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Experimental results on QCD from DIS

Theory Workshop
September 26th, 2002

- Introduction
- Jet physics, heavy quarks
- NLOQCD fits, α_s , parton distributions, etc
- Down below pQCD – the low Q^2 interface
- Further into the non-perturbative mire - diffraction
- Summary

Many thanks to Ken Long & Oscar Gonzales!

Introduction

- Kinem

$Q^2 = x$

- There is NO introduction!
- You're all experts!

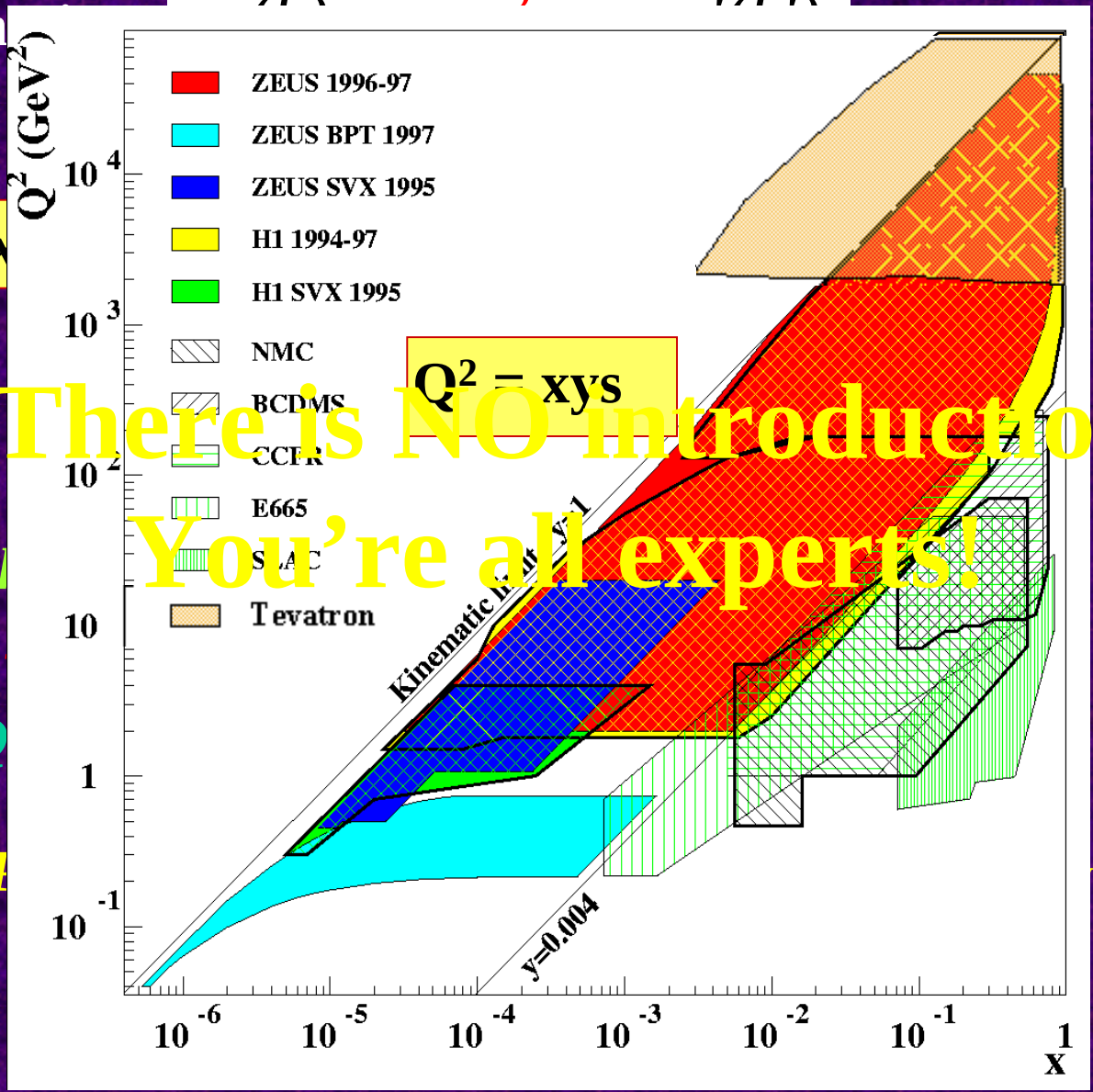
$\sqrt{s} =$

$Q^2 =$

$x = Q$

$y = (P$

$W^2 =$



Jet Physics

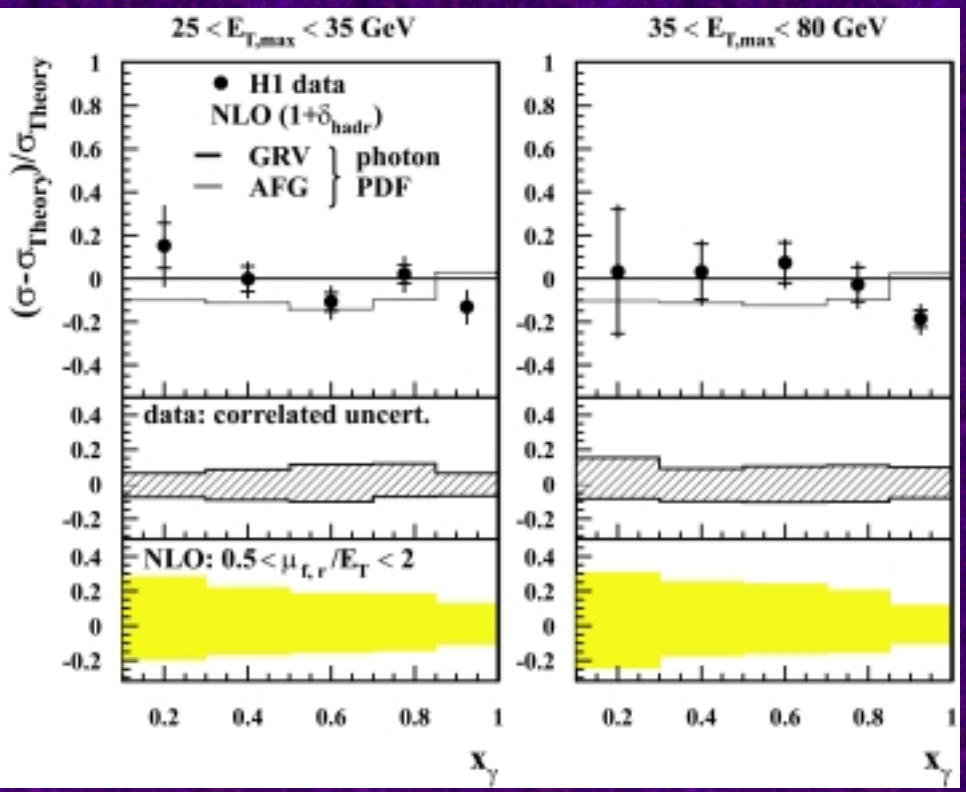
- The study of jet physics at HERA has now reached an impressive level of maturity and accuracy. The widespread use of longitudinally invariant k_T cluster algorithm, in Breit frame, and the accuracy of the calorimeter energy scale determination (for some analyses down at ~ 1%) has allowed a host of precise measurements and confrontation with NLO QCD and QCD evolution schemes.

- The following is just a small subset of the results available, selected to illustrate the power and variety of these studies at HERA.

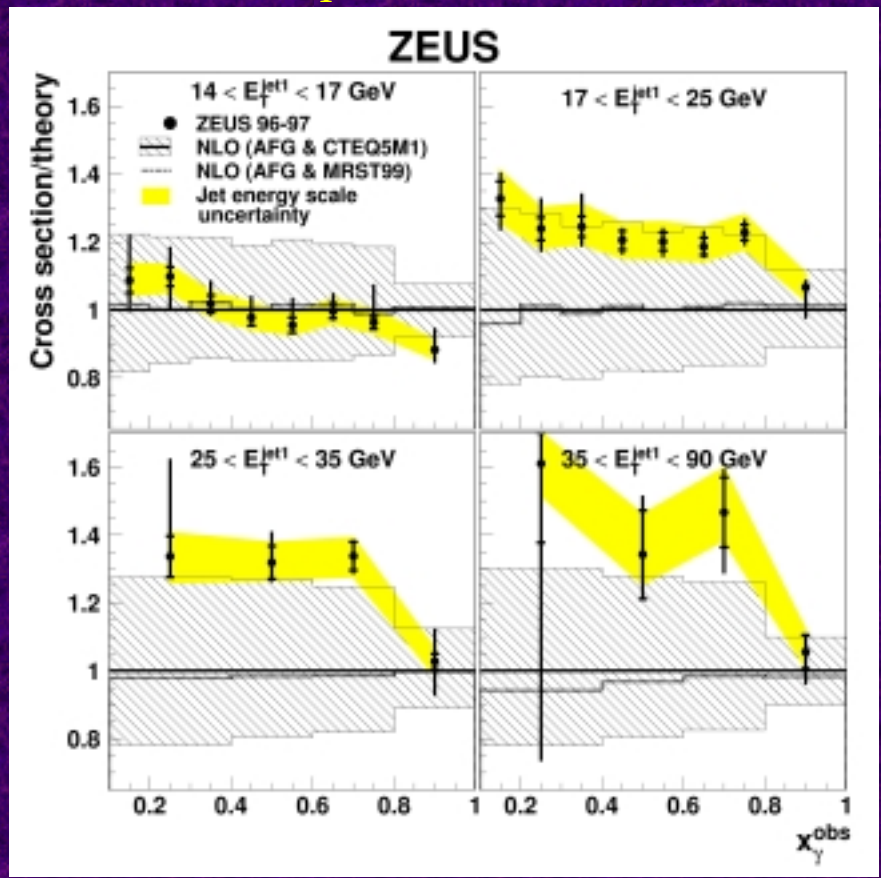
Dijets in γp

- In principle, study of dijects in photoproduction as function of x_γ^{obs} sensitive to photon structure. In practice, life is more complicated!

$E_T^{jet1} > 25$ GeV, $E_T^{jet2} > 15$ GeV, $-0.5 < \eta^{jet1,2} < 2.5$

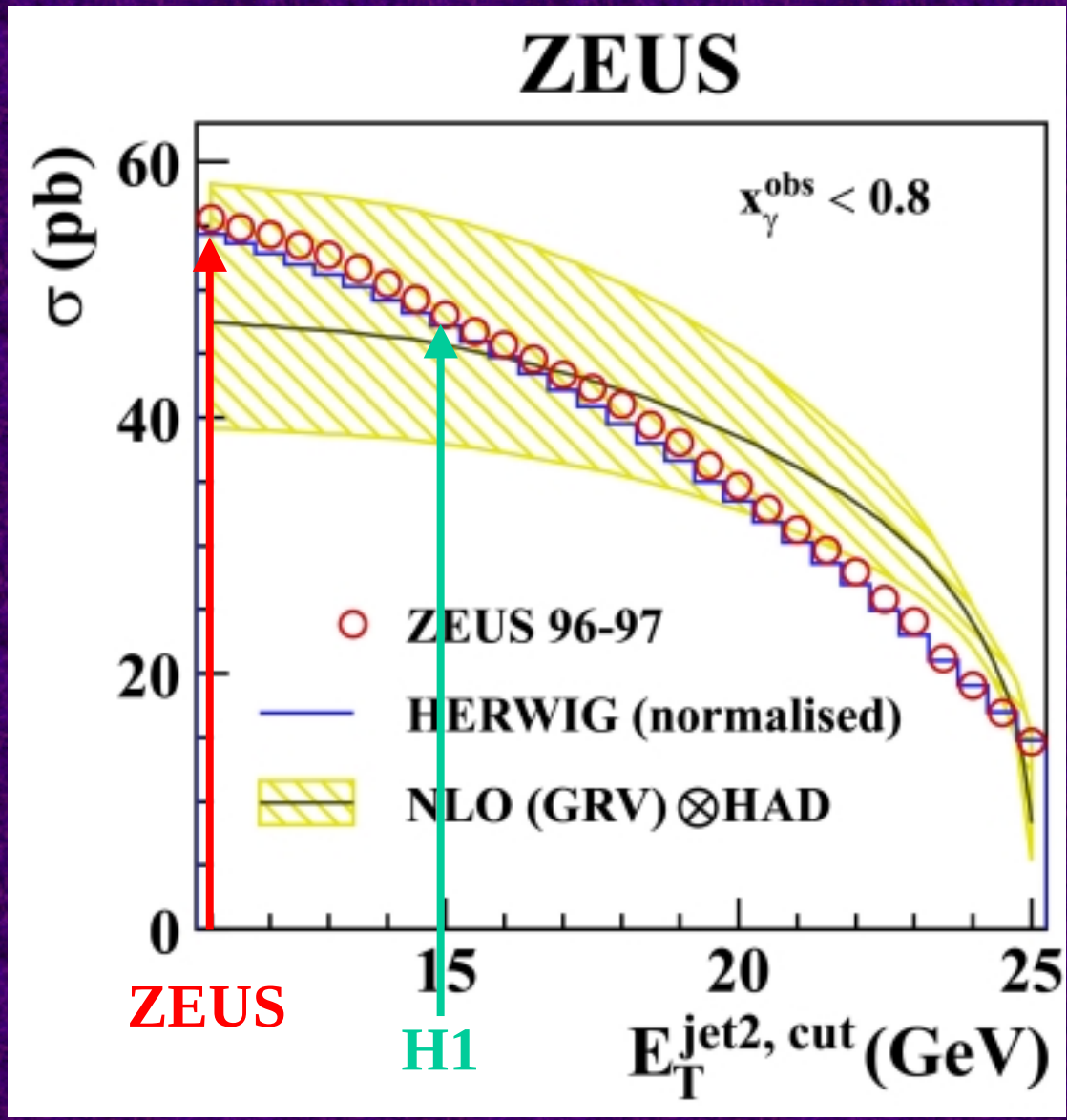


$E_T^{jet1} > 14$ GeV, $E_T^{jet2} > 11$ GeV, $-1 < \eta^{jet1,2} < 2.4$



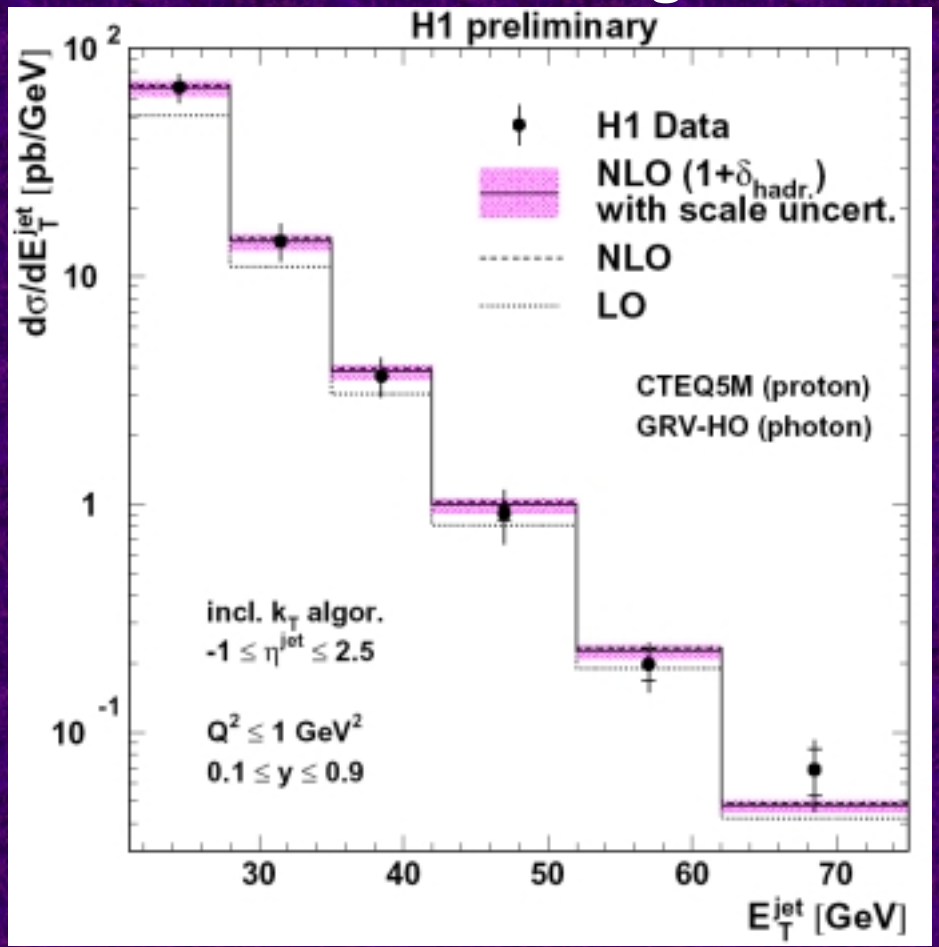
Dijets in γp

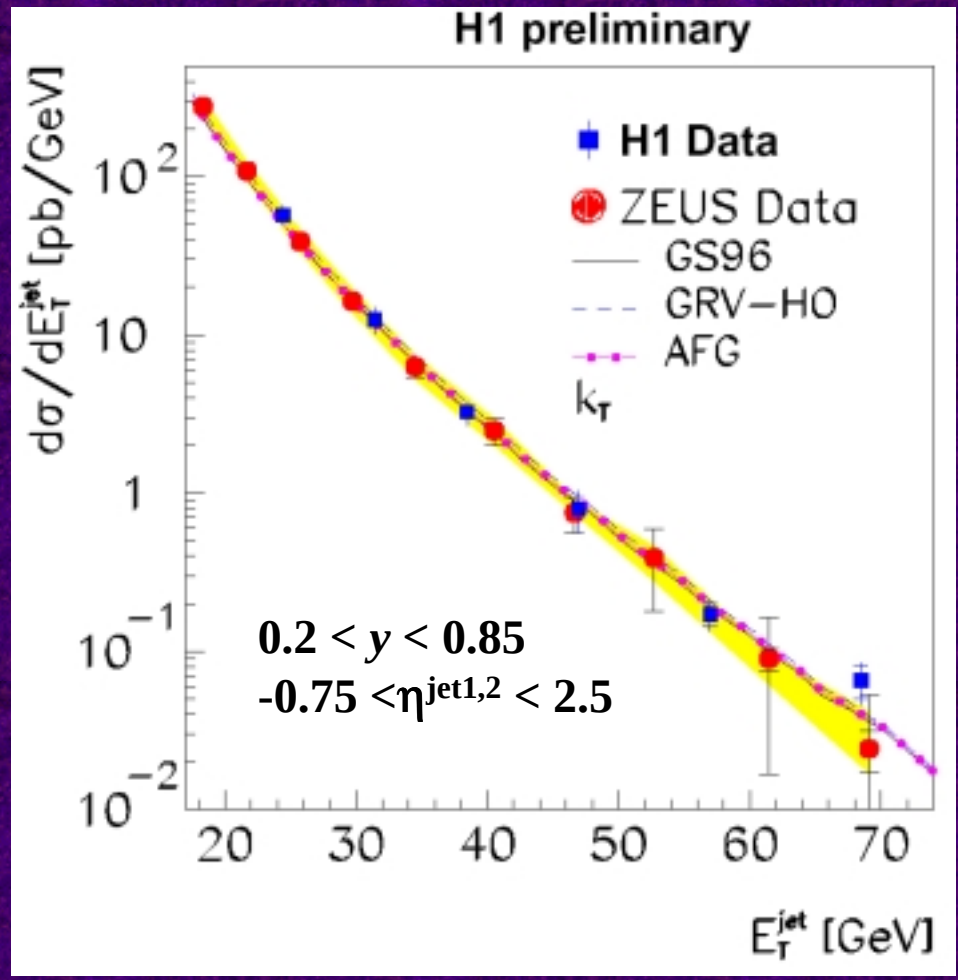
- LL MC describes the shape
- NLO QCD approximately right cross section, but wrong shape wrt E_T^{jet2} – NNLO required.



Inclusive jets in γp

- In general, inclusive jet measurements lead to smaller theoretical ambiguities.

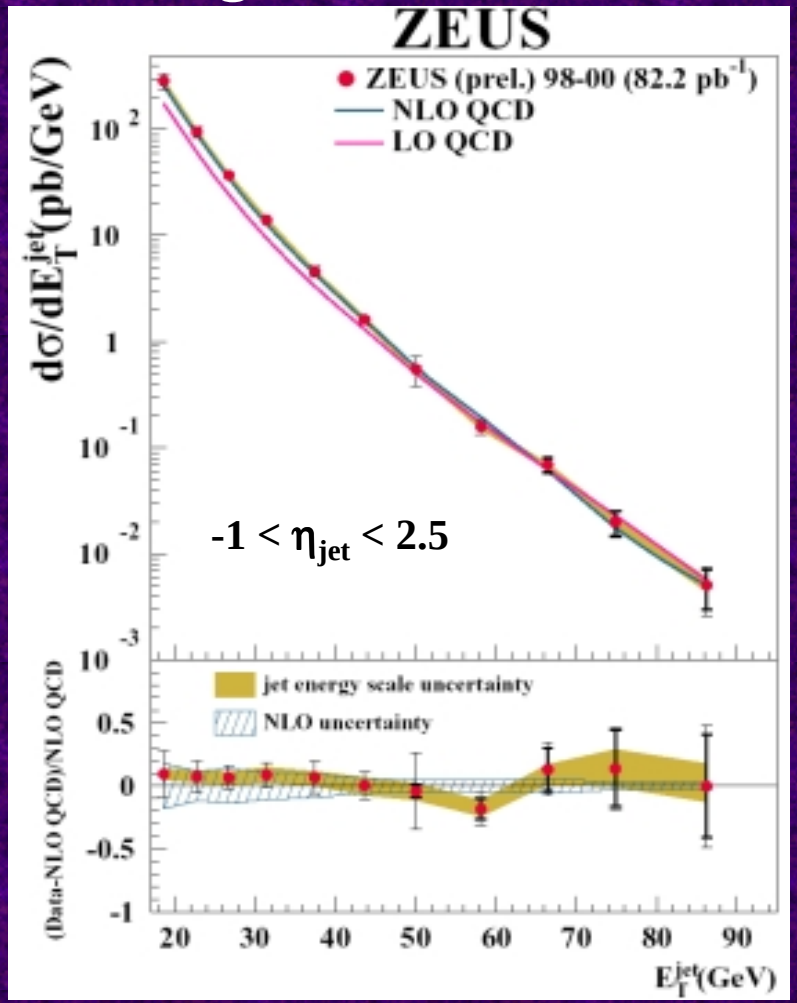


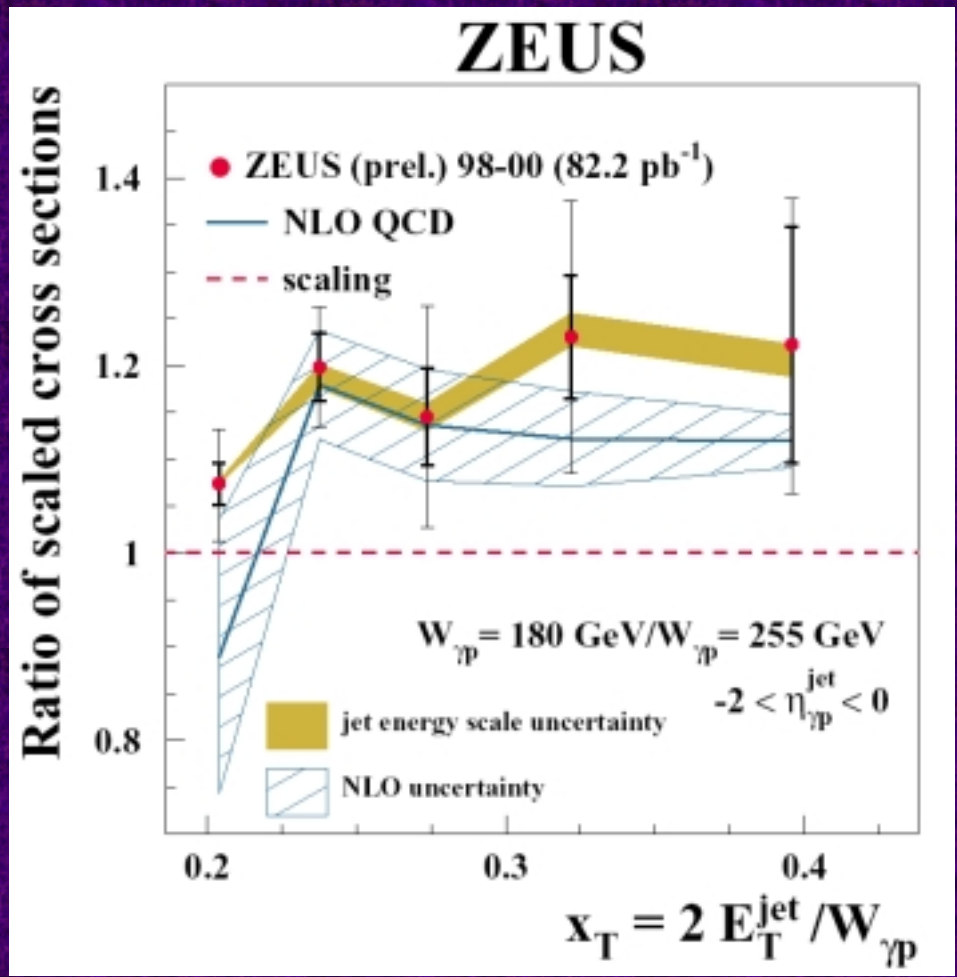


- Excellent agreement with NLO QCD.

Inclusive jets in γp

- ZEUS has used inclusive jet cross sections in 2 different W ranges, <W> ~ 180 GeV and 255 GeV, to test energy scaling.

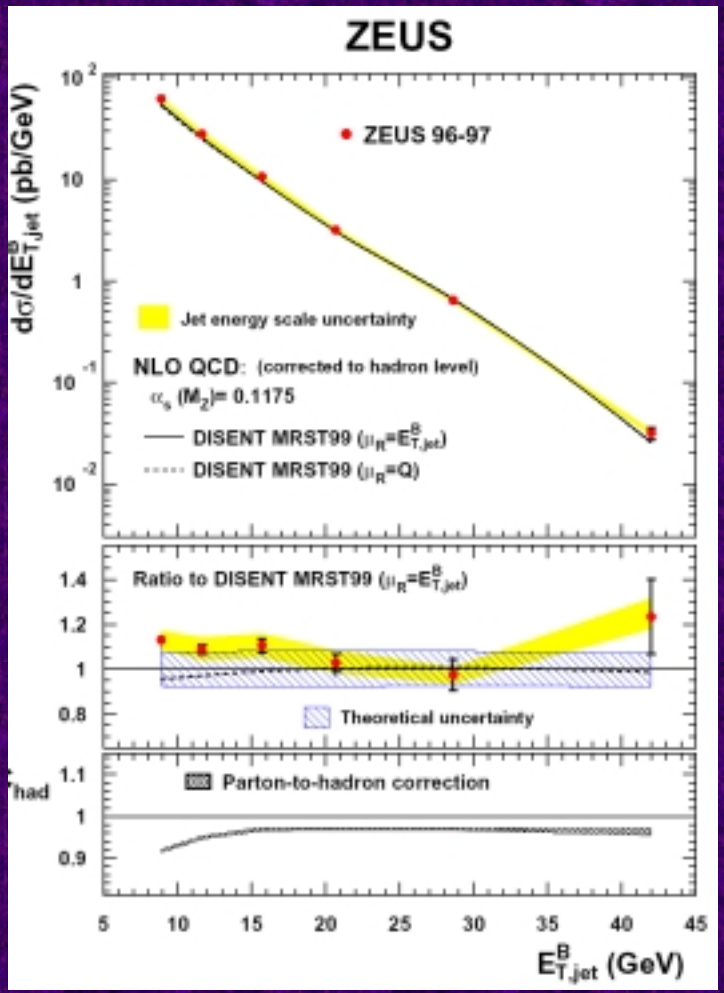


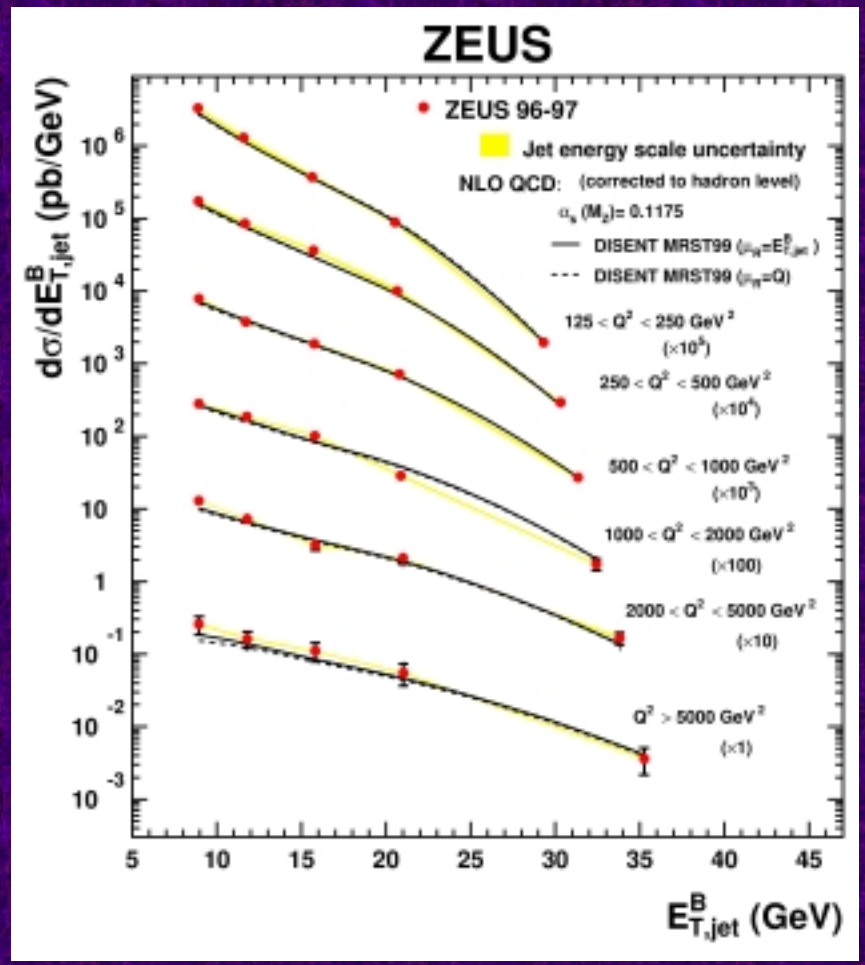


- Beautiful agreement with NLO QCD in both E_T^{jet} and x_T.

Inclusive jets in DIS

- ZEUS has measured inclusive jet cross sections in Breit frame for $Q^2 > 125$ GeV^2 and $E^B_{T,jet} > 8$ GeV.

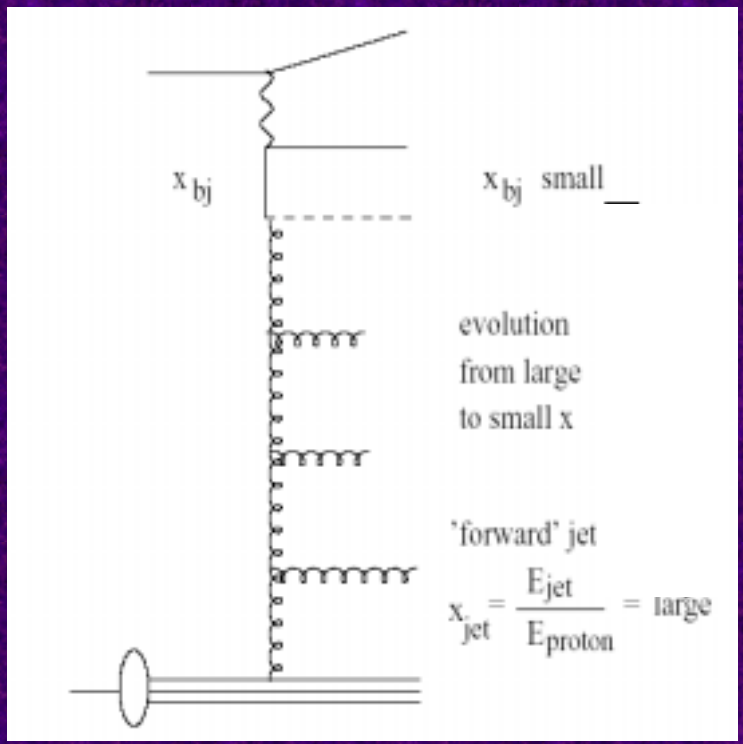


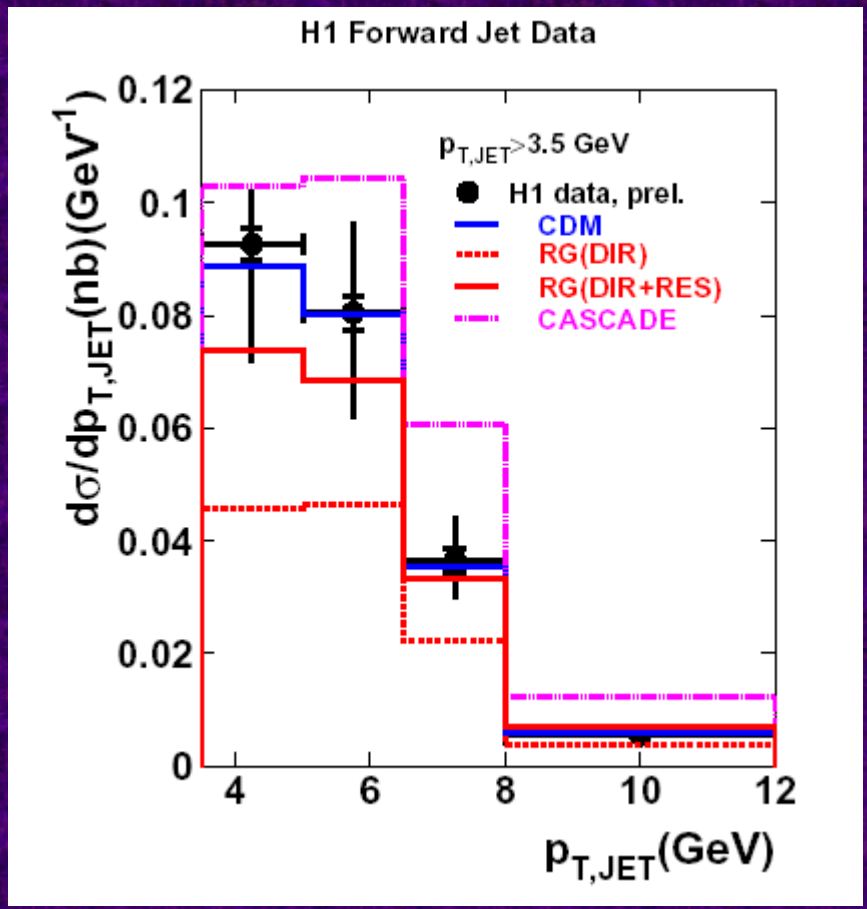


- Beautiful agreement with NLO QCD.

Forward jets

- H1 have investigated jet production almost in proton direction, where BFKL evolution can be strongly favoured over DGLAP.

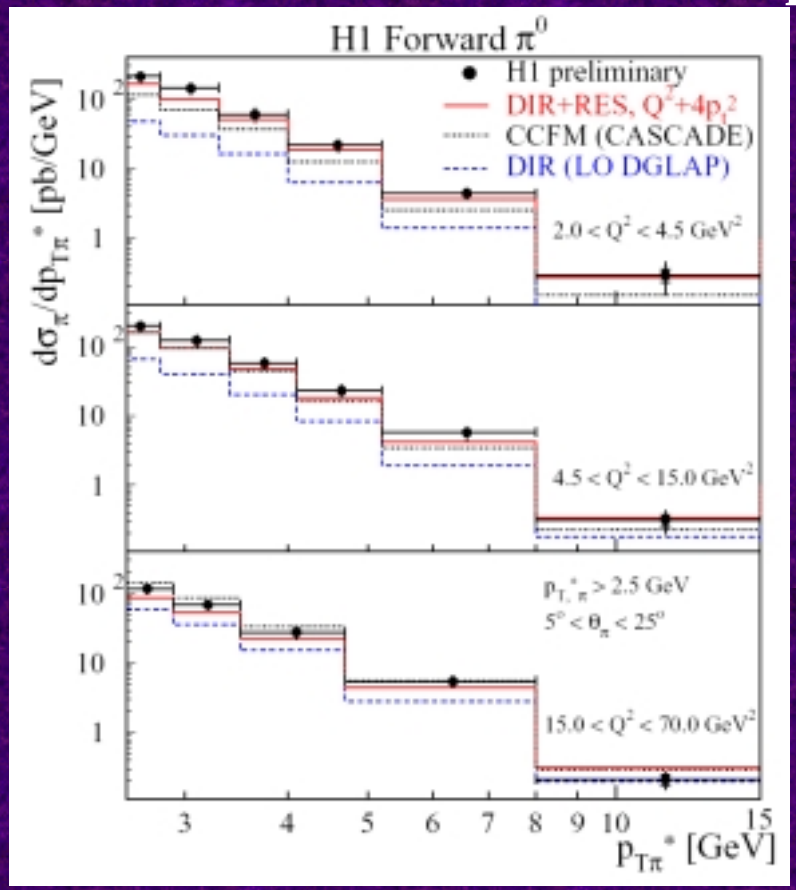


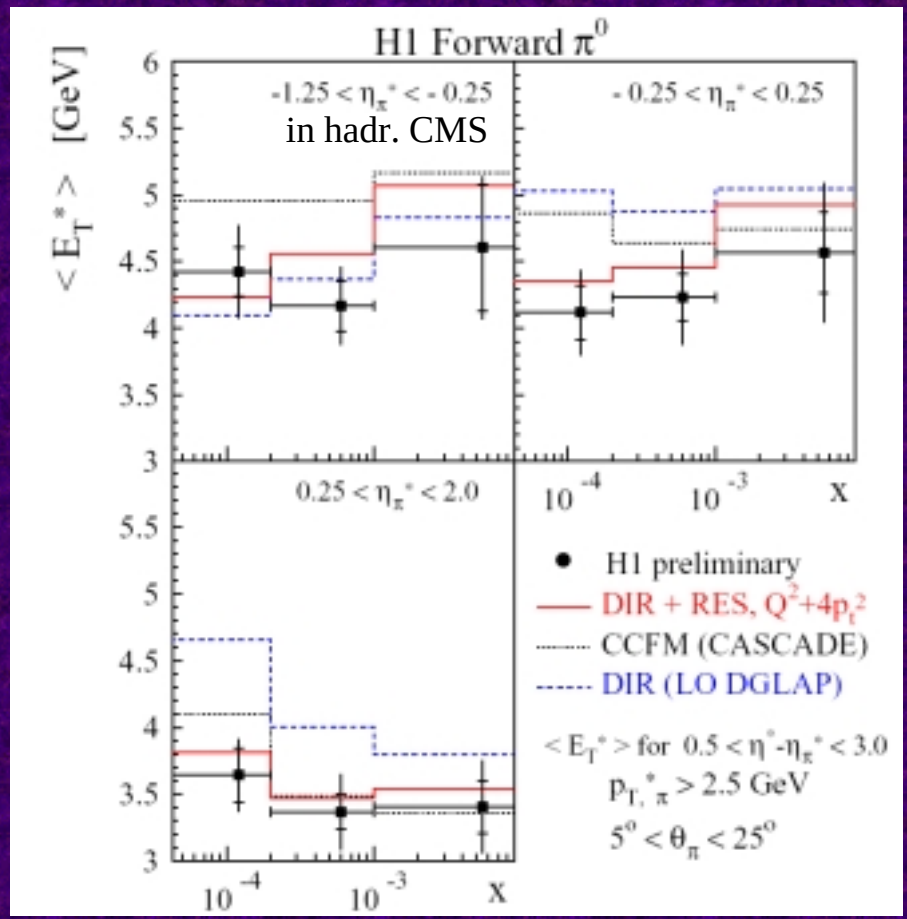


- Data still cannot discriminate between BFKL-like and DGLAP, but seem to disfavour CCFM?

Forward π^0

- Complementary to jets, giving access to even more forward kinematics but having fragmentation etc. complications, H1 have studied forward π^0 production.

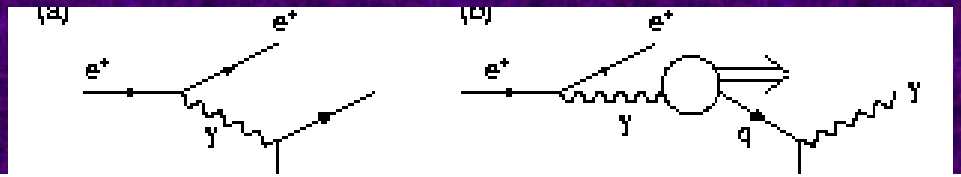


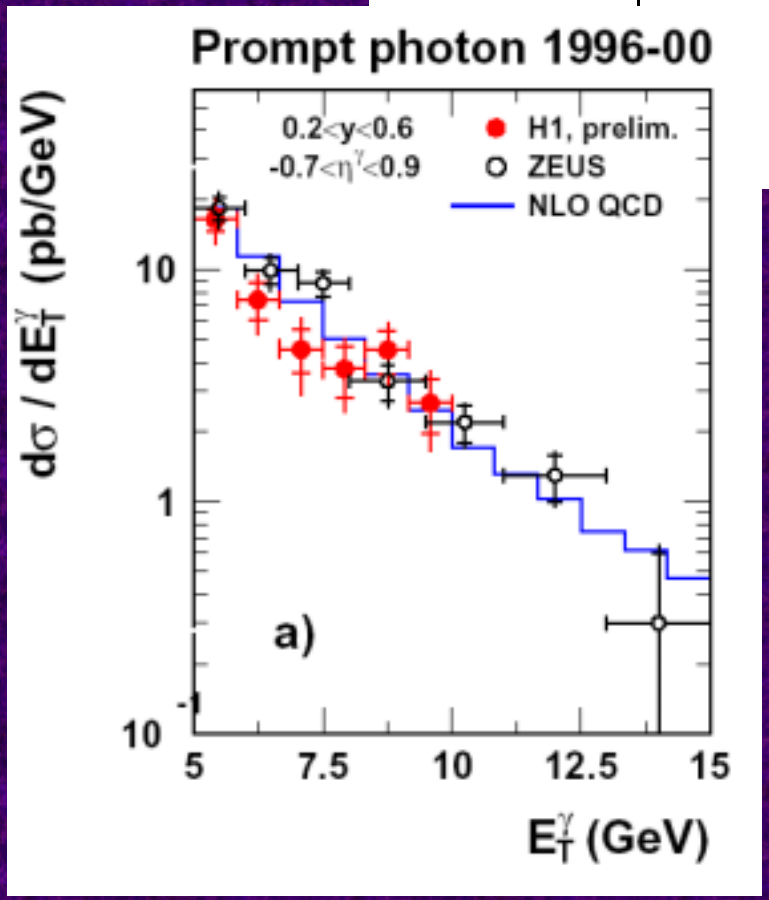


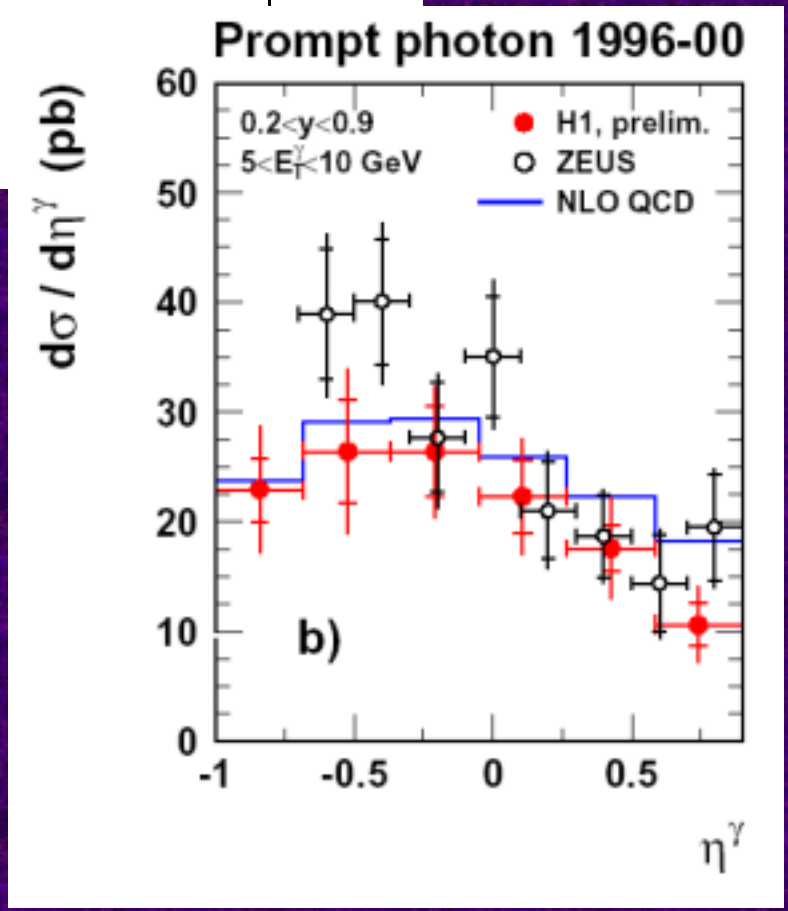
- Data still prefer DGLAP.

Prompt photons

- Replace jet now by photon leads to further insights:

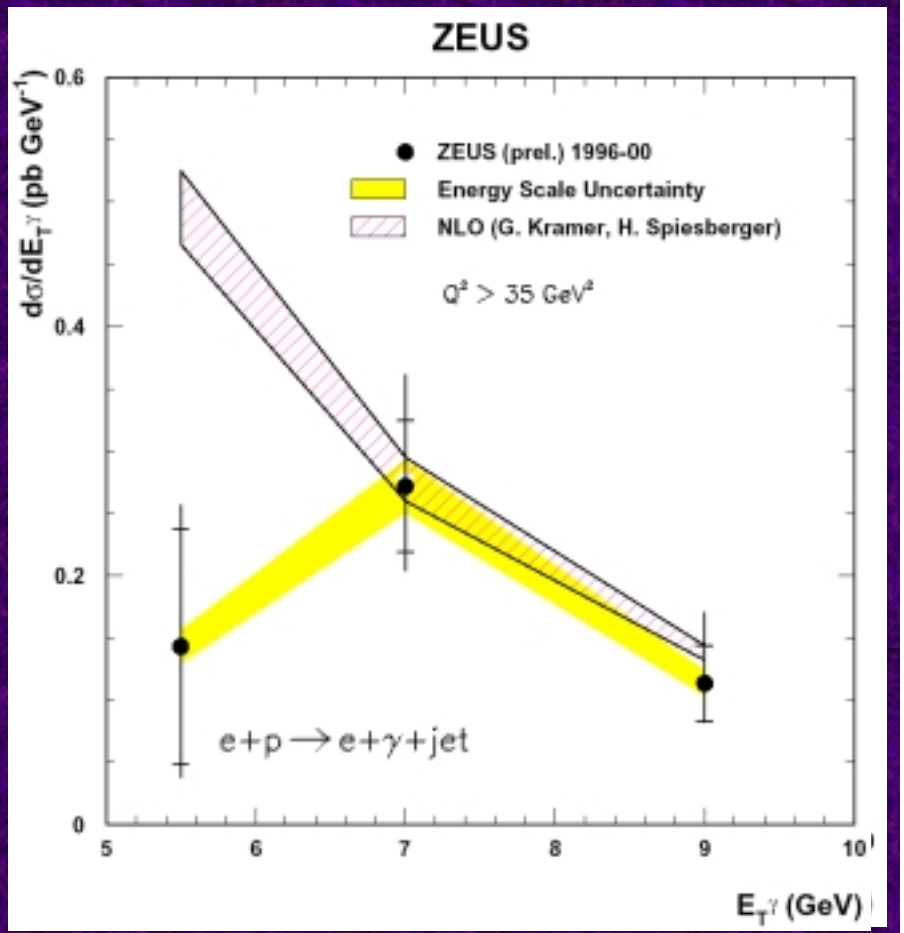


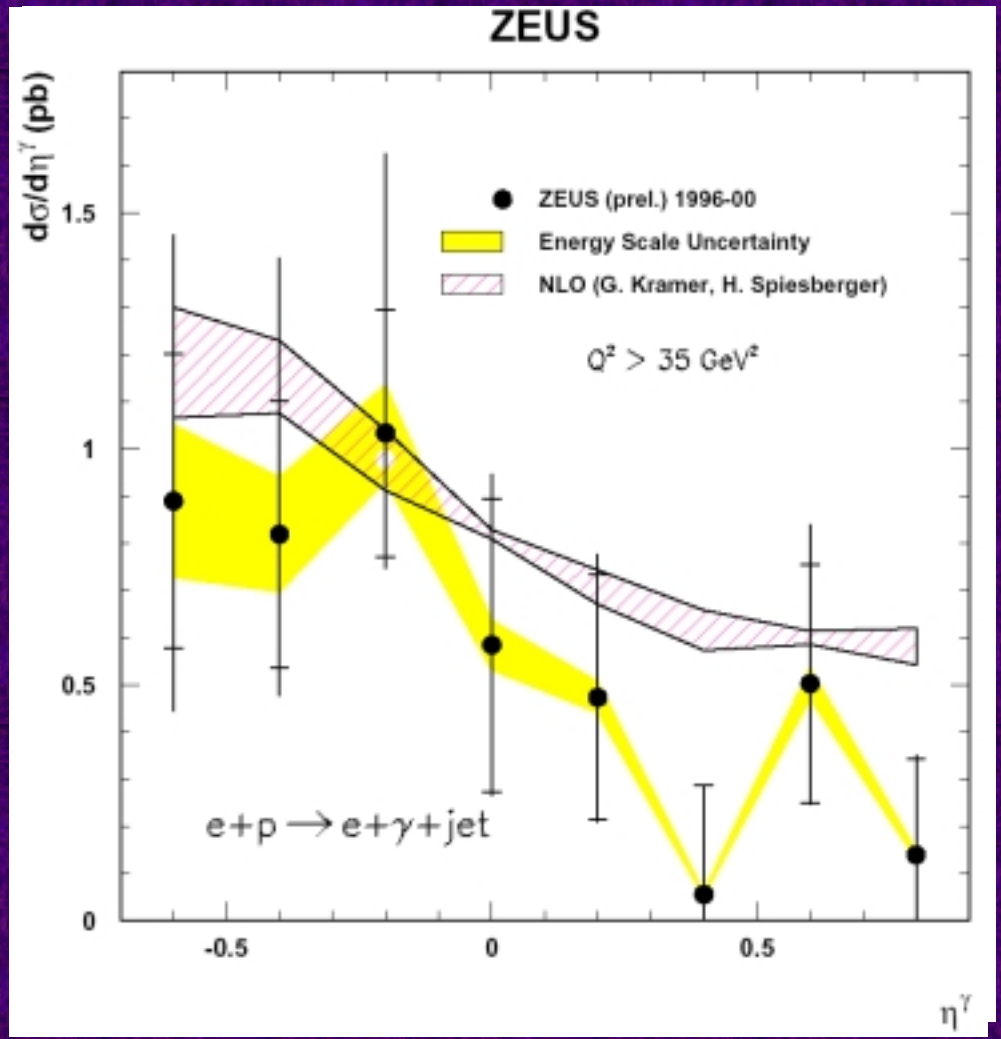




Prompt photons in DIS

- New result from ZEUS – first observation of prompt photons in DIS.

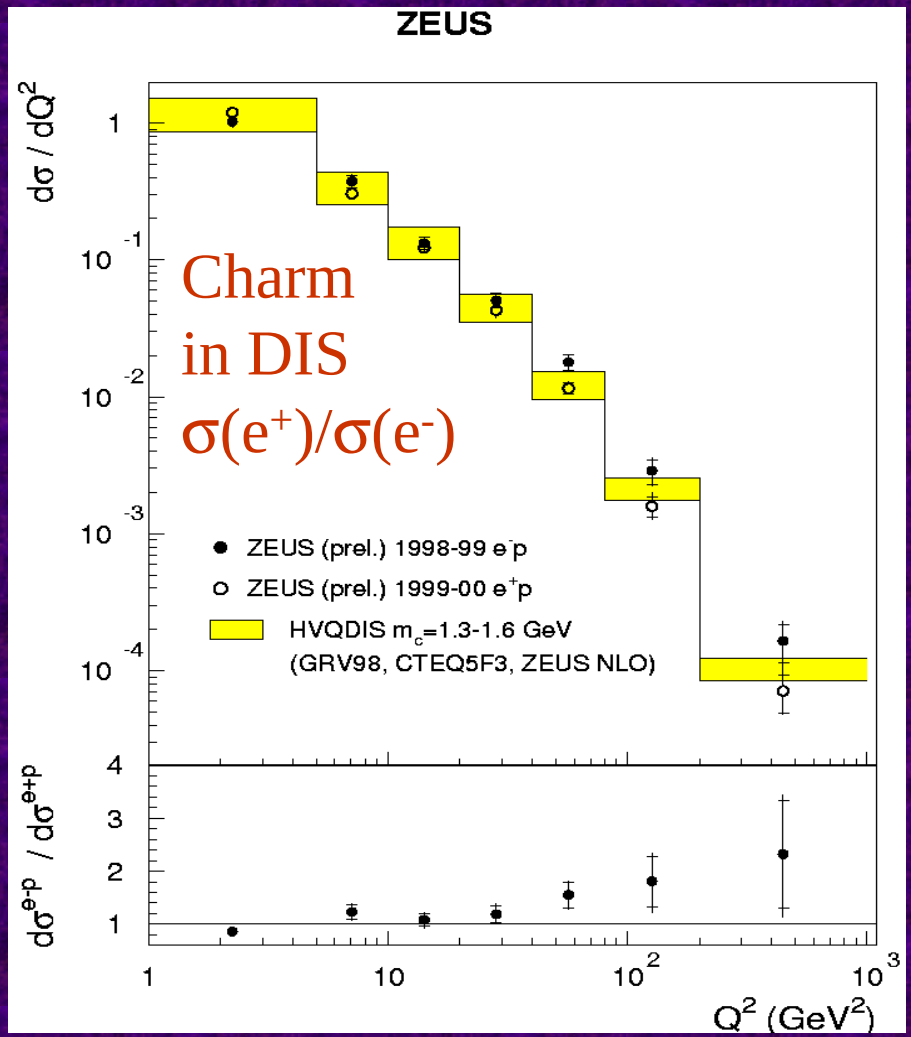


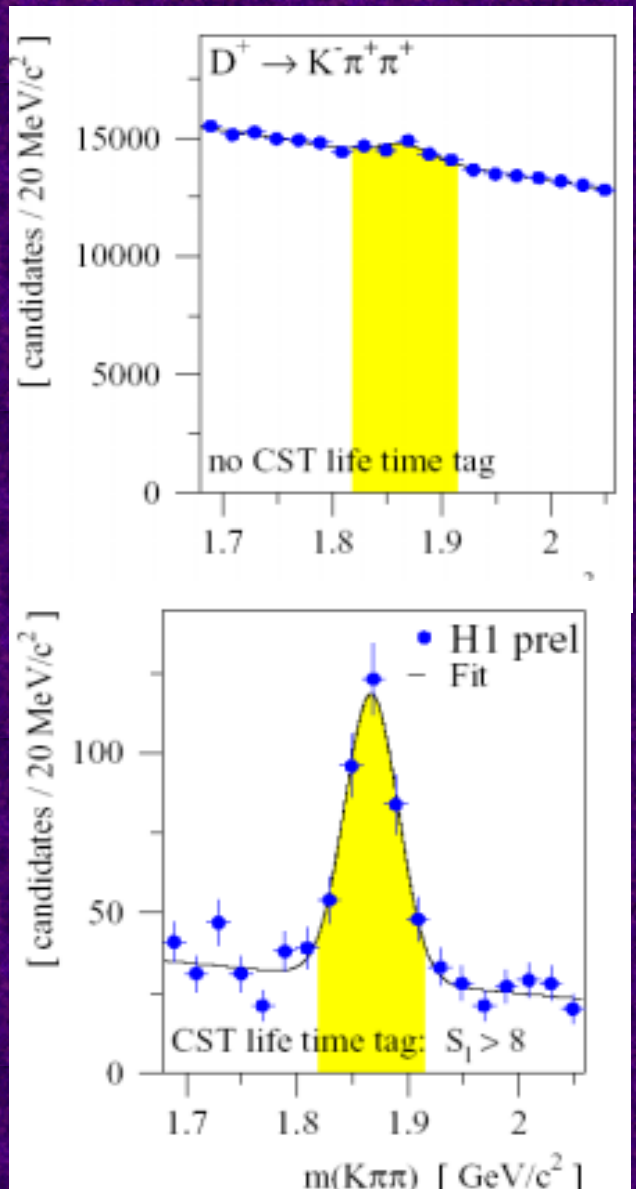


- Guess what? Agreement with NLO QCD.

Charm production

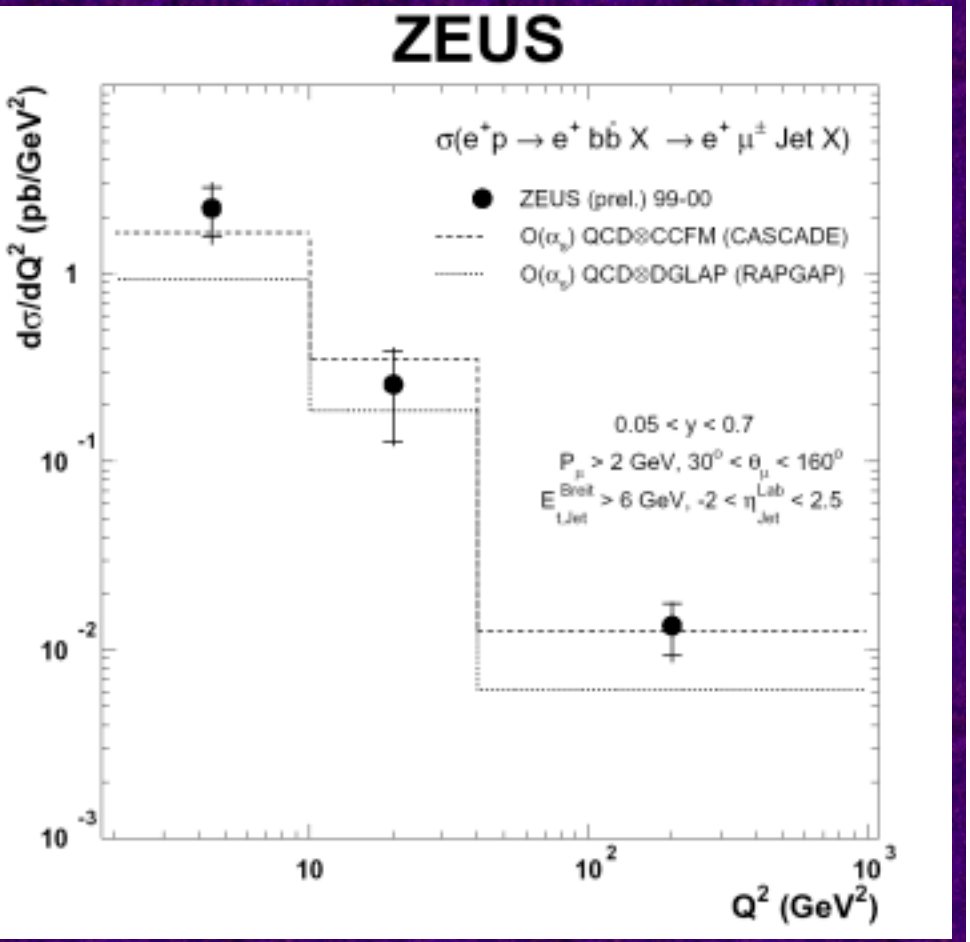
- Generally, c in both DIS & PHP agrees with pQCD;

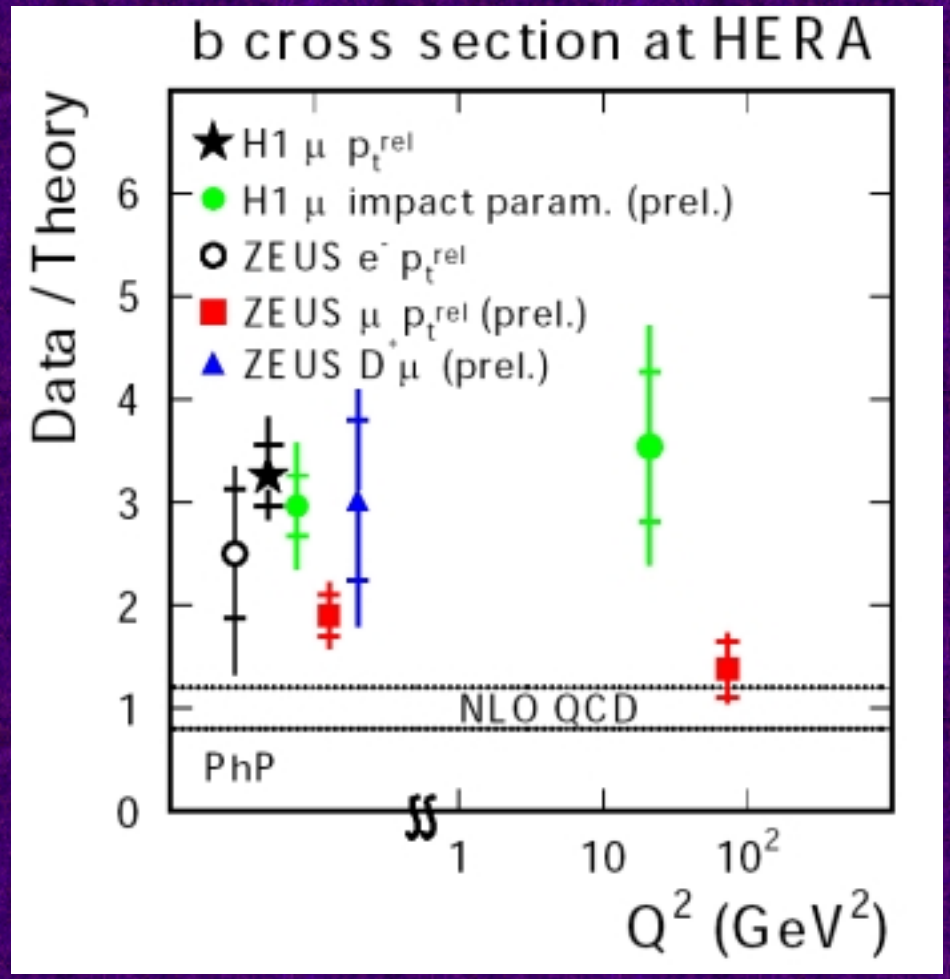




Beauty production

- New data from ZEUS seems to be much nearer to pQCD.



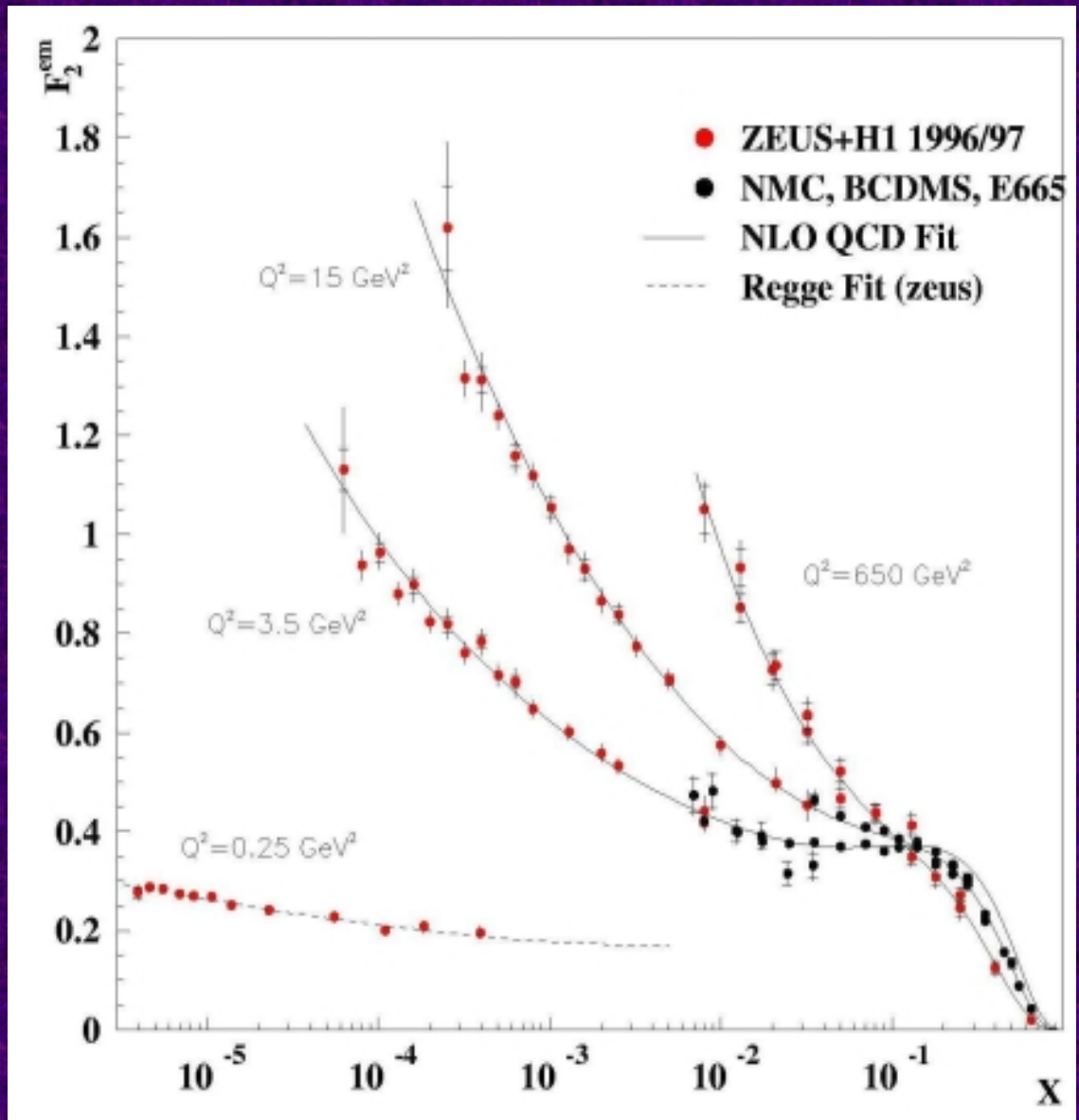


- At least in ep, experimental situation now more confusing than the theoretical.

F_2 structure function

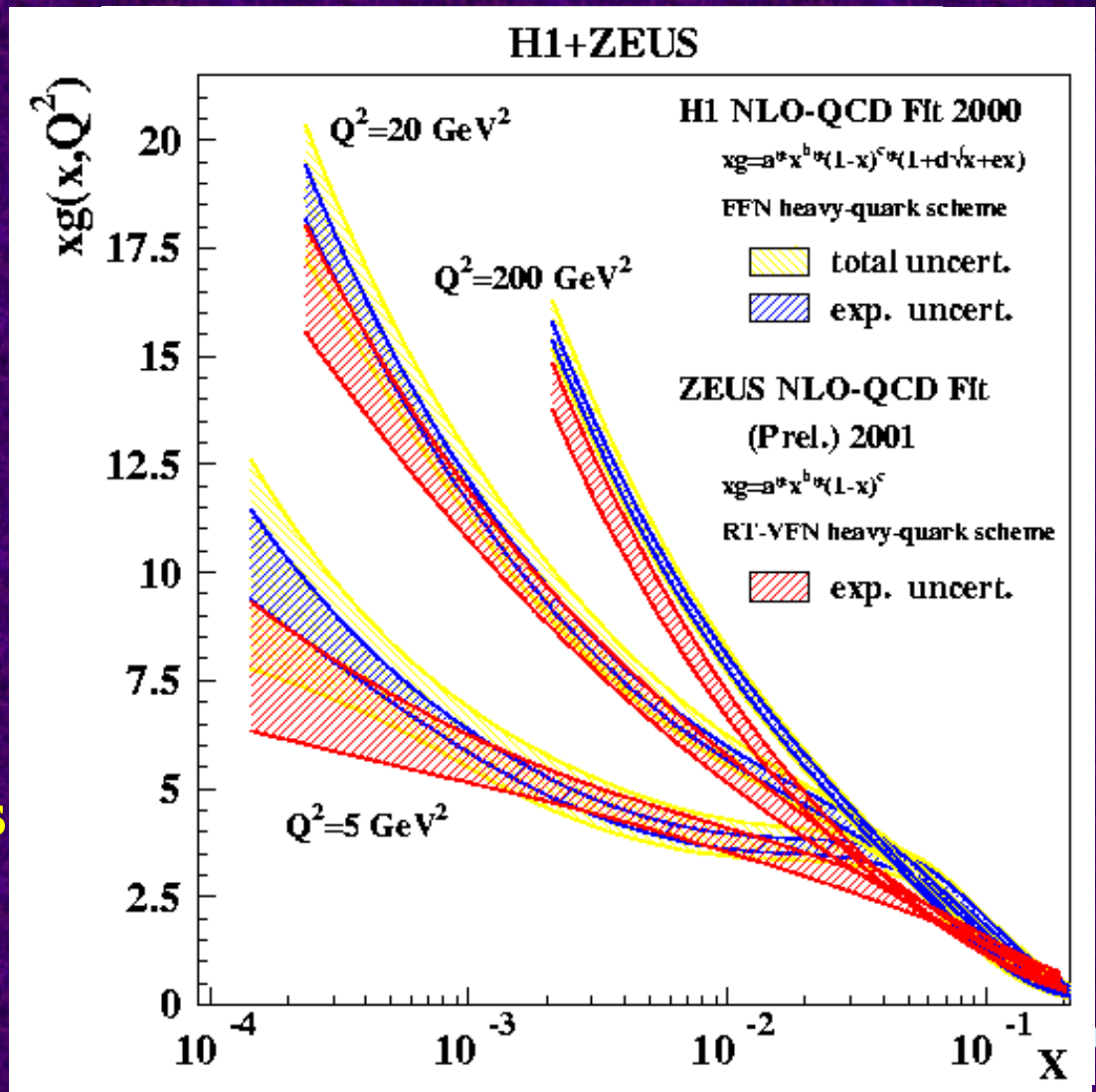
- Most recent HERA determinations from 96-97 data.

- Most notable feature “rapid rise” at low x - driven by g evolution.



NLO QCD Fits

- H1 & ZEUS have performed NLO QCD fits to the data, from which PDFs and values of α_s can be extracted from the data:
- Excellent fit quality using full correlated error matrices from each experiment.
- Reasonable agreement between ZEUS & H1, given very different fixed-target datasets and fit assumptions used.

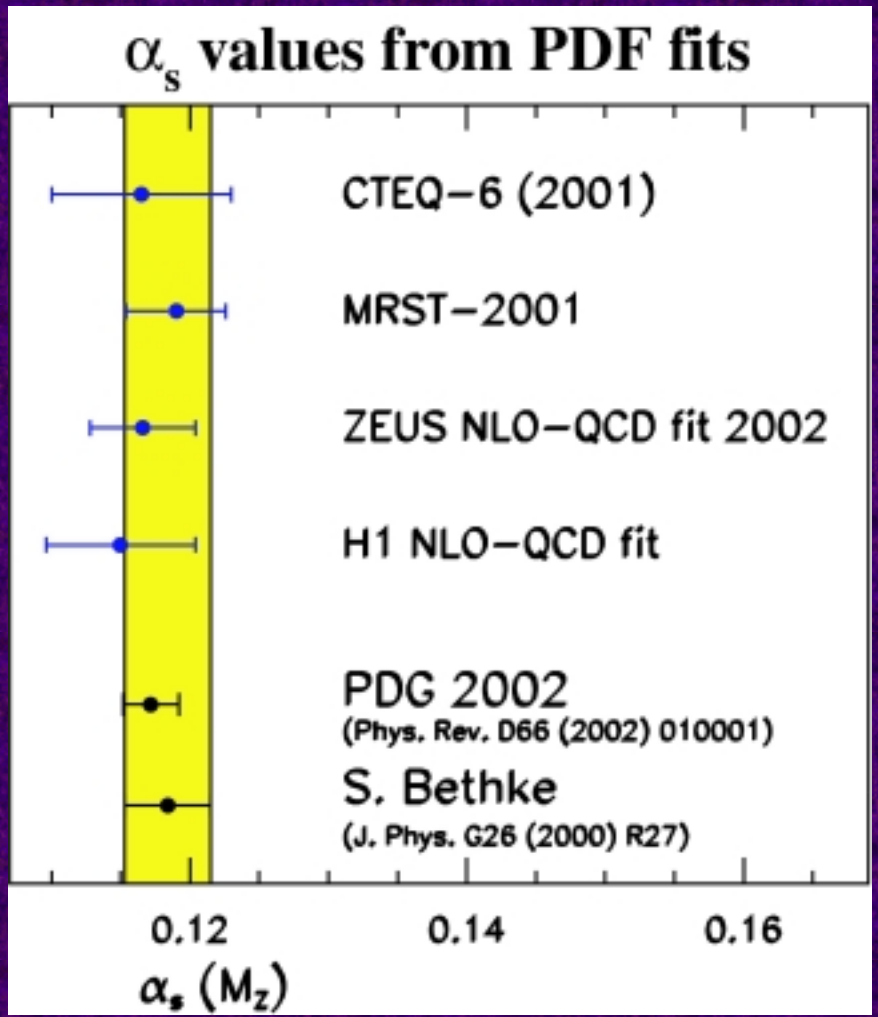


NLO QCD Fits

- Both H1 & ZEUS have exploited the NLO QCD fits to determine α_s, which is of course highly correlated with $g(x)$.

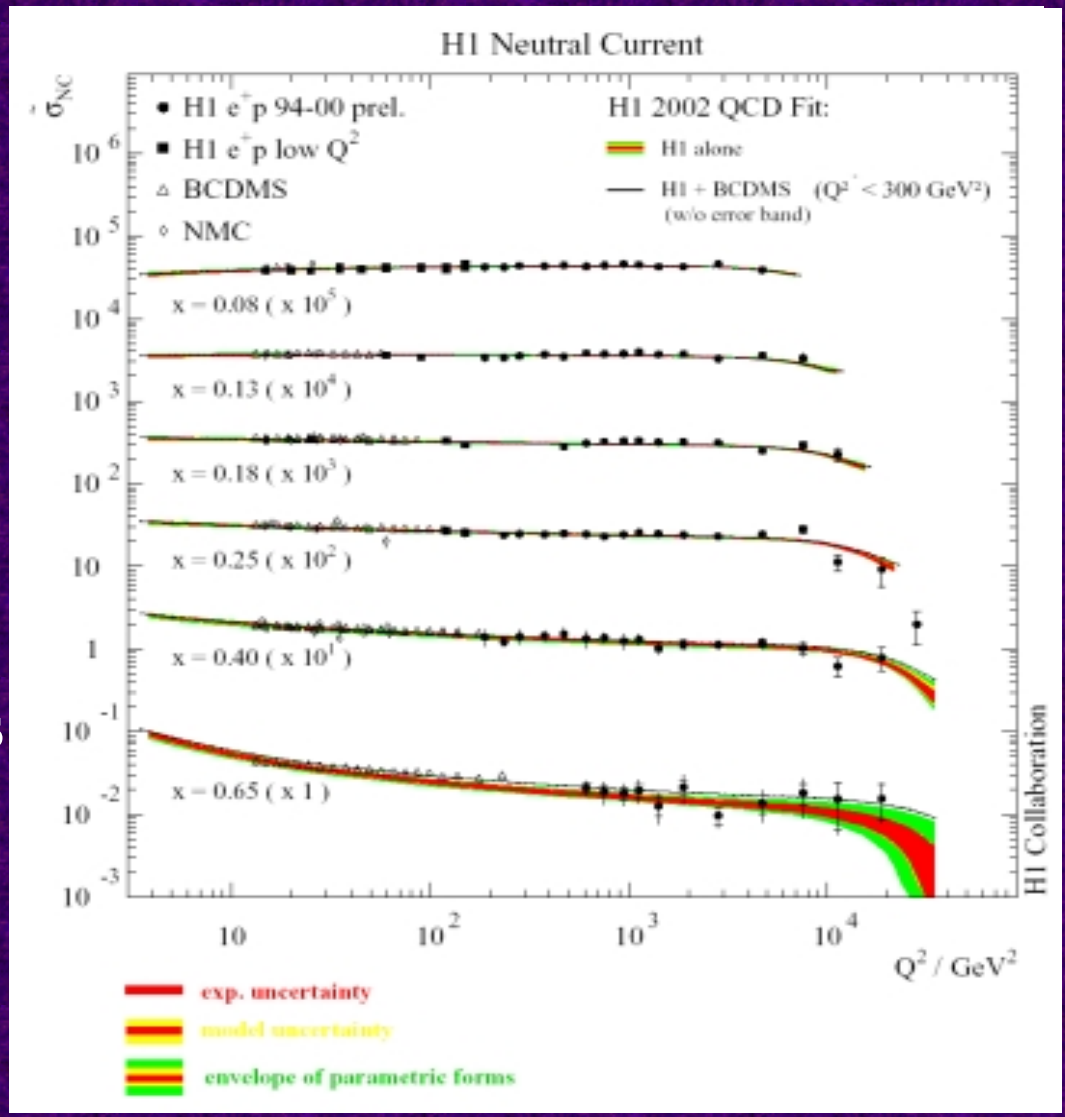
- Excellent agreement between ZEUS & H1, and with CTEQ and MRST – errors of same order as PDG.

- More on α_s later.



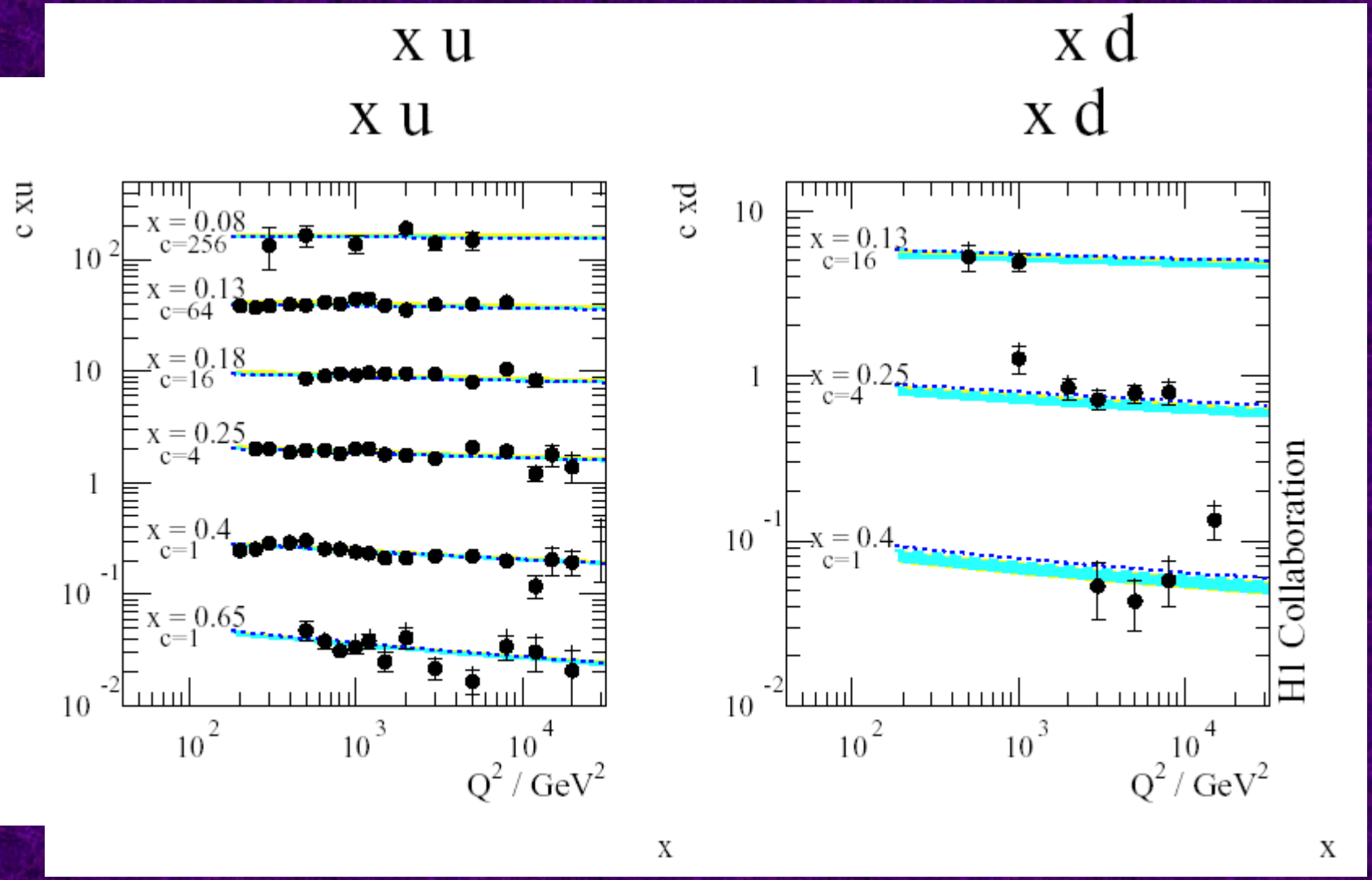
HERA alone

- Both H1 & ZEUS have fits to their data only.
- At least for the gluon pdf, fixed-target data no longer needed.
- For valence pdfs, fixed target still necessary, although use of all high-Q2 CC+NC data almost as good – certainly fixed target not required after HERA II.



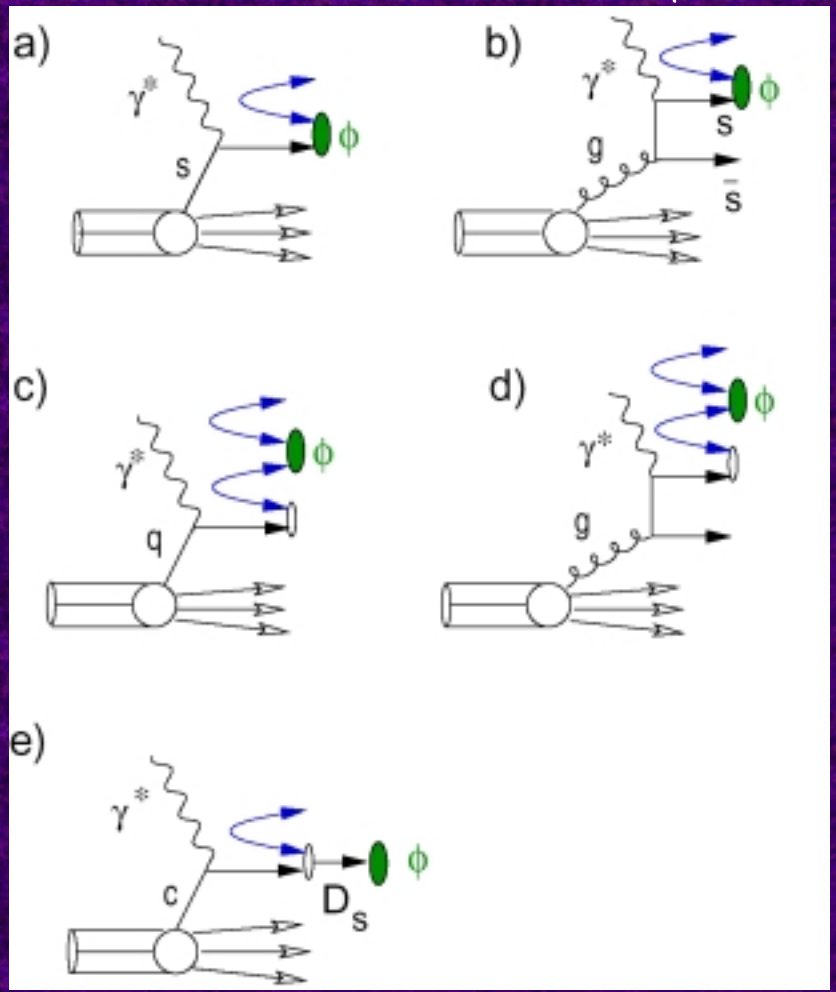
Flavour PDFs

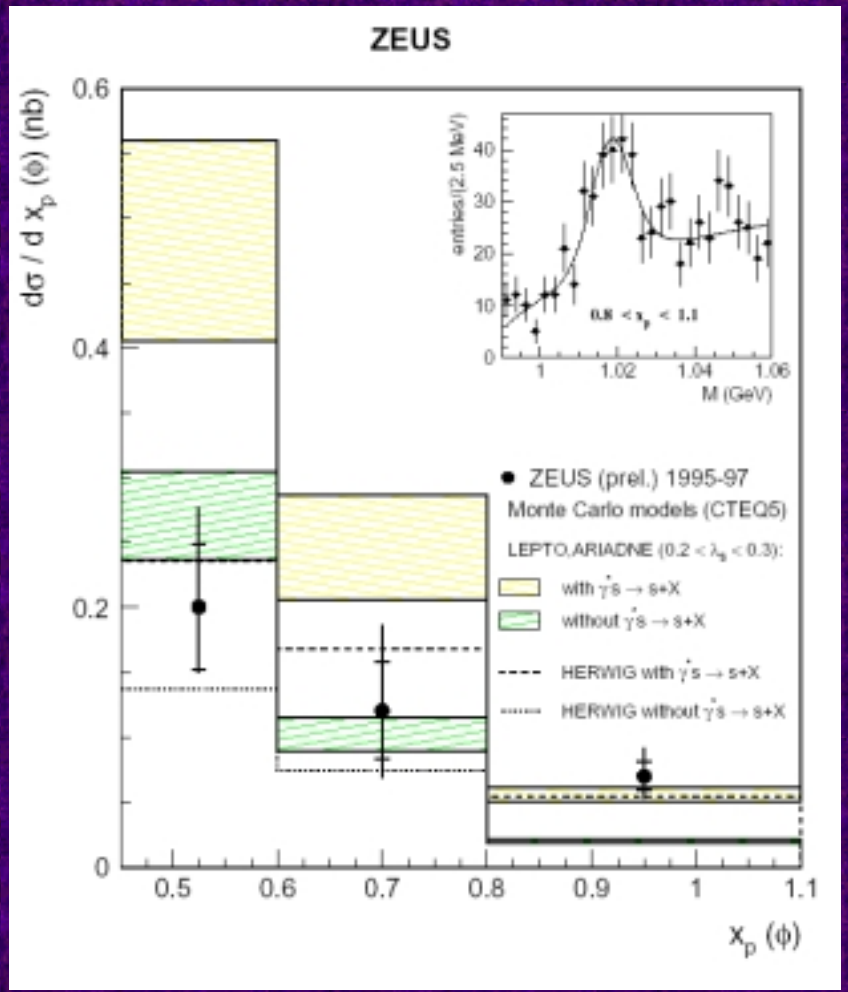
- **H1 have extracted u & d pdfs from $e^{\pm}$ NC, CC cross sections.**



Flavour PDFs

- ZEUS use inclusive ϕ in DIS to isolate s PDF.

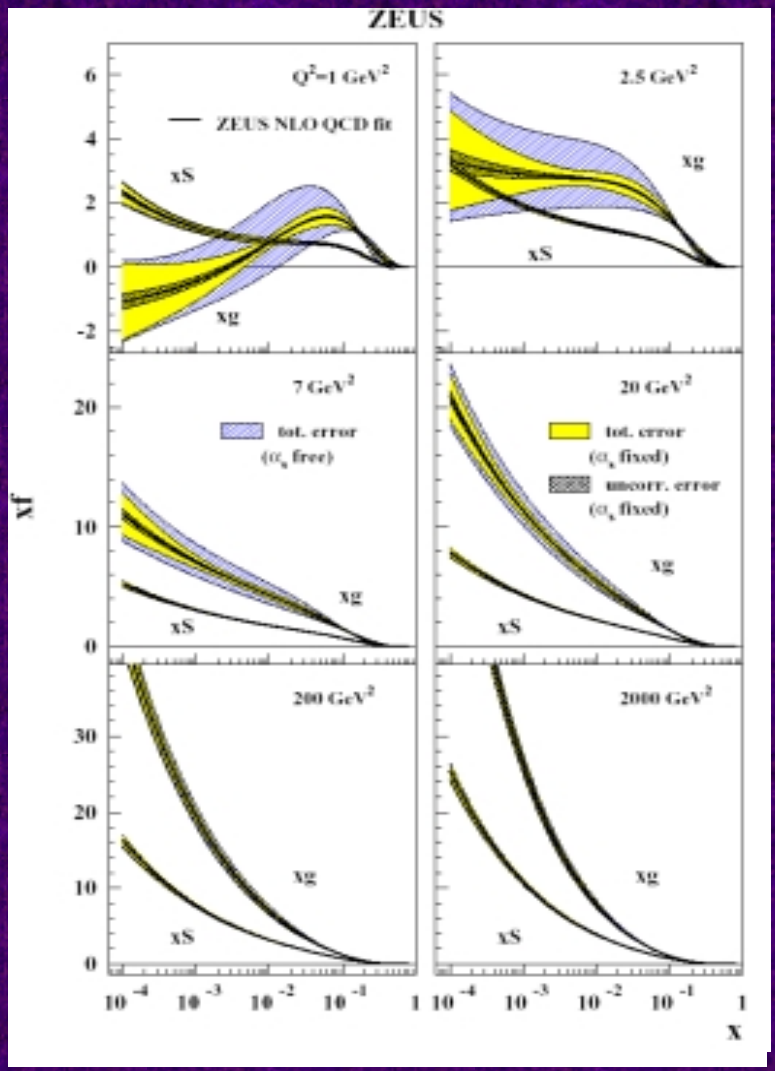


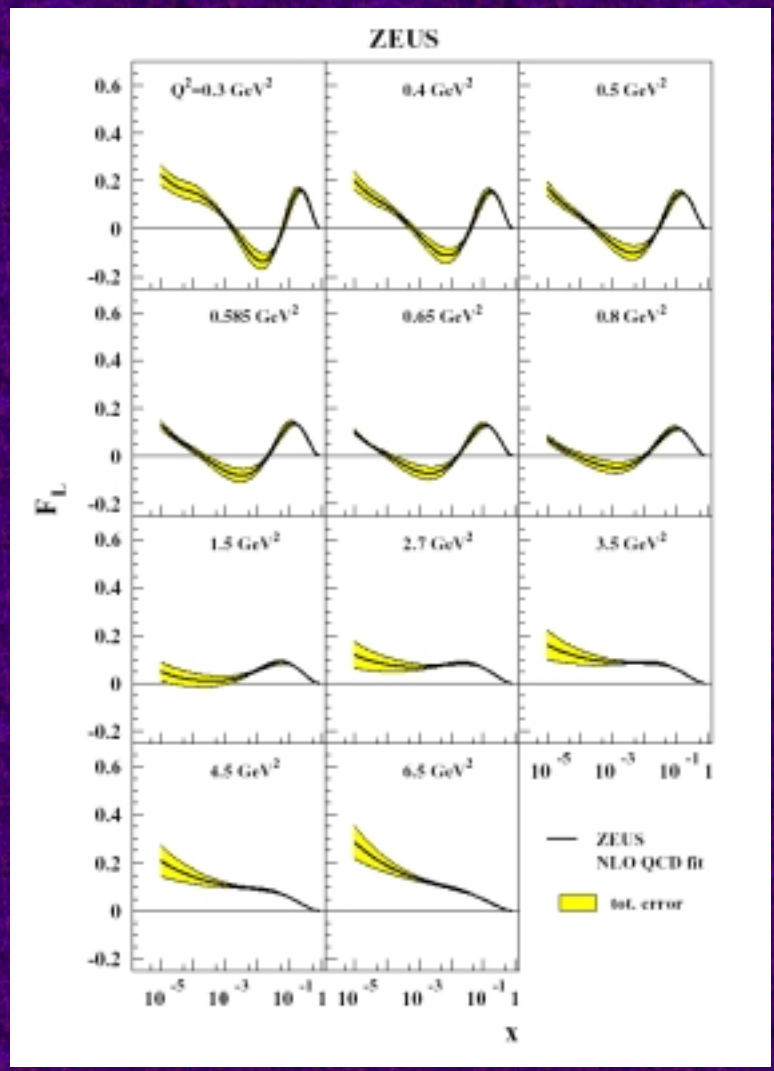


- For highest $x_p(\phi)$, fragmentation uncertainties small and necessity for strange sea clear.

What happens at low Q^2 ?

- Much can be learned from the QCD fit.

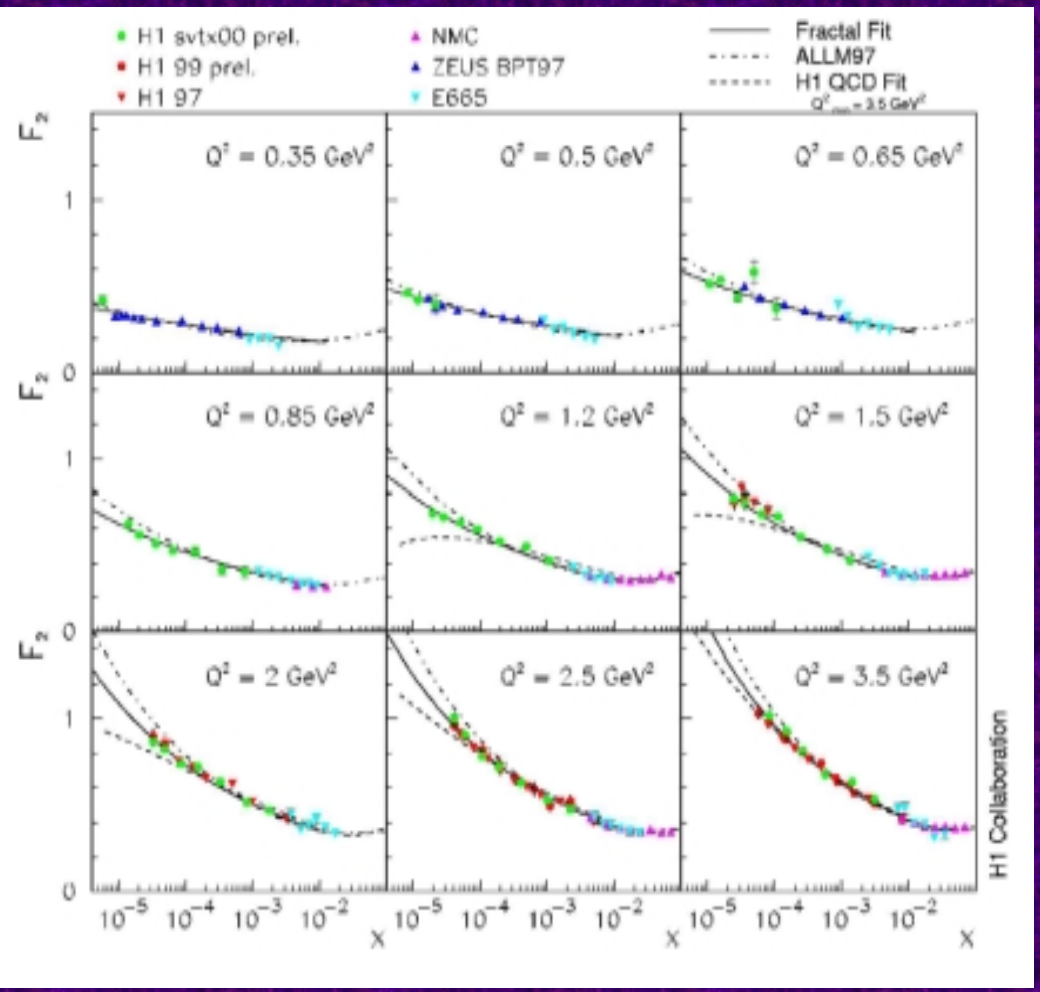


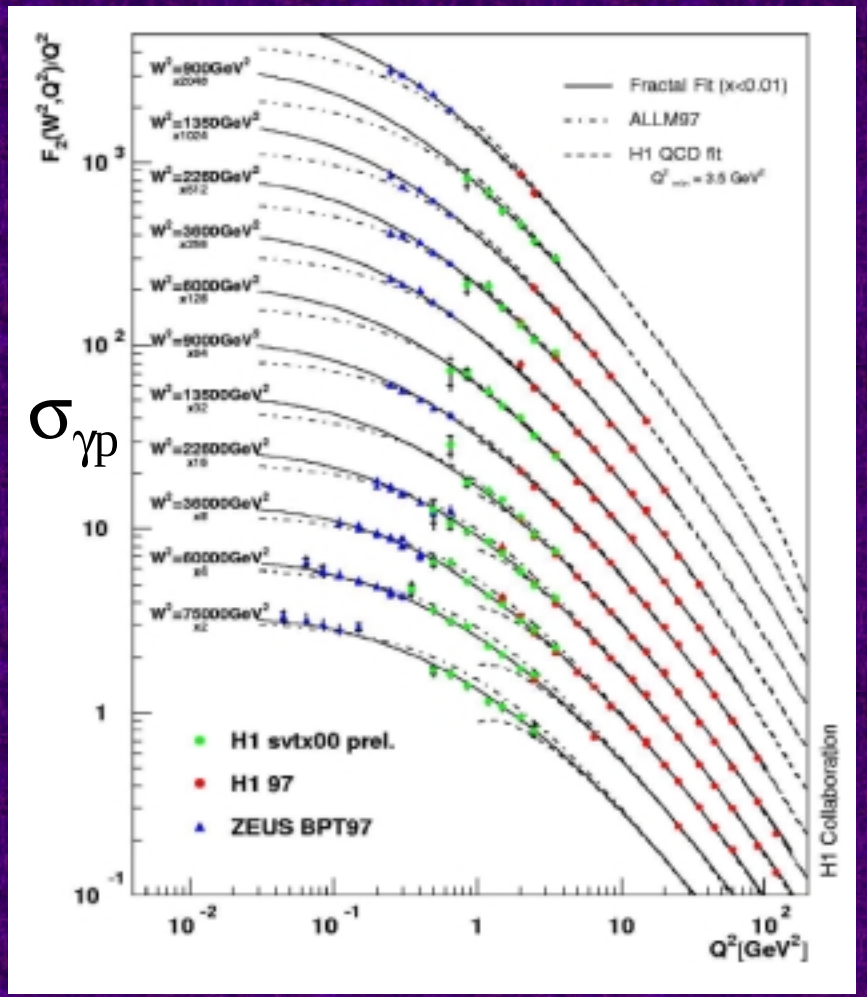


- The NLOQCD fit breaks down at $Q^2 \sim 1$ GeV^2

F_2 (low Q^2) from ZEUS & H1

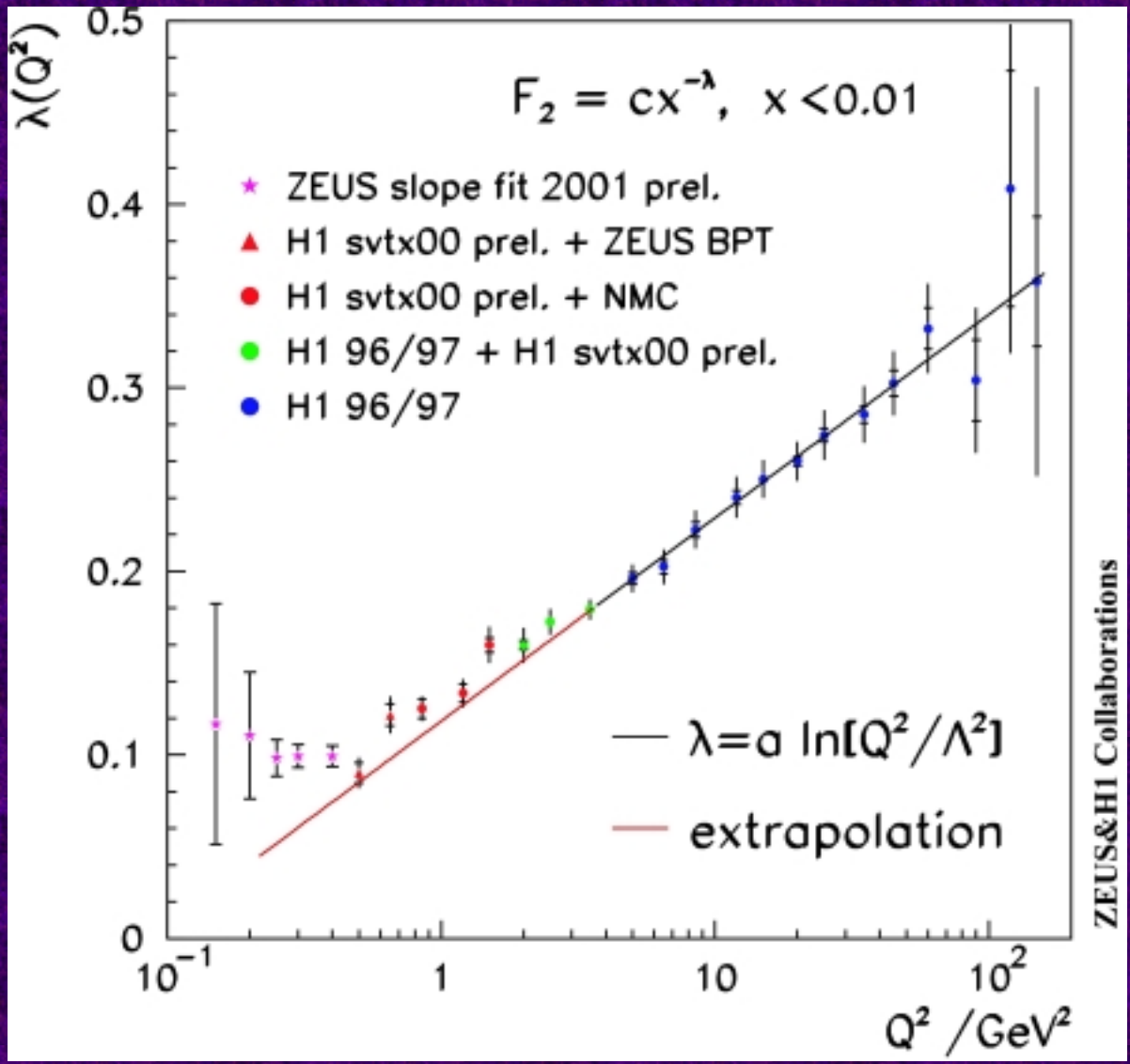
- **H1 SVX2000 data** **At low Q^2 , F_2 / Q^2 constant**





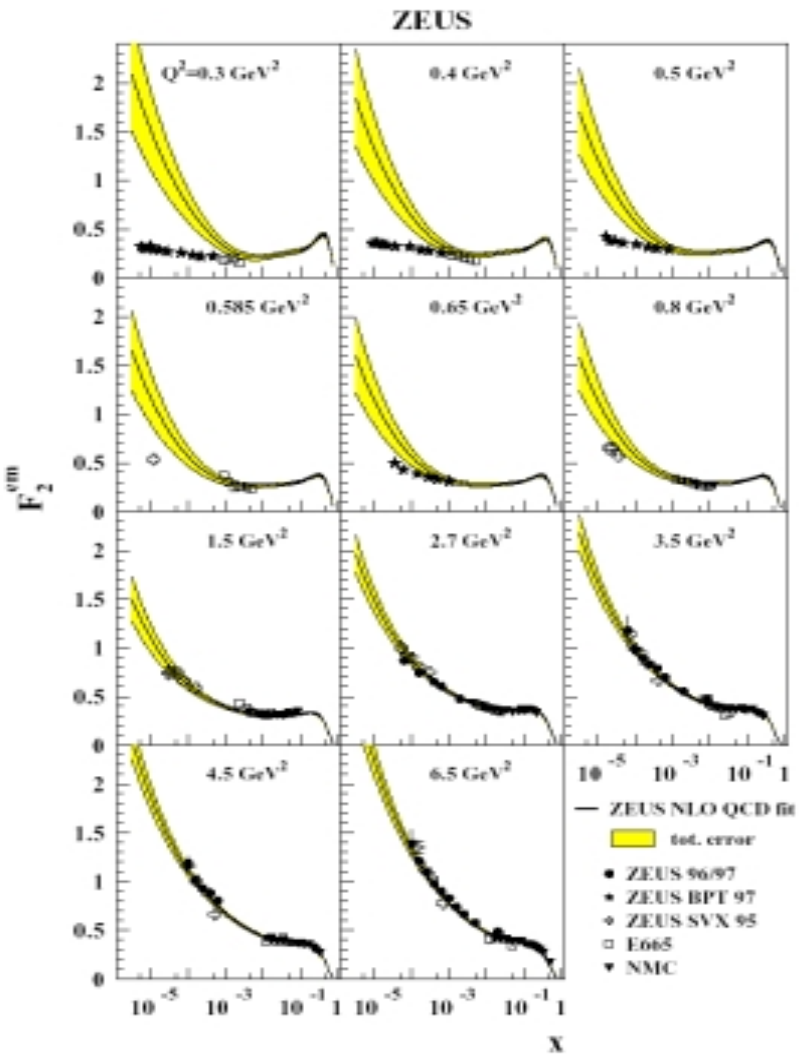
F_2 log slopes from ZEUS & H1

- For low x, $F_2 = cx^{-\lambda}$ – fit data as function of Q^2.
- Clear departure from linearity around $Q^2 = 1$ GeV^2



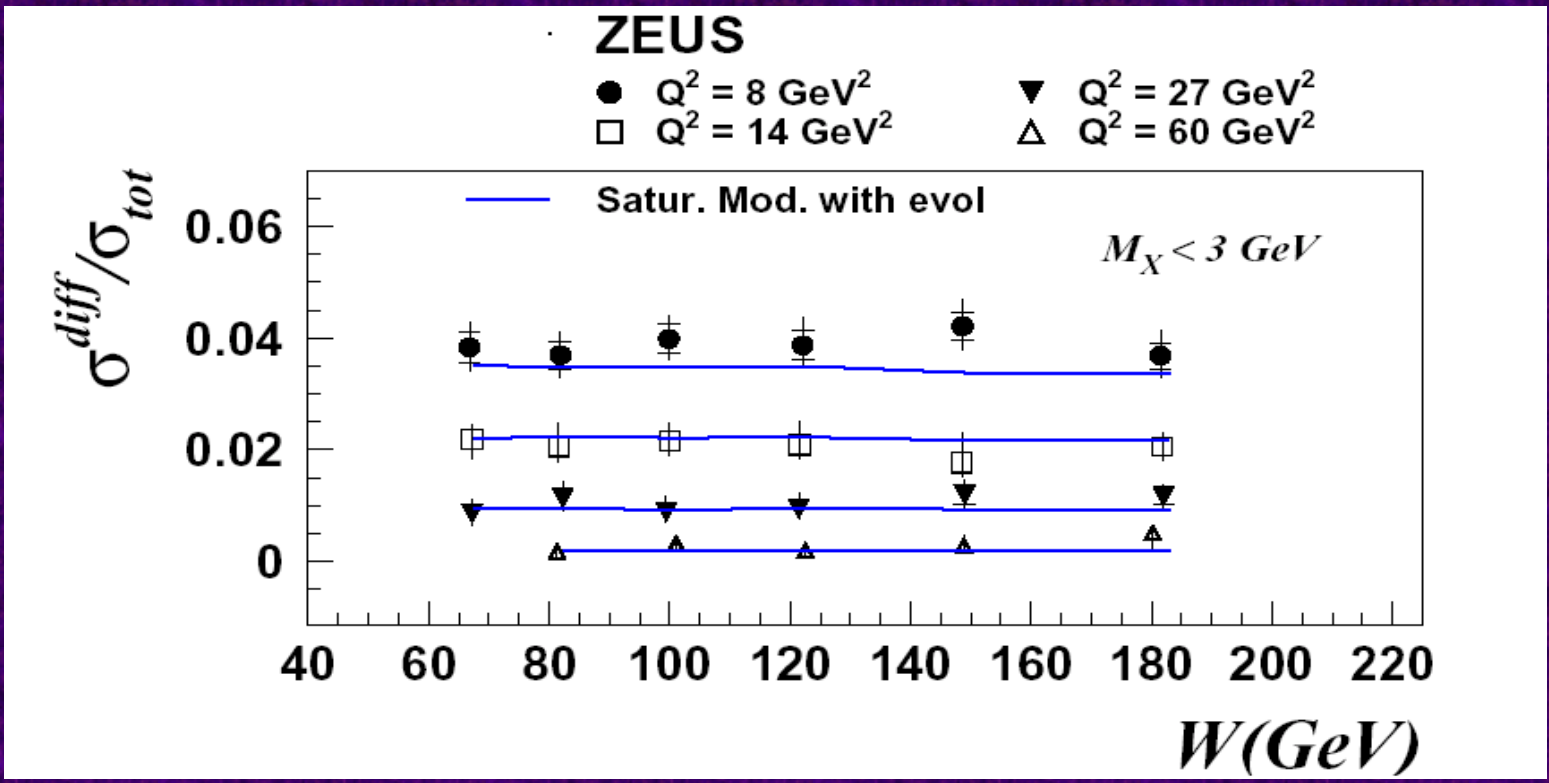
Fits to data

- **The Golec-Biernat&Wusthoff model shows new scaling wrt a saturation scale and does a reasonable quantitative job, including DGLAP evolution, at fitting F_2 for all Q^2.**
  - QCD also fits for $Q^2 > 1$ -2 GeV^2 as do a variety of simple parameterisations, but below this QCD formalism breaks down.



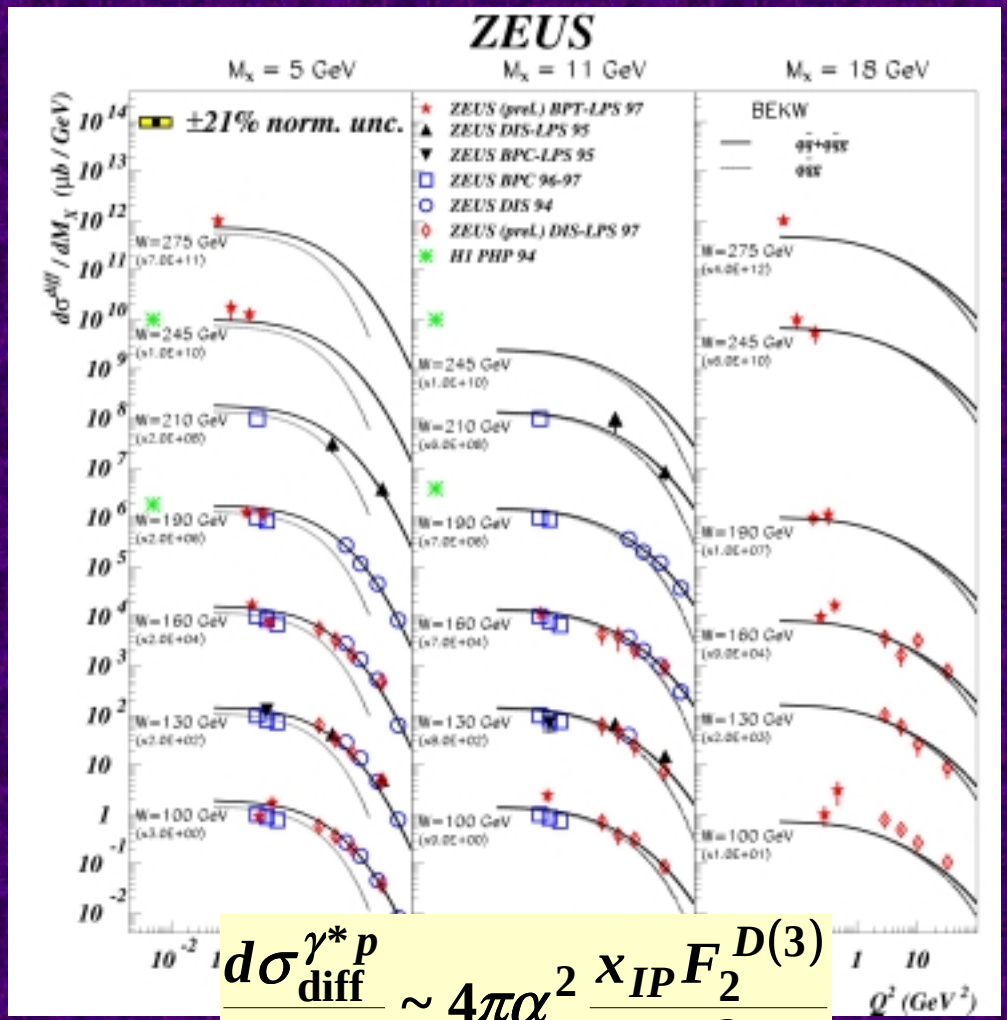
Diffraction

- The most basic measurement is the total cross section for diffraction. Does it agree with our naïve expectations?

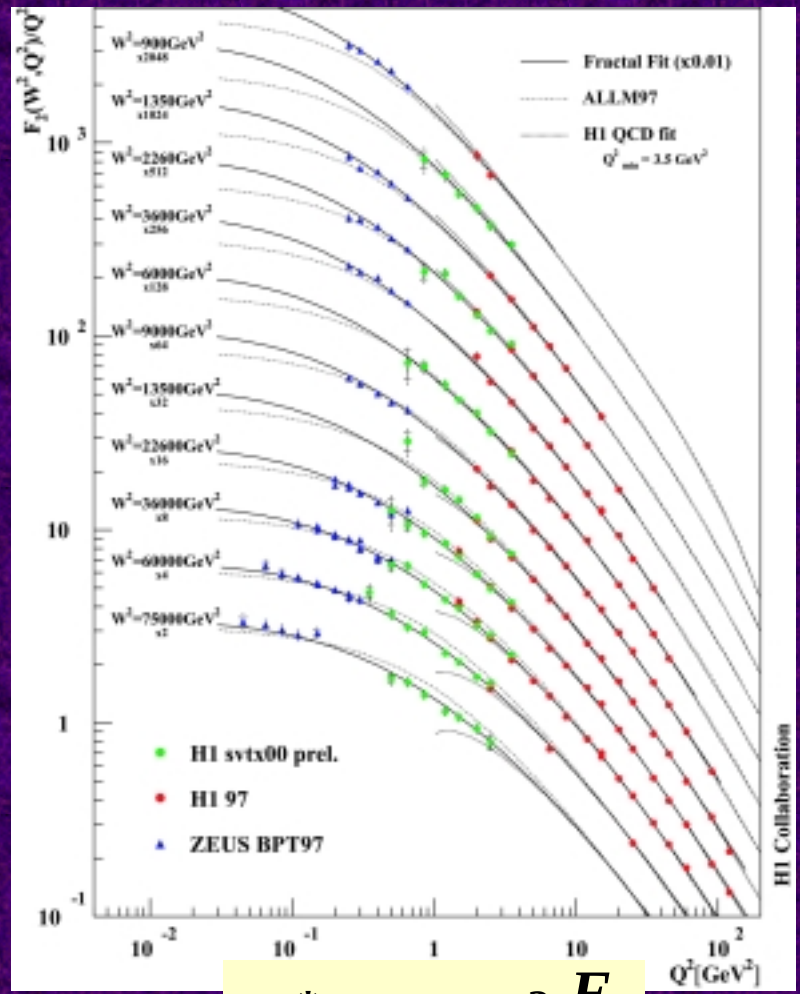


- No. It has same W^2 dependence as σ_{tot} - $W^{0.4}$. Contradicts optical theorem $\sigma_{tot} \sim W^{\alpha}$ => $\sigma_{diff} \sim W^{2\alpha}$; and if $\sigma_{tot} \sim g$, $\sigma_{diff} \sim g^2$; and Regge - from Pomeron traj. $\sigma_{tot} \sim W^{0.16}$.

Diffraction



$$\frac{d\sigma^{\gamma^* p}_{\text{diff}}}{dM_X} \sim 4\pi\alpha^2 \frac{x_{IP} F_2^{D(3)}}{Q^2}$$

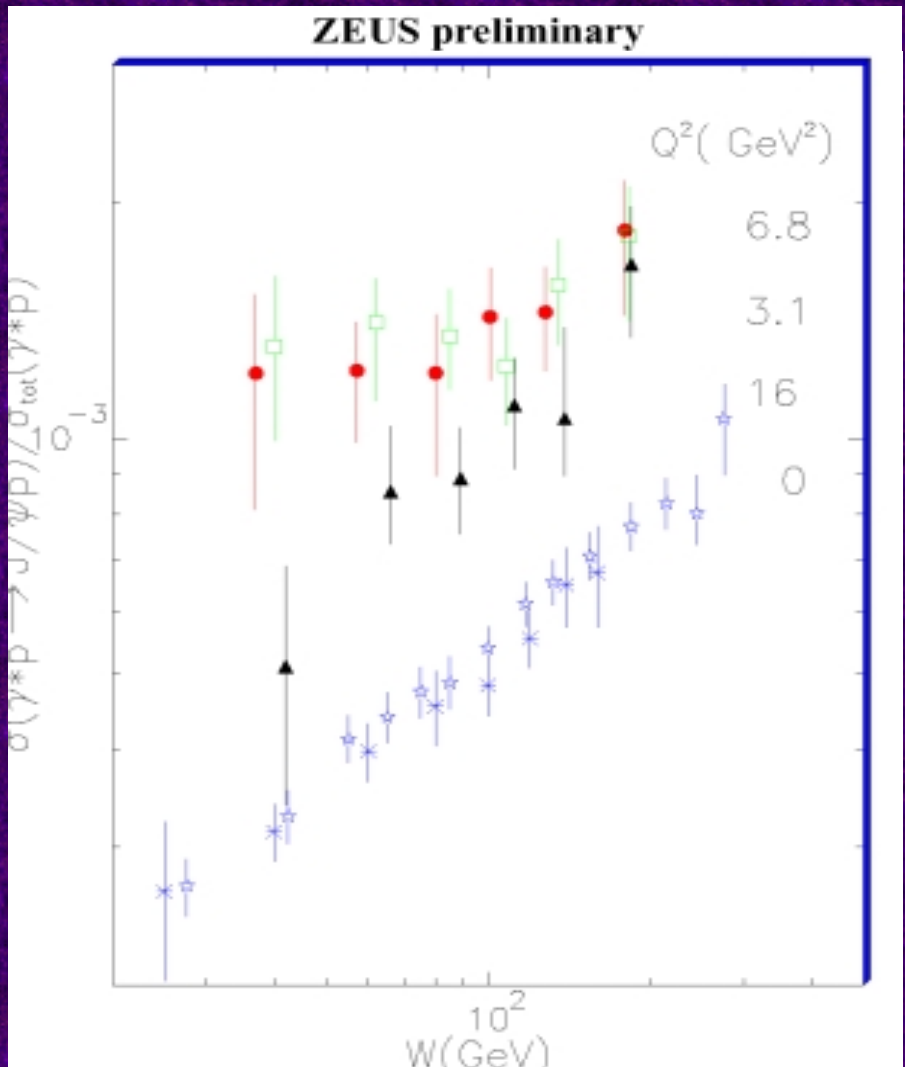


$$\sigma^{\gamma^* p}_{\text{tot}} = 4\pi\alpha^2 \frac{F_2}{Q^2}$$

- **Remarkable similarity of diffraction and total DIS apparent.**

Vector Mesons

- Similar picture when one looks at exclusive diffractive processes, e.g. elastic light-vector-meson production.

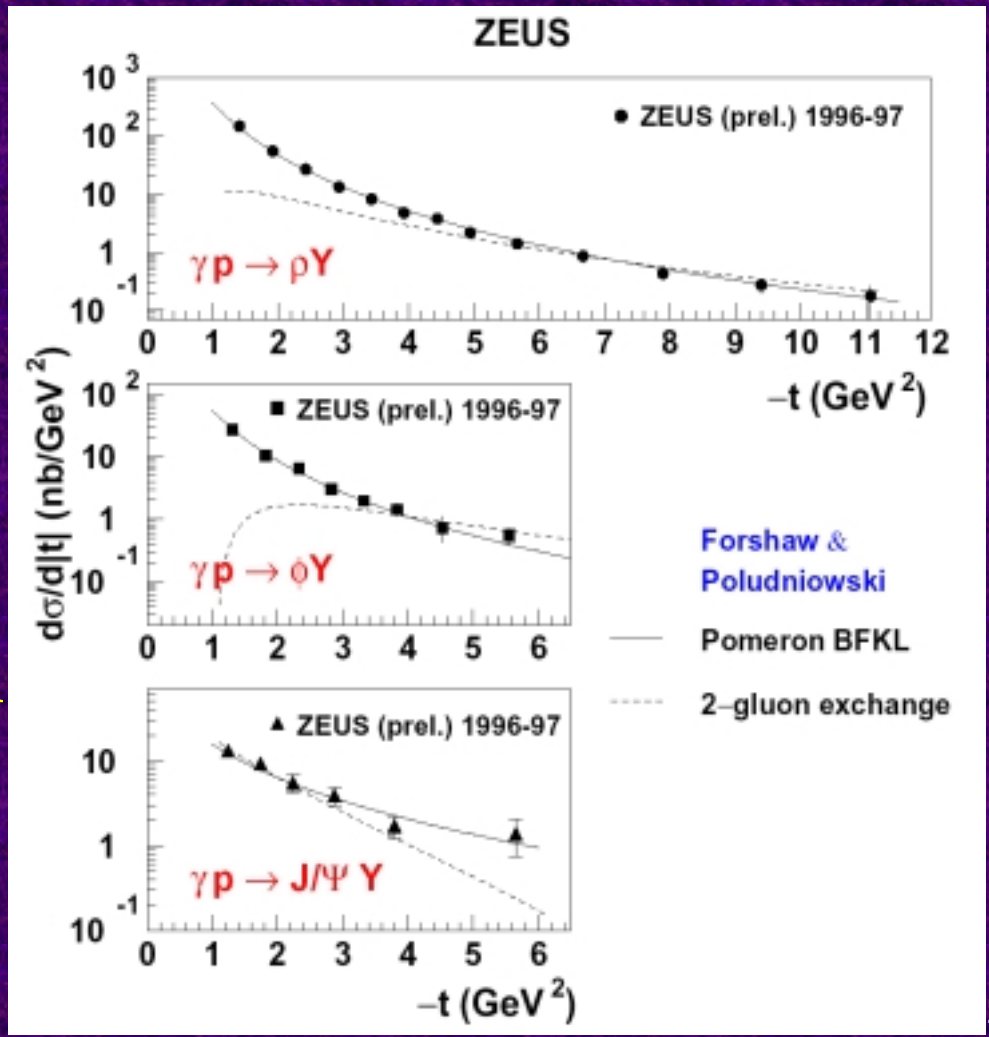


- For the J/ψ, however, the situation is different.

Vector Mesons

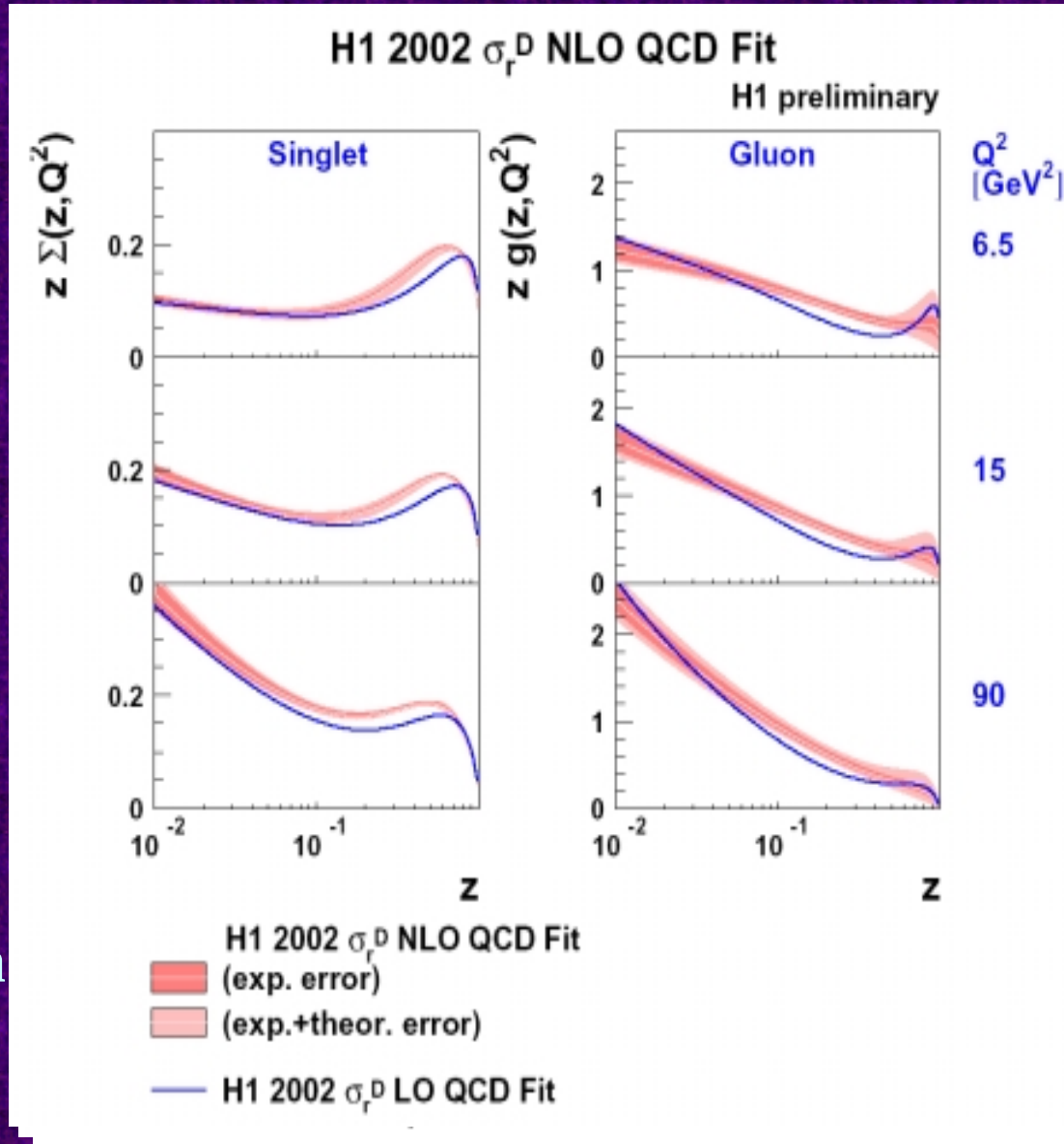
- Elastic vector-meson production great lab. for dipole models and application of pQCD to diffraction. Look at high *t*.

- Data can be fit beautifully to pQCD, but not with a simple 2-gluon exchange - BFKL dynamics required. Can also conclude that *t* does provide a QCD hard scale, although it leads to a somewhat different behaviour to Q^2 or M_V.



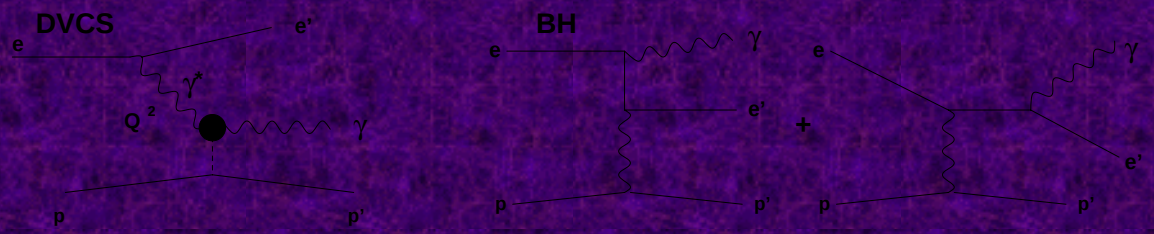
“Pomeron” structure

- Analogous to NLOQCD fit to proton F_2, the equivalent cross sections measured in diffraction, $\sigma_r^{D(3)}$, can also be fitted.
- Data give excellent fit to NLO QCD;
- PDFs show clear evidence for “DGLAP”-like evolution – dominated by gluon even at high “x”.

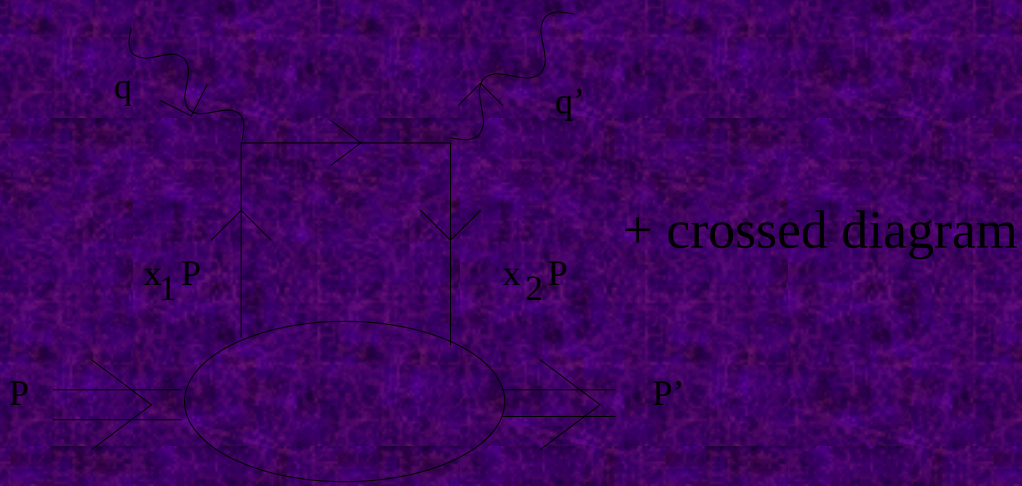


DVCS

- **Deeply virtual Compton scattering has simplest possible non-trivial diffractive final state.**

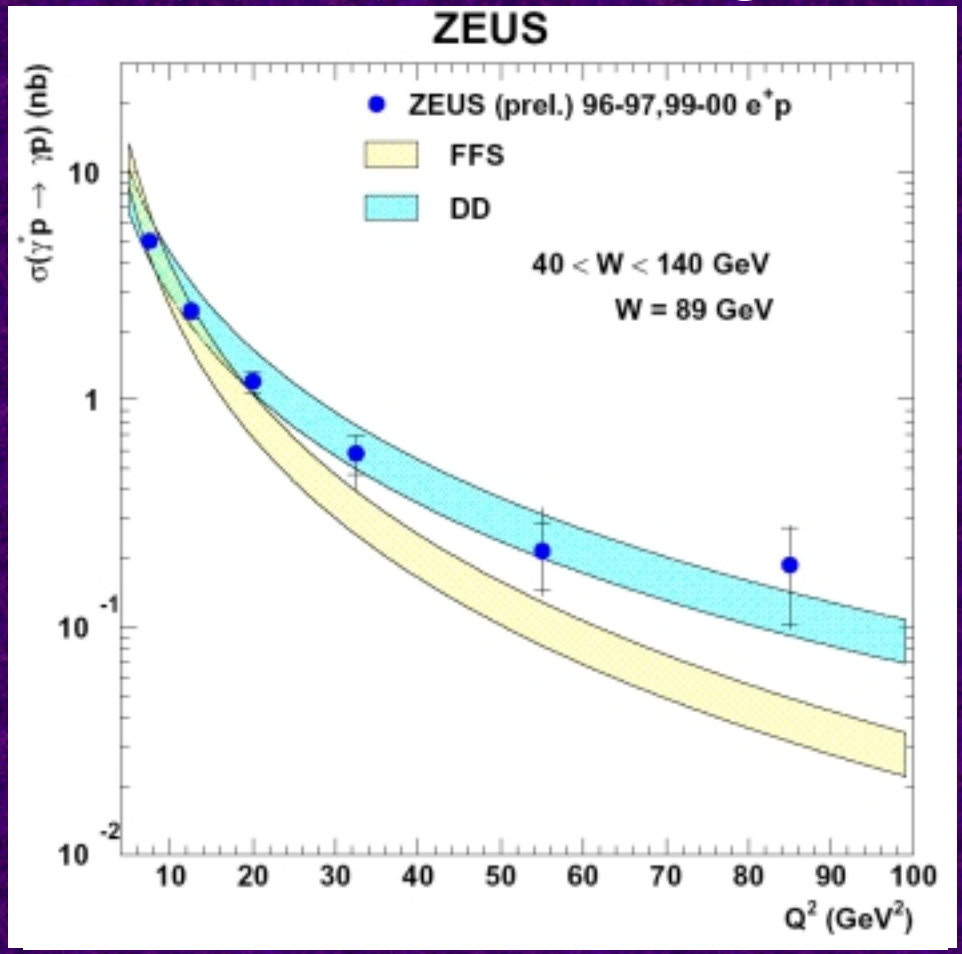


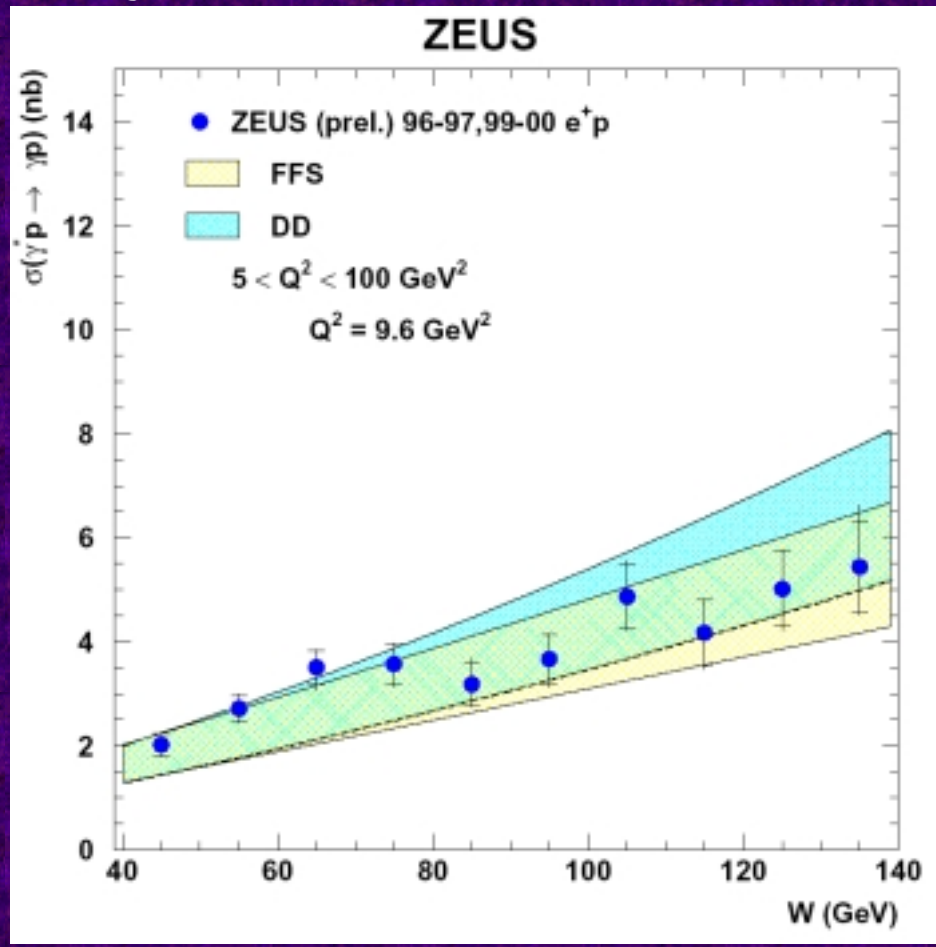
- **Measures "skewed parton" distribution and in principle sensitive to phase of QCD amplitude.**



DVCS

- $\sigma(e^+) \sim \sigma(e^-)$ within large uncertainty on e^-



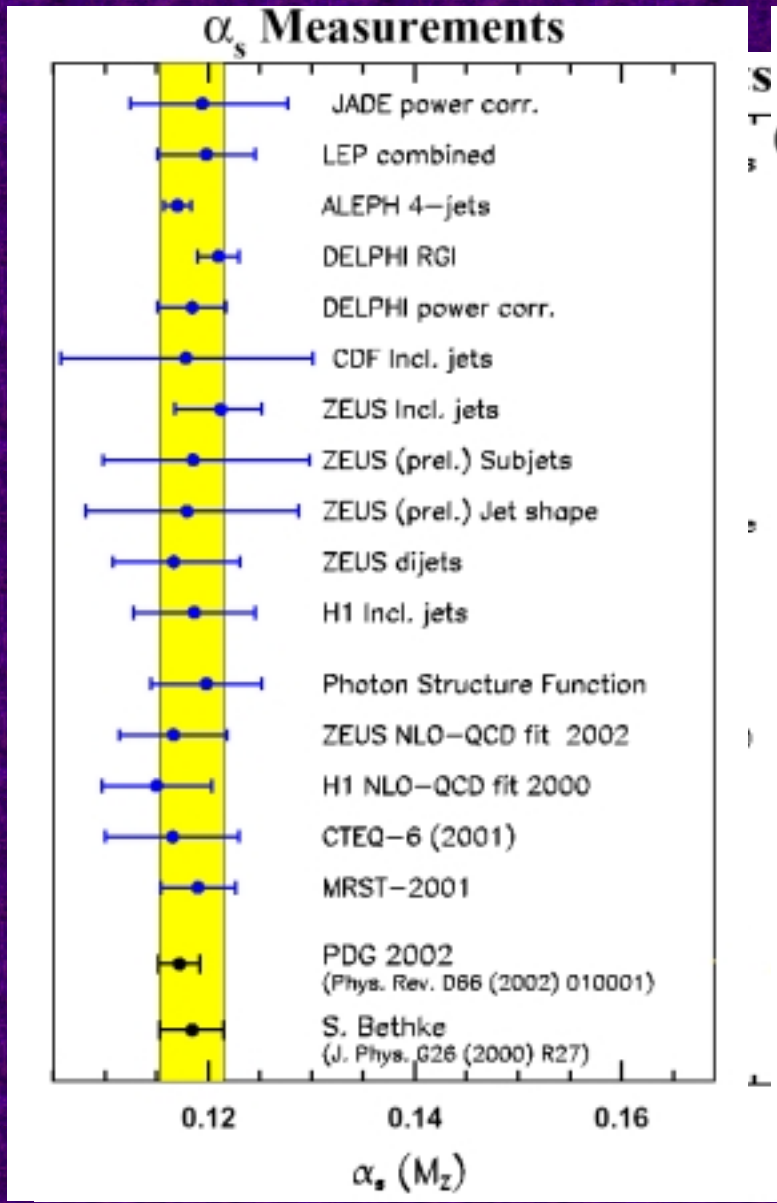


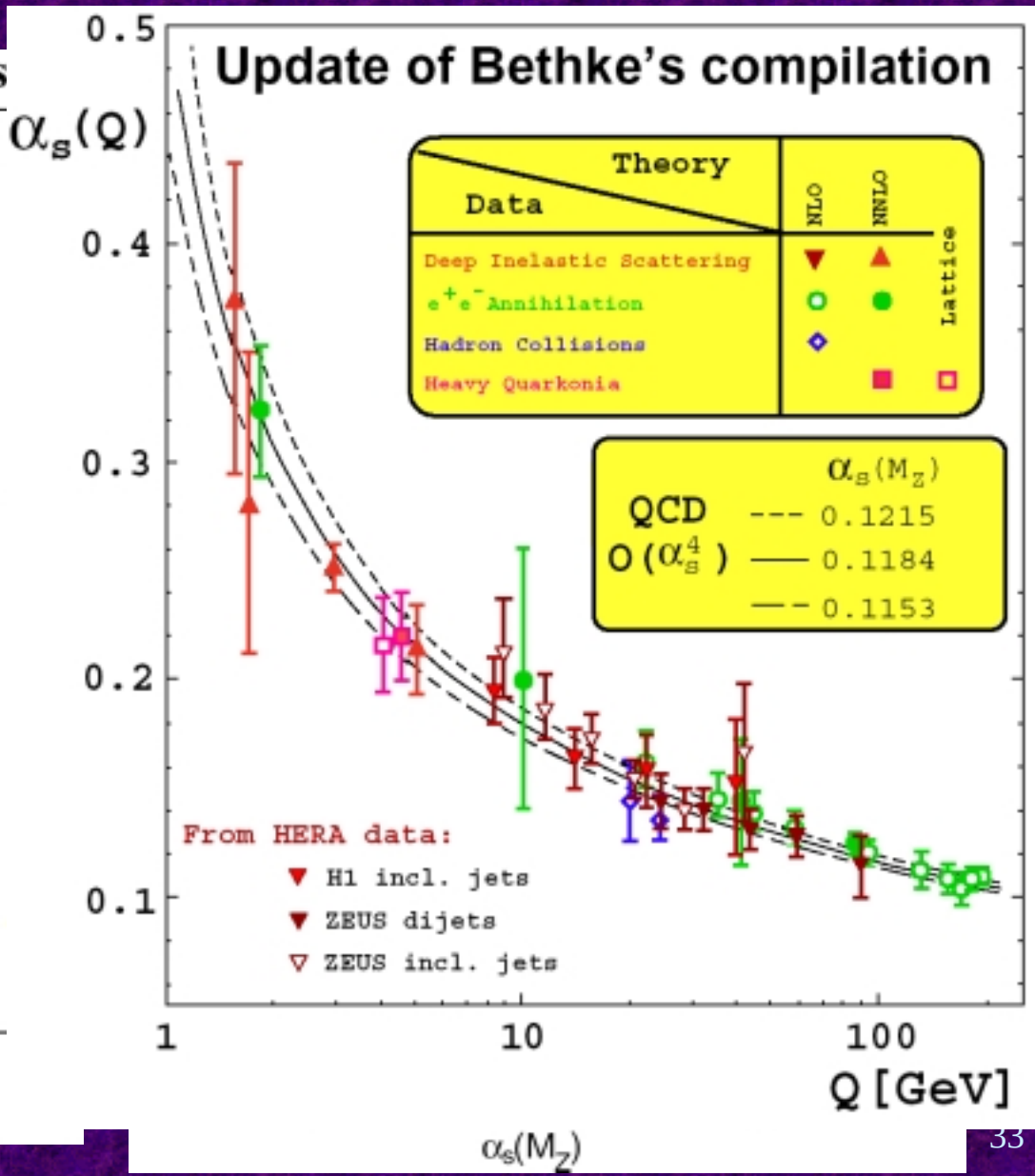
- **Accuracy of data now sufficient to discriminate among models.**

Summary.

- **Jet physics – the measurement and detection of multiple-jet and inclusive-jet final states at HERA has now reached a new level of maturity and accuracy; the advances in theoretical predictions have almost kept pace, but in some cases NNLO calculations now warranted by the data.**
- **NLOQCD fits have also reached new degrees of sophistication, taken proper account of correlated and uncorrelated errors. General agreement between H1 and ZEUS and the professional PDF fitters. HERA data alone now almost sufficient to determine all the PDFs.**
- **The above have combined to produce determinations of α_s of both startling profusion and quality – competitive with ~ any in the world. The strong coupling constant is now a precision parameter of the Standard Model.**

α_s from HERA





Summary.

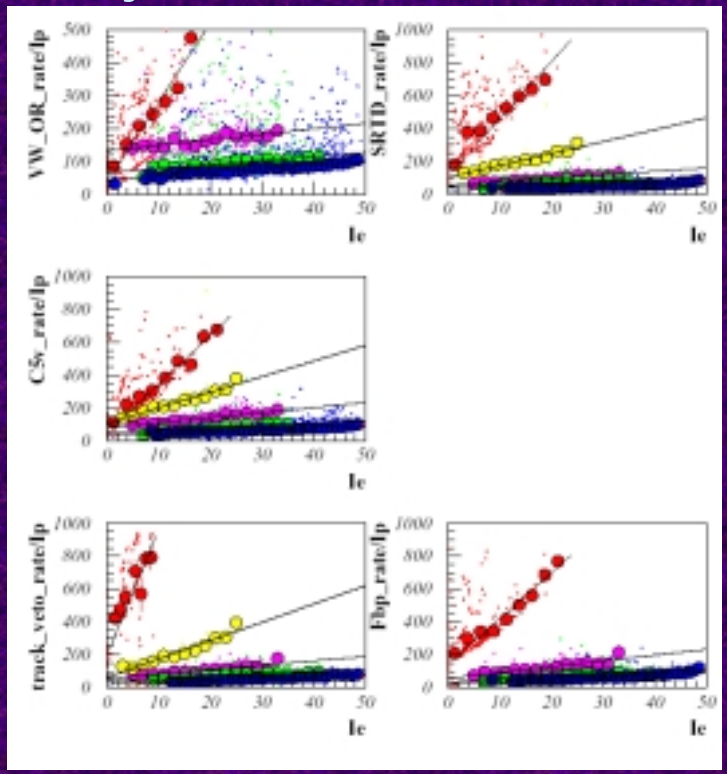
- **Heavy quarks – perhaps a combination of better theoretical understanding, higher-order effects, and new data, is diminishing the long-standing discrepancy between data and QCD.**
- **There is clearly a transition between the NLOQCD region and a non-perturbative region that sets in in ~ all processes at $Q^2 \sim 1$ GeV^2. G-B&W, and similar, models including saturation fit a remarkable range of data. However, the data do not stablish parton saturation.**
- **There is no "smoking gun" – or even a dripping water pistol – for non-DGLAP effects in the DIS data. The forward jet/π^0 data are inconclusive/confusing. The high-t VM production is tantalising – but more work and more processes necessary to establish unambiguous sighting of BFKL effects.**

Summary.

- **There is beautiful new diffractive data from H1 & ZEUS. The structure of the Pomeron is now revealing itself in unprecedented detail** - but does it exist?
- **I am not sure we have made much progress in the QCD understanding of diffraction. In DVCS however, the data is now sufficiently precise to challenge the theory.**
- **HERA I has been an enormous success in QCD studies – and there is still much more to come. We have long ago left the era of "tests of QCD" and entered a realm of precision measurements. The theory is rich enough to keep both theorists and experimentalists busy for a very long time to come.**

Summary.

- **There is much more to come from HERA II.**
- **If only we could move away from this**



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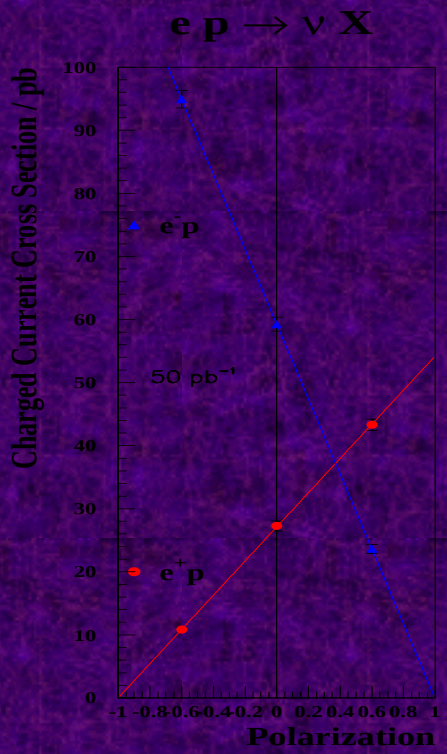

- **I am confident that this will happen soon and that HERA II will be an even more successful QCD factory than HERA I.**