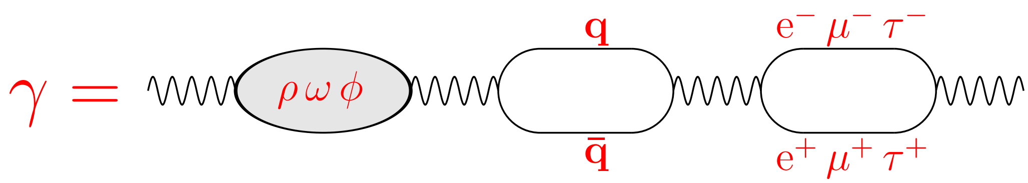
The Structure of the



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03.07.01

- Introduction

1) Electron-Photon Scattering
   a) QED Structure
   b) Hadronic Structure
2) Results from other Reactions
   a) Photon-Photon Scattering
   b) Electron-Proton Scattering at HERA
3) Future Measurements

- Conclusions and Outlook

More information:

http://home.cern.ch/nisius, and
R. Nisius, Phys.Rep. 332 (2000) 165, (hepex/9912049).

The 'history' of the Photon

Date	Event
8.11.1895	Röntgen discovers the X-rays (first Nobel Prize for physics 1901).
1900	Planck interprets light as 'energy quanta' $E = h\,\nu$, with $h = 6.626 \cdot 10^{-34} Js$.
1905	Einstein explains the photoelectric effect by 'photons'.
1922	Discovery of Compton scattering $\mathrm{e}\gamma \longrightarrow \mathrm{e}'\gamma'$.
1927	Heisenberg formulates the uncertainty principle e. g. $\Delta E \Delta t \geq \hbar$.
1930	Fist attempt to measure photon-photon scattering by Hughes et. al.
1936	First calculation of photon-photon scattering by Euler und Kockel.
1981	First measurement of the hadronic structure function of the photon by PLUTO.
2011	The Higgs Boson will be produced through photon-photon fusion at TESLA?

Properties of the photon

Property	
Mass (m)	$0 \quad (m/m_e < 4 \cdot 10^{-22}$, [1])
Charge (Q)	$0 \quad (Q/Q_e < 5 \cdot 10^{-30}$, [2])
Velocity (c)	299792458 m/s
Spin parity (J^{PC})	1^{--}
Coupling (α)	$1/137.03599976(50)$
Task	Carrier of the electromagnetic interaction, no self-coupling

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[1] Roderic Lakes, Phys. Rev. Lett. 80 (1998) 1826.

[2] Georg Raffelt, Phys. Rev. D50 (1994) 7792.

Photon-photon scattering anno 1930

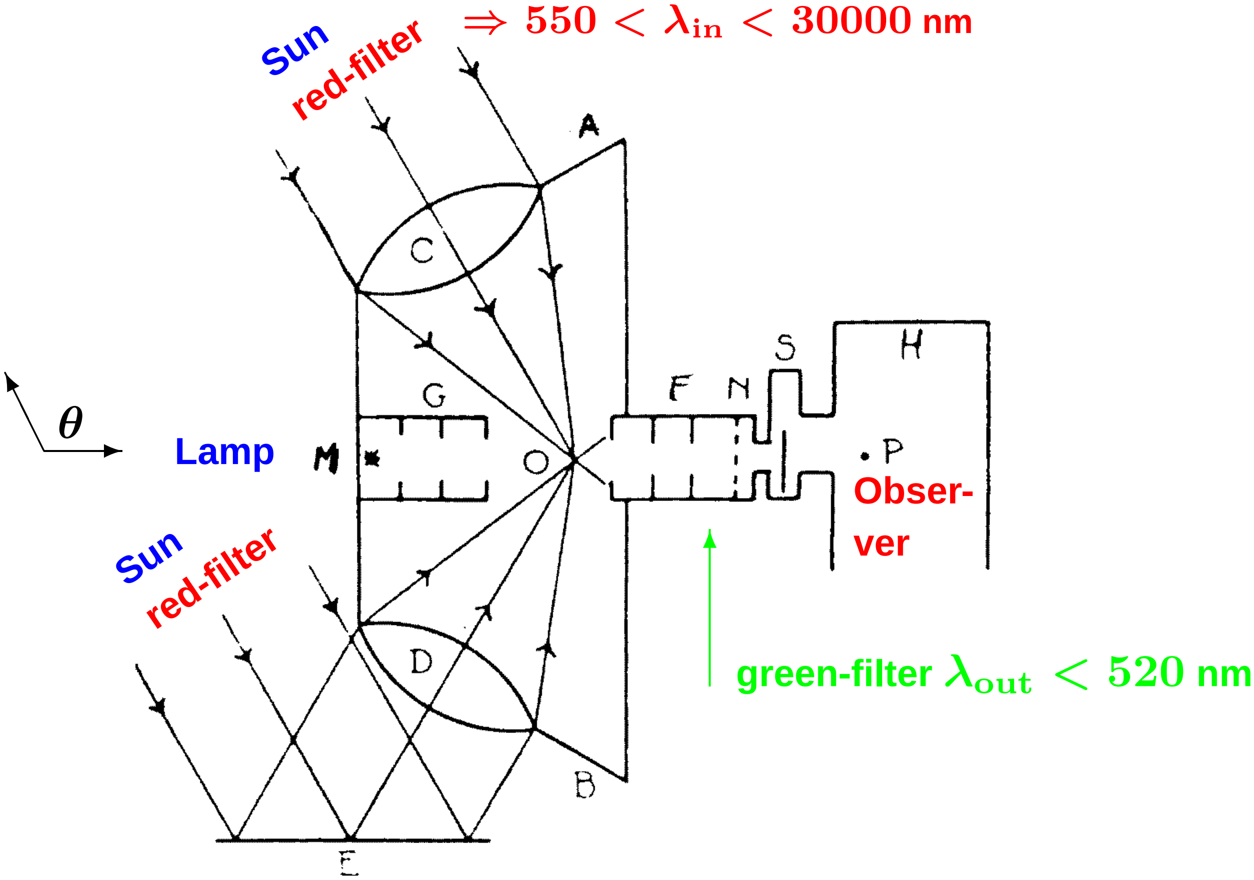


Fig. 2. Diagram of apparatus.

$$\gamma_1(\lambda_{in})\gamma_2(\lambda_{in}) \rightarrow \gamma_1'(\lambda_{out})\gamma_2'(\lambda_{out})$$

with: $$\lambda_{out} = \lambda_{in}(1+\cos\theta)$$

No light was observed.

$$\Rightarrow \sigma_{\gamma\gamma\to\gamma\gamma} < 3\cdot 10^8 \text{ pb}$$

A.L. Hughes and G.E.M. Jauncey, Phys.Rev. 36 (1930) 773.

The photon in our world

Observation	photon energy
	meV
Rotations of molecules	
	eV
Spectrum of the sun	
Hydrogen atomic spectra	
	keV
X-ray radiation	
	MeV
e^+e^- pair creation	
	GeV
⇒ Bremsstrahlung at LEP	⇐
	TeV
Cosmic rays	

The photon in the standard model

The building blocs of matter

Quarks $\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$

Leptons $\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$

Interactions of matter via gauge bosons

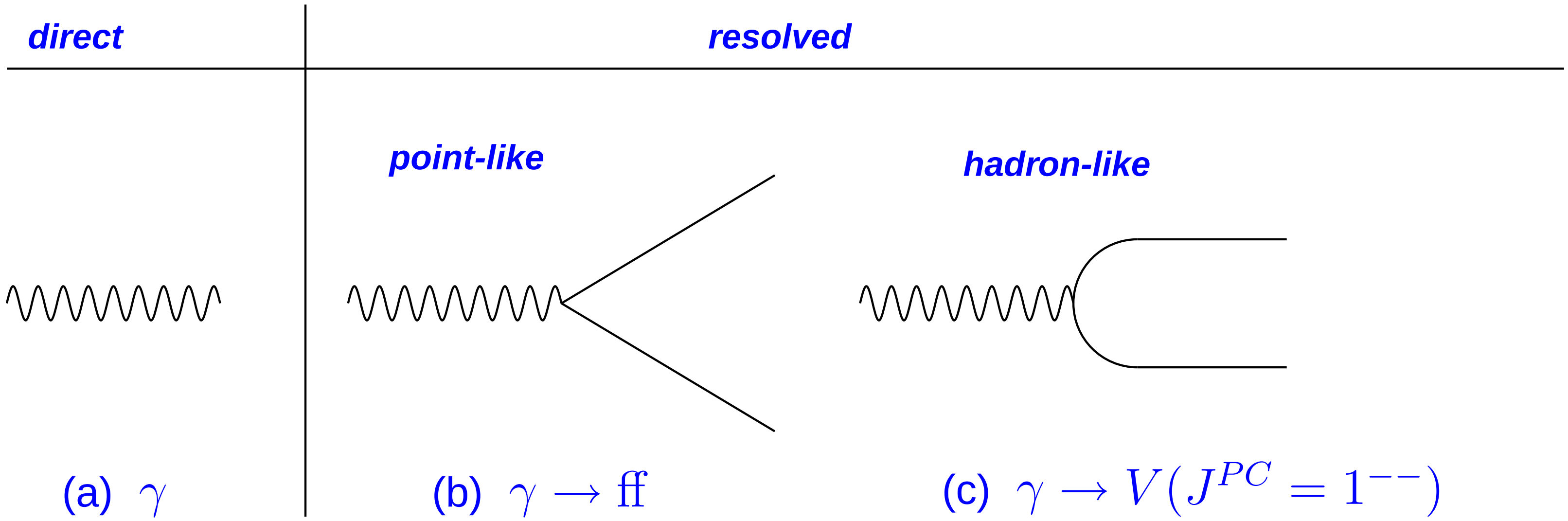
Photon (γ), $W^{\pm}$ and Z^0 bosons and gluons

Gauge boson measurements at LEP

Object	Measurement
Z^0	Precision measurements at LEP100
$W^{\pm}$	M_W to $40\ \mathrm{MeV}$ by LEP200
Gluons	QCD coupling α_s (M_{Z^0}) to about 5% at LEP100
Photon	Photon structure to $10-30\%$ at LEP100$-$200

Measurements of the photon structure give insight into a fundamental gauge boson of the standard model.

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

Predictions for the photon structure

QED structure

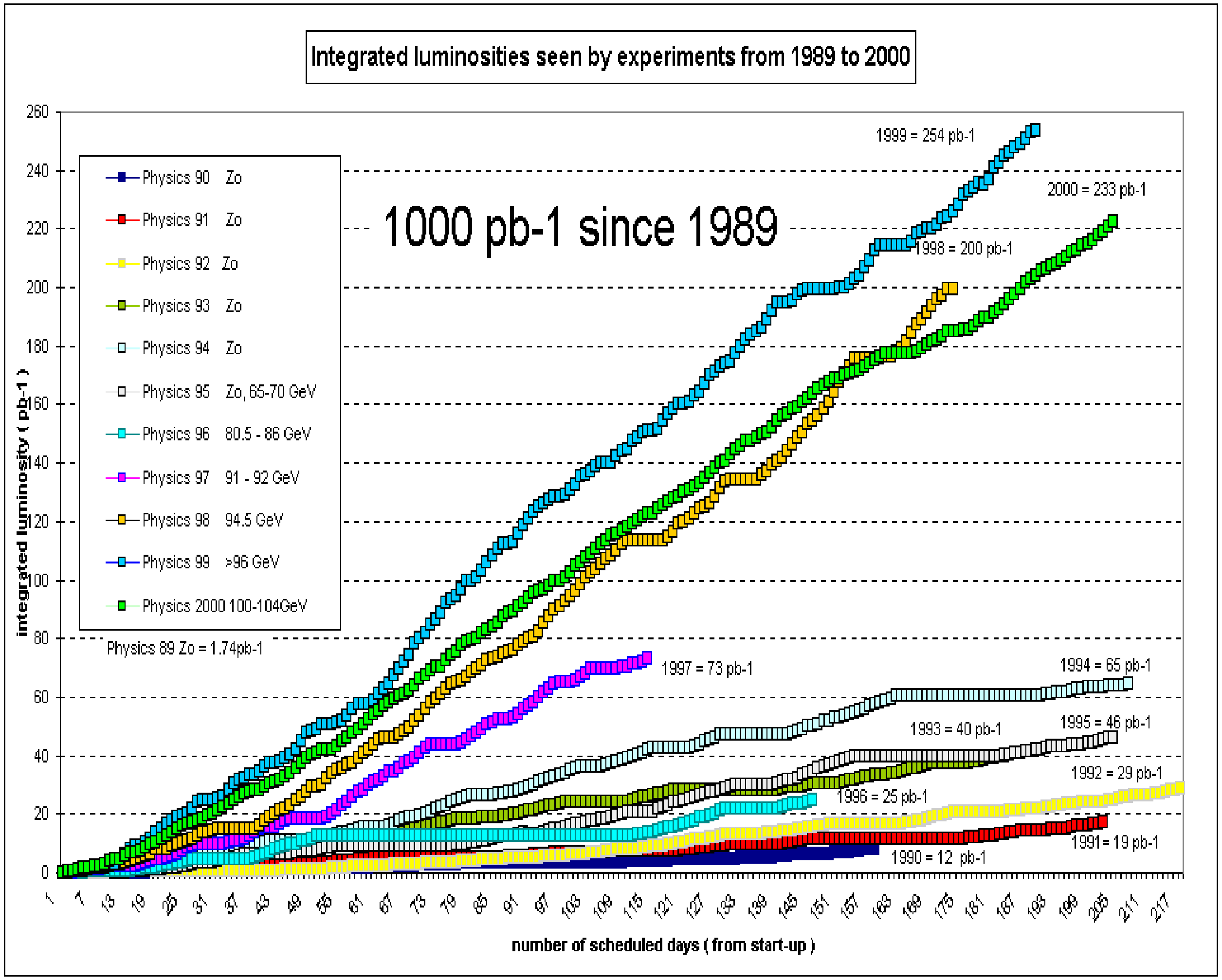
1. The point-like component leads to a rise of the QED structure at large x.
2. The structure of virtual photons is suppressed.
3. Interference terms are important for virtual photons.
4. $\cdots$

Hadronic structure

1. QCD predicts the charm production at large x at NLO accuracy.
2. The QCD dynamics enforces a steep rise of the photon structure for small values of x, at fixed Q^2.
3. The evolution of the photon structure exhibits a positive slope for all values of x.
4. $\cdots$

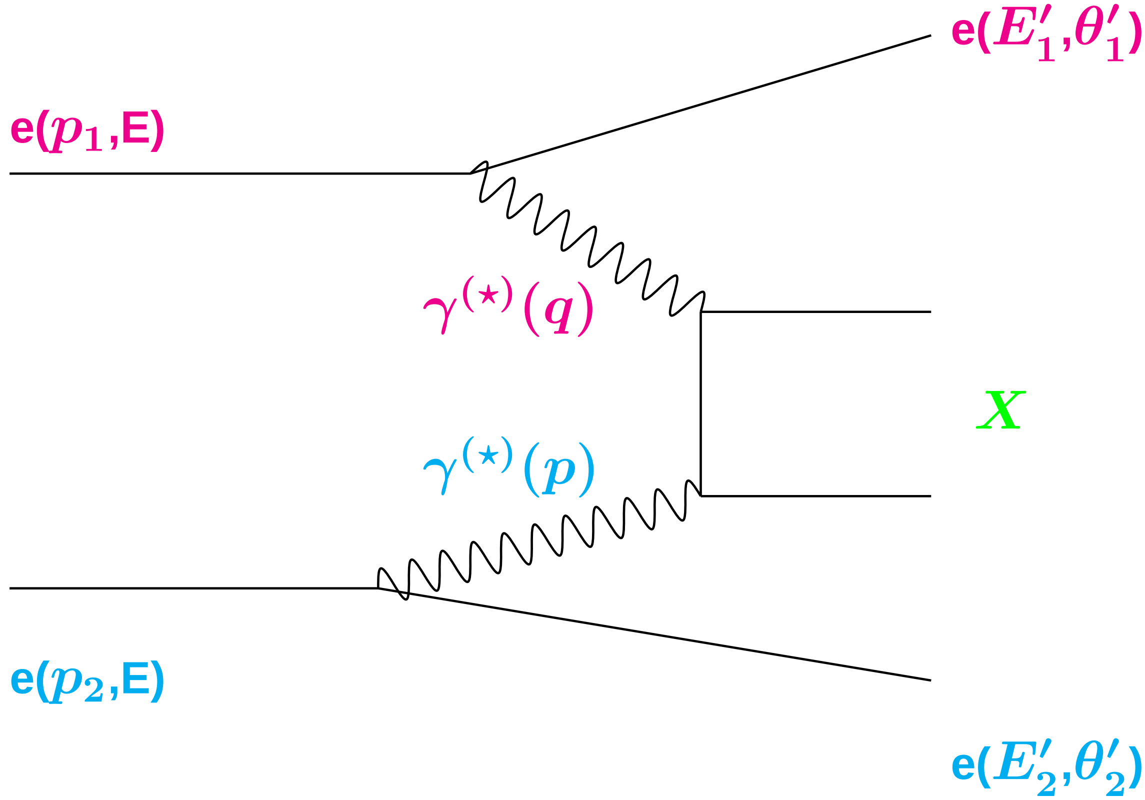
The LEP Accelerator

The integrated luminosities



The integrated luminosity of the LEP programme exceeds 1000 pb^{-1}.

Die Reaktion $e\,e \longrightarrow e\,e\,X$



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

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

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

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

The limit of deep inelastic electron-photon scattering

Using:

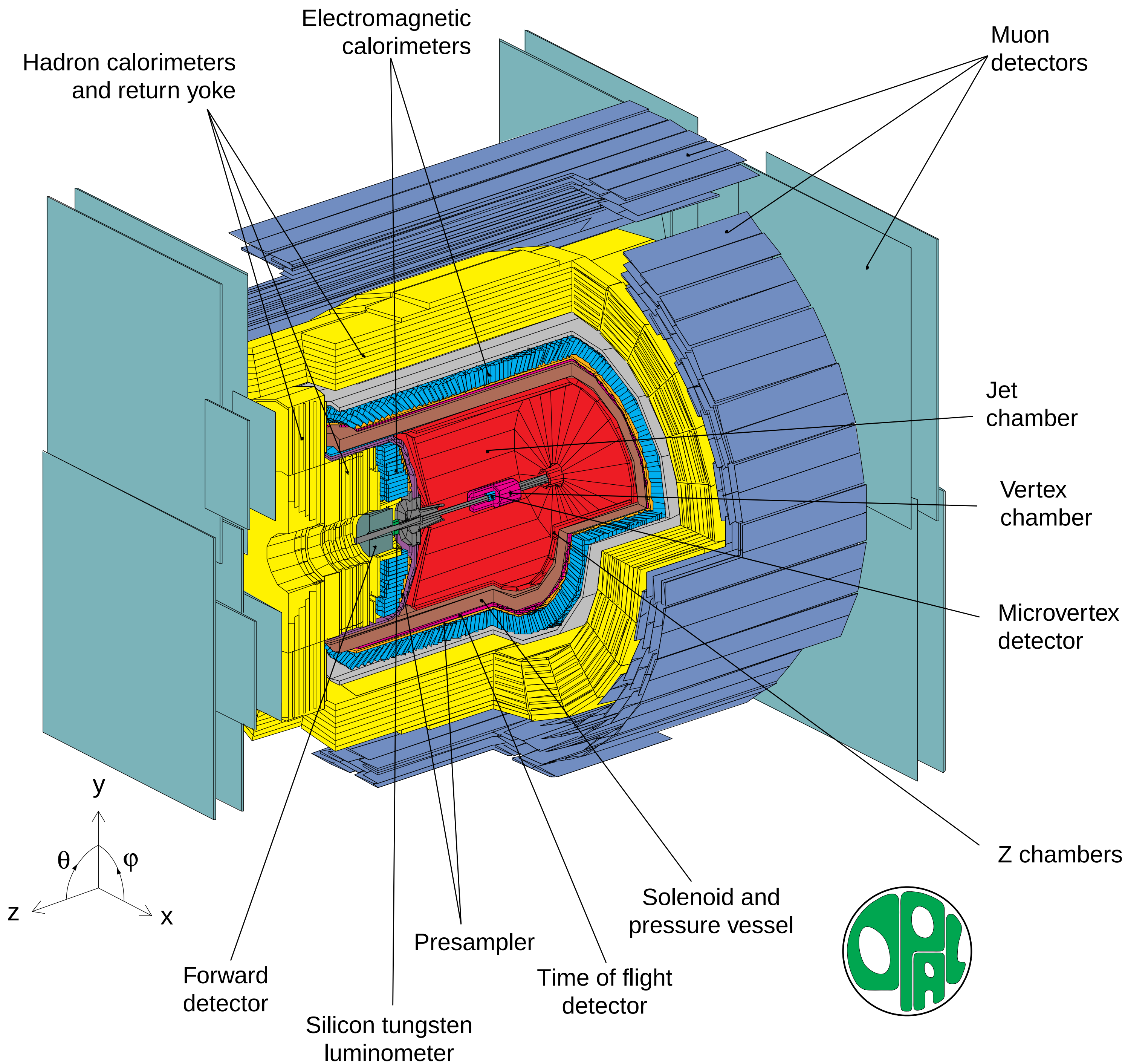
$$\begin{aligned} 2xF_{\mathrm{T}}^{\gamma} &= \frac{Q^2}{4\pi^2\alpha}\,\sigma_{\mathrm{TT}}(x,Q^2) \\ F_{\mathrm{L}}^{\gamma} &= \frac{Q^2}{4\pi^2\alpha}\,\sigma_{\mathrm{LT}}(x,Q^2) \\ F_2^{\gamma} &= 2xF_{\mathrm{T}}^{\gamma} + F_{\mathrm{L}}^{\gamma} \end{aligned}$$

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

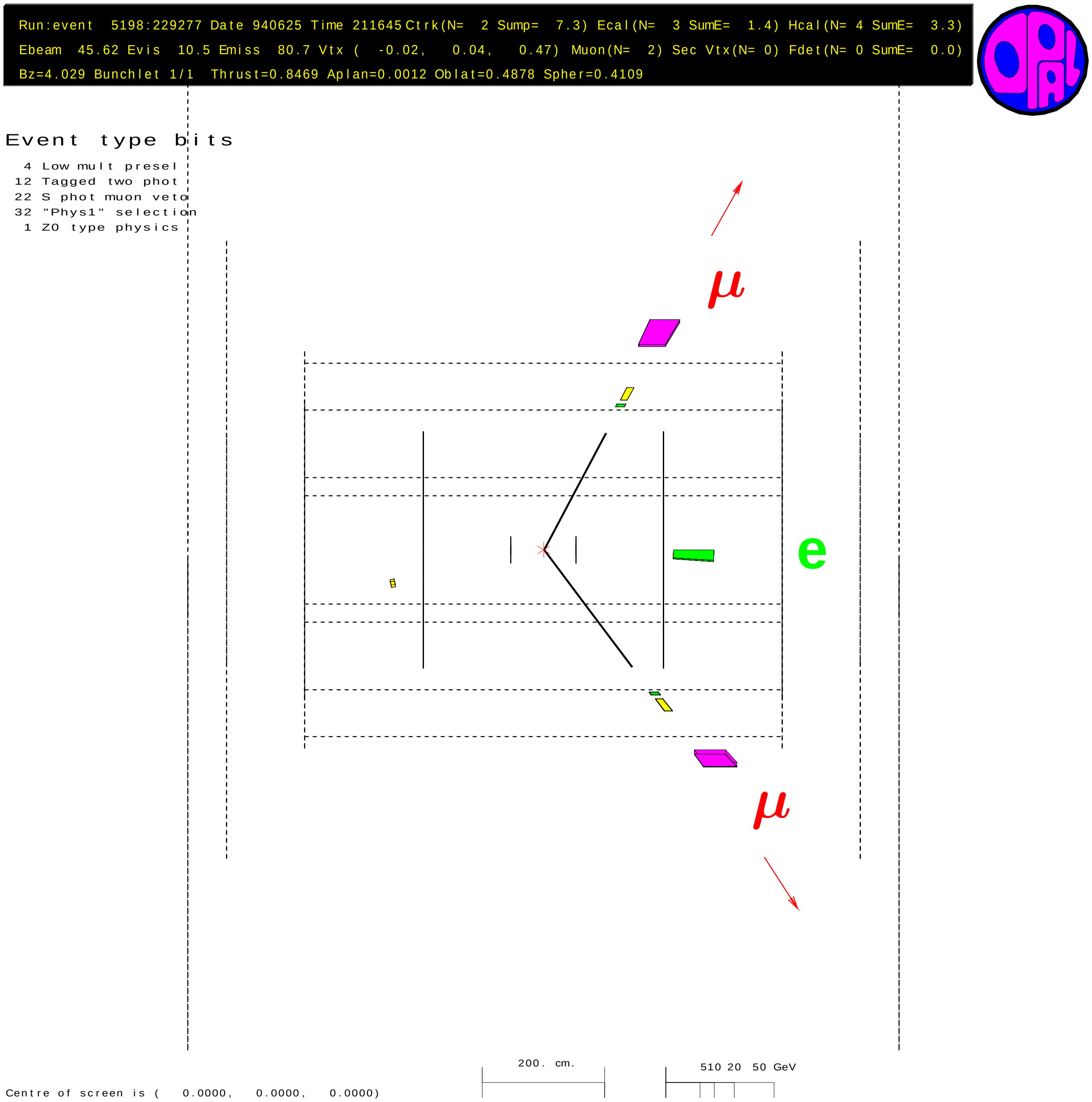
$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}x\,\mathrm{d}Q^2\,\mathrm{d}z\,\mathrm{d}P^2} = \frac{\mathrm{d}^2N_{\gamma}^{\mathrm{T}}}{\mathrm{d}z\mathrm{d}P^2}\cdot\frac{2\pi\alpha^2}{x\,Q^4}\cdot\left[1+(1-y)^2\right]\cdot \underbrace{\left[2xF_{\mathrm{T}}^{\gamma}(x,Q^2) + \frac{2(1-y)}{1+(1-y)^2}F_{\mathrm{L}}^{\gamma}(x,Q^2)\right]}_{\to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

with:

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

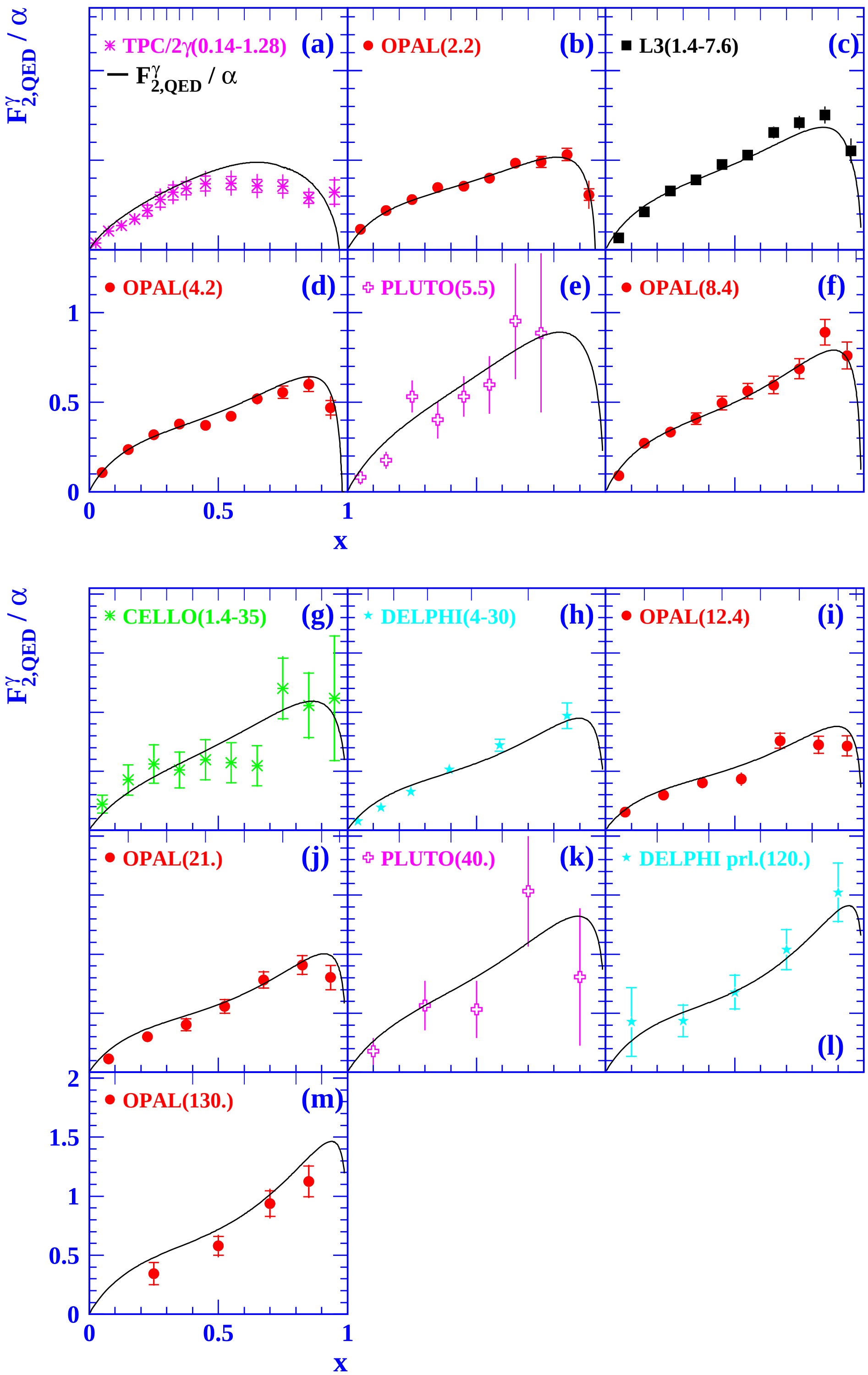

Hadron calorimeters and return yoke
Electromagnetic calorimeters
Muon detectors
Jet chamber
Vertex chamber
Microvertex detector
Z chambers
Solenoid and pressure vessel
Time of flight detector
Presampler
Silicon tungsten luminometer
Forward detector
y
θ
φ
z
x

The muon pair final state

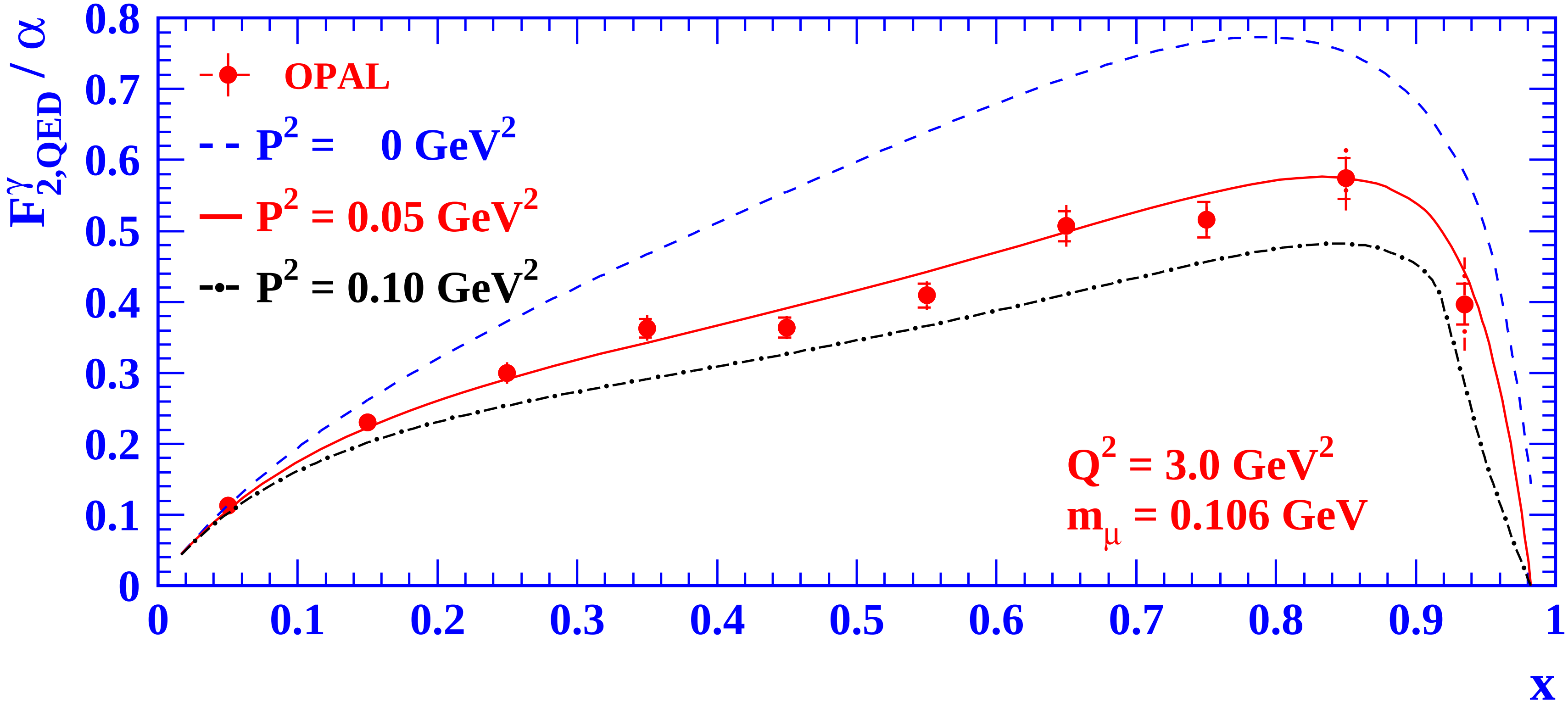


The muon pair final state is a clear topology with good mass resolution.

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

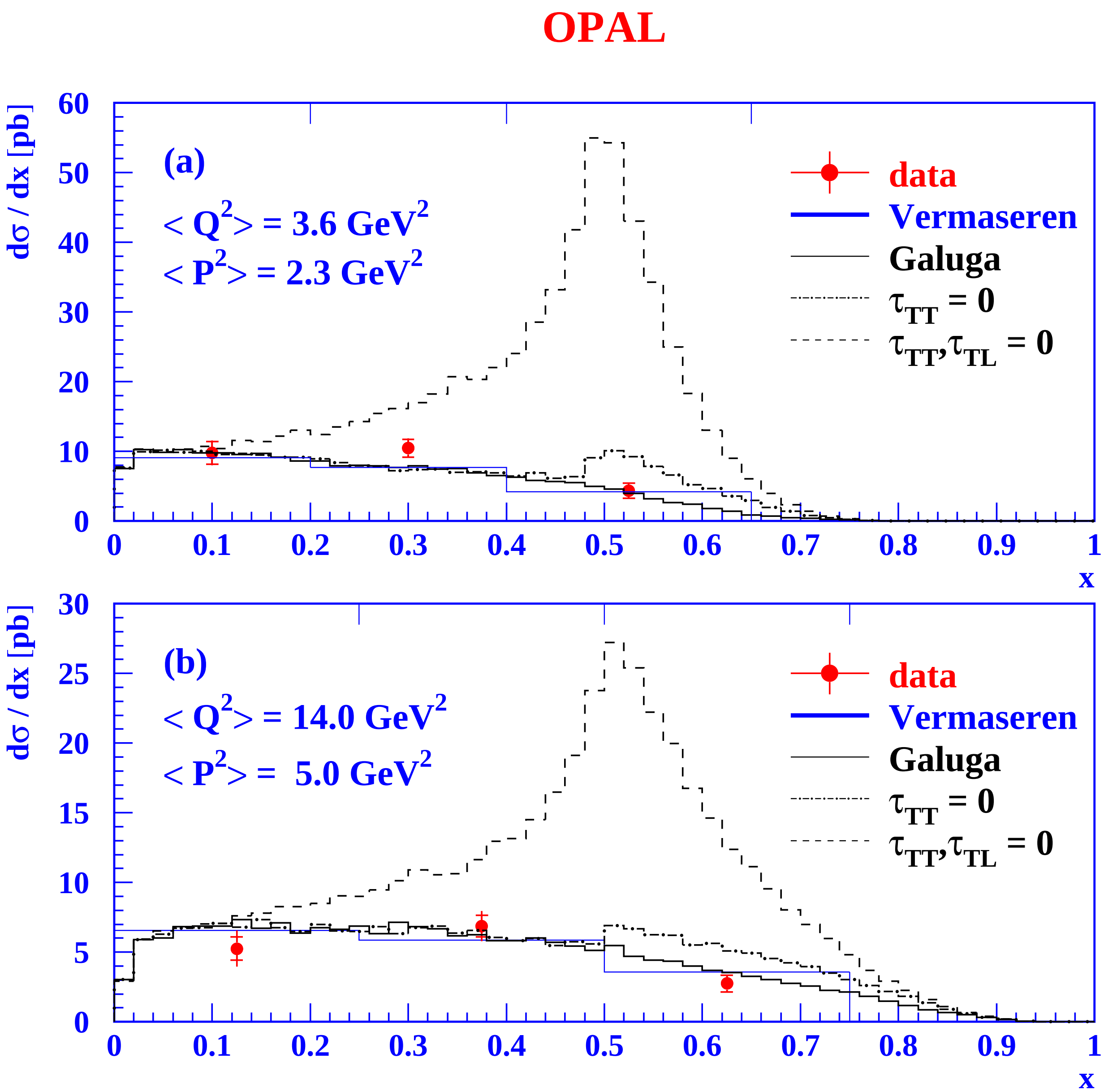


The P^2 dependence of F_2^γ



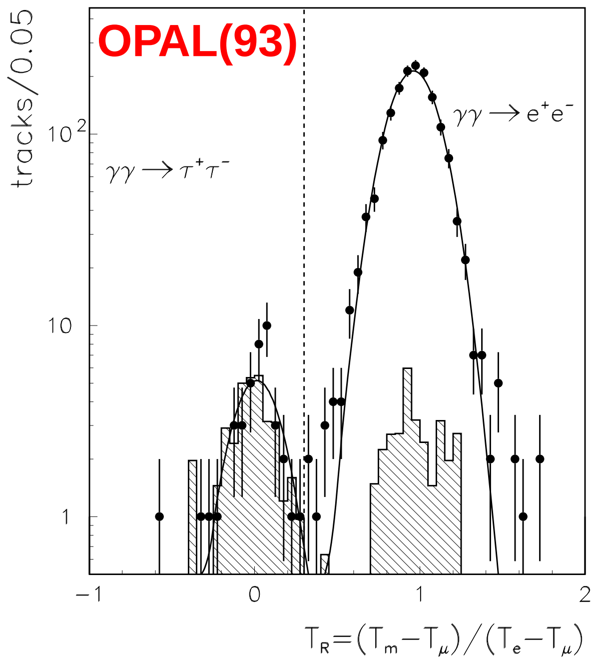
The suppression of the photon structure with the photon virtuality P^2 is clearly observed in the data.

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.

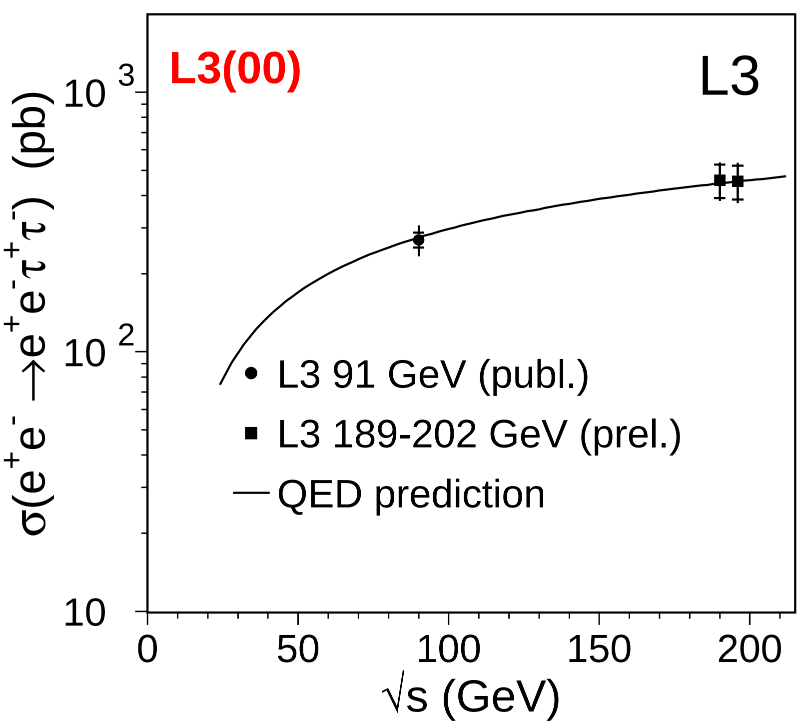
Production of tau pairs at LEP



First seen in $\gamma\gamma^\star \longrightarrow \tau\tau$

$\tau\tau \longrightarrow (e\,\bar{\nu}_e\nu_\tau)(\mu\,\bar{\nu}_\mu\nu_\tau)$

Leptons identified by dE/dx



Cross-section for

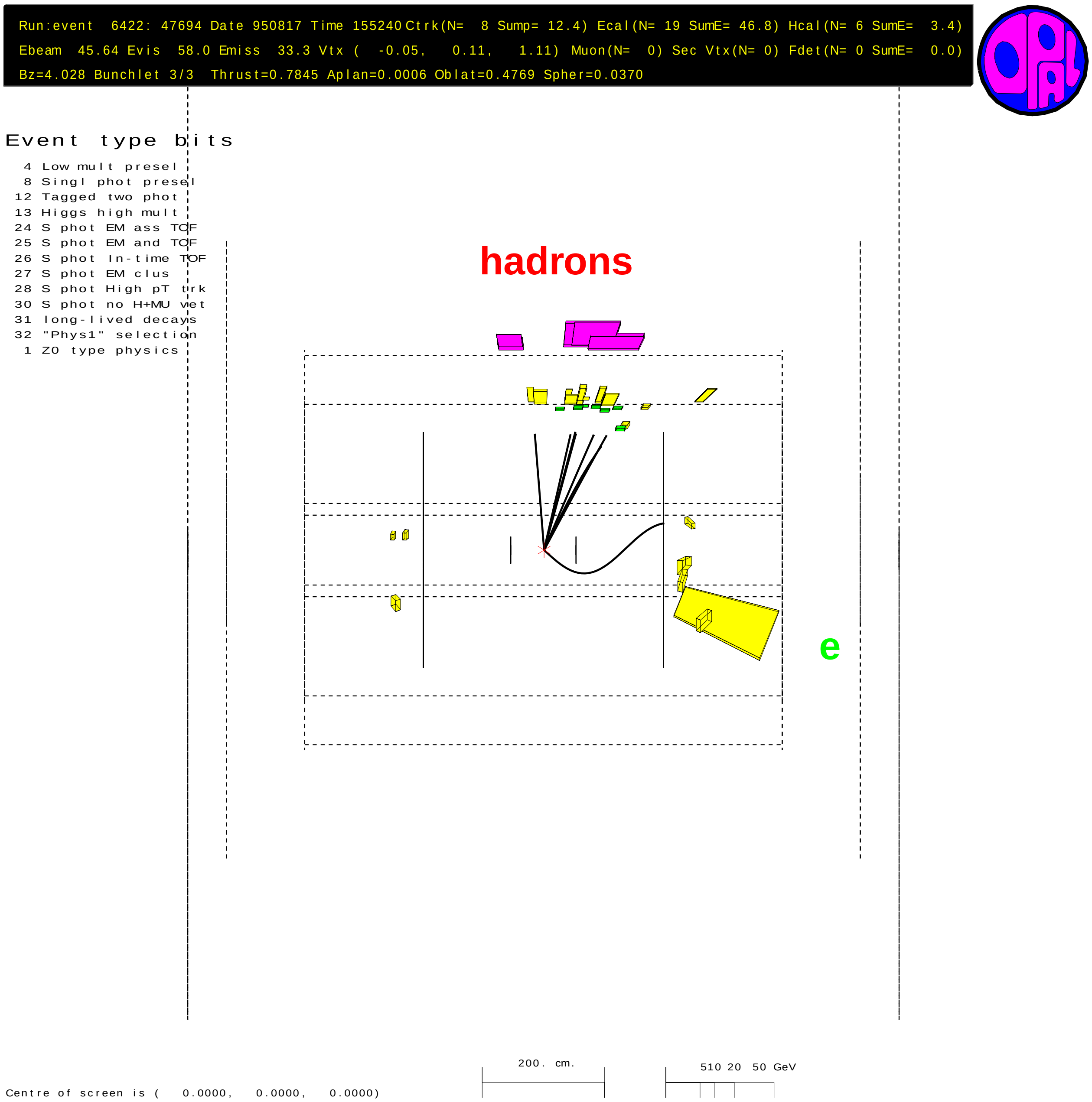
$\gamma\gamma \longrightarrow \tau\tau$ using

$\tau\tau$ decays into

$(e\,\bar{\nu}_e\nu_\tau)(\pi\pi^0\nu_\tau)$

Tau pair production has been measured at LEP.

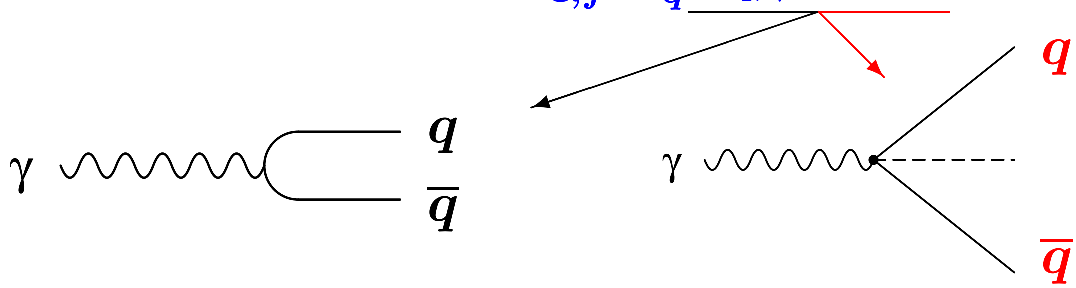
The hadronic final state



The scattered electron is clearly visible.
However, the hadronic final state may partly disappear along the beam axis.

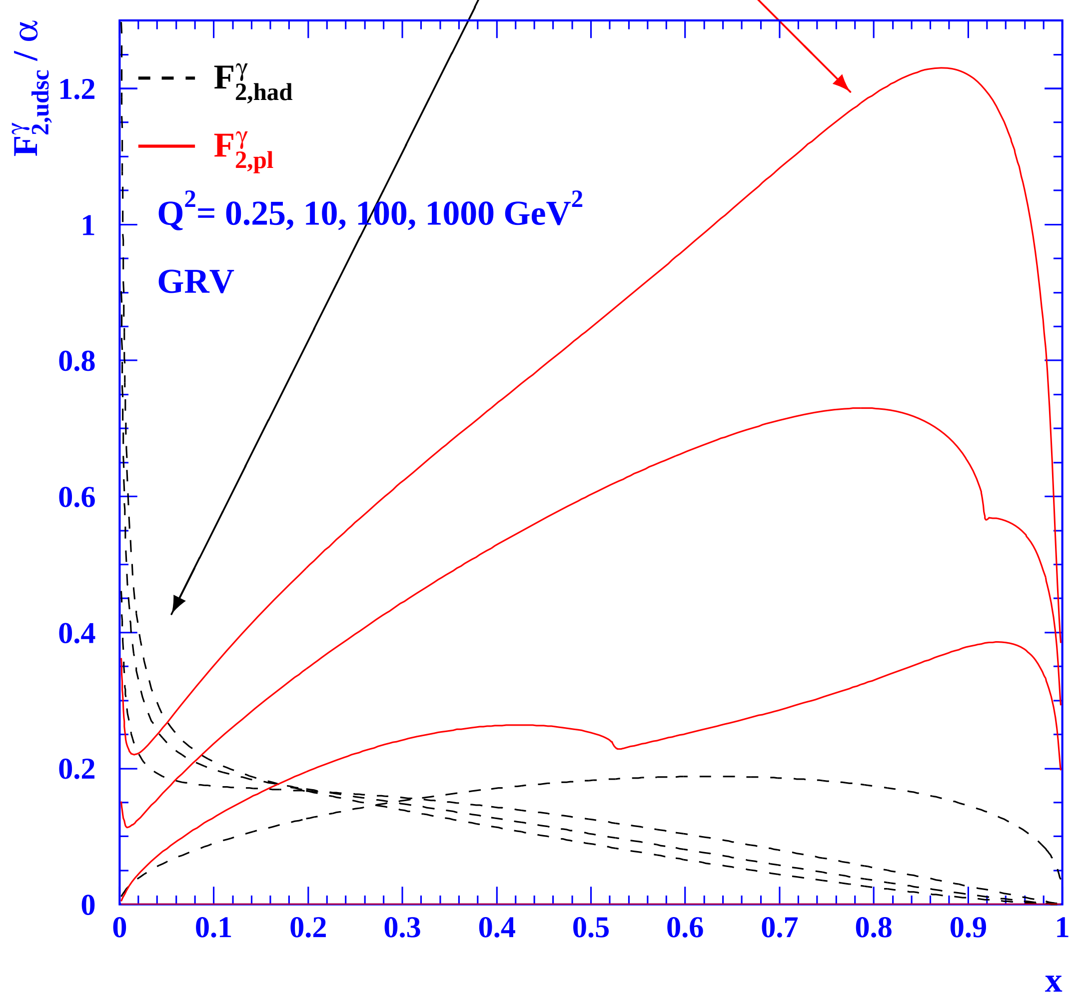
The contributions to $F_2^\gamma(x, Q^2)$

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

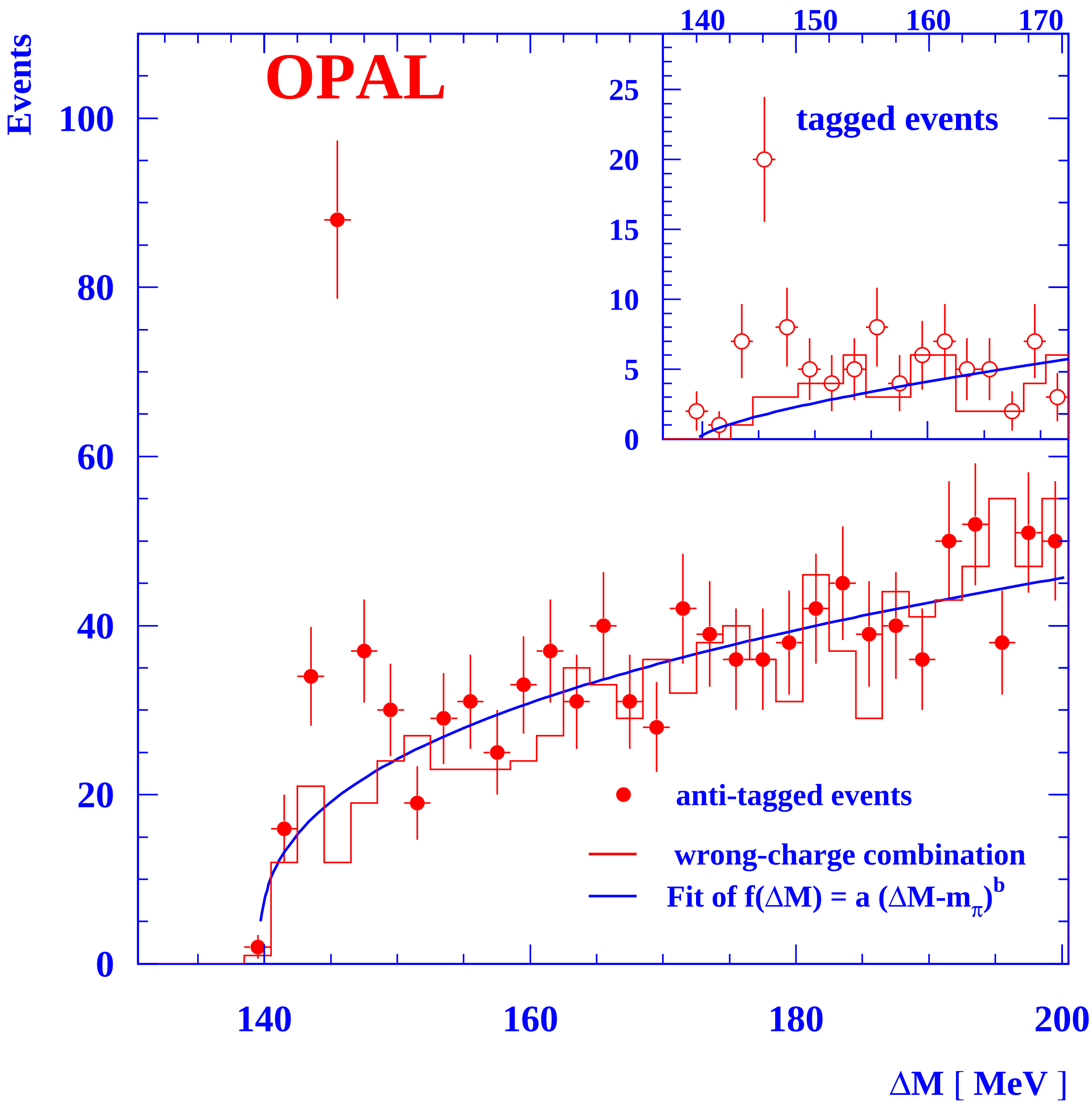


hadron-like, *non–perturbative*
e.g. VMD(ρ, ω, ϕ), low-x

point-like, *perturbative*
high-x

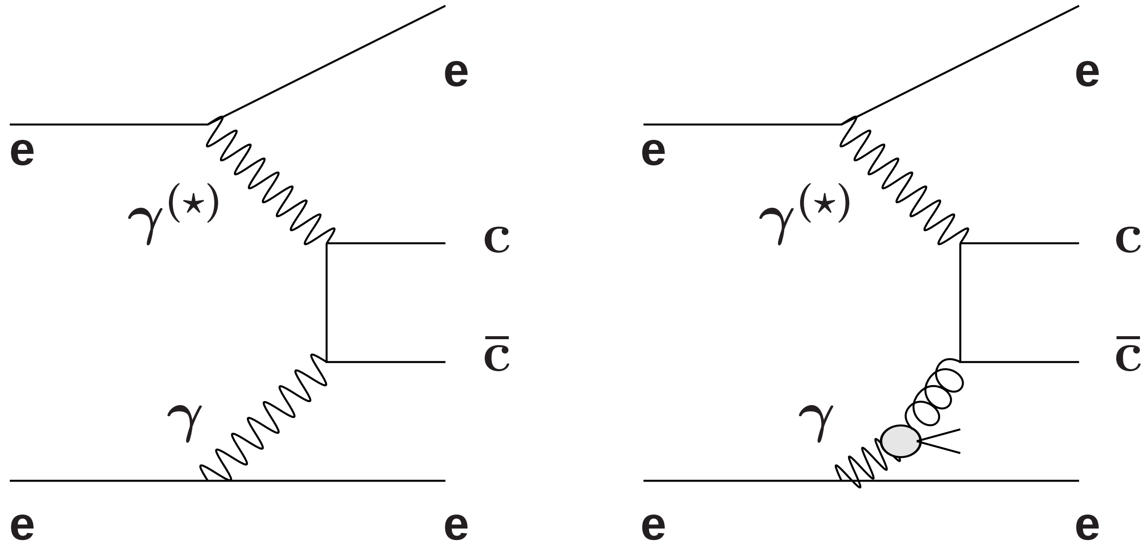


Charm production tagged by D*s



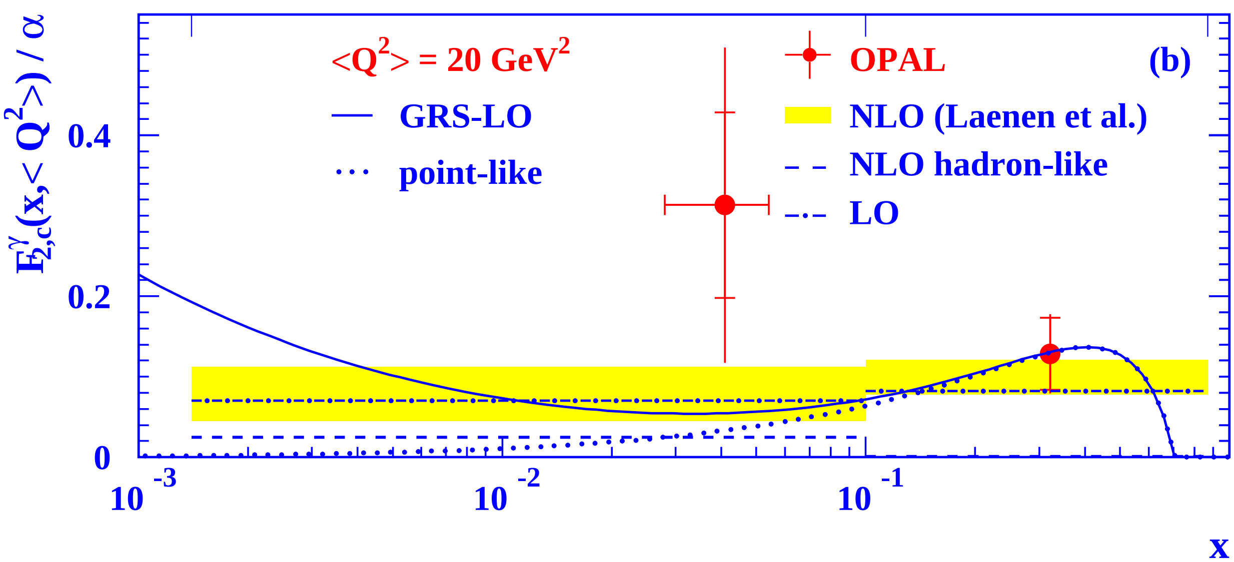
A clear signal in the $\Delta(M) = M(D^\star) - M(D^0)$ mass spectrum is seen for anti-tagged and tagged events

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



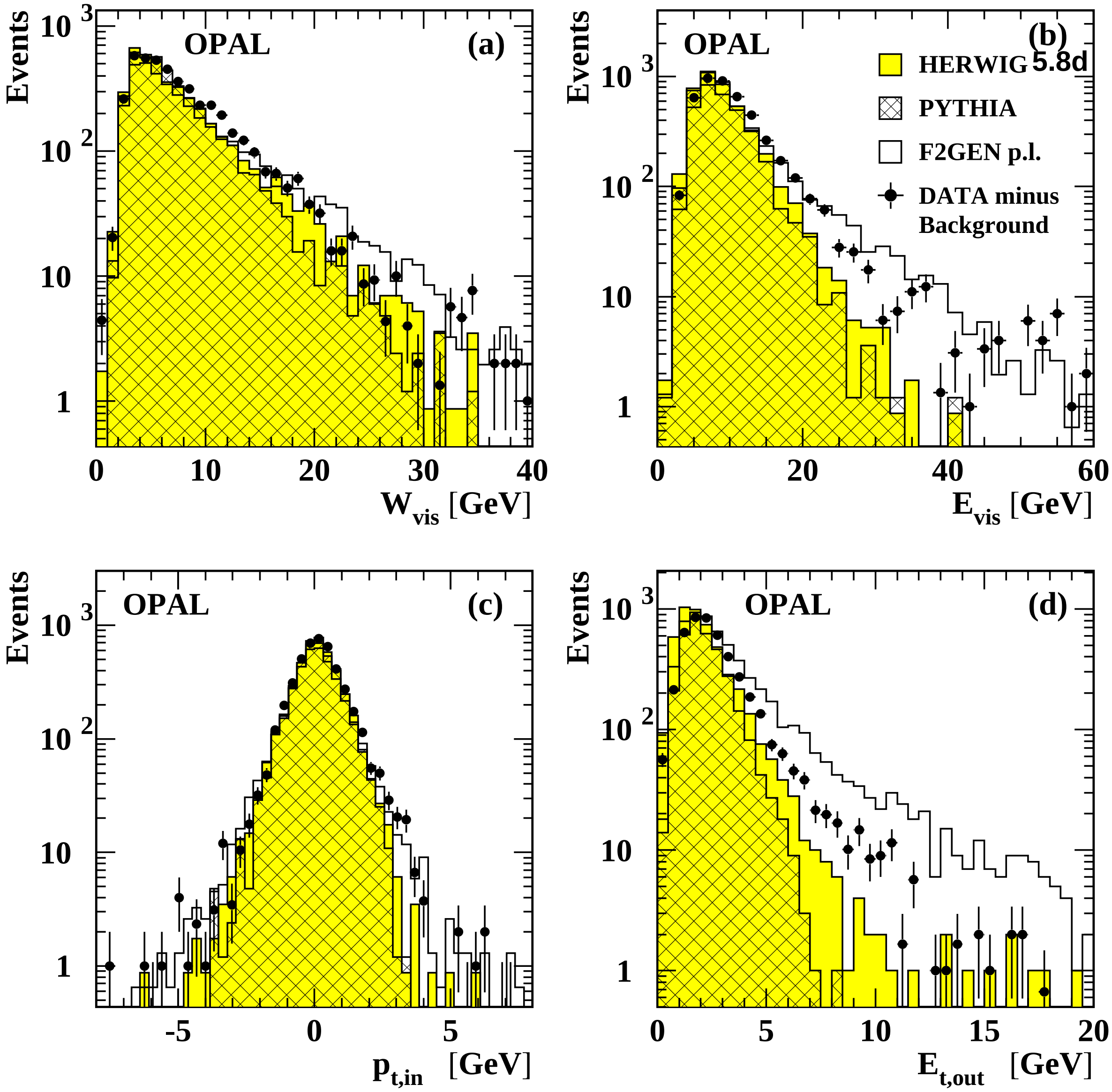
point-like, purely perturbative QCD prediction, dominates at **high-x**

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



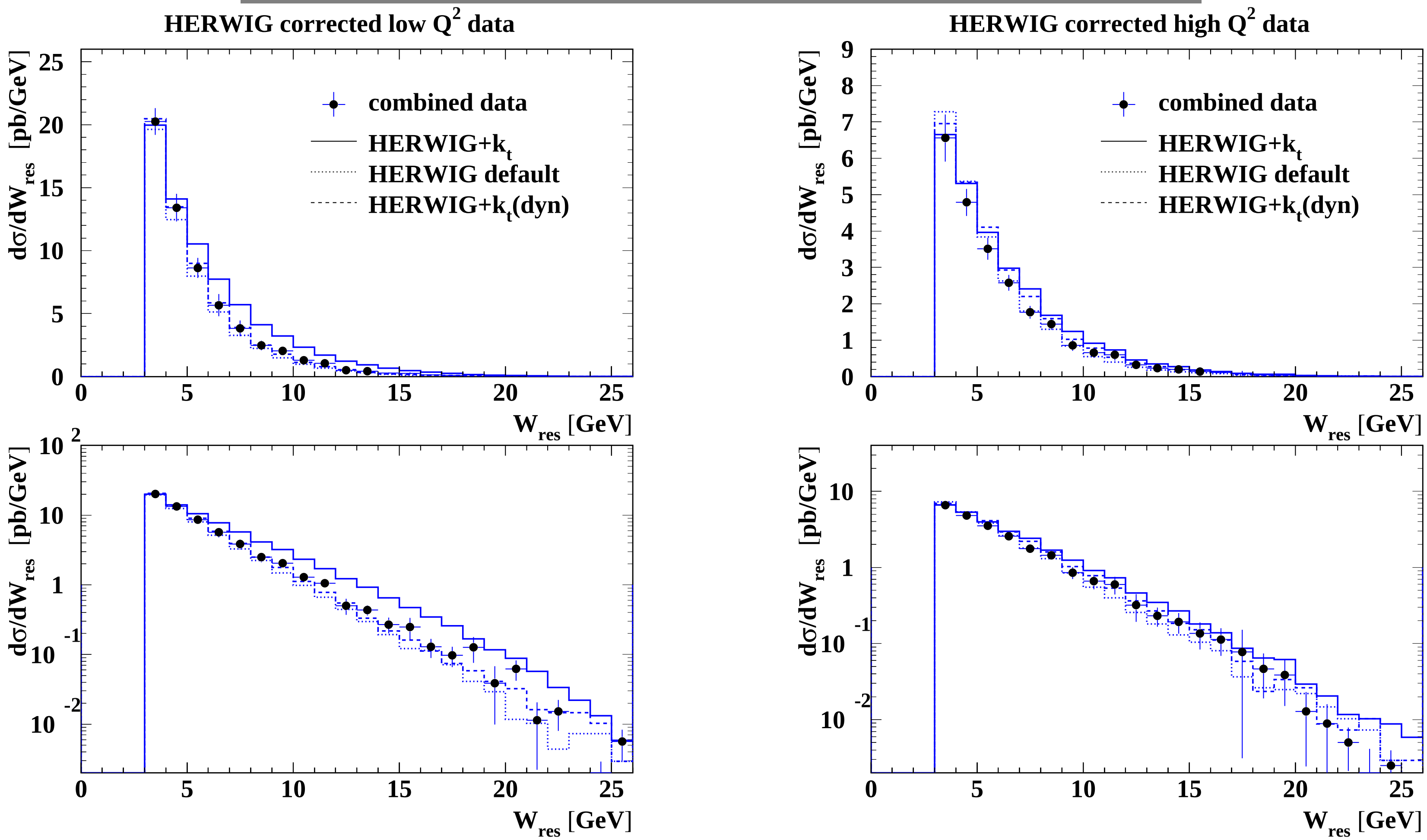
OPAL Collab., Eur. Phys. J. C16 (2000) 579.

The description of the hadronic final state



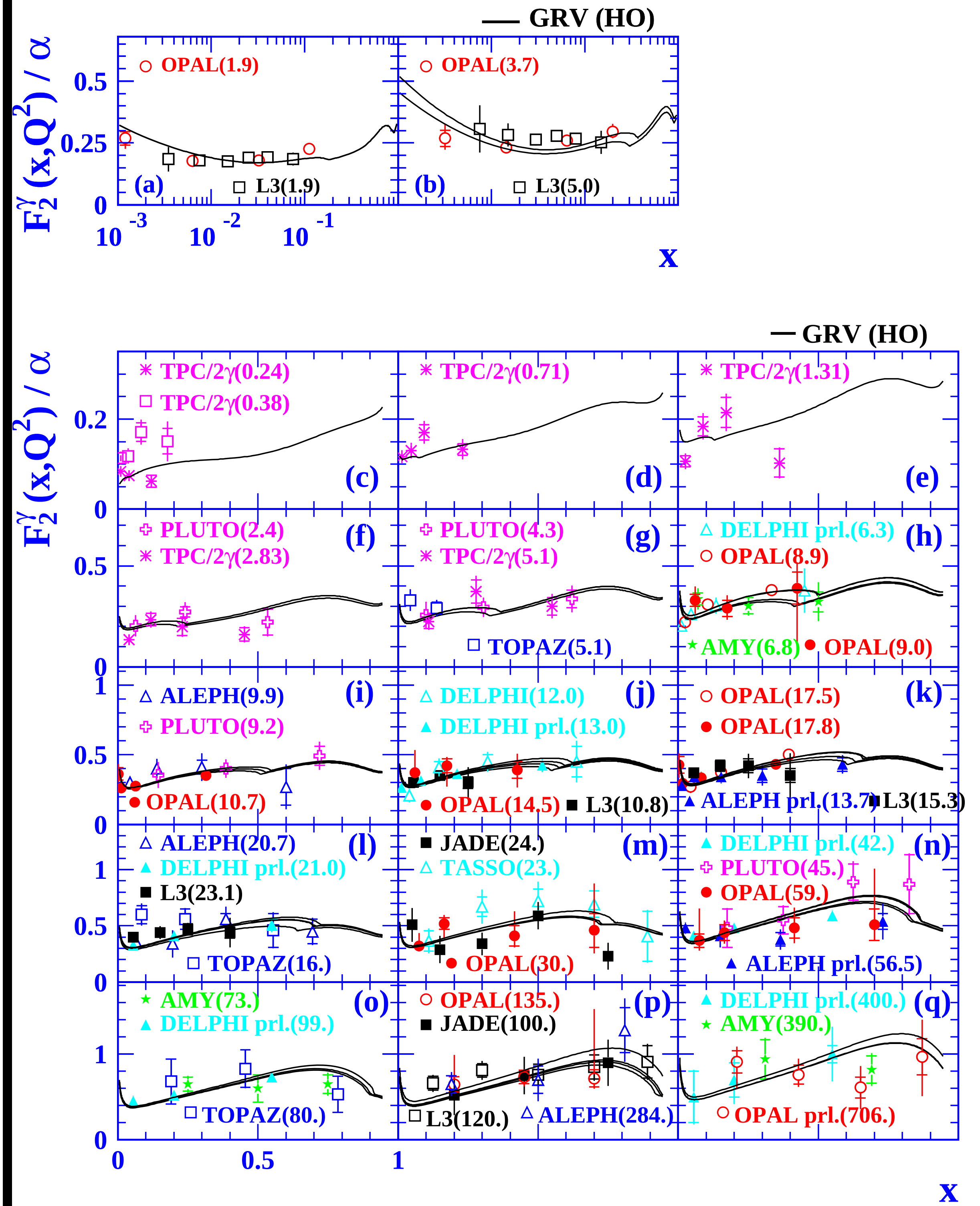
There are significant differences between the data and the Monte Carlo predictions (OPAL '96)

Comparison to LEP combined data

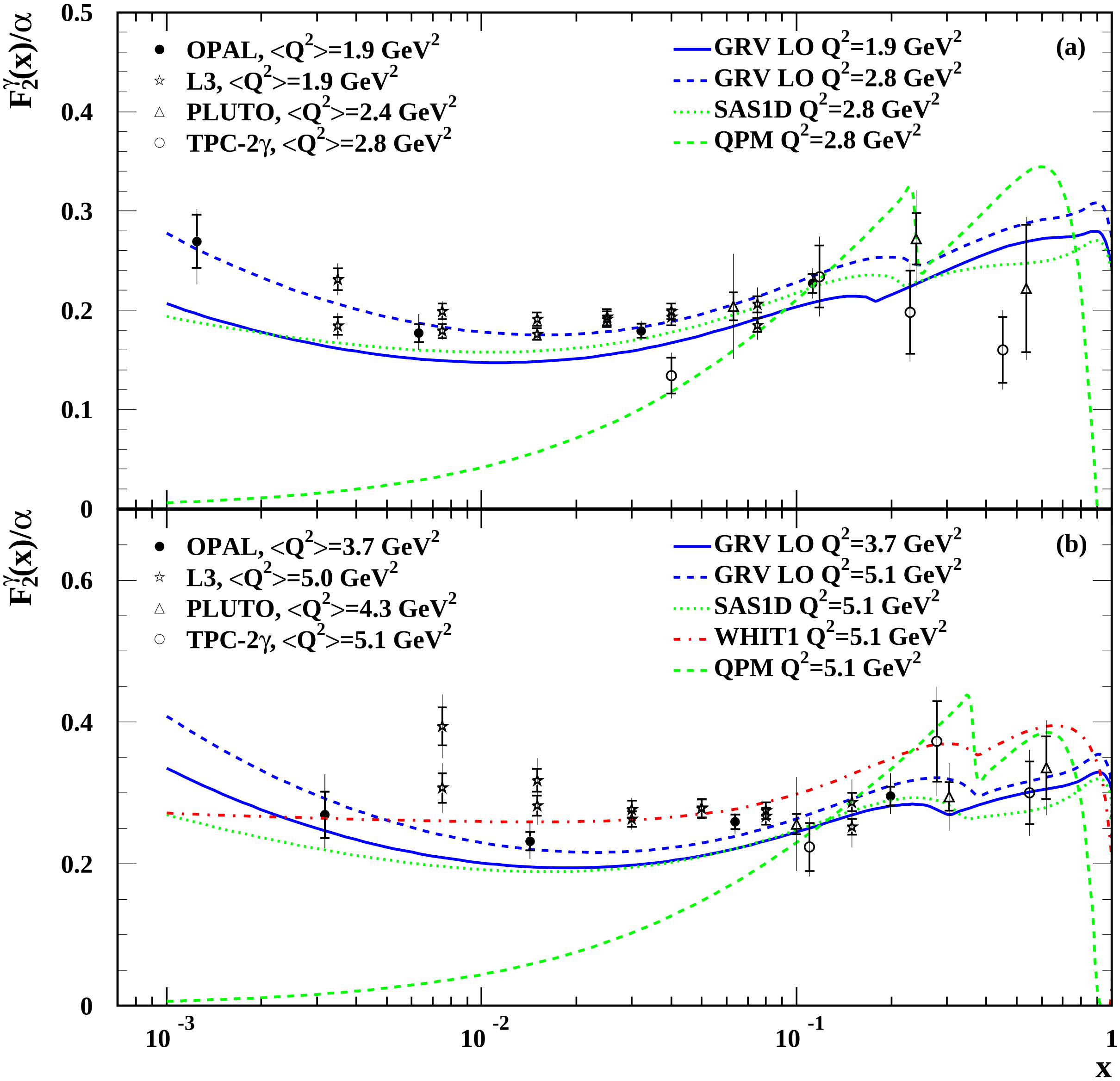


The combined data are a valuable input to constrain the Monte Carlo models
(LEP Two-Photon WG CERN-EP-2000-109)

The world data on F_2^γ



Measurements at low Q^2 and x

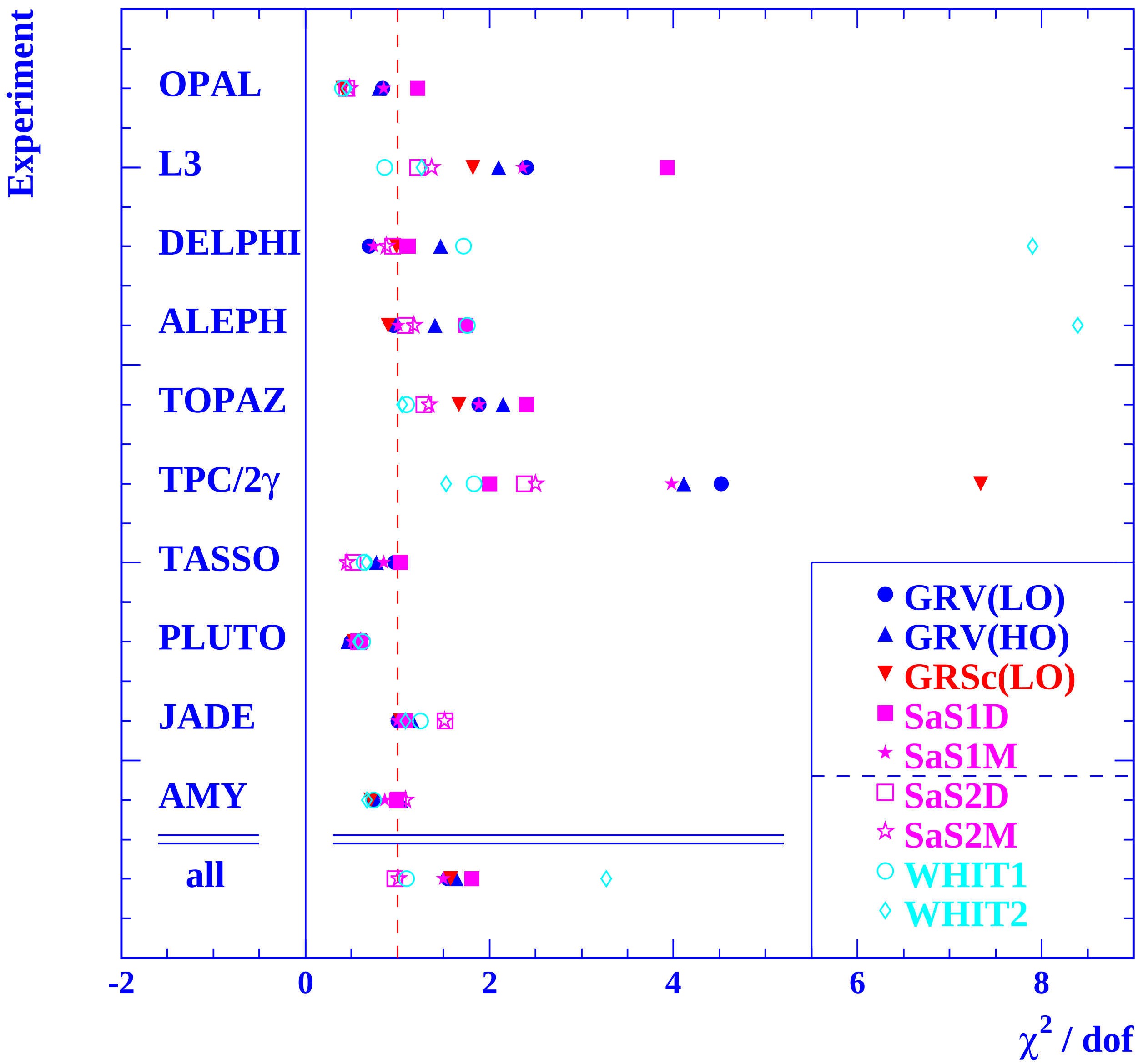


GRV(LO) and SaS1D are slightly too low compared to the data.

OPAL Collab., Eur. Phys. J. C18 (2000) 15.

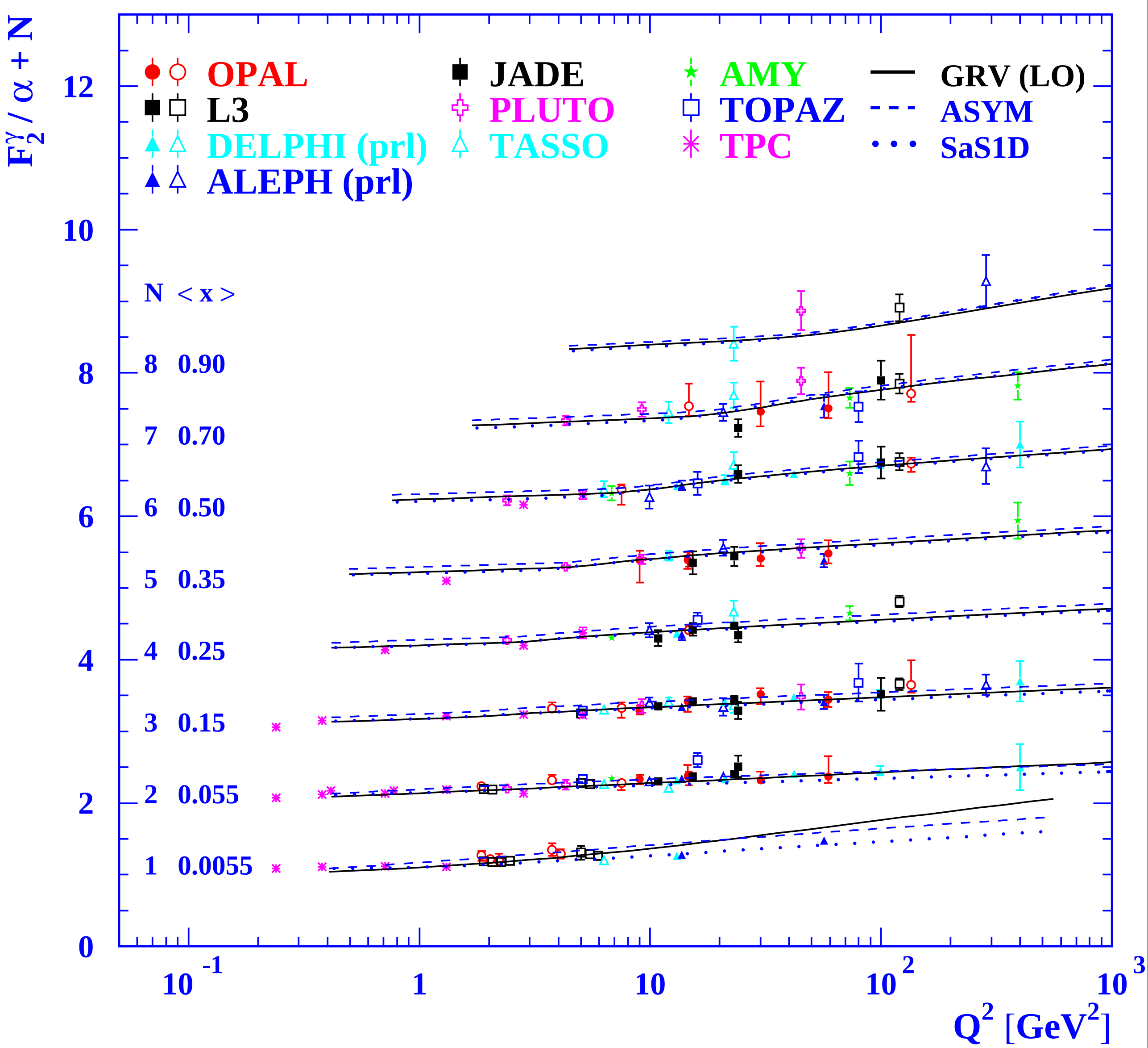
Data description by existing pdf's

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



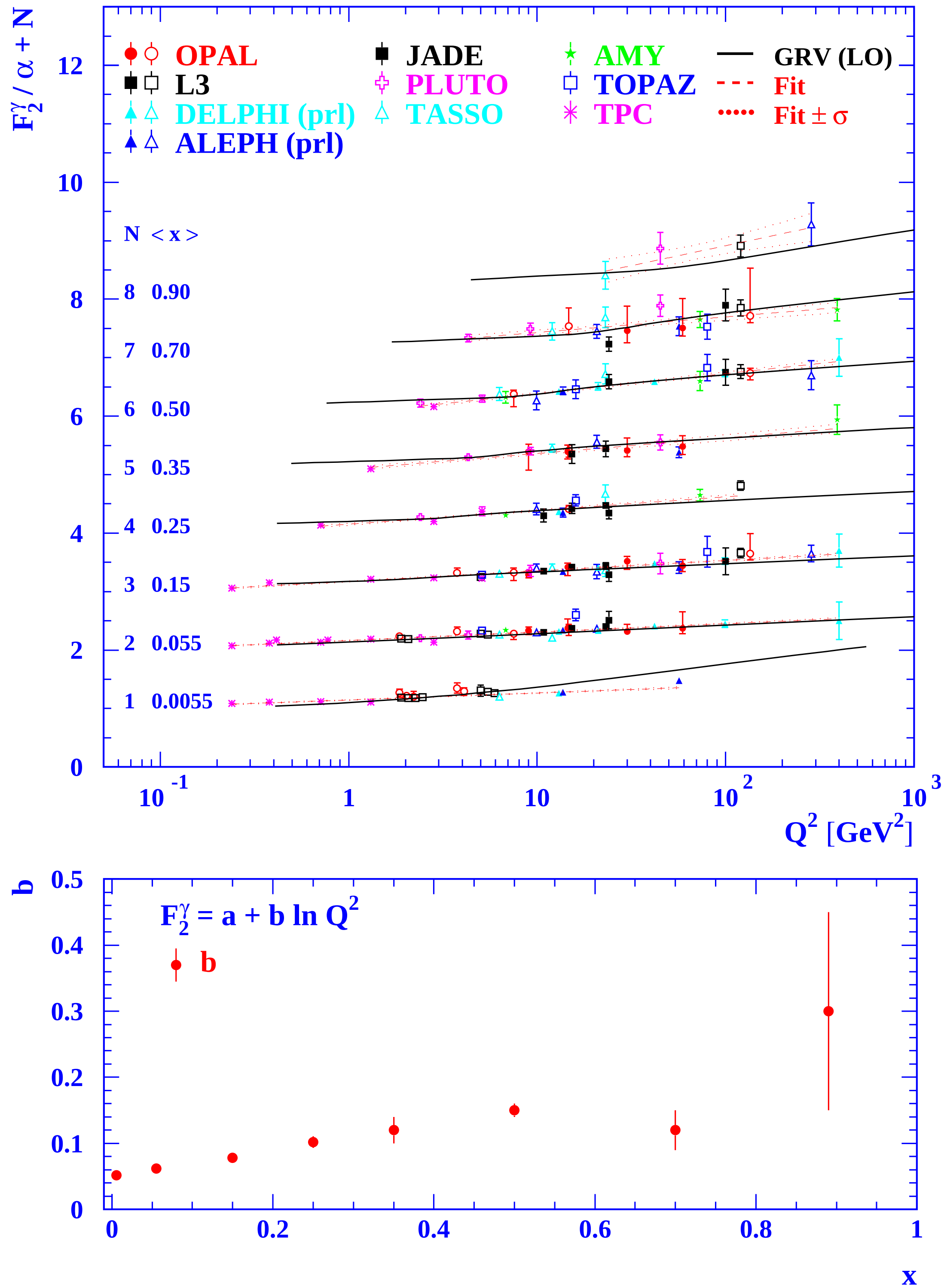
Most of the data can be accounted for by existing pdf's, but...

The Q^2 evolution of F_2^γ for $n_f = 4$



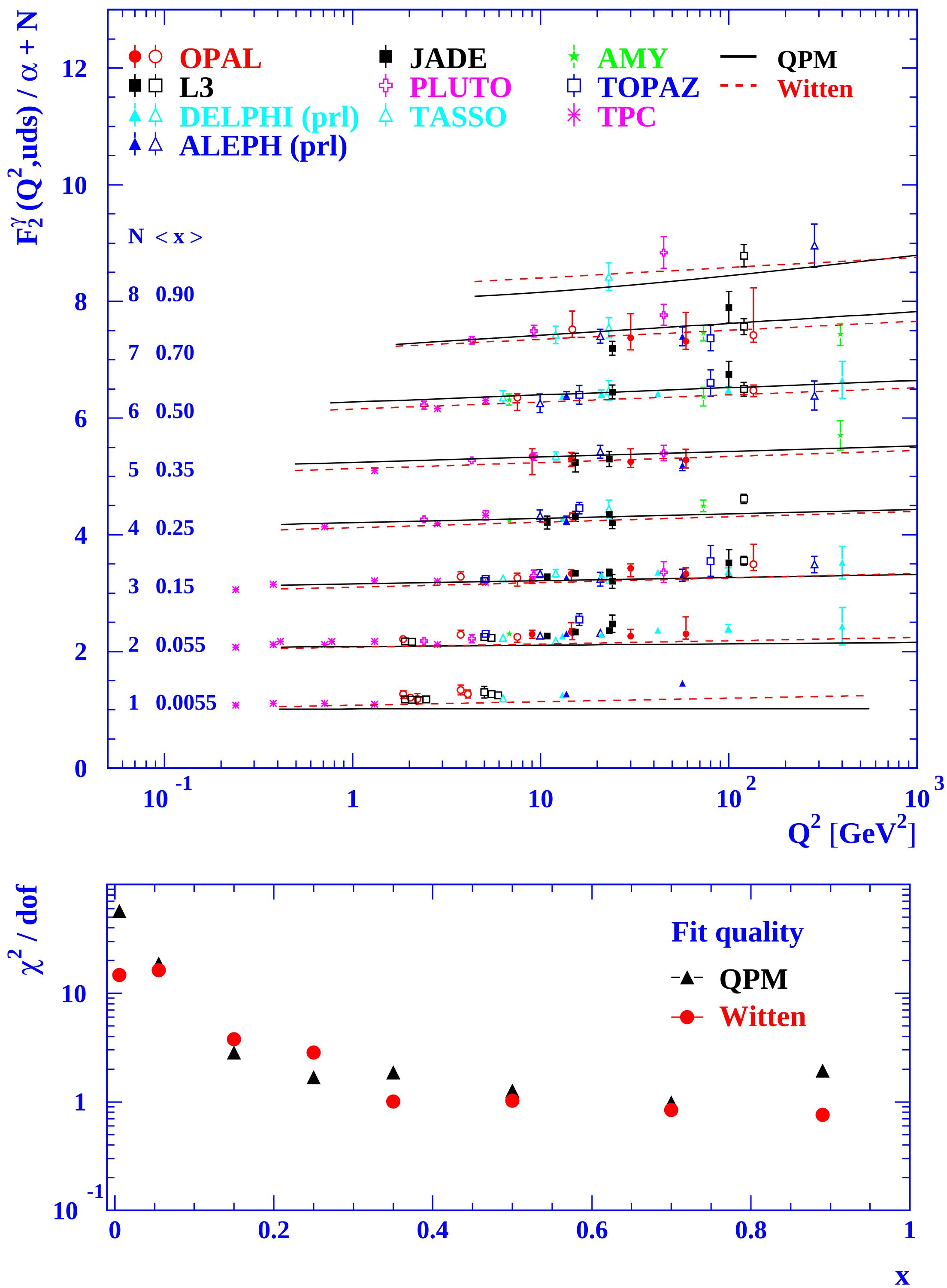
The general trend of the data is followed by the parametrisations.

Q^2 evolution compared to linear fits



An increasing slope as a function of x is observed.

Q^2 evolution after charm subtraction



Which prediction is verified ?

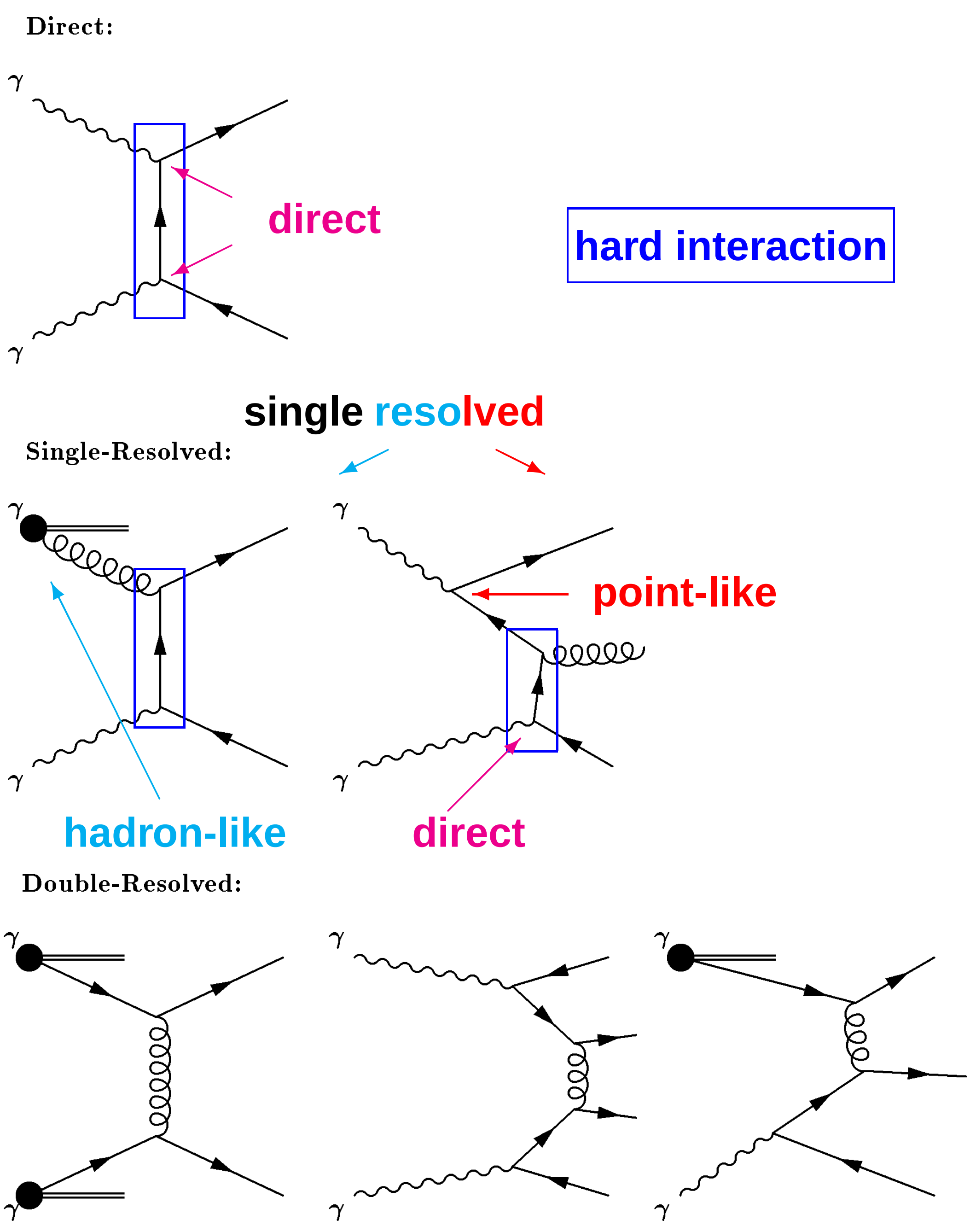
QED structure

1. The rise of the QED structure for large x ist clearly seen.
2. The suppression of the QED structure function with the photon virtuality is verified.
3. There is an indirect evidence for the existence of the interference terms.

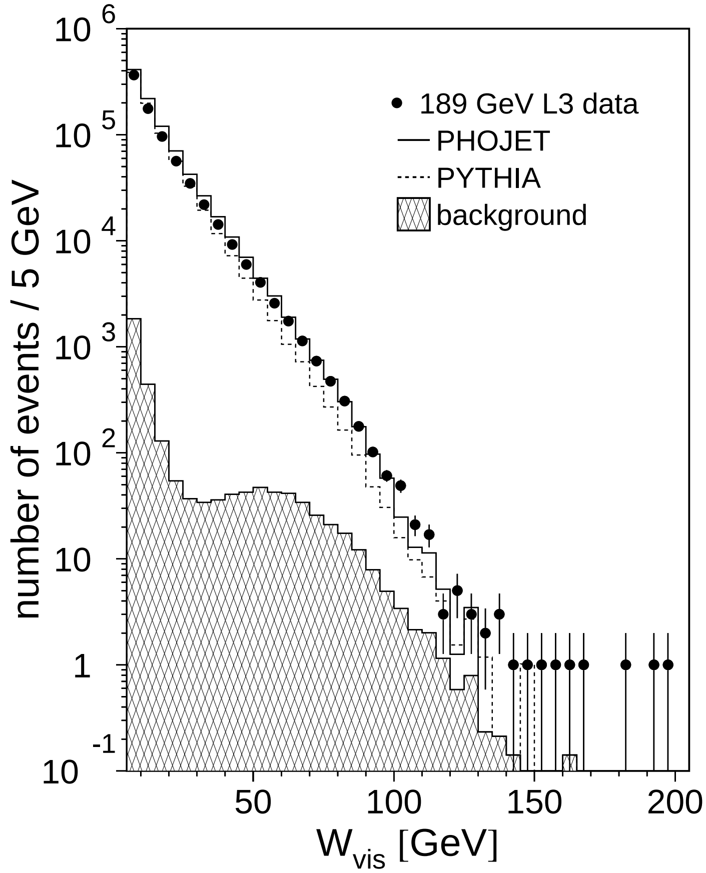
Hadronic structure

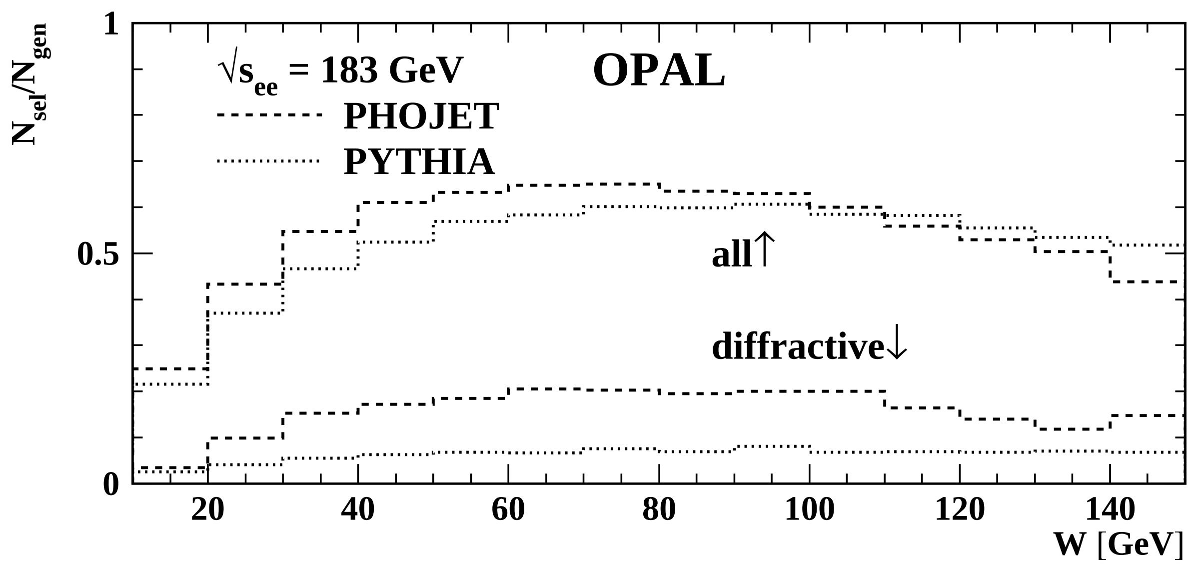
1. The measured $F_{2,c}^{\gamma}$ is accurately described by NLO QCD at large x.
2. The acceptance is not sufficient to see the predicted rise of F_2^{γ} at low values of x.
3. The Q^2 evolution of the photon structure shows a clear rise for all values of x.

Leading order diagrams



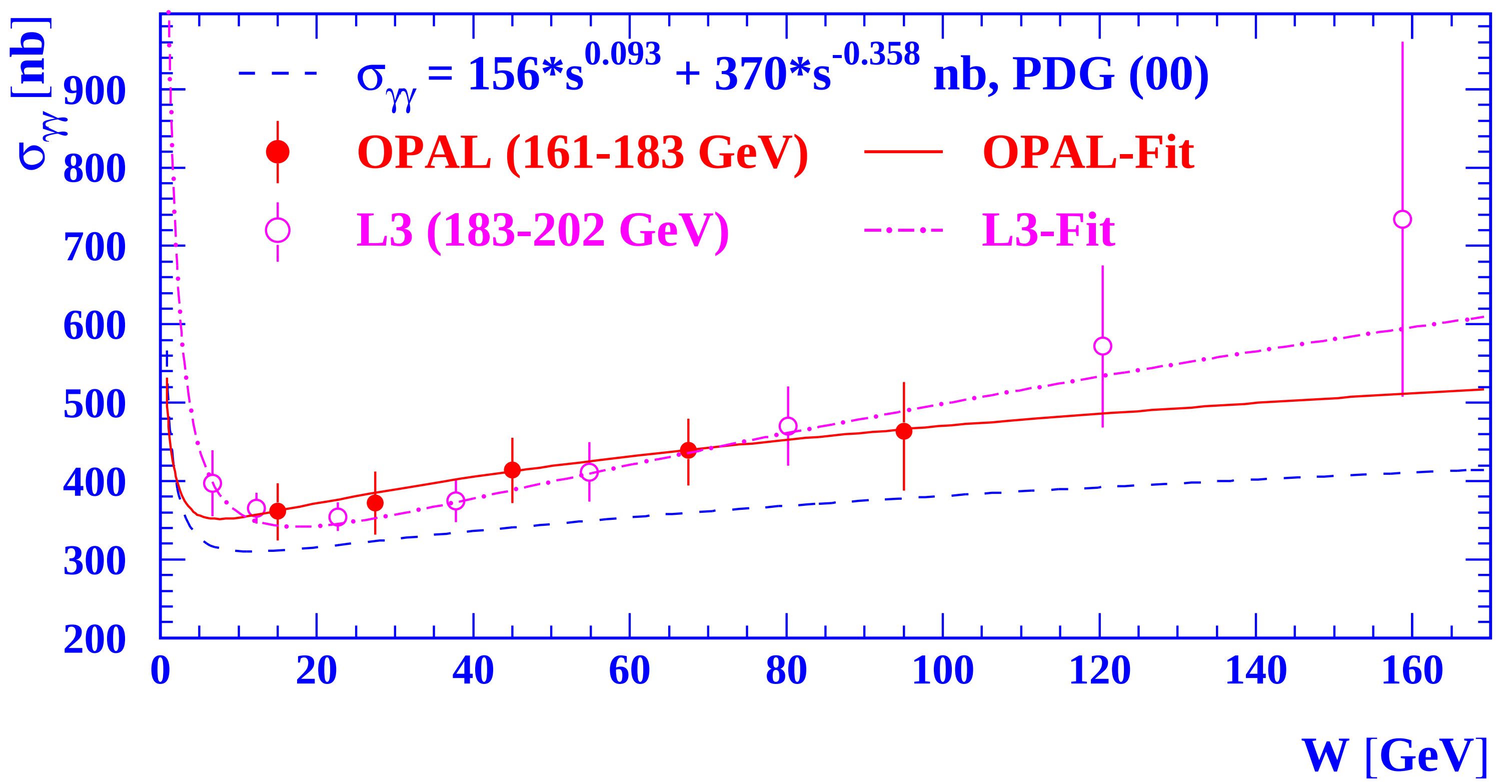
W distributions for anti-tagged events





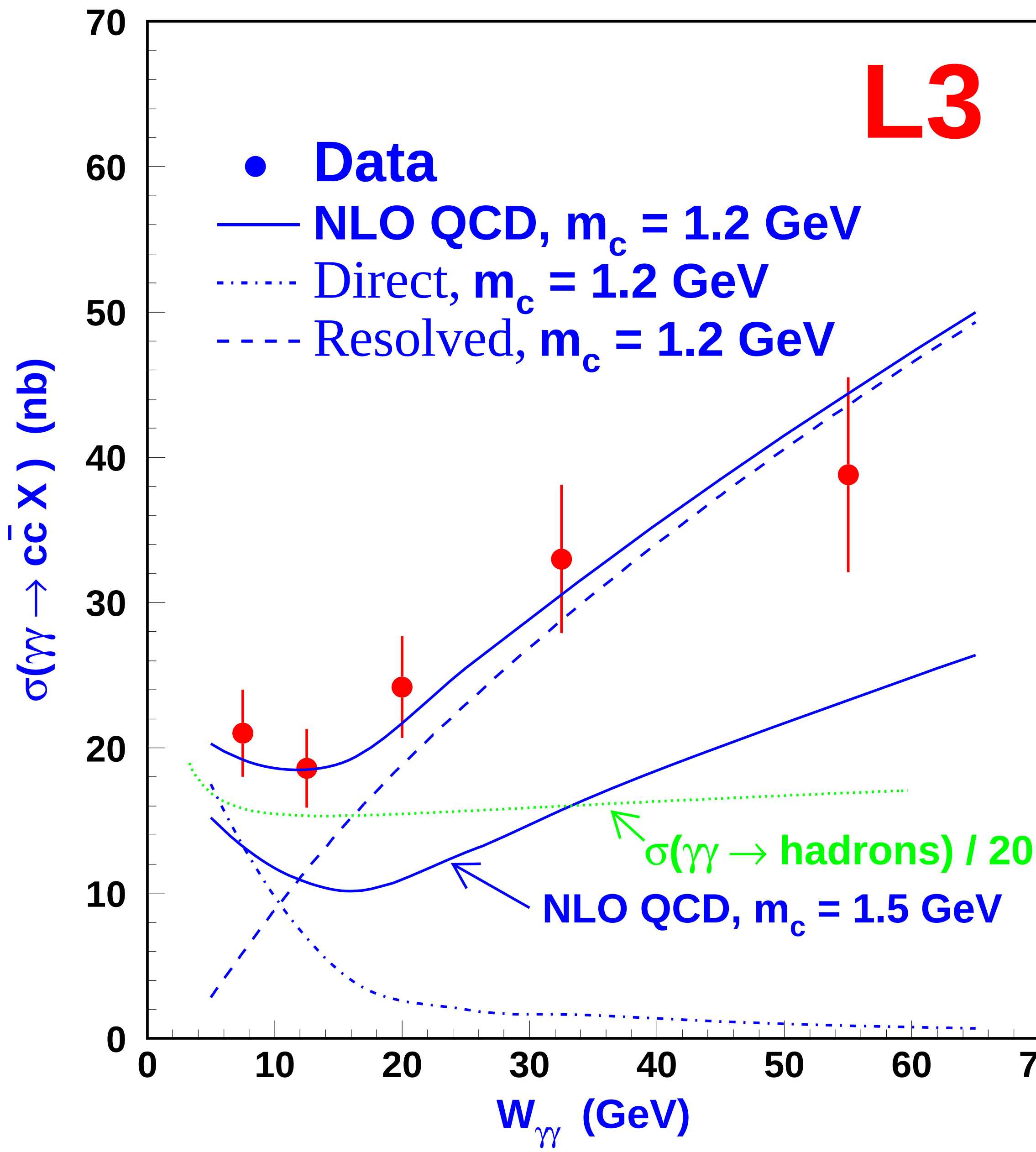
The acceptance for diffractive events is very different for the PHOJET and PYTHIA models.

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



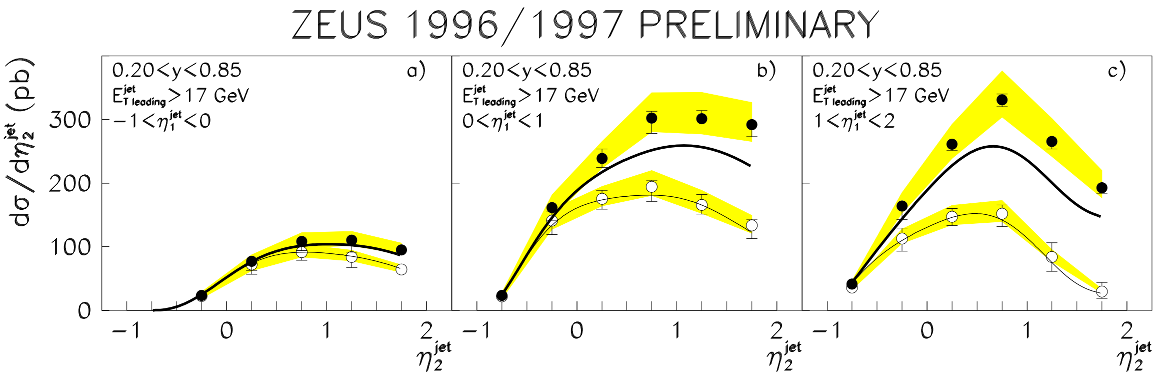
A clear rise of the total cross-section is observed in the data.

Charm cross-section as a function of W

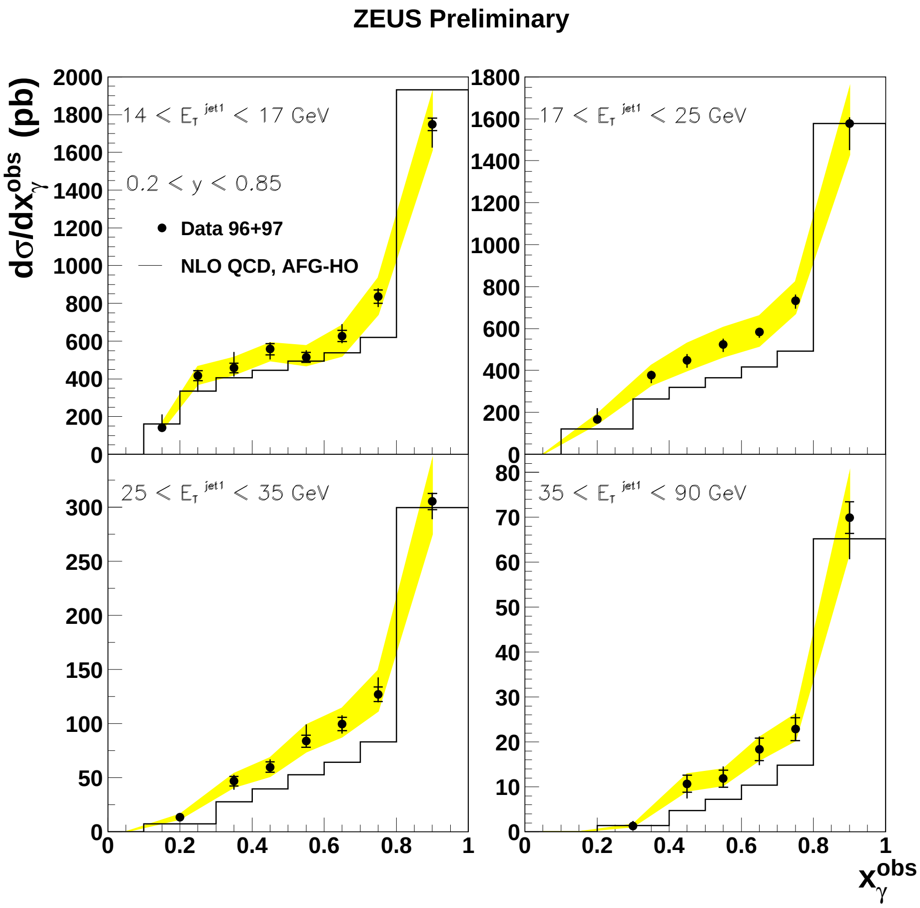


The charm cross-section rises faster than the total hadronic cross-section.

Jet production from ZEUS

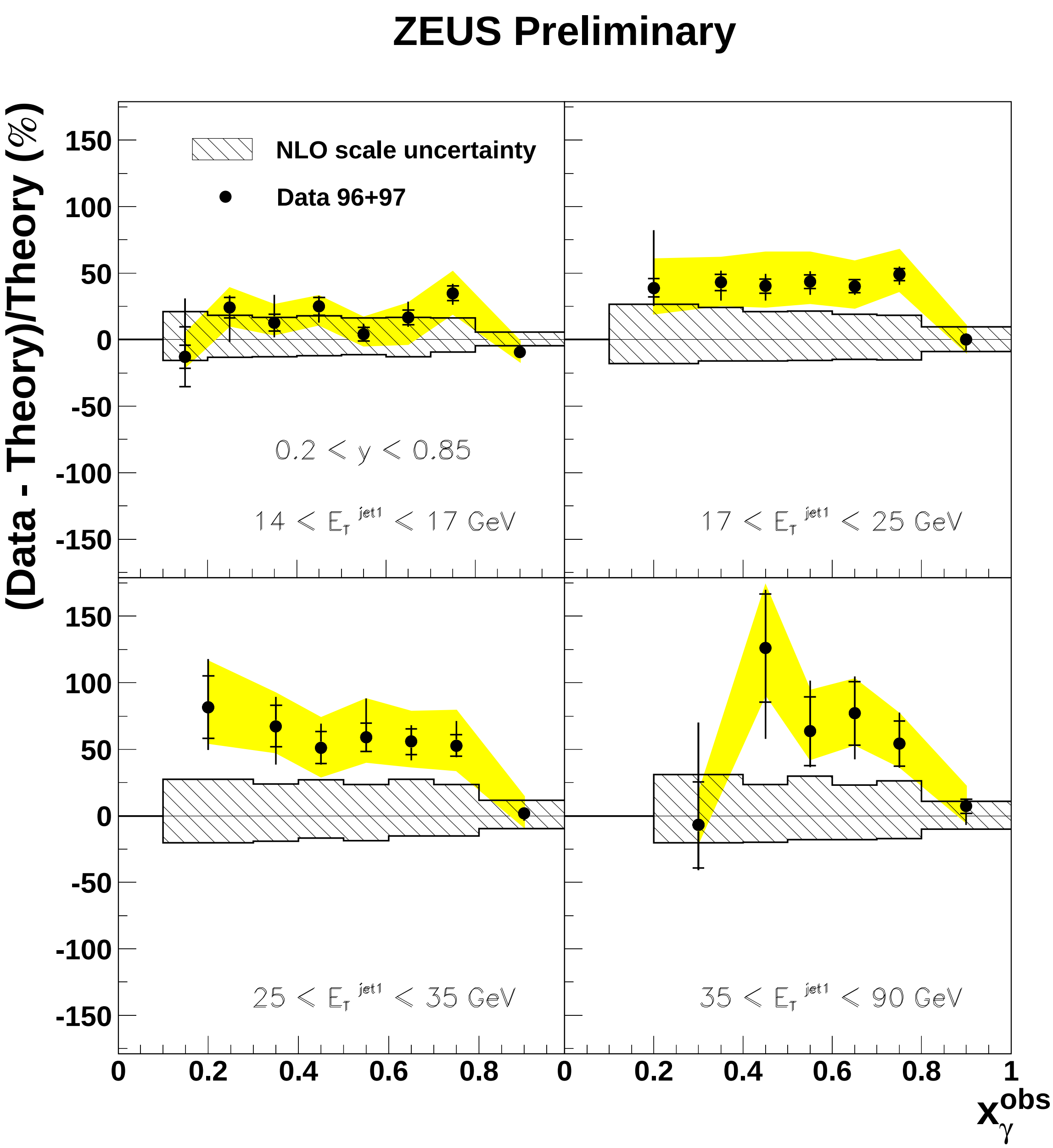


$$x_\gamma = \frac{E_T^{\rm jet1}\, e^{-\eta^{\rm jet1}} + E_T^{\rm jet2}\, e^{-\eta^{\rm jet2}}}{2yE}$$



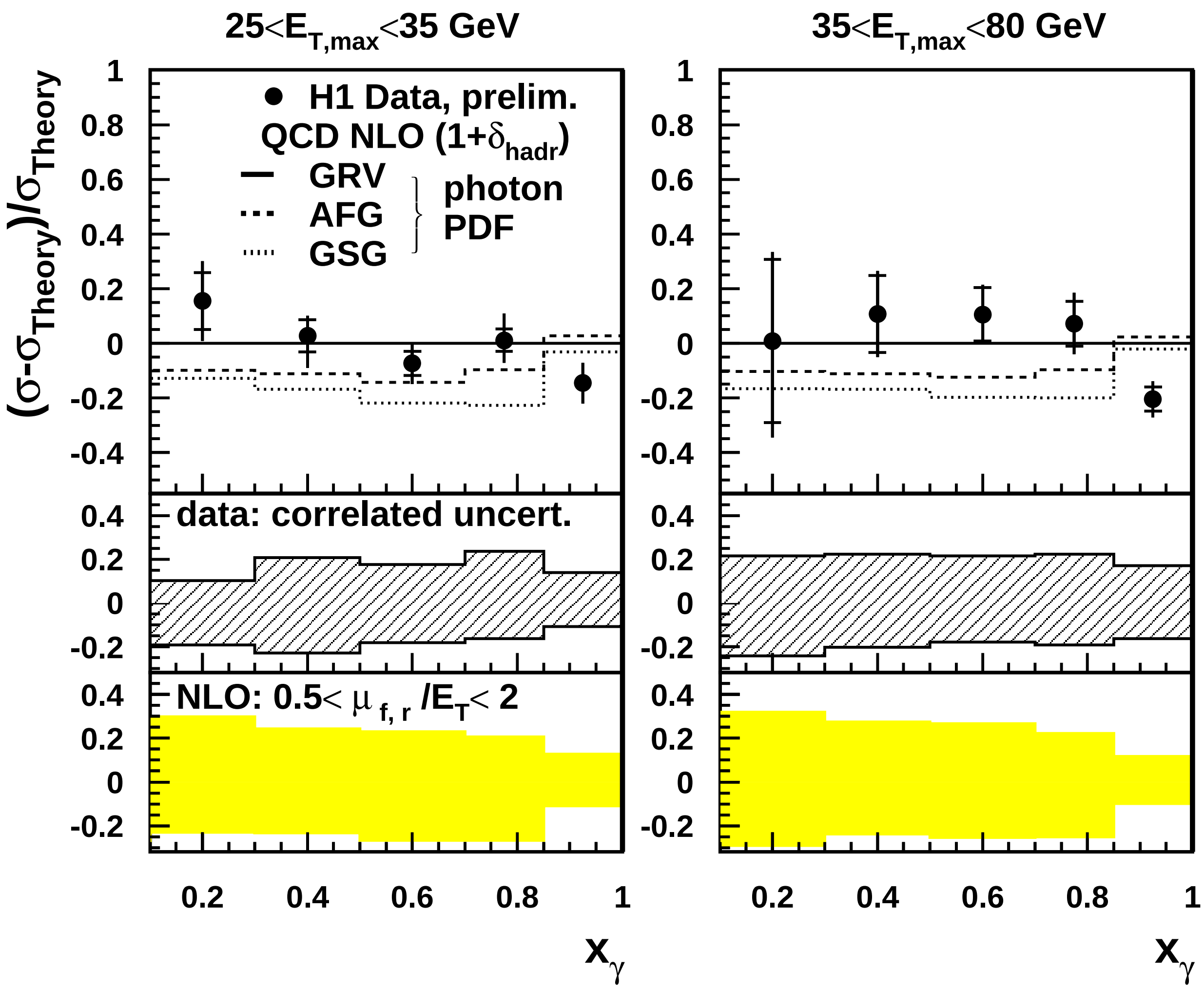
The NLO prediction is too low at medium x values

Comparison with NLO predictions



The discrepancy gets larger with increasing factorisation scale.

Comparison with NLO predictions from H1



The NLO predictions are consistent with the data.

The concept of effective parton distribution functions

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

with:

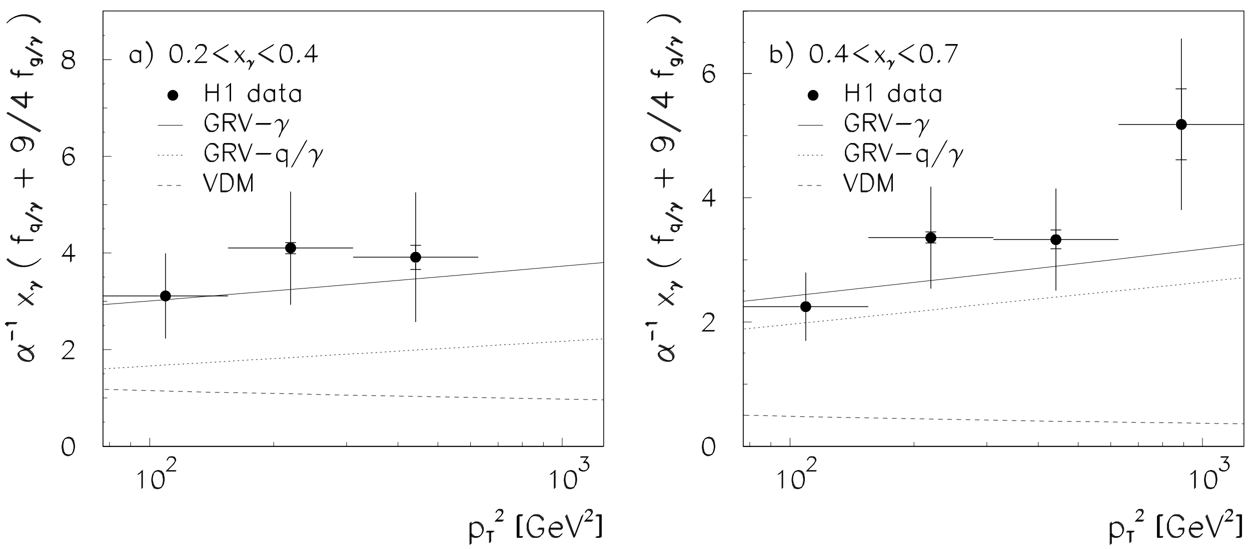
$$\tilde{f}_\mathrm{p}(x_\mathrm{p},Q^2) \equiv \sum_{k=1}^{n_f}\left[q_k^\mathrm{p}(x_\mathrm{p},Q^2) + \bar{q}_k^\mathrm{p}(x_\mathrm{p},Q^2) \right] + \frac{9}{4}g^\mathrm{p}(x_\mathrm{p},Q^2)$$

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

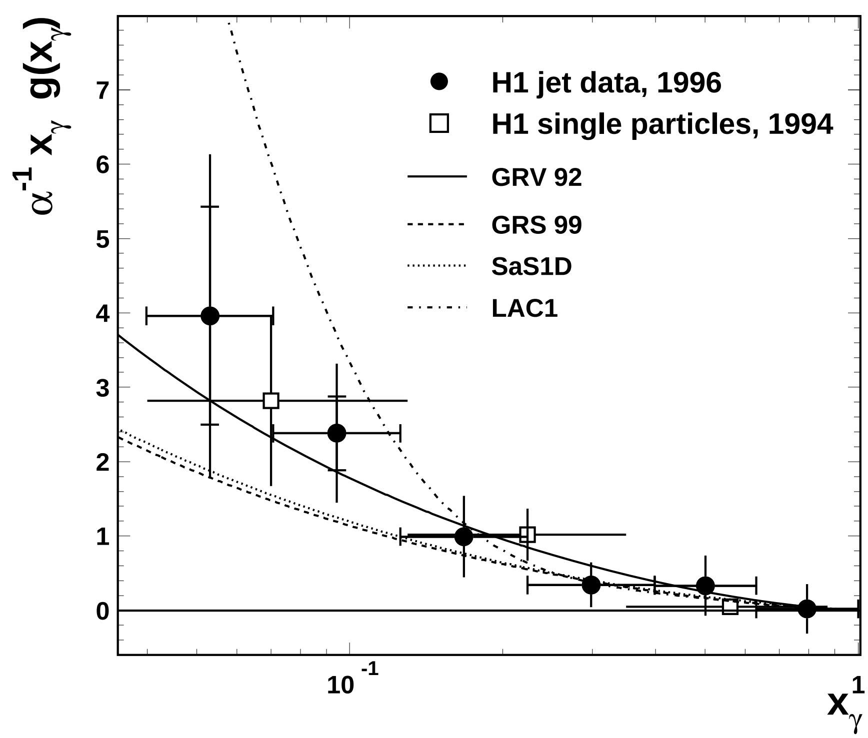
$$\tilde{f}_\gamma = \tilde{f}_\gamma^\mathrm{T} + \frac{2(1-z)}{1+(1-z)^2}\tilde{f}_\gamma^\mathrm{L}$$

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

Structure of quasi-real photons from H1

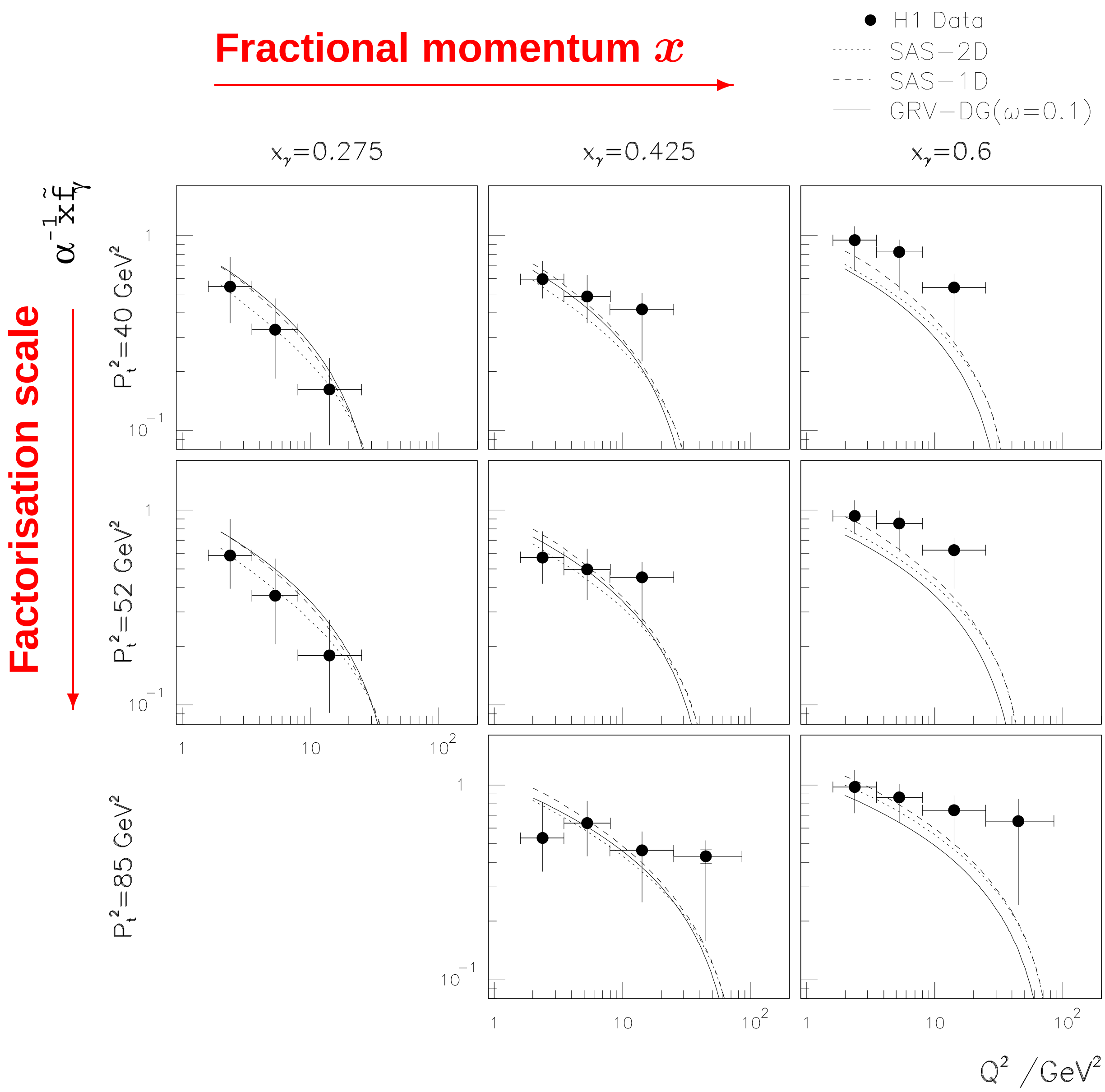


The hadron-like part is too low for all x, and the quark part is not sufficient $\Rightarrow$ gluons are needed.



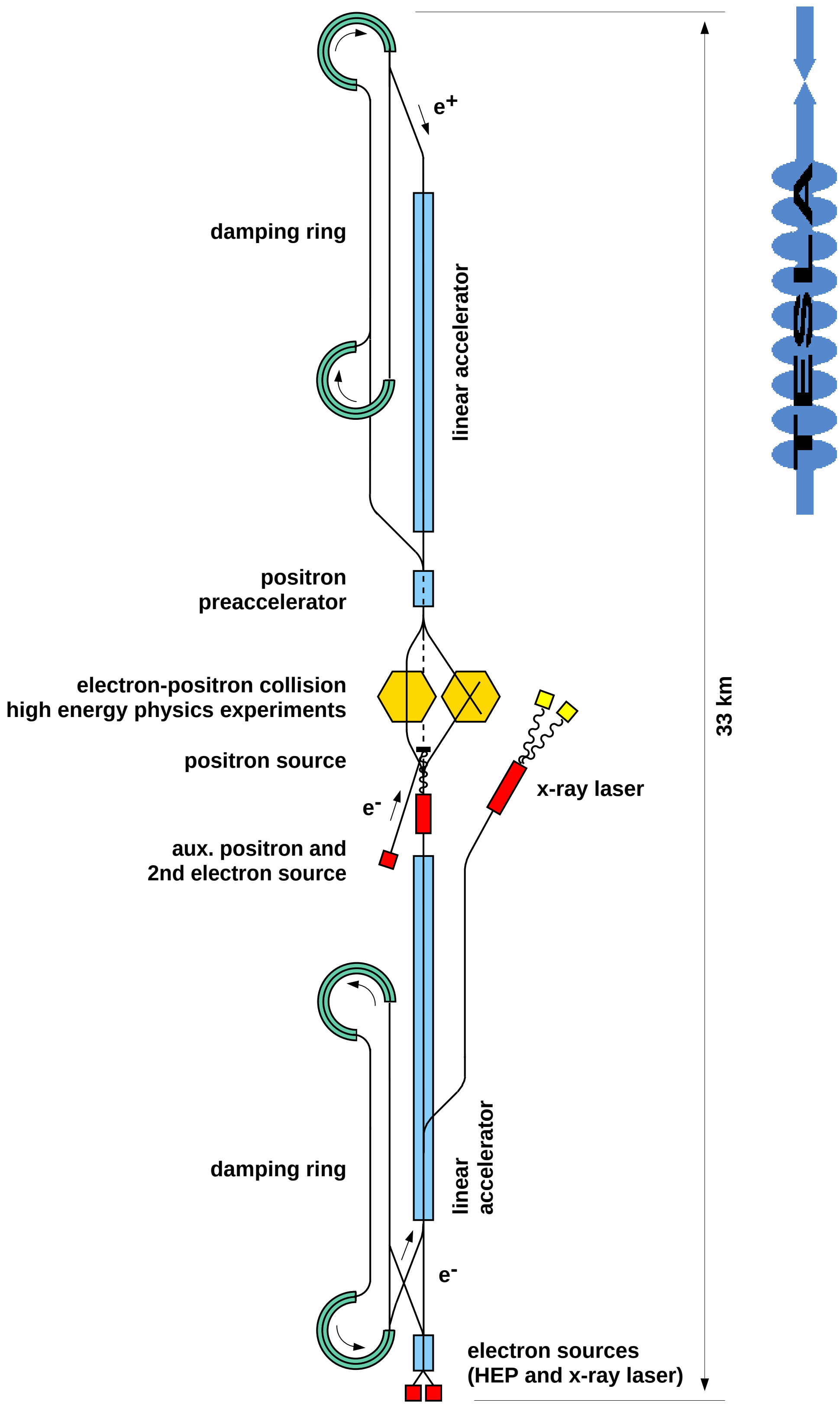
The gluon rises towards low x, and is small at large x

Structure of virtual photons from H1



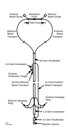
A strong suppression with increasing photon virtuality is observed.

Layout of a future Linear Collider

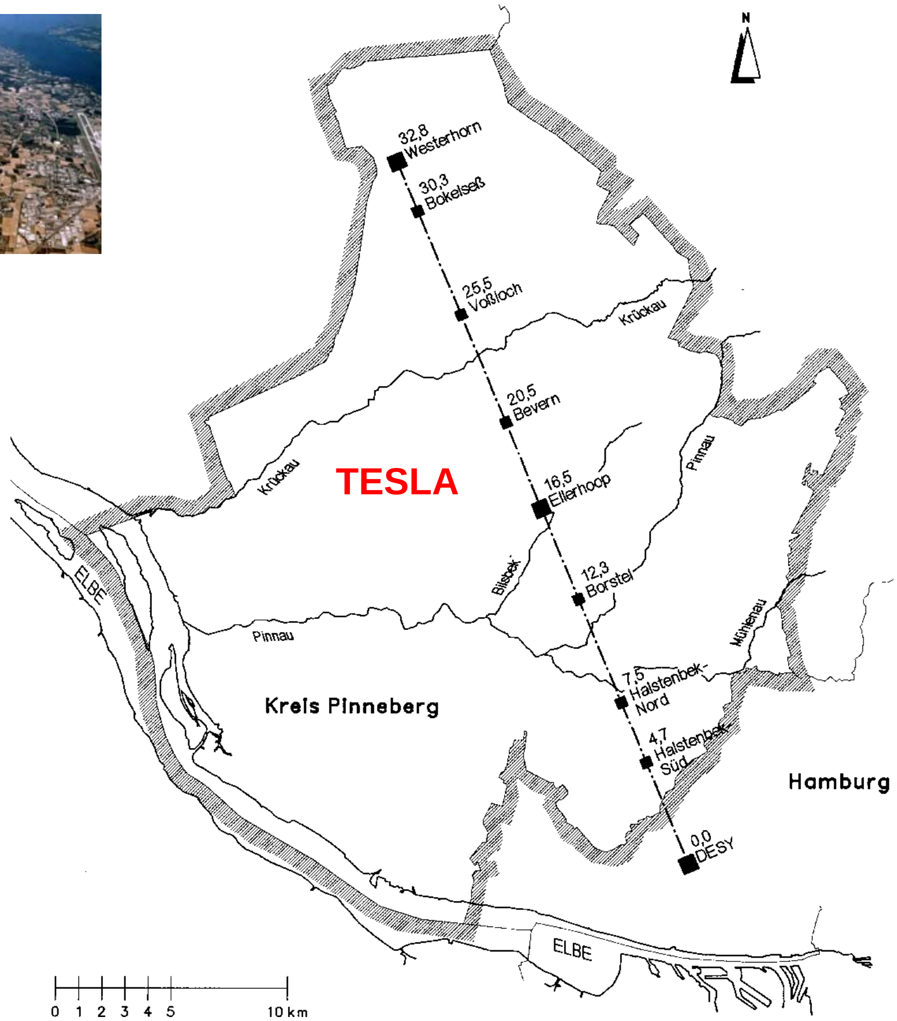


From LEP/ SLC to TESLA

LEP

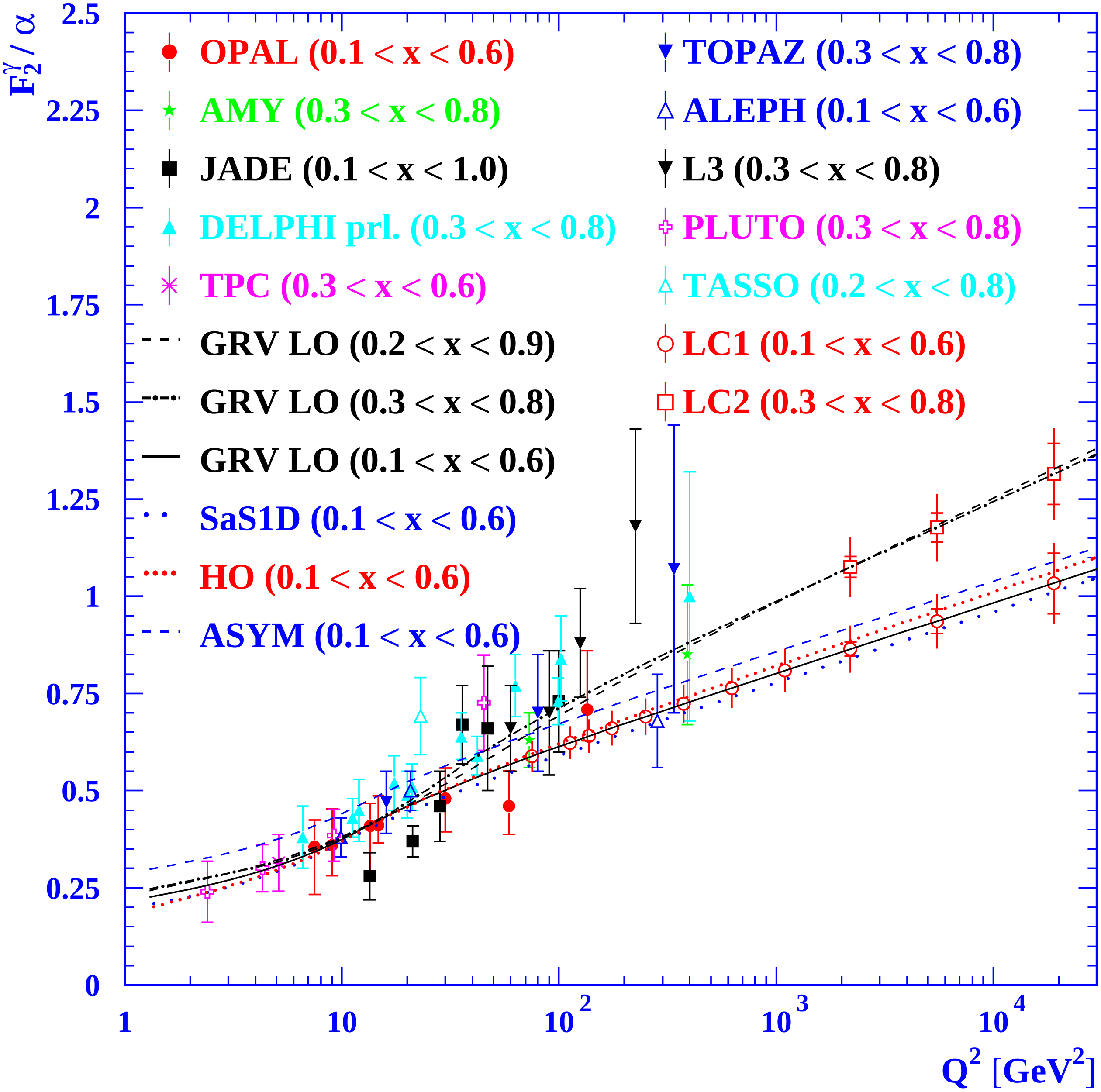


← SLC



		LEP	SLC	TESLA
radius	[km]	8.5	∞	∞
length	[km]	26.7	4	33
gradient	[MV/m]	6	10	23,4
σ_x/σ_y	[μm/μm]	110 / 5	1.4 / 0.5	0.553/0.005
energy	[GeV]	100	50	250
lumi.	[10^{31}/cm^{2}s]	7.4	0.1	3400
$\mathcal{L}_{\rm int}$	[1/pb y]	250	15	10000

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.

Conclusion

- Many different measurements concerning the structure of the photon have been performed. The global properties of the photon are theoretically understood, however, there are many aspects which need improvements to arrive at a precise understanding of the structure of the photon.

Outlook

- With the large luminosity of the LEP programme, and the improved understanding of the underlying physics, several measurements will get more precise.
- In the far future, the planned linear collider programme will allow for an extension of the measurements of the photon structure to much larger momentum transfers.