Les Rencontres de Physique de la Vallée d'Aoste

QCD Studies at HERA

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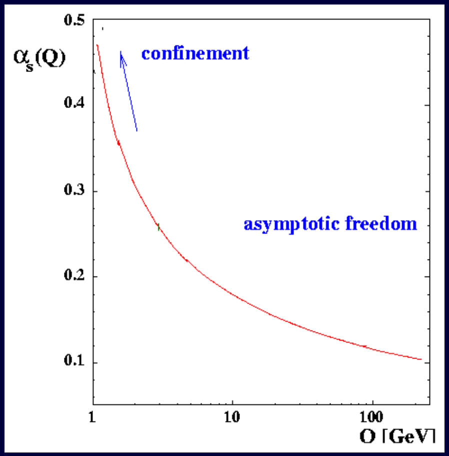
HERA and QCD

- Talk could/should cover >50% of HERA I physics!
- Have to be selective

QCD Prejudices

- Nice theory
- Hard to be precise!
- Quarks produced, but hadrons seen



- Experiments
  – Data has few % accuracy for a number of measurements
- NLO QCD
  – Theory getting to same level in some regions
  – Boldly going to places where no theory has gone before!
  – Factorisation and renormalisation scale uncertainties?
- NNLO QCD
  – First calculations coming
  – We want more!

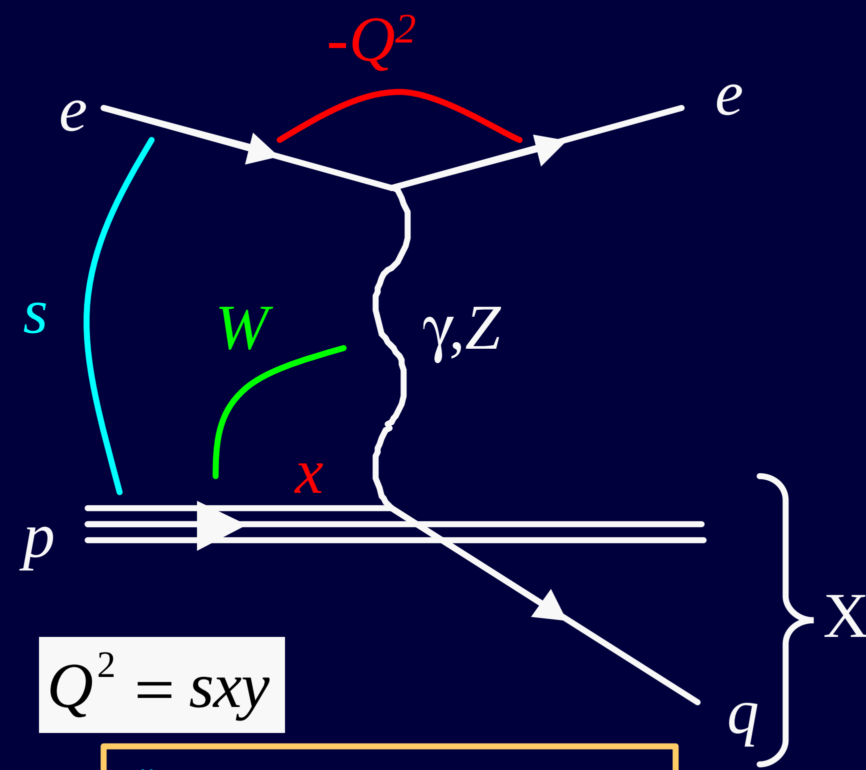
Topics

- Parton Density Functions
  - F_2 , F_L and $xg(x)$
- Determination of α_s
  - From PDFs
  - High E_T inclusive jets and dijets
  - Jet substructure
- 3 jet production
- Dijets in photoproduction
  - Direct vs. resolved photons
  - Comparison with NLO QCD predictions
- Data vs. theory at highest Q^2
- Heavy flavour production

HERA Kinematics

- Lots of interdependent variables used!
- s: e-p c.m. energy
- $Q^2 = -q^2$: 4-momentum transfer squared
- x: fraction of proton momentum carried by quark
- y: inelasticity parameter
- W: γ-p c.m. energy

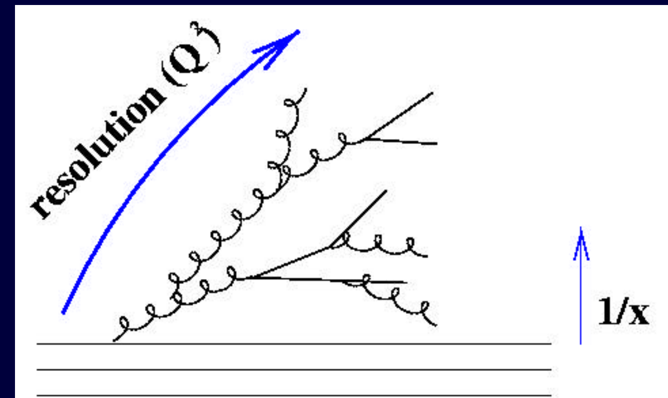
Lowest order diagram



$$Q^2 = sxy$$

$$\sqrt{s} = 300 - 318 \text{ GeV}$$

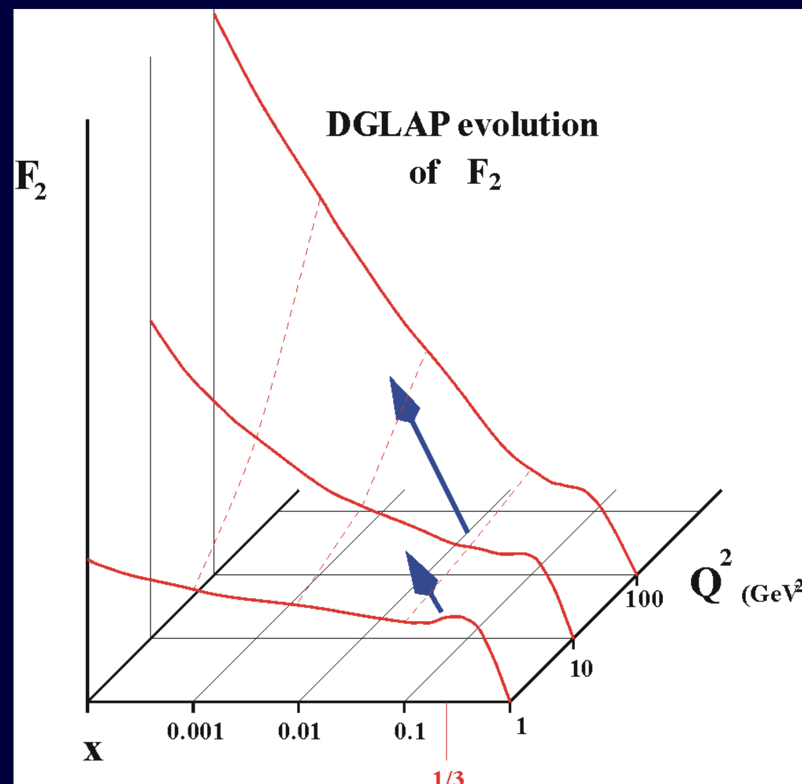
QCD and PDFs



- Factorise cross section into short range ⊗ PDFs

s_{DIS} □ $f_p(x) \otimes \hat{s}$

- Use DGLAP to evolve parton density functions
- Experimental data has to constrain input at Q_0^2

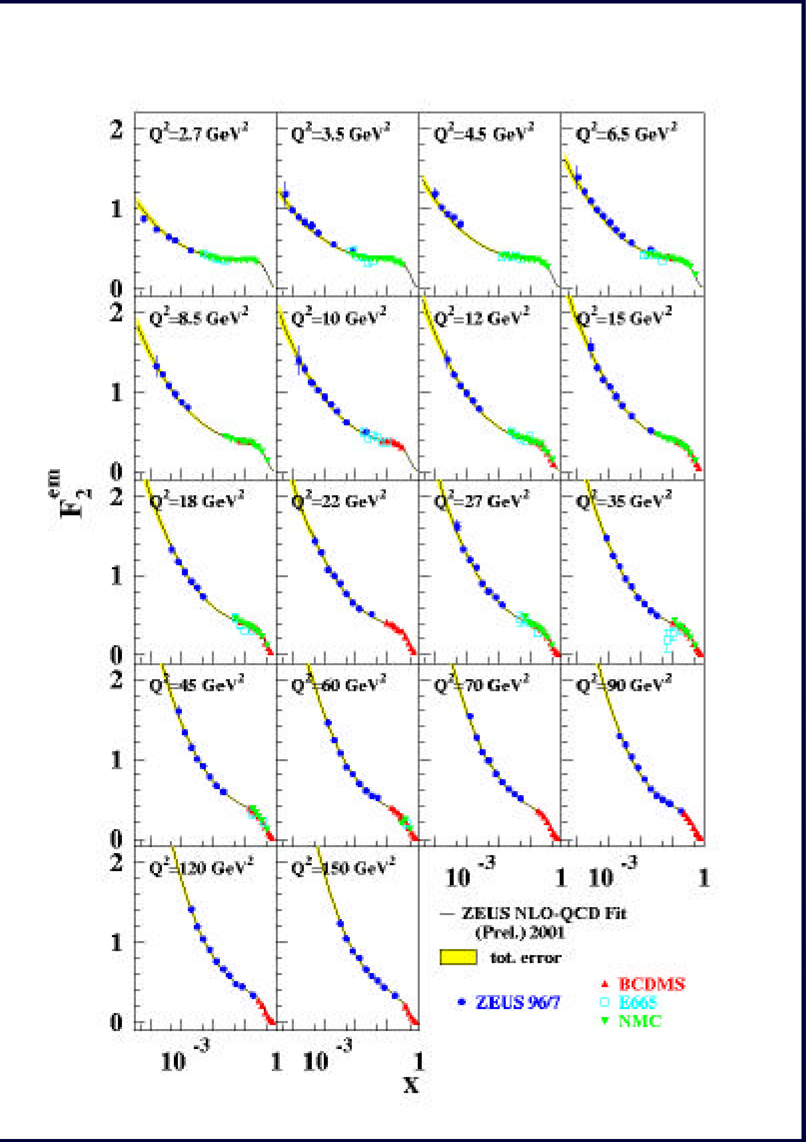


F_2 Results

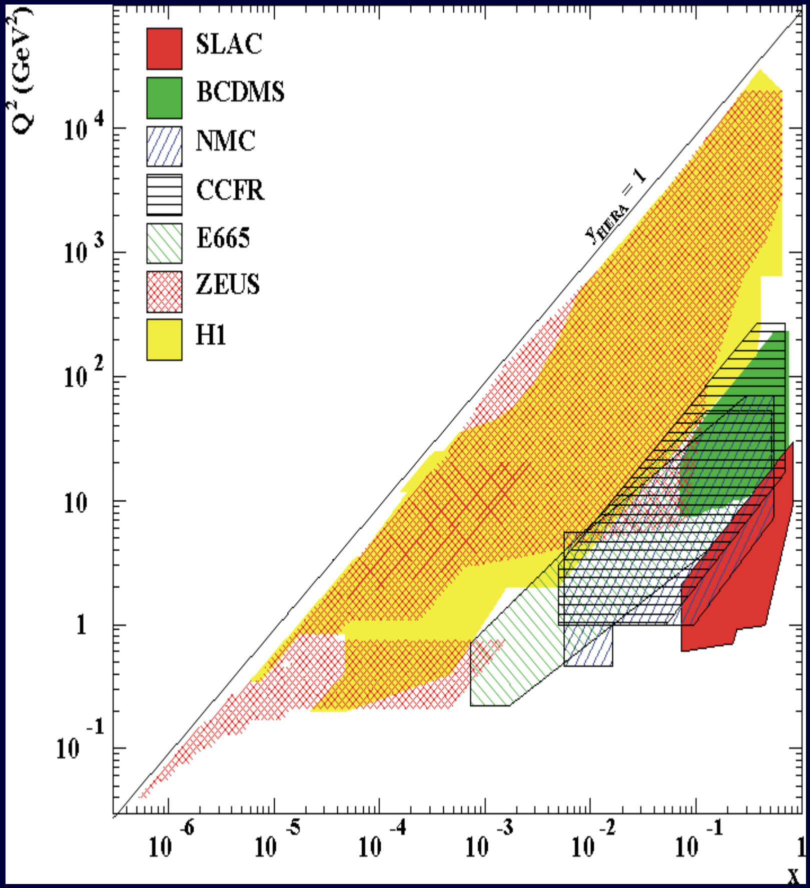
$$\frac{d^2 s}{dx\,dQ^2} = \frac{2pa^2}{xQ^4}\left(Y_+ F_2 - y^2 F_L \pm Y_- xF_3\right)$$

$$y = Q^2/xs \qquad Y_\pm = \left(1 \pm (1-y)^2\right)$$

- Structure functions:
  - F_2
  - F_L: longitudinal component
  - xF_3: small for $Q^2 \ll M_Z^2$



Fit of PDFs



- Fit HERA data on F_2
- Include best fixed target data
- Have to parametrise PDFs

$$f = p_1 x^{p_2} (1-x)^{p_3} (1 + p_4 \sqrt{x} + p_5 x)$$

- Do fits with fixed and free a_s

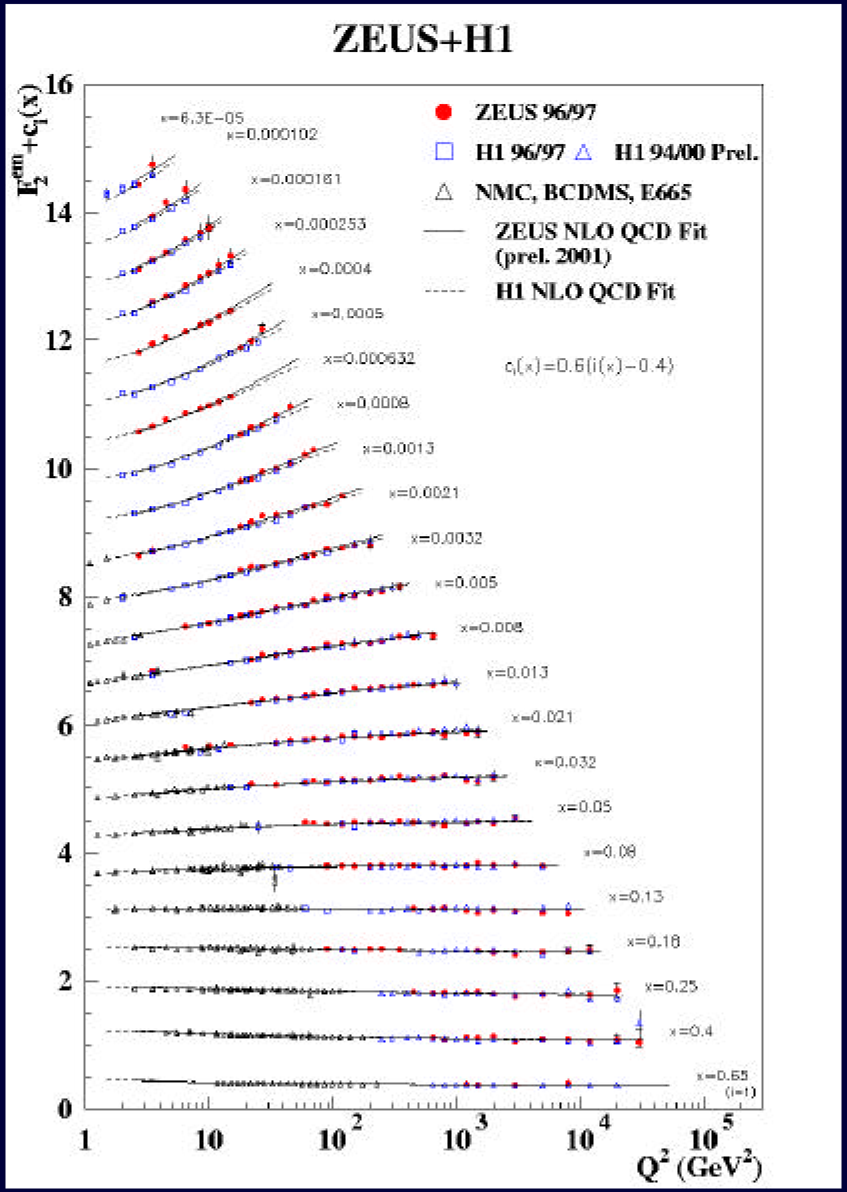
ZEUS and H1 Fits

- ZEUS
  - ZEUS + BCDMS, E665, NMC
  - Start at $Q_0^2 = 7\,\mathrm{GeV}^2$
  - $p_4 = 0$ plus additional constraints
  - Heavy quarks: RT variable flavour number scheme
- H1
  - H1 + BCDMS
  - Start at $Q_0^2 = 4\,\mathrm{GeV}^2$
  - $p_4 = 0$ for the gluon
  - Heavy quarks: Fixed flavour number scheme

NLO DGLAP equations used

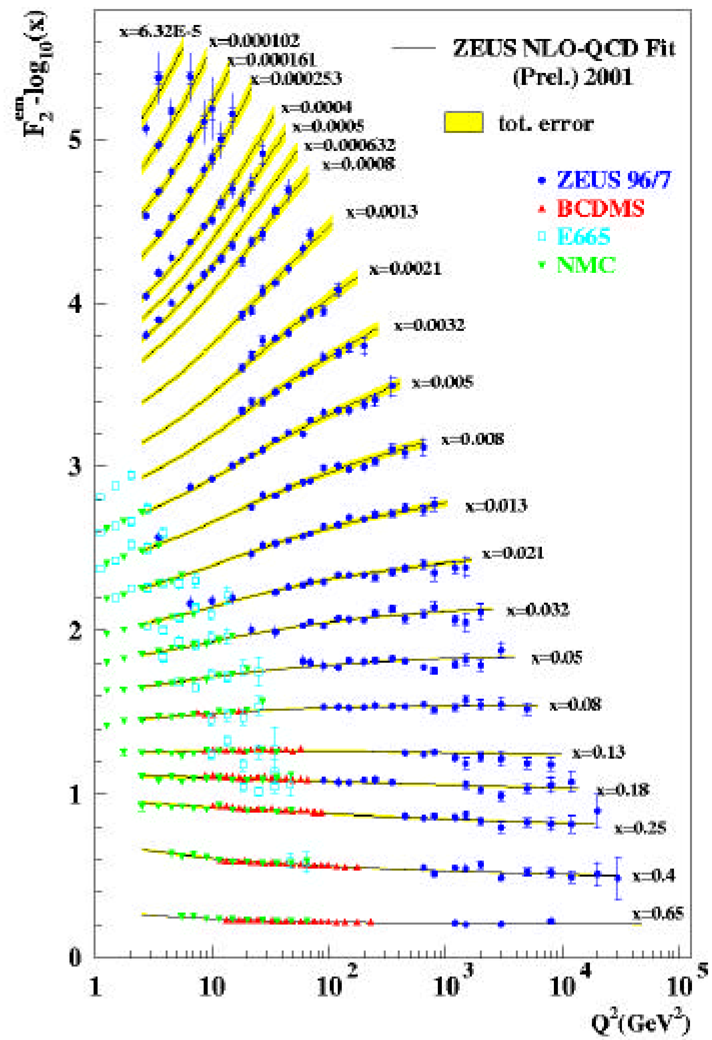
HERA Fits

- Over very large range ZEUS and H1 data and fits agree very well
- Some differences at small x
- Limited statistics at large Q^2



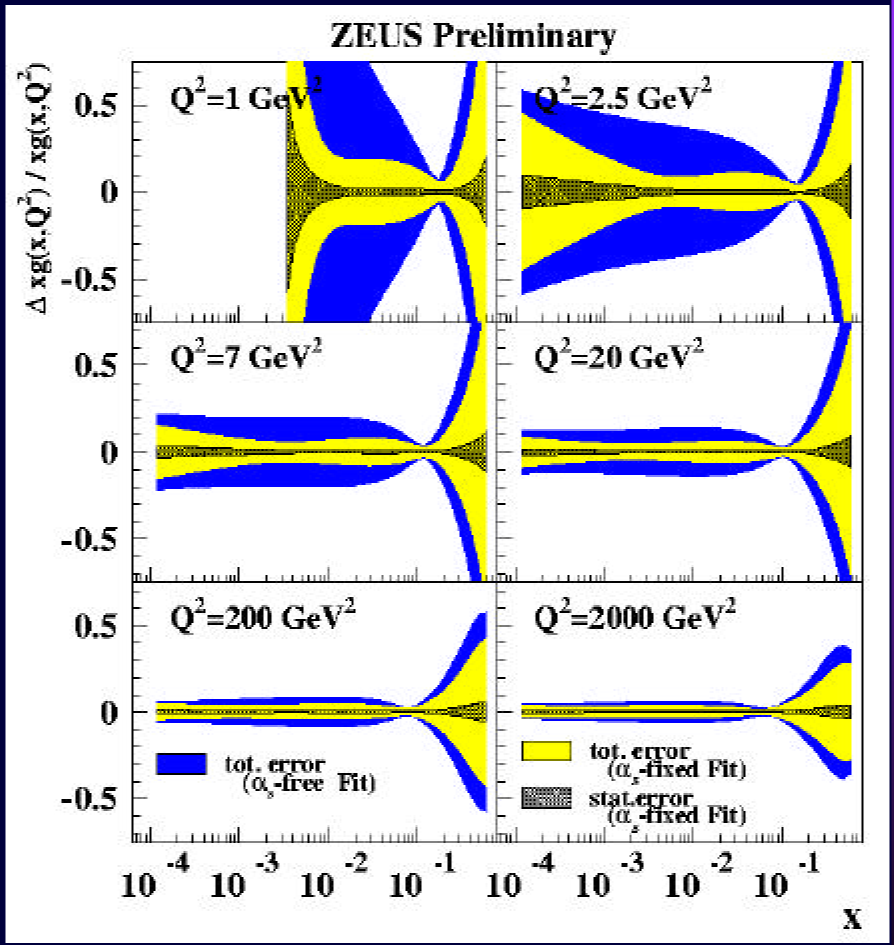
Errors on PDFs

- Fits now calculate errors on PDFs
- Correlations between experimental errors taken into account
- Low x and high Q^2 regions have largest errors



H1 and ZEUS Gluon Density

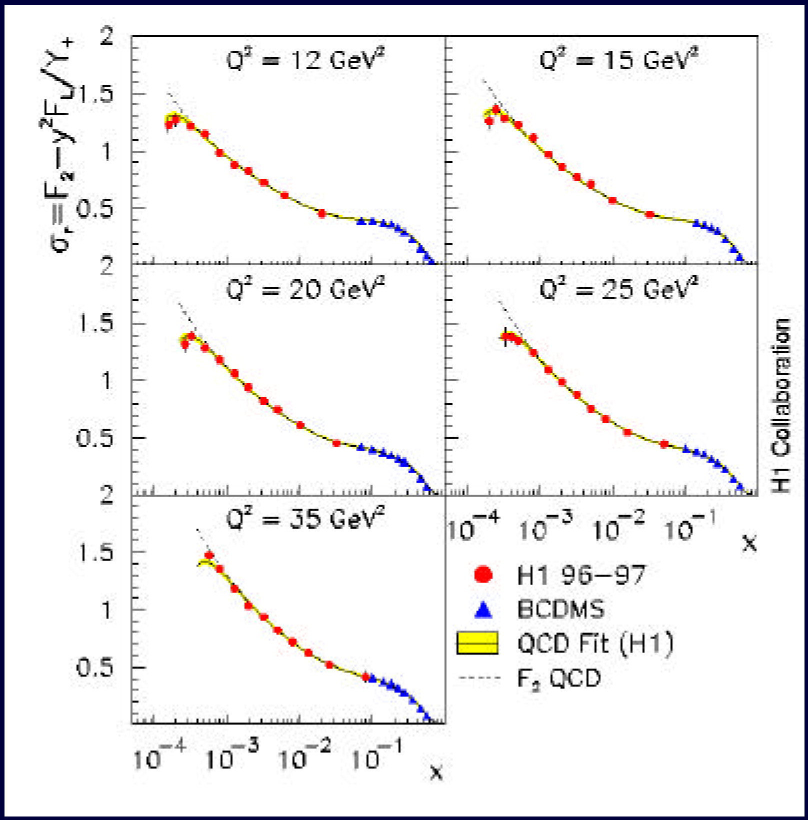
- Fit of gluon distribution
- See evolution of gluon density as a function of Q^2
- Can overlay H1 and ZEUS distributions
- General agreement – differences probably due to:
  - heavy flavour scheme
  - *xg(x)* parameterisation
- a_S correlation clearly visible in error on *xg(x)*



$$\frac{Q^4 x}{2\pi\alpha^2 Y_+} \cdot \frac{d^2\sigma}{dx\,dQ^2} = \sigma_r = F_2 - \frac{y^2}{Y_+} F_L$$

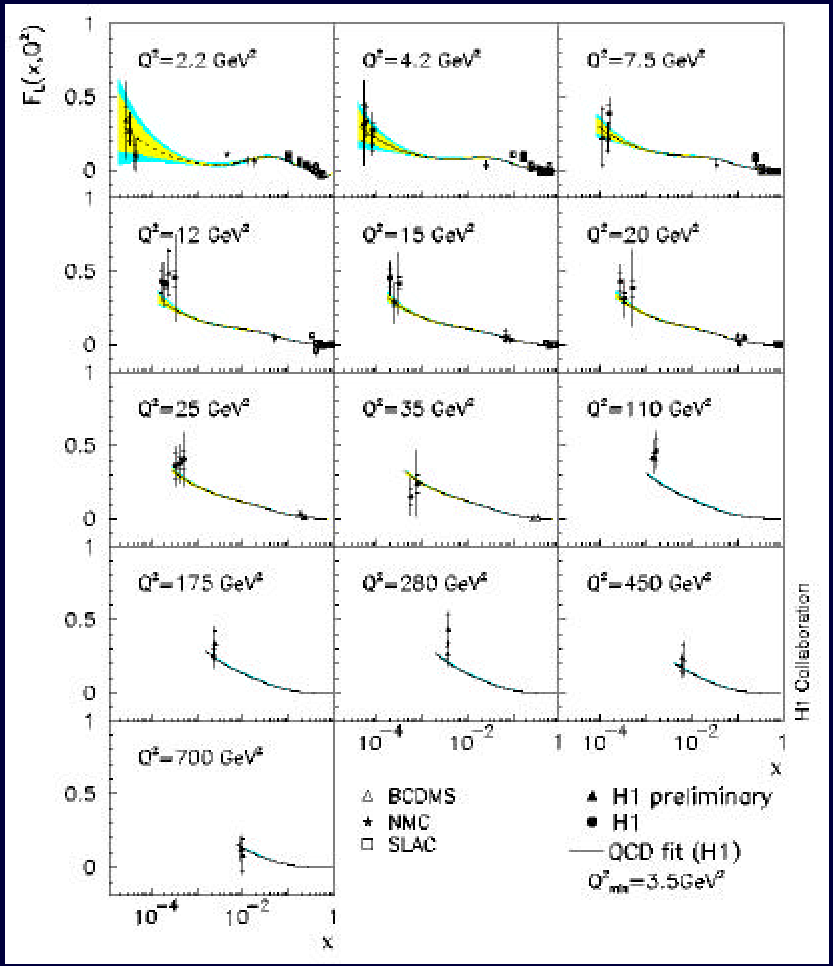
F_L Results

- Really need different s
  $Q^2 = sxy$
- ZEUS used ISR events
- H1 measure σ_r; use F_2 from lower y to predict value at high y (low x)
  - DGLAP gives very consistent picture
  - Works best at higher Q^2



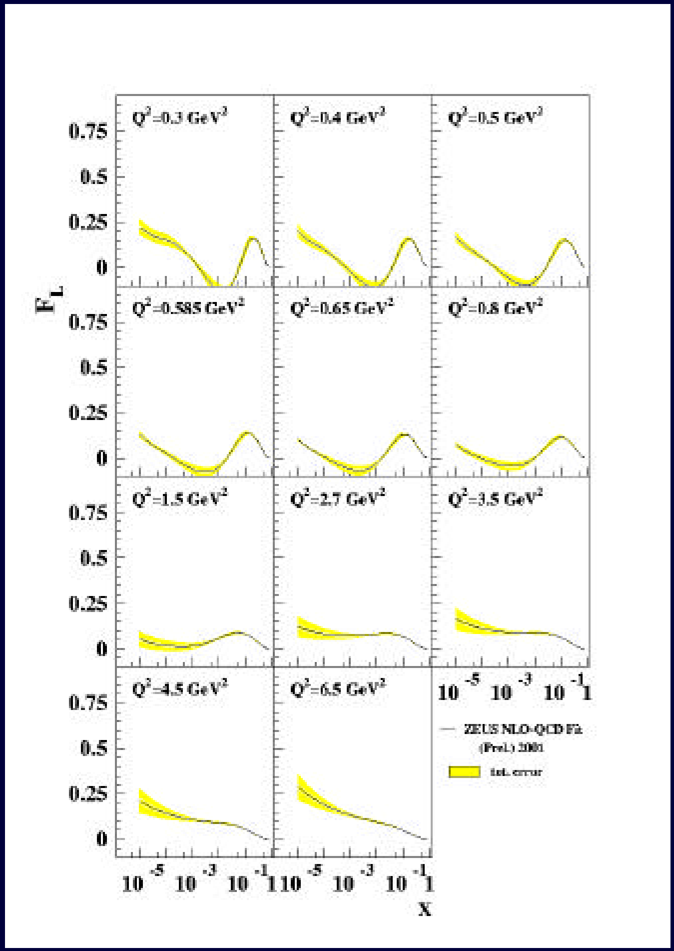
F_L using derivative

- Can also use $\partial s / \partial \ln y$
  - Works best at low Q^2
  - F_2 and F_L contributions similar
- Plot $\partial s / \partial \ln y$ as a function of y for different Q^2 ranges



Lower Limit of pQCD

- Use PDF fits and DGLAP evolution
- See that QCD description only fails below about 0.8 GeV^2
- Same effect seen in F_L determination - value physical for $Q^2 > 0.8$ GeV^2

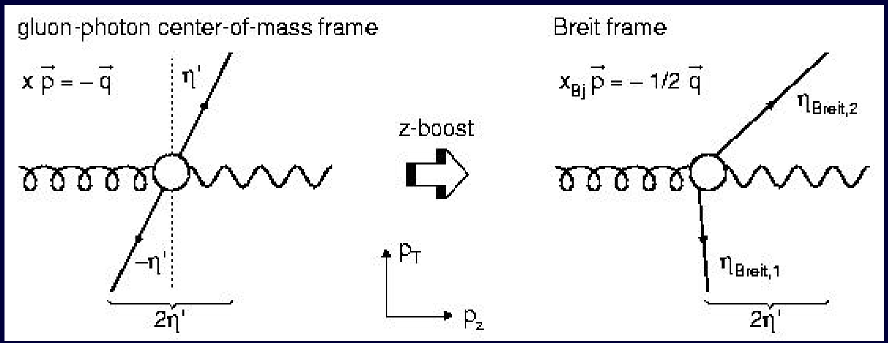


Measurements with Jets

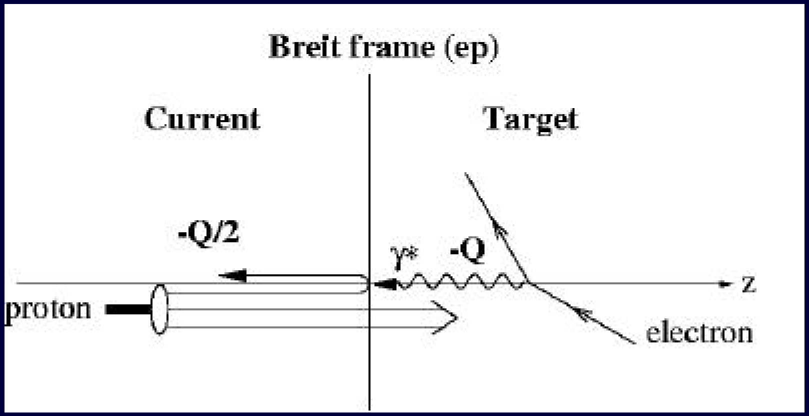
- Often made in Breit frame
- Breit frame defined as

$$2x\vec{p} + \vec{q} = 0$$

- Related to γ-p c.m. by a longitudinal boost



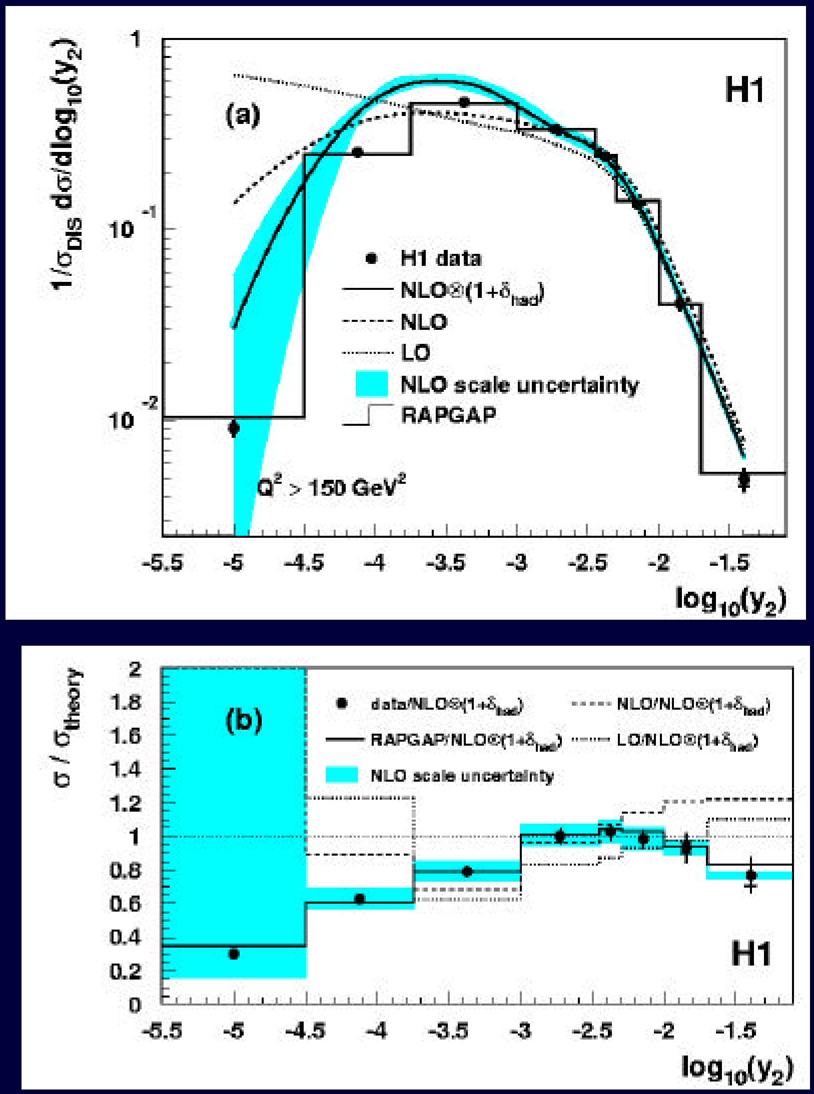
Single jets have no transverse energy



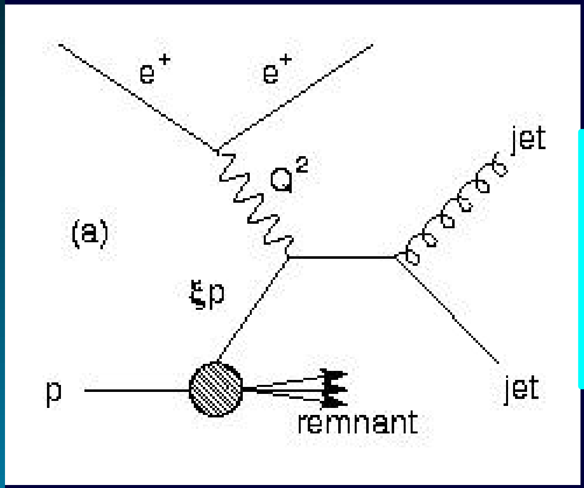
Current jet can be compared with e^+e^- jets

Jets in PQCD

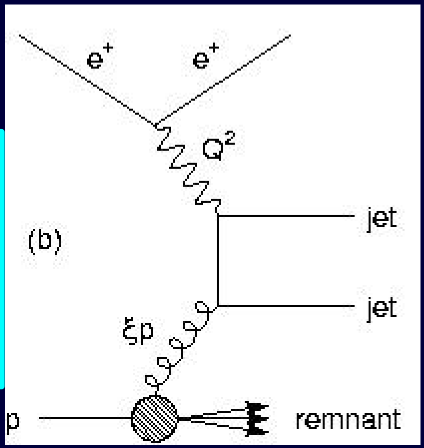
- Use typical clustering algorithms to define jets
- How far can one lower y_{cut} and still describe jets with pQCD?
- Surprisingly far – 30% of events in DIS can be classified as having 2 or more jets with $y_{\mathrm{cut}} \sim 0.001$



Jets in Breit frame – H1 and ZEUS



QCDC: Dominates at high Q^2



BGF: Dominates at low Q^2

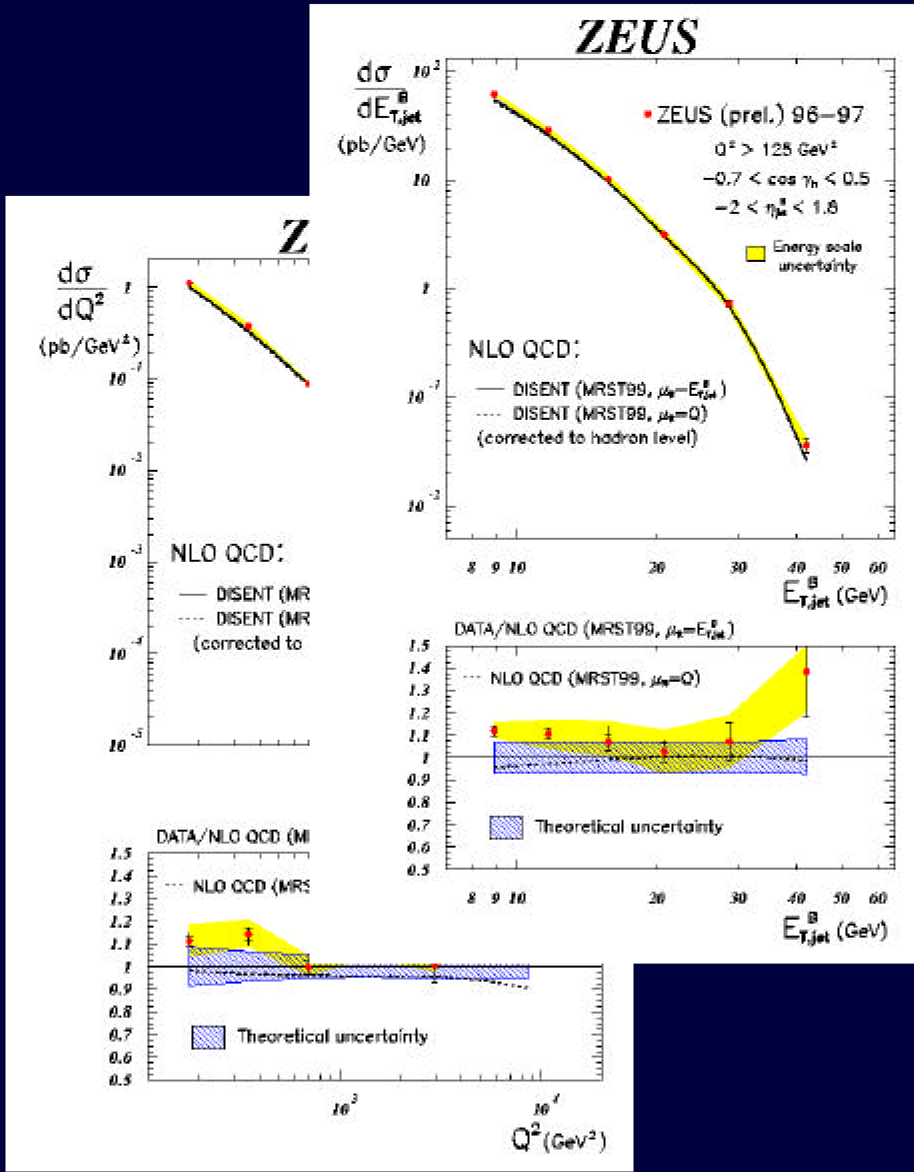
- Jets with significant E_T usually produced via QCD Compton or boson-gluon fusion process.
- Production rate clearly depends on α_S, but data mostly sensitive to

$$\alpha_S \cdot xg(x)$$

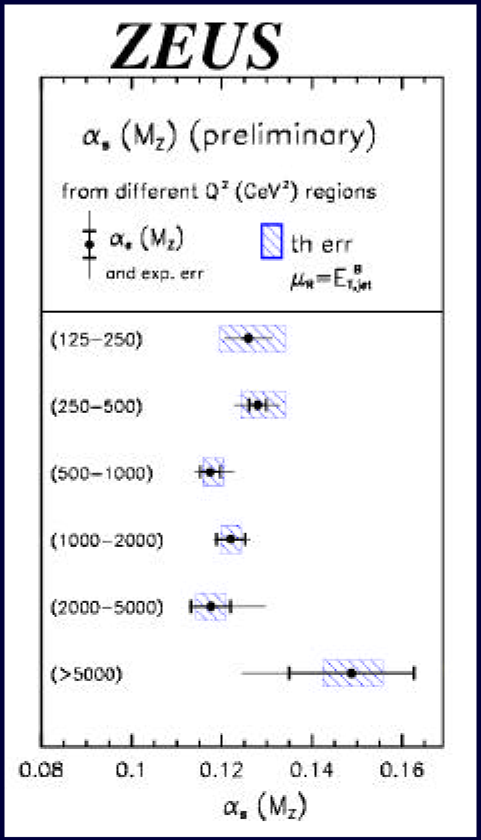
- Breit frame provides good separation from proton remnant

Jet Cross Section

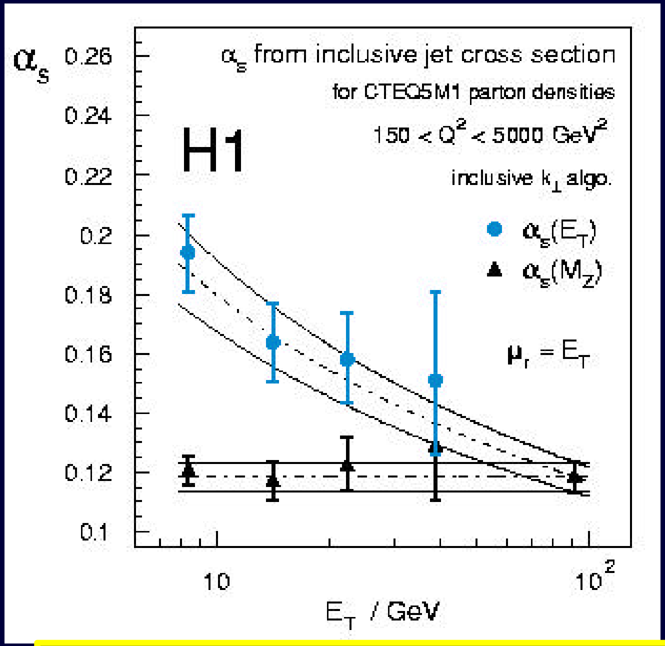
- Select DIS events with high E_T jets
- Compare inclusive jet cross sections with NLO QCD prediction
- 2 scales: Q^2 & E_T
- Good agreement seen
- How much should scale be varied?
  A factor of 2?



Inclusive Jet Cross Sections



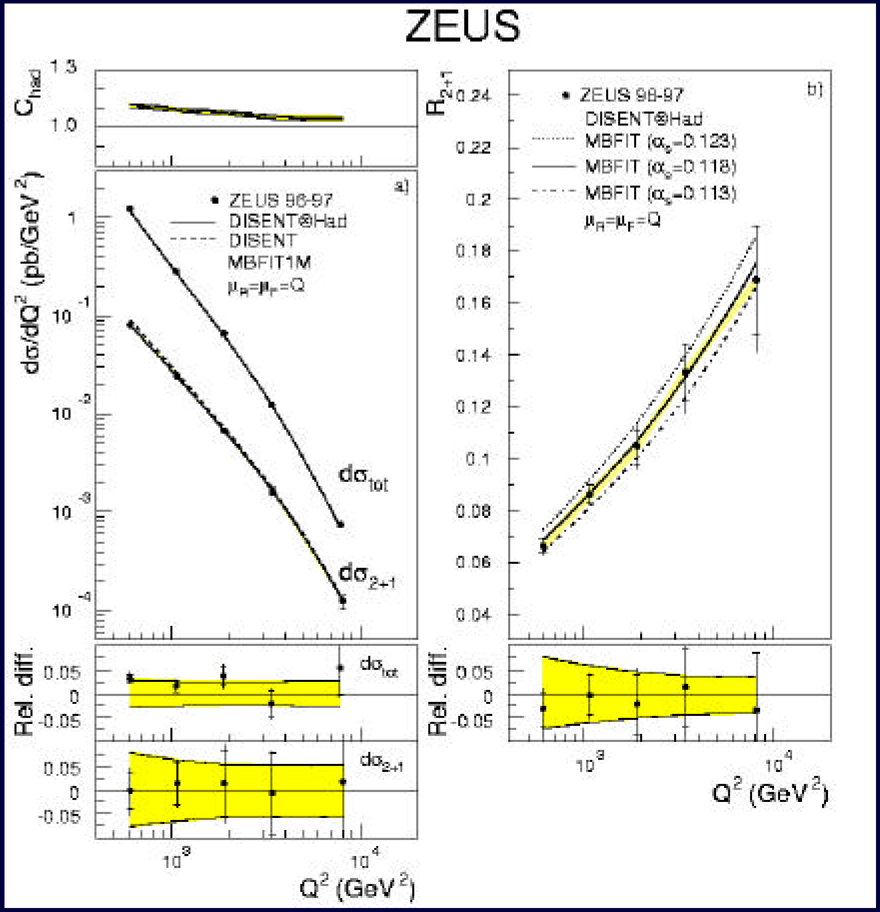
- Can determine α_S in different $E_{T,jet}$ regions or as a function of E_T
- Extraction reliable for $Q^2 > 500$ GeV^2 or $E_T > 15$ GeV
- Running seen in a single experiment



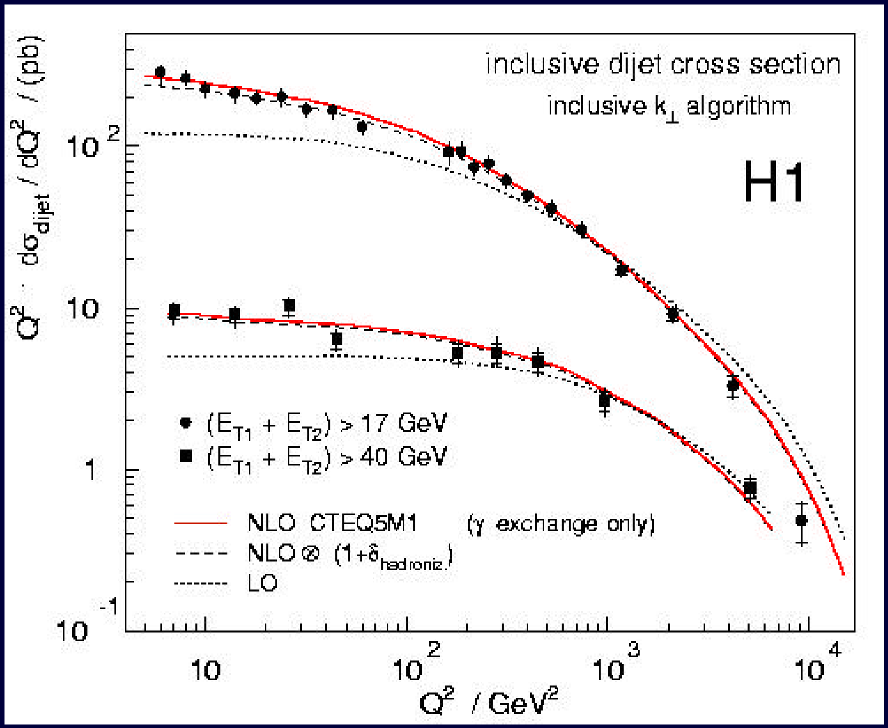
Theory error ~5% due to renormalisation and factorisation scale uncertainty

ZEUS Dijet Cross Sections

- Cross section for single and dijet production
- Ratio of dijet to single jet cross section proportional to α_s



H1 Dijet Cross Sections

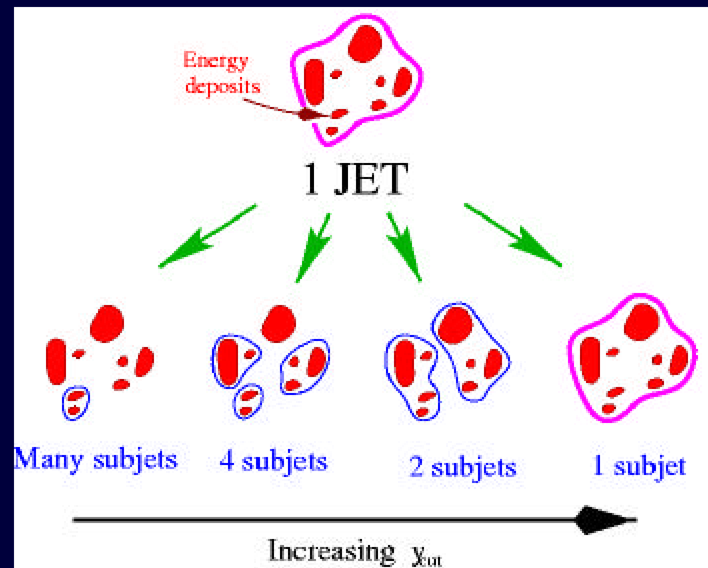


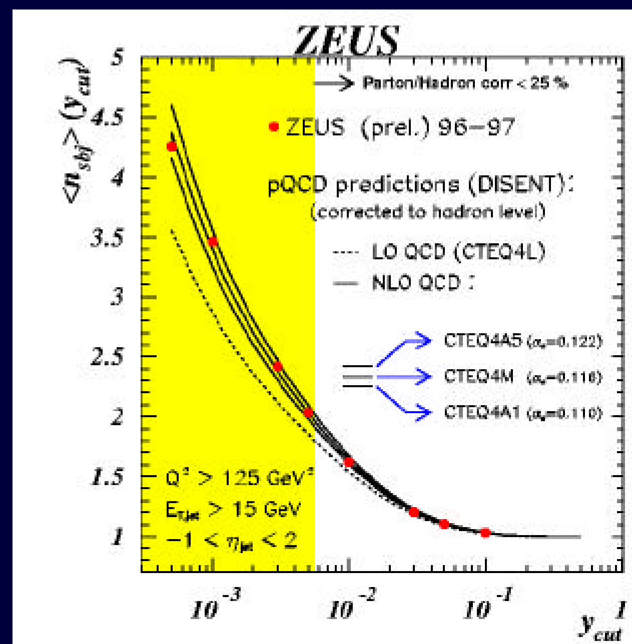
- Dijet cross section with different E_T cuts
- Different jet algorithms compared at high Q^2
- NLO is clearly needed
- a_S extraction uses

$$150 \leq Q^2 \leq 5000 \text{GeV}^2$$

Jet Substructure - ZEUS

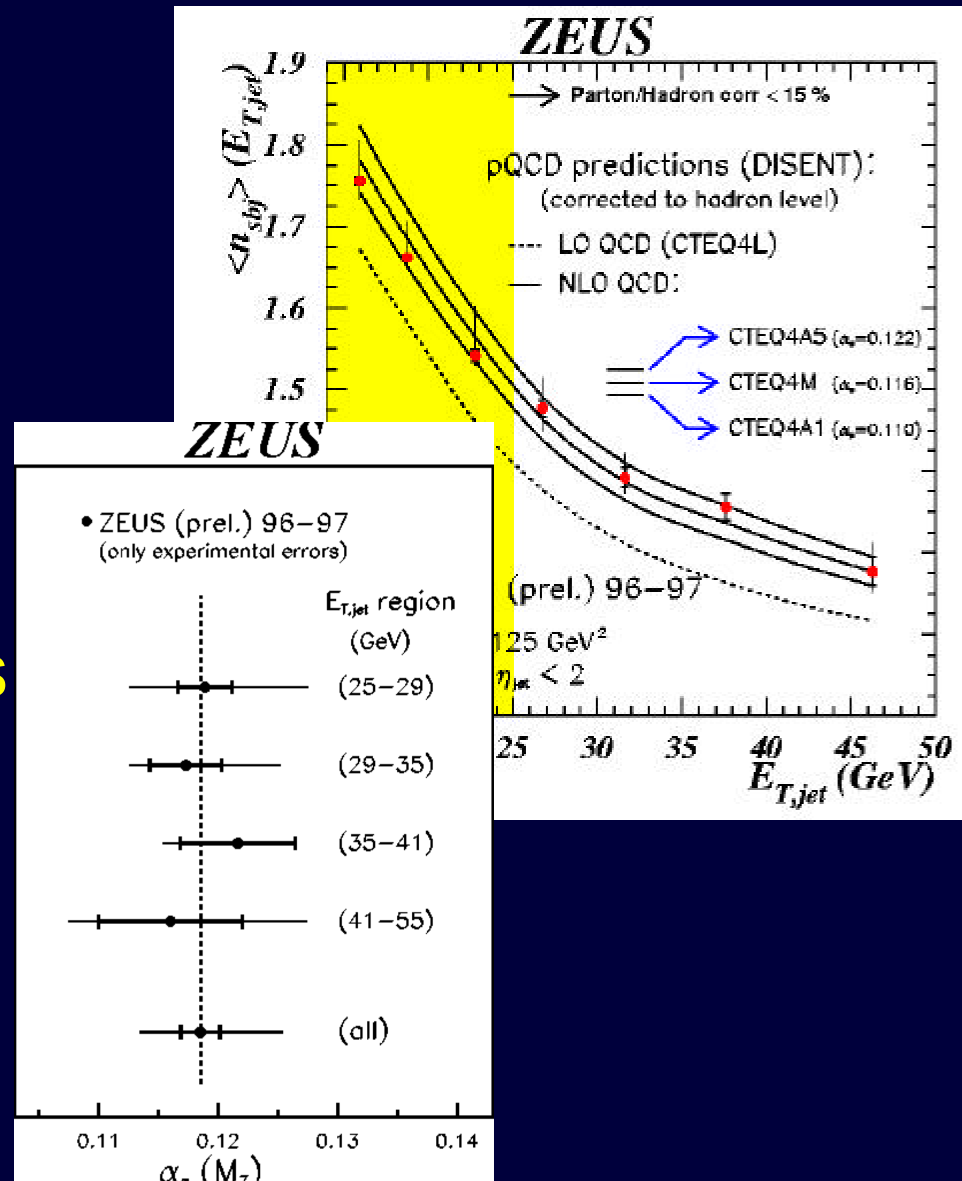
- Look for jet-like components inside a jet
- Find jets in lab system to keep large single jet sample
- Subjets calculated in NLO
- Pick a region where parton/hadron corrections are < 15%





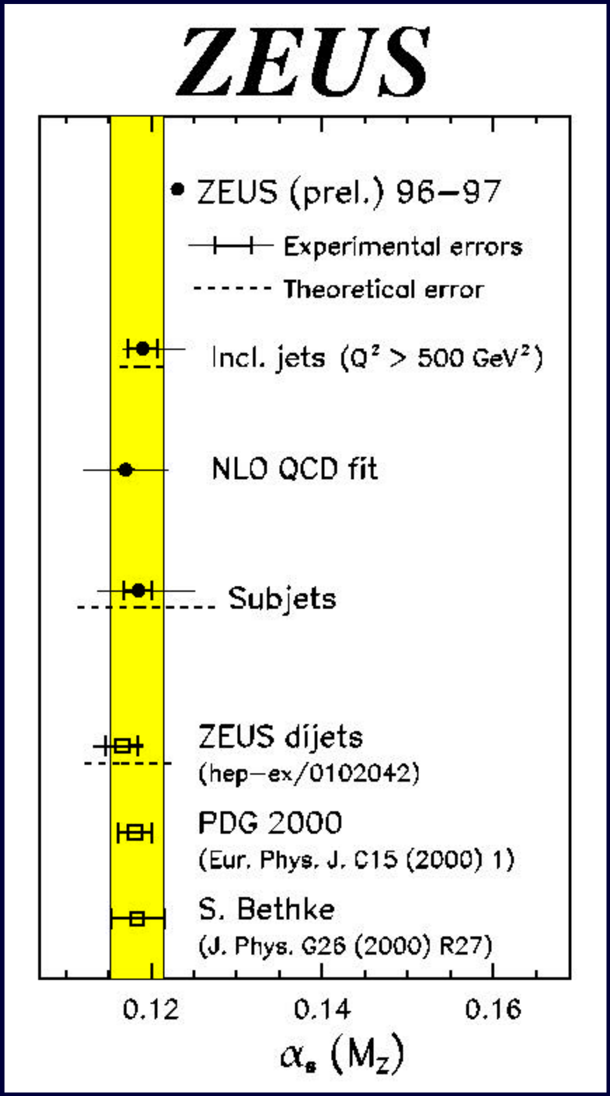
Jet Substructure

- Measurements are sensitive to α_S
- α_S values are consistent in different E_T regions
- Systematic errors mainly from factorisation and renormalisation scale uncertainty



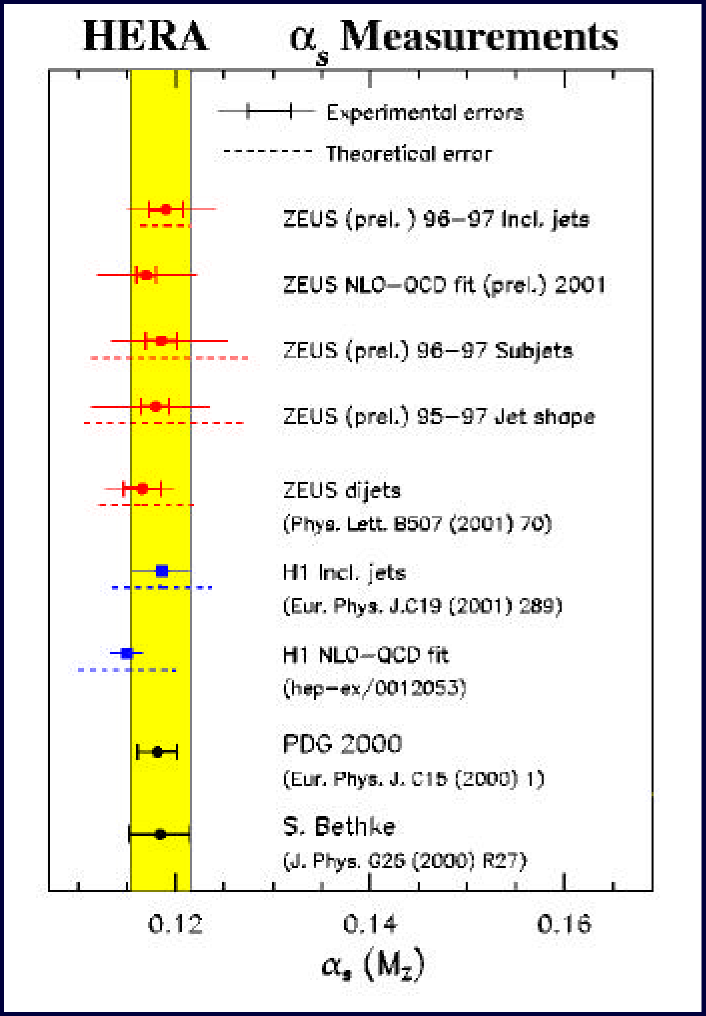
ZEUS α_s Summary

- Comparison of different ZEUS measurements shows good agreement between them all
- In jet measurements theory error dominates
- Needs theoretical input on scale uncertainty (NNLO calculations)



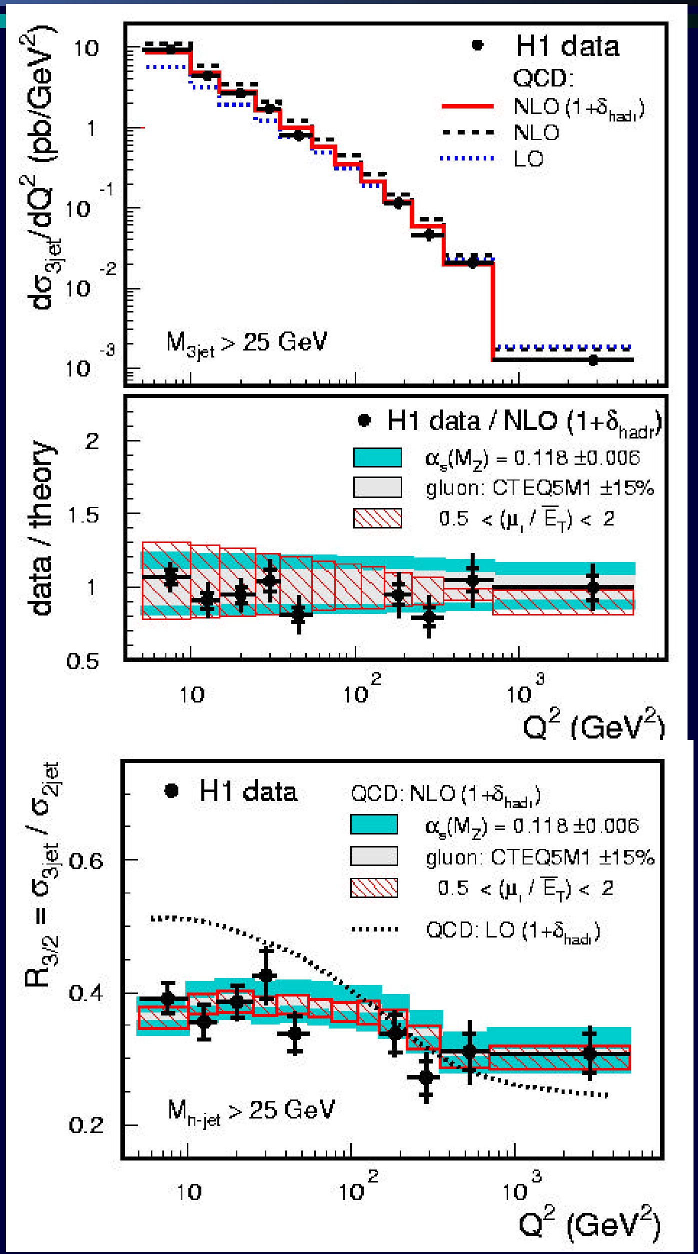
Compare with PDG and Bethke world average

- Good agreement
- HERA results are competitive
- Running of α_s seen in single experiment
- Influence on world average depends on reducing theoretical uncertainties



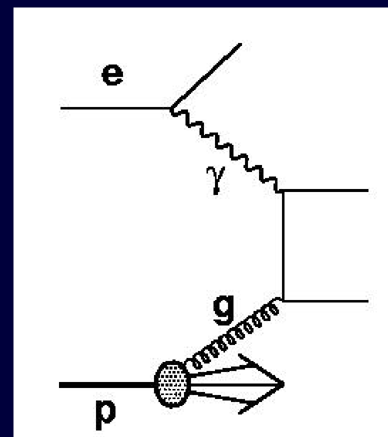
Three Jets – H1

- Look at 3 jet cross section as a number of variables
- Cross section is proportional to a_S^2 in lowest order
- Again well described by NLO calculations

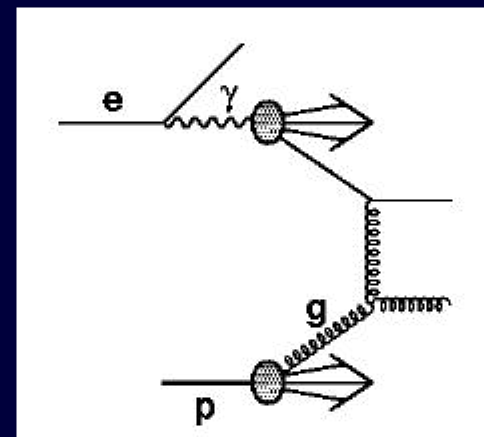


Dijets in Photoproduction

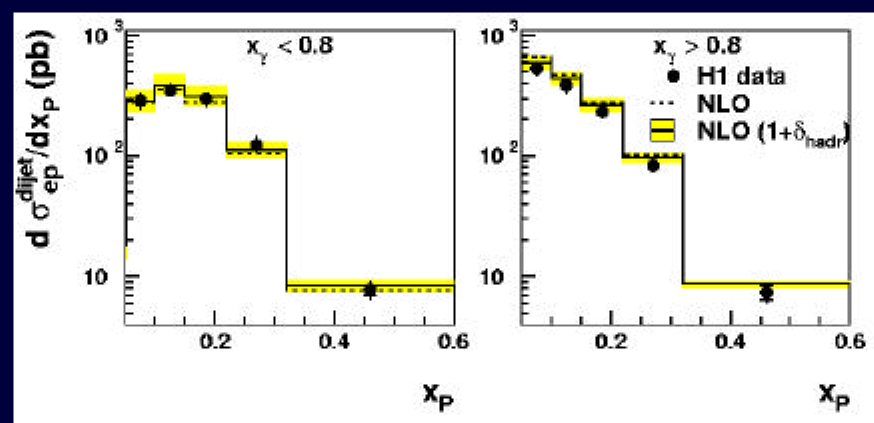
- Select events with 2 high E_T jets
- Measure cross section as a function of:
  - E_T
  - x_g
  - x_p
- NLO clearly needed especially at high x_g



direct

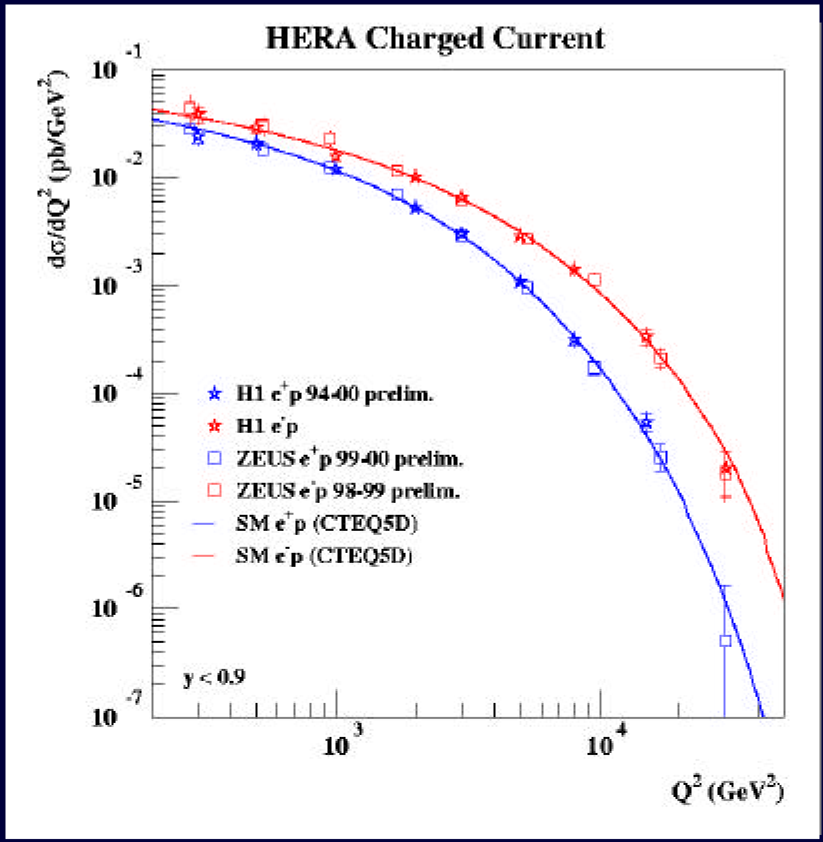


resolved



High Q^2

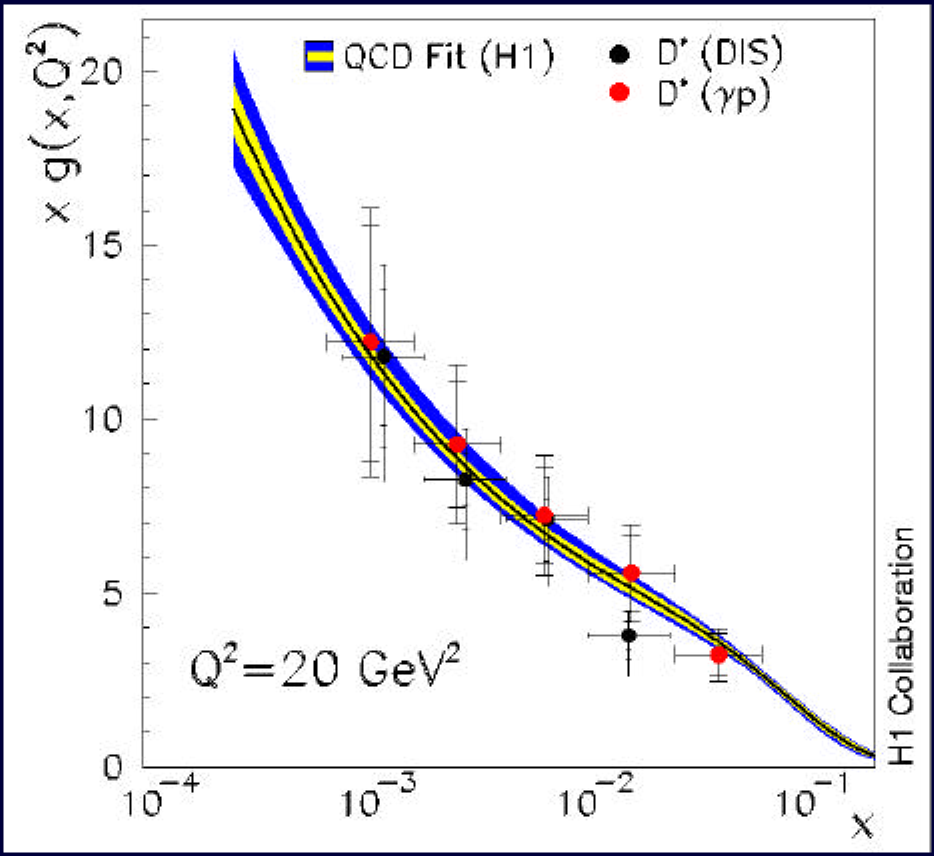
- Clearly see effect of W/Z exchange in cross section
- Newest HERA data extend kinematic range – good agreement with expectation seen
- QCD + EW effects completely explain data
- More statistics + longitudinal lepton polarisation coming with HERA II



Charm and Gluons

Quark mass provides hard scale

- Boson-gluon fusion is main production mechanism
- Charm production directly proportional to gluon content
- With current statistics PDF fits still do a better job



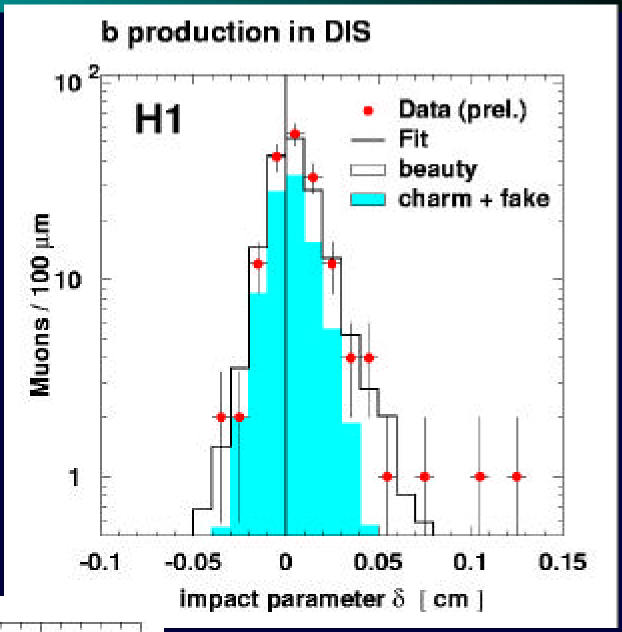
b Quarks at HERA

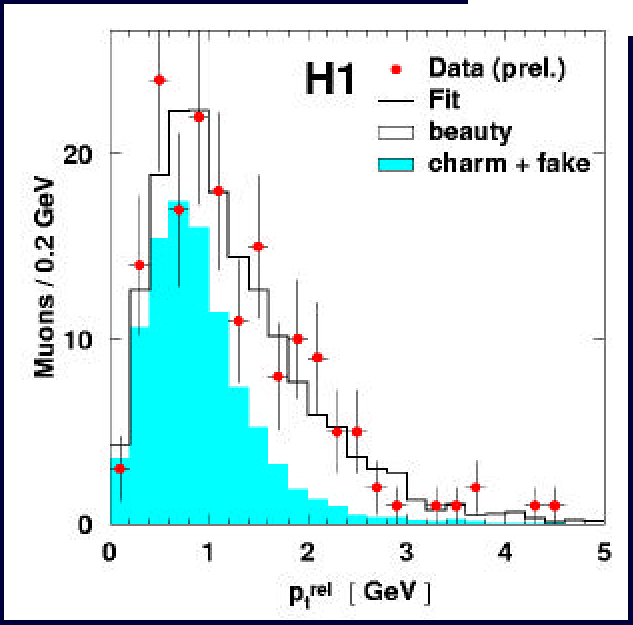
- *c* quark production cross section in marginal agreement with expectations
- *b* quark production 2 to 3 orders of magnitude smaller than *c* (c.f. LEP)
- Should be calculable in pQCD, *b* should be better than *c* as scale is harder

- Use semileptonic muon decay mode to identify *b*'s
  - ZEUS also uses electrons
- H1 can use silicon microvertex detector as well

H1 Results

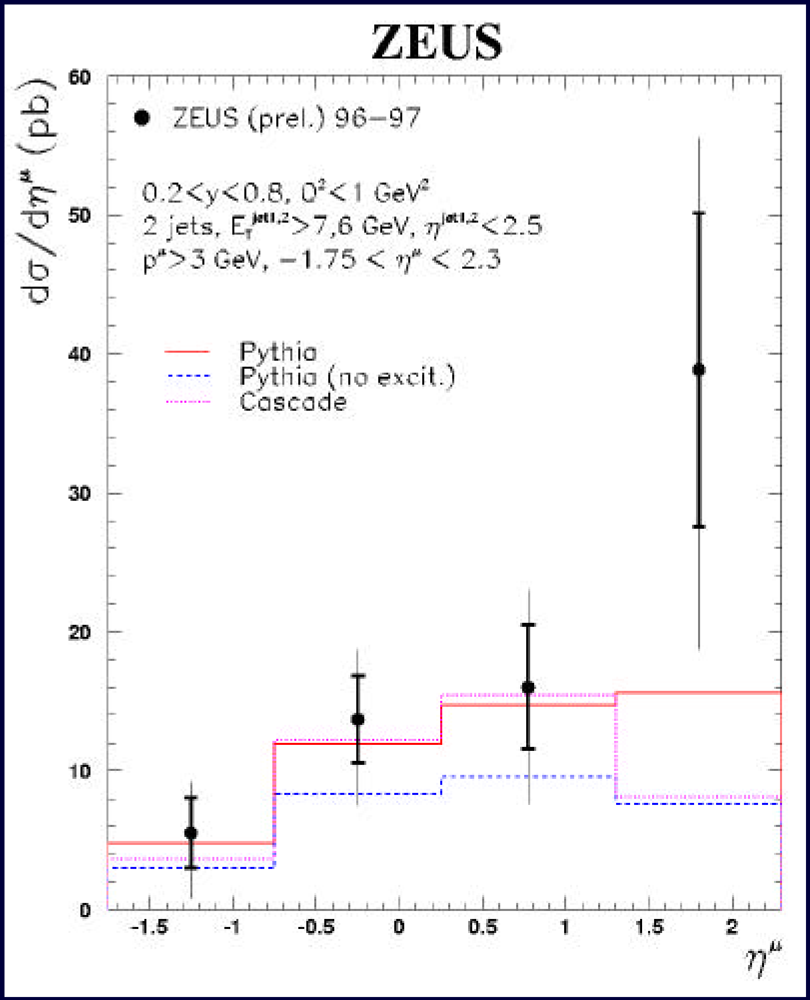
- Combine muon tag with impact parameter
- S/B about 1:1
- Clear b signal





HF in Photoproduction + DIS

- Signal seen in photoproduction and DIS
- Ratio of data to expectation about a factor of 2 too high!
- 2-3 σ effect
- ZEUS result is consistent
- Smaller discrepancy if *b* excitation included
- Really need HERA II + microvertex detectors



Conclusions

- HERA data provides many precise tests of pQCD
- NLO QCD reaches places that no other theory can reach!
- NLO predictions show remarkably good agreement with measurements over a huge kinematic range
- Errors due to scale uncertainties often dominate
- NNLO calculations needed
- Different α_s results are precise and agree well with each other and world average
- *b* quark production cross section is still a problem
- Heavy quark results will benefit from HERA II lumi and microvertex detectors
- HERA II programme with 5x lumi + polarised lepton beams getting underway
- 1 fb^{-1} per experiment by 2006

α_s – the numbers

ZEUS incl. jets	$0.1190 \pm 0.0017(\text{stat})^{+0.0049}_{-0.0023}(\text{exp})^{+0.0026}_{-0.0026}(\text{th})$
ZEUS NLO fit	$0.1172 \pm 0.0008(\text{stat}) \pm 0.0054(\text{syst})$
ZEUS Subjets	$0.1185 \pm 0.0016(\text{stat})^{+0.0067}_{-0.0048}(\text{exp})^{+0.0089}_{-0.0071}(\text{th})$
ZEUS Jet shape	$0.1179 \pm 0.0014(\text{stat})^{+0.0054}_{-0.0065}(\text{exp})^{+0.0094}_{-0.0073}(\text{th})$
ZEUS dijets	$0.1166 \pm 0.0019(\text{stat})^{+0.0024}_{-0.0033}(\text{exp})^{+0.0057}_{-0.0044}(\text{th})$
H1 incl. Jets	$0.1186 \pm 0.0030(\text{exp})^{+0.0039}_{-0.0045}(\text{th})$
H1 NLO-QCD fit	$0.1150 \pm 0.0017(\text{exp})^{+0.0009}_{-0.0005}(\text{model}) \pm 0.005(\text{scale})$
PDG 2000	0.1181 ± 0.002
Bethke	0.1184 ± 0.0031