XXII Physics in Collision Conference

SLAC, California, June 20^{th} to 22^{th}, 2002.

Precision Tests of QCD at HERA

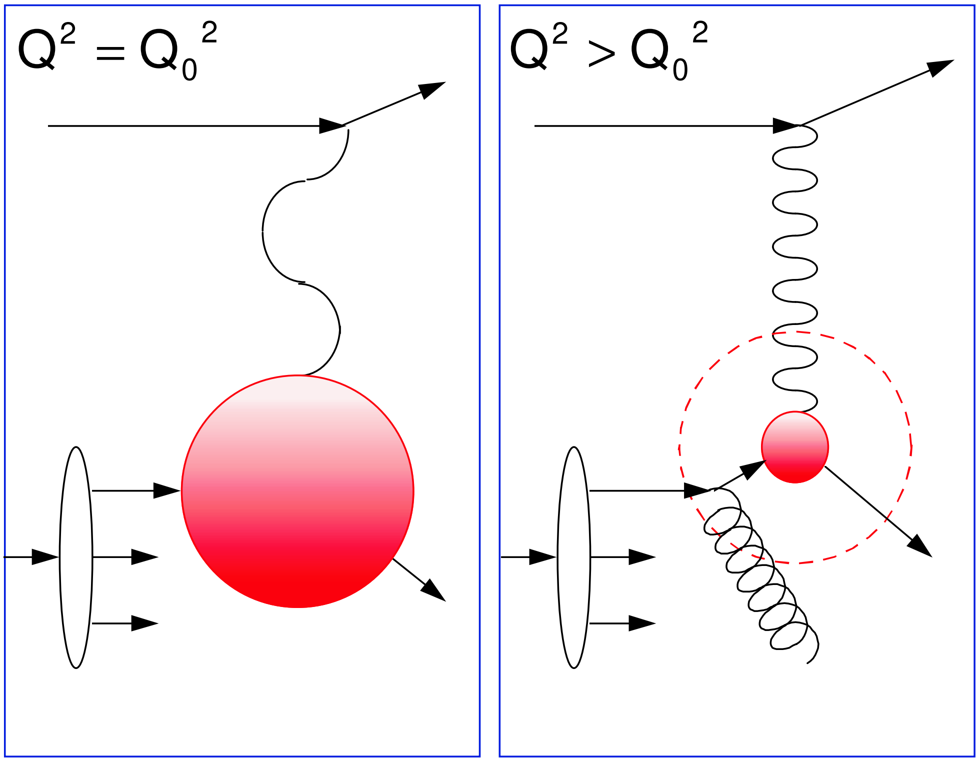
David Milstead

The University of Liverpool

Representing

H1 Collaboration **ZEUS Collaboration**

Looking at the Proton with an Electron Microscope !



Scatter a photon from the electron off a quark in the proton.

Characterise Deep Inelastic Scattering Interactions (DIS) with following variables:

- $Q^2 = -(k' - k)^2$ **Resolving power of probe** $(\lambda = h/Q)$

Q^2/GeV^2	**0.1**	**1.0**	**100**	**10,000**
λ/m	10^{-15}	10^{-16}	10^{-17}	10^{-18}

Photon can probe $\frac{1}{1000}^{th}$ proton size!

- **Bjorken-$x = \frac{Q^2}{2P.q}$** **Fraction of proton's momentum carried by struck quark.**

The electron-proton collider at HERA

The Hadron Electron Ring Accelerator (HERA) is a 6.3km circumference ring at DESY, Hamburg.

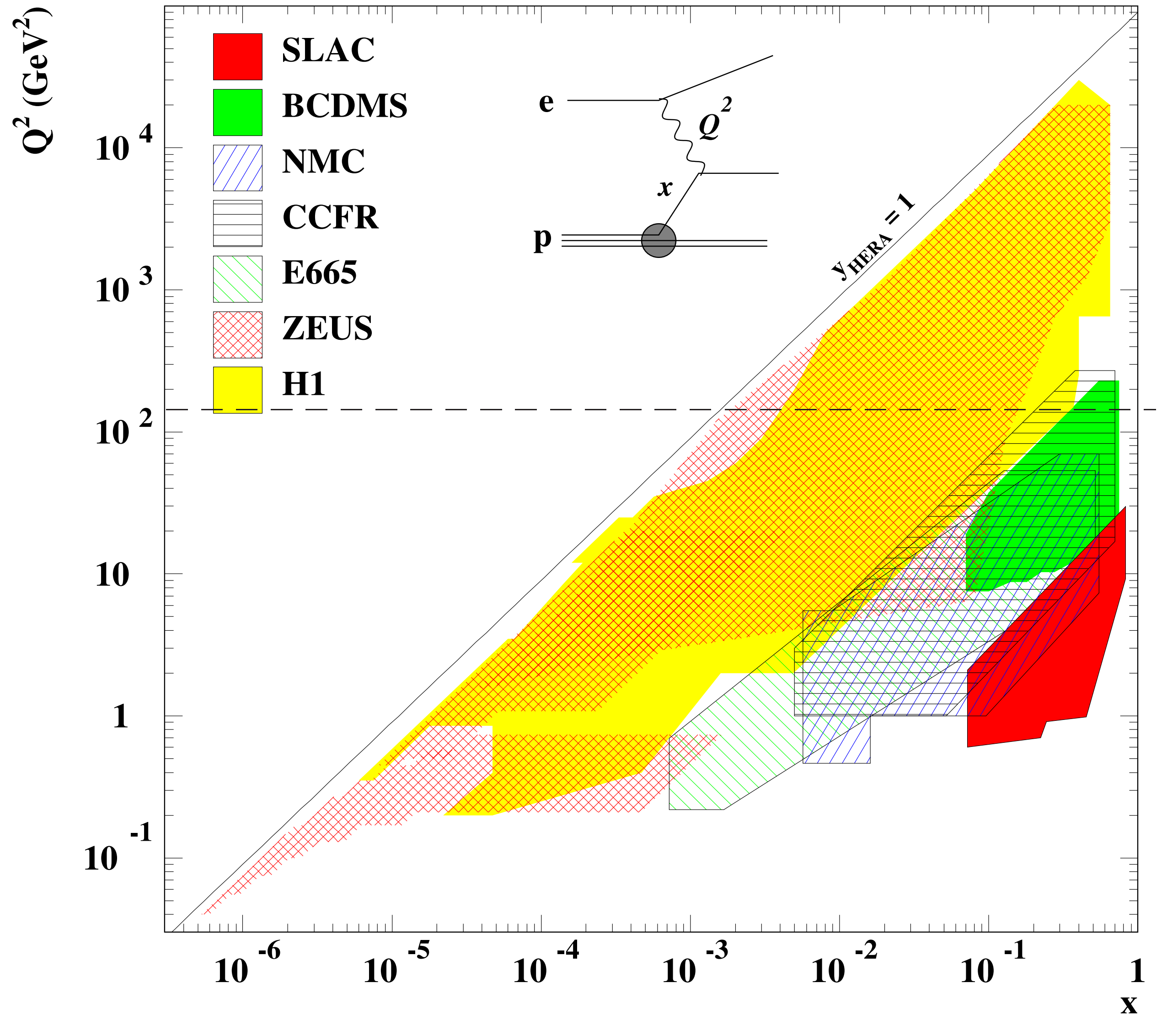
27.5 GeV electrons and 920 GeV protons are collided at 318 GeV centre of mass energy.

The H1 and ZEUS experiments study ep interactions in the kinematic range:

$$10^{-5} < x_{bj} < 0.8,\ 0 < Q^2 < 50,000\ \textbf{GeV}^2$$

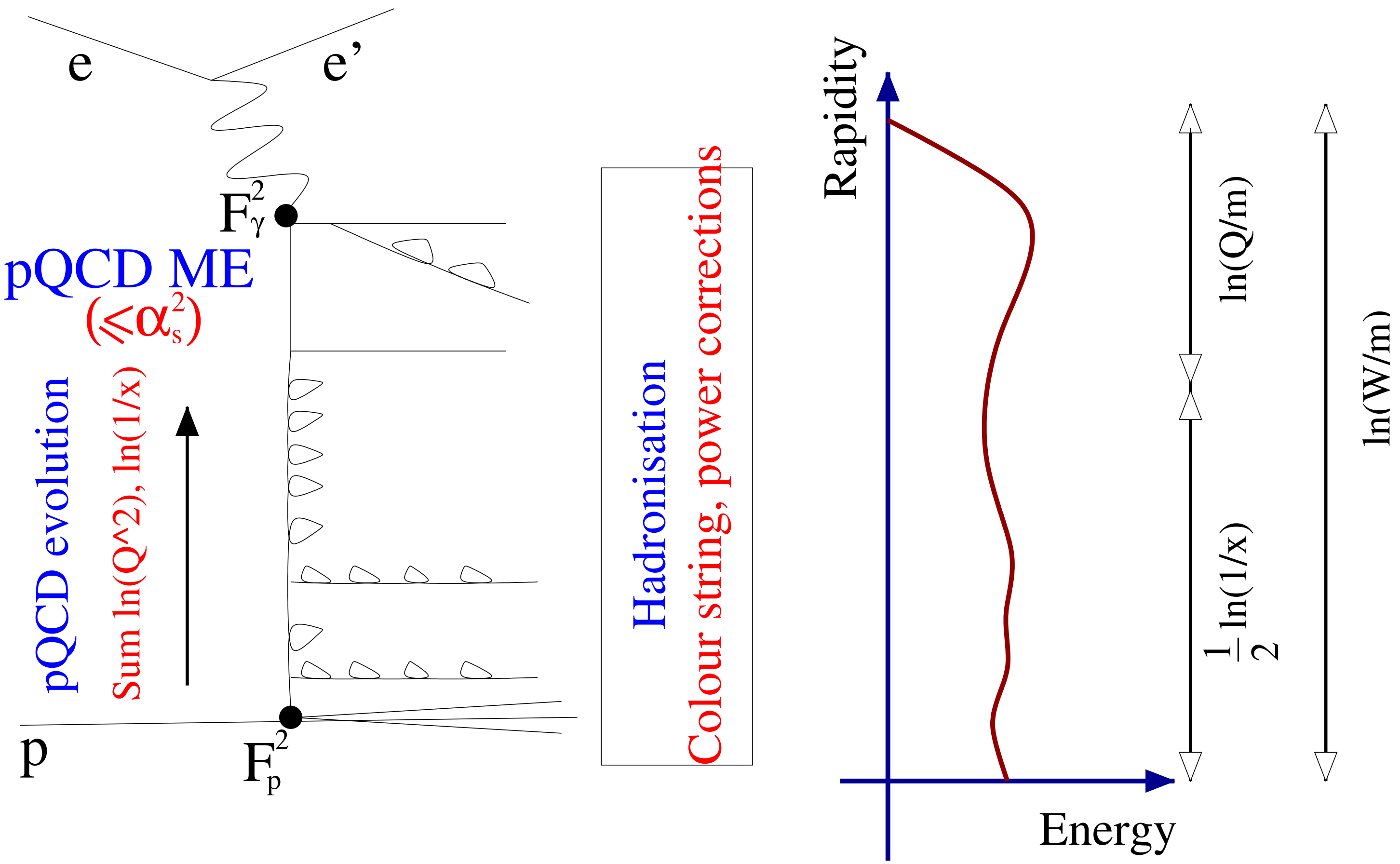
Each experiment accumulated $\approx$ 150 pb^{-1}

The kinematic plane opened up by HERA



HERA offers orders of magnitude more phase space than previous expts.

QCD Processes at HERA



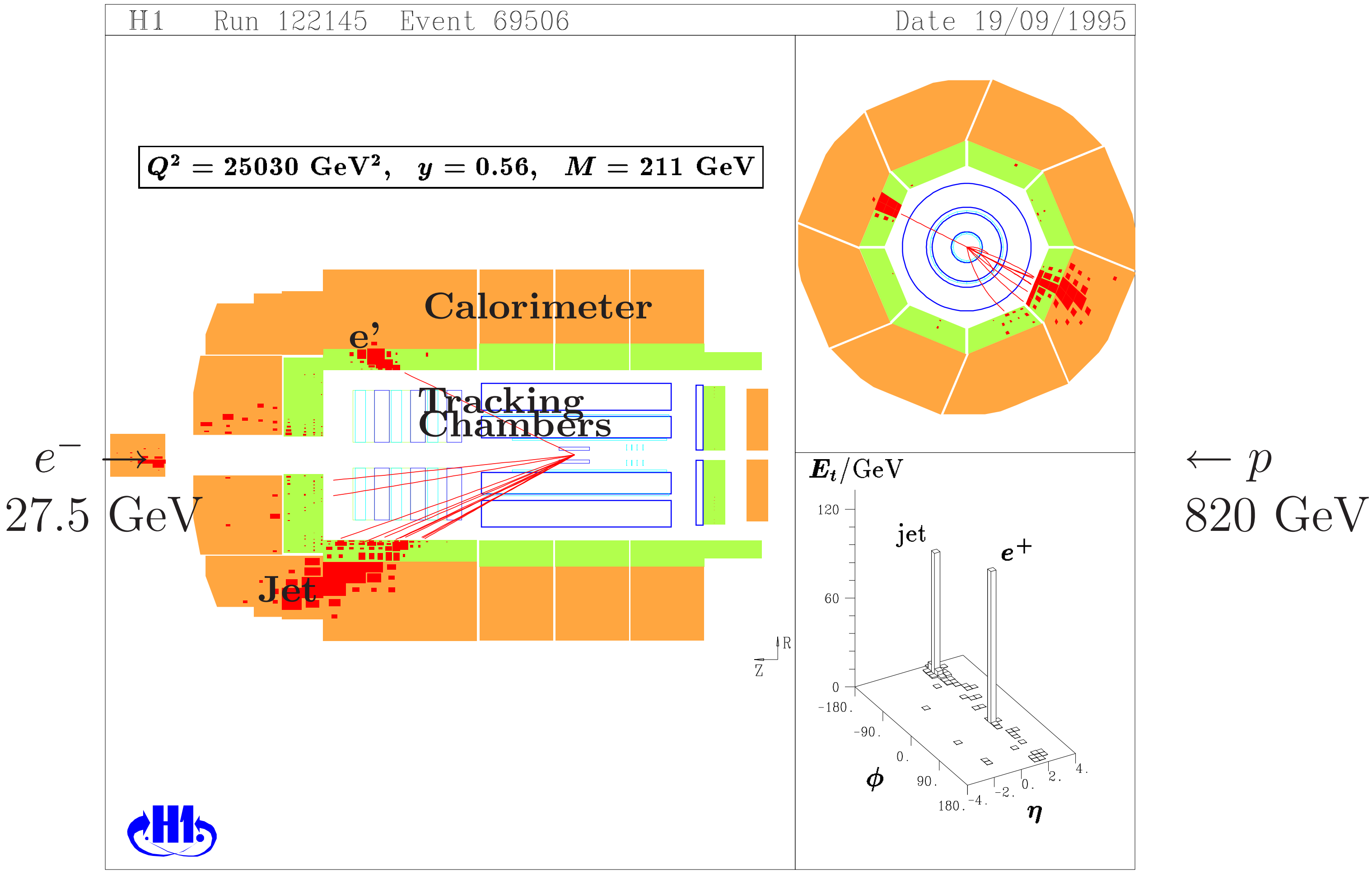
High energy ep scattering reveals proton, photon structure.

High p_T jet and hadron measurements test pQCD via exact ME and resummed calculations.

Varying ep kinematics $\rightarrow$ varying physics.

A HERA Experiment

Use the H1 detector to study $ep \to e'X$.

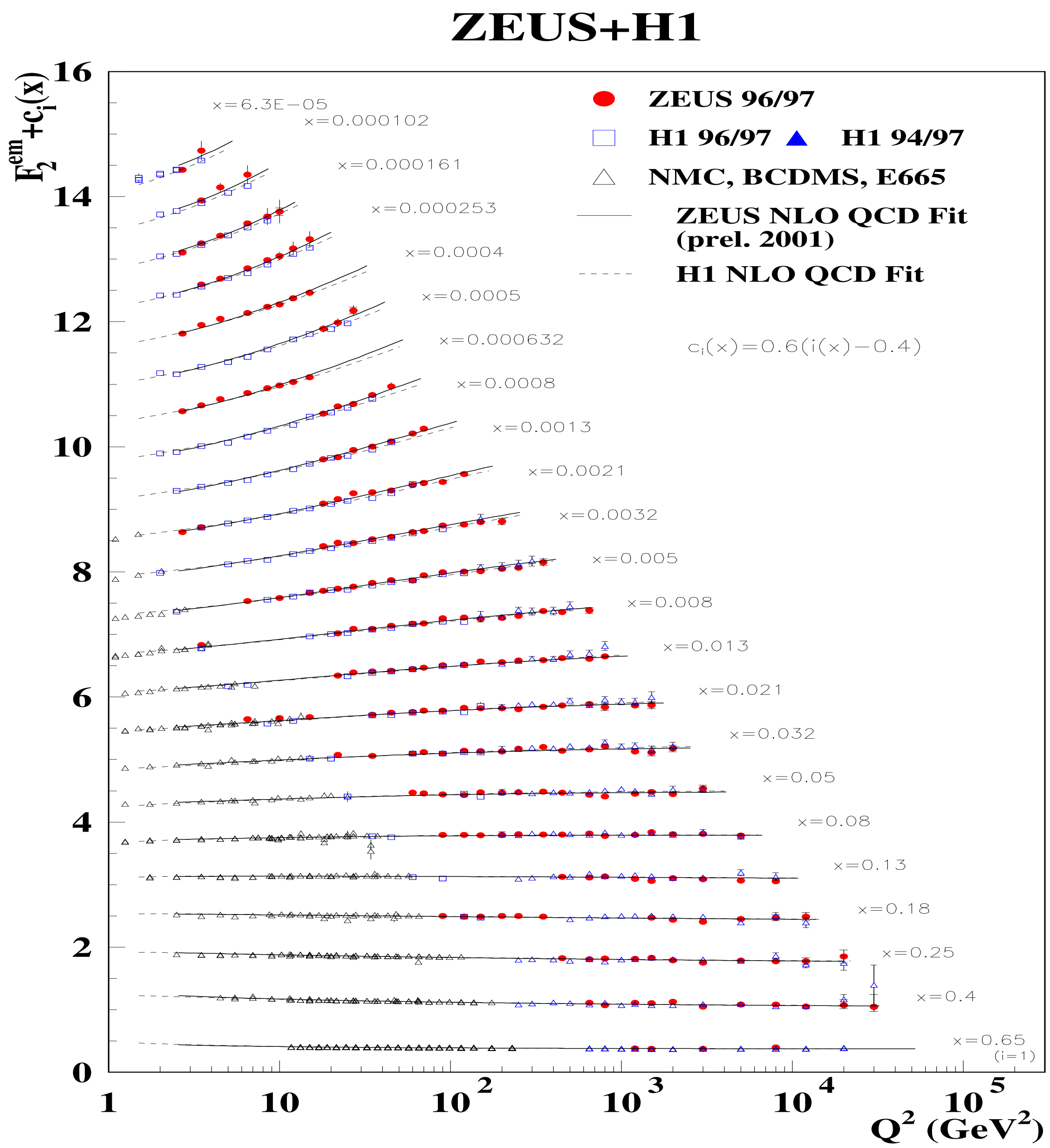


- **Asymmetric design due to larger proton beam energy.**
- **Calorimetry and charged particle tracking chambers measure kinematics of produced particles.**
  - **Reconstruct the scattered electron (e') and kinematics of the interaction**
  - **Measure the hadronic final state (X)**

The Proton Structure Function F_2

DIS cross-section can be approximated as :

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[2(1-y) + \frac{y^2}{1+R}]F_2(x, Q^2)$$



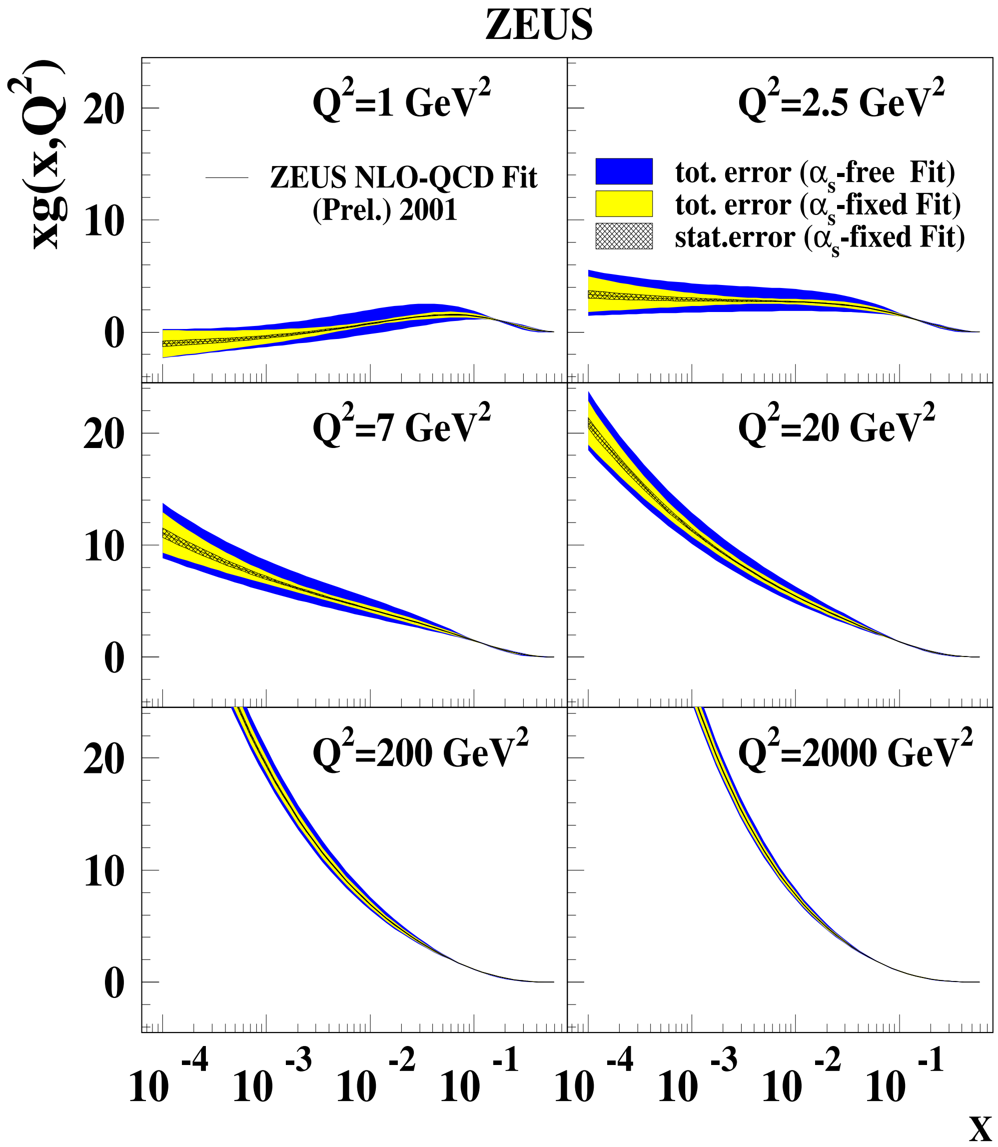
Gluon branching leads to softer structure with increasing resolution.

$$\frac{dF_2}{dlogQ^2} \propto xg(x).\alpha_s$$

The Gluon Density in the Proton

The scaling violation of F_2 at low x is dominated by the gluon density

$$\frac{dF_2}{dlogQ^2} \propto xg(x).\alpha_s$$

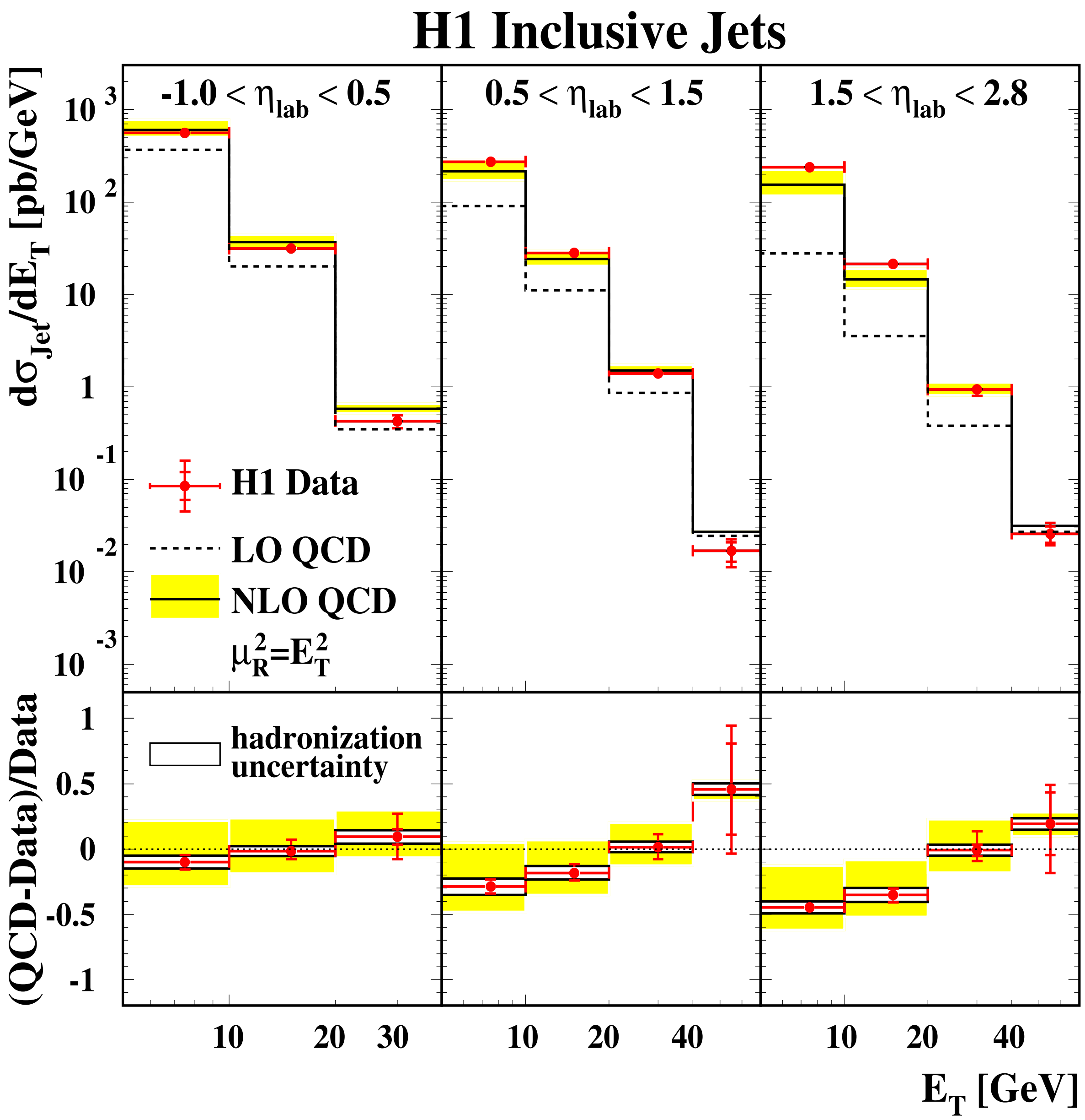


Strong rise of the gluon density towards low x.

xg vanishes at low x ($x < 0.02$) and $Q^2 \sim 1\text{GeV}^2$ ("valence like").

Complementary approach to testing QCD is to study the hadronic final state.

Measurements of Single Inclusive Jets in DIS

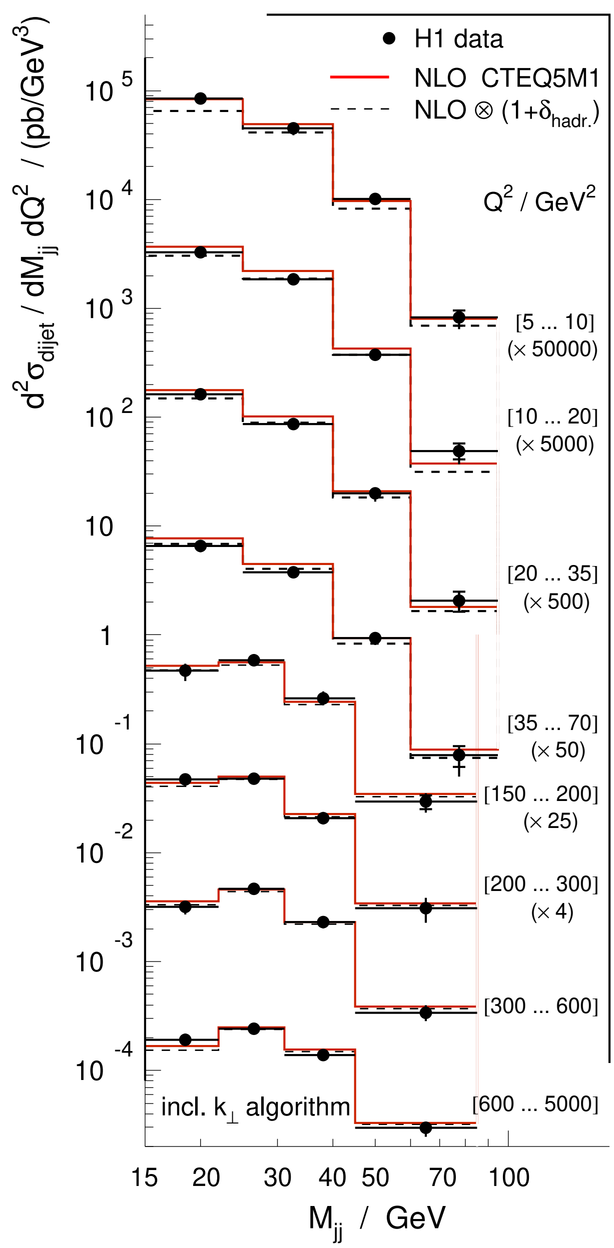


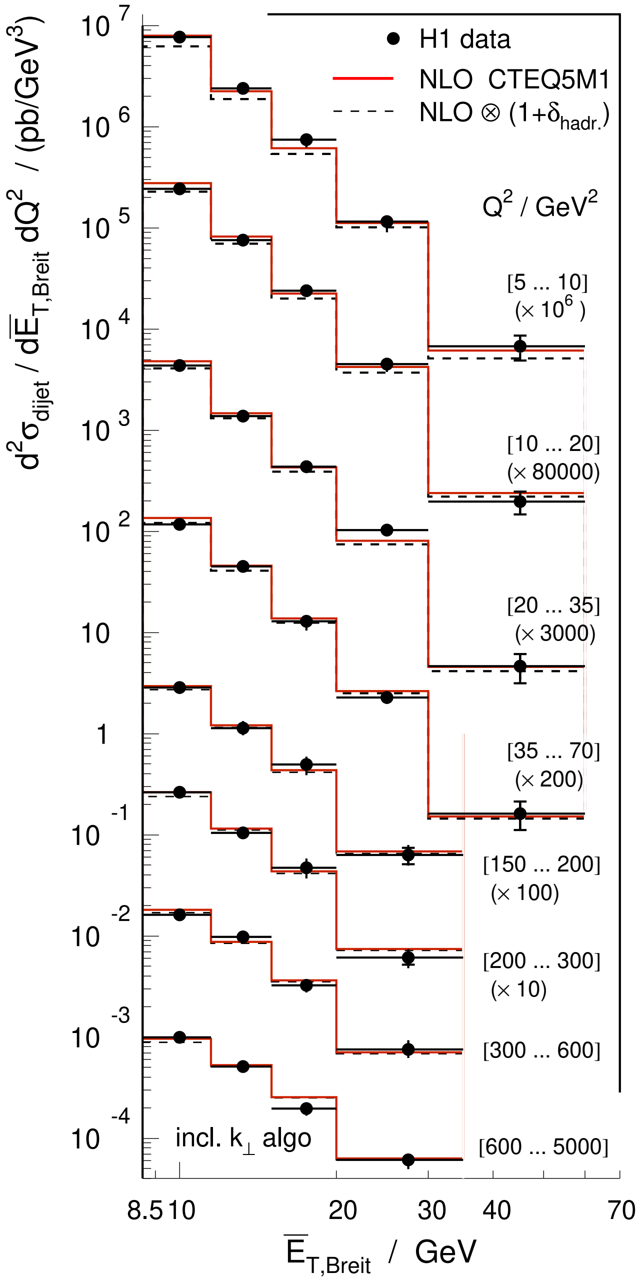
Cross-section measured over several orders of magnitude.

LO QCD underestimates data.

NLO QCD describes data with possible discrepancy in the forward region.

Dijet Rates in DIS

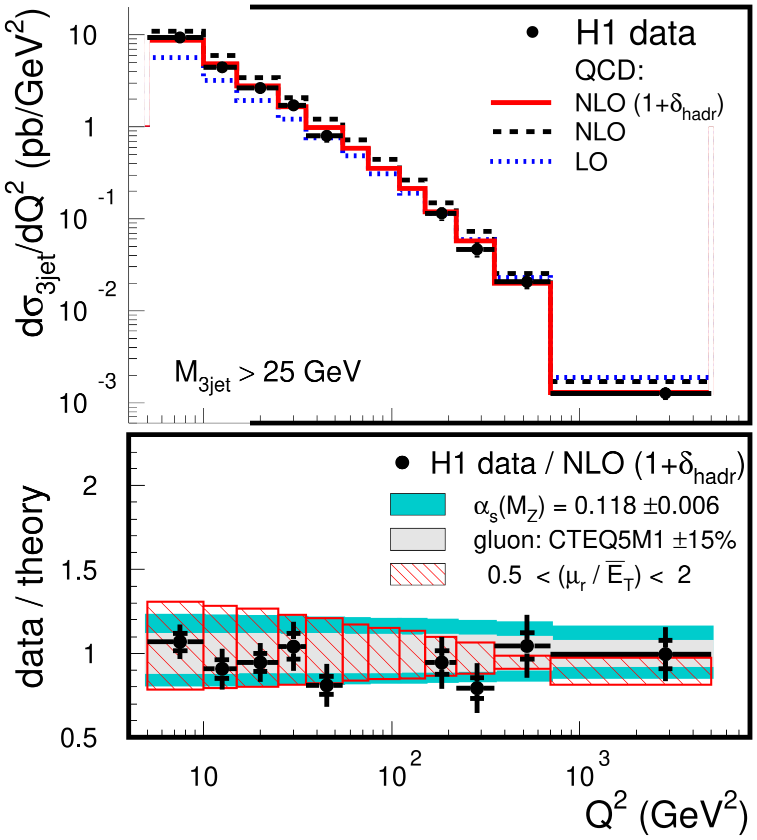


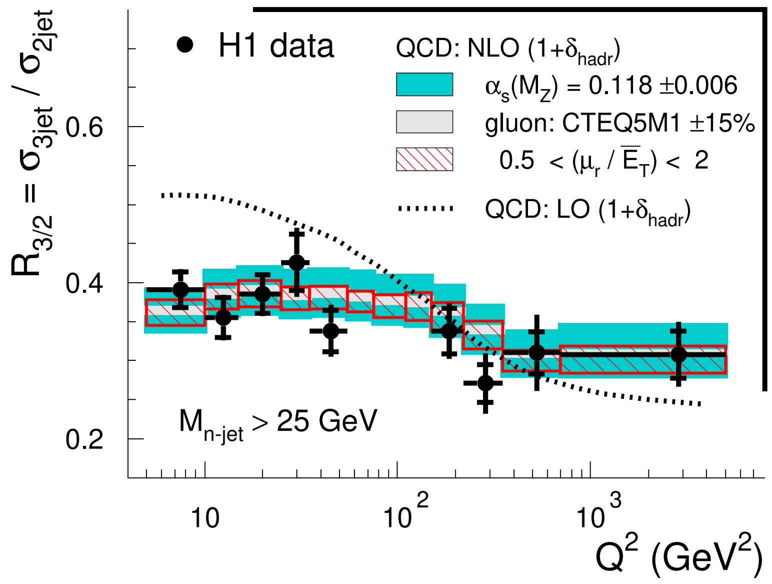


Cross-sections measured over several order of magnitude

NLO QCD describes data well.

3-jet Production in DIS



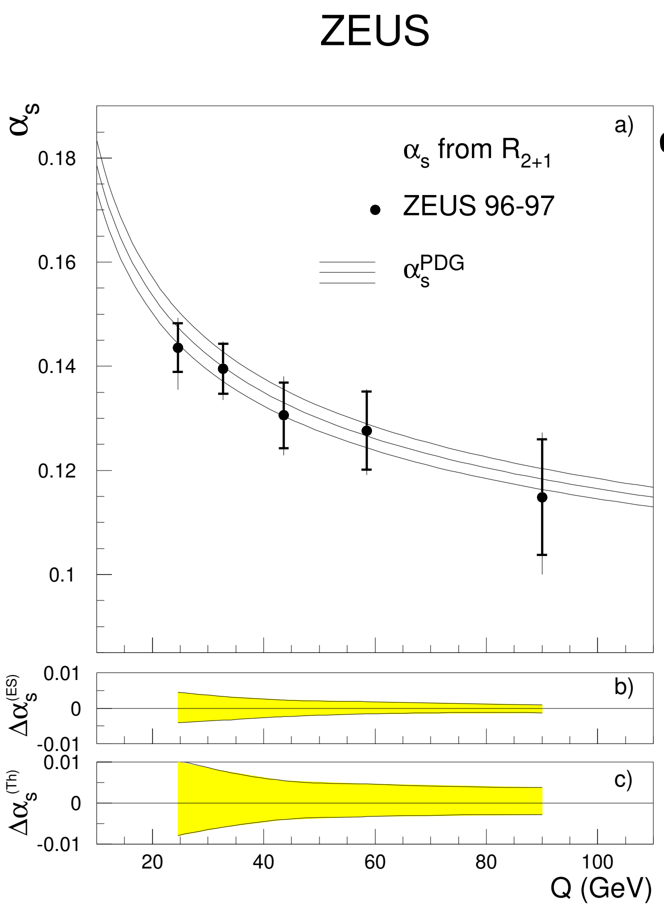


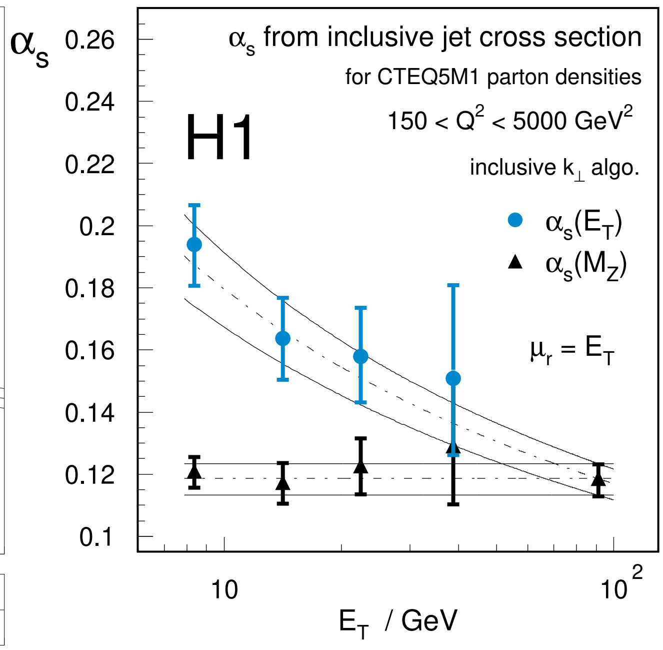
NLO QCD describes well higher order processes

3-jet/2-jet ratio promises precision extraction of α_s

Determination of α_s

ZEUS: $\mu_r = Q$ – use Q^2 dependence of dijet rate
H1: $\mu_r = E_T$
– use E_T dependence of inclusive jet cross section

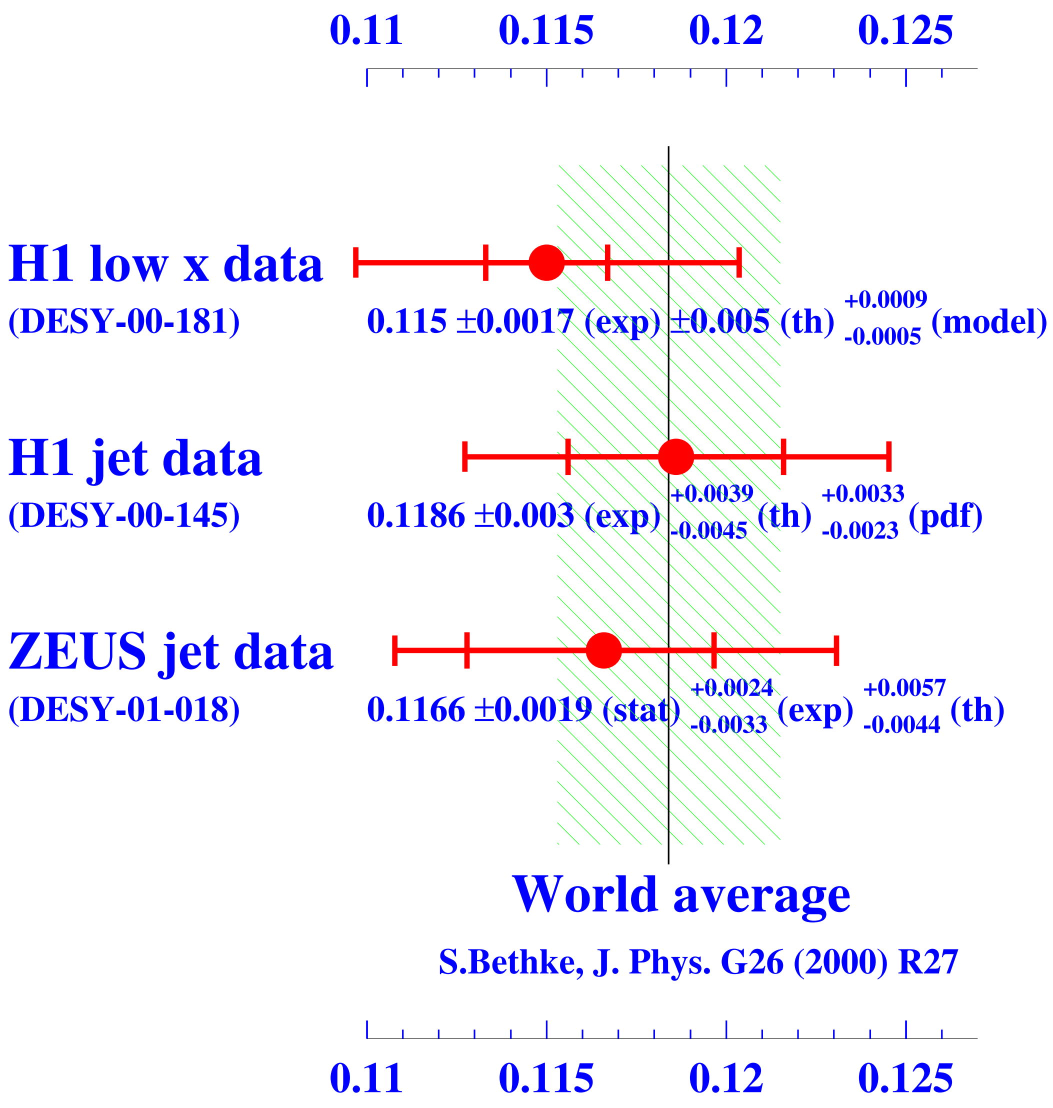




Energy dependence of $\alpha_s(M_z)$ consistent with prediction of renormalisation group equation.

α_s from Jet and Inclusive Measurements

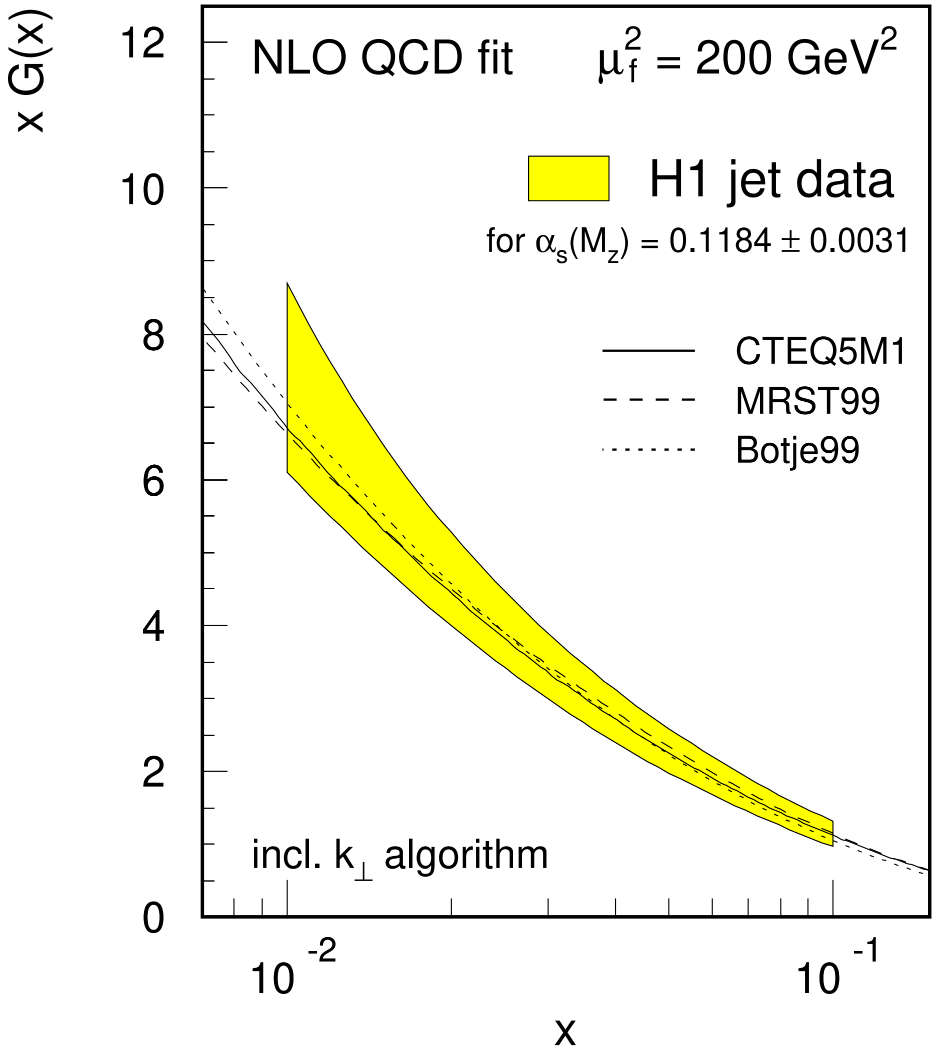
Recent α_s measurements at HERA



→ Consistent picture of α_s measurements from HERA.

Derivation of the Gluon Density in the Proton

inclusive DIS cross section	$d^2\sigma_{\mathrm{DIS}}/dQ^2\,dx_{\mathrm{Bj}}$
dijet cross section	$d^2\sigma_{\mathrm{dijet}}/d\xi\,dQ^2$
inclusive jet cross section	$d^2\sigma_{\mathrm{jet}}/dE_T\,dQ^2$



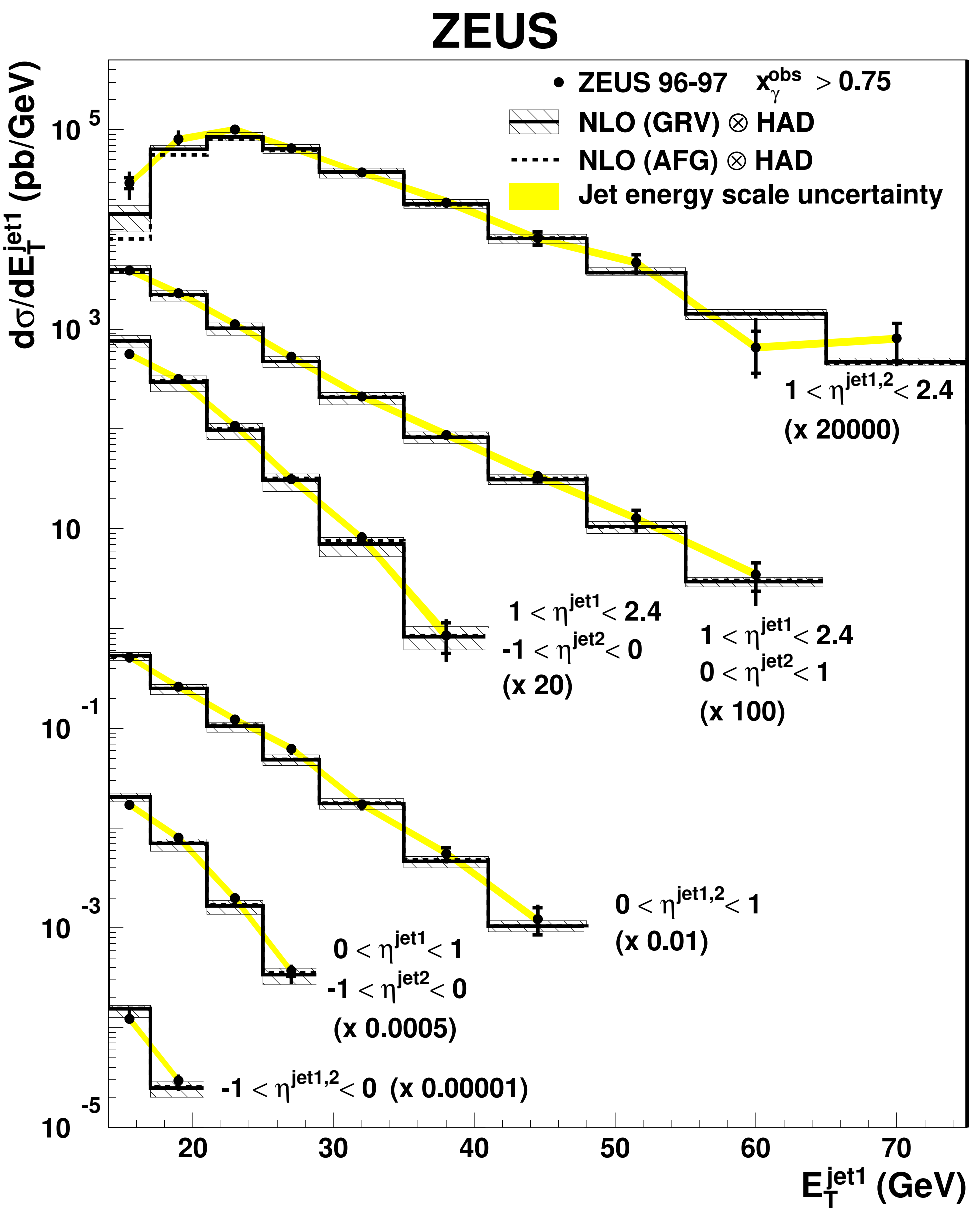
Direct determination from jets at $0.01 < x < 0.1$ consistent with results from global fits.

$\Rightarrow$ Universality of gluon density.

Dijet Rates in Photoproduction

Double differential cross-sections measured.

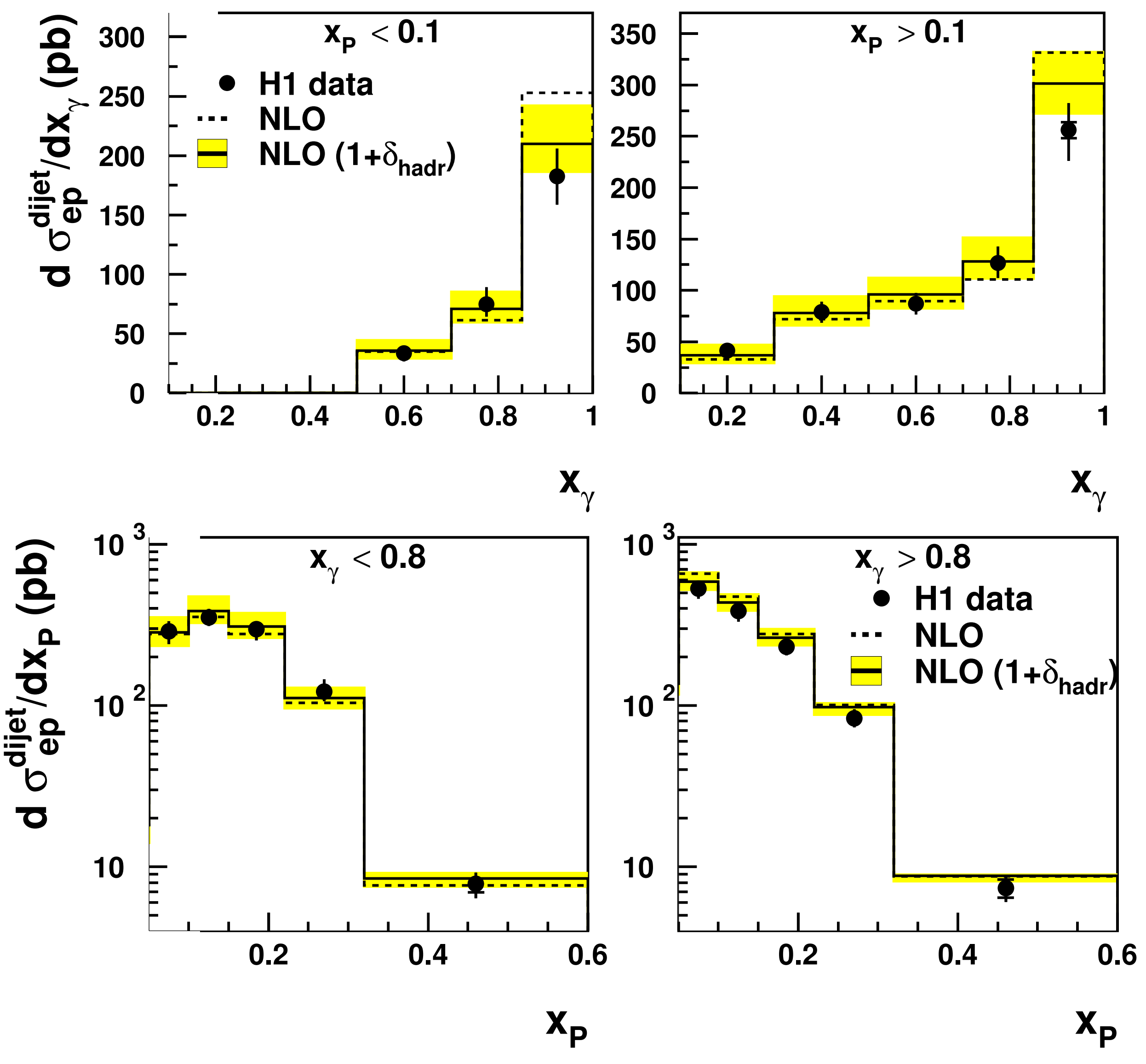
Sensitivity to photon and proton structure.



NLO QCD describes data well over wide ranges of E_T and rapidity.

Dijet Rates in Photoproduction

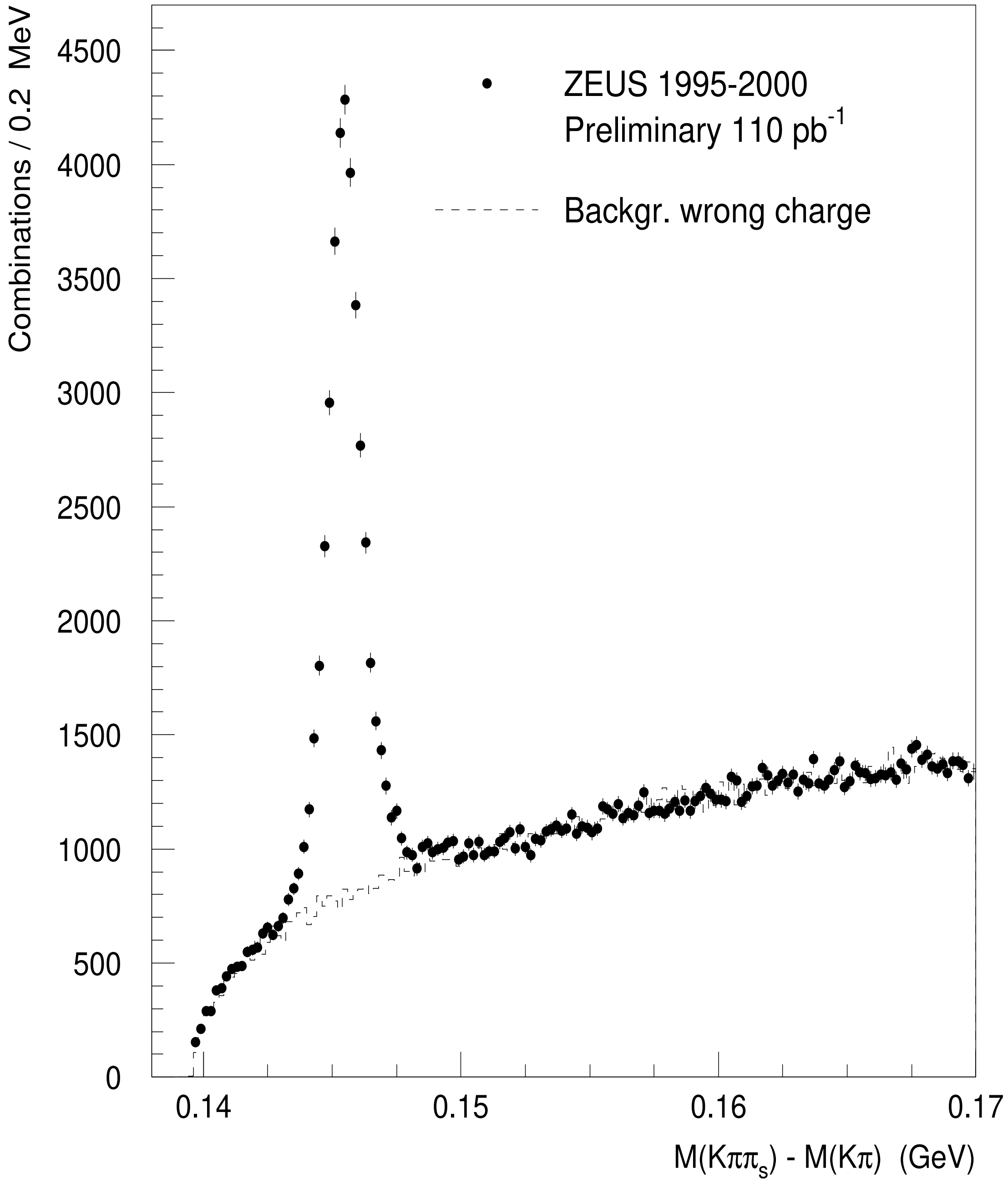
Measure the fractional momenta of photon and proton taking part in the scattering.



Data cover orders of magnitude in partonic momenta.

NLO QCD using fits from F_2 describe data well.

HERA as a charm factory

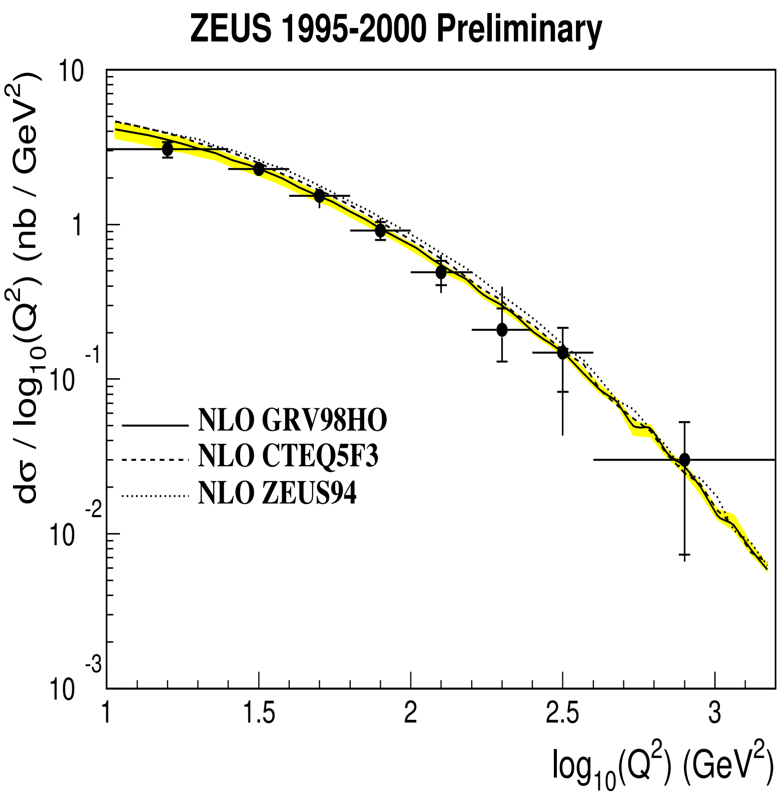


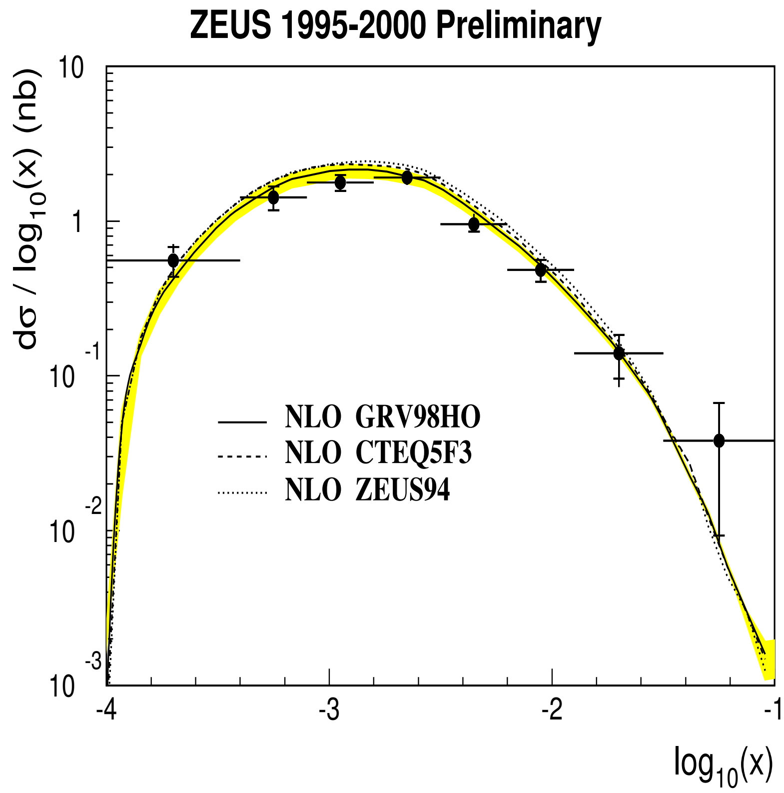
27,000 $D^* \rightarrow K\pi\pi$ decays reconstructed.

Charm produced via photon-gluon fusion.

$\Rightarrow$ Precision test of pQCD.

D^* cross-section in DIS





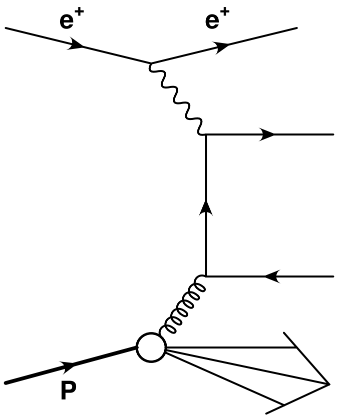
NLO QCD using parton densities from F_2 scaling violations describe data well.

F_2^{charm} from HERA

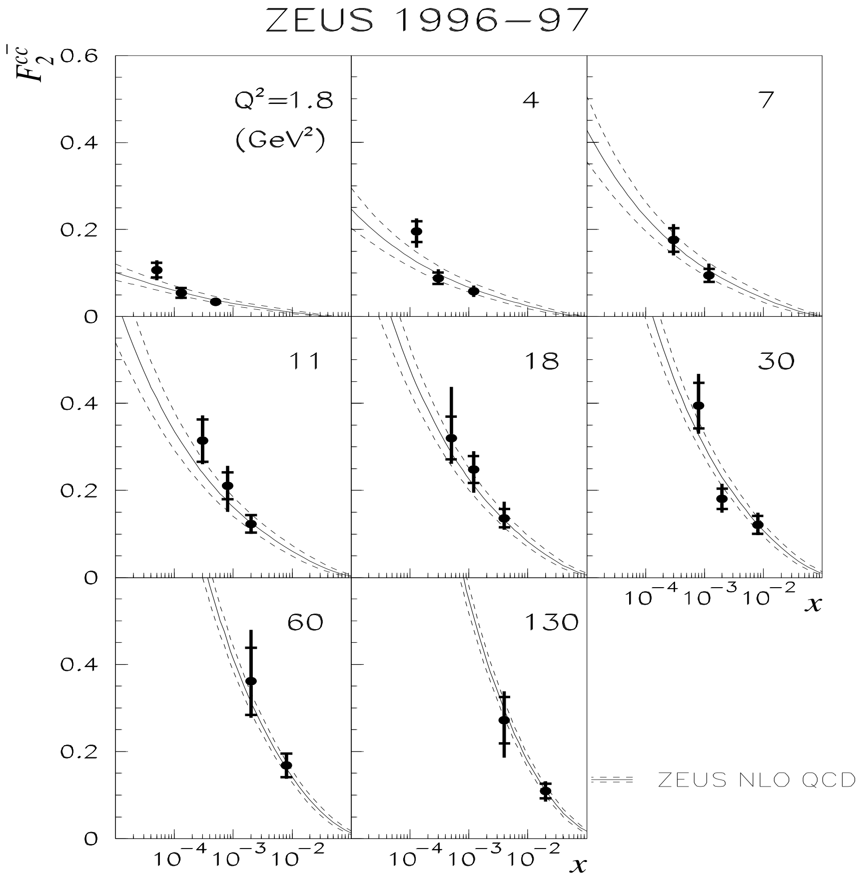
Boson-Gluon Fusion process (BGF)

as a direct handle of the gluon density $\Rightarrow$

tag by charm (or jets) in the final state

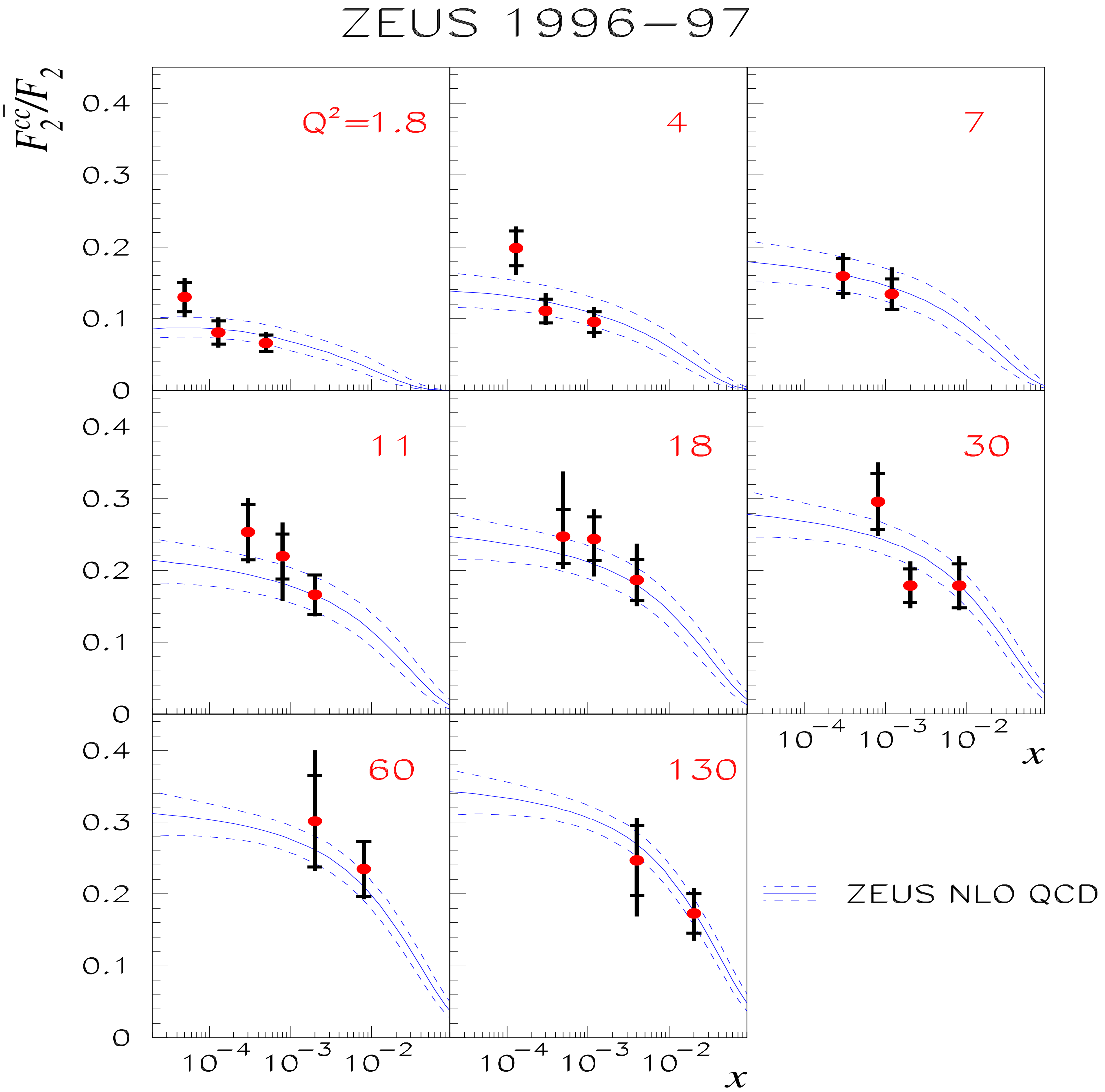


$$\frac{d^2\sigma(ep \to ec\bar{c}X)}{dxdQ^2} = \frac{2\pi^2\alpha}{xQ^4}(Y_+ F_2^{c\bar{c}} - y^2 F_L^{c\bar{c}})$$



Good description of charm yields by QCD fit to inclusive ep cross-section.

Ratio of $F_2^{c\bar{c}}$ to F_2^p



$F_2^{c\bar{c}}$ rises faster than F_2^p.

At low x $F_2^{c\bar{c}}$ accounts for up to 30% of F_2

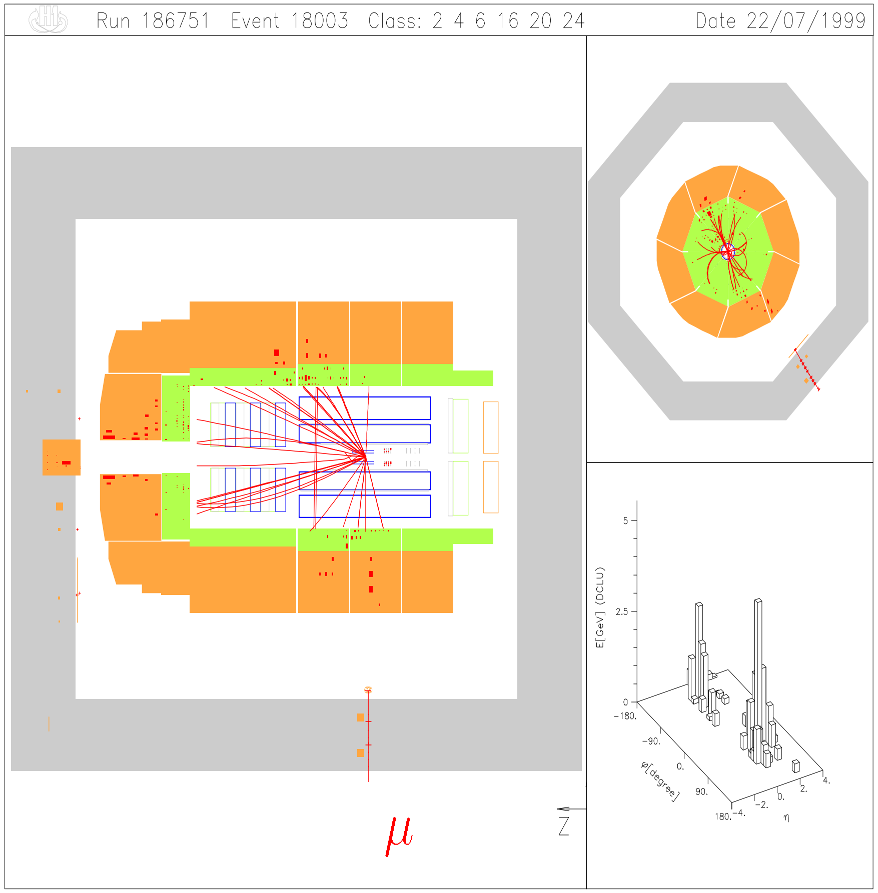
Signatures of Beauty

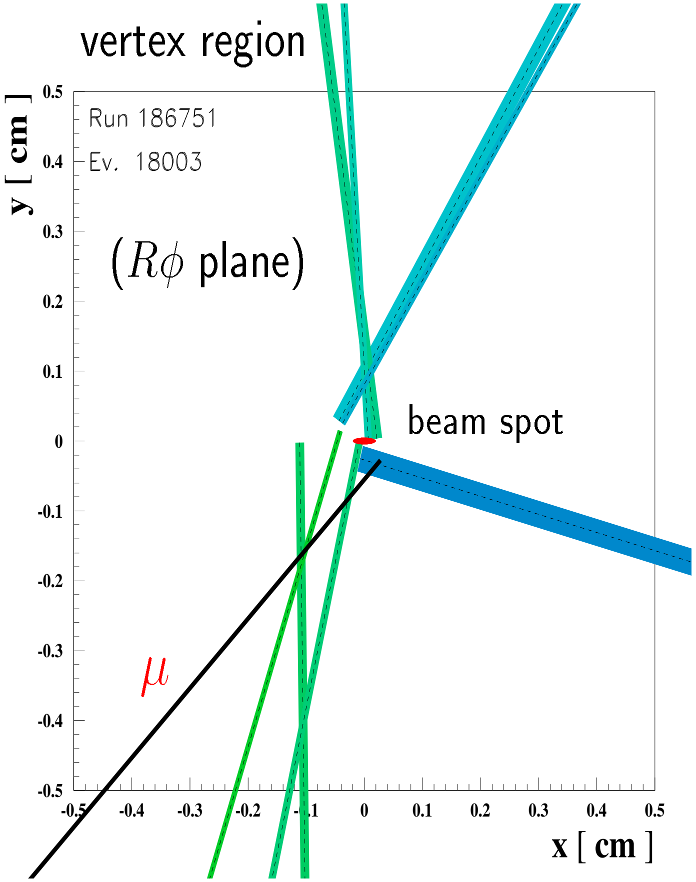
1. Mass

   → rel. transverse momentum p_T^{rel}

2. Lifetime

   → impact parameter δ

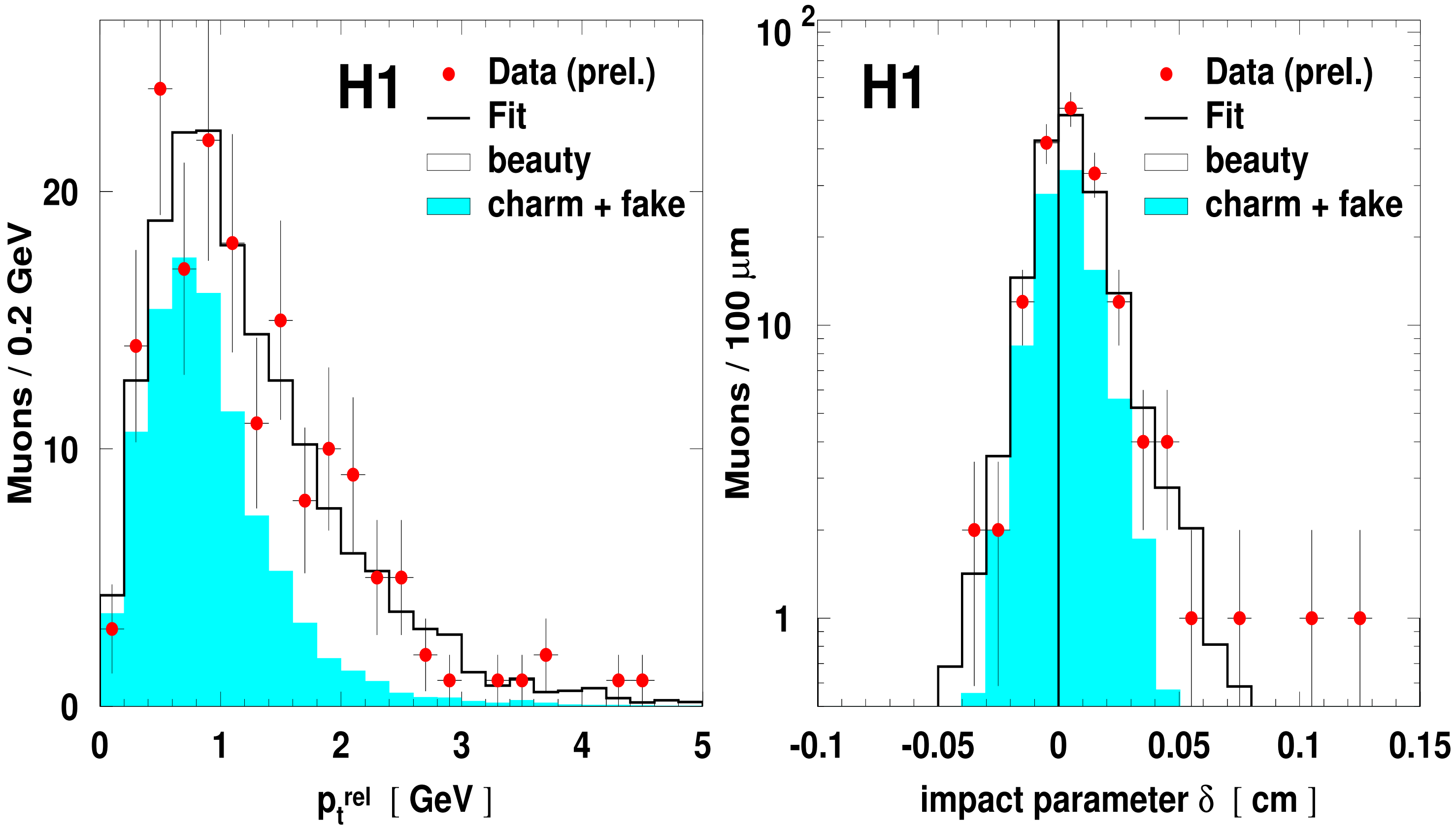




First Measurements of Open Beauty in DIS

Study events with high P_T jets and μ.

$2 < Q^2 < 100$ $\mathbf{GeV}^2$, $0.05 < y < 0.7$



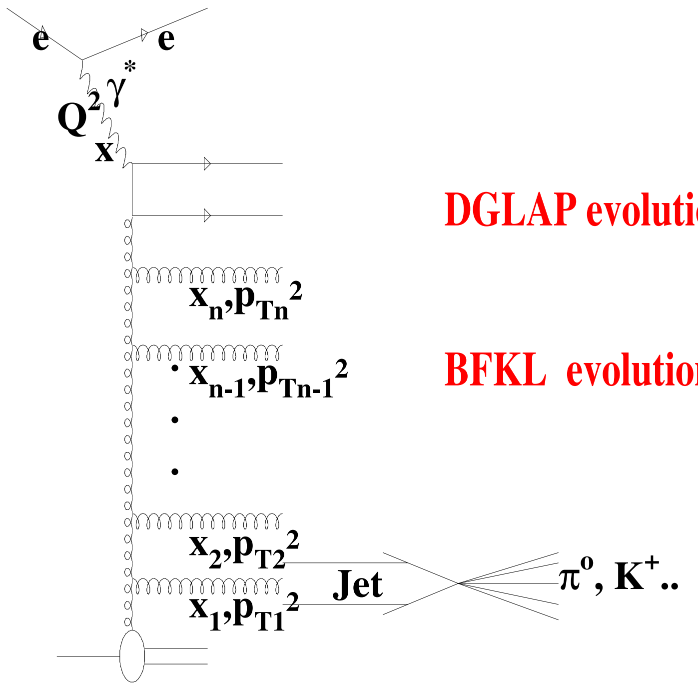
Combined fit to spectra $\rightarrow f_b = (43 \pm 8)\%$

$\sigma_{vis}(ep \rightarrow b\bar{b}eX) = 39 \pm 8 \pm 10$ **pb**

$\sigma_{vis}^{NLO} = 11 \pm 2pb, \sigma_{vis}^{LO} = 9$ **pb**

Forward Particle Production at Low x

Probing the QCD Evolution of Proton Structure



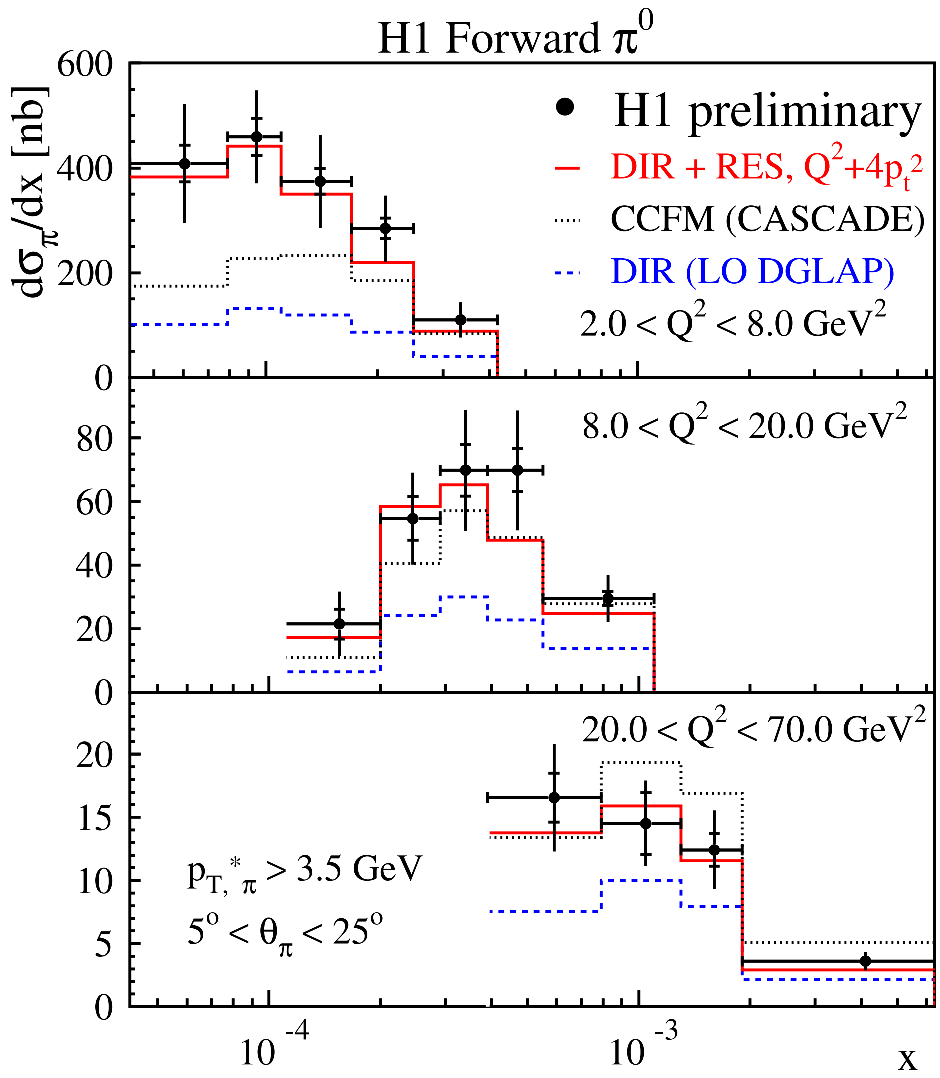
DGLAP evolution strongly orders p_T, $p_{Tp}^2 >> p_{Tp-1}^2$

BFKL evolution has no ordering $p_{Tp}^2 \sim p_{Tp-1}^2$

- **DGLAP and BFKL QCD approximations predict parton "ladder" with different dynamical features.**
- **DGLAP evolution successful at high Q^2 but questionable towards low x.**
- **BFKL should be applicable at low x but never seen.**
- **BFKL predicts more hard parton emissions near the proton.**
- **Look for high momentum particles in the forward (proton) region.**

Forward π^0 Cross-section at Low x

Tag high momentum π^0s next to QCD ladder.



Insufficient QCD radiation from ordered k_T emissions.

Future Prospects

HERA II era now commencing.

Upgraded H1 and ZEUS experiments to receive 150 pb^{-1} per annum.

1. **Extend physics at highest Q^2 (~ 50000 GeV^2) and P_T (~ 100 GeV/c)**
2. **Multi-jet (4-5) rates**
3. **Precision beauty measurements**
4. **α_s from fragmentation functions.**
5. **much more....**

Require theorists to keep pace with experiment!

Summary

HERA opened up the high energy DIS kinematic region.

Precision measurements of proton structure functions and the hadronic final state made.

Perturbative QCD tested

- Competitive measurements of α_s made.
- Exact perturbative QCD calculations to NLO precisely tested.
- High P_T hadron production in the forward region not described by DGLAP evolution.

Next steps in QCD to be made with HERA II.