THE PHOTON

and
(its) Hadronic Interaction

PHOTON 2003
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Maria Krawczyk
Warsaw U.

The Electron

- The Photon - The Rho - The Pion

- The Proton

THE PHOTON and the rest of the world (of elem.

• "Structure" of the photon? Apparently - yes!

•The DIS on a photon: structure functions (and interference terms - we can not forget on electron- the primarly particle)
partonic content of the photon: PM prediction (pure QED) $q^\gamma \sim \ln Q^2$, large at large x
- QCD ($\ln Q^2$) corrections: inhomo. evol. equations
- asymptotic solutions or the input needed ?
- are quark densities in γ prop. to α/α_s?

•Large p_T processes involving photons: direct and resolved photons

•Both: DIS and hard processes with real and virtual photons:
Q^2 or p_T^2 larger that P^2- "virtuality" of the γ^*.

THE PHOTON and THE PROTON

The proton is a not a pointlike particle - this is known from 1923

•The DIS on a proton - photon as a probe only? We measure cross section for $\gamma^* p$ - property of both particles

•Forward particle production at HERA at large Q^2; BFKL or resolved γ^*?

•NLO analysis on Deep Inelastic Compton process:

$\gamma p \to \gamma X$ - intrinsic k_T in the proton?

NEWS

•New data for a proton and photon
•New standards in parton parametrizations: for proton: NNLO DGLAP, error analysis, heavy quark thresholds

DGLAP, BFKL, CCFM...

•for photon: as above however we need to know in addition a structure of the ρ, ω...
or to model (sic !) them by a π

the hope that the photon is so fundamental that the perturbative picture is sufficient is gone long ago

THE PROTON

A dream - F_2^p

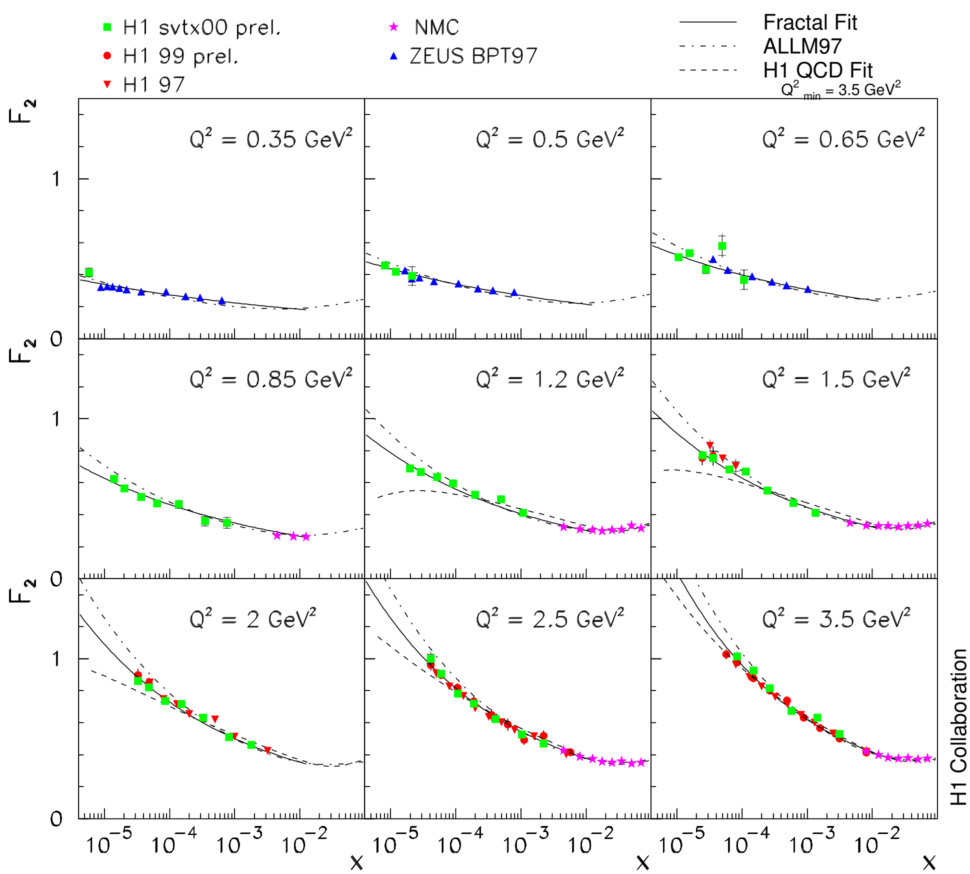


Figure 4: Measurements of the structure function $F_2(x, Q^2)$ - H1 shifted vertex data 2000, this analysis (green squares), H1 99 and 97 nominal vertex data (red points and triangles), compared to larger x data from ZEUS (BPT97 blue triangles) and from NMC (purple stars). Solid curves: phenomenological parameterisation of $F_2(x, Q^2)$ based on the fractal proton structure concept; Dashed curves: NLO QCD fit to the H1 96/97 data which was performed to data for $Q^2 \geq 3.5$ GeV^2, i.e. it is extrapolated here into the lower Q^2 region. Dashed-dotted curves: ALLM97.

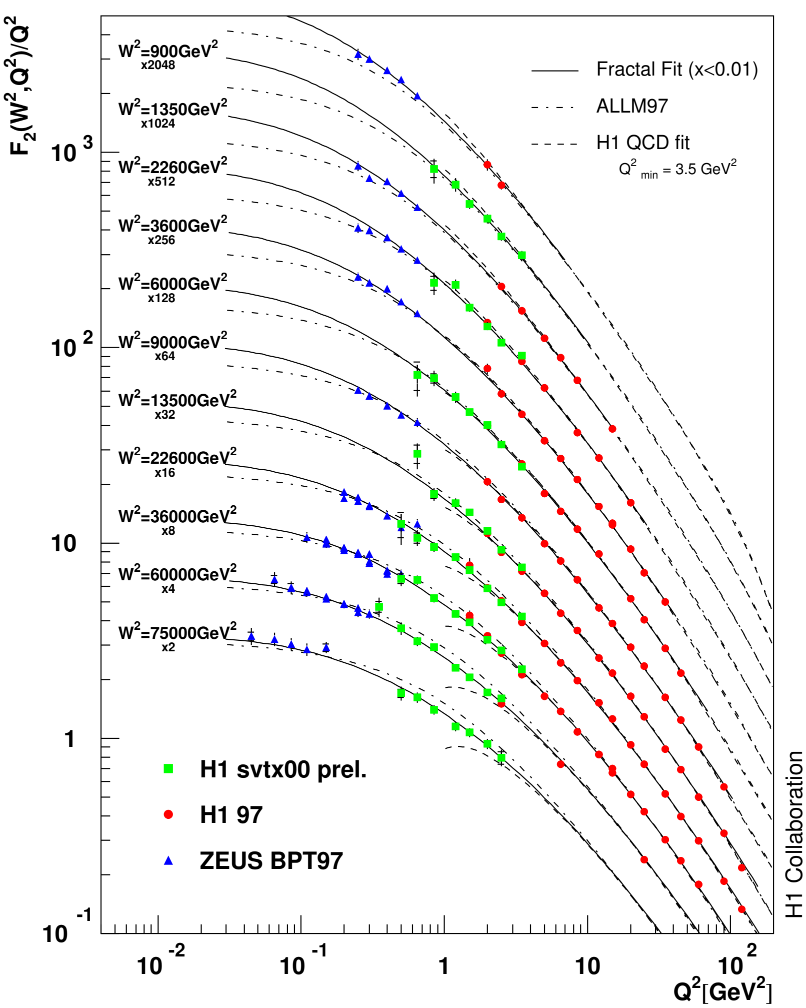


Figure 5: Measurements of the structure function F_2 represented as F_2/Q^2 which is proportional to the total cross section for virtual photon-proton scattering. Green squares: H1 2000 shifted vertex data, this analysis. The solid curves represent the fractal F_2 fit which was fixed using the two data sets shown at lower Q^2 (ZEUS 97 BPT, blue triangles) and higher Q^2 (H1 96/97, red points). Dashed-dotted curves: the ALLM97 parameterisation; Dashed curves: H1 NLO QCD fit, with $Q^2_{min} = 3.5$ GeV^2, extrapolated down to 1 GeV^2.

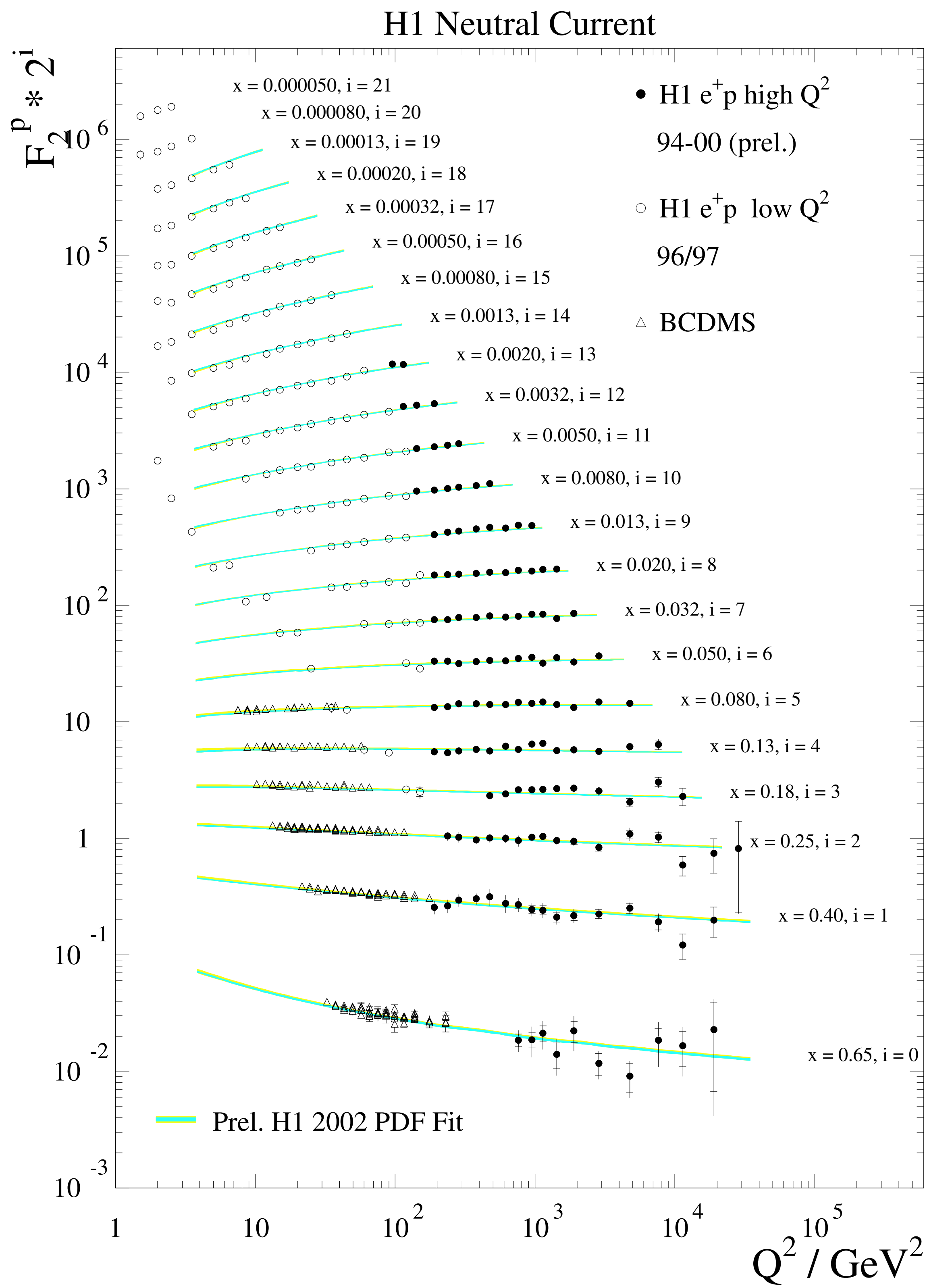


Figure 9: *The proton structure function F_2 from H1 data compared to the Preliminary H1 2002 PDF Fit. Also shown are the F_2 μp scattering measurements from BCDMS.*

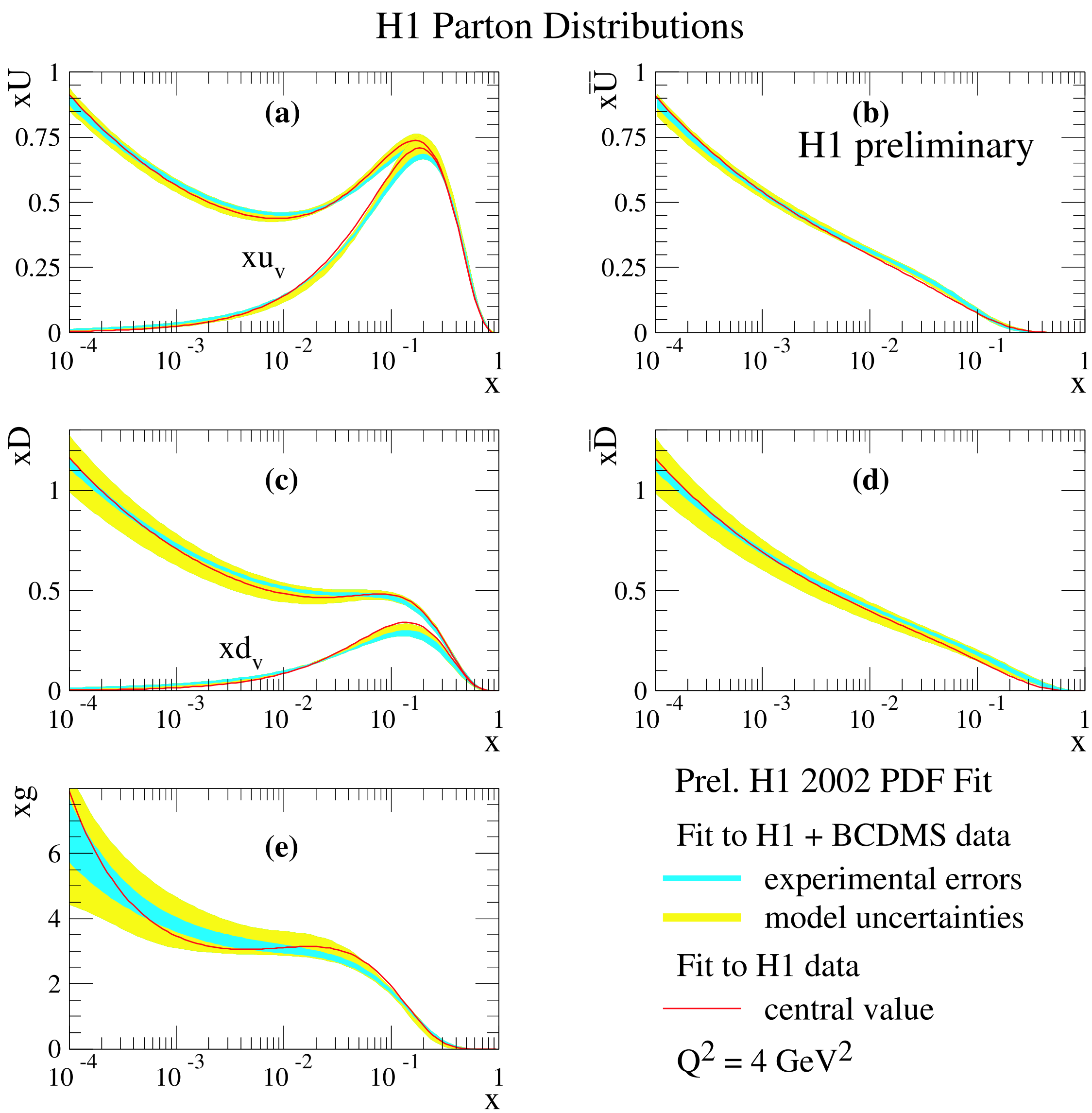
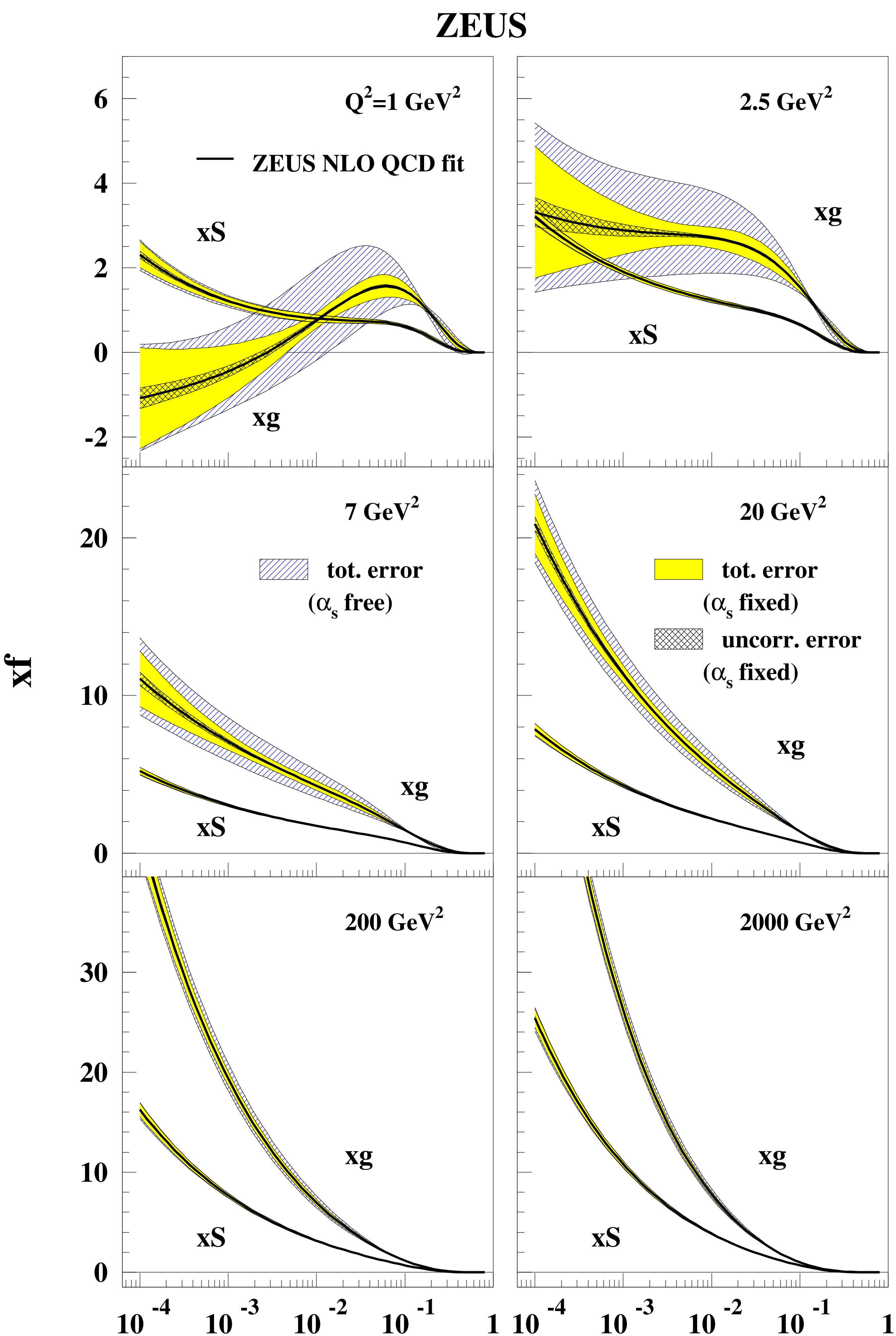


Figure 1: Parton distributions (a) xU, (b) $x\bar{U}$,(c) xD, (d) $x\bar{D}$, and (e) xg as determined from the Preliminary H1 2002 PDF Fit to H1 and BCDMS data. The distributions are shown at $Q^2 = 4$ GeV^2 with experimental and model uncertainties. The valence quark densities xu_v (a) and xd_v (c) are also shown. determined with H1 and BCDMS. For comparison, the central values from the fits to H1 data alone are also shown.

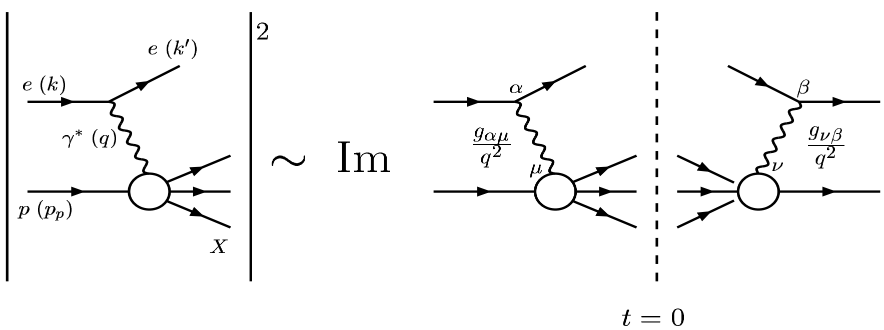


ZEUS
Q^2=1 GeV^2
ZEUS NLO QCD fit
xS
xg
2.5 GeV^2
xg
xS
7 GeV^2
tot. error
(α_s free)
xg
xS
20 GeV^2
tot. error
(α_s fixed)
uncorr. error
(α_s fixed)
xg
xS
200 GeV^2
xg
xS
2000 GeV^2
xg
xS
xf

Photon - one of the oldest elem. particle with very well known (QED) properties, a tool ("ideal probe") to test the structure of more complicated objects like hadrons:

eg. $\rightarrow$ DIS$_{ep}$ where F_2^{proton} is measured

F_2^{proton} prop. to cross section for $\gamma^* p \rightarrow hadrons$



$$d\sigma^{ep\rightarrow eX} = \Gamma_T\, d\sigma_T^{\gamma^* p\rightarrow X} + \Gamma_L\, d\sigma_L^{\gamma^* p\rightarrow X} \equiv d\sigma_T + d\sigma_L$$

A *factorization* to the lepton and hadron parts and a *separation* between the contributions of the longitudinal-and transverse photons

Hand'63,Budnev'75

Is photon only an neutral probe in this game...?

Small x physics in DIS$_{ep}$:
the BFKL ($\ln 1/x$) or DGLAP ($\ln Q^2$) approach, or the partonic content of the virtual photon ?

103 years of (light) quanta!

- 1900 - Planck $\to$ quanta of e-m energy $E = h\nu$
- 1905 - Einstein $\to$ quanta of light (γ) - Einstein's photon: $E = h\nu = pc$ .....
- 1915 - Millikan (photoemission from metal) experiment
- 1922 - Compton experiment: $\gamma e \to \gamma e$
- 1925-7 - Born, Heisenberg, Jordan, Dirac $\to$ QED photon - a gauge particle of quantum electrodynamics

(• 1926 - Lewis (chemist) $\to$ the name: photon)

- 1931 - Wigner $\to$ description of the angular-momentum states - Wigner's photon: helicity states of spin 1 massless particle

•1934 Luis de Broglie $\to$ The Neutrino Theory of Light
suggestion to apply ν (Pauli 1933) to QED $\to$
the light quanta is composed of a $\nu\bar{\nu}$ pair
Pauli, Heisenberg, Wentzel, Jordan, Kronig, Scherzer, Born, Nagendra Nath, Fock, Stueckelberg, Sokolov, Pyrce...
Problems:
Bose statistics of light quanta from Fermi statistics (ν):
criticism by Fock, Pyrce (1936-7), Berezinsky (1966)
however works up to 60-ies.. and even now (2001)

•New theoretical ideas: Non Commutative QED (selfinteraction of photons

Photon-hadron interaction: basic concepts

- 1960-72 - Sakurai, Stodolski, Schildknecht... → hadronic properties of the photon - ($\rho(\omega,\phi)$-photon analogy, Vector Dominace Model (also GVDM))
- 1969-71 - Artega-Romero, Balakin, Brodsky, Brown, Carlon, Tung, Budnev, Ginzburg, Serbo → an importance of $\gamma\gamma \to hadrons$ processes in e^+e^- collisions
- 1971-73 - Brodsky, Kinoshita, Terazawa, Walsh, Zerwas, Kinsley,Cherniak,Serbo ...→ structure functions of the real photon (parton model prediction!) - partonic content of the photon
- 1975 - Ahmed, Ross → various structure functions in AFGT
- 1977 - Witten → asymptotic (point-like) solution for a real photon fully calculable in QCD ! - clean test of QCD
- 1979-83 - Duke, Owens,Bardeen, Buras, Frazer, Gunion, Lewellyn Smith, De Witt at al, Uematsu, Walsh, Antoniadis, Grunberg, Rossi, Peterson, Zerwas, Sasaki ... → singularities in asymptotic solutions for a real photon
- 1981- Walsh, Uematsu, Rossi ..→ structure functions of virtual photons - a unique test of QCD!
- 1989-93 Gorsky, Ioffe, Efremov, Terayev, Bass, Brodsky, Narison, Shore, Veneziano...→ polarized str. functions, sum rule...

- 1981-2003 - DATA → structure functions of real and virtual photons (F_2^{had} and F_2^{QED}); also data on resolved photon processes
- ? - DATA → spin-dependent structure functions of polarized real and virtual photons

Main (?) information on the strong (hadronic,part
properties of :

→ real photon γ

→ virtual photon γ^*

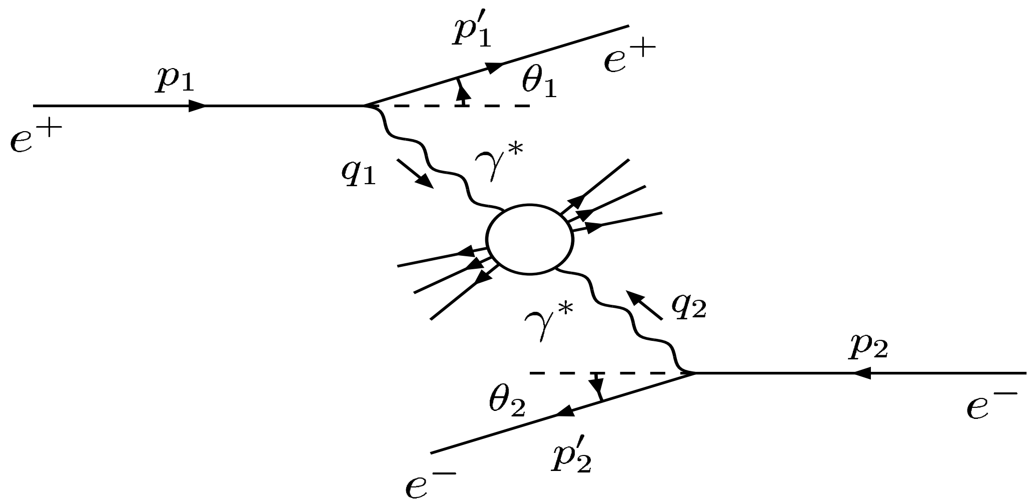
comes from

Deep Inelastic Scattering on a photon

in the e^+e^- collisions (LEP)

Importance of the measurements of resolved photon processes in e^+e^- (LEP) and ep (HERA) collisions.

recent review 2000-2: Nisius, Krawczyk at al, Klasen



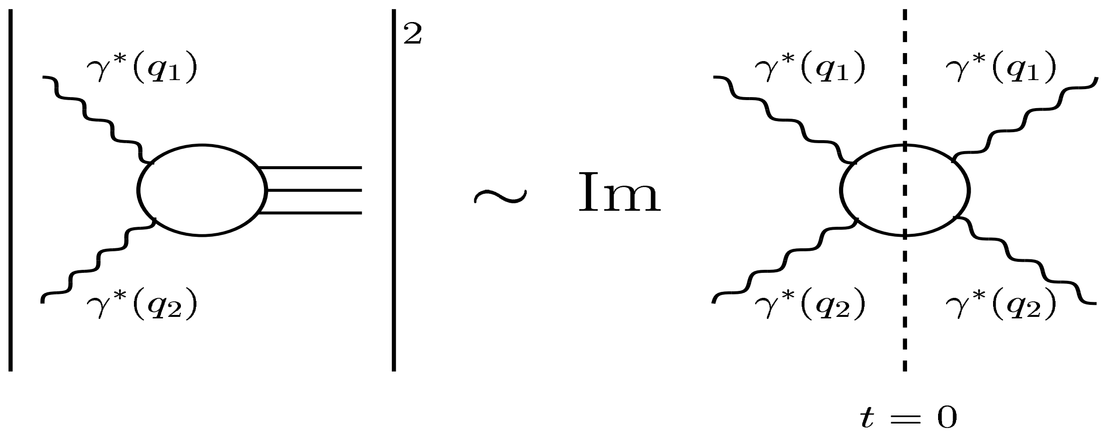
Various limits possible..
introducing virtualities: $|q_1^2| = Q^2$ $|q_2^2| = P^2$

•for final states = hadrons we have:

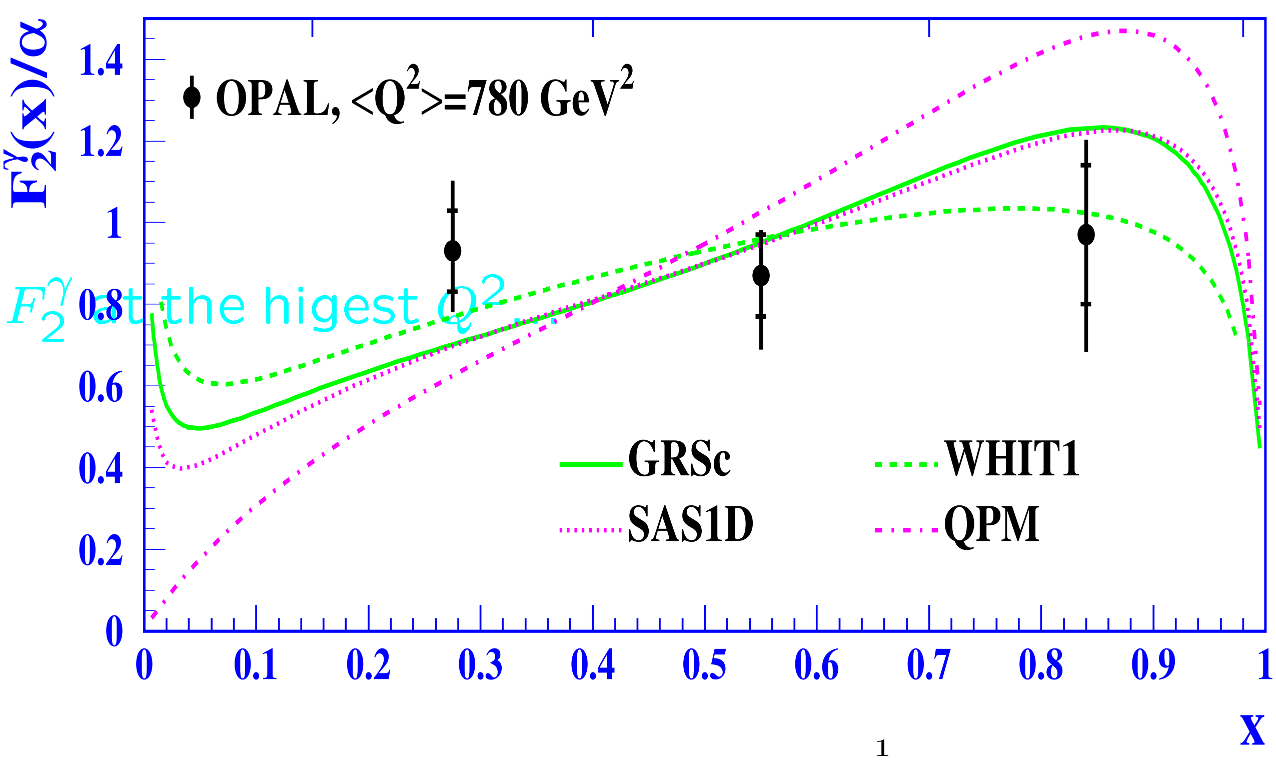
$Q^2 \gg P^2 \gg \Lambda^2_{QCD}$: DIS$_{e\gamma^*}$
$Q^2 \gg \Lambda^2_{QCD}$, $P^2 \sim 0$: DIS$_{e\gamma}$
$Q^2 \sim P^2 \sim 0$: $\sigma^{tot}_{\gamma\gamma}$...
various structure functions and intererence terms
LL,TT,LT,T1T1,T1T2..

•for final state = large p_T particles (or jets):
(provided the hard scale $p_T^2 \gg P^2$)
processes with resolved real or virtual photons

$\gamma^*\gamma^* \to hadrons$ - 8 structure functions



F_2^γ at the higest Q^2



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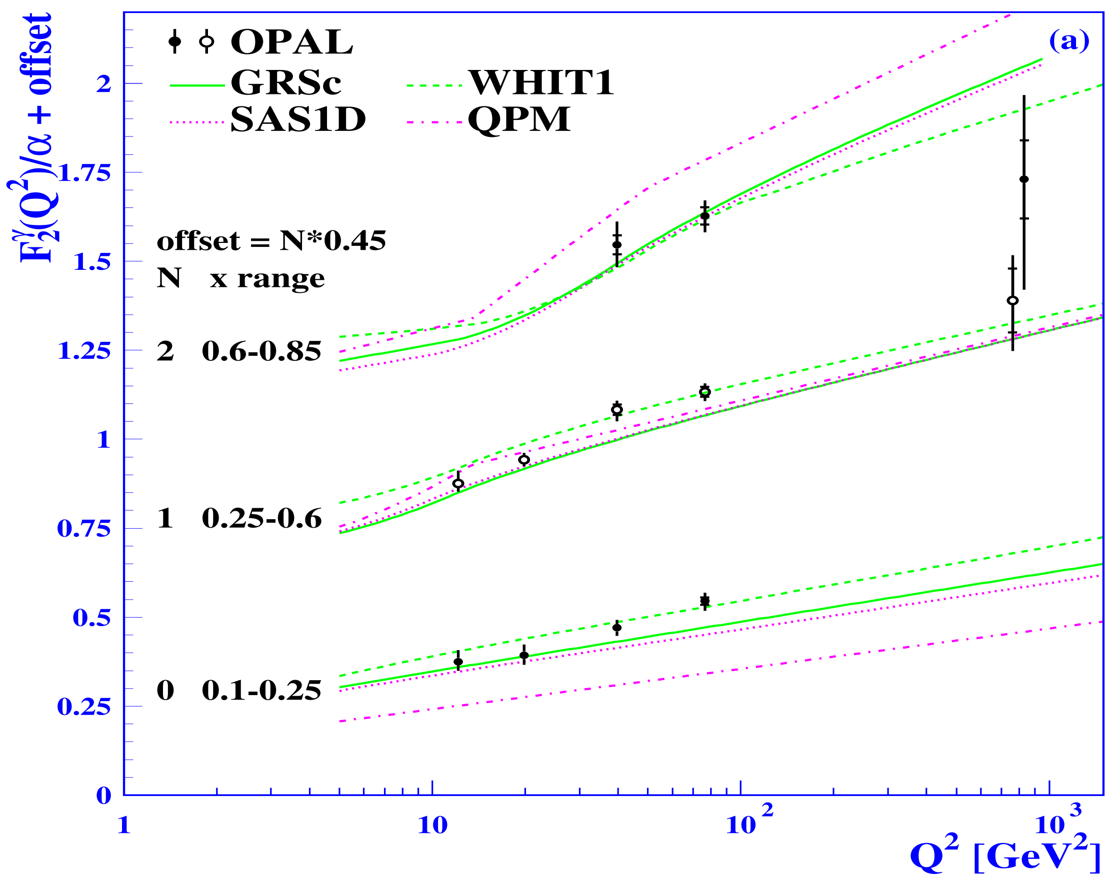
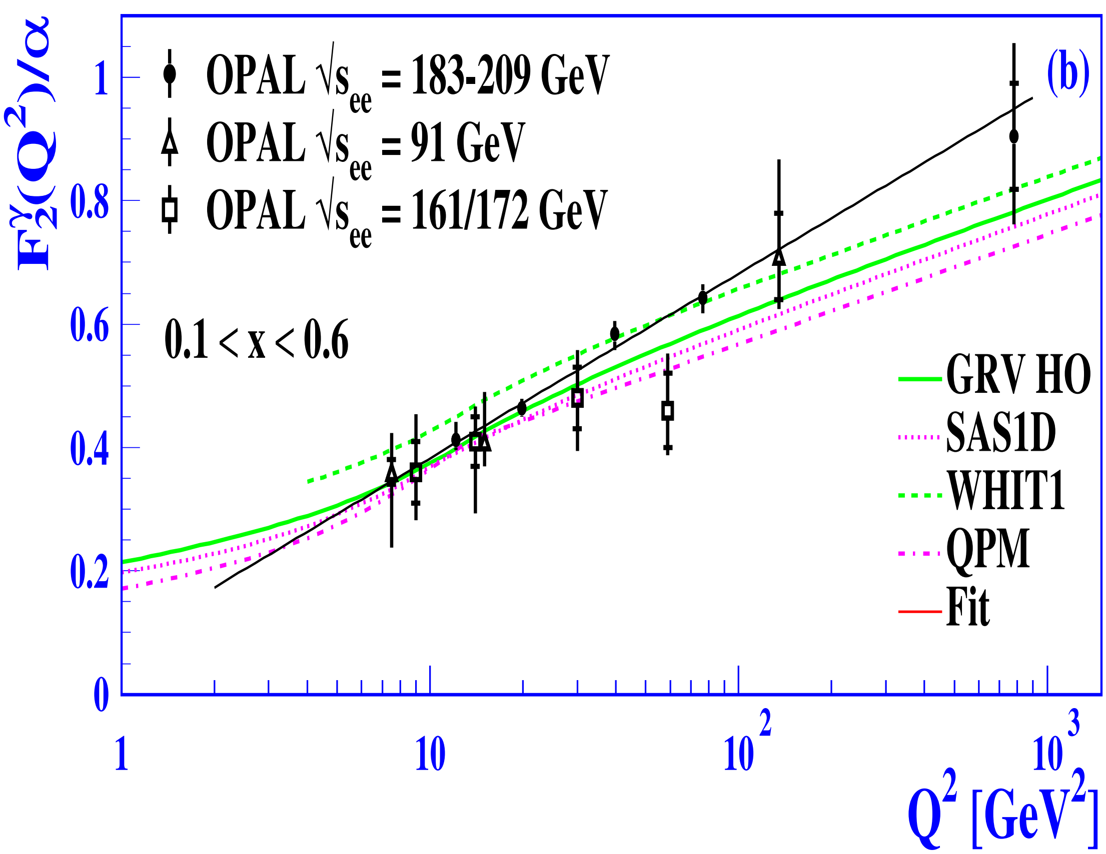
F_2^γ Q^2-dependence





OPAL √s_ee = 183-209 GeV
OPAL √s_ee = 91 GeV
OPAL √s_ee = 161/172 GeV
0.1 < x < 0.6
(b)
GRV HO
SAS1D
WHIT1
QPM
Fit
F2γ(Q2)/α
Q2 [GeV2]

Parton parametrizations for the real photon

Duke - Owens (DO) '83

Drees - Grassie (DG)

Field - Kapusta - Poggioli (FKP)

Levy - Abramowicz - Charchuła (LAC)

Gordon - Storrow (GS)

Glück - Reya - Vogt (GRV)

Aurenche - Chiappetta - Fontannaz - Guillet - Pilon (ACFGP)

Aurenche - Guillet - Fontannaz (AGF)

Hagiwara - Izubuchi - Tanaka - Watanabe (WHIT)

Schuler - Sjöstrand (SaS)

Glück - Reya - Schienbein (GRSch)

Laenen - Riemersma - Smith - Neerven (LRSN)

Gorski - Ioffe - Khodjamirian - Oganesian (GIKO)

Ioffe - Oganesian (IO)

H. Abramowicz, E. Gurvich, A. Levy (GAL)

F. Cornet, P. Jankowski, M. Krawczyk, A. Lorka (CJKL)

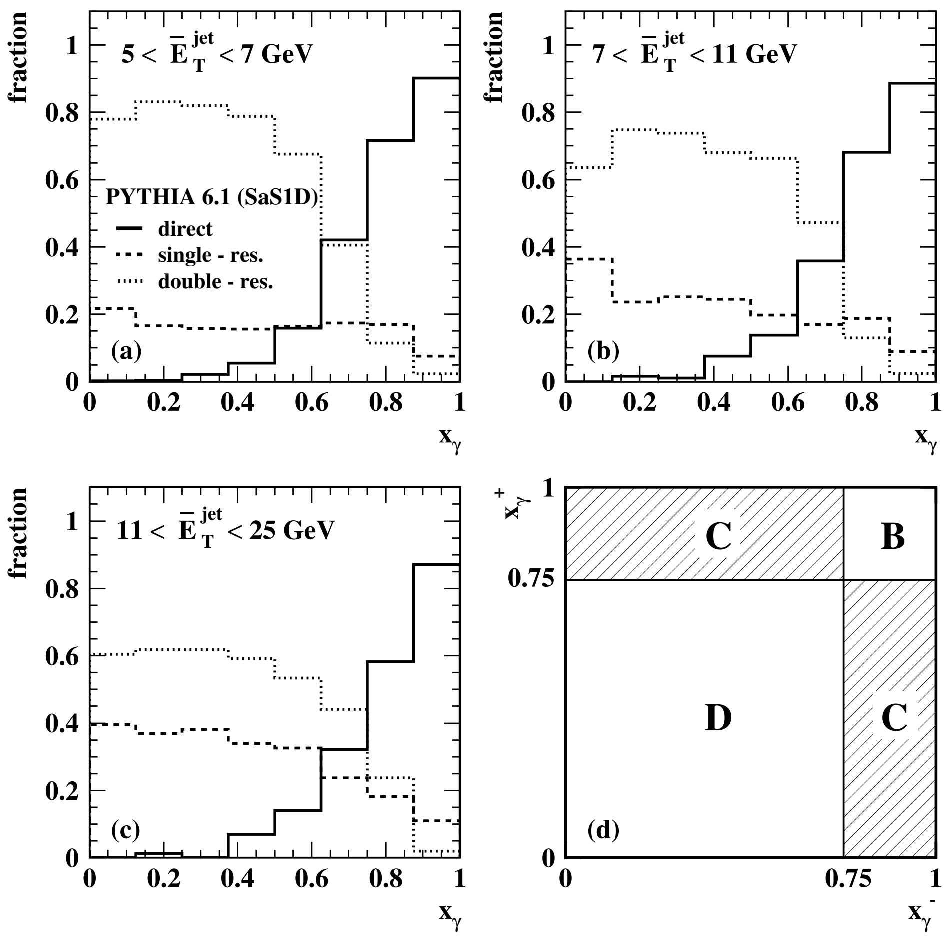
Parton parametrizations for the virtual photon

The parton distributions in the virtual photon can be calculated in the perturbative QCD for $\Lambda^2 \ll P^2 \ll Q^2$ without any input...

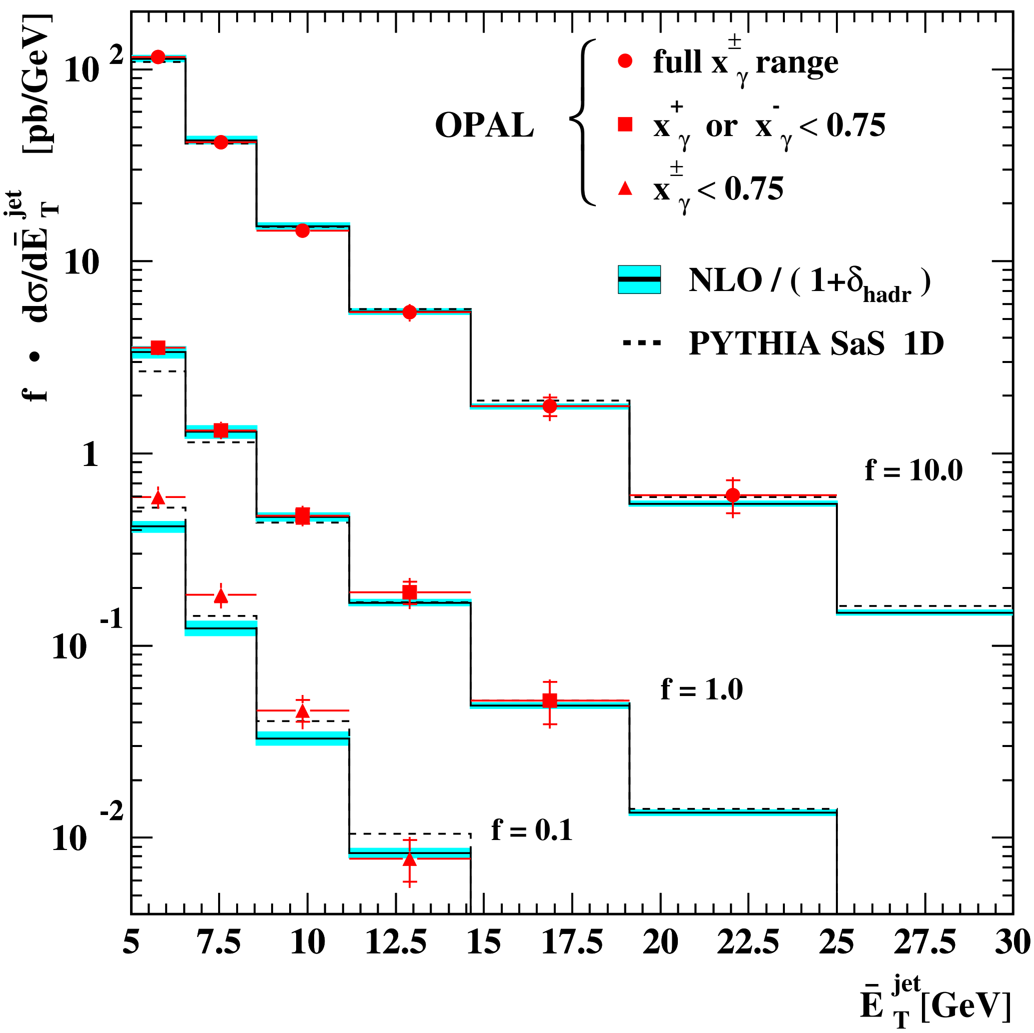
Drees - Godbole
Glück - Reya - Stratmann (GRS)
Schuler - Sjöstrand (SaS)
Glück - Reya - Schienbein (GRSch)
Gorski - Ioffe - Khodjamirian - Oganesian (GIKO)
Ioffe - Oganesian (IO)
Chýla (res.long. γ^*)

LEP (OPAL) 20 Dec. 2002

Dijets productions in photon-photon collisions at $\sqrt{s_{ee}}$ from 189 to 209 GeV (quasi-real photons $Q^2 < 4.5$ GeV^2, with median 10^{-4} GeV^2)



contribution due to direct $x^\gamma_{1,2} = 1$, single-resolved $x^\gamma_1 = 1, x^\gamma_1$ less than 1 and double resolved photons $x^\gamma_{1,2}$ less than 1

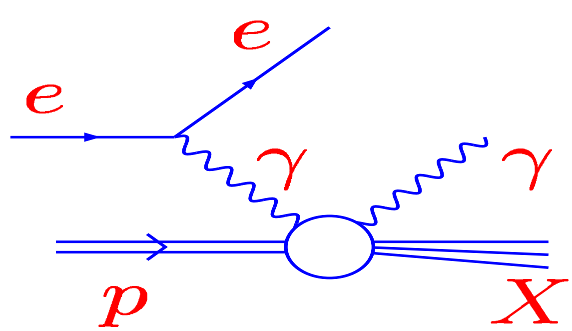


OPAL
full $x_\gamma^\pm$ range
x_γ^+ or x_γ^- < 0.75
$x_\gamma^\pm$ < 0.75
NLO / (1+δ_{hadr})
PYTHIA SaS 1D
f = 10.0
f = 1.0
f = 0.1
f • $d\sigma/d\bar{E}_T^{jet}$ [pb/GeV]
$\bar{E}_T^{jet}$ [GeV]
10^2
10
1
10^{-1}
10^{-2}
5
7.5
10
12.5
15
17.5
20
22.5
25
27.5
30

Resolved processes at HERA- with a real photon

Photoproduction of photons with large $p_T \rightarrow$ at HERA

Deep Inelastic Compton process with isolated photon in NLO QCD



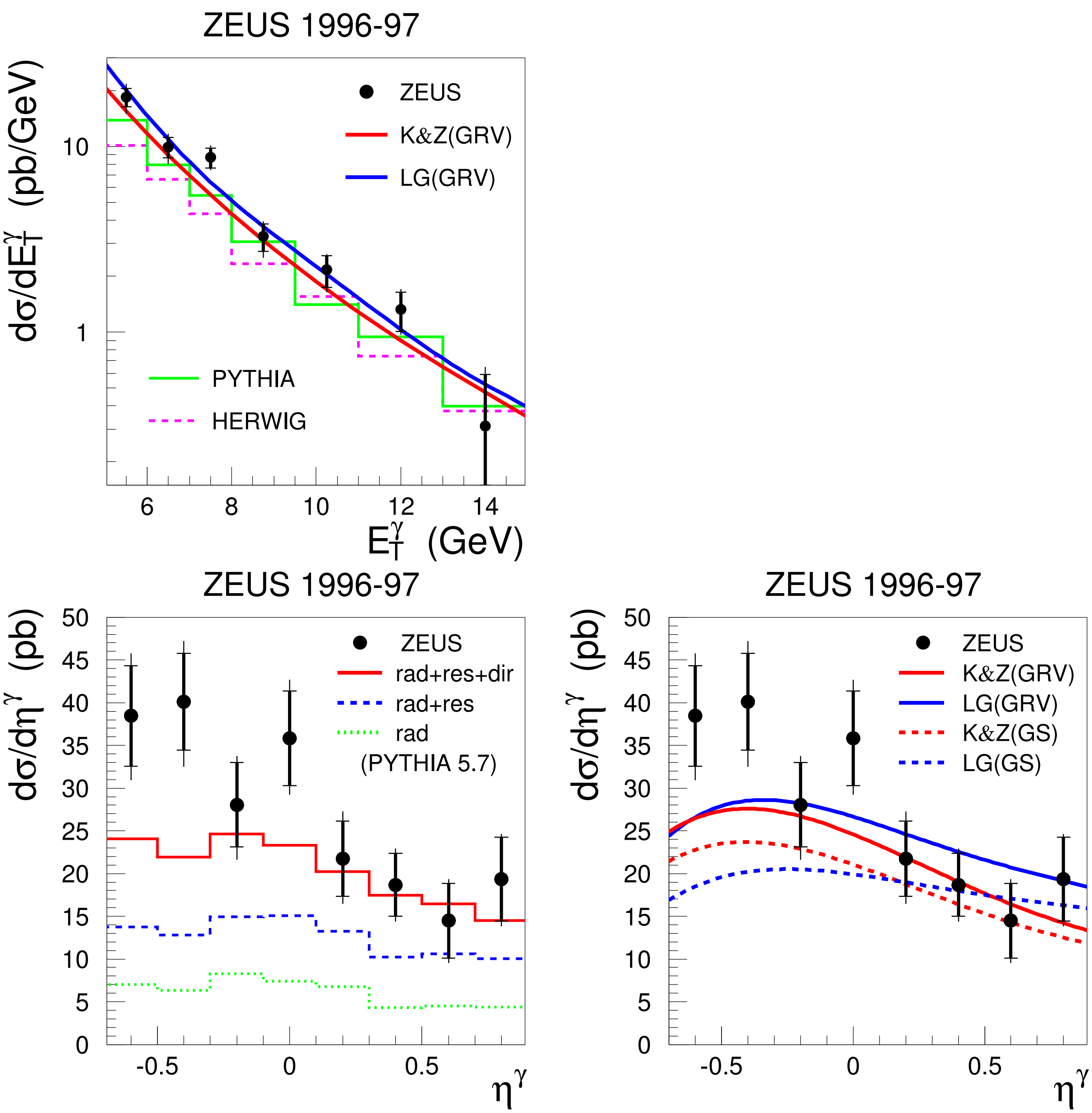
DIC process: $q^2 \sim 0$, $p_T \gg \Lambda_{QCD}$

•testing: Parton Model '69 Bjorken, Paschos
QCD LO, NLO,

•probing the parton densites in γ and p

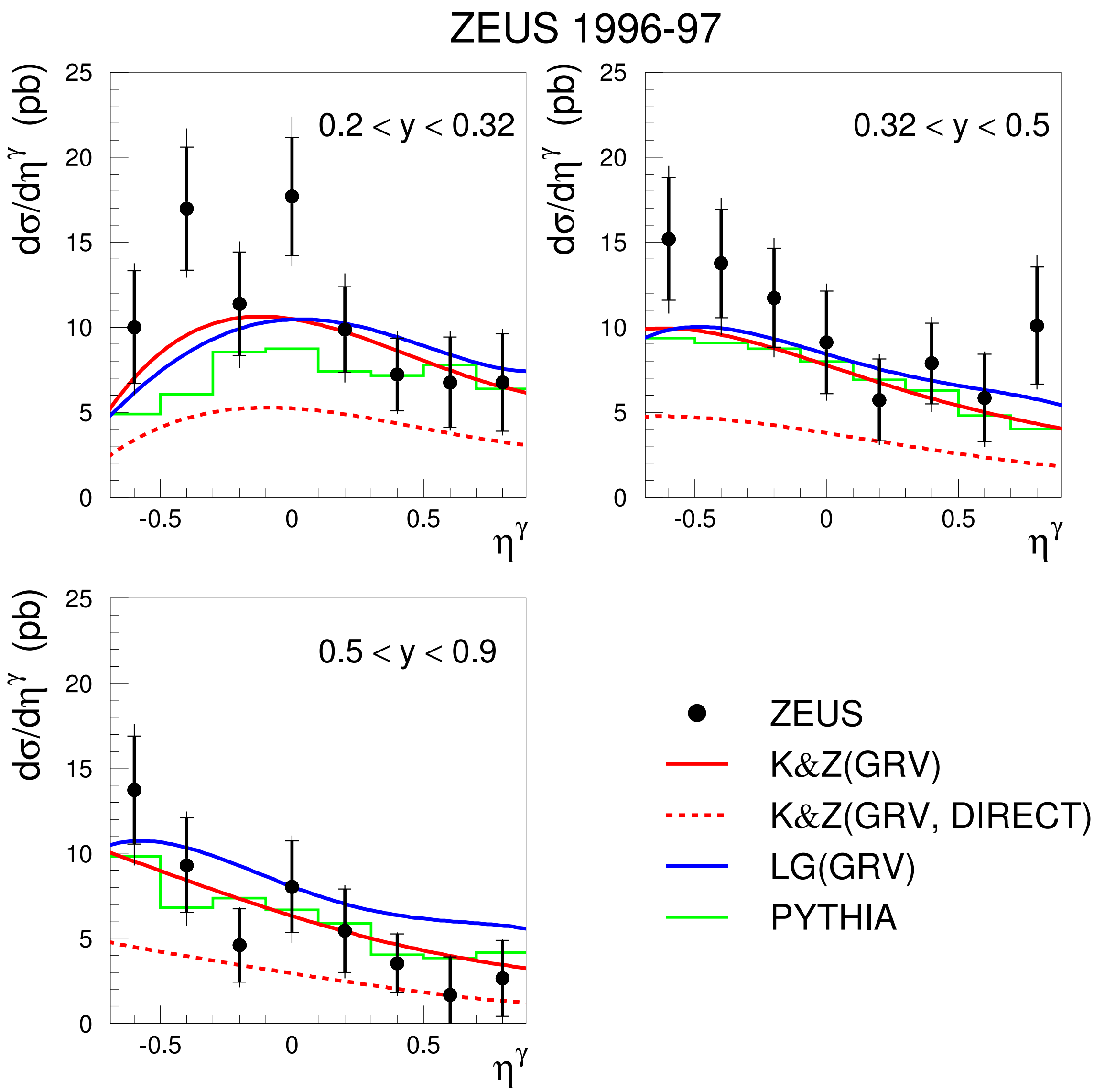
INCLUSIVE PROMPT PHOTONS

$E_T > 5$ GeV, $134 < W < 285$ GeV PLB 472 (2000) 175



PYTHIA does only fairly well (HERWIG is lower).
NLO calculations an improvement.
GRV photon structure apparently favoured.

Divide incident E_γ range into 3 bands:



As $E_\gamma = yE_e$ increases, peak moves to –ve η.
Suggestion of possible discrepancy at high x_γ.

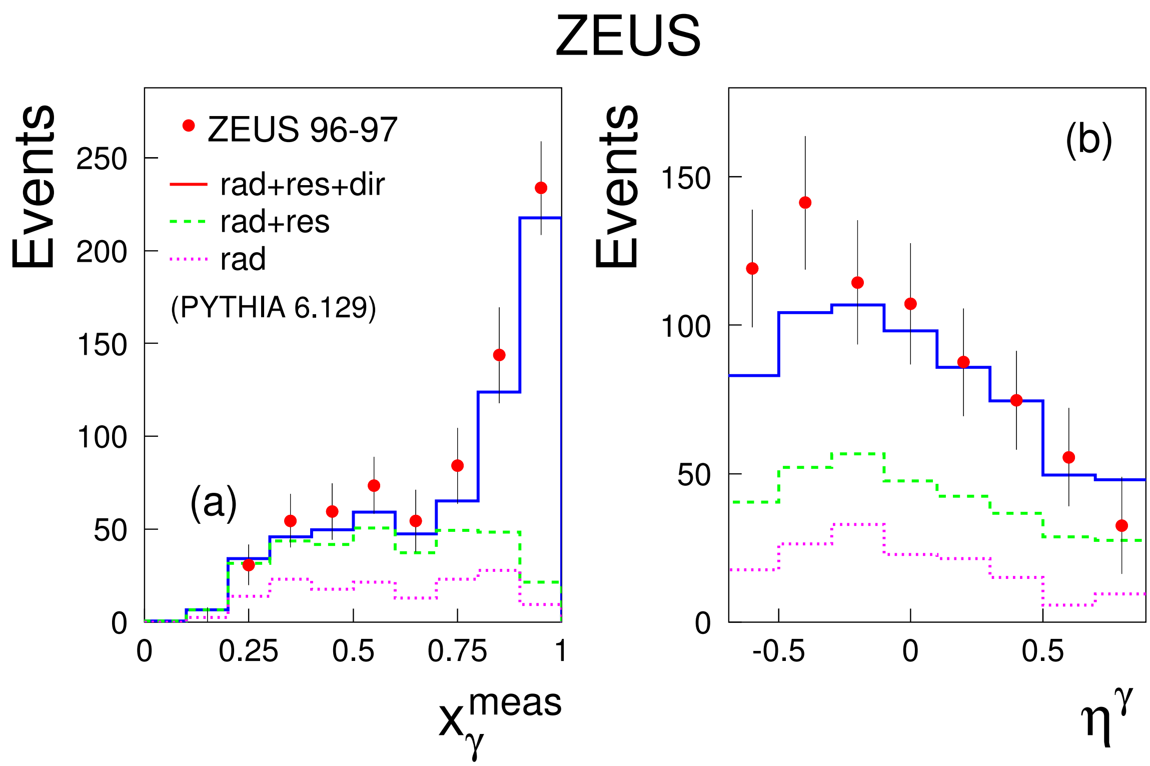
ZEUS: PROMPT PHOTON + JET in γp

Select: photon: $E_T > 5$ GeV, $-0.7 < \eta < 0.9$

jet: $E_T > 5$ GeV, $-1.5 < \eta < 1.8$

$0.2 < y_{JB} < 0.7$

Jet finder: KTCLUS



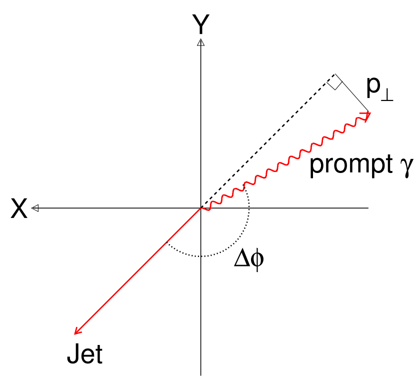
Prominent peak near $x_\gamma = 1$ corresponding to Direct Compton process $\gamma q \to \gamma q$.

PYTHIA OK! – differences are compatible with LO→NLO.

Select a highly direct-enhanced sample

$<k_T>$ OF PARTONS IN PROTON

Use direct γ + jet kinematics to determine $<k_T>$



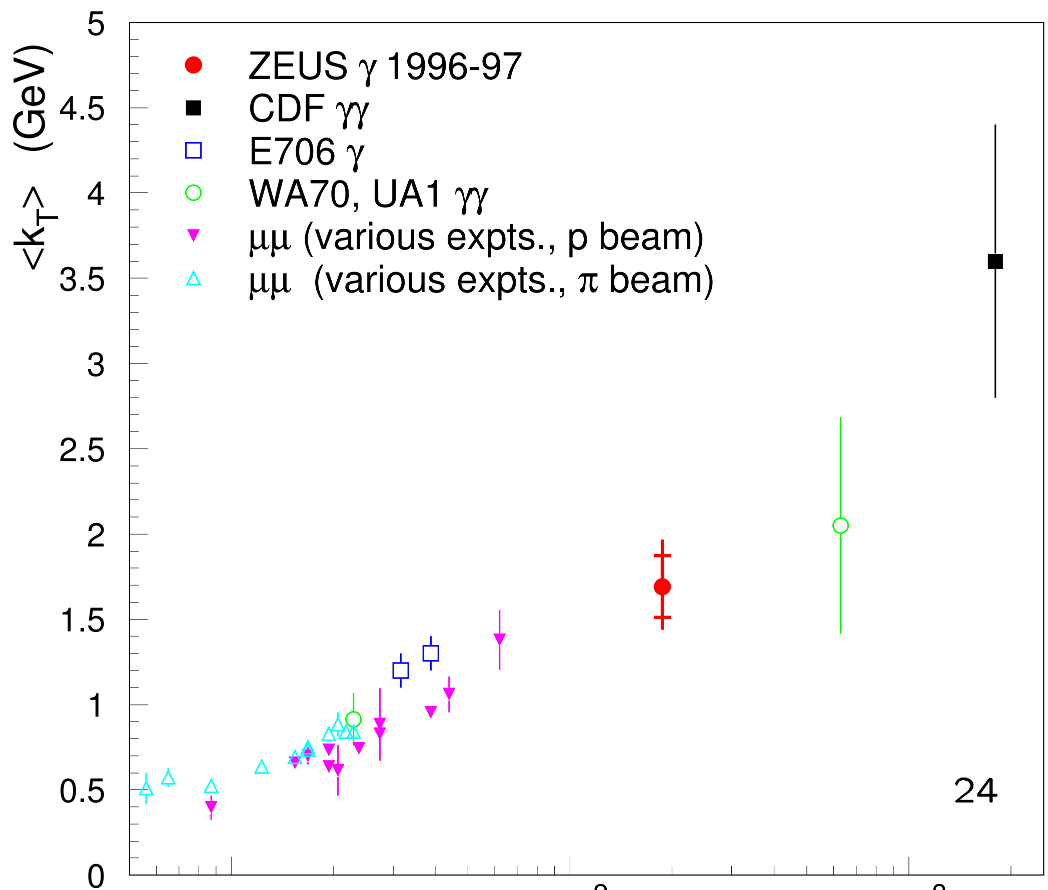
– Use direct-enhanced sample to minimise sensitivity to resolved photon

– Vary 'intrinsic' contribution k_0 in PYTHIA.

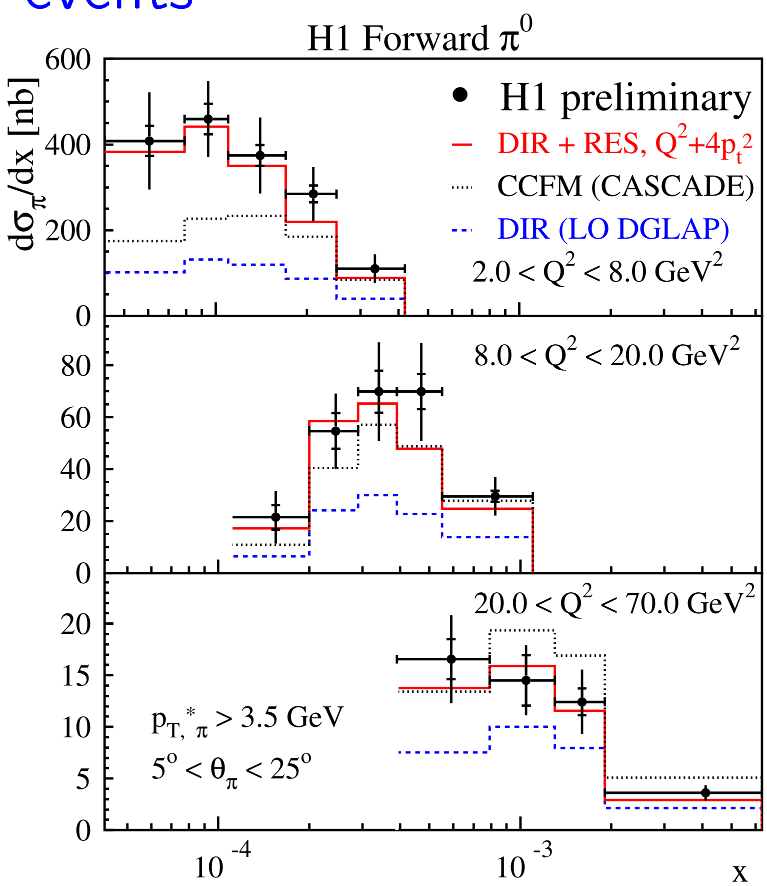
– Fit $p_\perp$ distribution using series of k_0 values

– Use PYTHIA at parton level to incorporate parton shower effects

$$< k_T >= 1.69 \pm 0.18 \, ^{+0.18}_{-0.20} \text{ GeV}$$



DIS events



Resolved virtual photon?

Forward particle production at HERA - with γ^*

DIC - a forward production of photons

A method of probing a partonic (gluonic) content of the photon

just a simple kinematic that in the forward direction (proton direction) $\rightarrow$ small x_γ is probed while in the backward - a small x_p

$x_\gamma^{min}(\eta) = \frac{x_T e^\eta}{2 - x_T e^{-\eta}}$,

where $x_T = \frac{2 p_T}{\sqrt{(S_{\gamma p})}}$

η - (pseudo)rapidity $\eta = -\ln \tan(\theta/2)$

min of $x_\gamma^{min}(\eta) = x_T^2$, where $e^\eta = x_T$.

Conclusions

Structure function measurements remain a main source of our knowledge
of the “structure” of the photon and proton

combining with resolved photon processes data $\rightarrow$ results for the individual parton densities in the real and virtual photon

Understanding of the “structure” of photon and of proton is a must

for particle physics !