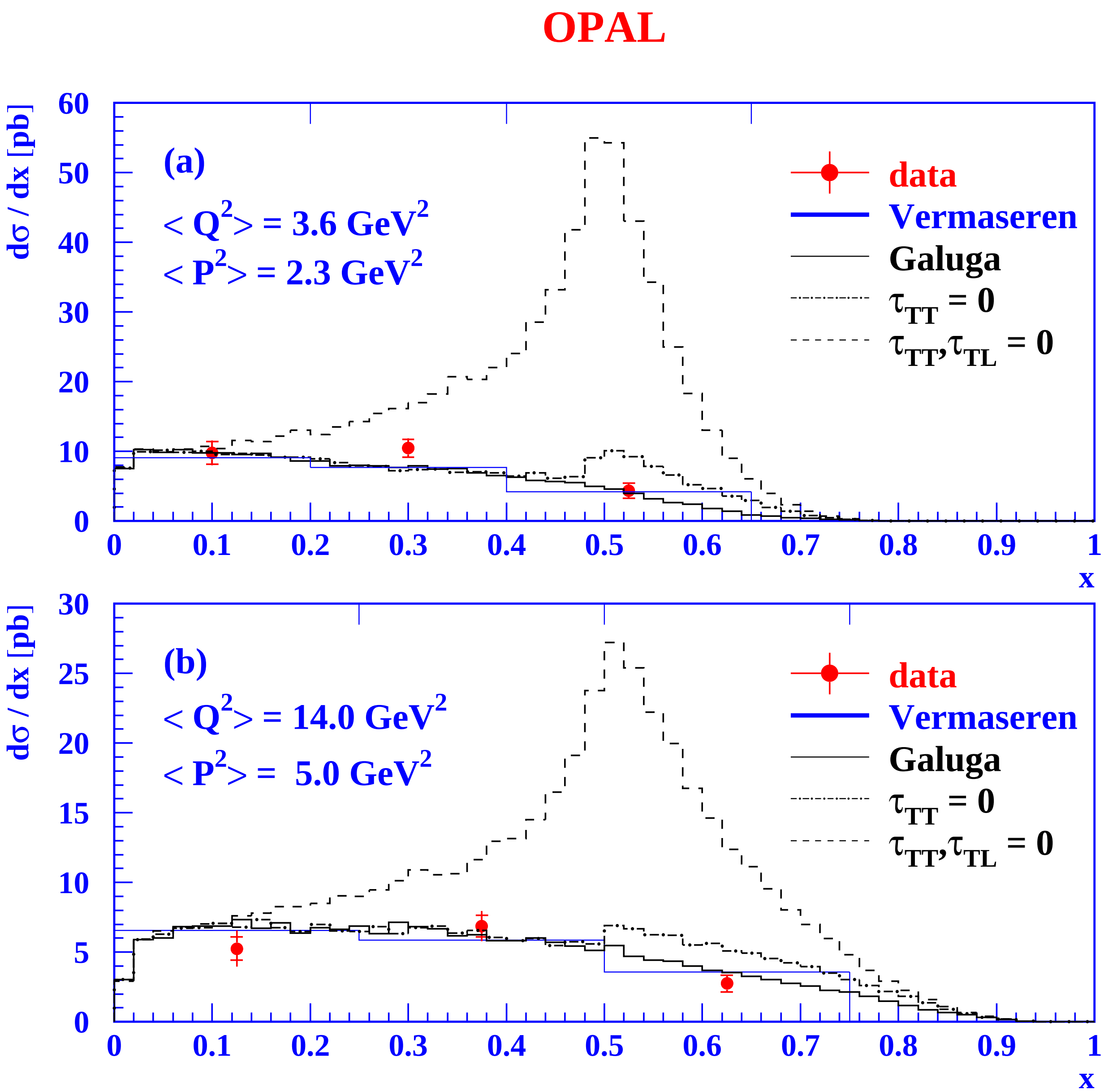
$$\mathrm{d}^6\sigma = \frac{\mathrm{d}^3\mathrm{p}_1'\mathrm{d}^3\mathrm{p}_2'}{E_1' E_2'} \frac{\alpha^2}{16\pi^4 q^2 p^2} \left[\frac{(q\cdot p)^2 - q^2p^2}{(p_1\cdot p_2)^2 - m_e^2 m_e^2}\right]^{1/2} 4\rho_1^{++}\rho_2^{++} \cdot \left(\sigma_{TT} + \sigma_{TL} + \sigma_{LT} + \sigma_{LL} + \frac{1}{2}\tau_{TT}\cos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

The Measurements of $F_{\mathrm{eff}}^{\gamma}$



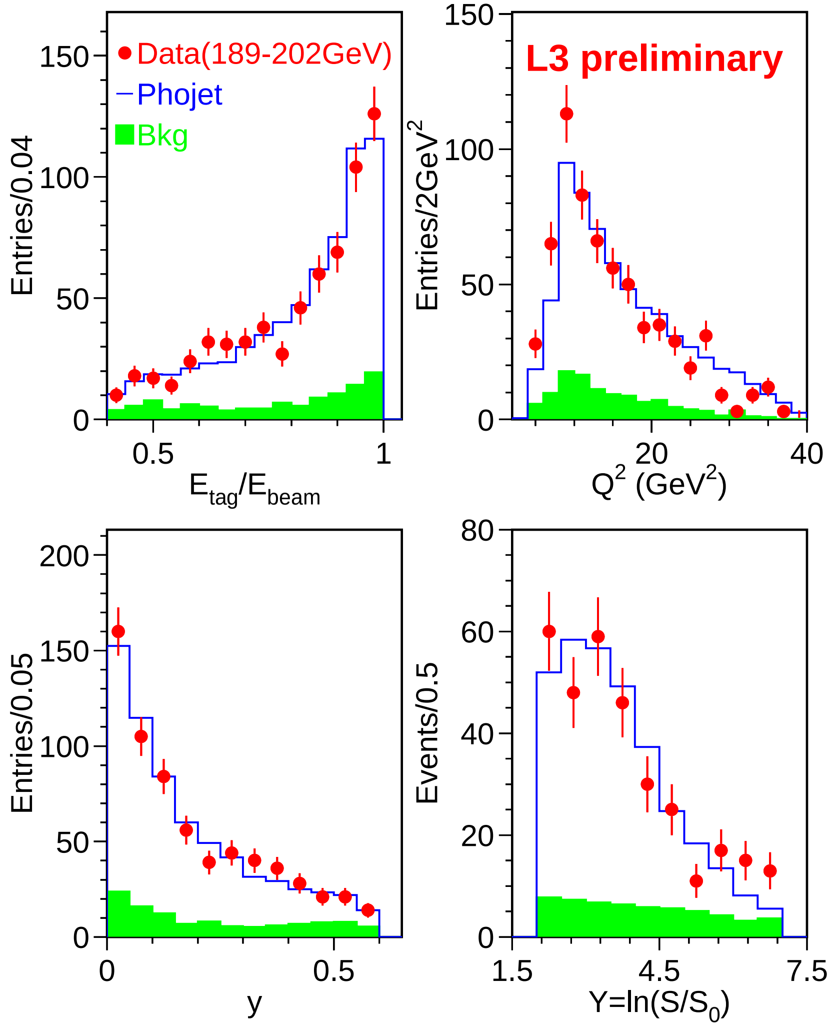


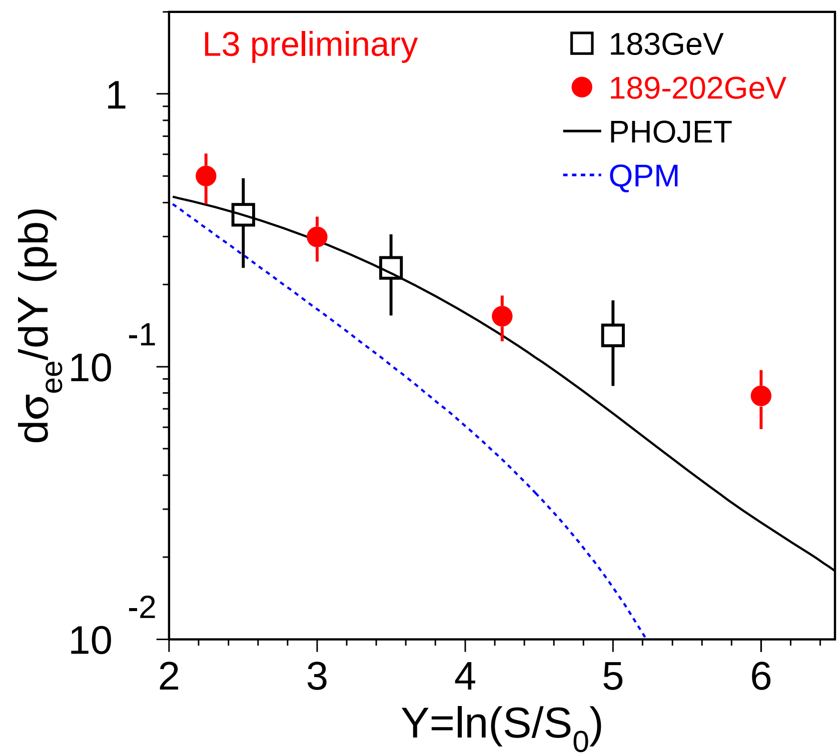
The cross-section for double tags for $ee \longrightarrow ee\gamma^\star\gamma^\star \longrightarrow ee\mu^+\mu^-$



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

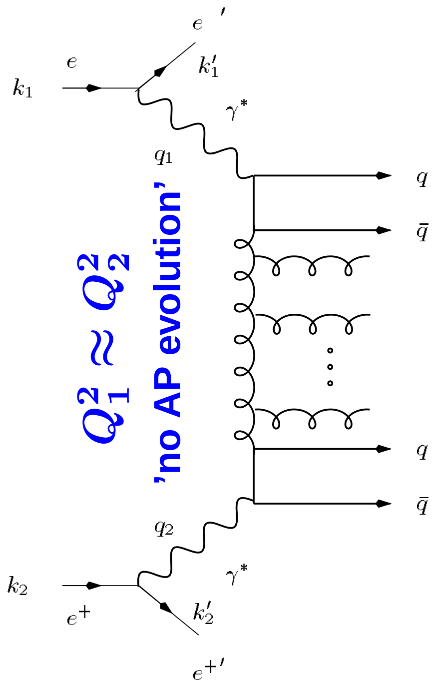
Double tag hadronic cross-section





$$\approx \ln\left(\frac{W^2}{\sqrt{Q_1^2 Q_2^2}}\right)$$

BFKL interpretation of $\sigma_{\gamma^\star\gamma^\star}$

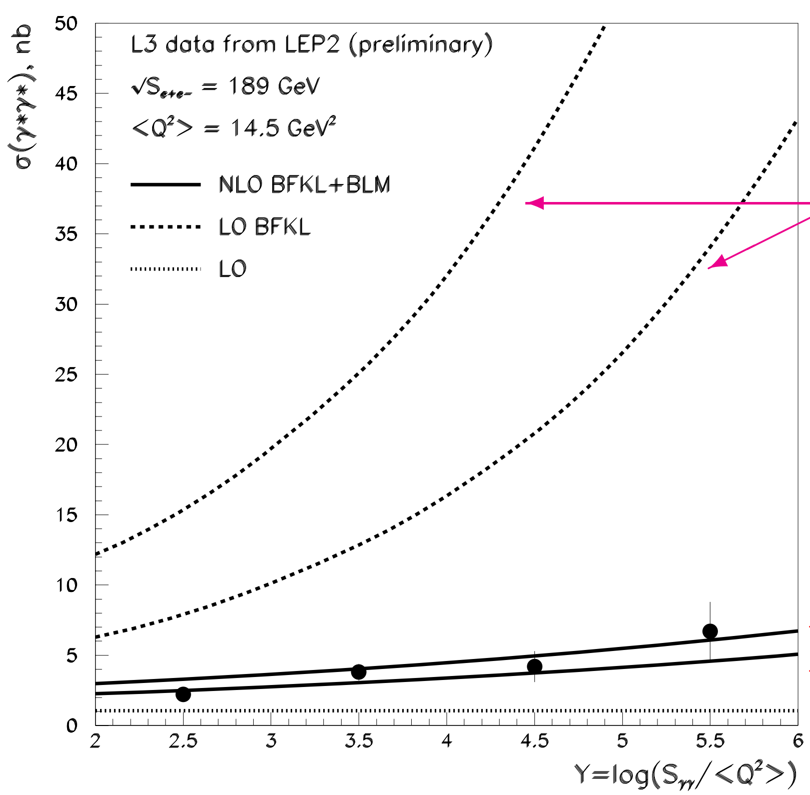


$$y_1 = \frac{q_1 k_2}{k_1 k_2}\,, \quad Q_1^2 = -q_1^2$$

$$s = (k_1 + k_2)^2, s_0 = \frac{\sqrt{Q_1^2 Q_2^2}}{y_1 y_2}$$

$$\hat{s} = W^2 \approx s\, y_1 y_2$$

BFKL needs $\frac{W^2}{Q_{1,2}^2} \gg 1$

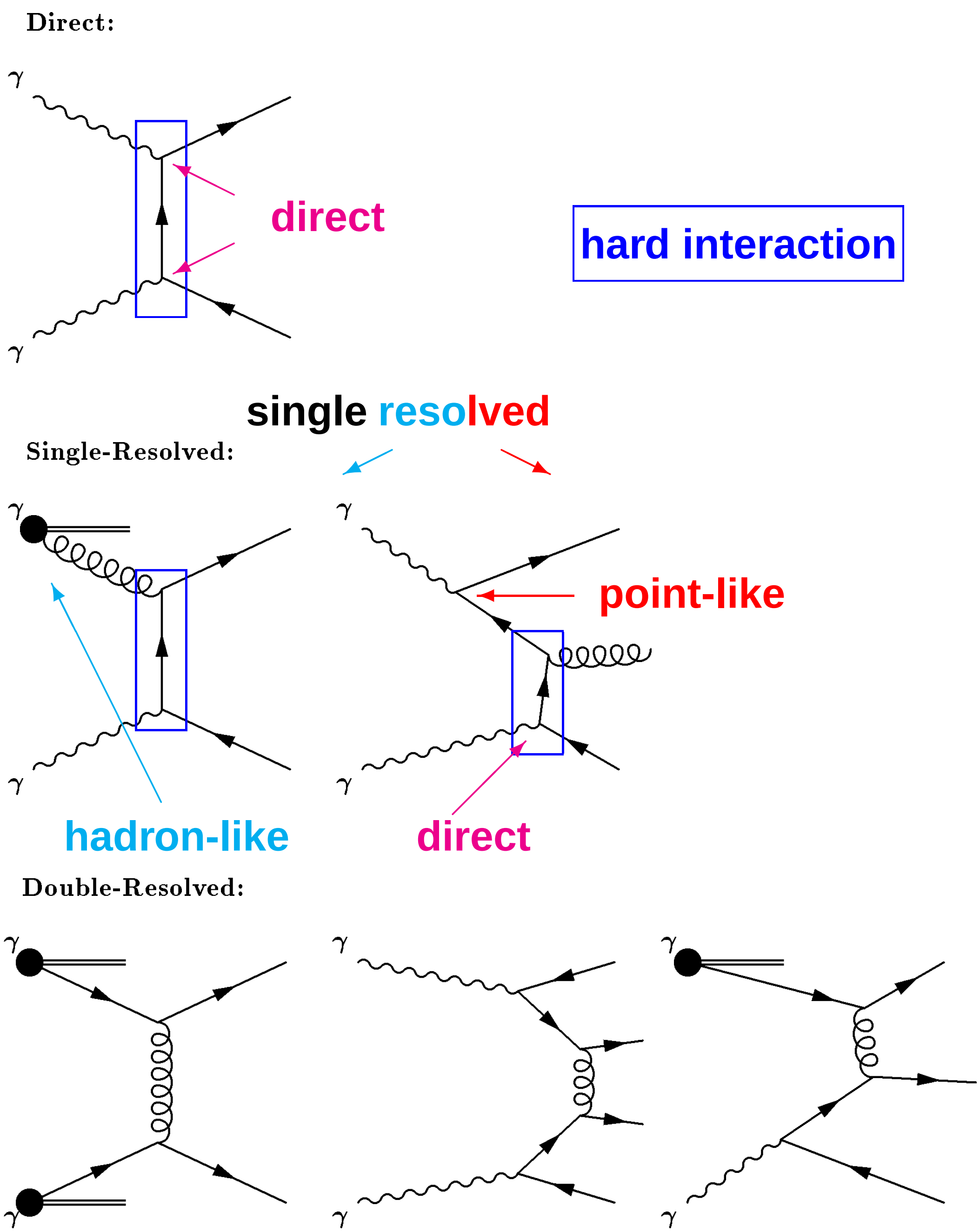


$$7 \lesssim \frac{W^2}{\langle Q_{1,2}^2 \rangle} \lesssim 333$$

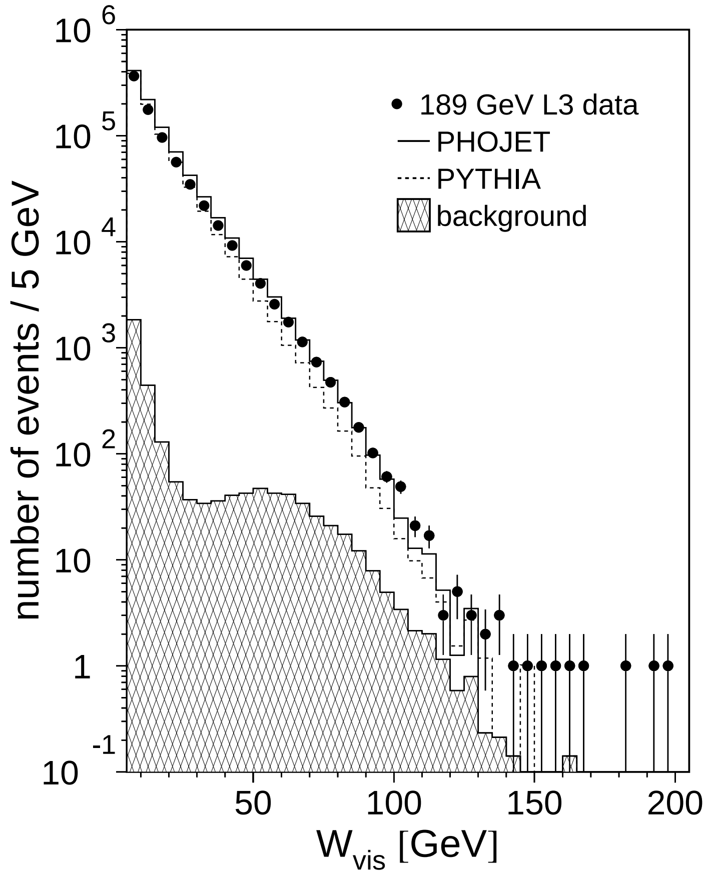
LO BFKL

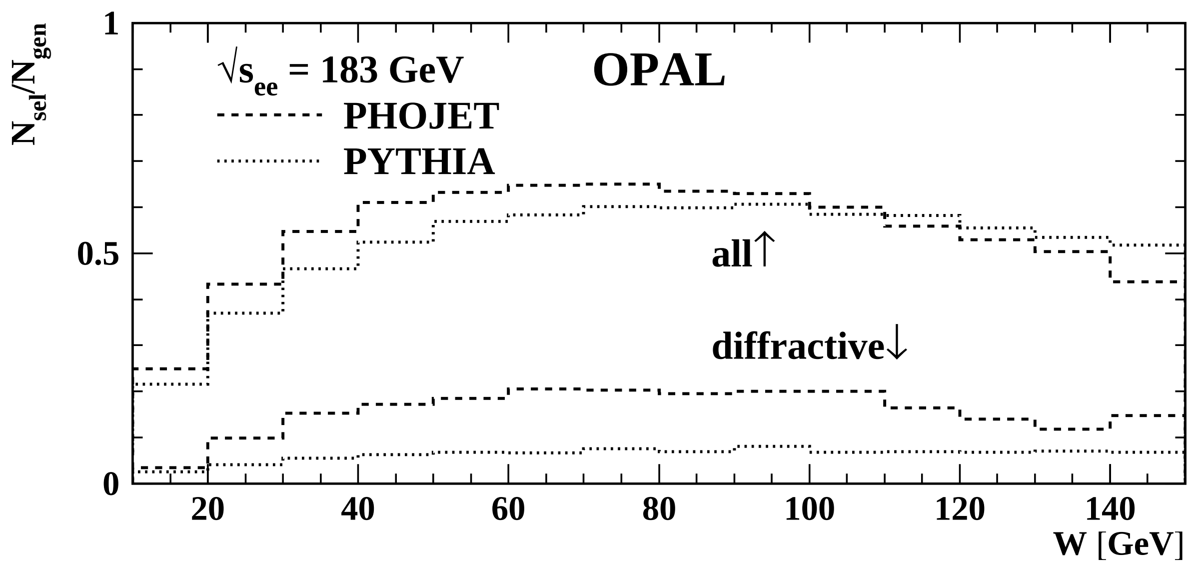
} NLO BFKL

Leading order diagrams



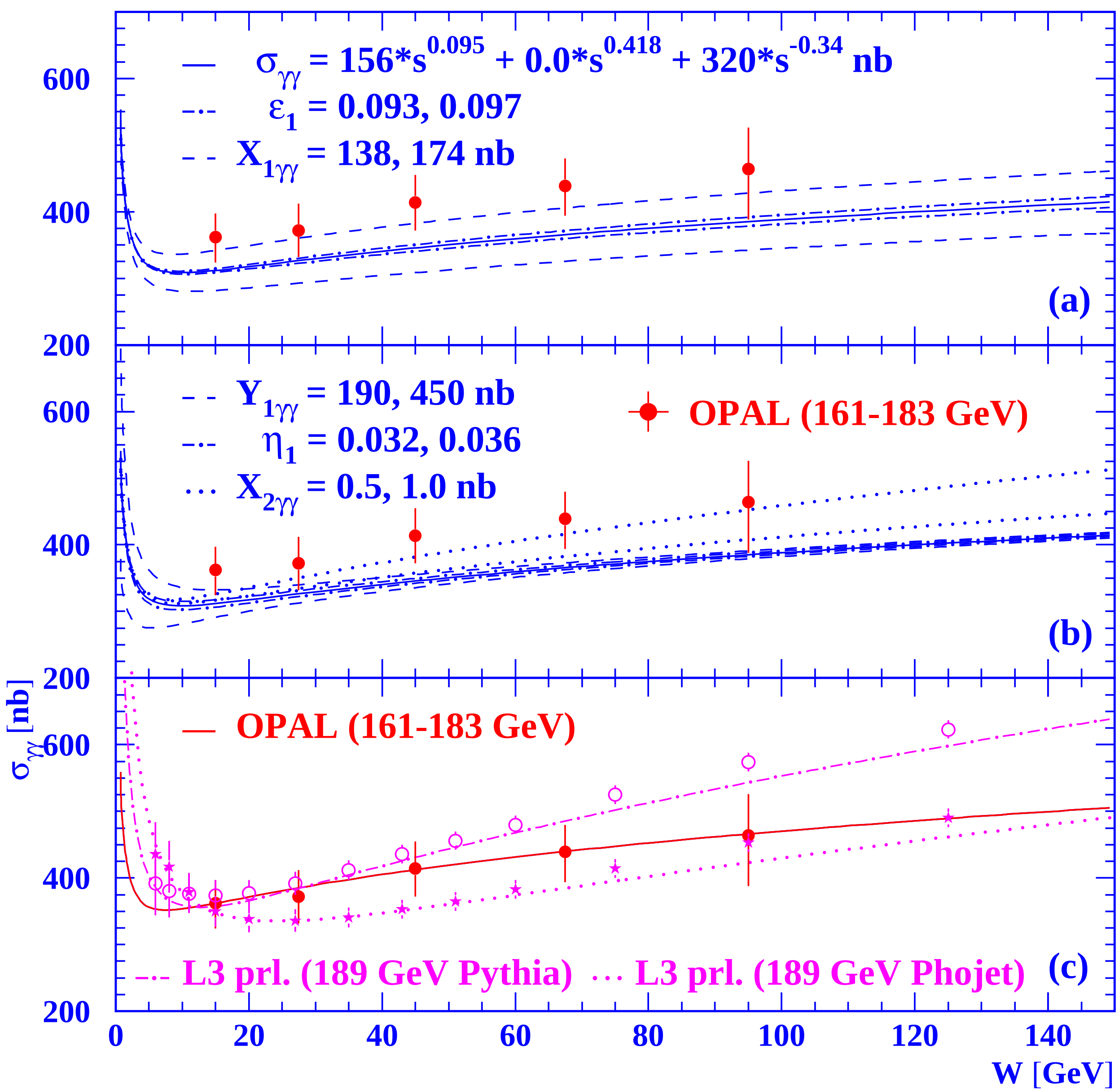
W distributions for anti-tagged events





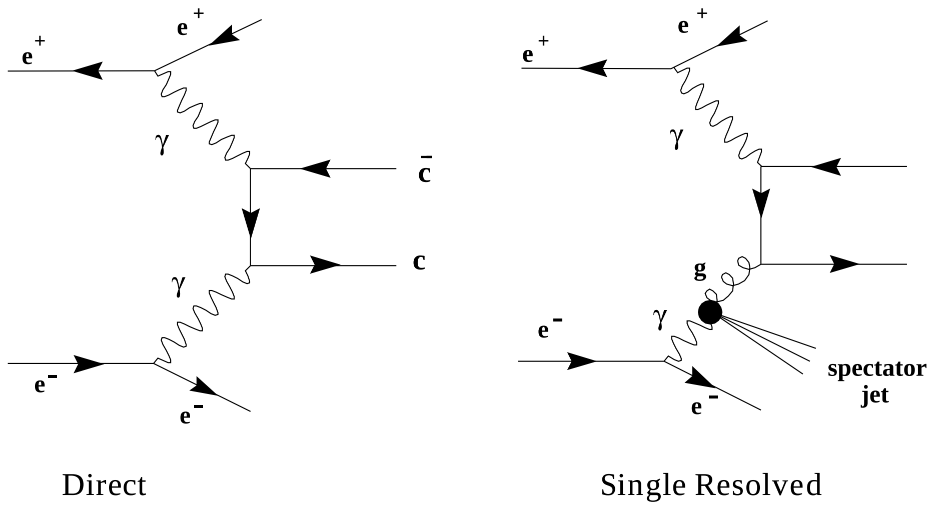
The acceptance for diffractive and elastic events is very different for the PHOJET and PYTHIA models

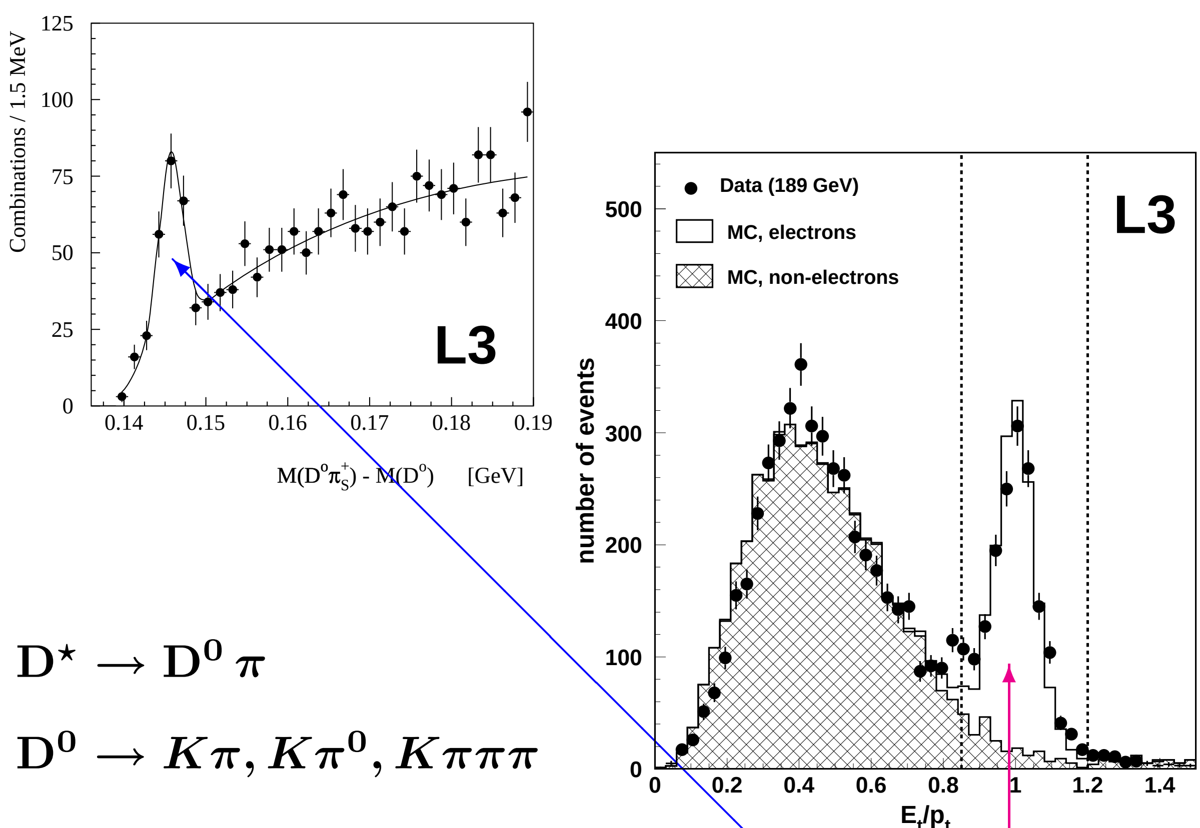
The total hadronic cross-section $\sigma_{\gamma\gamma}$



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

Inclusive charm production



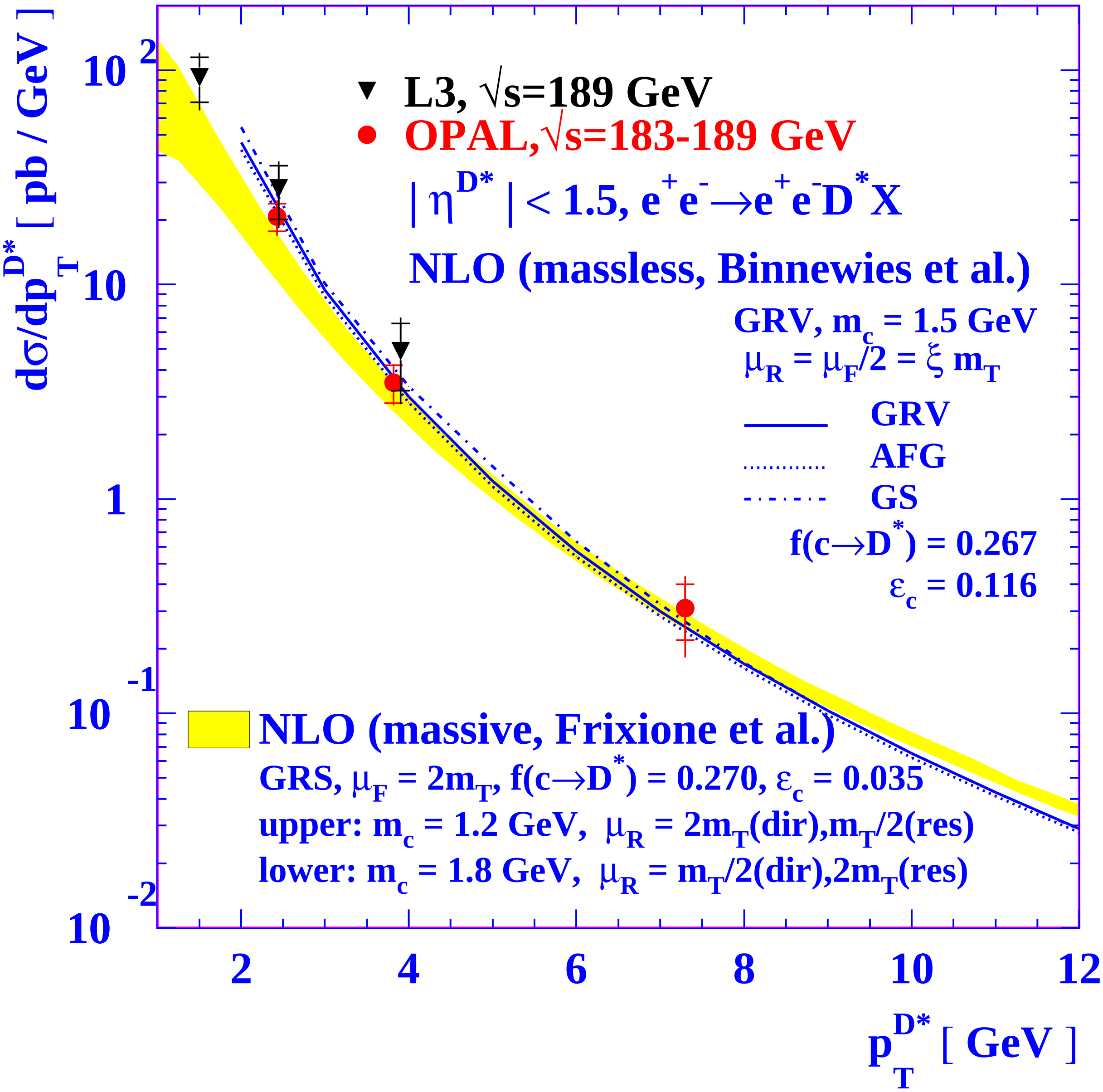


$$D^\star \longrightarrow D^0\,\pi$$

$$D^0 \longrightarrow K\pi, K\pi^0, K\pi\pi\pi$$

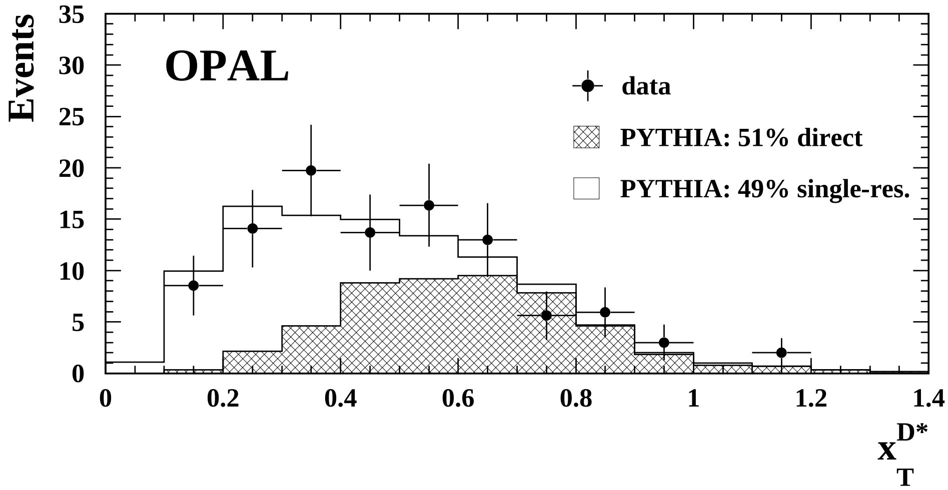
Clean charm tags can be obtained using leptons from the semileptonic decays or $D^\star$ mesons.

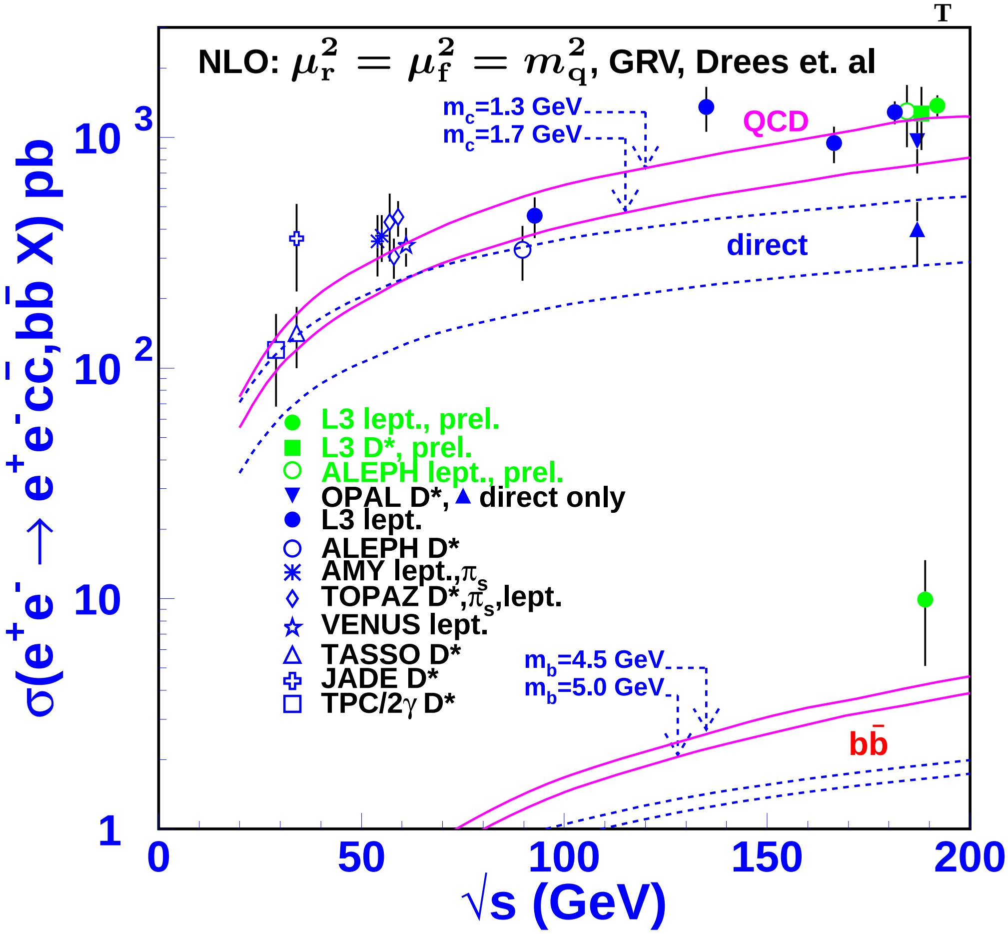
Differential D* cross-sections



The NLO QCD calculations agree well with the data for $p_{\mathrm{T}}^{D^\star} \geq 3\ \mathrm{GeV}$.

The heavy quark cross-sections

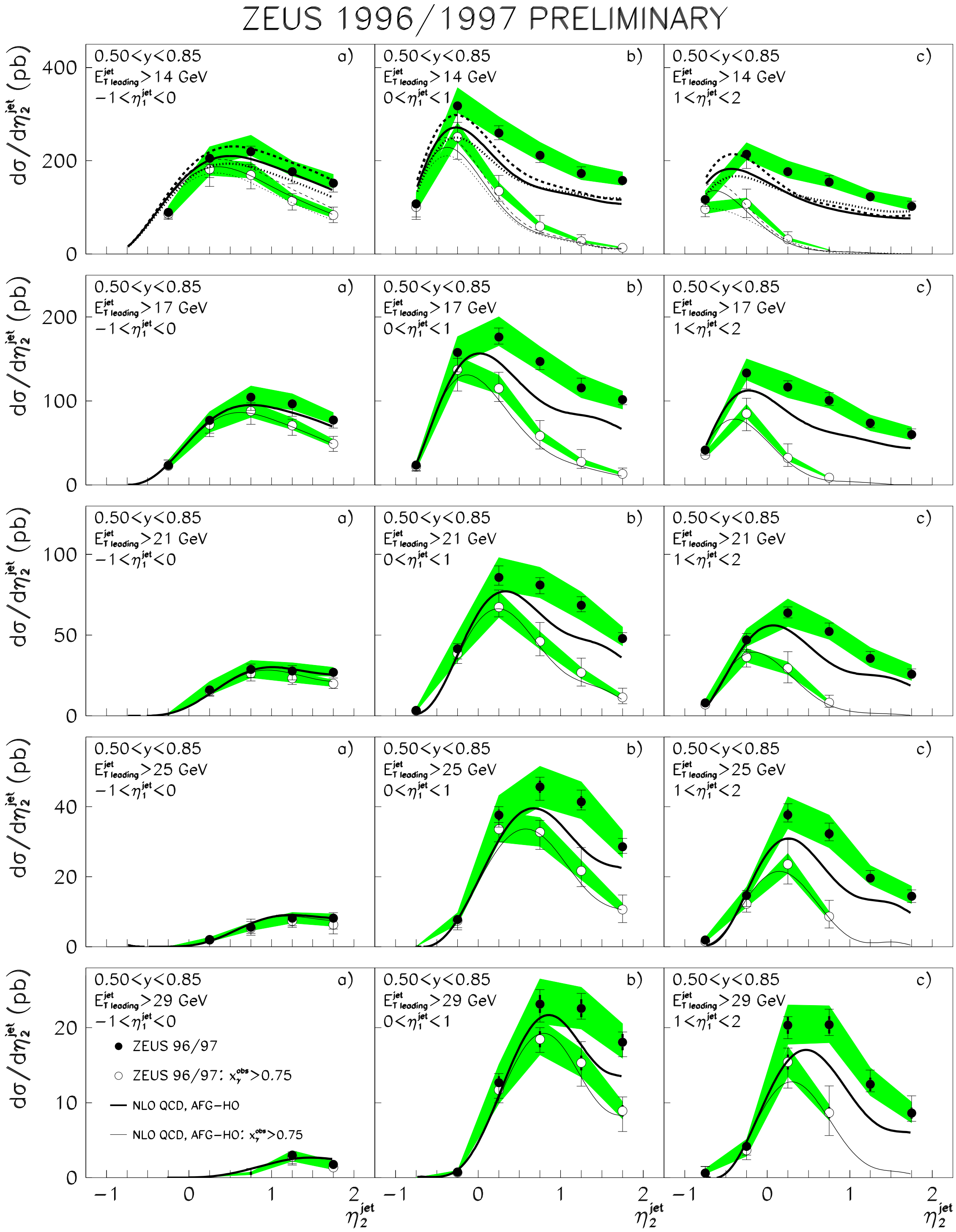




$$\sigma_{b\bar{b}} = 9.9 \pm 2.9(\text{stat}) \pm 3.8(\text{sys})\ \text{pb}$$

The direct heavy quark production is insufficient

Jet production from ZEUS



The predictions are too low at medium x

The concept of effective parton distribution functions

$$\frac{\mathrm{d}^5\sigma}{\mathrm{d}z\,\mathrm{d}x_\gamma\,\mathrm{d}x_\mathrm{p}\,\mathrm{d}\cos\theta^\star\,\mathrm{d}P^2} \propto \frac{1}{z}\frac{\mathrm{d}^2 N_\gamma^\mathrm{T}}{\mathrm{d}z\,\mathrm{d}P^2}\frac{\tilde{f}_\gamma(x_\gamma,Q^2,P^2)}{x_\gamma}\frac{\tilde{f}_\mathrm{p}(x_\mathrm{p},Q^2)}{x_\mathrm{p}}|M_\mathrm{SES}(\cos\theta^\star)|^2$$

with:

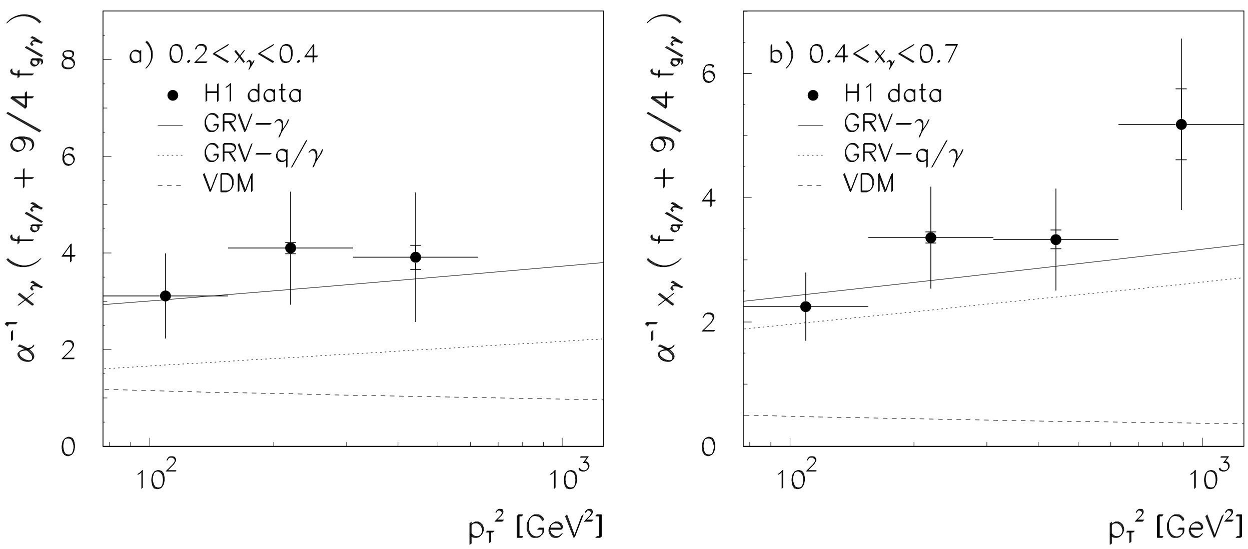
$$\tilde{f}_\mathrm{p}(x_\mathrm{p},Q^2) \equiv \sum_{k=1}^{n_f}\left[q_k^\mathrm{p}(x_\mathrm{p},Q^2) + \bar{q}_k^\mathrm{p}(x_\mathrm{p},Q^2)\right] + \frac{9}{4}g^\mathrm{p}(x_\mathrm{p},Q^2)$$

$$\tilde{f}_\gamma(x_\gamma,Q^2,P^2) \equiv \sum_{k=1}^{n_f}\left[q_k^\gamma(x_\gamma,Q^2,P^2) + \bar{q}_k^\gamma(x_\gamma,Q^2,P^2)\right] + \frac{9}{4}g^\gamma(x_\gamma,Q^2,P^2)$$

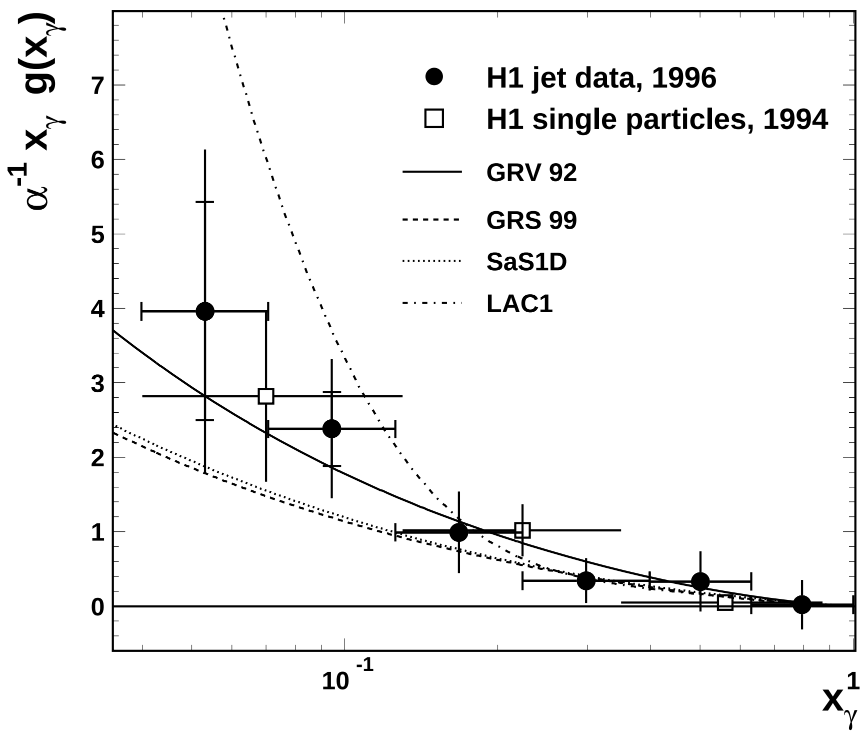
$$\tilde{f}_\gamma = \tilde{f}_\gamma^\mathrm{T} + \frac{2(1-z)}{1+(1-z)^2}\tilde{f}_\gamma^\mathrm{L}$$

$$\frac{\mathrm{d}^2 N_\gamma^\mathrm{T}}{\mathrm{d}z\,\mathrm{d}P^2} = \frac{\alpha}{2\pi}\left[\frac{1+(1-z)^2}{z}\frac{1}{P^2} - \frac{2\,m_\mathrm{e}^2\,z}{P^4}\right]$$

Structure of quasi-real photons from H1

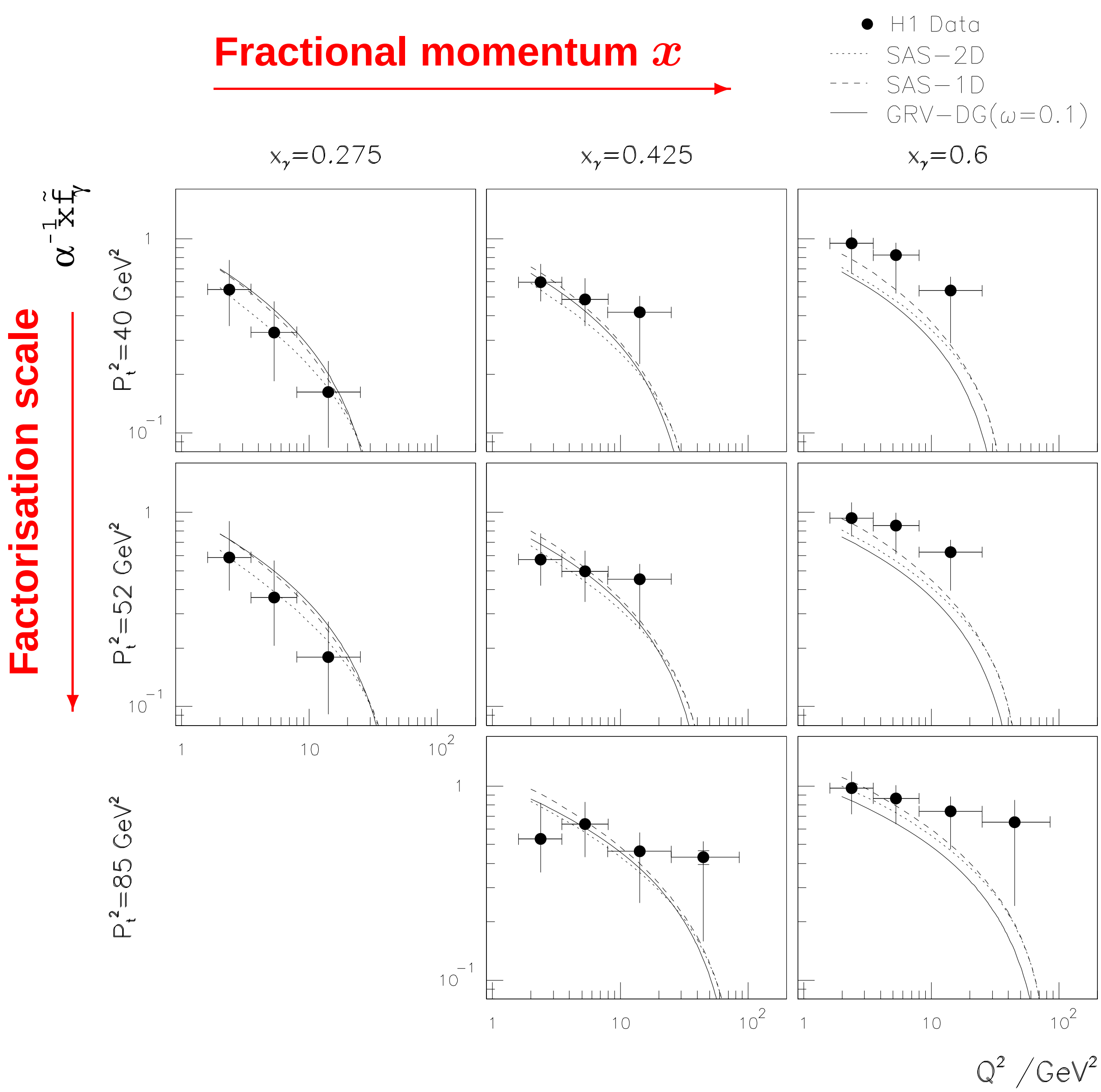


The hadron-like part is too low for all x, and the quark part is not sufficient $\Rightarrow$ gluons are needed.



The gluon rises towards low x, and is small at large x

Structure of virtual photons from H1



A strong suppression with increasing photon virtuality is observed.

Conclusions

1. The photon is a very interesting object, and our present knowledge is based on complementary information from different reactions.
2. The QED and the hadronic structure of quasi-real and virtual photons has been investigated using many observables.
3. A rather consistent picture emerges and the general features of the photon structure can be accounted for by the theoretical predictions.
4. However, there is still a long way to go until we reach precise measurements of all features of the structure of the photon.

Due to the limited amount of time not all measurements concerning the photon structure could be shown and a personal selection has been made.

Thanks to all who made this presentation possible, and especially to V. Andreev and S. Söldner-Rembold for providing me with figures.

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