Precision Tests of QCD Using Final State Jets and Particles

Mihajlo Mudrinic
(“Vinca” Institute of Nuclear Sciences)
on behalf of the H1 and ZEUS Collaborations

- Inclusive Jets in DIS at Low and High $Q^2$.
- Extraction of $\alpha_s$.
- Hadronic Final State Charge Asymmetry.
Hadron-Elektron-Ring-Anlage (HERA) at DESY

$e^\pm p$ collider, HERA at DESY, Hamburg, Germany.
Luminosity collected: 0.5 fb$^{-1}$ per experiment

$E_e = 27.6$ GeV $E_p = 920$ GeV ($\sqrt{s} \approx 320$ GeV)
Jet X-section depends on:
- QCD matrix elements.
- Strong coupling $\alpha_s$.
- Parton density functions of the proton.

Experimental study and comparison with pQCD predictions give us access to:
- Precision measurement of strong coupling constant $\alpha_s$.
- Stringent test of pQCD.

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 $g^*q \rightarrow qq$ and $g^*q \rightarrow qg$.
- Direct sensitivity to hard QCD process ($\alpha_s$) $\rightarrow$ gluon density.
Jet Production at Low $Q^2$

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:**
- Single diff. inclusive NC jet X-section in function of \(Q^2\) or \(E_T\) or \(\eta^{\text{jet}}\).
- Double diff. X-section in function of \(Q^2\) and \(E_T\)

**Experimental uncertainties:**
- Hadronic energy scale \(\Delta \sigma/\sigma = 5\%\)
- Model dependence 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 \(\mu_r=\mu_f=E_T^{\text{jet}}\)
Double differential inclusive jet $X$-section as a function of $E_T$ and $Q^2$ shows good description of all data by NLO QCD.

$\mu_R$ 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.
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:
Single jet $7 < P_T < 50$ GeV
2(3) jets, $7 < P_T < 50$ GeV and $M_{12} > 16$ 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 $Q^2$

Data are well described by NLO pQCD,
Experimental uncertainties (2-6%),
Theory error (5-10%),
missing higher order $\rightarrow \mu_R$ dependence
Individual fits:
- adjust $\alpha_s$ in NLO QCD prediction to match each data point
- evolve $\alpha_s (M_Z)$ to relevant $f_{\mu_R}$.

Combined fits:
- $\chi^2$ 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.
Extraction of strong coupling constant:
• $\alpha_s$ from multi-jet rates: Combined fit to all observables.
  Experimental uncertainty 0.6%.
• result with best experimental precision.
  Total uncertainty 3.6%.

Running of $\alpha_s$ agrees with QCD expectations.

Determination of $\alpha_s$ from jet rates at High $Q^2$
Running of $\alpha_s$ from low and high $Q^2$

- $\alpha_s$ 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.

**H1 Experiment**

| Low $Q^2$ | High $Q^2$ |
|-----------|------------|
| $\alpha_s(M_Z) = 0.1186 \pm 0.0014\, (exp) + 0.0132\, (theory) \pm 0.0021\, (pdf)$ | $\alpha_s(M_Z) = 0.1168 \pm 0.0007\, (exp) + 0.0046\, (th.) \pm 0.0016\, (PDF)$ |

**ZEUS Experiment**

- To minimize total uncertainty, $\alpha_s$ extracted for $Q^2 > 500\, GeV^2$

\[\alpha_s(M_Z) = 0.1192 \pm 0.0009\, (stat.) + 0.0035\, (exp.) + 0.0020\, (th.)\]

- 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!

$$A(x_p,Q) = \frac{(D^+(x_p,Q) - D^-(x_p,Q))}{(D^+(x_p,Q) + D^-(x_p,Q))}$$

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

• $A(x_p,Q)$ 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.
HFS Charge Asymmetry at High $Q^2$ (DIS) at HERA

Insight into non-perturbative regime of QCD.

- The Parton Shower model (PS) RAPGAP
  - Evolution of the parton shower DGLAP
- Coulour 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 $x_p$.

DATA with integrated luminosity of 44 pb$^{-1}$ and kinematic range $100 < Q^2 < 8000$ GeV$^2$ and $0.05 < y < 0.6$
• Precise $\alpha_s$ extraction.
  ✓ very high experimental precision.
  ✓ running $\alpha_s$ verified over $5 < Q^2 < 10000$ 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:  [Link]
• ZEUS: [Link]
Backup !!
DIS

\[ ep \rightarrow eX \]
\[ ep \rightarrow \nu X \]
\[ \gamma^*, Z \text{ exchange} \]
\[ W \text{ exchange} \]

**DIS**

\[ e(k) + p(P) \rightarrow e'(k') + X \]

- 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-\( x \): \[ x_{Bj} = Q^2 / 2qP \approx Q^2 / sy \]
NLO pQCD Theory

Proton PDF

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

Hadronisation correction

Matrix Element

CTEQ6.5 error: ± 20 eigenvectors
±5%

Assess theoretical uncertainty due to missing higher orders through \( \mu_R \) (and \( \mu_F \)) dependence of \( \sigma_{\text{jet}} \)
convention: \( \mu_{R,F} \uparrow \times 2 \) and \( \mu_{R,F} \downarrow \times 0.5 \)
±5%

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

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