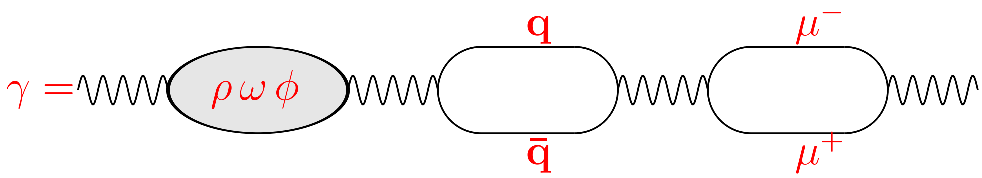
The Partonic Structure of the



Richard Nisius (CERN) Dortmund, 25.01.00

- Introduction

1. Quasi-Real Photons
   1. QED structure
   2. Hadronic structure
2. Virtual Photons
   1. QED structure
   2. Hadronic structure
3. Results from Other Reactions
   1. Photon-Photon Scattering
   2. Results from HERA

- Conclusions

The limit of deep inelastic electron-photon scattering

Using:

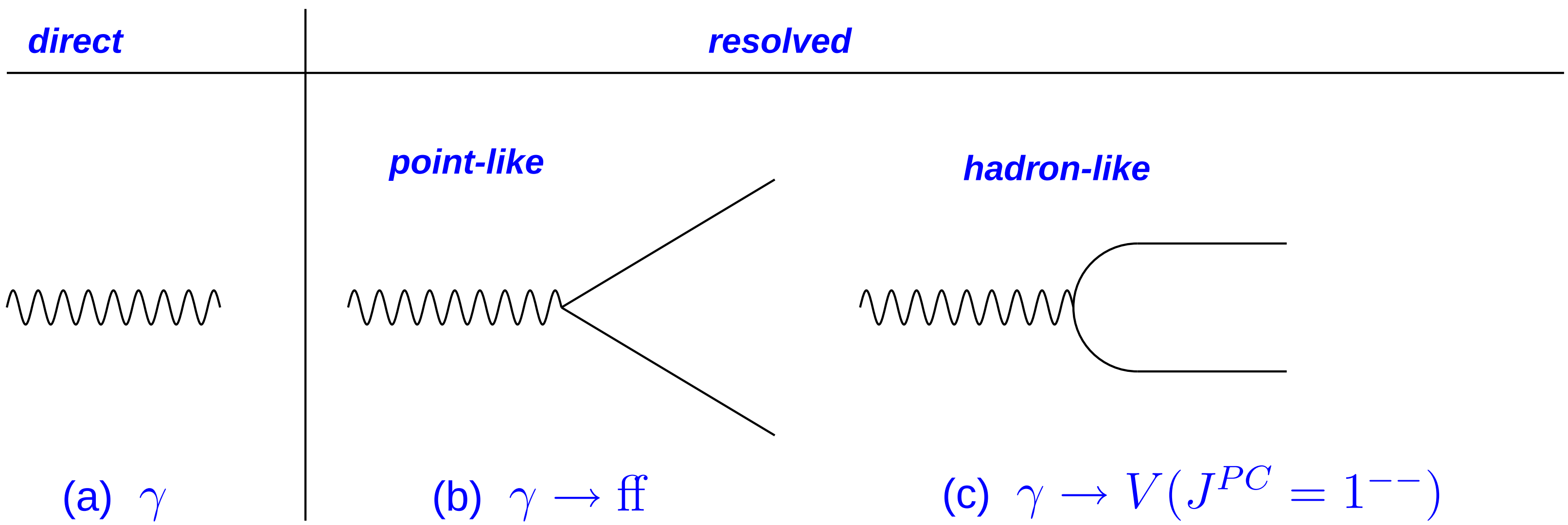
$$\begin{aligned}
2xF_\mathrm{T}^\gamma &= \frac{Q^2}{4\pi^2\alpha}\,\sigma_\mathrm{TT}(x,Q^2)\\
F_\mathrm{L}^\gamma &= \frac{Q^2}{4\pi^2\alpha}\,\sigma_\mathrm{LT}(x,Q^2)\\
F_2^\gamma &= 2xF_\mathrm{T}^\gamma + F_\mathrm{L}^\gamma
\end{aligned}$$

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

$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}z\,\mathrm{d}P^2} = \frac{\mathrm{d}^2N_\gamma^\mathrm{T}}{\mathrm{d}z\mathrm{d}P^2}\cdot\frac{2\pi\alpha^2}{x\,Q^4}\cdot\left[1+(1-y)^2\right]\cdot \underbrace{\left[2xF_\mathrm{T}^\gamma(x,Q^2) + \frac{2(1-y)}{1+(1-y)^2}F_\mathrm{L}^\gamma(x,Q^2)\right]}_{\to F_2^\gamma \text{ for } y\ll 1}$$

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

Why do we talk about Photon Structure?

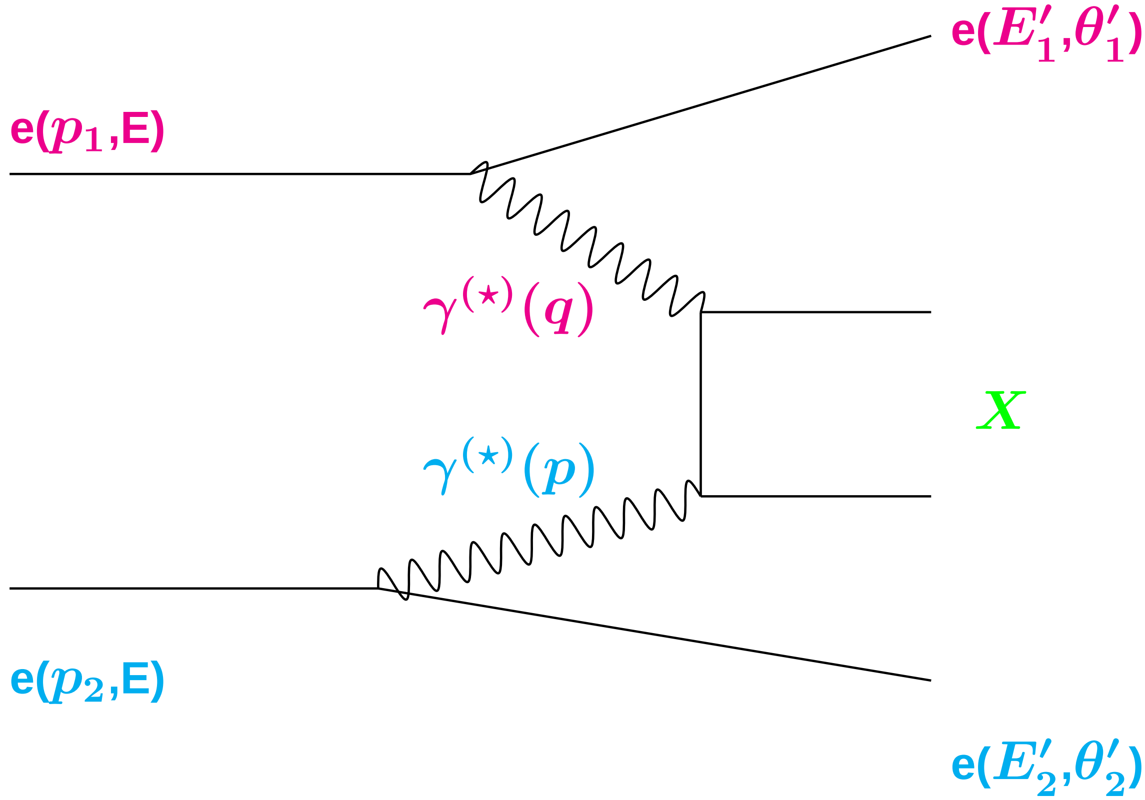


In (a) the whole photon interacts $\Rightarrow$ NO structure

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 ⟶ e e X



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

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

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

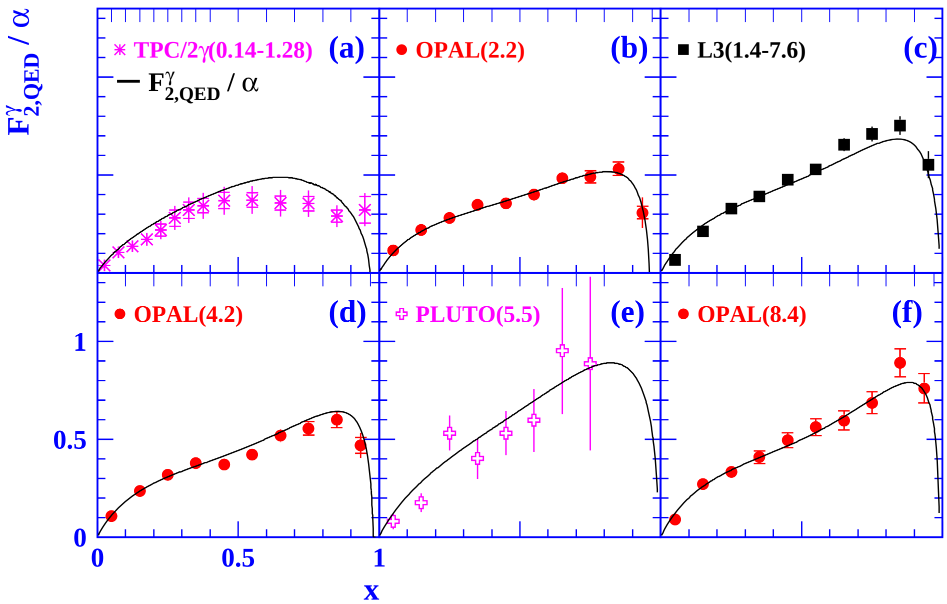
$$2|\rho_1^{+-}\rho_2^{+-}|\tau_{TT}\cos 2\bar{\phi} - 8|\rho_1^{+0}\rho_2^{+0}|\tau_{TL}\cos\bar{\phi}\Big)$$

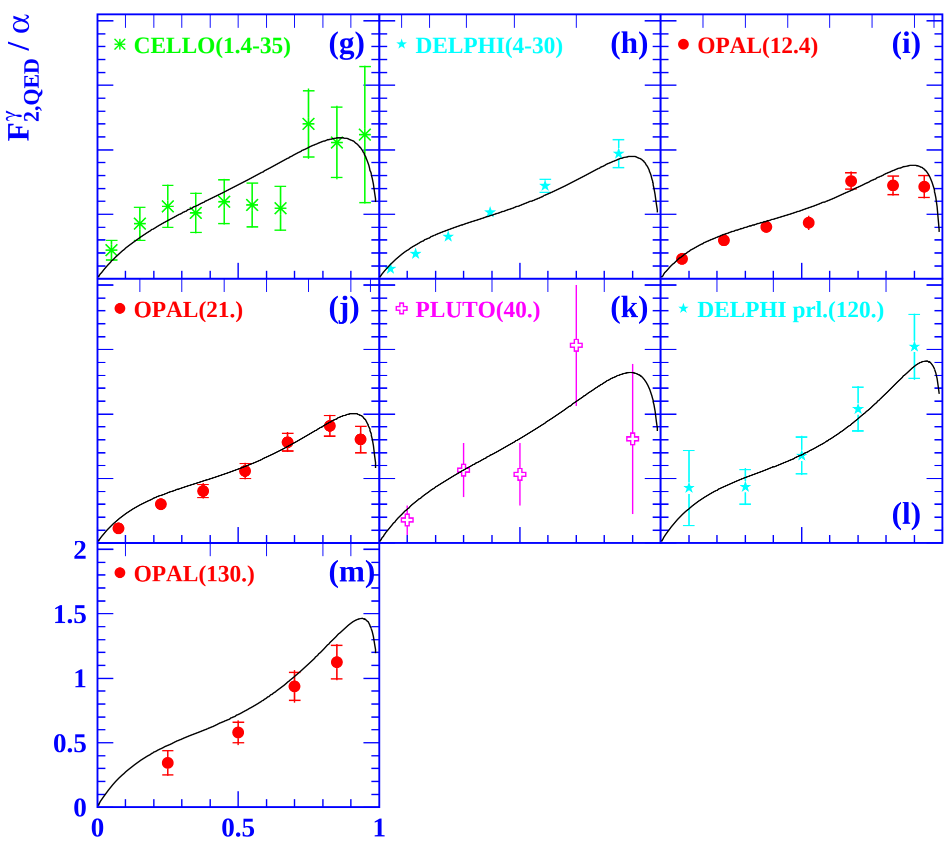
$$Q^2 = -q^2 = 2\,E\,E_1'\,(1-\cos\theta_1')$$

$$P^2 = -p^2 = 2\,E\,E_2'\,(1-\cos\theta_2')$$

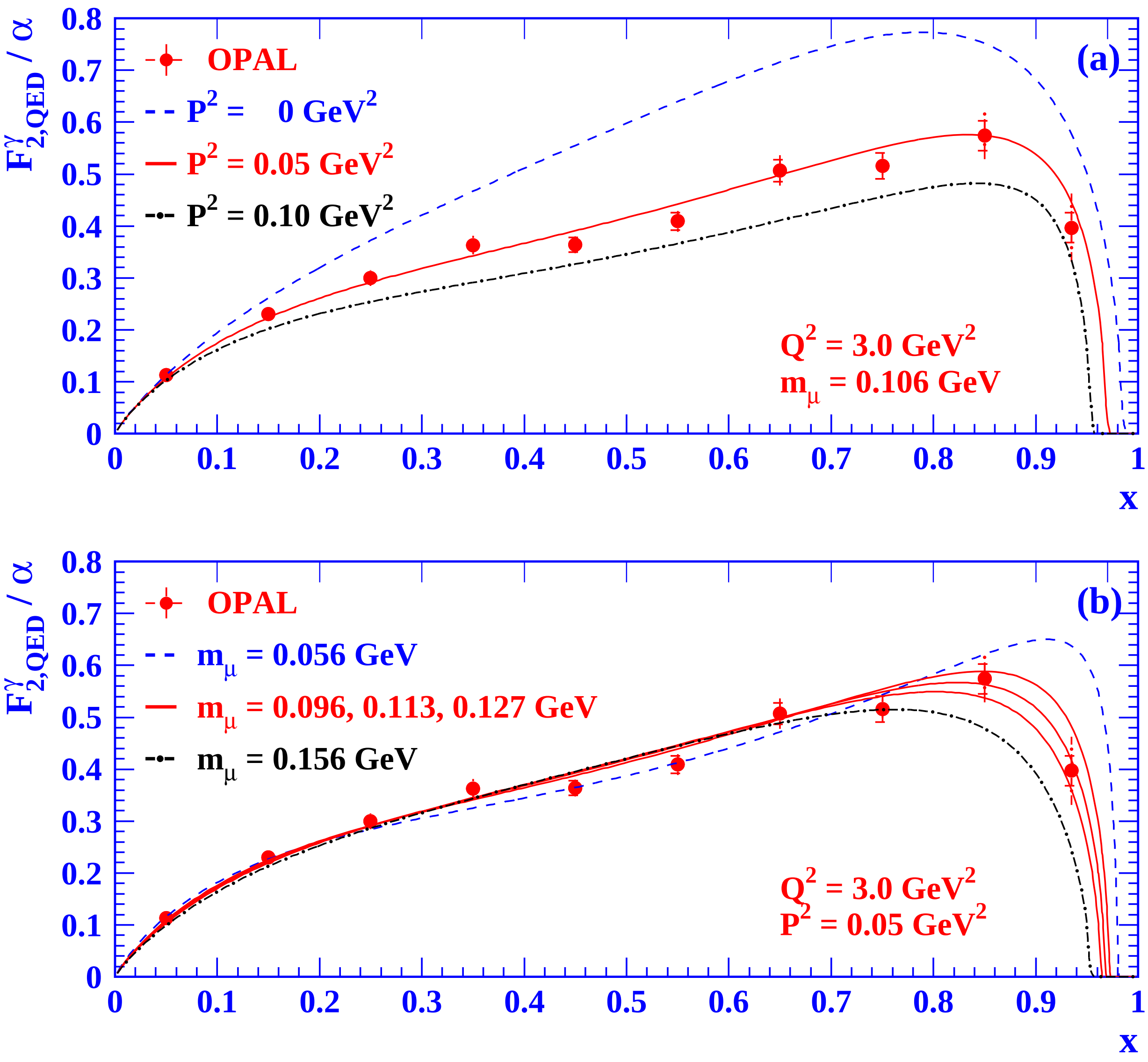
$$x = \frac{Q^2}{Q^2 + W^2 + P^2}$$

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



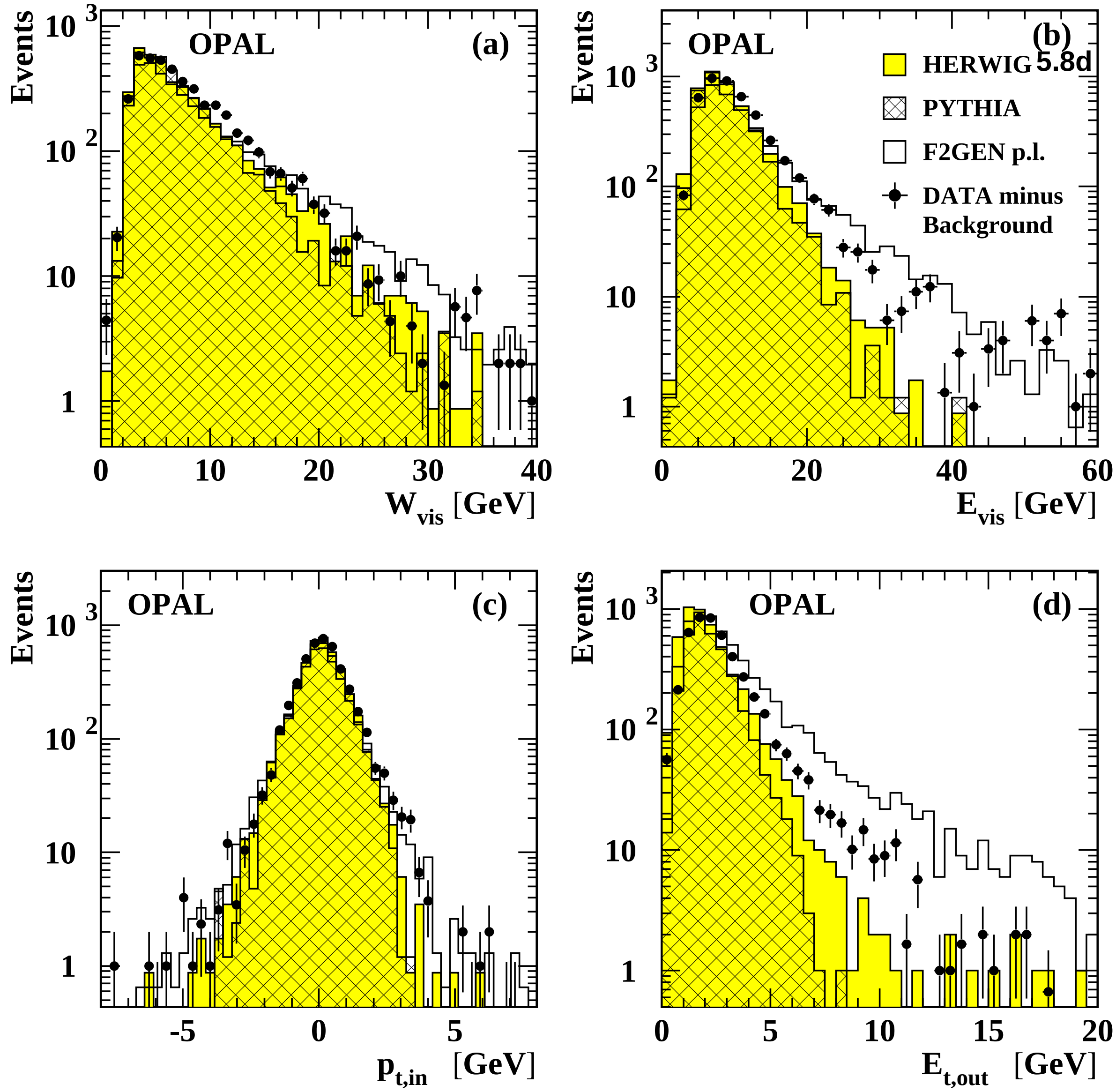


The dependence of $F_{2,\mathrm{QED}}^{\gamma}$ on P^2 and m_μ



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

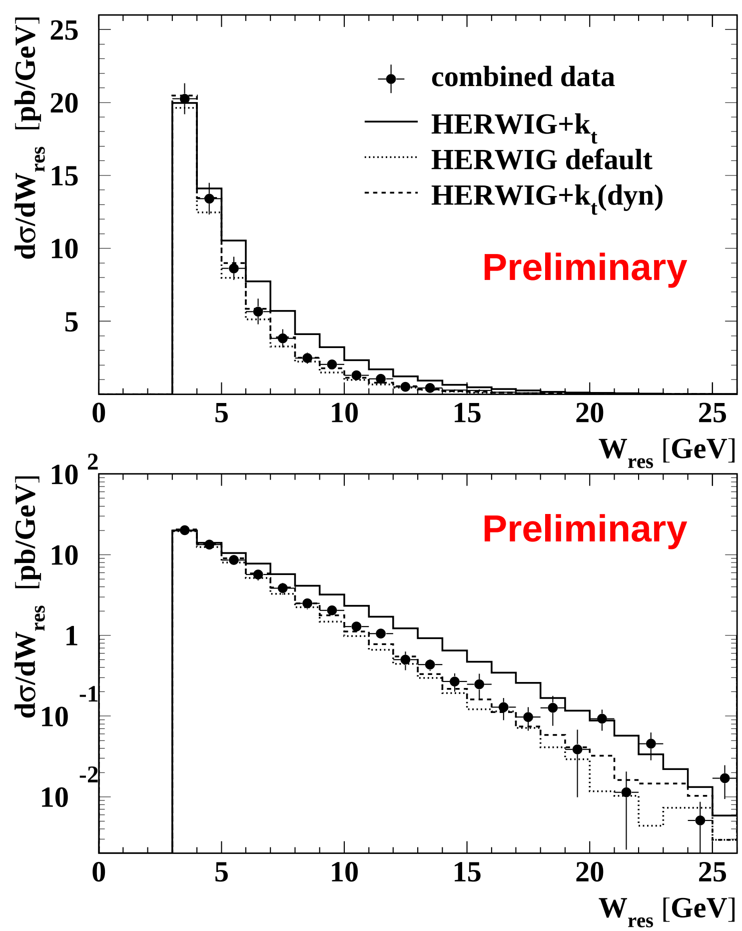
The description of the hadronic final state



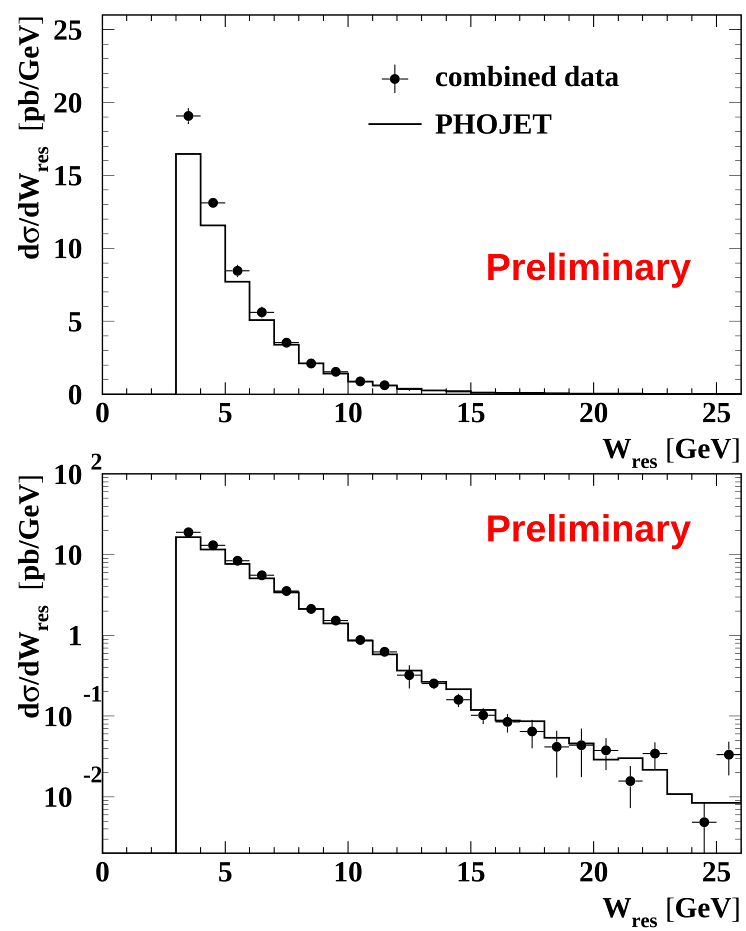
There are significant differences between the data and the Monte Carlo predictions (OPAL '96)

Comparison to LEP combined data

HERWIG corrected low Q^2 data



PHOJET corrected low Q^2 data

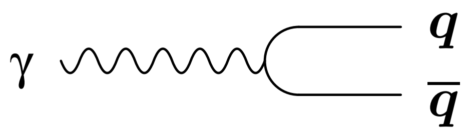


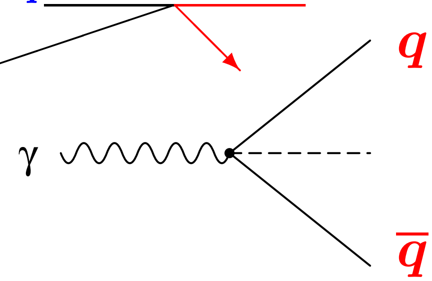
The combined data are a valuable input to constrain the Monte Carlo models

(LEP Two-Photon WG '99)

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

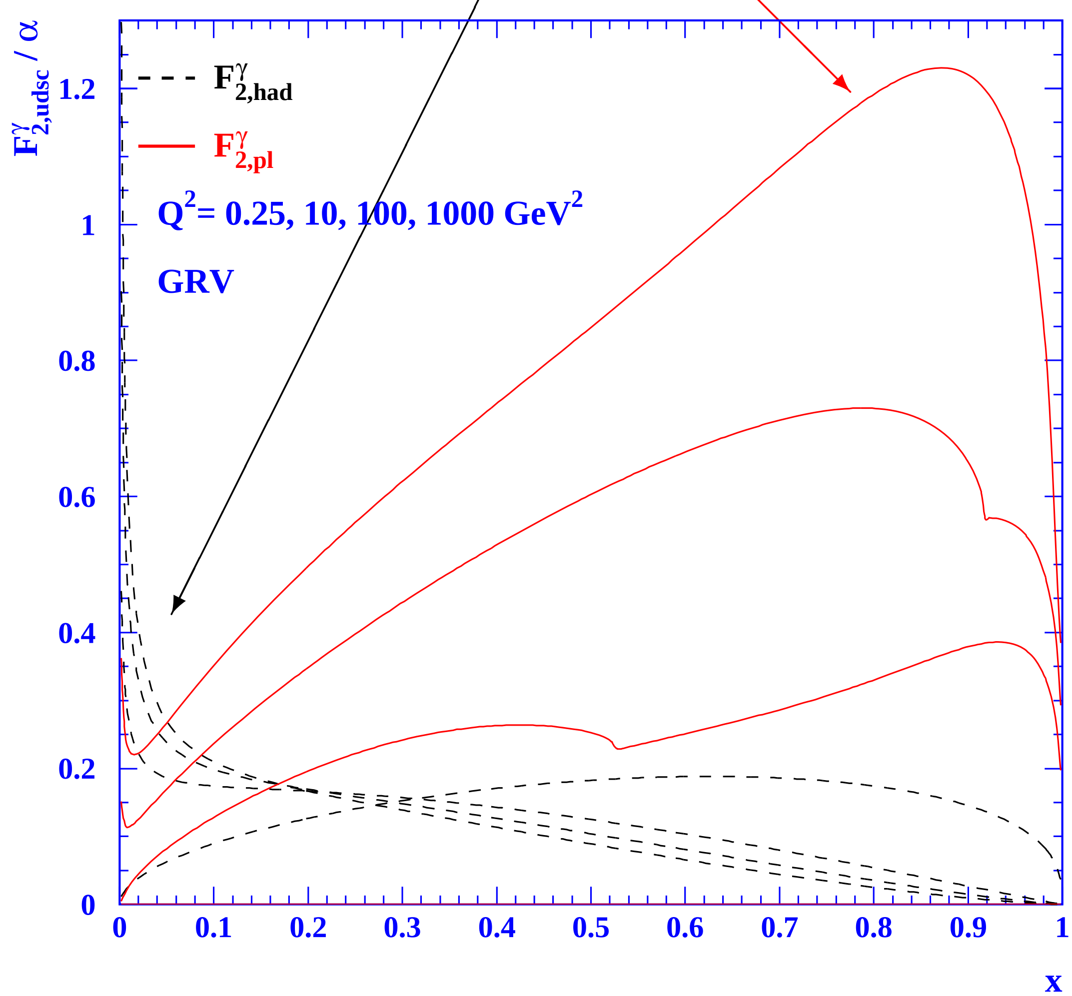
$$F_2^\gamma(x,Q^2) = x \sum_{c,f} e_q^2 \, f_{q,\gamma}(x,Q^2)$$



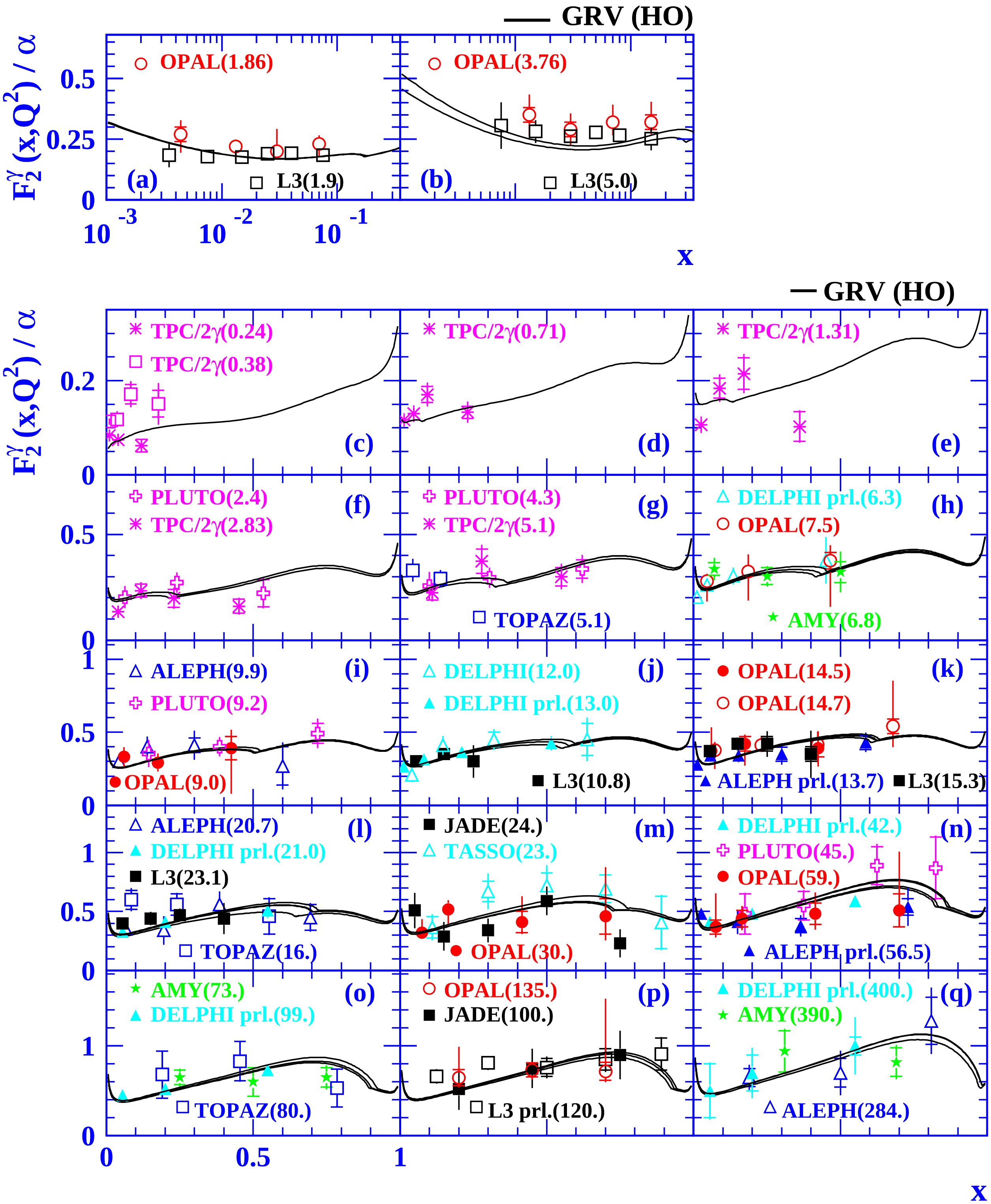


hadron-like, *non–perturbative* **point-like,** *perturbative*

e.g. VMD(ρ, ω, ϕ), low-x **high-x**

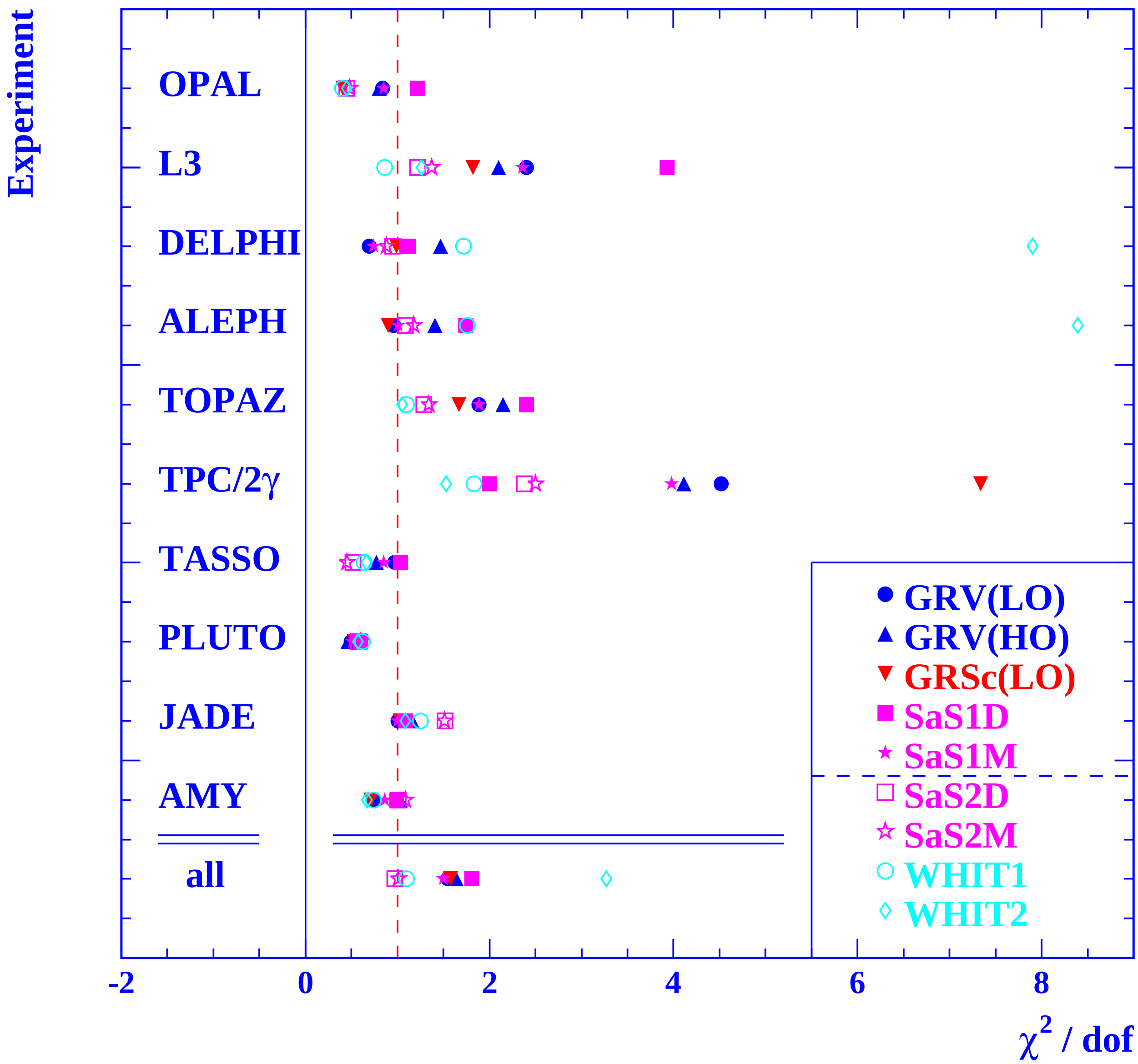


The world data on F_2^γ



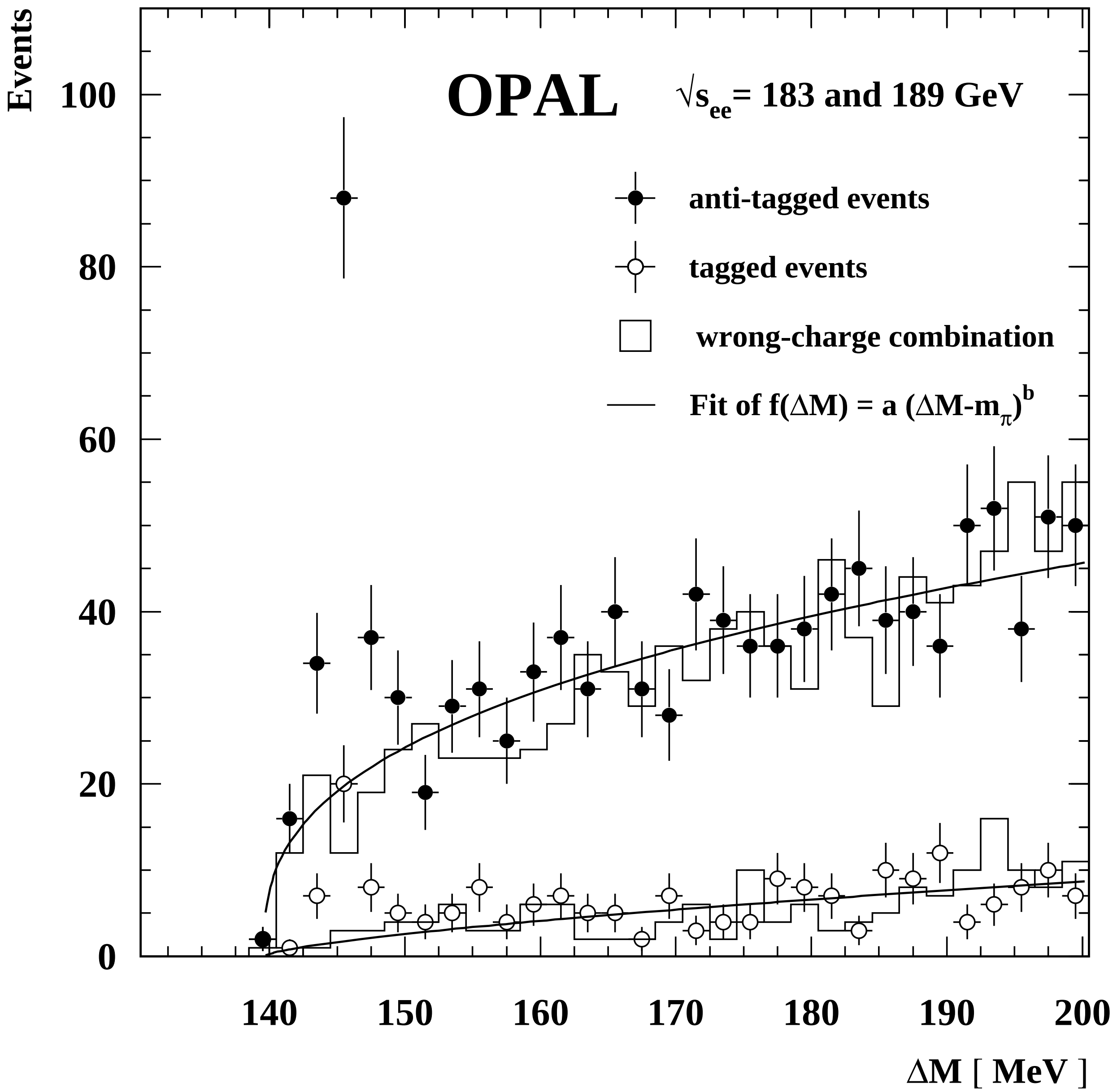
Data description by existing pdf's

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



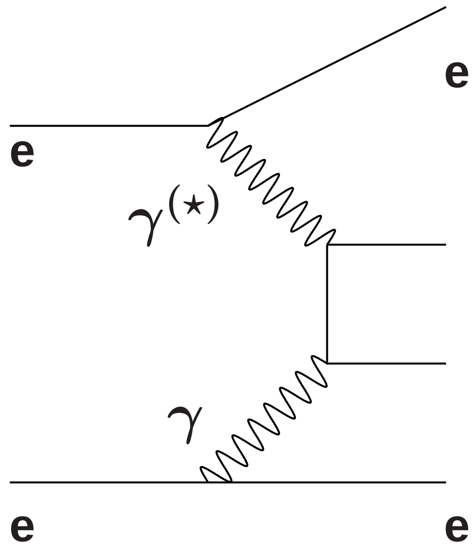
Most of the data can be accounted for by existing pdf's, but...

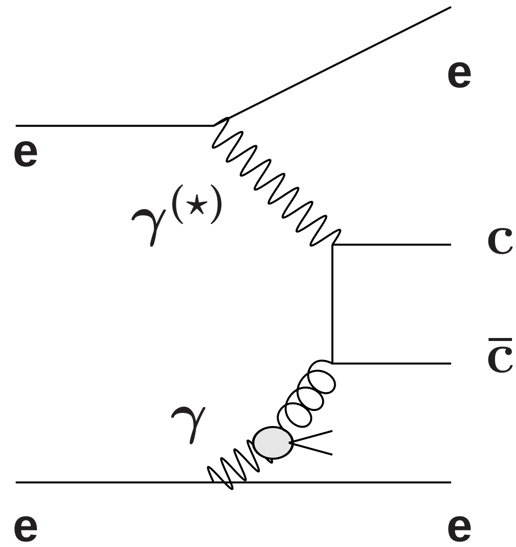
Charm production tagged by D*s



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

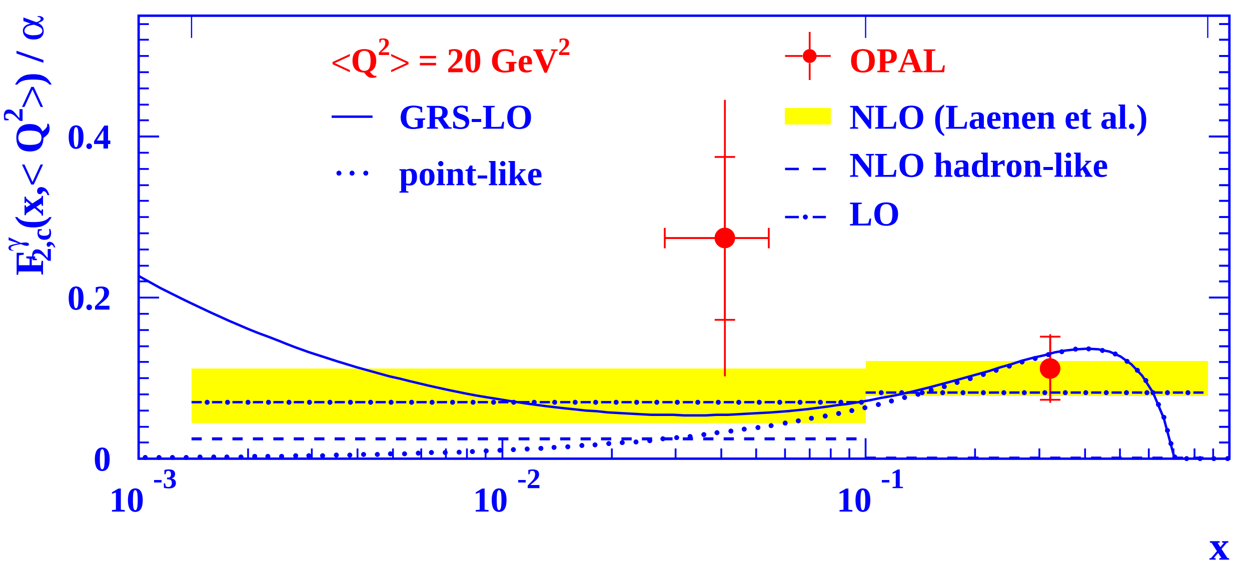
The first measurement of $F_{2,c}^{\gamma}$



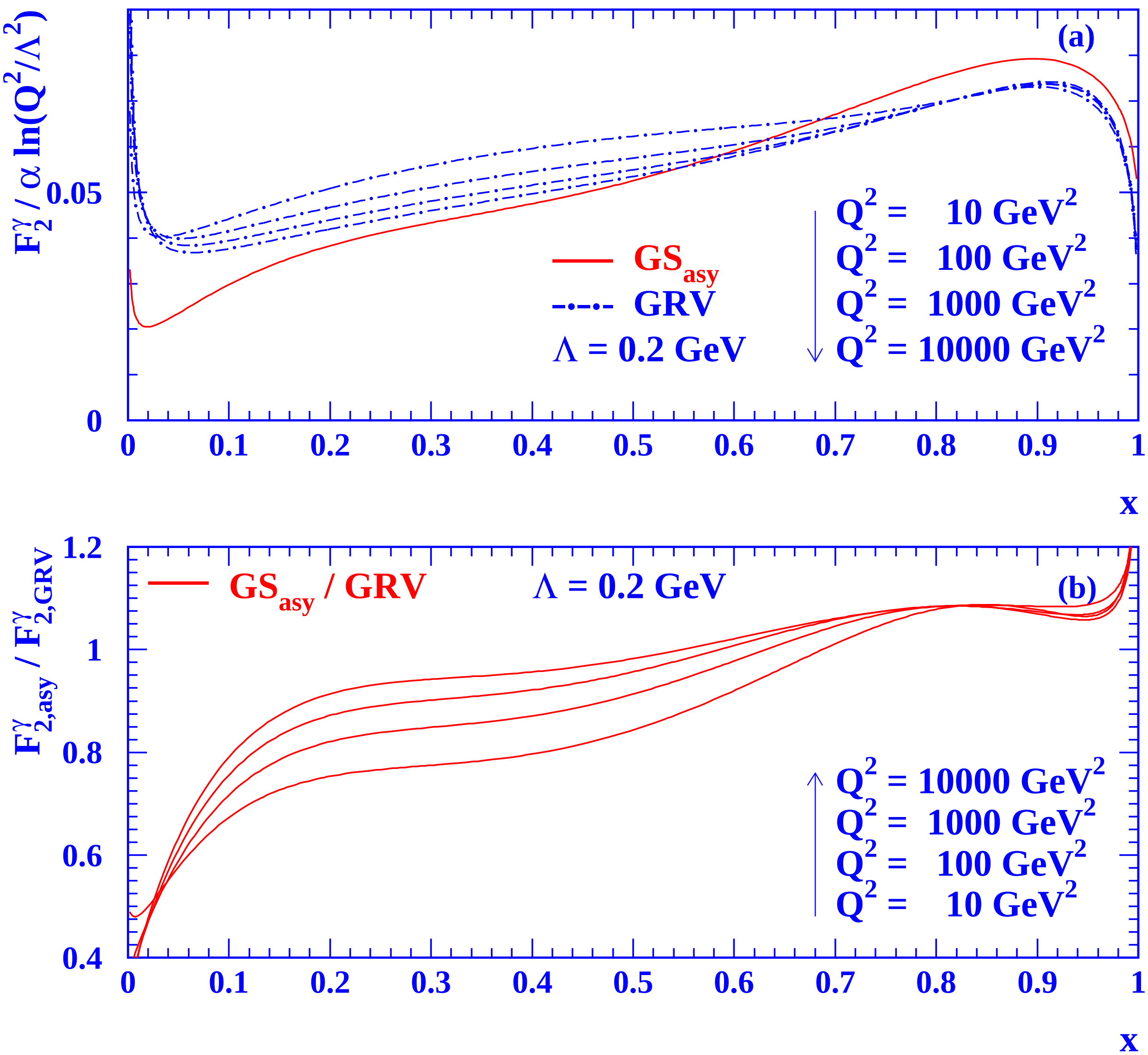


point-like, purely perturbative QCD prediction, dominates at high-x

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

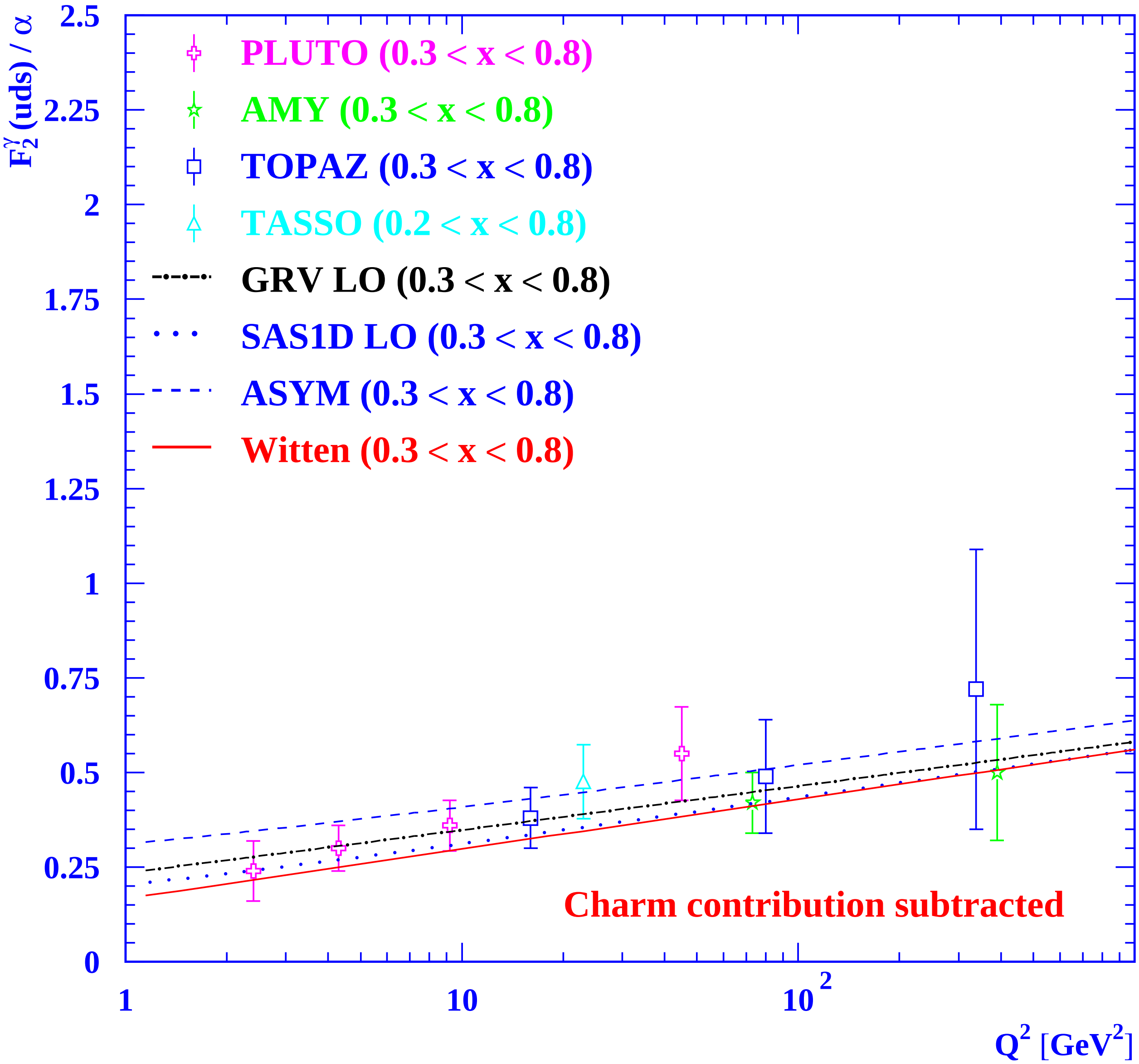


The x dependence of F_2^γ (GRV) and F_2^γ (asy)



The asymptotic solution approaches the full F_2^γ at large x and Q^2.

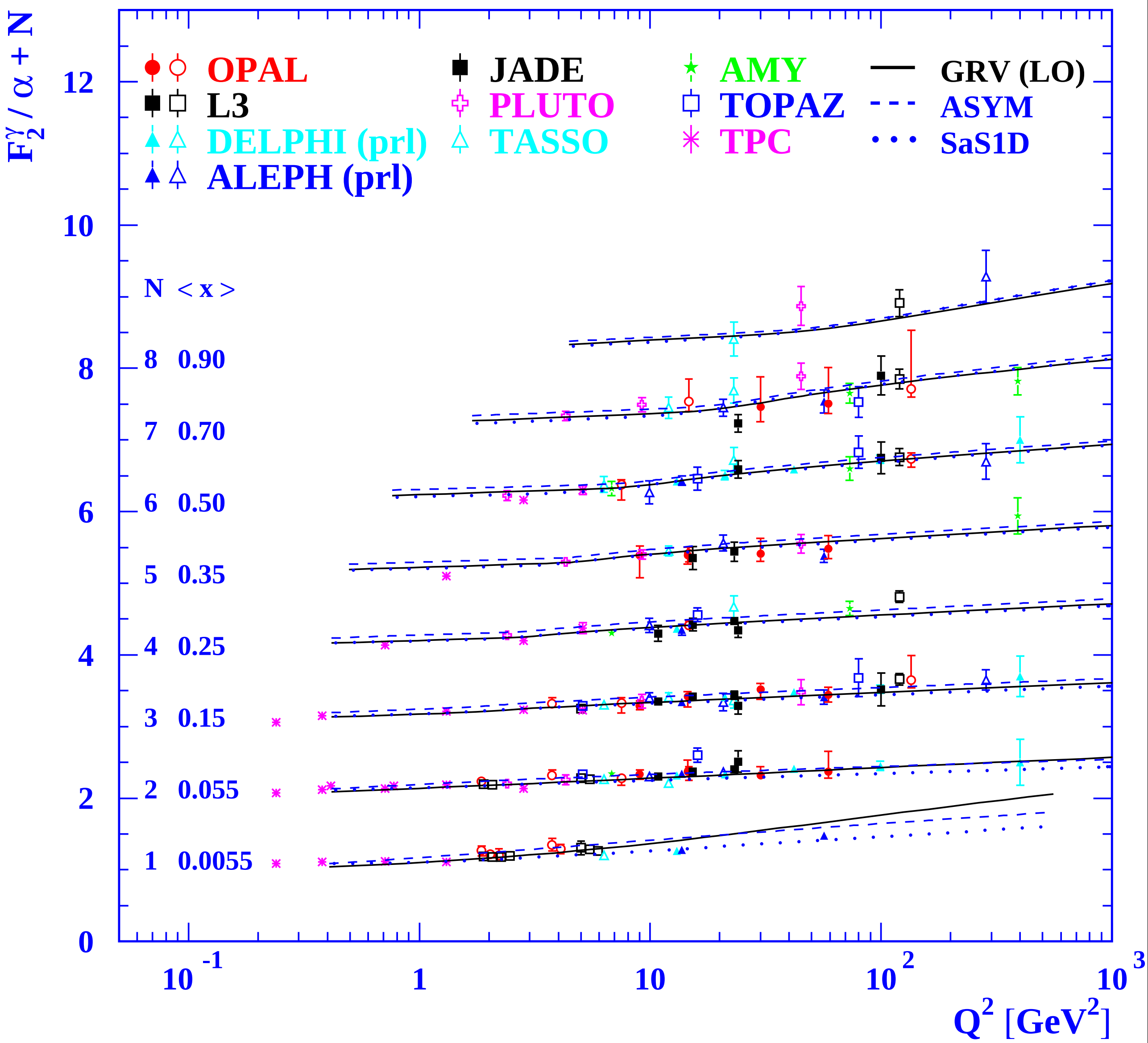
The Q^2 evolution of F_2^γ for $\mathrm{n_f} = 3$



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

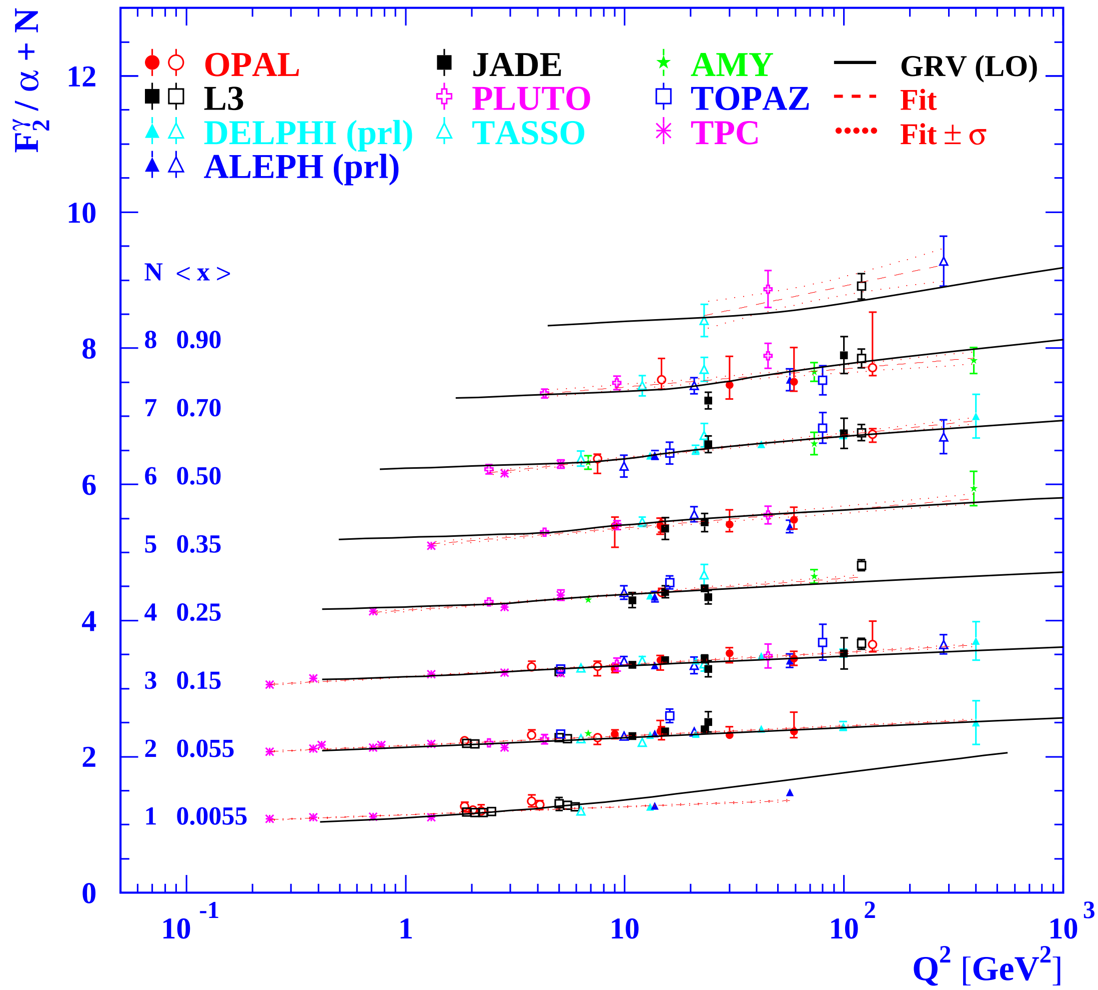
All predictions are consistent with the data.

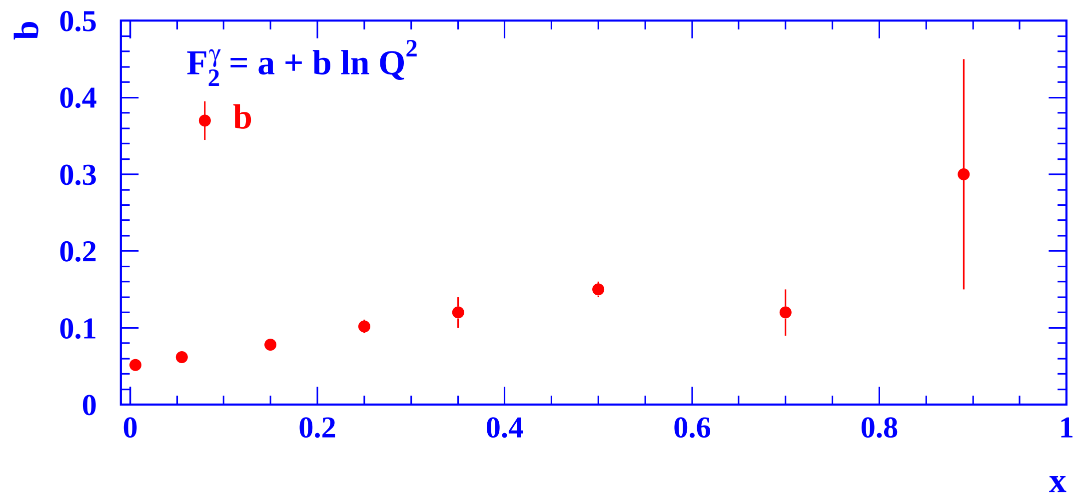
The Q^2 evolution of F_2^γ for $\mathrm{n_f} = 4$



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

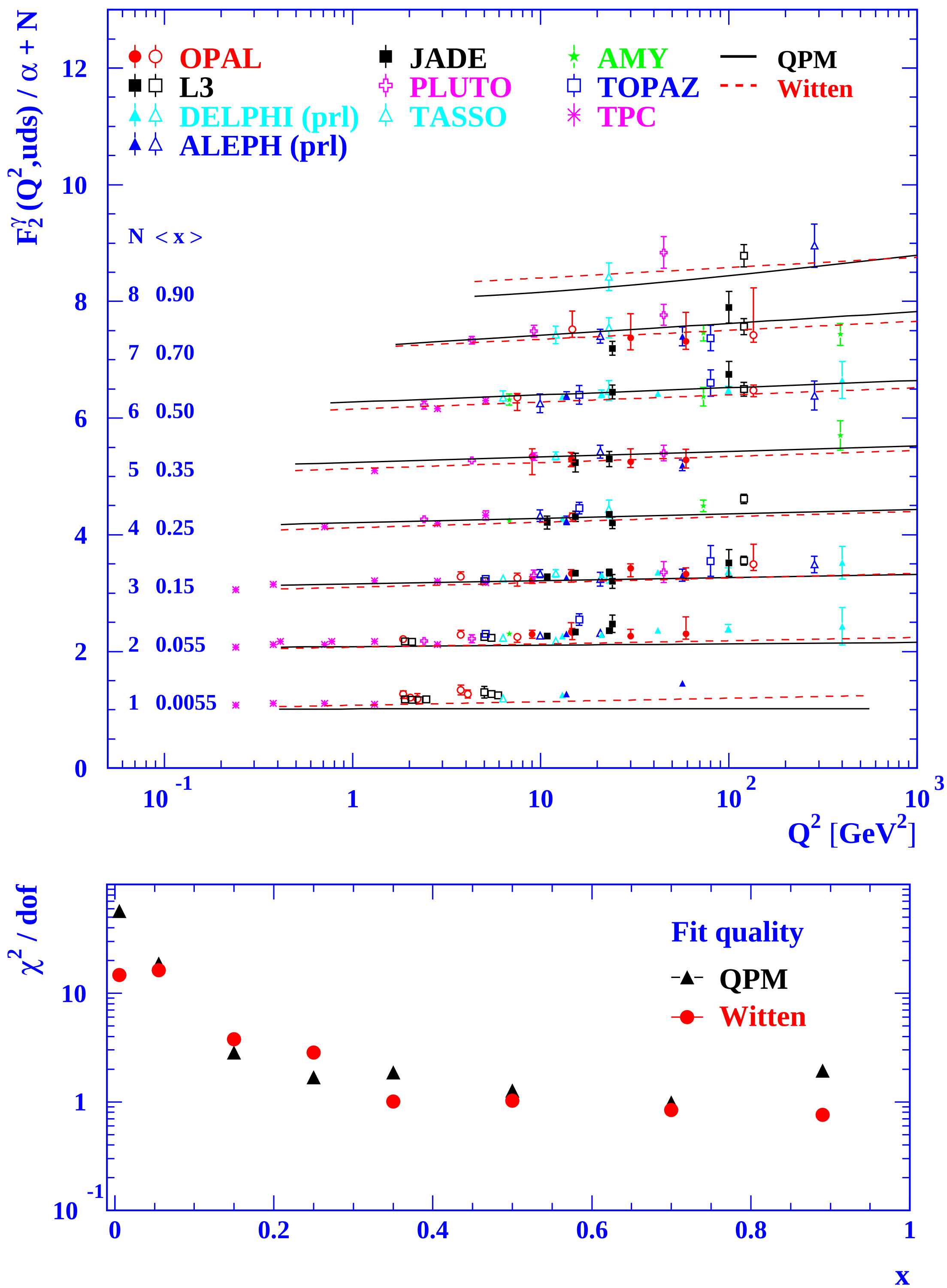
Q^2 evolution compared to linear fits



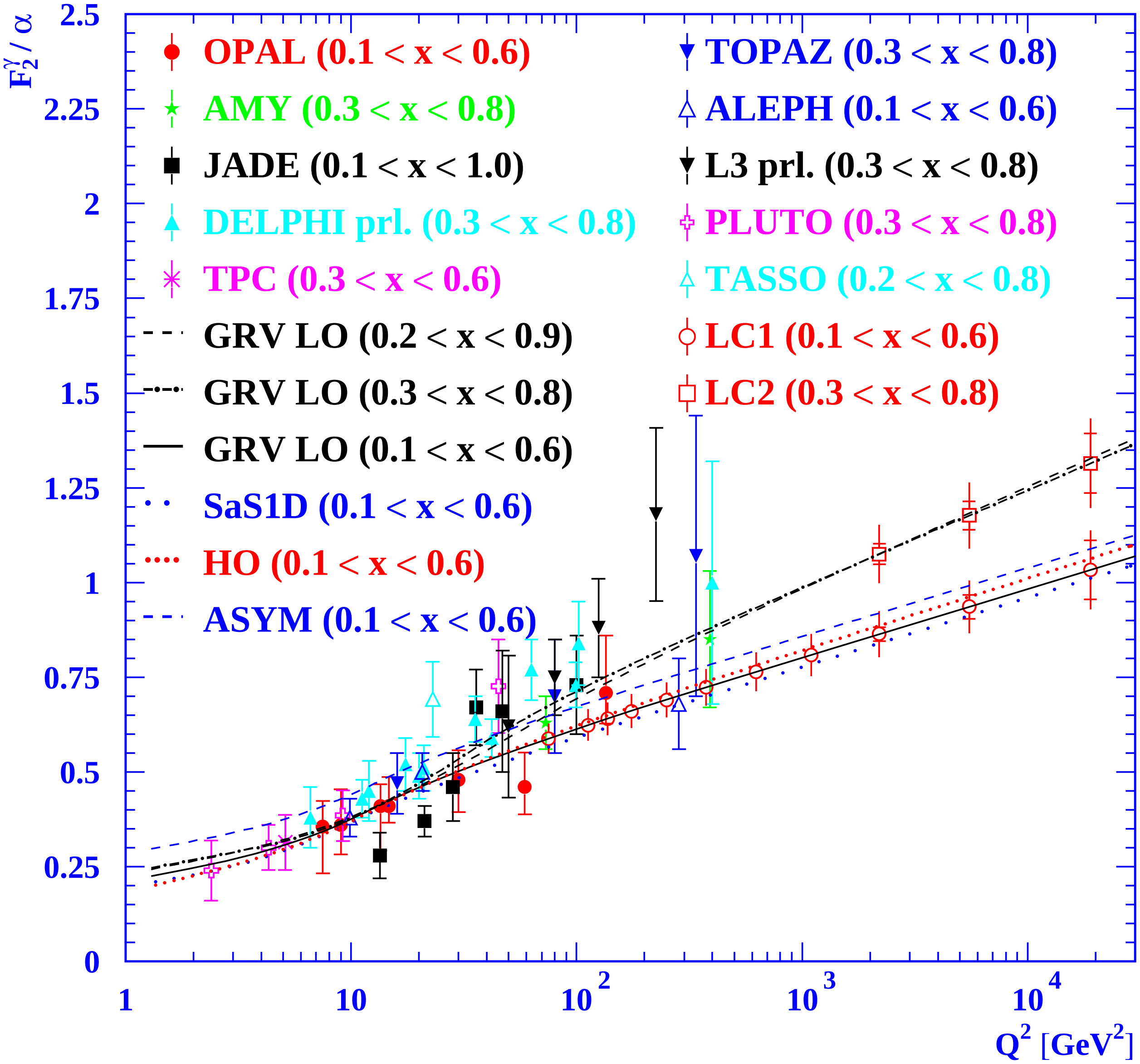


An increasing slope as a function of x is observed.

Q^2 evolution after charm subtraction

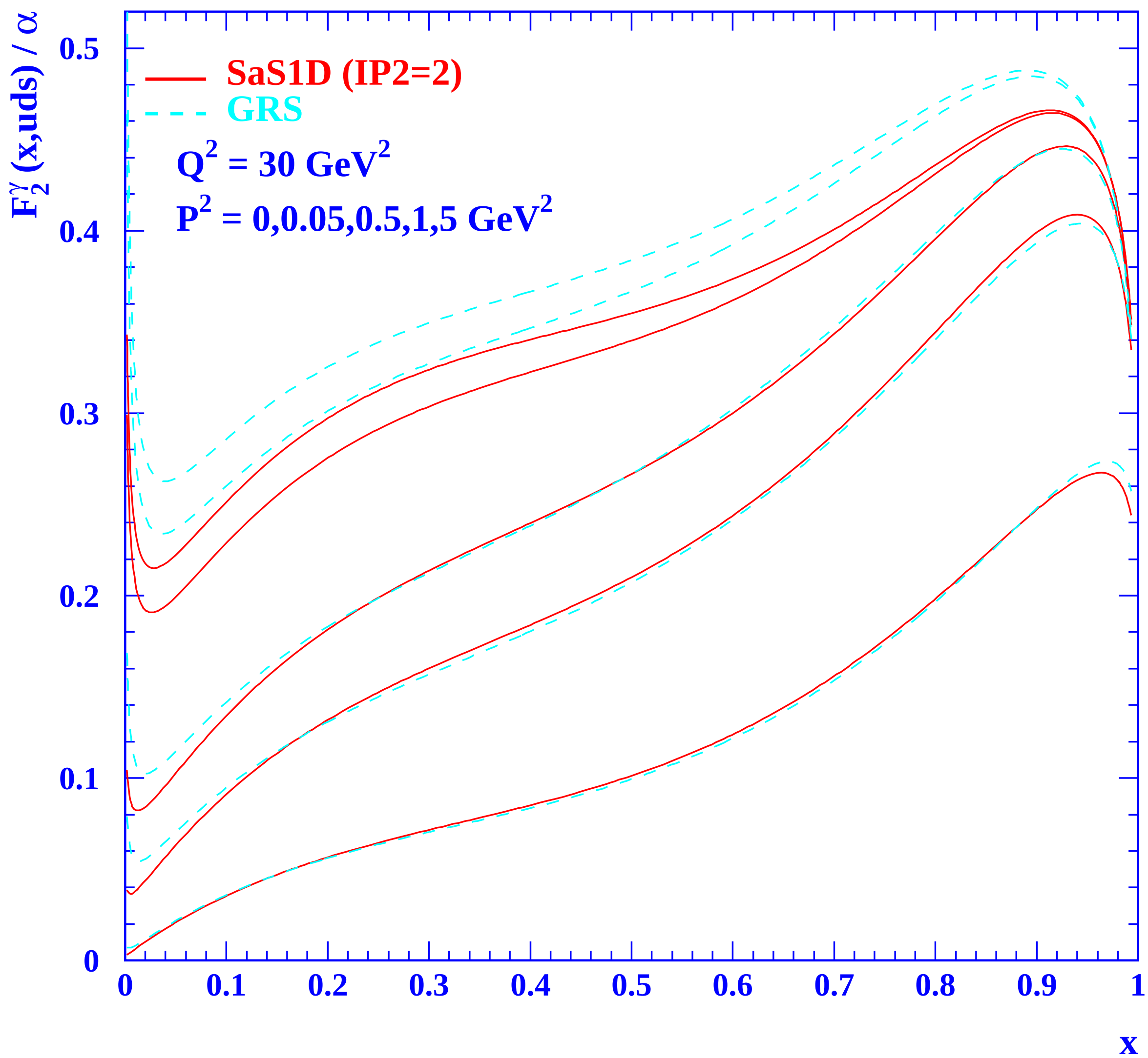


The future of the F_2^γ measurements



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

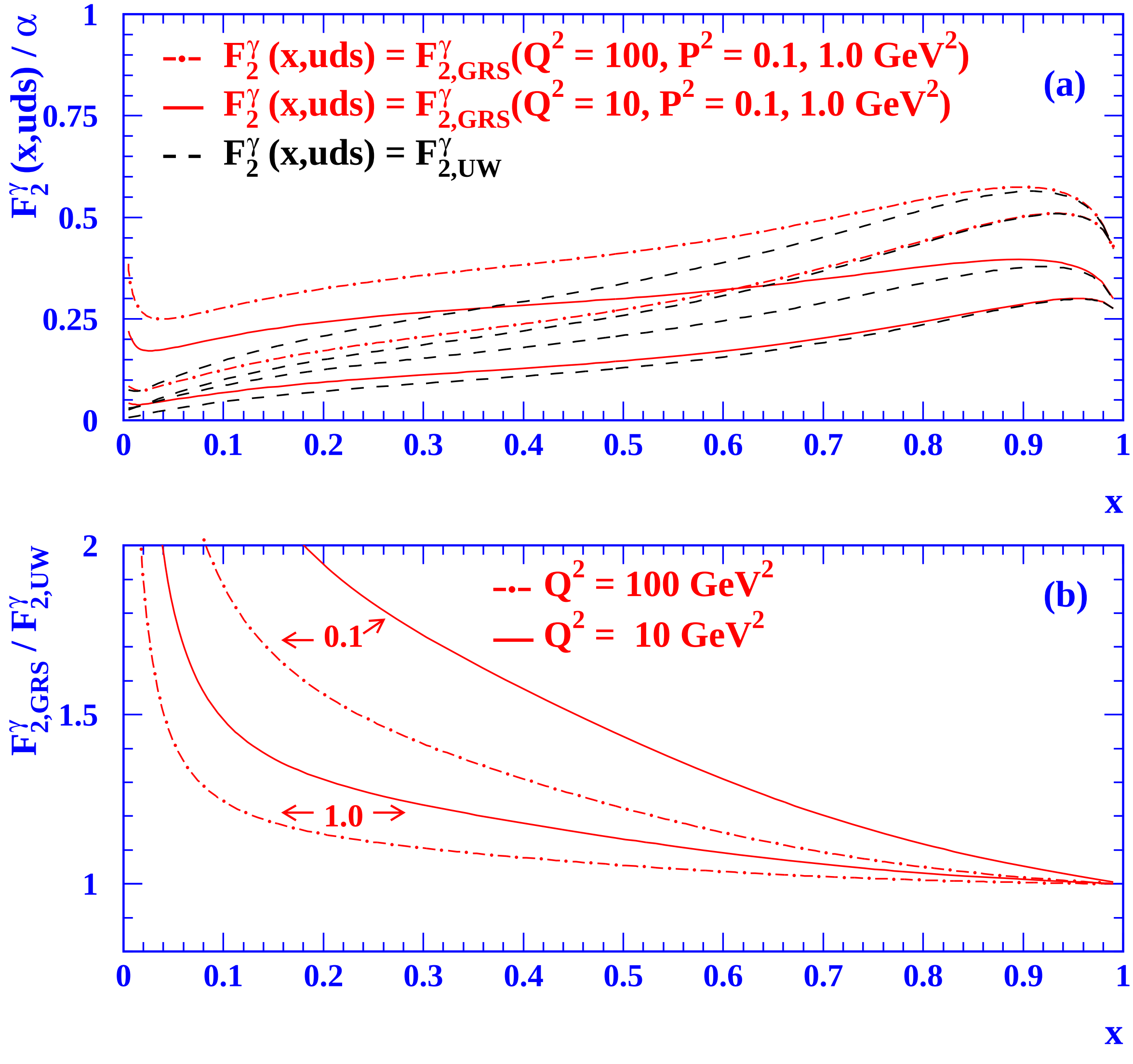
F_2^γ for virtual photons



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

The x dependence of

F_2^γ (P^2)(GRS) and F_2^γ (P^2)(pl)

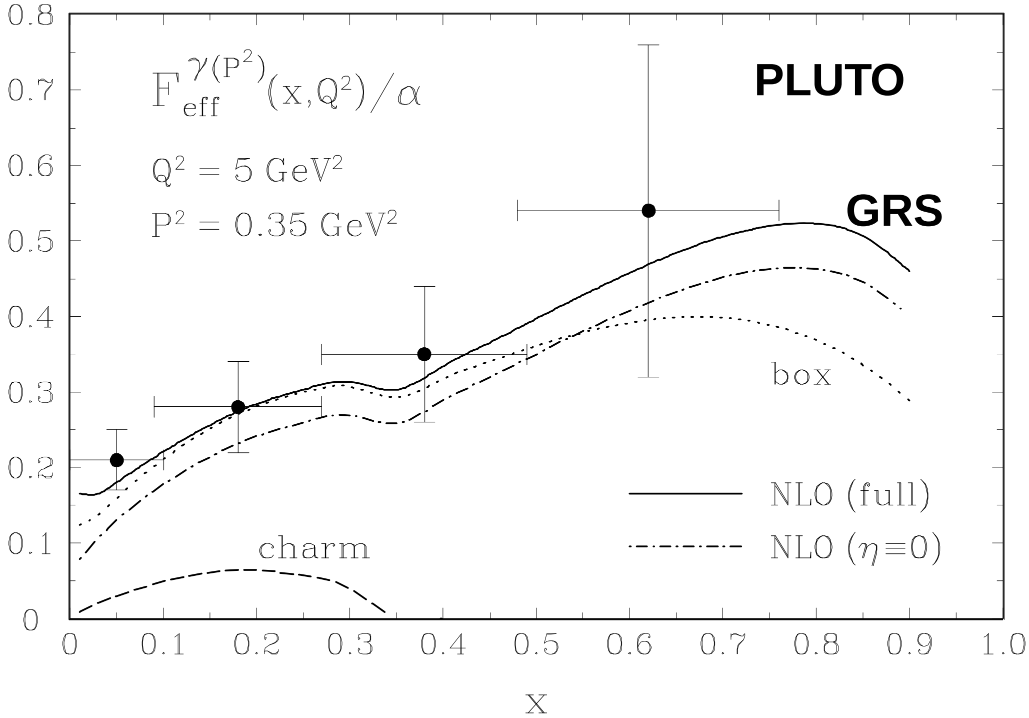


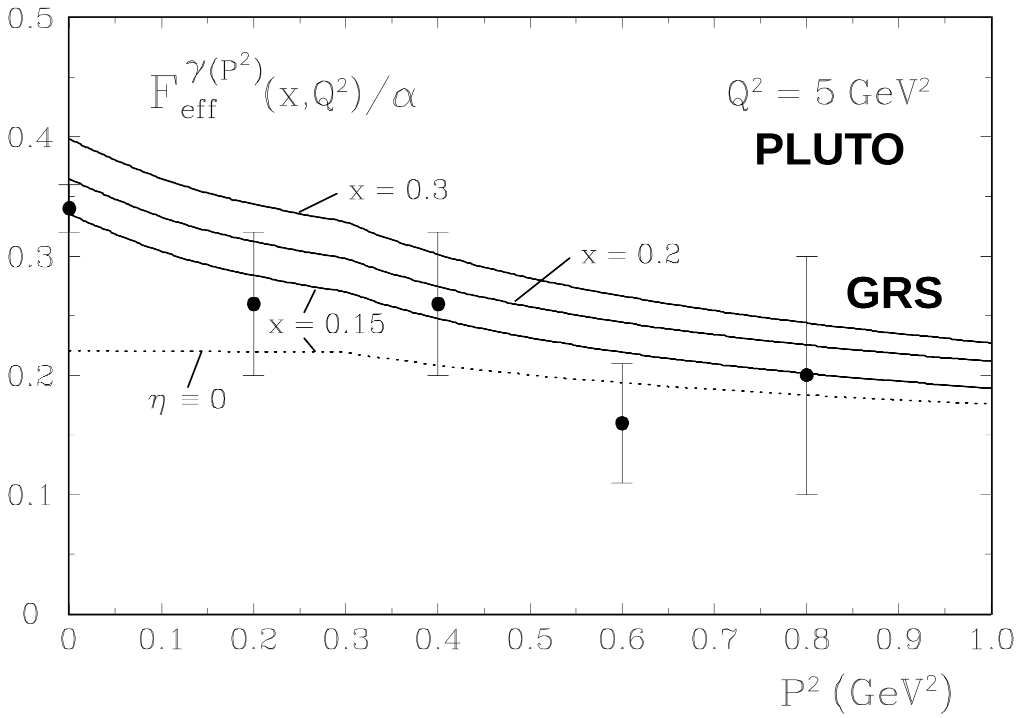
The non perturbative part is a 10% correction for $x > 0.3$, $Q^2 = 100$ GeV^2 and $P^2 = 1$ GeV^2

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

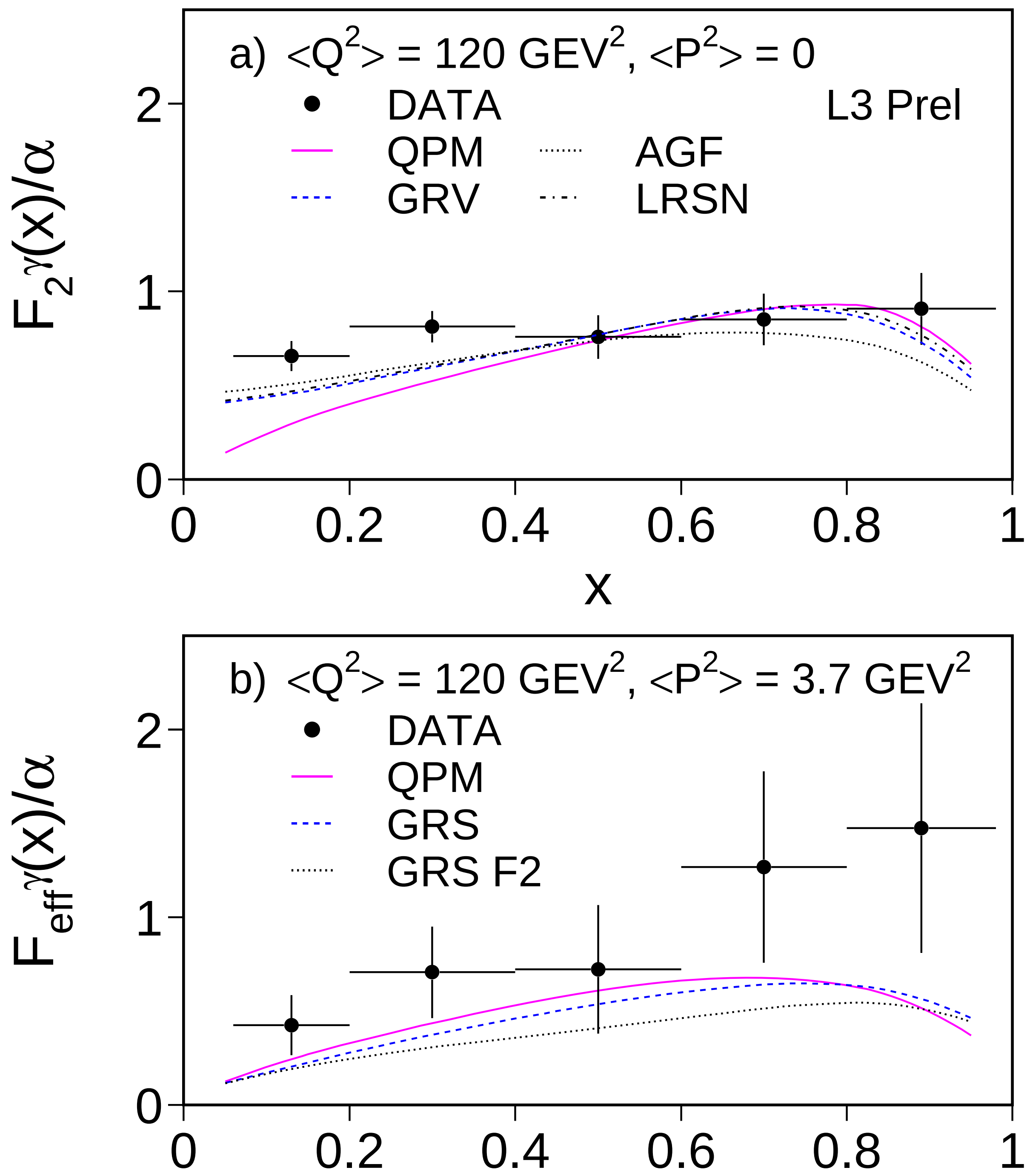
$$\begin{aligned} d^6\sigma &= \frac{d^3p_1' d^3p_2'}{E_1' E_2'} \frac{\alpha^2}{16\pi^4 q^2 p^2} \left[\frac{(q\cdot p)^2 - q^2p^2}{(p_1\cdot p_2)^2 - m_e^2 m_e^2} \right]^{1/2} 4\rho_1^{++}\rho_2^{++} \cdot \\ & \left(\sigma_{TT} + \sigma_{TL} + \sigma_{LT} + \sigma_{LL} + \frac{1}{2}\tau_{TT}\cos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

The Measurement of $F_{\mathrm{eff}}^{\gamma}$ from PLUTO

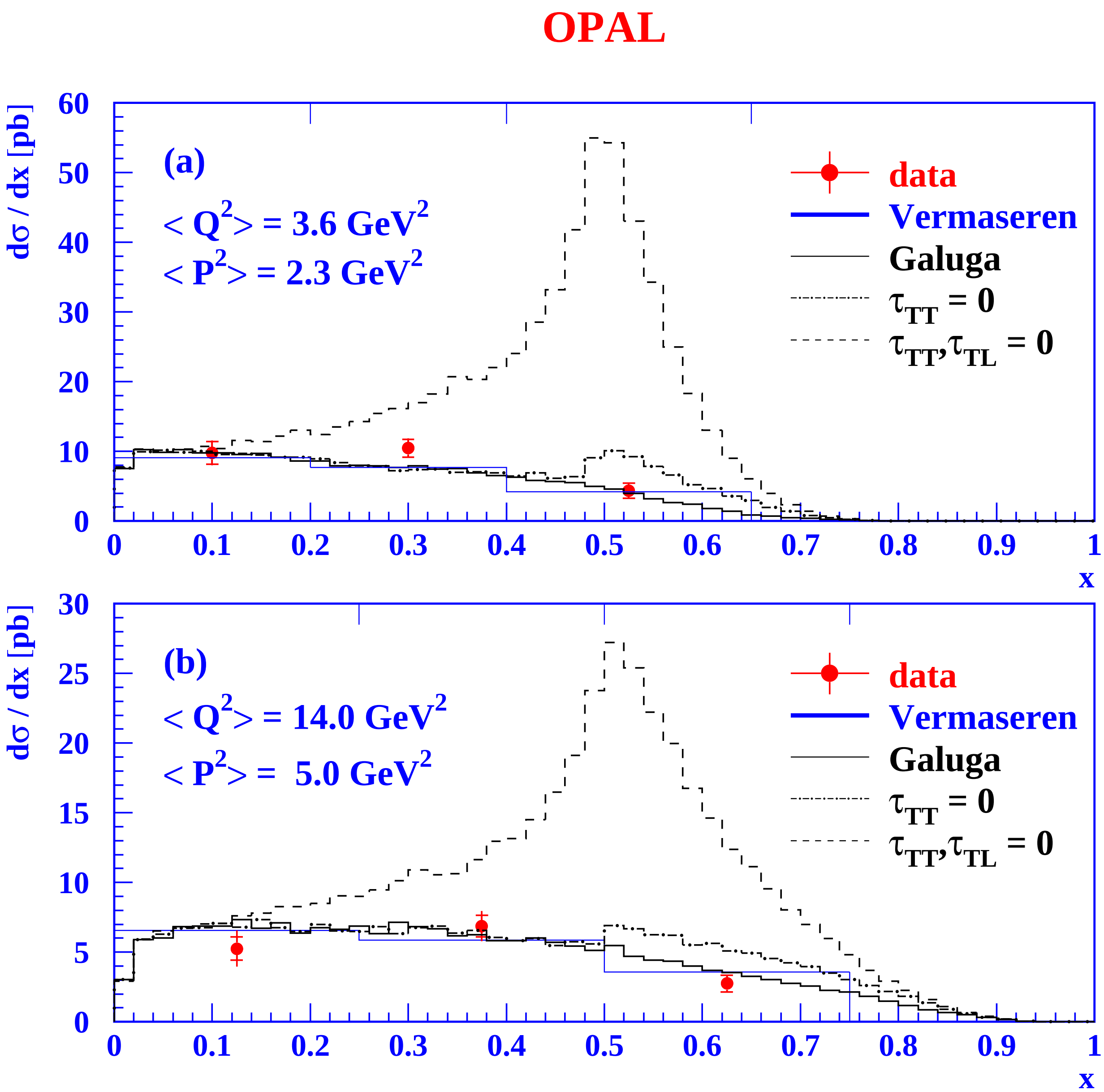




F_2^γ and $F_{\rm eff}^\gamma$ from L3

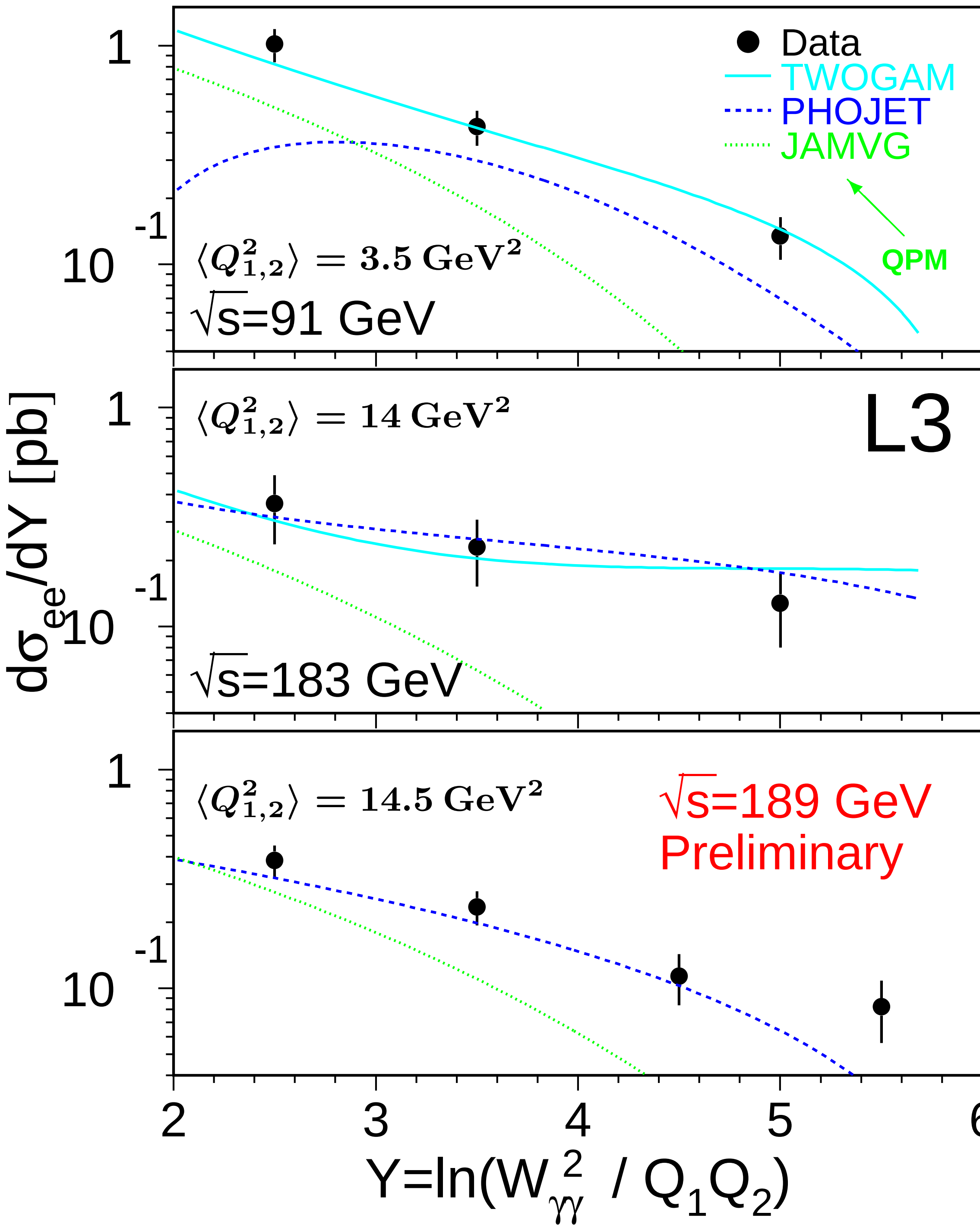


The cross-section for double tags for $ee \to ee\gamma^\star\gamma \to ee\mu^+\mu^-$

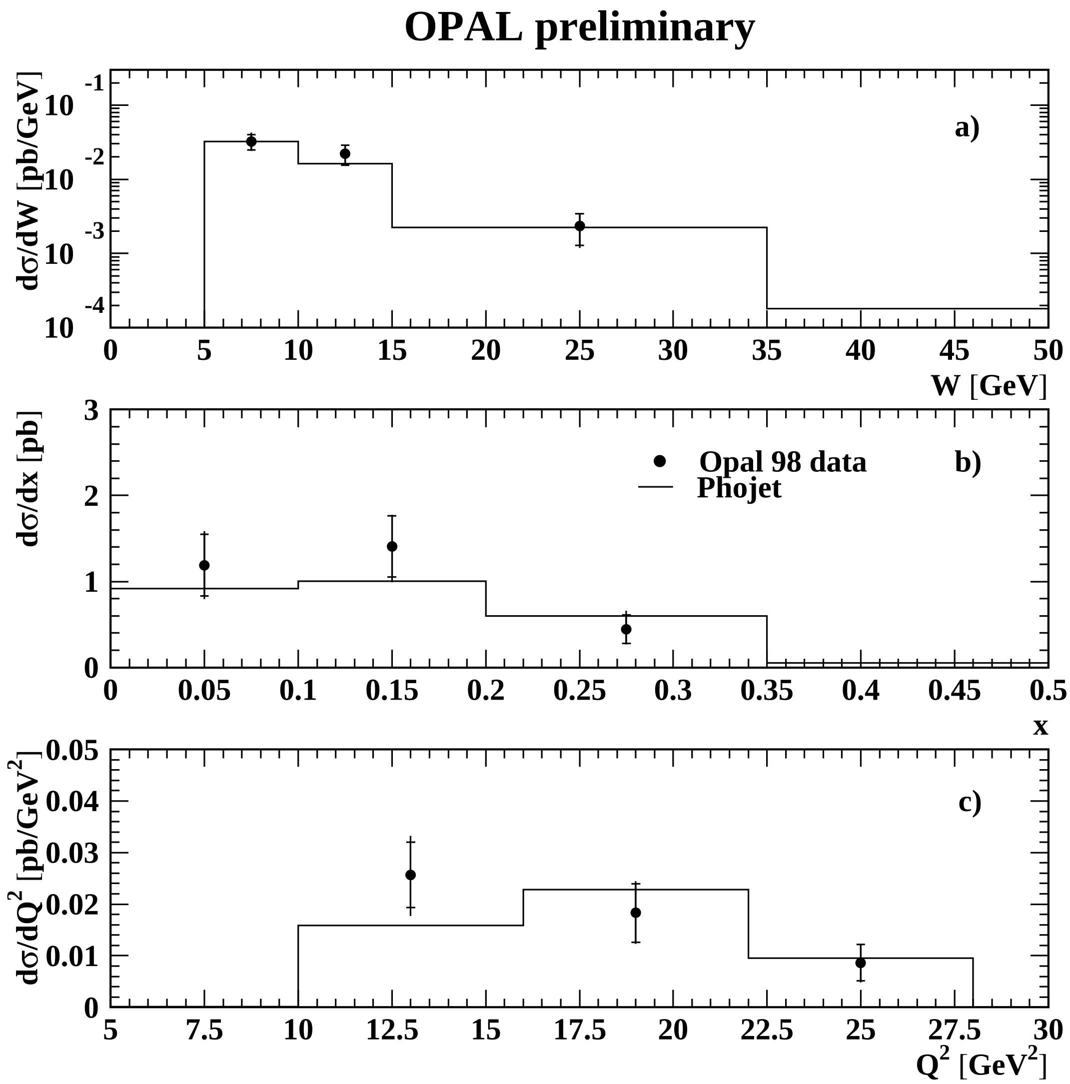


QED agrees well with the data and the presence of the interference terms is clearly seen for the first time.

Cross-section for $ee \longrightarrow ee$ hadrons



Differential cross-sections

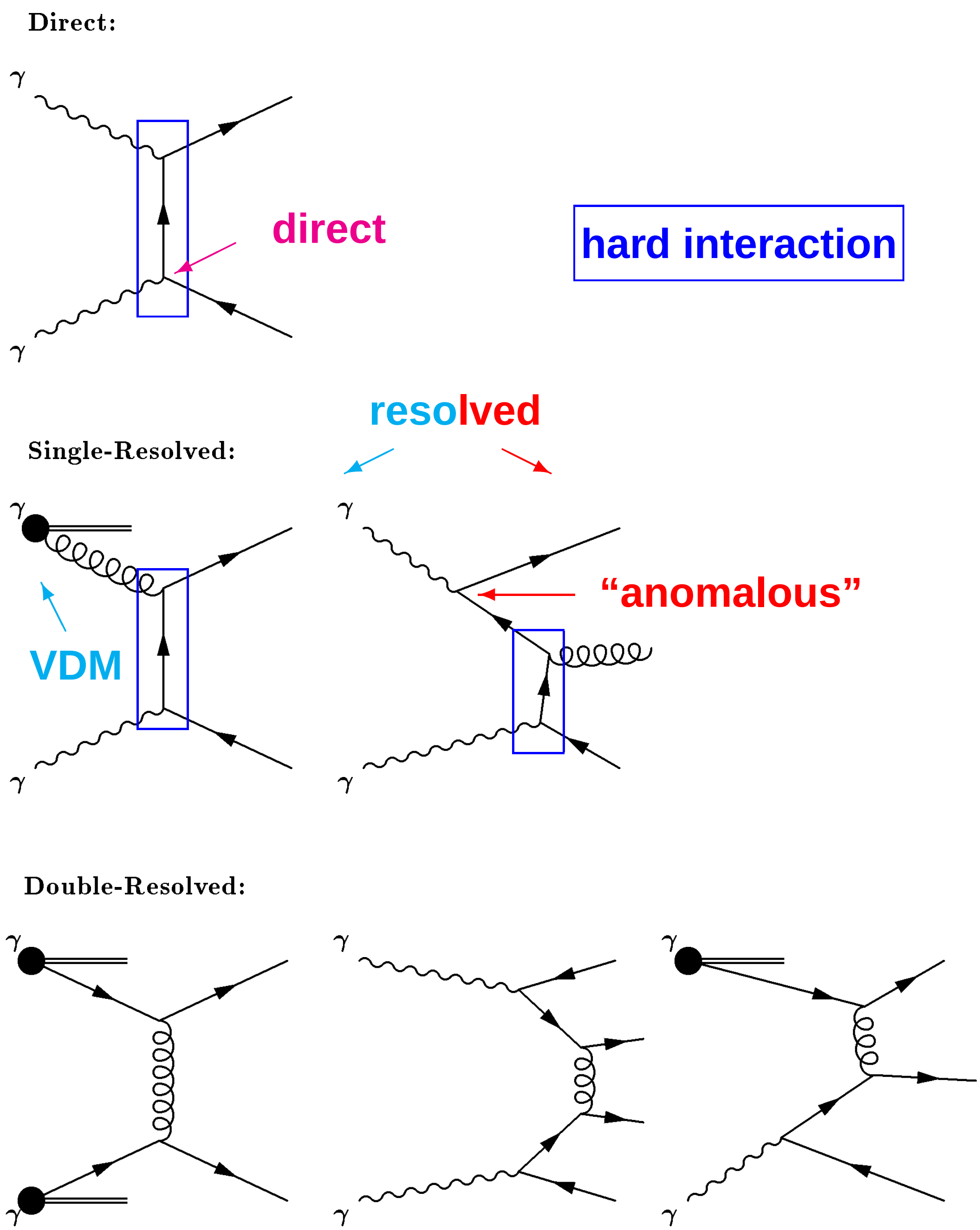


Cross-section corrected to:

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

Cross-section integrated for $2 < Y < 6$ in [pb]				
E	OPAL preliminary	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

Leading order diagrams



Monte Carlo models

PYTHIA and PHOJET

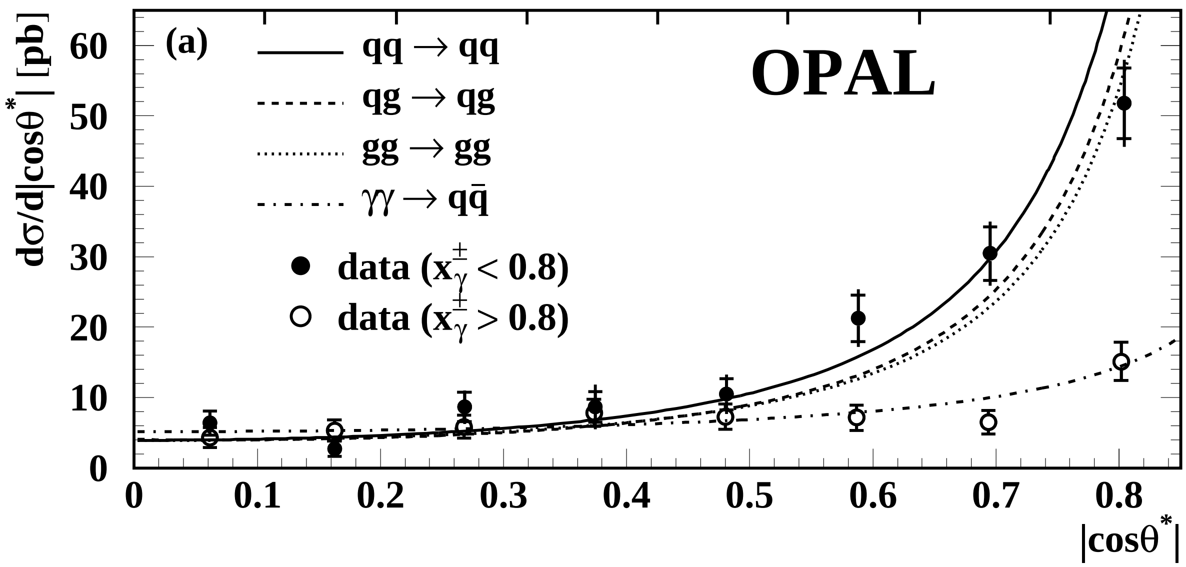
Monte Carlo ingredients:

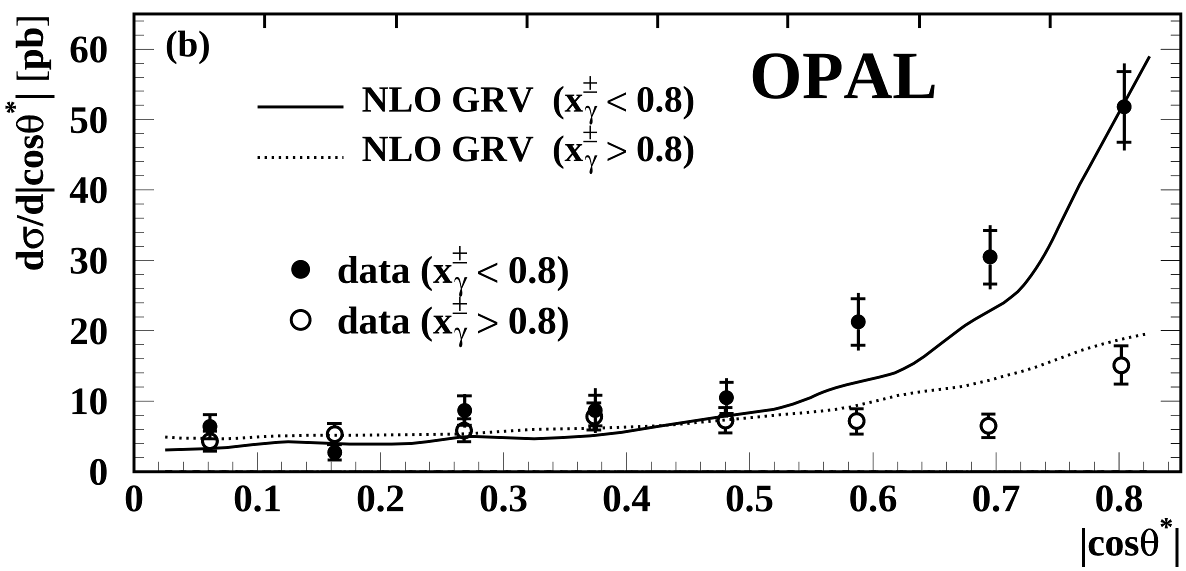
1. Leading order (LO) QCD matrix elements
2. Hard and soft processes
3. Total cross sections from Regge models
4. Initial state parton radiation
5. Fragmentation based on JETSET
6. Multiple interactions

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

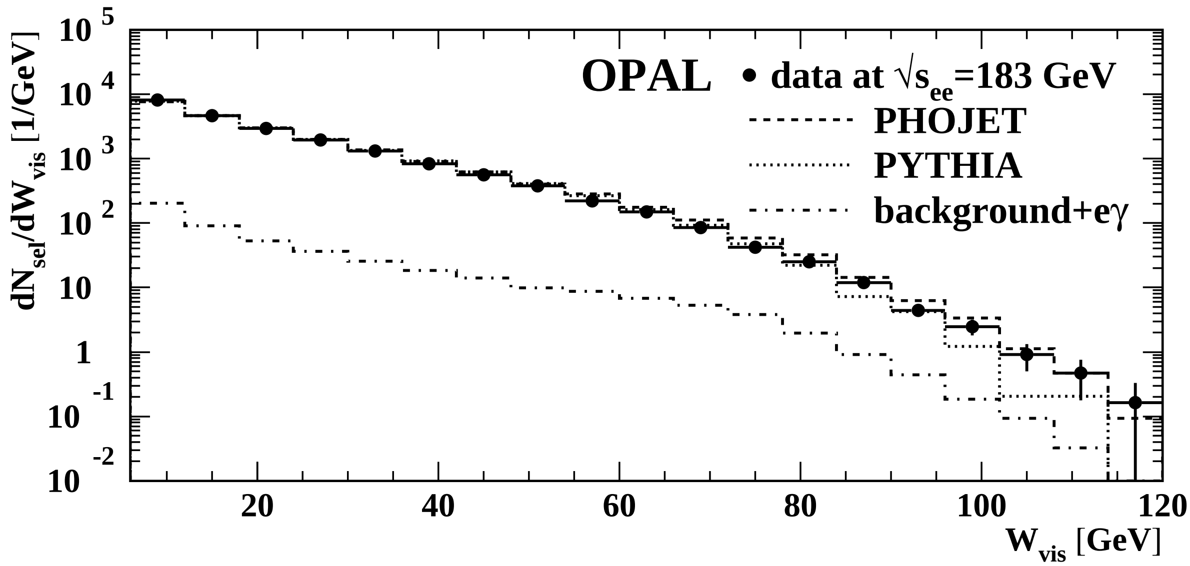
The angular dependencies of different processes

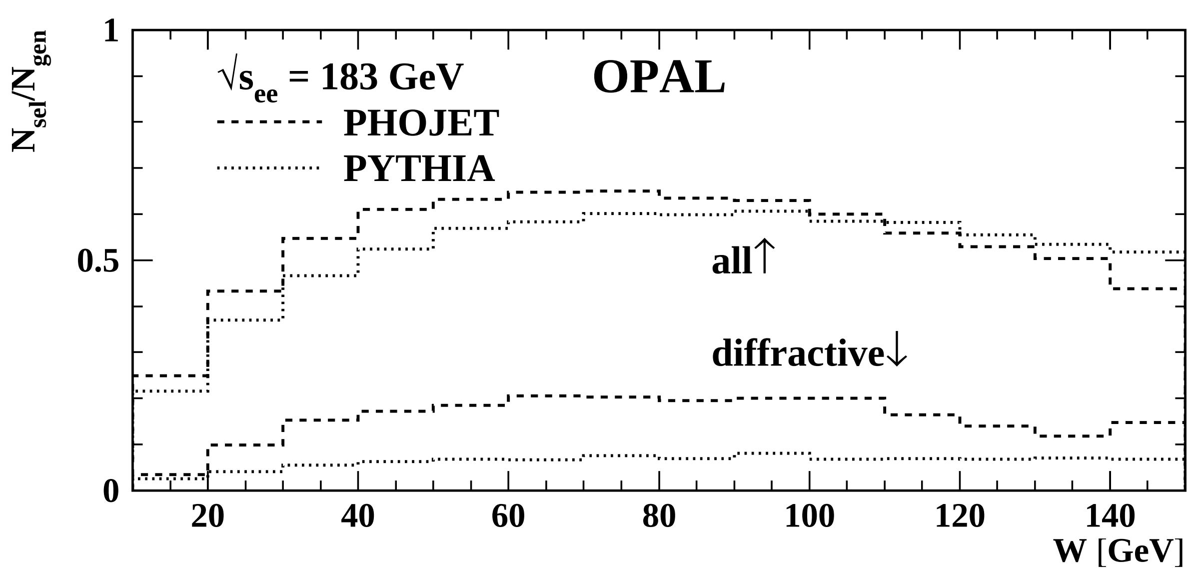




The angular dependencies of the different processes can be clearly disentangled

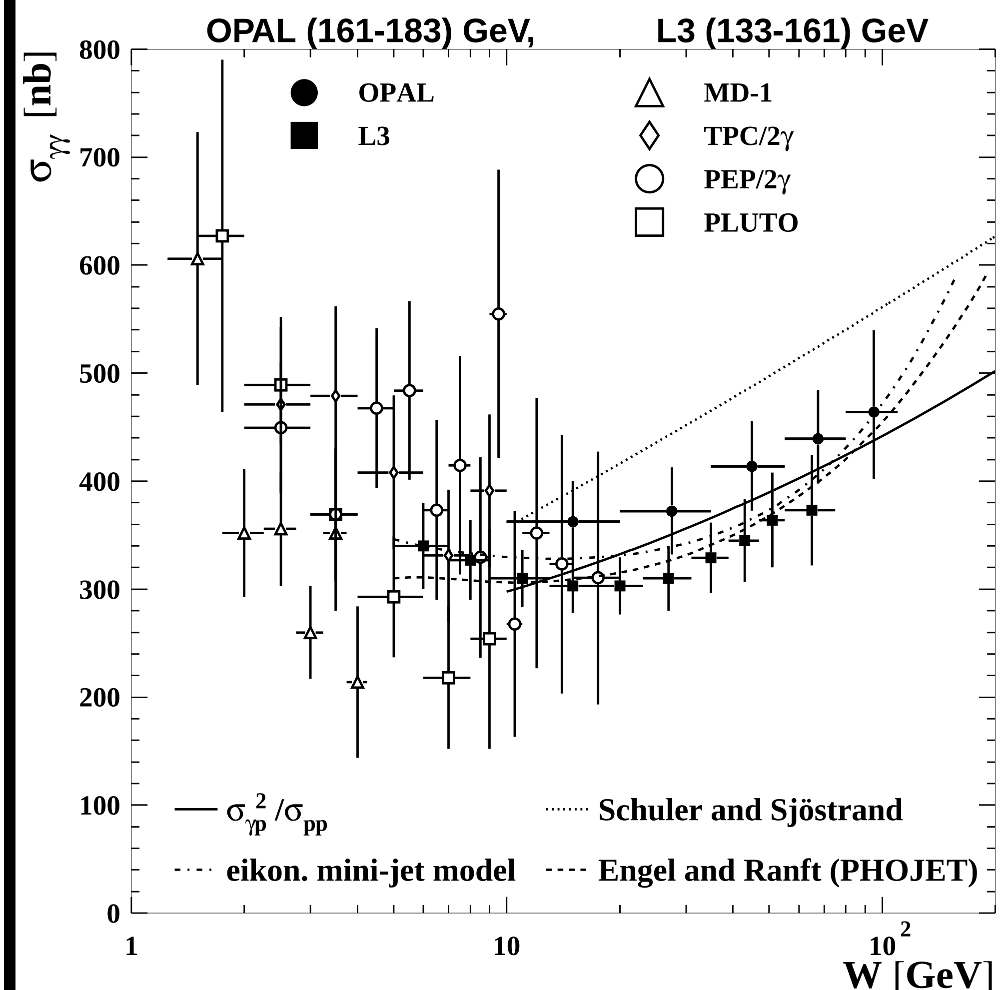
The W distributions for anti-tagged events

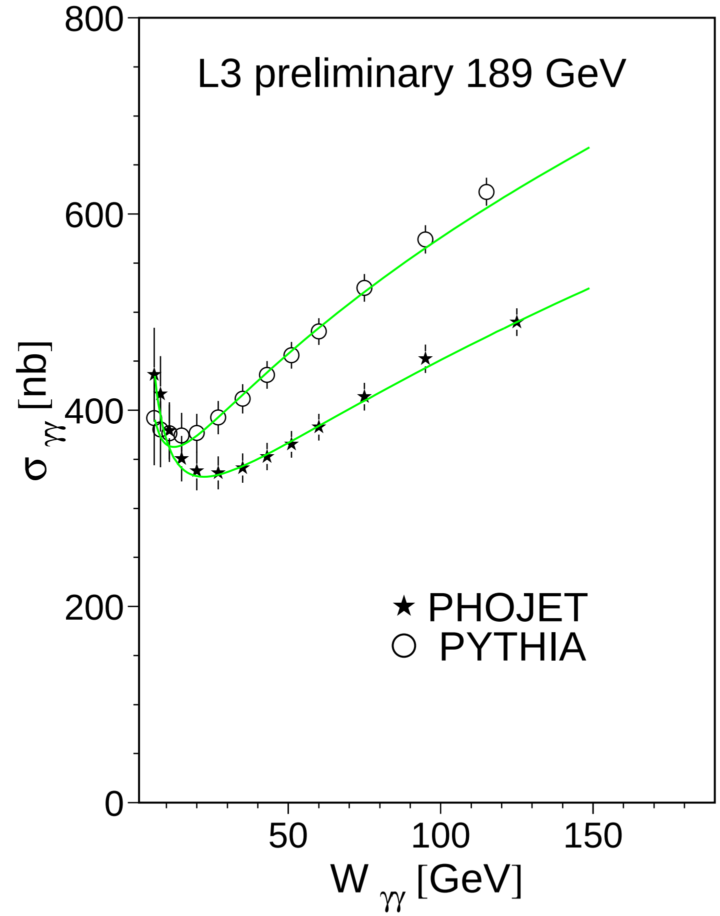




The acceptance for diffractive and elastic events is very different for the Phojet and Pythia models

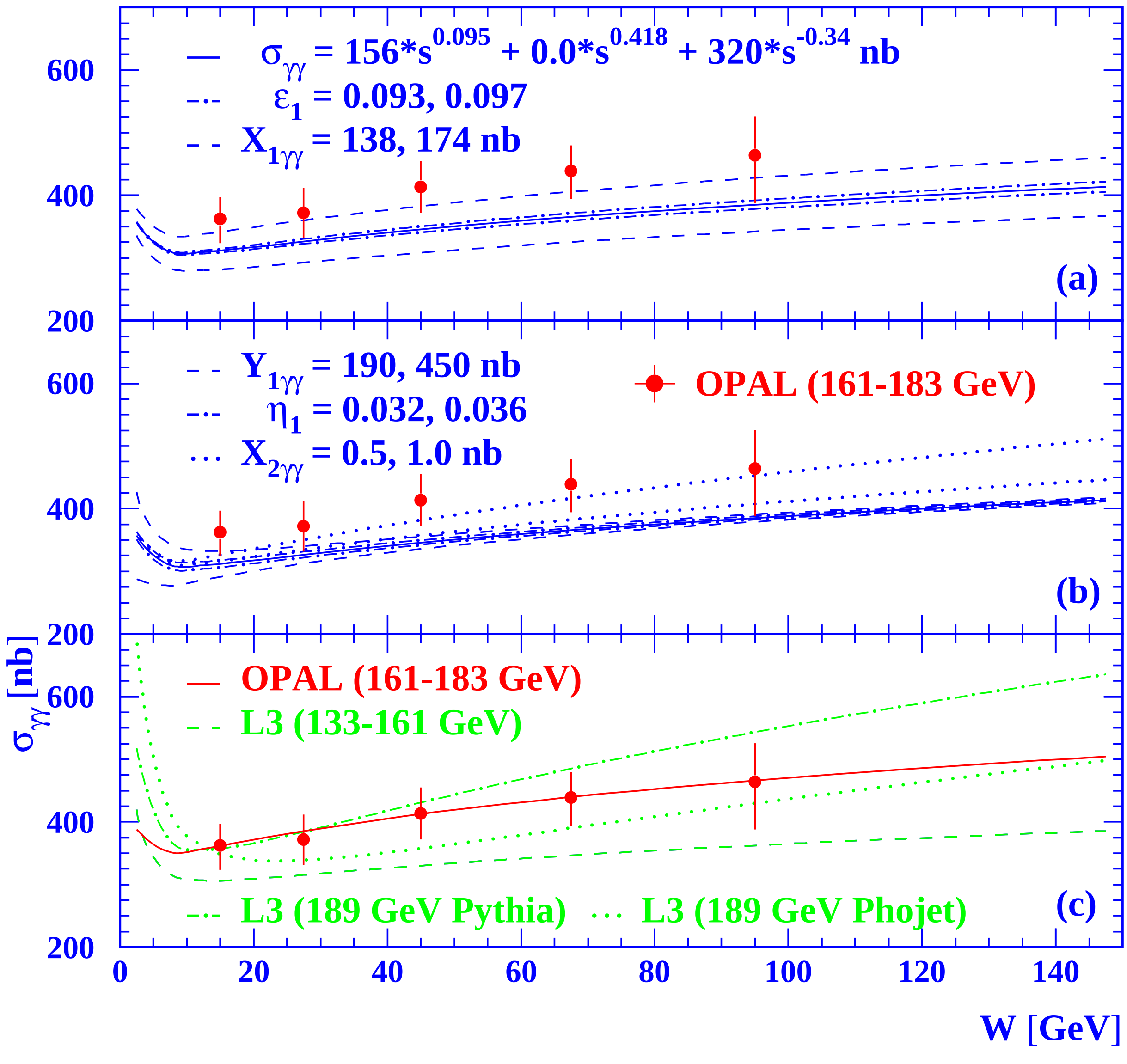
The total hadronic cross-section at various $\sqrt{s_{ee}}$





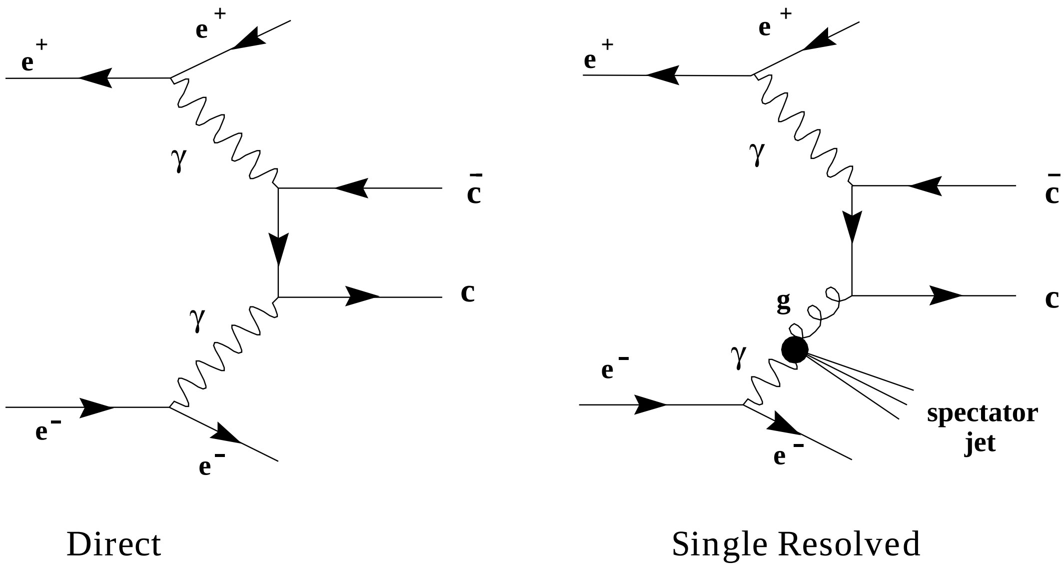
A clear rise of the total cross-section is observed in the data

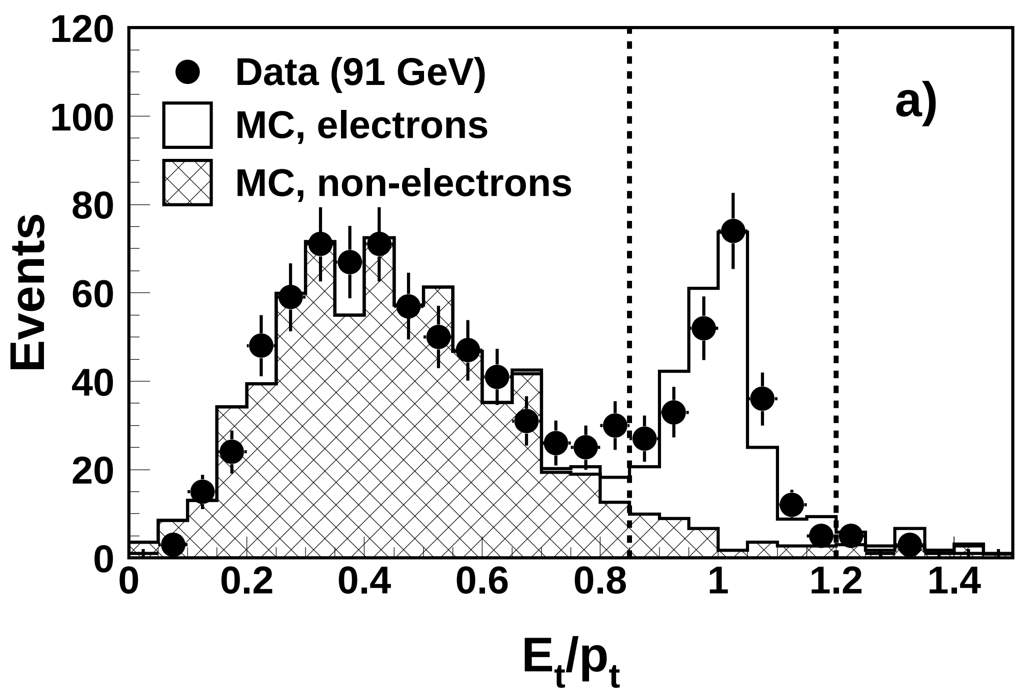
The various fits to $\sigma_{\gamma\gamma}$



A clear rise of the total cross-section is observed in the data. The size of the rise, however, is unclear at the moment.

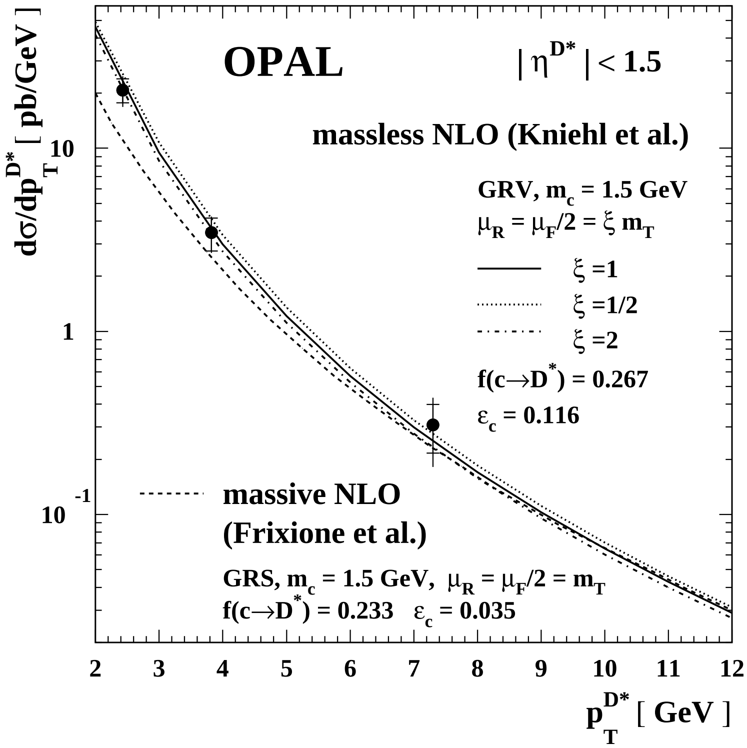
Inclusive charm production

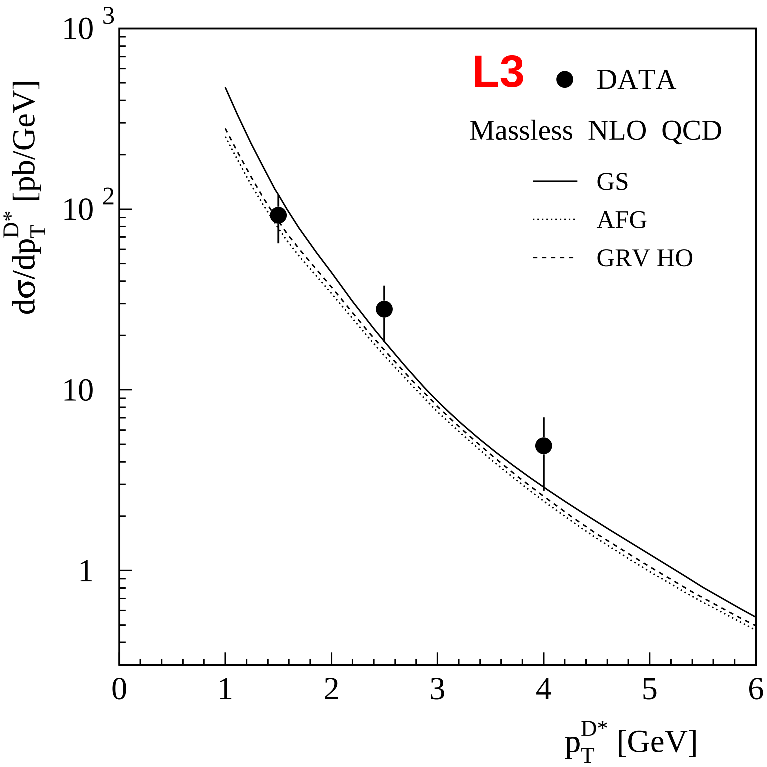




A clear electron signal of the semileptonic charm decays is observed

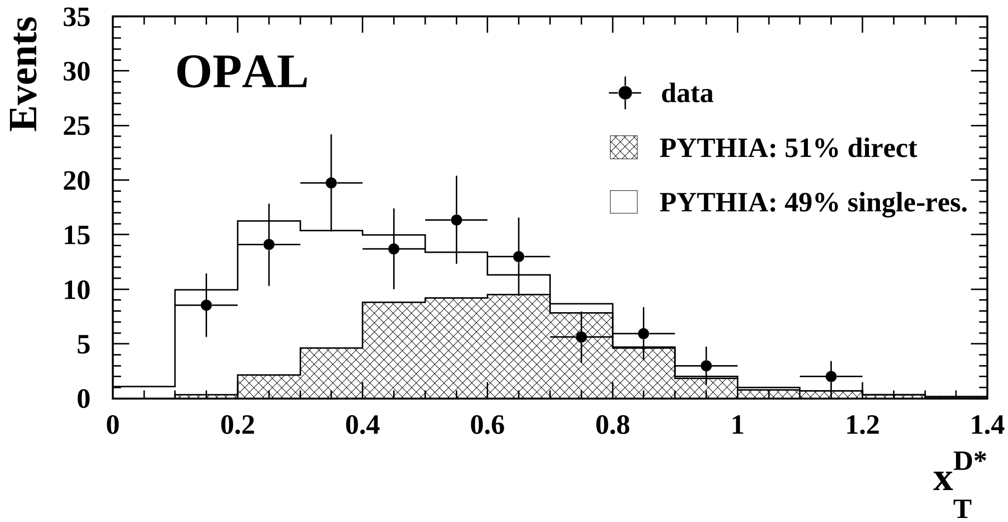
The differential D* cross-section

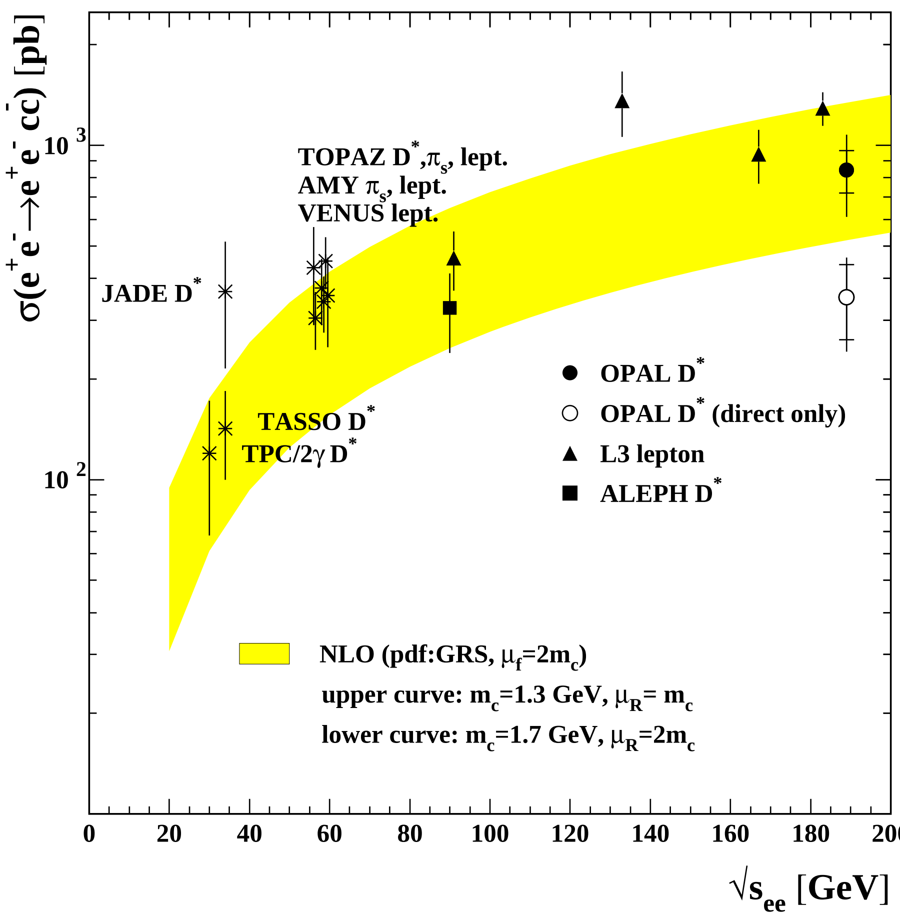




The NLO QCD calculation agrees well with the data.

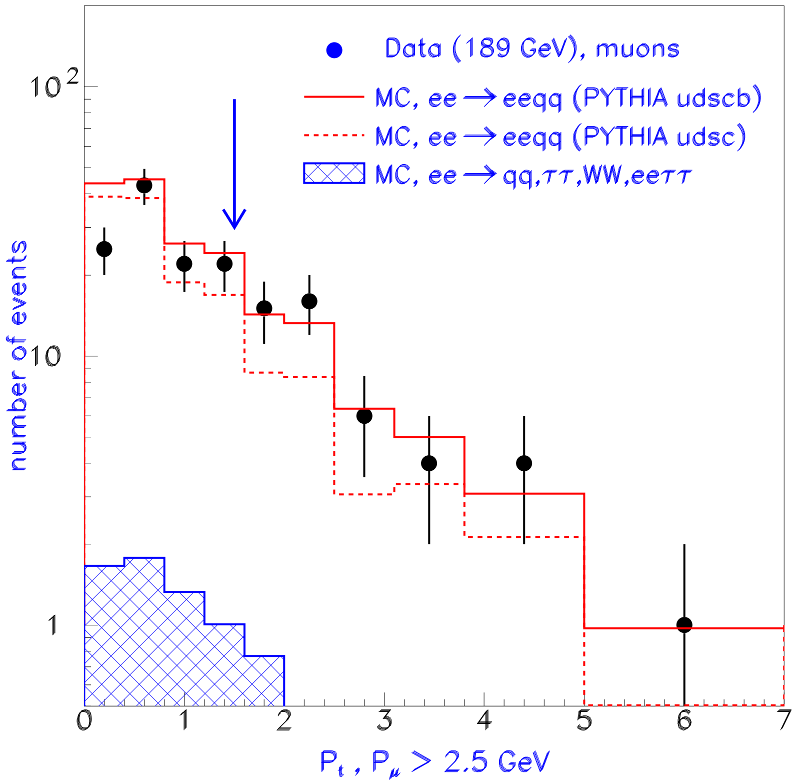
The inclusive charm cross-section





The direct charm production alone is insufficient to describe the data

Search for Bottom production

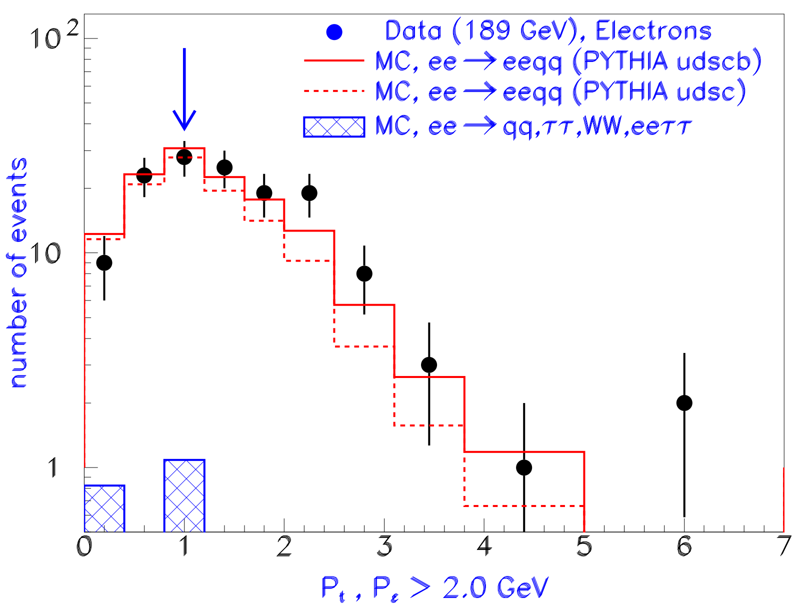


$p_t^{\mu} > 1.5$ GeV

$N_{ev}^{\mu} = 49$

$\epsilon_b^{\mu} = 0.9\%$

$\Pi_b^{\mu} = 34\%$



$p_t^{e} > 1.0$ GeV

$N_{ev}^{e} = 96$

$\epsilon_b^{e} = 1.6\%$

$\Pi_b^{e} = 28\%$

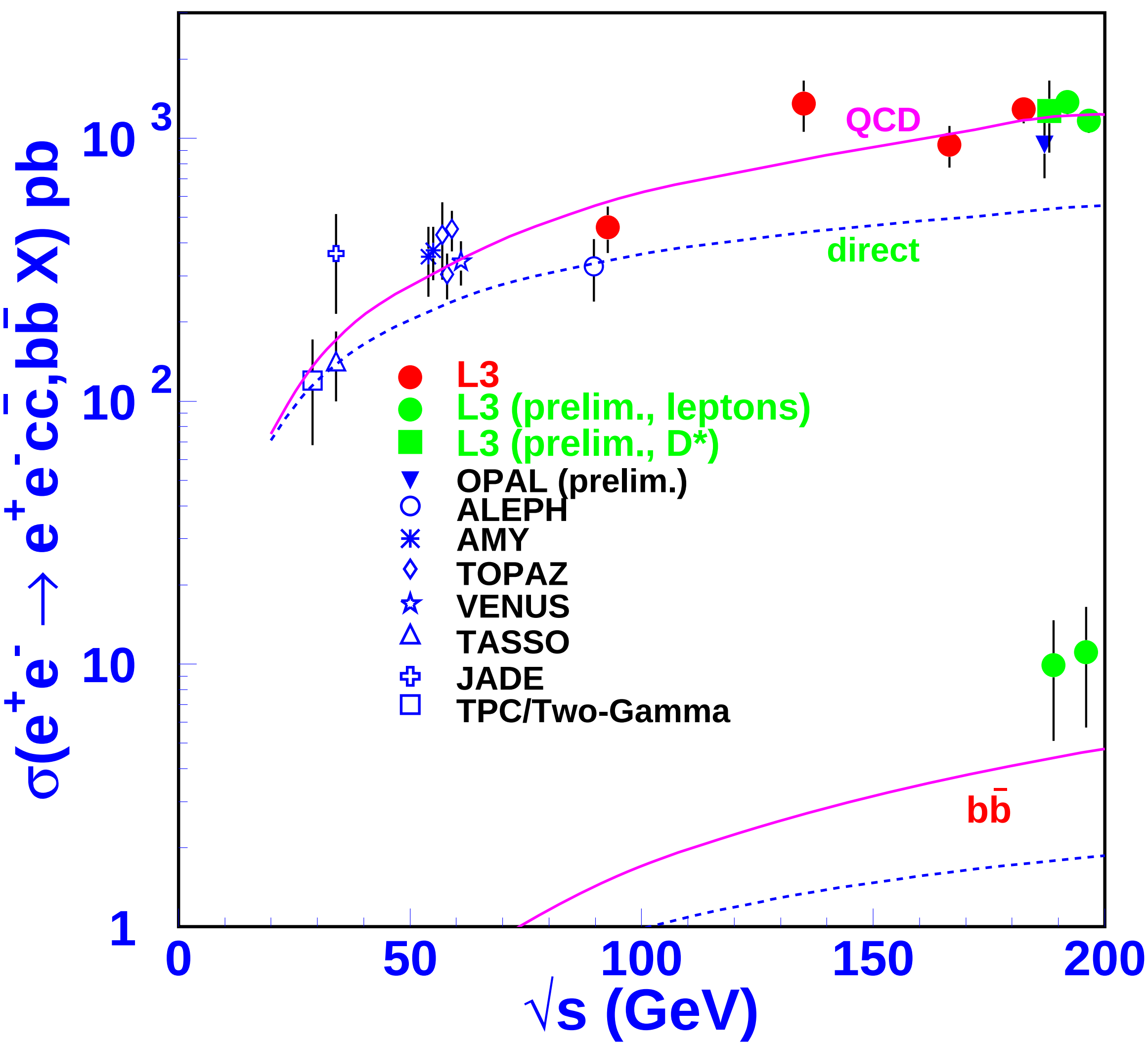
The excess in the tail is attributed to bottom.

Heavy quark production from L3

Results for $\sqrt{s_{ee}} = 189$ GeV

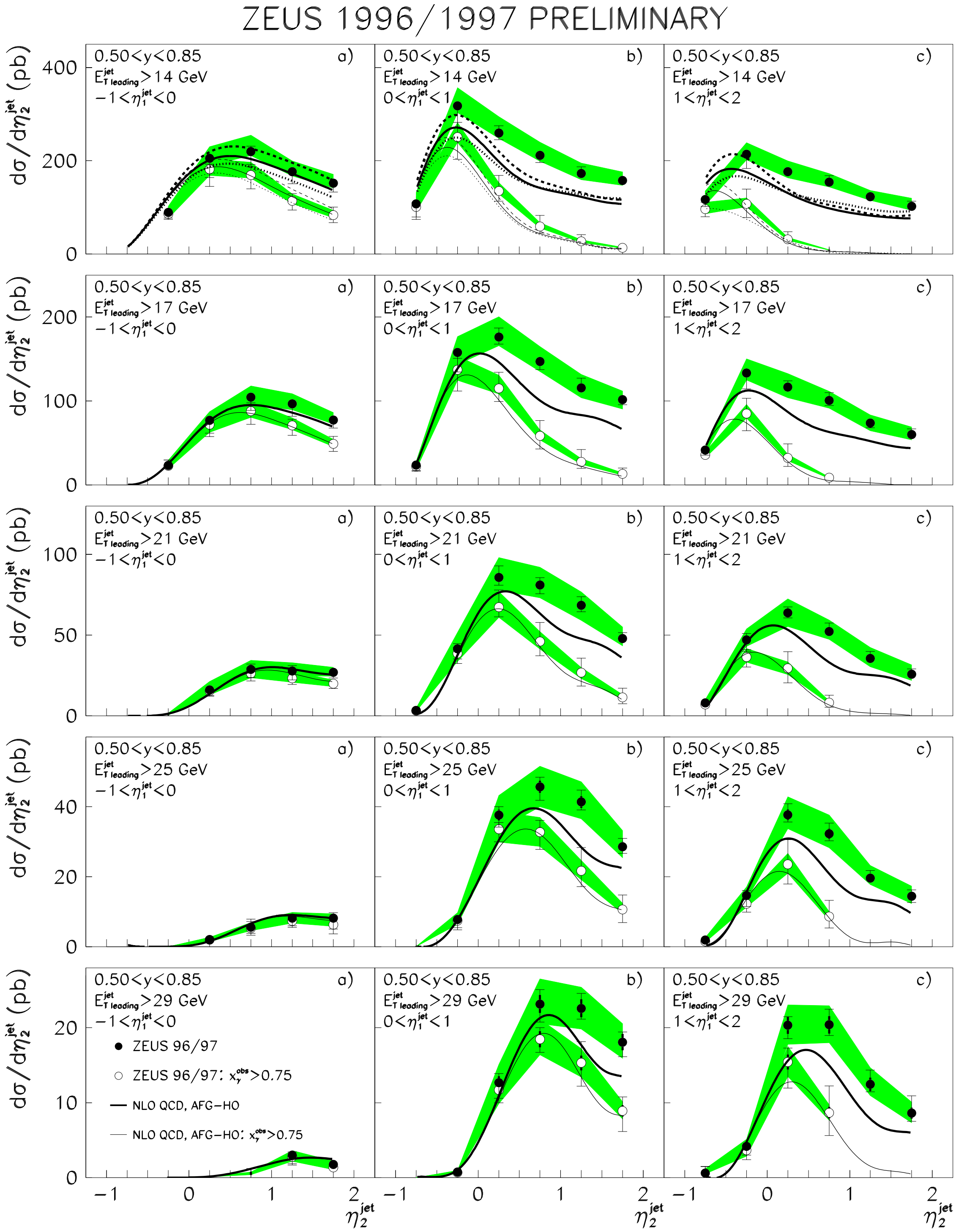
$$\sigma^{\mu}_{b\bar{b}} = 10.3 \pm 4.6(\text{stat}) \pm 3.3(\text{sys})$$
$$\sigma^{e}_{b\bar{b}} = 9.6 \pm 3.6(\text{stat}) \pm 4.1(\text{sys})$$

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



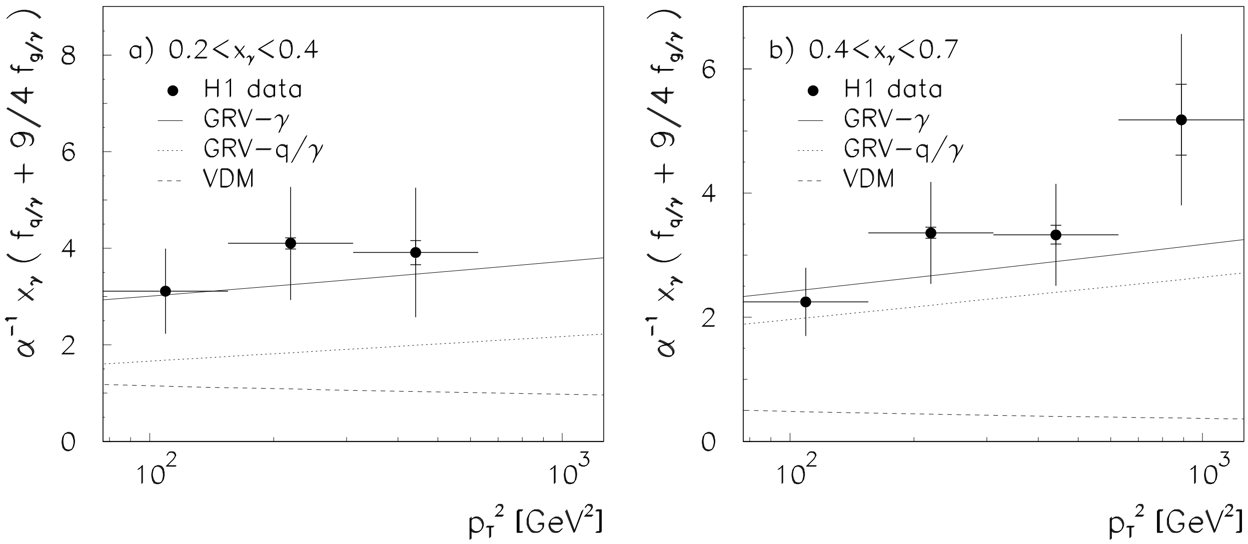
First result on bottom production in $\gamma\gamma$ scattering.

Jet production from ZEUS

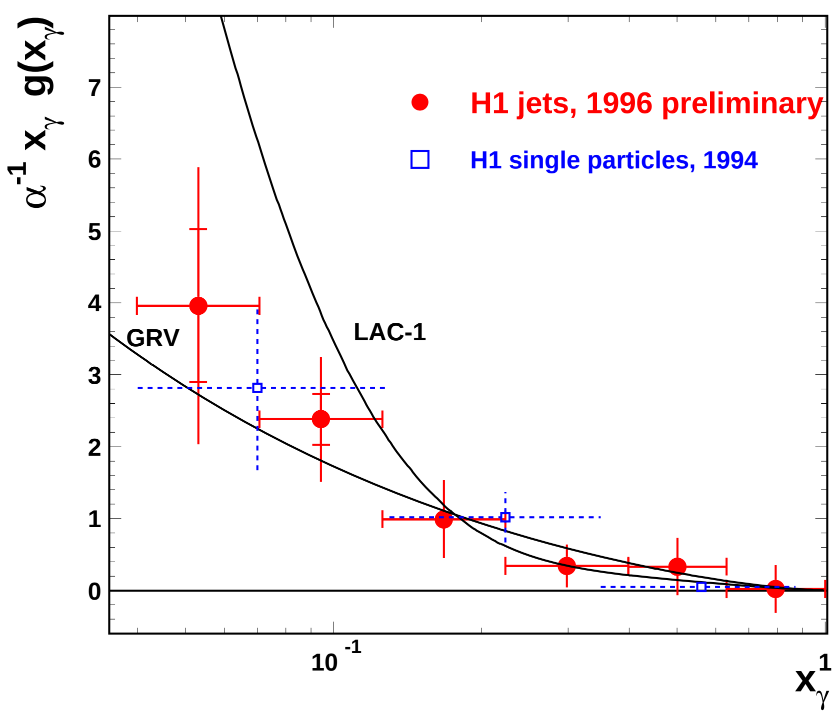


The predictions are too low at medium and large x

Structure of quasi-real photons from H1

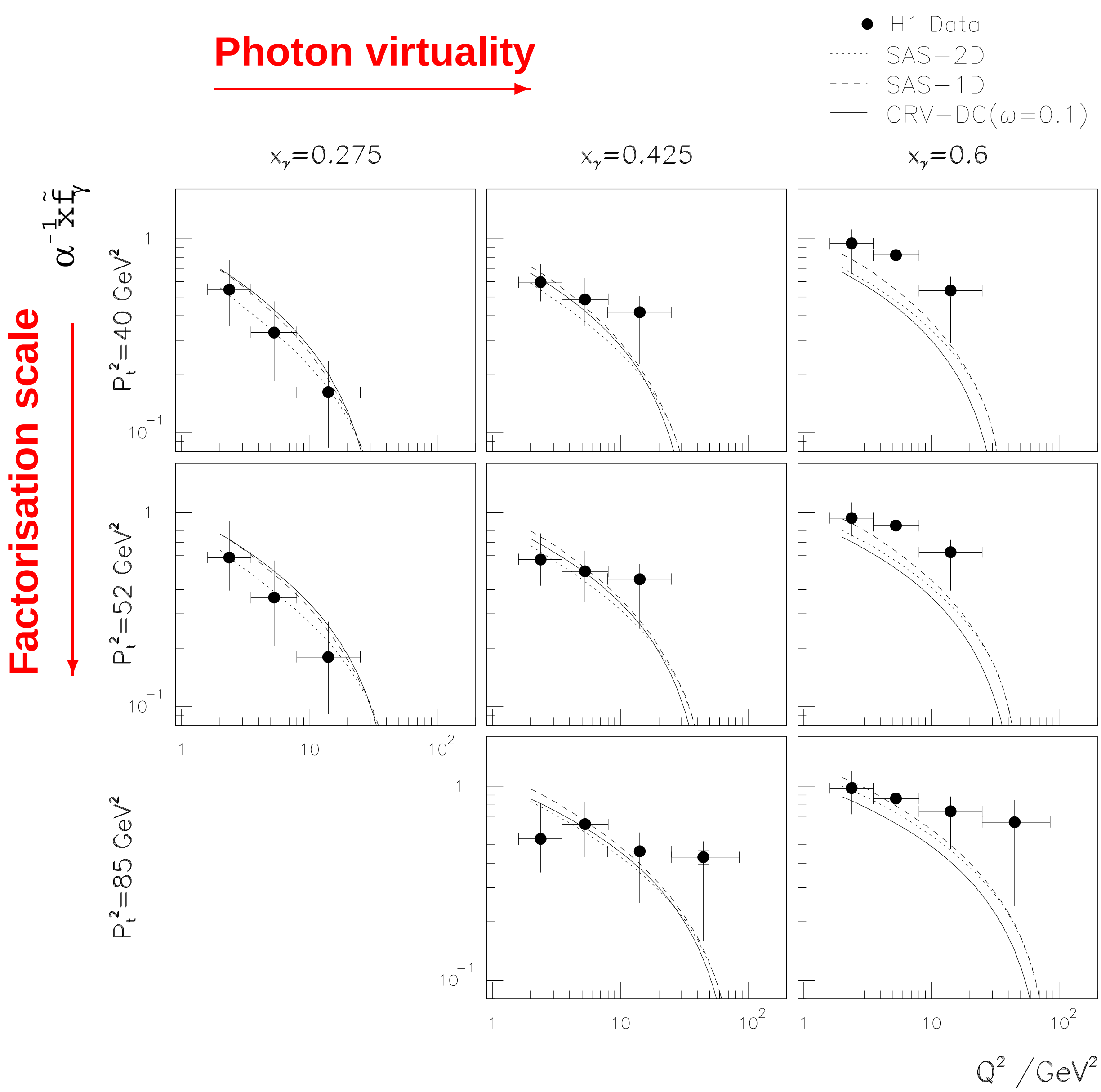


The hadron-like part is too low for all x, and the quark part is not sufficient $\Rightarrow$ gluons are needed.



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 leptonic structure of the photon is well described by QED
   (a) $F^{\gamma}_{2,\mathrm{QED}}$ is accurately predicted 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 differential cross section $\mathrm{d}\sigma/\mathrm{d}x$ for $1.5 < P^2, Q^2 < 20, 30\ \mathrm{GeV}^2$, shows significant contributions from interference terms as predicted by QED.
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^{γ}_{2} is clearly seen and the asymptotic solution is closer to the data than the QPM prediction.
   (c) The low-x behaviour of F^{γ}_{2} is intensively studied.
   (d) The first measurement of $F^{\gamma}_{2,\mathrm{c}}$ has been performed.
   (e) The information on the structure of virtual photons is improved by a new measurement, but is still very limited.
3. Photon-Photon Scattering
   (a) Particle production and jet cross sections are described by NLO calculations, and $\sigma^{\gamma\gamma}_{\mathrm{tot}}$ is found to rise with W.

...continued

(a) The production of charm quarks has been measured, and is satisfactorily described by NLO calculations. The contributions from direct and resolved charm production at LEP2 are of similar size.

(b) The first measurement of bottom production has been performed.

1. Photon Structure from HERA

(a) The measured jet cross-sections indicate a larger quark contribution to F_2^γ at medium to large x than is contained in present parametrisations. It remains to be seen whether both F_2^γ and the jet cross-sections can be accommodated in new global fits.

(b) The gluon distribution function of the photon rises towards low-x and is small at large-x.

(c) The structure of virtual photons is found to die out fast for increasing photon virtuality.

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

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