HERA

The HERA e^±p collider 1992-2007:

- $E_{e^\pm} = 27.6$ GeV
- $E_p = 920$ GeV
- $\sqrt{s} = 319$ GeV
- Integrated luminosity: $\sim 0.5$ fb$^{-1}$ (per experiment)

Standard DIS variables:

- $Q^2$: virtuality of the exchanged boson
- $x_{Bj}$: in QPM fraction of proton momentum carried by struck quark
- $y = Q^2/xs$: inelasticity
Jet production at HERA

Jet production and determination of strong coupling constant

- H1 jet production at high $Q^2$ and determination of $\alpha_s$
  
  High $Q^2$ measurements with inclusive jets, dijet and trijet events
  arXiv:1406.4709
  Subm to EPJC

- ZEUS jet production and determination of $\alpha_s$
  
  High $Q^2$ measurements with trijet events
  ZEUS-prel-14-008

QCD measurements

- H1 QCD Instantons searches at high $Q^2$
  H1-prel-14-031
Jet production in NC DIS

The fraction of the proton momentum carried by the parton that enters the hard subprocess:

\[ \xi = x_{\text{Bj}} \left( 1 + \frac{M_{jjj}^2}{Q^2} \right) \]

In Breit frame only hard QCD process can generate significant \( P_T \).

Direct sensitivity to \( \alpha_s \) and gluon PDF
H1 High $Q^2$ Jet Production Analysis

Jets reconstruction
- Overconstrained system in DIS
- Energy flow algorithm
  - Calibration using neural networks
- $k_T$ and anti-$k_T$ algorithm in the Breit frame

Phase space and Jet samples
- HERA II data, 351 pb$^{-1}$
- Inclusive jets: every jet in an event exceeding a min $P_T$ contribute to a cross section $\sigma_{\text{jet}}$
- Dijets (Trijets): events with at least 2 (3) jets above a given $P_T$ contribute to a cross section $\sigma_{\text{dijet (trijet)}}$
- Normalised cross sections: $\sigma_{\text{jet}} / \sigma_{\text{NC DIS}}$

Unfolding
- Regularized unfolding with TUnfold*
- Multidimensional unfolding in $Q^2$, $y$, $P_T$
- Migrations of up to 7 observables and correlations between samples taken into account

Hadronic energy scale uncertainty 1%


Measurement phase space for jet cross sections

\[\begin{array}{c}
150 < Q^2 < 15,000 \text{ GeV}^2 \\
0.2 < y < 0.7 \\
-1.0 < \eta_{\text{lab}}^{\text{jet}} < 2.5 \\
7 < P_T^{\text{jet}} < 50 \text{ GeV} \\
5 < P_T^{\text{ct}} < 50 \text{ GeV} \\
M_{12} > 16 \text{ GeV}
\end{array}\]
H1 Data
- 150 < Q^2 < 200 GeV^2 (i = 16)
- 400 < Q^2 < 700 GeV^2 (i = 1)
- 200 < Q^2 < 270 GeV^2 (i = 11)
- 700 < Q^2 < 5000 GeV^2 (i = 0)
- 270 < Q^2 < 400 GeV^2 (i = 6)
- 5000 < Q^2 < 15000 GeV^2 (i = 0)

NLO QCD predictions, corrected for hadronisation and electroweak effects, in good agreement with data within uncertainties.
The determination and running of $\alpha_S$

From normalised multijet:

$$\alpha_S(M_Z) = 0.1165 \pm 0.0038 \text{ (pdf, theo)}$$

The most precise measurement from jet cross sections so far

The prediction for running using RGE and measured $\alpha_S$ agrees well with previous measurements at different scales
**ZEUS trijet measurements**

**Phase space:**

\[ 125 < Q^2 < 20000 \text{ GeV}^2 \]
\[ 0.2 < y < 0.6 \]

- At least three jets with
  \[ E_{T,B}^{\text{jet}} > 8 \text{ GeV} \text{ and } -1 < \eta_{\text{LAB}}^{\text{jet}} < 2.5 \]
- \( M_{jj} > 20 \text{ GeV} \)

**Prediction:** NLOJet++

- pPDF: HERAPDF1.5
- \( \mu_R^2 = Q^2 + \langle E_t^{\text{jet}} \rangle^2 \)
- \( \mu_f^2 = Q^2 \)

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**Figure:**

- **Trijets**
  - ZEUS (prel.) 295 pb \(^{-1}\)
  - NLOJET++ (HERAPDF1.5)
  - jet energy-scale unc.

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ZEUS trijet measurements

Double differential cross sections

Good agreement between data and NLO calculations
QCD Instantons

Instantons
- Solutions to Yang-Mills equations of motion
- Physical interpretations:
  *pseudo particle or tunneling process between topologically different vacuum states

QCD Instantons at HERA
- Produced in quark-gluon fusion*
- Analysis phase space:

\[ 150 < Q^2 < 15000 \text{ GeV}^2 \]
\[ 0.2 < y < 0.7 \]

- QCDINS Monte Carlo: access to full event topology

Selected Signatures
- One hard jet
- Densely populated eta band, flat in \( \phi \)
- Large particles multiplicities

Variables of \( I \)-subprocess:

\[ Q'^2 \equiv -q'^2 = -(\gamma - q'')^2 \]
\[ x' \equiv Q'^2 / (2 \, g \cdot q') \]
\[ W_l^2 \equiv (q' + g)^2 = Q'^2 \left( 1 - x' \right) / x' \]

QCD Instantons - strategy

Strategy I

- Find jets in hadronic center of mass frame
  - Remove hardest jet from objects of hadronic final state (HFS)
- Boost to instanton rest frame and define variables
  - Topological: sphericity, Fox-Wolfram moments, azimuthal isotropy ($\Delta_B$), ...
  - Number of charged particles $n_B$
  - Transverse energy of the band...
- Variables are used as input to MVA
QCD Instantons - strategy

Multivariate Analysis

• Probability density estimator with range search (PDERS)

• Training with Rapgap/Djangoh MC as background and QCDINS as signal MC

• Good discriminator description in the background region

• Signal region: D > 0.86
QCD Instantons - results

Data are *consistent with background*

No evidence for QCD Instantons

Limit calculations

- CL$_S$ method used
- Input for limit calculations: QCD Instanton cross section
  - Uncertainties: systematic and model
- Full range of the PDERS discriminator for better method reliability

Theoretical prediction in the analysis phase space: \(10 \pm 2\) pb

Upper limit for the instanton cross section at 95%CL: \(1.6\) pb

Exclusion of the Ringwald-Schrempp's predictions for the QCD Instantons at HERA
Summary

New interesting QCD results from the HERA experiments

Jet production in $ep$ collisions at HERA and determination of $\alpha_s$

- ZEUS and H1 measurements consistent with NLO calculations
- Most precise $\alpha_s(M_Z)$ is extracted from fit to the normalised multijet cross section, yielding

$$\alpha_s(M_Z)|_{k_T} = 0.1165 \, (8)_{\text{exp}} \, (38)_{\text{pdf, theo}}$$

- The running of $\alpha_s(\mu_r)$ consistent with the RGE and with results from other jet data
- Precision of the measurement (H1) is better than that of NLO calculations

Need NNLO

QCD Instantons searches

- Ringwald-Schrempp's predictions for the QCD Instantons at HERA appears to be excluded
Thank you for your attention
Backup slides
Observables not used in the TMVA training

Full range of the discriminator
Observables not used in the TMVA training

Signal range of the discriminator

No excess of events in the signal region
Azimuthal isotropy

\[ \Delta_b = \frac{E_{in,B}' - E_{out,B}'}{E_{in,B}'} \]

\[ E_{out} = \min \sum_{n \text{ Hadr.}} |p_n \cdot \vec{i}| \]

\[ E_{in} = \max \sum_{n \text{ Hadr.}} |p_n \cdot \vec{i}| \]

\[ \Delta_b \approx 1 \]

\[ \Delta_b \approx 0 \]
Test statistic distribution

Let's construct test statistics for Data, Background and Backgr+Signal

\[ CL_S = \frac{CL_{SB}}{CL_B} \]

Confidence Level: \( CL = 1 - CL_S \)