Precision Tests of QCD Using Final State Jets and Particles

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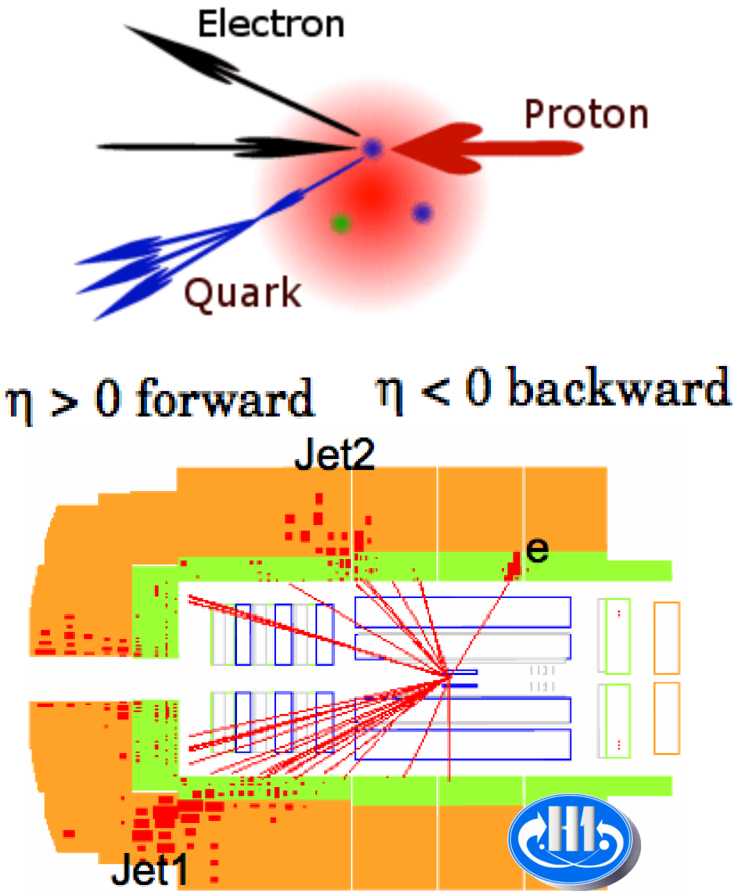
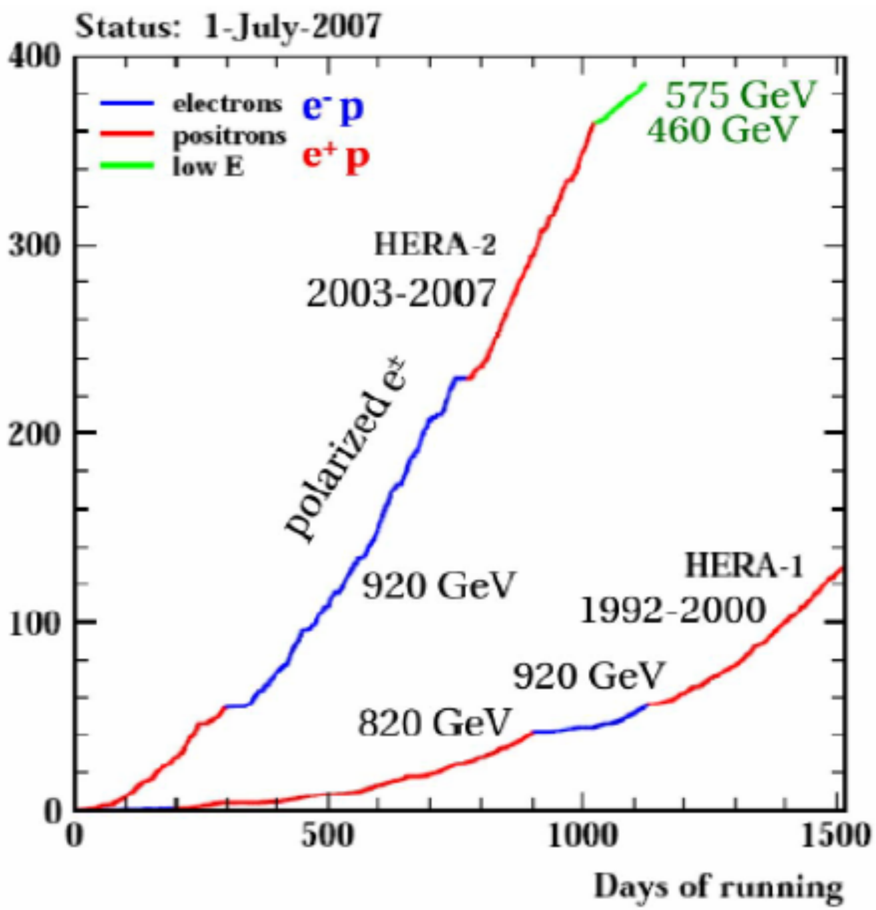
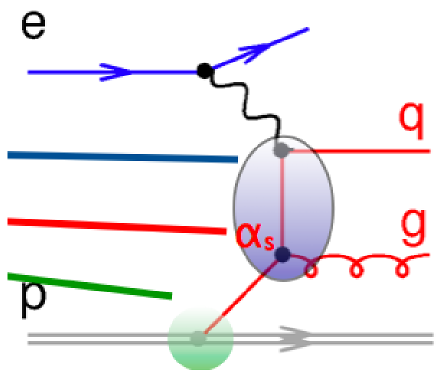
on behalf of the H1 and ZEUS Collaborations

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

$e^{\pm}$ p collider , HERA at DESY, Hamburg, Germany.
Luminosity collected: **$0.5fb^{-1}$ per experiment**
Ee= 27.6 GeV Ep= 920 GeV ($\sqrt{s} \approx 320$ GeV)





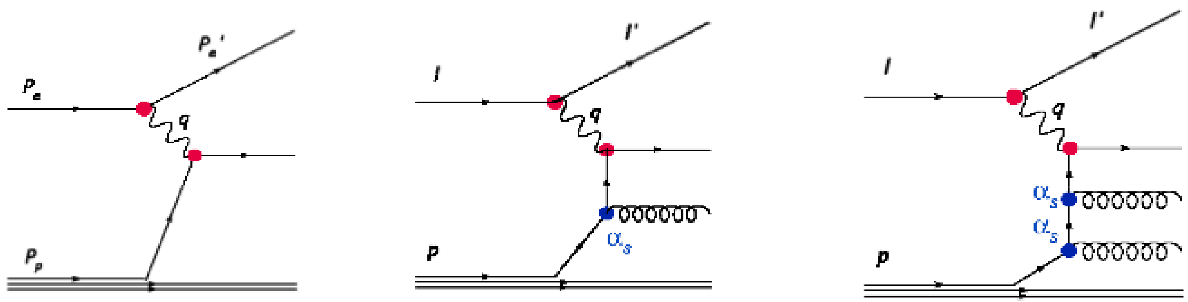


Jet X-section depends on:

- *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.***

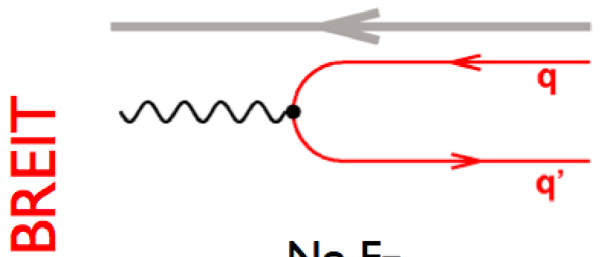


DIS Born $\propto \alpha_S^0$ 2-jets $\propto \alpha_S^1$ Inclusive jets $\propto \alpha_S^1$ 3-jets $\propto \alpha_S^2$

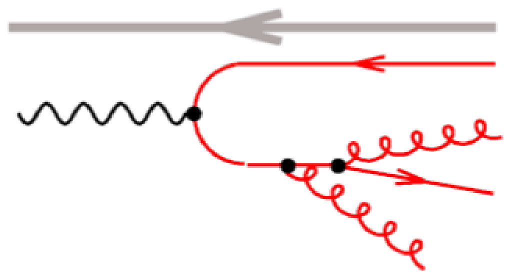
2-jet and inclusive jets cross sections sensitive to the proton gluon PDF

Jet Finding: inclusive kT algorithm in the Breit frame.

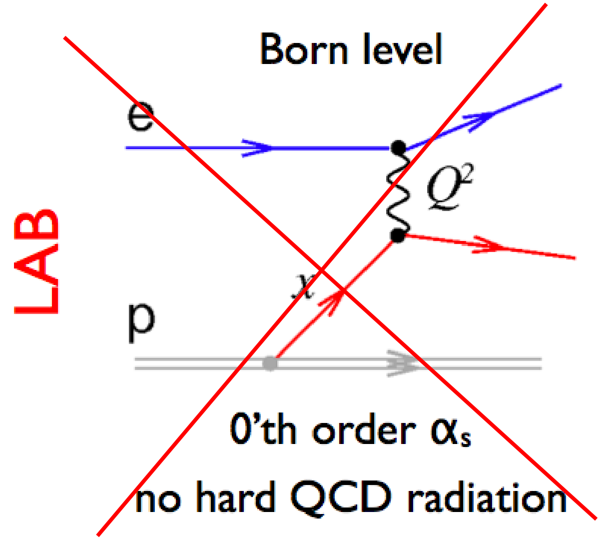
- *Suppression of the Born contribution (struck quark has zero E_T).*
- *Suppression of the beam remnant jet (zero E_T).*
- *Lowest order contribution from g*q -> qq and g*q -> qg.*
- *Direct sensitivity to hard QCD process (α_s) -> gluon density.*



No E_T ,
No jets in Breit frame!



In the Breit frame, QCD radiation generates E_T



One jet in Lab frame

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

Measurement:

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

Events selection:

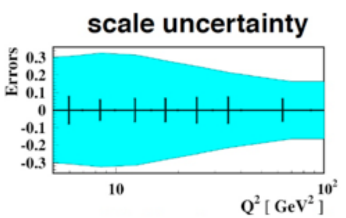
Singe jet $P_T > 5$ GeV

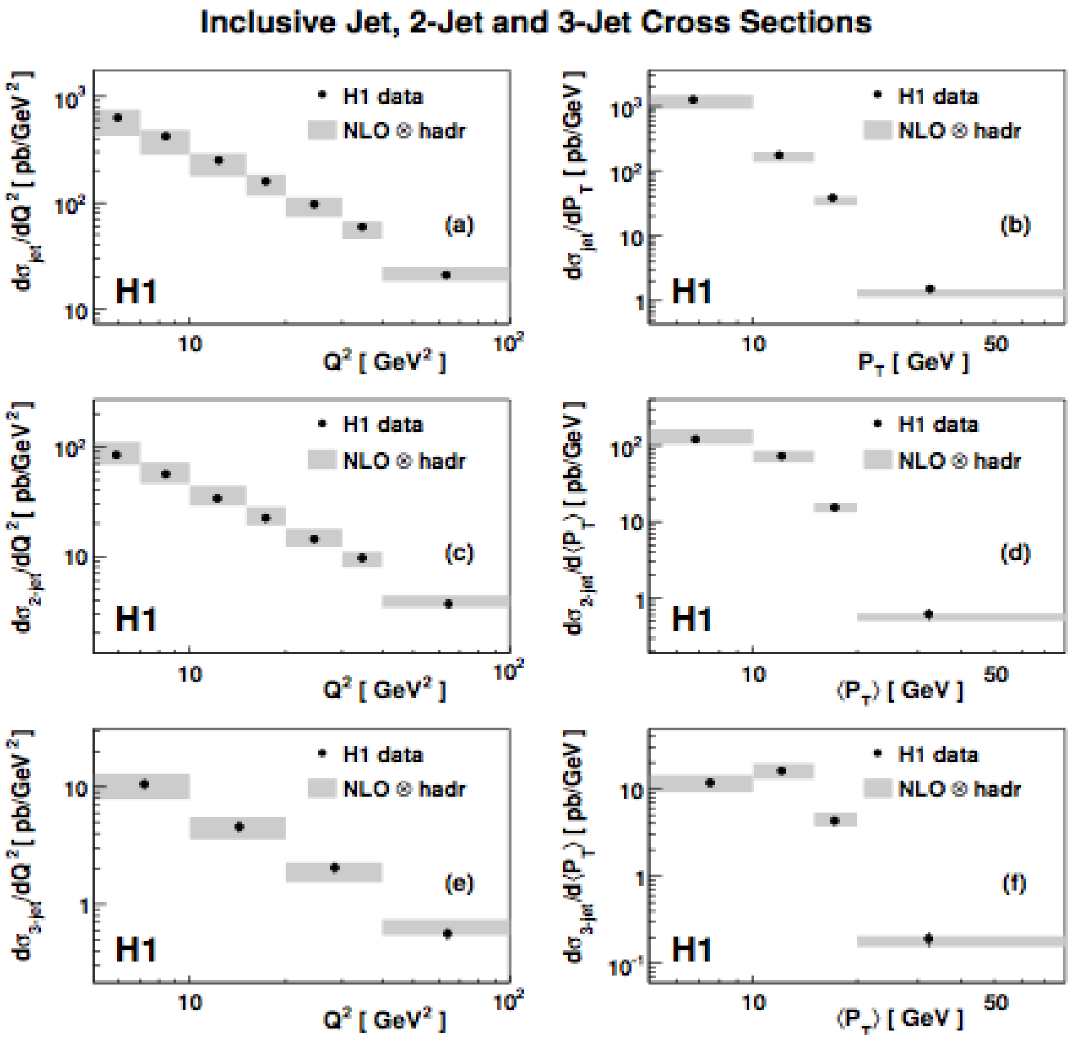
Experimental uncertainties:

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

Theoretical uncertainties.

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





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

Measurement:

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

Experimental uncertainties:

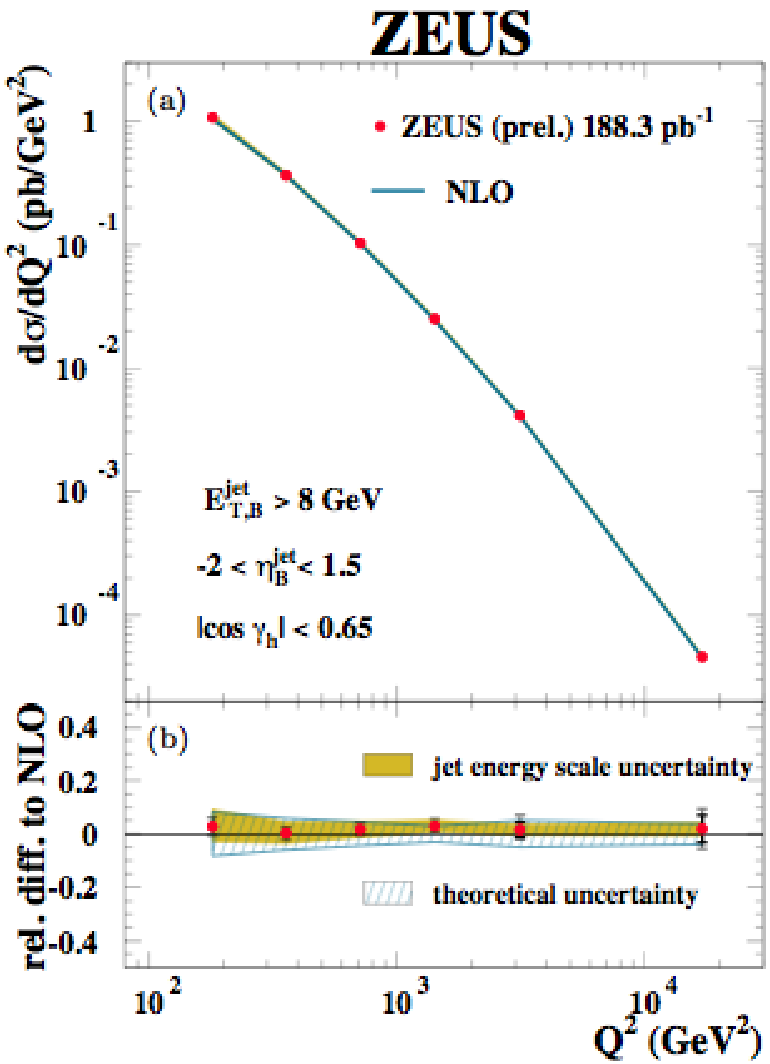
hadronic energy scale $\Delta\sigma/\sigma = 5\%$

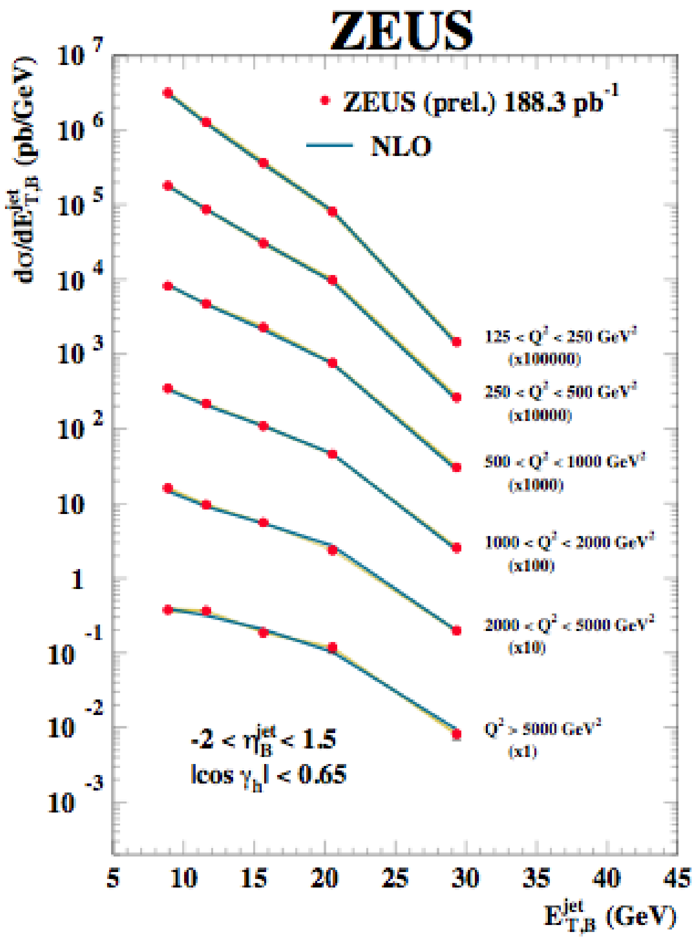
Model dependance of acceptance correction $\Delta\sigma/\sigma = 3\%$

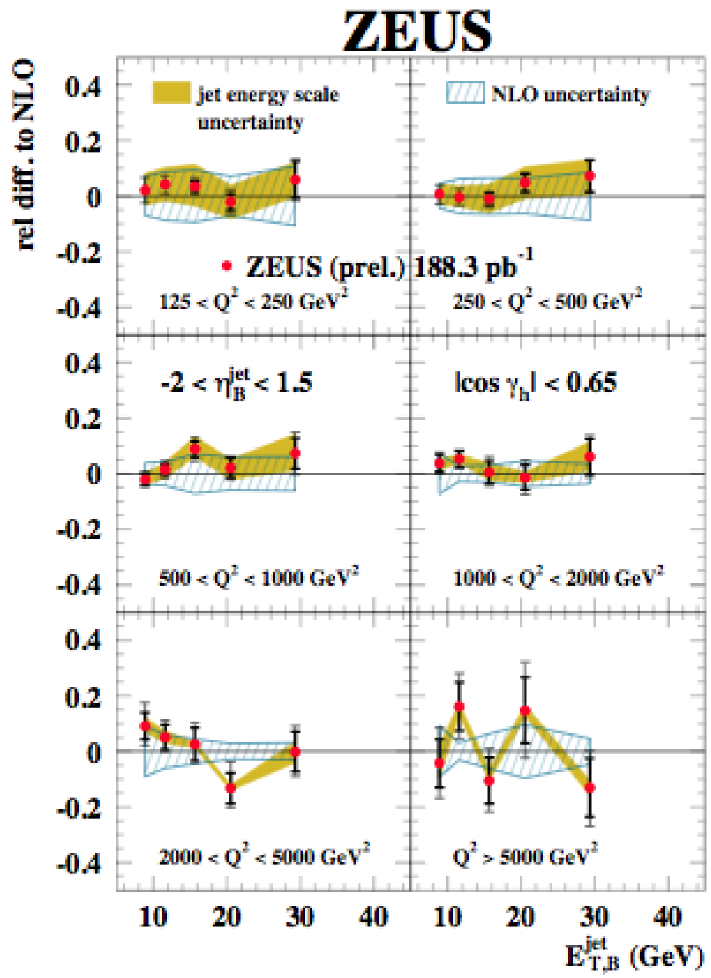
Theoretical uncertainties.

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

- *Very good description of data by NLO QCD (DISENT)*
- *ZEUS_S PDF and $\mu r = \mu f = E_T^{jet}$*







•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 ⇒ **potential to further constrain the gluon density in the proton.***

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

Measurement:

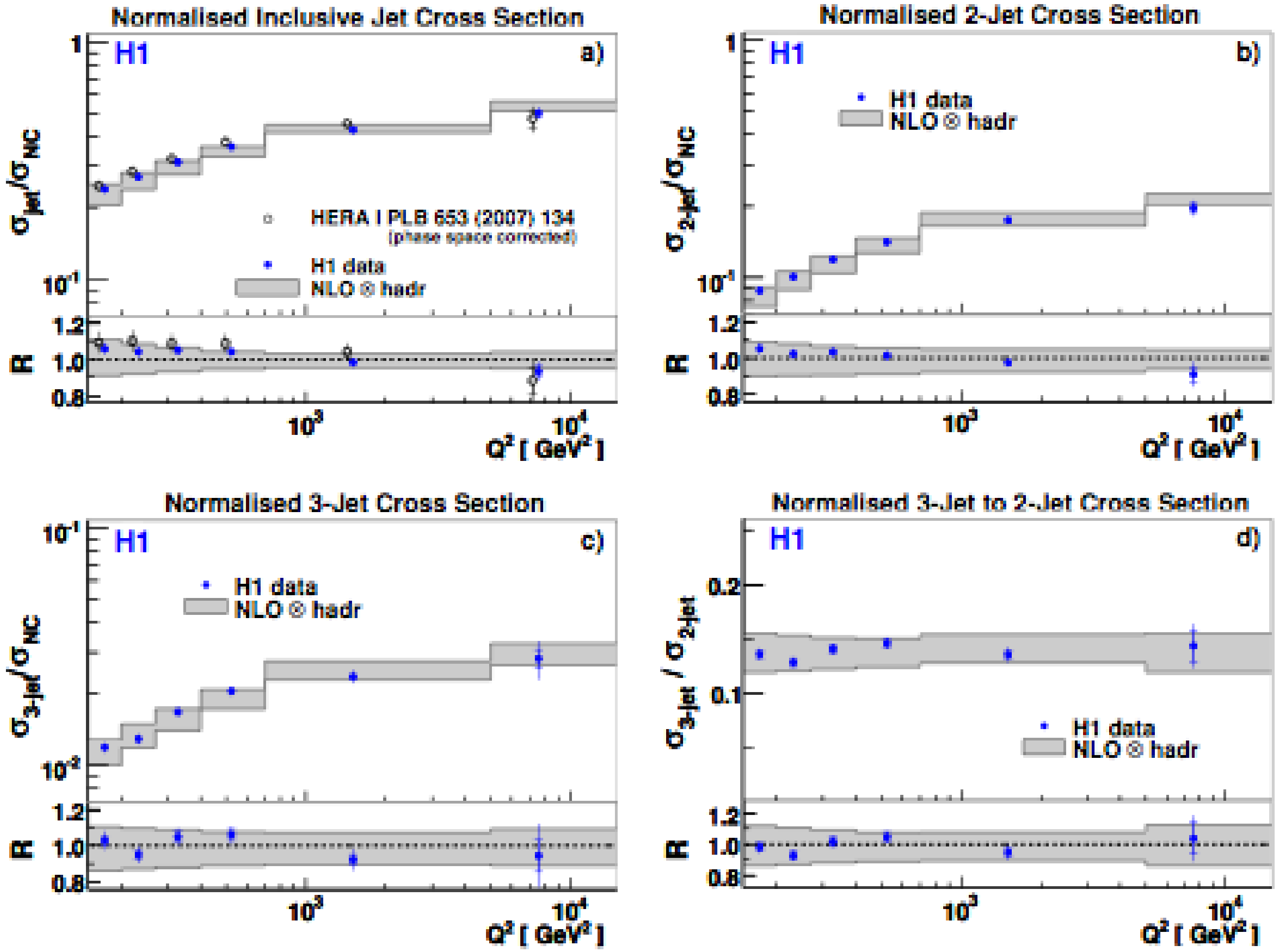
Normalised X-section reduce experimental uncertainty and influence of PDF's

Events selection:

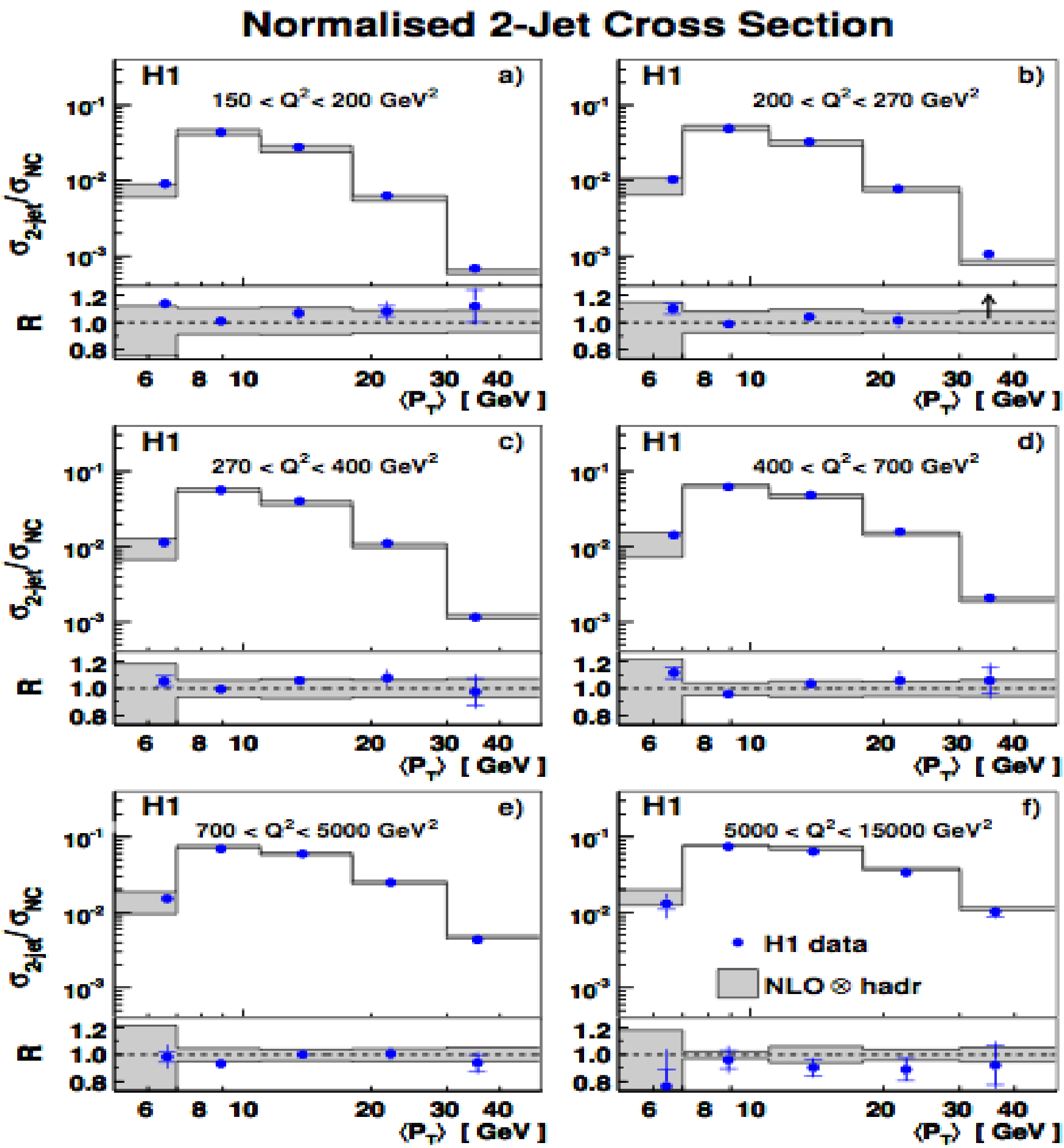
Singe jet s $7 < P_T < 50$ GeV
2(3) jets, $7 < P_T < 50$ GeV and $M_{12} > 16$ GeV

Experimental uncertaintie

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



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

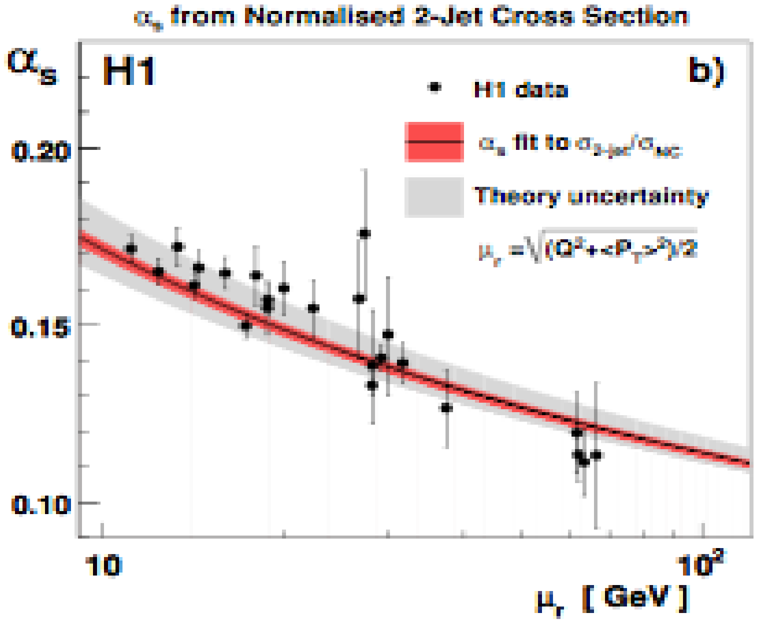


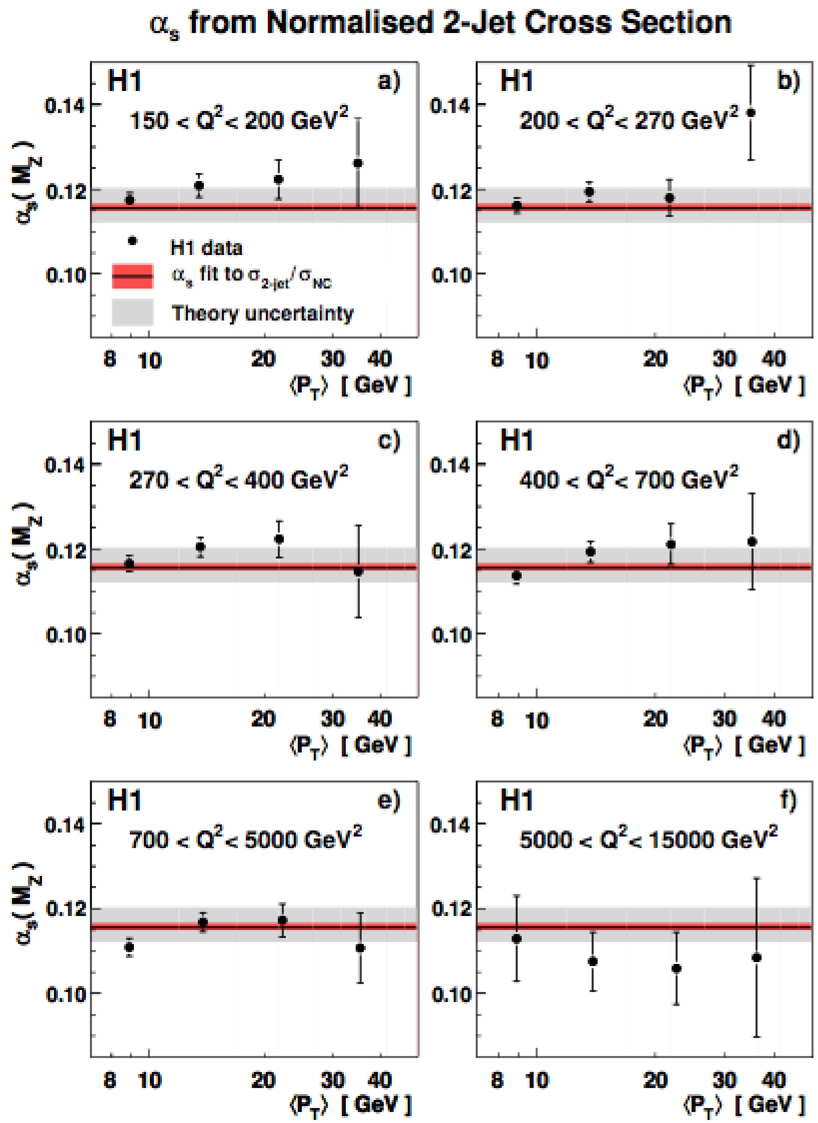
- *Data are well described by NLO pQCD,*
- *Experimental uncertainties (2-6%))*
- *Theory error (5-10%), missing higher order -> μ_R dependence*

Determination of α_s from jet rates at High Q^2

Individual fits:

o adjust α_s in NLO QCD prediction to match each data point
o evolve α_s (Mz) to relevantf μ_R.





Combined fits:

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

Determination of α_s from jet rates at High Q^2

Extraction of strong coupling constant:

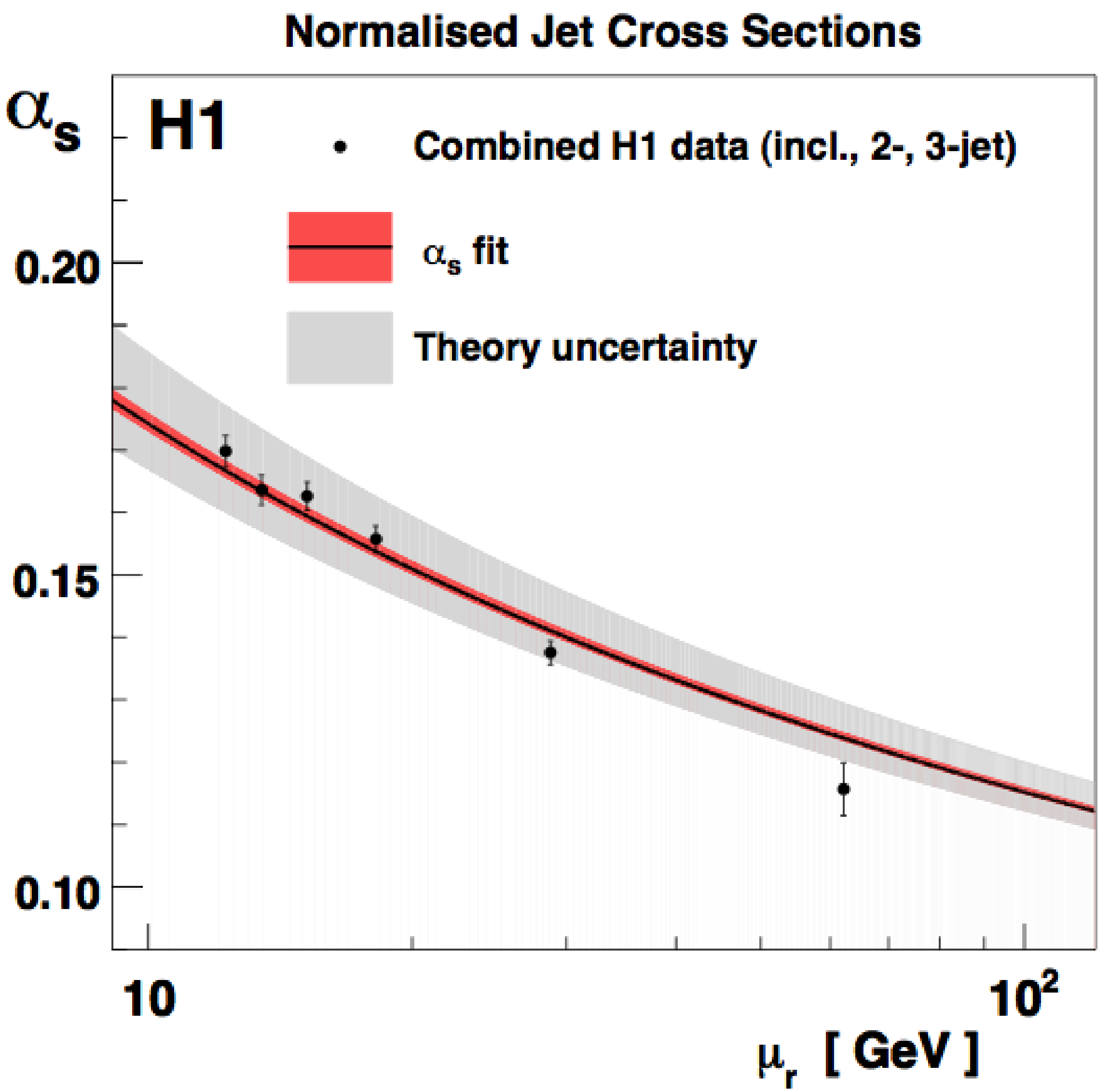
- ***α_s from multi-jet rates : Combined fit to all observables.***

Experimental uncertainty 0.6%.

- ***result with best experimental precision.***

Total uncertainty 3.6%.

Running of α_s agrees with QCD expectations.



- ***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**

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

high Q^2 **H1 Experiment**

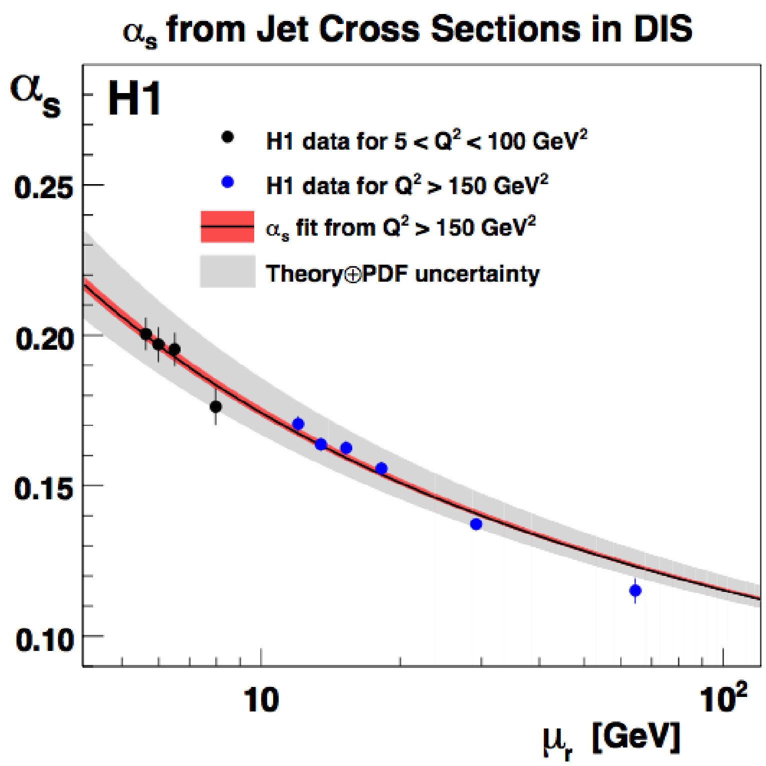
$$\alpha_s(M_Z) = 0.1168 \pm 0.0007\,(\text{exp.})\,^{+0.0046}_{-0.0030}\,(\text{th.}) \pm 0.0016\,(\text{PDF})$$

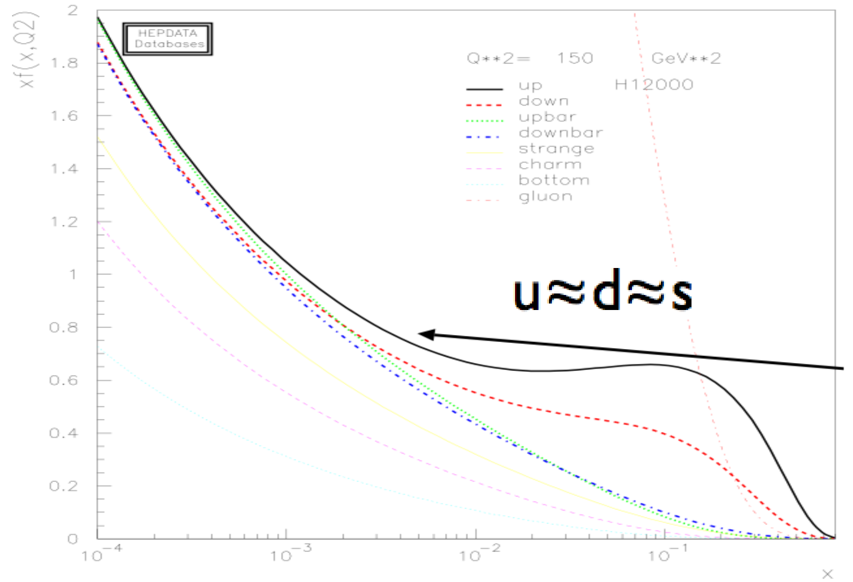
ZEUS Experiment

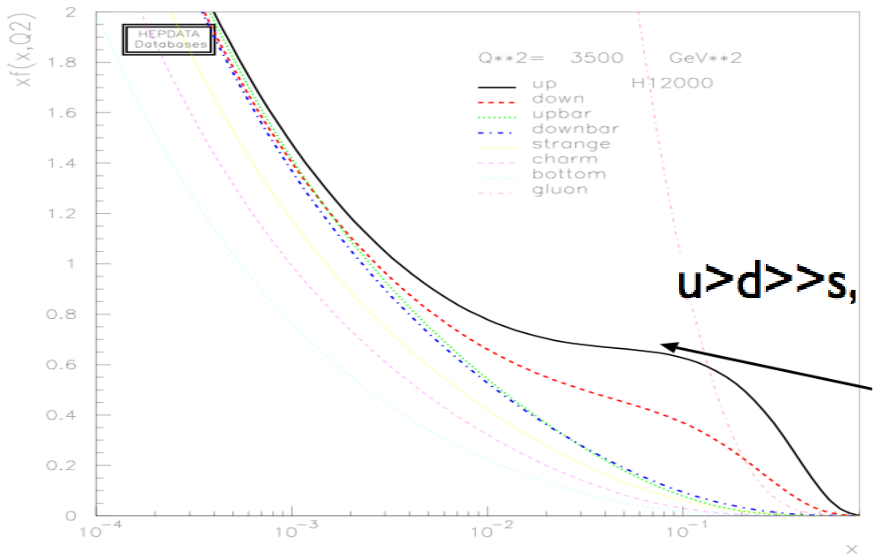
- to minimize total uncertainty, α_S extracted for $Q^2 > 500$ GeV^2

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

- 2.9% experimental uncertainty
- 3.5% total uncertainty.







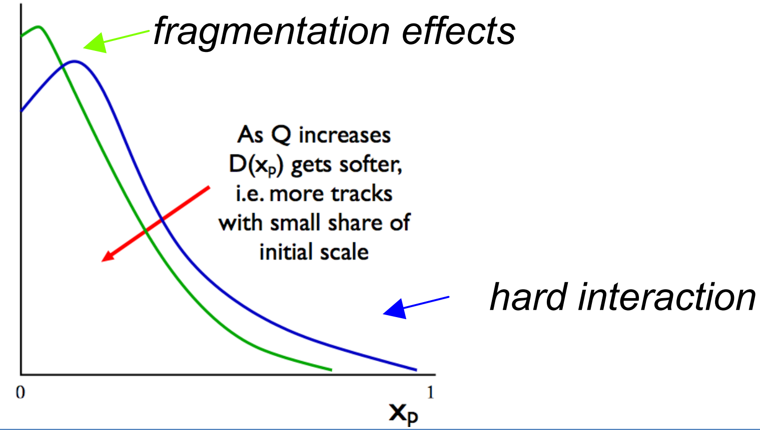
Motivation:

- ***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!***

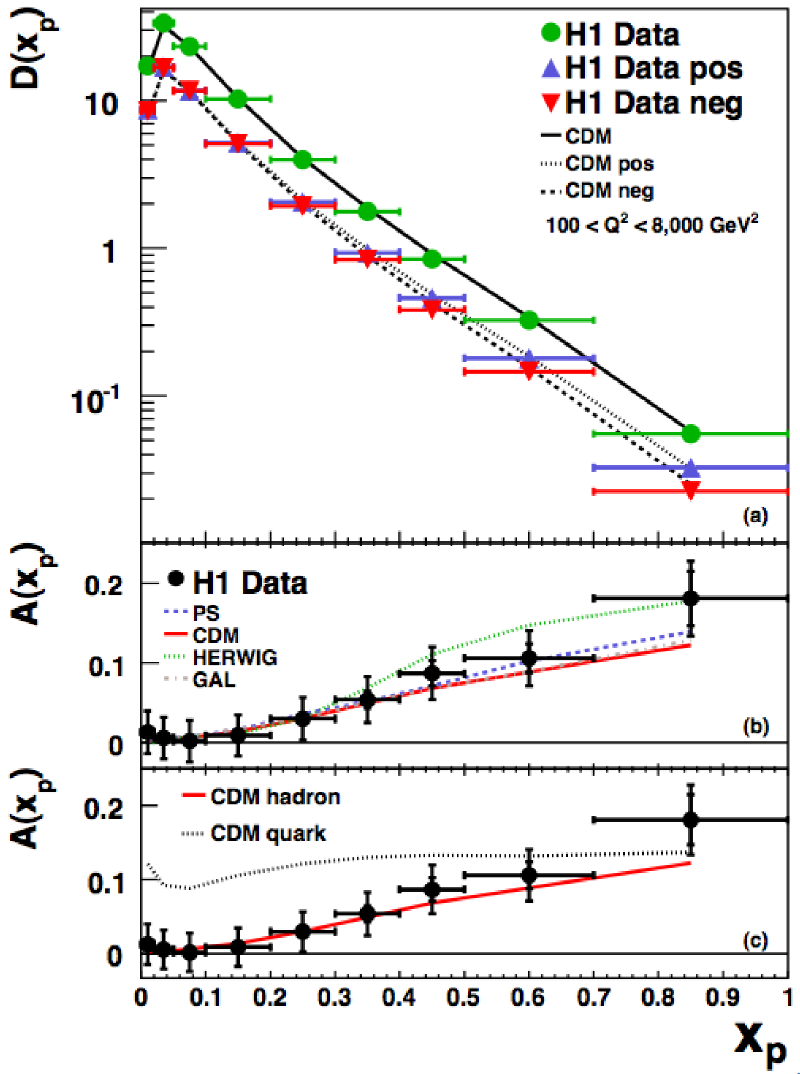
$$A(x_p,Q)=(D^+(x_p,Q)-D^-(x_p,Q))/(D^+(x_p,Q)+D^-(x_p,Q))$$

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

- ***$A(x_p,Q)$ 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.***



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



Insight into non-perturbative regime of QCD.

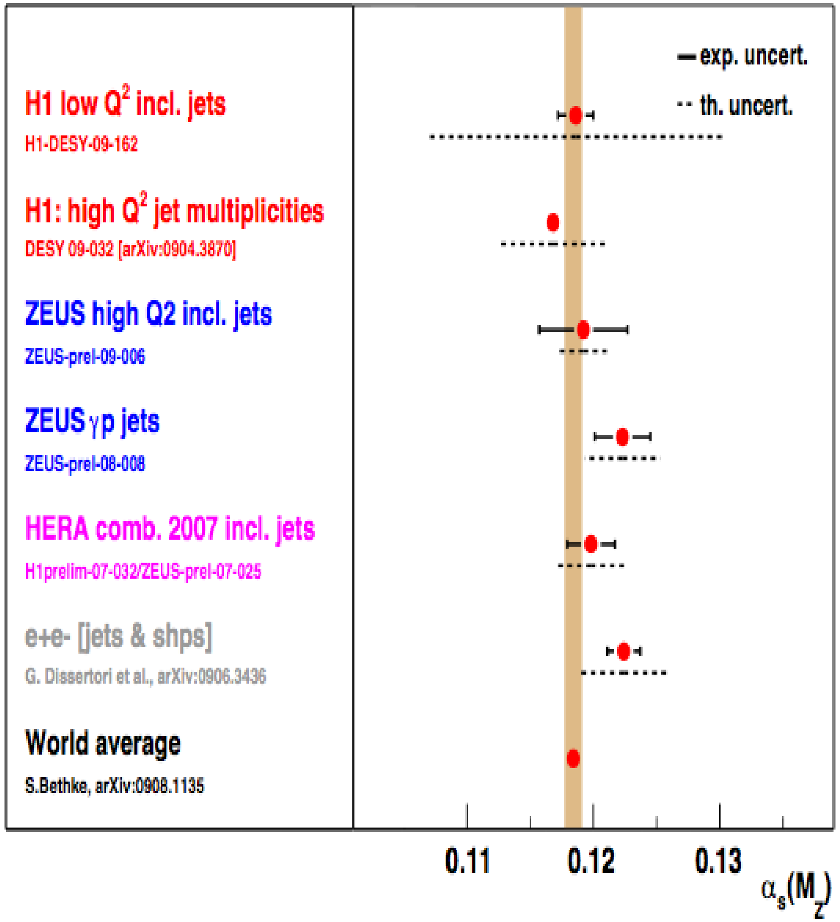
- ***The Parton Shower model (PS) RAPGAP***
  - ***Evoution of the patron shower DGLAP***
- ***Coulor Dipole Model (CDM) DJANGO***
  - ***Parton evolution similar to BFKL***
- ***Soft Colour Interaction model (SCI) and generalised area law (GAL) LEPTO***
- ***The RAPGAP, DJANGO and LEPTO use Lund string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

Measurement

- ***At low x_p simular 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 hadrnisation turned off.***
- ***Simular 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

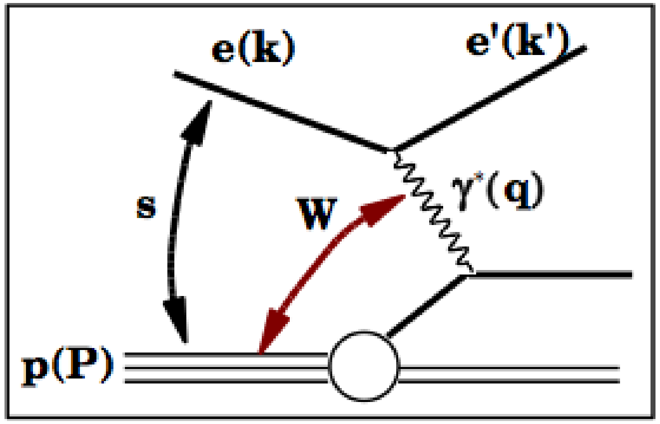
- ***Precise α_s extraction.***
  - ✓very high experimental precision.
  - ✓running α_s verified over $5 < Q2 < 10\ 000\ GeV^2$.
- ***Data are well described by NLO QCD.***
- ***Theory scale uncertainties dominate over the experimental uncertainties.***
- ***Higher order calculations necessary to take 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

$$ep \rightarrow eX$$

γ^*, Z exchange

CC

$$ep \rightarrow \nu X$$

W exchange

e(k) + p (P) → 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 $x_{Bj} = Q^2 / 2qP \approx Q^2 / sy$

NLO pQCD Theory

Proton PDF

Matrix Element

Hadronisation correction

$$\sigma_{\text{jet}} = \sum_{i=q,\bar{q},g} \int dx\, f_i(x, \mu_F, \alpha_S)\, \hat{\sigma}_{\text{QCD}}(x, \mu_F, \mu_R, \alpha_S(\mu_R)) \cdot (1 + \delta_{\text{had}})$$

CTEQ6.5
error: ± 20 eigenvectors
±5%

Assess theoretical uncertainty due to missing higher orders through μ_R (and μ_F) dependence of σ_{jet}
convention : $\mu_{R,F}$ ↑ x2 and $\mu_{R,F}$ ↓ x0.5
±5%

Apply hadronisation correction (δhad) to parton level predictions to be able to compare with data
uncertainty taken from difference of Monte Carlo models (PS /CDM)
±2%