



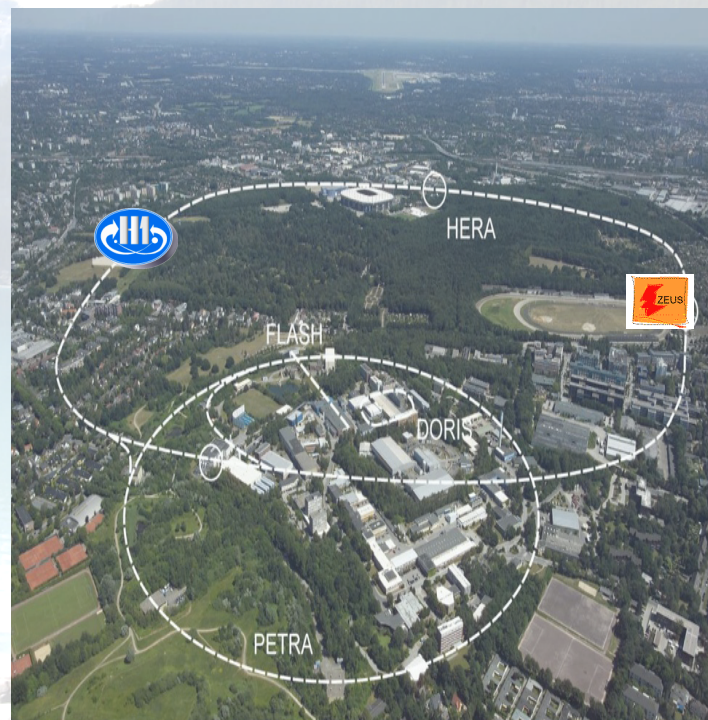
Precision Tests of QCD Using Final State Jets and Particles

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on behalf of the H1 and ZEUS Collaborations

- Inclusive Jets in DIS at Low and High Q^2 .
- Extraction of α_s .
- Hadronic Final State Charge Asymmetry.



Lake Louise Winter Institute
15th-20th February 2010, Alberta, Canada

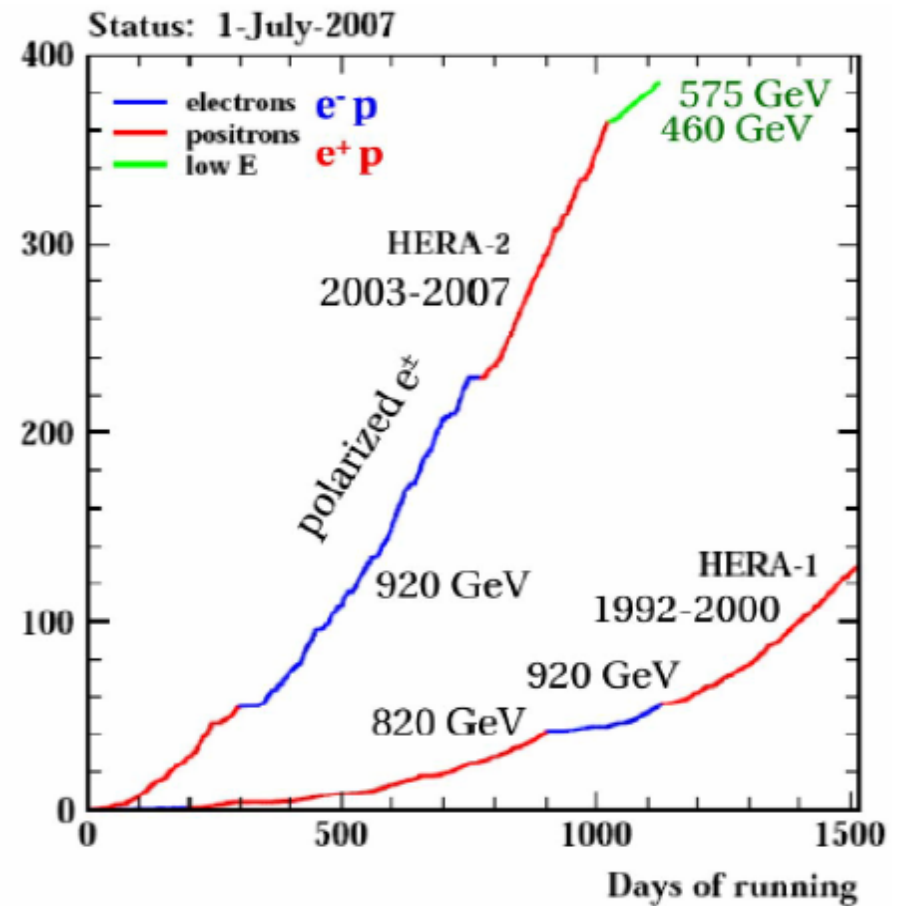
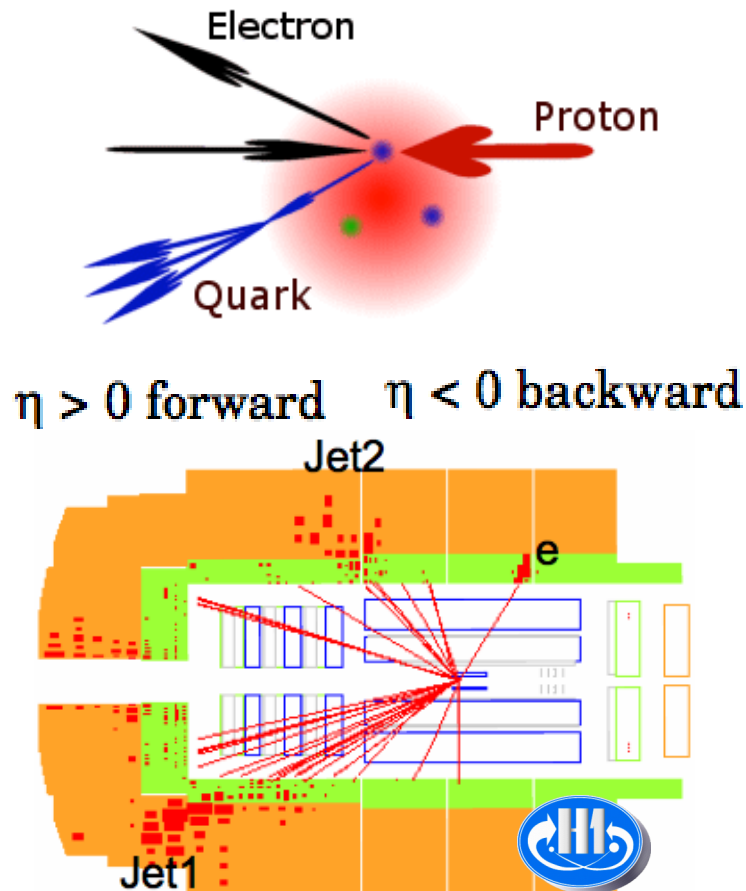


Hadron-Elektron-Ring-Anlage (HERA) at DESY

$e^\pm p$ collider, HERA at DESY, Hamburg, Germany.

Luminosity collected: 0.5fb^{-1} per experiment

$E_e = 27.6\text{ GeV}$ $E_p = 920\text{ GeV}$ ($\sqrt{s} \approx 320\text{ GeV}$)

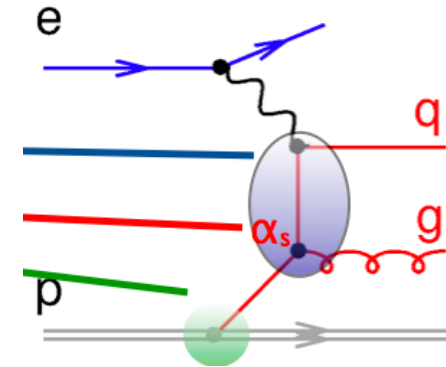




Jet Production in DIS at HERA

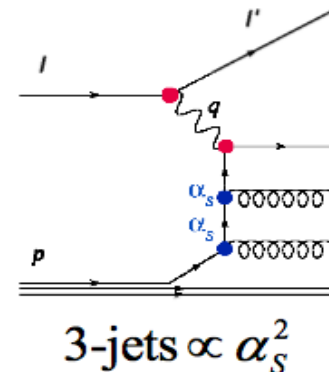
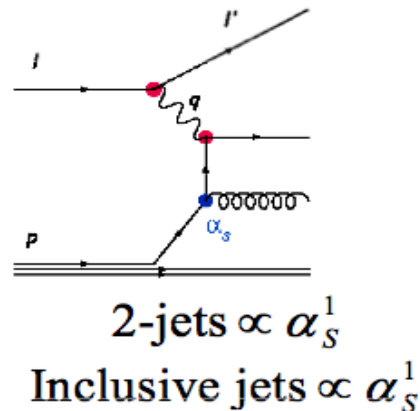
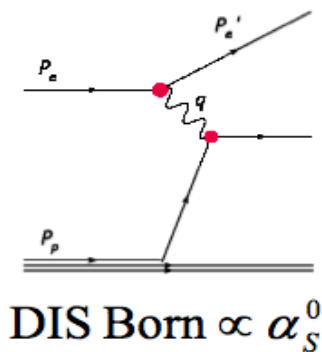
Jet X-section depends on:

- QCD matrix elements.
- **Strong coupling α_s .**
- **Parton density functions of the proton.**



Experimental study and comparison with pQCD predictions give us access to:

- Precision measurement of strong coupling constant α_s .
- Stringent test of pQCD.



2-jet and inclusive jets cross sections sensitive to the proton gluon PDF

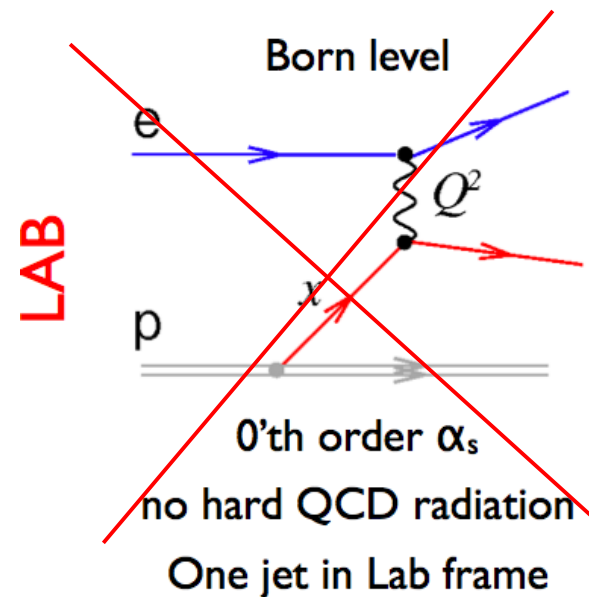
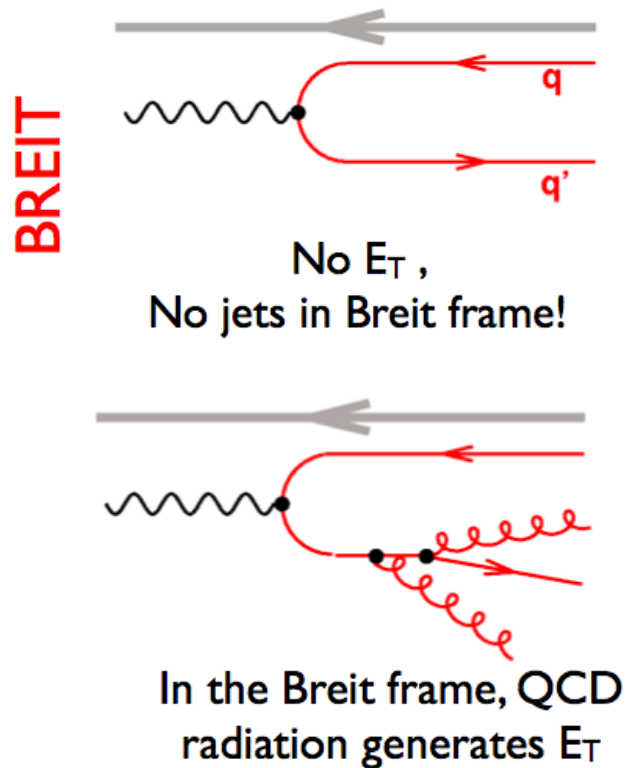




Jet Production in DIS at HERA

Jet Finding: inclusive k_T algorithm in the Breit frame.

- **Suppression of the Born contribution (struck quark has zero E_T).**
- **Suppression of the beam remnant jet (zero E_T).**
- **Lowest order contribution from $g^*q \rightarrow qq$ and $g^*q \rightarrow qg$.**
- **Direct sensitivity to hard QCD process (α_s) \rightarrow gluon density.**





DATA H1 : From 1999-2000, luminosity of 43.5 pb^{-1} ; $5 < Q^2 < 100 \text{ GeV}^2$ and $0.2 < y < 0.77$

Measurement:

X-section, double X-section in fun. of Q^2, P_T .

Events selection:

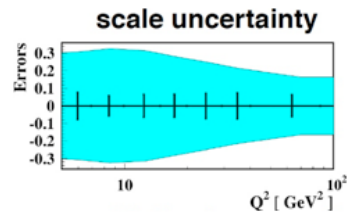
Singe jet $P_T > 5 \text{ GeV}$

Experimental uncertainties:

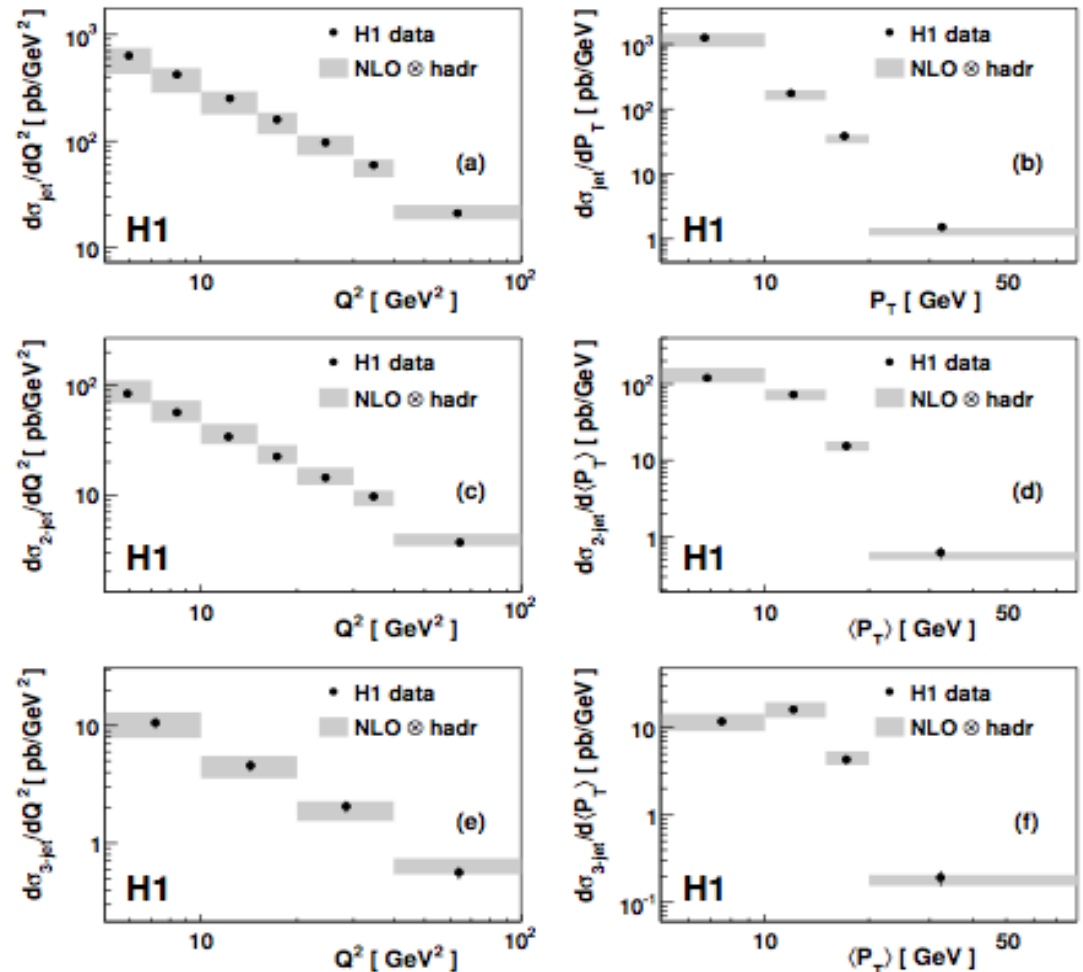
- 2% on energy and reconstructed HFS $\Delta\sigma/\sigma = 4\text{-}10\%$
- 7% on scattered positron energy scale $\Delta\sigma/\sigma = 1\%$
- acceptance and QED radiation $\Delta\sigma/\sigma = 2\text{-}10\%$

Theoretical uncertainties.

- 15-30% renormalization scale dominates and increases with decrease of Q^2 .



Inclusive Jet, 2-Jet and 3-Jet Cross Sections





Jet Production at High Q^2

DATA ZEUS : From 2005-2006, luminosity of 188 pb^{-1} ; $Q^2 > 125 \text{ GeV}^2$

Measurement:

- Singe diff. inclusive NC jet X-section in function of Q^2 or E_T or η_B^{jet} .
- Double diff. X-section in function of Q^2 and E_T

Experimental uncertainties:

hadronic energy scale $\Delta\sigma/\sigma = 5\%$

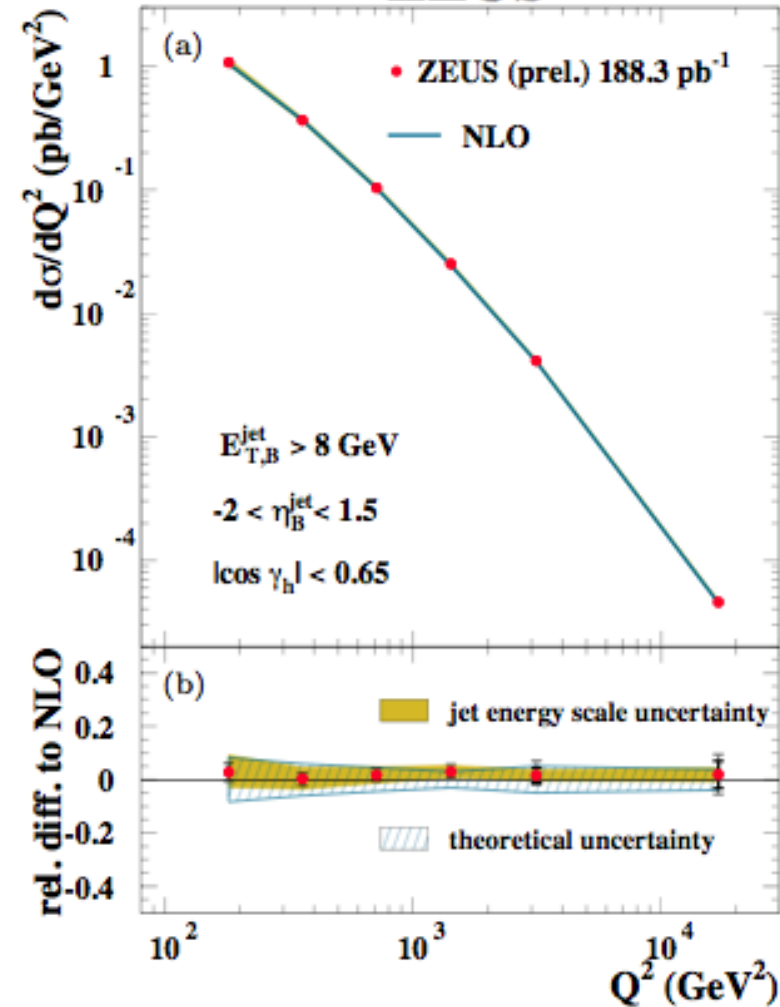
Model dependance of acceptance correction $\Delta\sigma/\sigma = 3\%$

Theoretical uncertainties.

- Still dominates over experimental, except at high Q^2

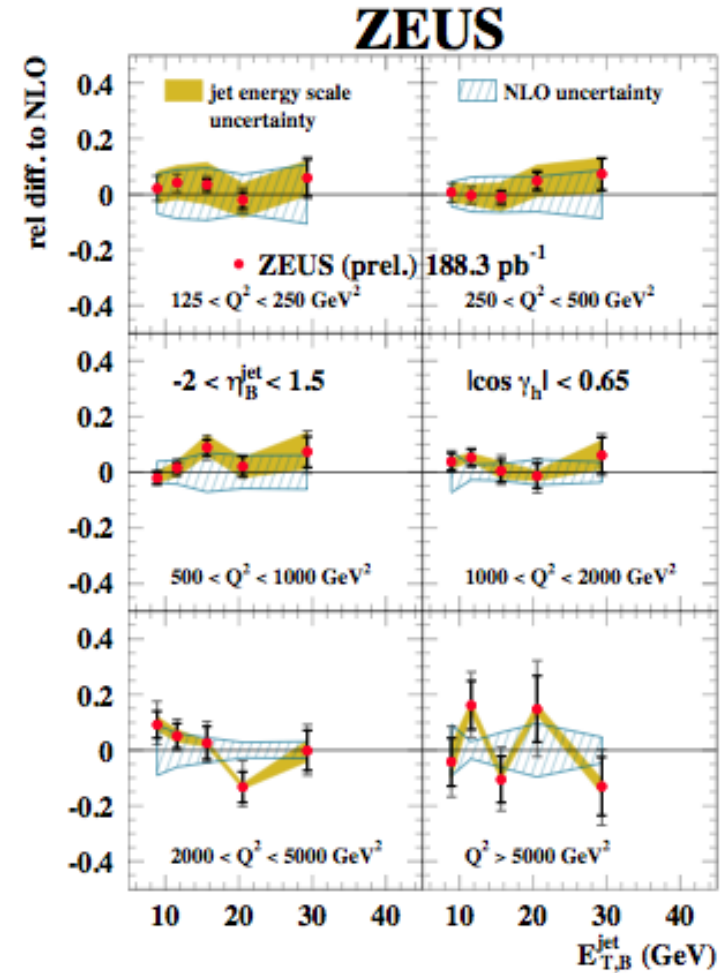
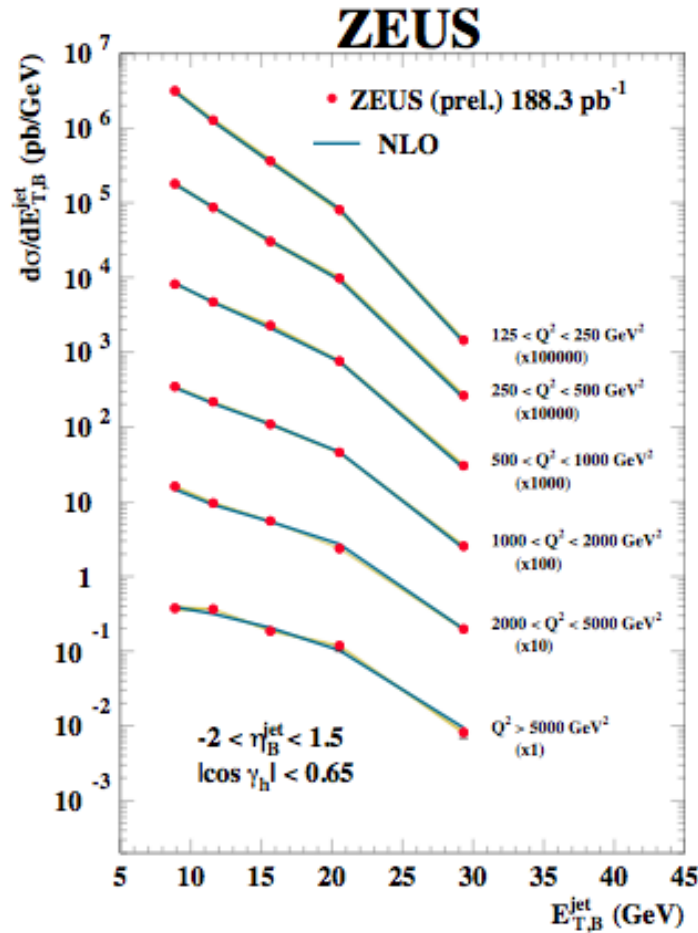
- Very good description of data by NLO QCD (DISENT)
- ZEUS_S PDF and $\mu_r = \mu_f = E_T^{\text{jet}}$

ZEUS





Jet Production at High Q^2



- Double differential inclusive jet X-section as a function of E_T and Q^2 shows good description of all data by NLO QCD
- μ_R uncertainty dominates except at high $E_{T,B}$ where the PDF uncertainty is dominant \Rightarrow potential to further constrain the gluon density in the proton.





Jet Rates Measurement at High Q^2

DATA H1 : From 1999-2007, luminosity of 395 pb^{-1} ; $150 < Q^2 < 15000 \text{ GeV}^2$ and $0.2 < y < 0.7$

Measurement:

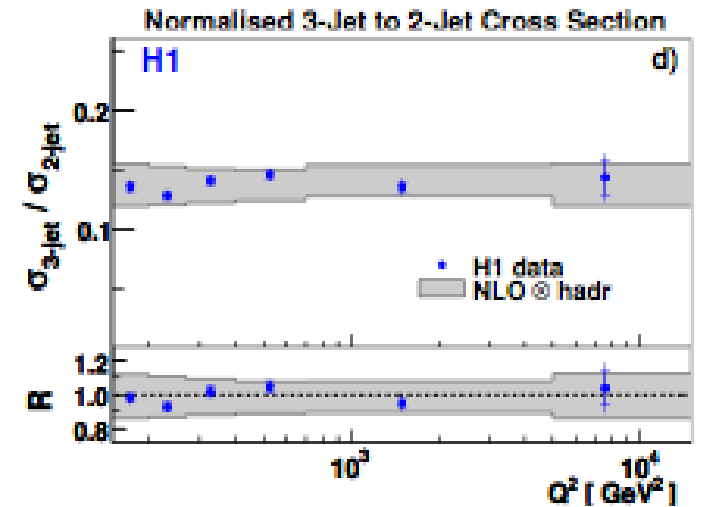
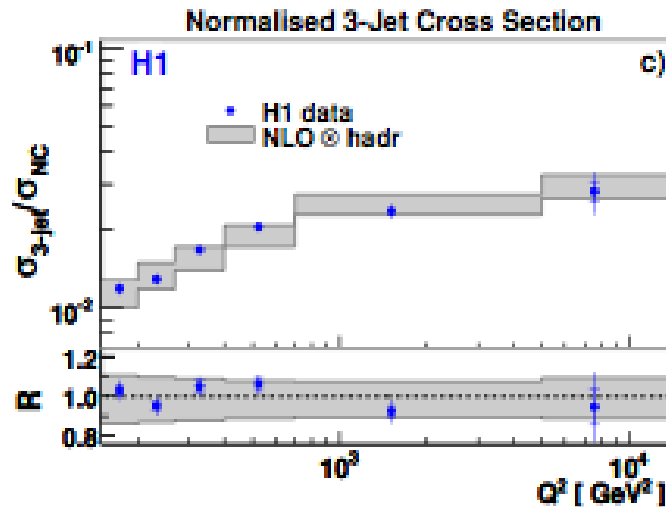
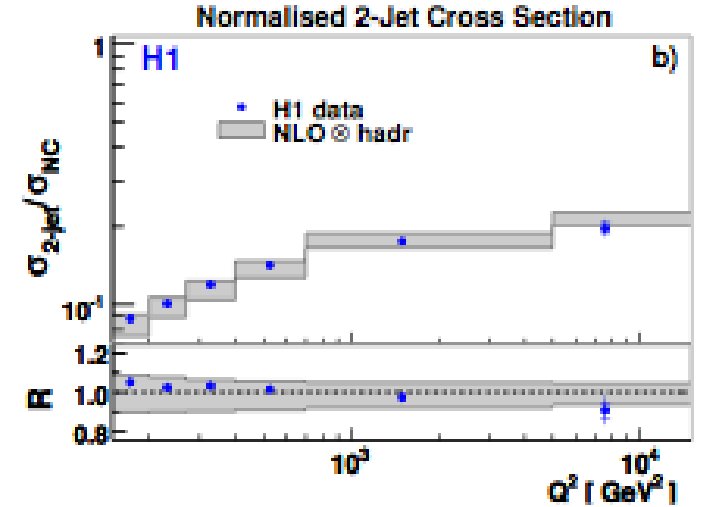
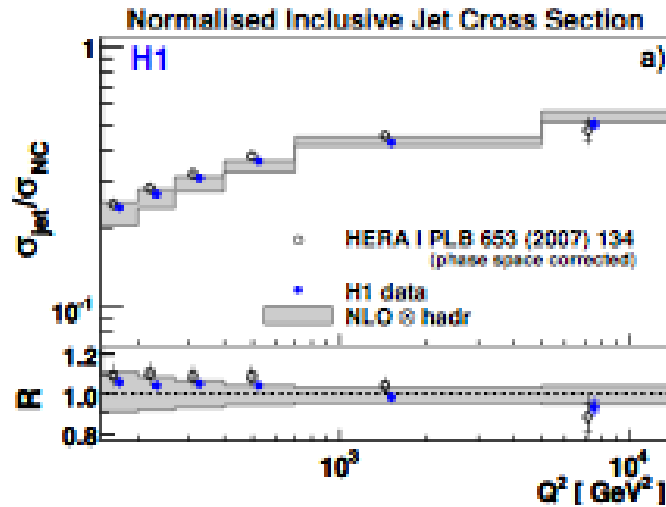
Normalised X-section reduce experimental uncertainty and influence of PDF's

Events selection:

Singe jets $7 < P_T < 50 \text{ GeV}$
2(3) jets, $7 < P_T < 50 \text{ GeV}$
and $M_{12} > 16 \text{ GeV}$

Experimental uncertainty

Hadronic energy scale dominates and shows 1-5% effect on X-section:
Overall experimental uncertainty 3-6% up to 15% for highest P_T .

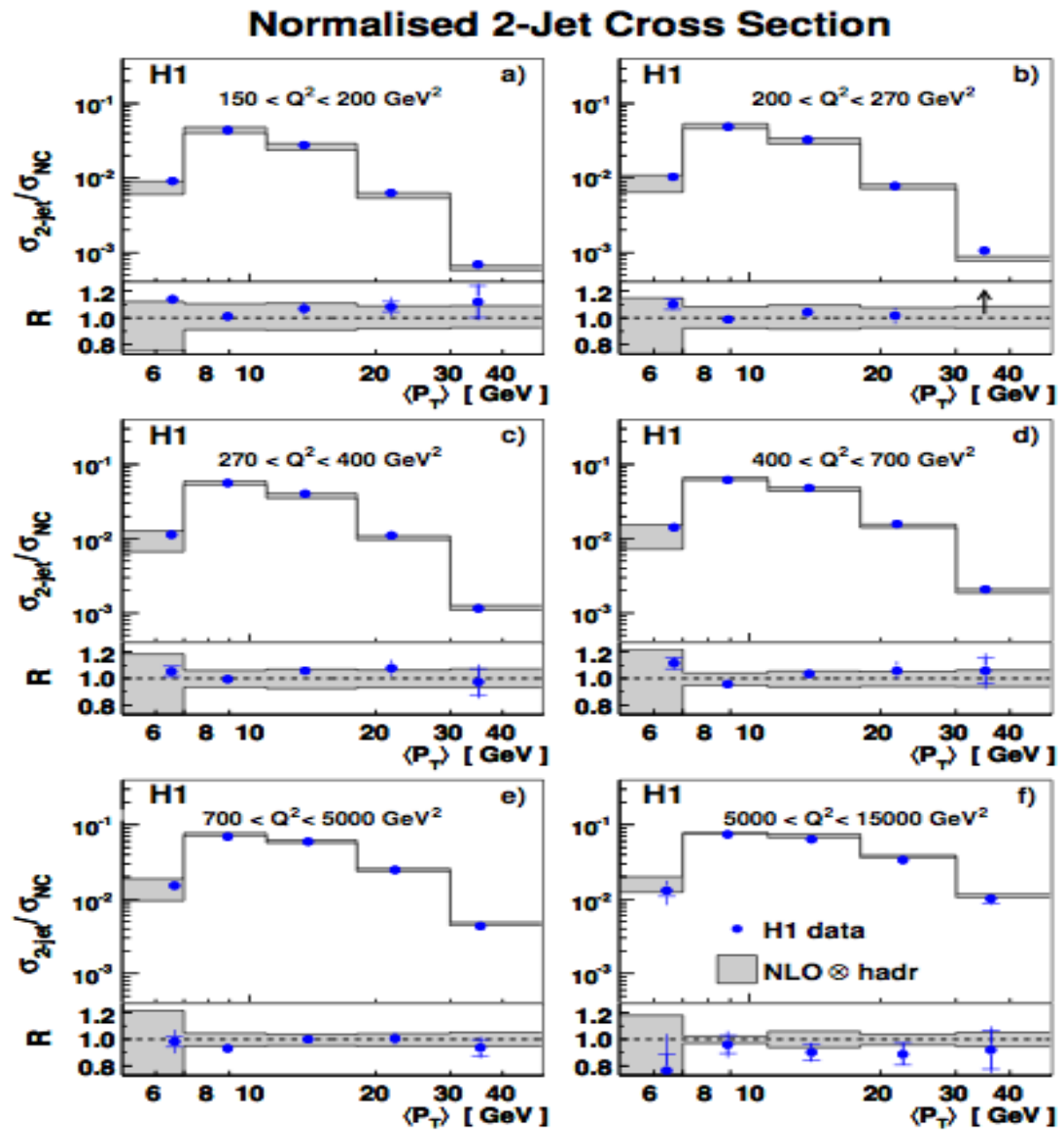




Jet Rates Measurement at High Q^2

$$\frac{\sigma_{2\text{jet}}(Q^2, \langle p_T \rangle)}{\sigma_{\text{NC}}}$$

- Data are well described by NLO pQCD,
- Experimental uncertainties (2-6%)
- Theory error (5-10%), missing higher order $\rightarrow \mu_R$ dependence

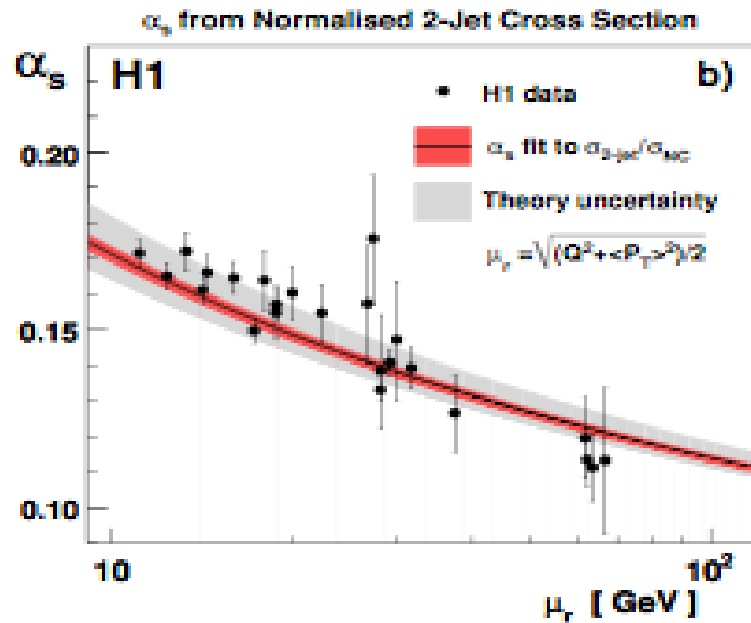




Determination of α_s from jet rates at High Q^2

Individual fits:

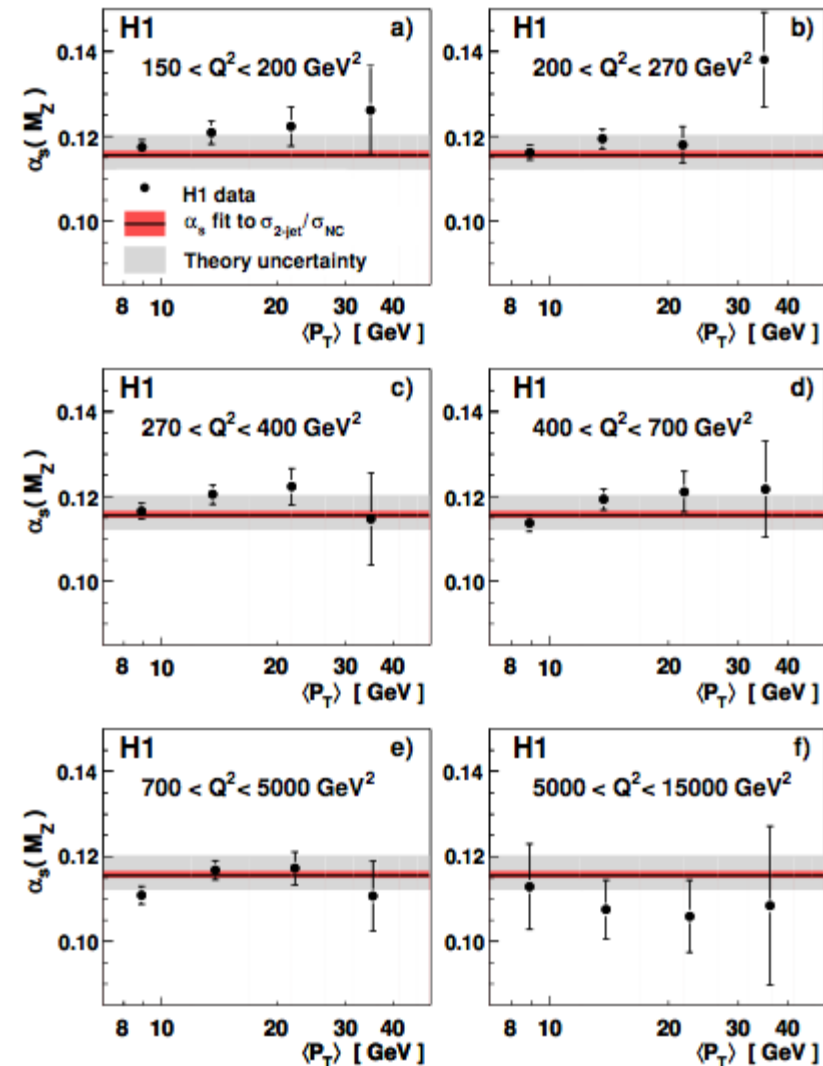
- adjust α_s in NLO QCD prediction to match each data point
- evolve $\alpha_s(M_Z)$ to relevant μ_R



Combined fits:

- χ^2 fit of NLO QCD predictions to data with $\alpha_s(M_Z)$ as free parameter.
- Include correlated systematical errors (jet energy scale) by "Hessian procedure".
- Statistical correlations are taken in account.

α_s from Normalised 2-Jet Cross Section





Determination of α_s from jet rates at High Q^2

Extraction of strong coupling constant:

- α_s from multi-jet rates : Combined fit to all observables.

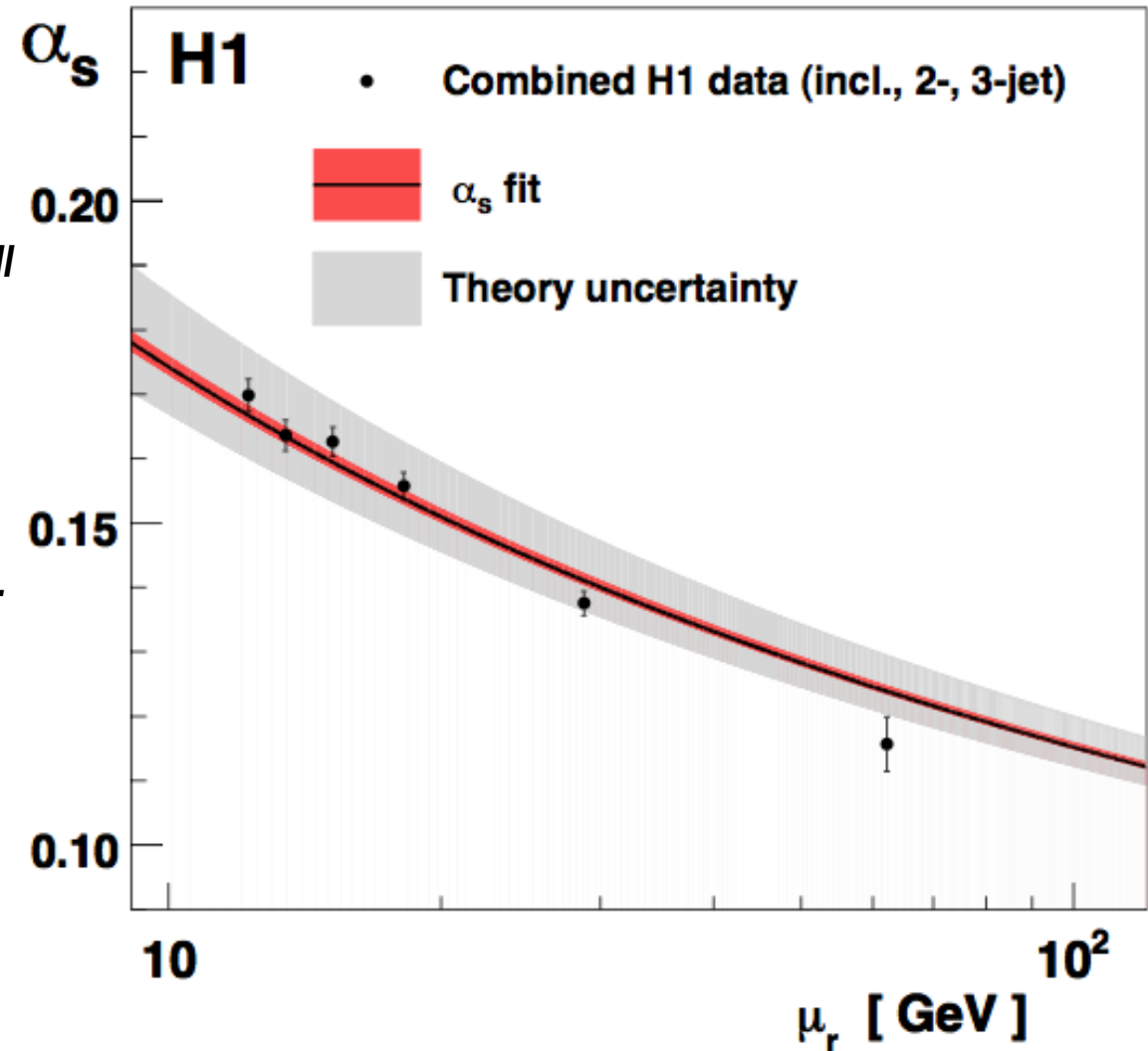
Experimental uncertainty 0.6%.

- result with best experimental precision.

Total uncertainty 3.6%.

Running of α_s agrees with QCD expectations.

Normalised Jet Cross Sections





Running of α_s from low and high Q^2

- α_s from low Q^2 added to high Q^2 curve, low Q^2 data lie within the theory uncertainty of the high Q^2 fit.

low Q^2 H1 Experiment

$$\alpha_s(M_Z) = 0.1186 \pm 0.0014(\text{exp})_{-0.0101}^{+0.0132}(\text{theory}) \pm 0.0021(\text{pdf})$$

high Q^2 H1 Experiment

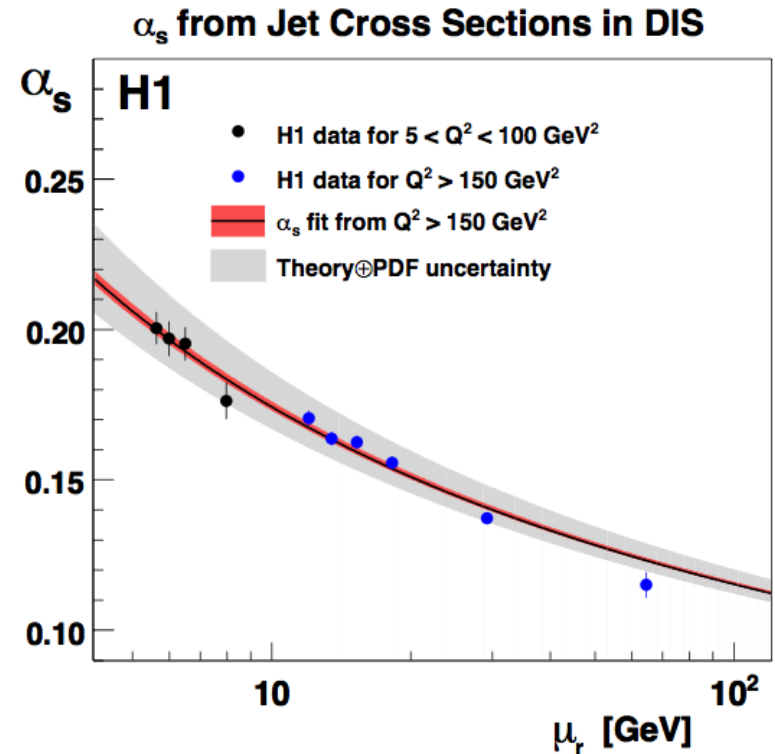
$$\alpha_s(M_Z) = 0.1168 \pm 0.0007(\text{exp.})_{-0.0030}^{+0.0046}(\text{th.}) \pm 0.0016(\text{PDF})$$

ZEUS Experiment

- to minimize total uncertainty, α_s extracted for $Q^2 > 500 \text{ GeV}^2$

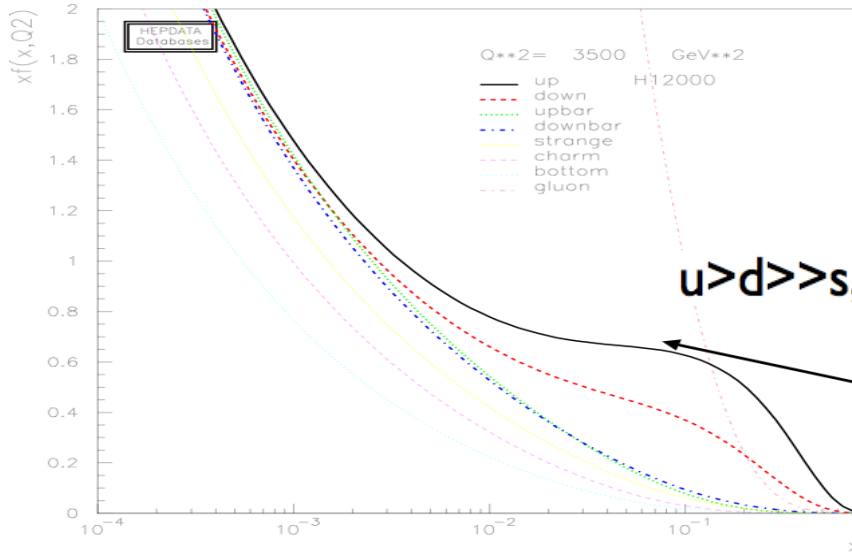
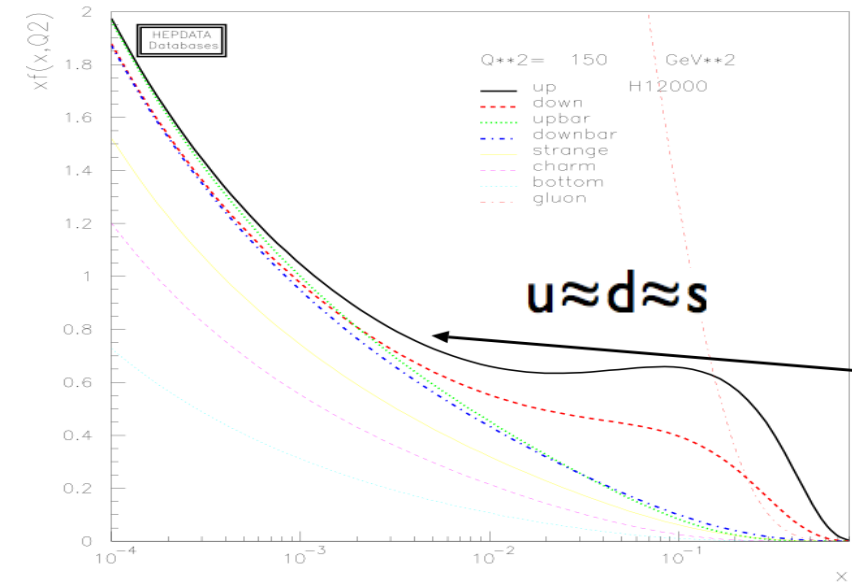
$$\alpha_s(M_Z) = 0.1192 \pm 0.0009(\text{stat.})_{-0.0032}^{+0.0035}(\text{exp.})_{-0.0021}^{+0.0020}(\text{th.})$$

- 2.9% experimental uncertainty
- 3.5% total uncertainty.





HFS Charge Asymmetry at High Q^2 (DIS) at HERA



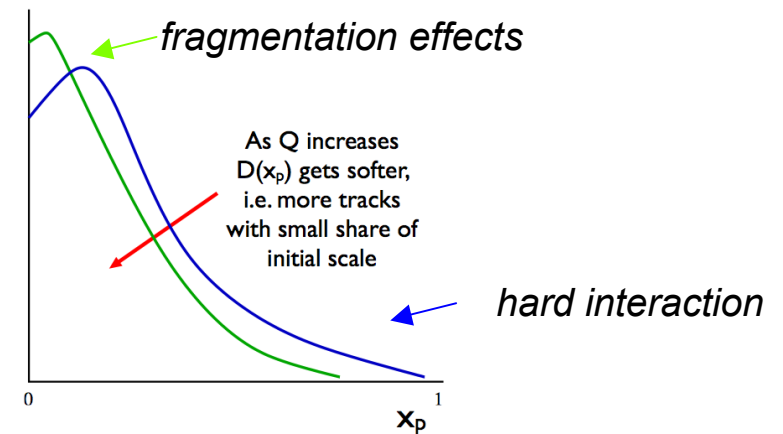
Motivation:

- At low Q^2 and low x_{bj} proton PDF dominated by sea quarks and gluons.
- At higher Q^2 and large x_{bj} valence quark dominates.
- Contribution of u valence quarks from the proton to the hard interaction dominates at high Q^2 over that from d valence quarks!

$$A(x_p, Q) = (D^+(x_p, Q) - D^-(x_p, Q)) / (D^+(x_p, Q) + D^-(x_p, Q))$$

$$D(x_p) = (1/N_{\text{event}}) * (dn/dx_p) ; x_p = 2p_h/Q$$

- $A(x_p, Q)$ is charge asymmetry
- P_h is momentum of charged particle in the current region of the Breit frame.
- $D(x_p)$ is event normalized, charged particle, scaled momentum distribution.

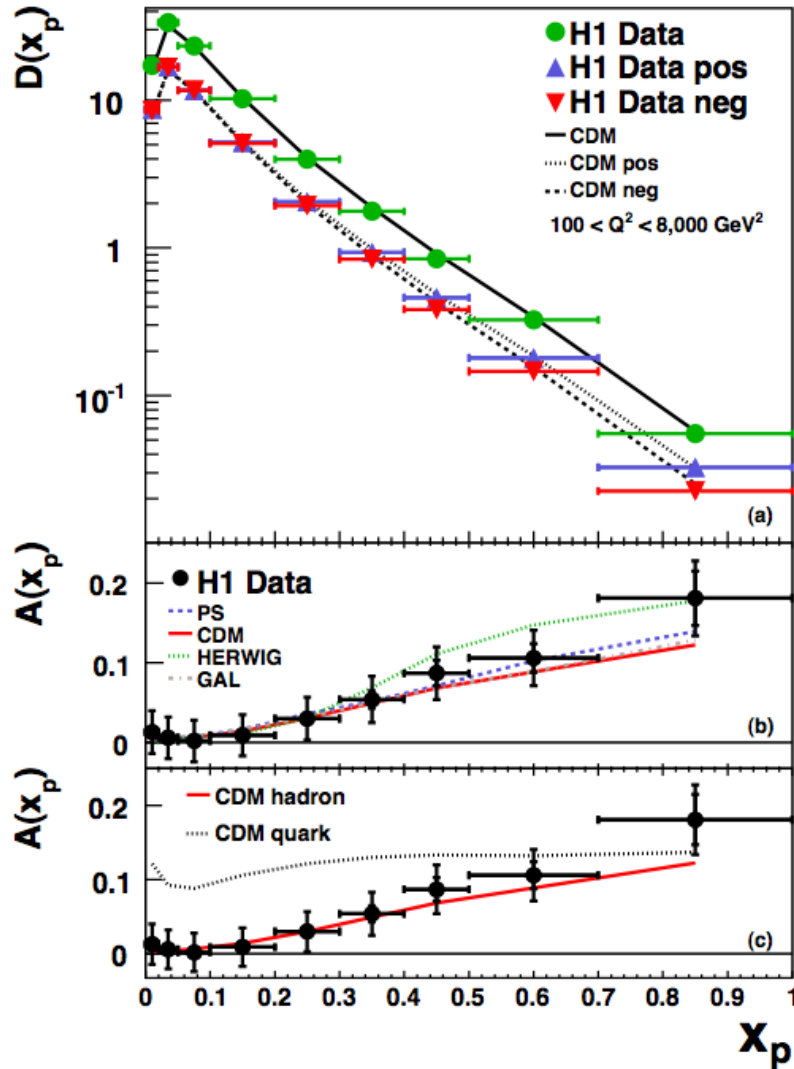




HFS Charge Asymmetry at High Q^2 (DIS) at HERA

DATA with integrated luminosity of 44 pb^{-1} and kinematic range $100 < Q^2 < 8000 \text{ GeV}^2$ and $0.05 < y < 0.6$

Insight into non-perturbative regime of QCD.



- The Parton Shower model (PS) **RAPGAP**
 - Evolution of the parton shower DGLAP
- Colour Dipole Model (CDM) **DJANGO**
 - Parton evolution similar to BFKL
- Soft Colour Interaction model (SCI) and generalised area law (GAL) **LEPTO**
- The **RAPGAP**, **DJANGO** and **LEPTO** use Lund string model of hadronisation.

Measurement

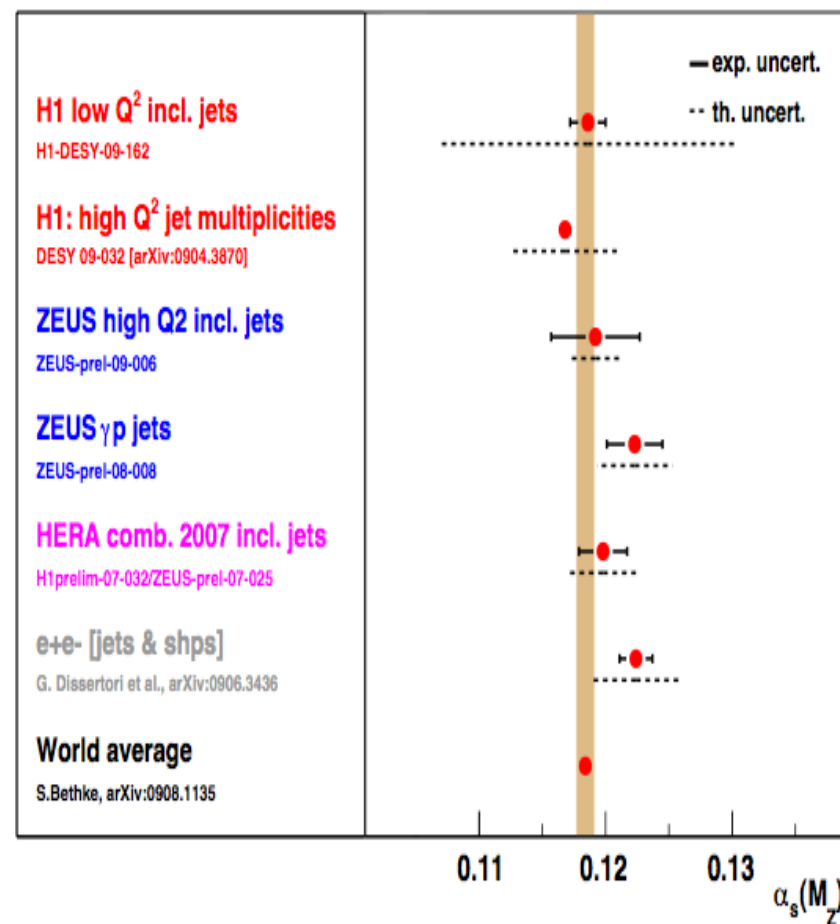
- At low x_p similar distributions.
- At large x_p clear difference in distributions.
- Difference described by MC.
- Asymmetry magnitude and evolution described by various MC models.
- Quark level prediction from CDM MC with hadronisation turned off.
- Similar asymmetry between data and CDM at large x_p .
- Consistent with expectation that fragmentation dominates at low x_p and hard interaction at large x_p .





Summary

- **Precise α_s extraction.**
 - ✓ very high experimental precision.
 - ✓ running α_s verified over $5 < Q^2 < 10\,000 \text{ GeV}^2$.
- **Data are well described by NLO QCD.**
- **Theory scale uncertainties dominate over the experimental uncertainties.**
- **Higher order calculations necessary to take full advantage of the data.**
- **Measurement of charge asymmetry.**
 - ✓ At high x_p the asymmetry is directly related to valence quark content.



- H1: http://www-h1.desy.de/general/home/intra_home.html
- ZEUS: <http://www-zeus.desy.de/>

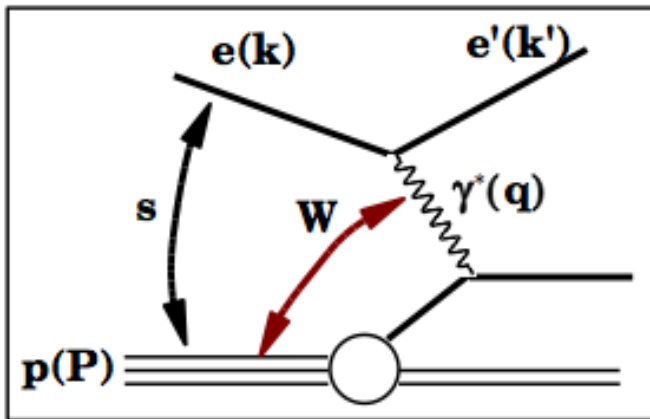


Backup !!





Backup !!



DIS

NC

CC

$$ep \rightarrow eX$$

$$ep \rightarrow \nu X$$

γ^* , Z exchange

W exchange

$$e(k) + p(P) \rightarrow e'(k') + X$$

- Centre of mass energy $s = (P + k)^2$
- Energy of hadronic system $W^2 = (P + q)^2$
- Photon virtuality $Q^2 = -q^2 = -(k + k')^2$
- Inelasticity $y = qP / kP \approx (W^2 + Q^2) / s$
- Bjorken-x $x_{Bj} = Q^2 / 2qP \approx Q^2 / sy$





Backup !!

NLO pQCD Theory

