QCD at HERA

R. Yoshida
Argonne National Laboratory
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Outline

• Jet measurements and $\alpha_s$
• Parton distributions from structure function measurements.
• Parton distributions and $\alpha_s$ from structure functions and jets.
Jet measurements at HERA

Jets in DIS

Jet measurements at HERA has typical uncertainty ~5%.

Compare to ~60% at Tevatron
Jet measurements at HERA

- HERA jet energies can be calibrated using the energy balance with the scattered electron—achieve **1-2% energy uncertainty** for jets.

- HERA jets are reconstructed using the **theoretically robust algorithms** (typically $k_t$ rather than cone)—comparison to QCD theory does not suffer from large hadronization uncertainties.
Jet production processes at HERA

DIS

LO

QCD-COMPTON

BGF

Photoproduction

RESOLVED

DIRECT
Jet measurements and $\alpha_s$

Example: DIS jets in Breit frame

\[ \frac{d^2 \sigma_{\text{jet}}}{dE_T dQ^2} / (\text{pb}/\text{GeV}^2) \]

- $Q^2 / \text{GeV}^2$
  - [150 ... 200] (x 200)
  - [200 ... 300] (x 29)
  - [300 ... 600] (x 2)
  - [600 ... 5000]

- incl. $k_T$ algorithm

- $E_{T,\text{jet, Breit}} / \text{GeV}$

- $\alpha_s$ from inclusive jet cross section for CTEQ5M1 parton densities

- $\alpha_s(\mu_T)$
- $\alpha_s(M_Z)$

Current

- QCD-COMPTON
- BGF

Breit frame (ep)

- LO
- \( e^+ e^- \rightarrow e^+ e^- \)
- \( e^+ e^- \rightarrow \mu^+ \mu^- \)

Proton \( -Q/2 \)

Electron \( -Q \)

$\mu_T = E_T$
Jet measurements and $\alpha_s$

Example: 3 to 2 jet rate ratio
pdf uncertainty tends to cancel
Jet measurements and $\alpha_s$

Correlations between pdf and $\alpha_s$

- **Pdfs** are extracted assuming some value of $\alpha_s$ (or determines the value of $\alpha_s$)
- Jet cross-sections at HERA depends on pdfs
- $\alpha_s$ from jets is extracted taking this correlation into account.
- In effect the value of $\alpha_s$ is varied simultaneously in pdf and cross-section calculations when fitting data to optimum $\alpha_s$—this is done using a set of pdfs determined at various values of $\alpha_s$. 
Jet measurements and $\alpha_s$

NLOQCD fits to st. fcn

Jet shapes in NC DIS
ZEUS (DESY 04-072 - hep-ex/0405065)
Multi-Jets in NC DIS
ZEUS prel. (contributed paper to ICHEP04)
Inclusive jet cross sections in $\gamma p$
Subjet multiplicity in CC DIS
ZEUS (Eur Phys Jour C 31 (2003) 149)
Subjet multiplicity in NC DIS
ZEUS (Phys Lett B 558 (2003) 41)
NLO QCD fit
H1 (Eur Phys J C 21 (2001) 33)
NLO QCD fit
ZEUS prel. (contributed paper to ICHEP04)
NLO QCD fit
Inclusive jet cross sections in NC DIS
H1 (Eur Phys J C 19 (2001) 289)
Inclusive jet cross sections in NC DIS
ZEUS (Phys Lett B 547 (2002) 164)
Di-jet cross sections in NC DIS
ZEUS (Phys Lett B 507 (2001) 70)
World average
(S. Bethke, hep-ex/0407021)

Measurements combined (C. Glasman et al.) →

$\alpha_s(Q)$

Deep Inelastic Scattering
$e^+e^-$ Annihilation
Hadron Collisions
Heavy Quarkonia

$\alpha_s(M_Z) = 0.118 \pm 0.003$
Structure functions and pdf

Example: ZEUS NLO QCD fit (similar results for H1)

Fixed target results are used in fit to fix the high x pdf
Structure functions and pdf

Use all of HERA I data (>100 pb-1) to replace fixed target experiments in the fit.

No low Q2, heavy target corrections.

H1 data: similar for ZEUS
Structure function and pdf

HERA only fit: H1 results similar for ZEUS

High x statistics dominated

\( \alpha_s \) weakly constrained

note: \( \alpha_s \) enters multiplied by the gluon density at lower \( x \) where HERA has high precision data.
Jet measurements and pdf

Note: cross-section is directly proportional to gluon. For structure function Q2 slope is proportional.
Jet measurements and QCD fit

- Up to now, no QCD fit made rigorous use of jet data. CTEQ, MRST global fits use LO + k-factor for their jet descriptions.
- Although NLO jet calculations exist (DISENT, PHOJET, NLOJET etc.), their use in an iterative fitting procedure is not possible due to prohibitive computing time requirements.
- ZEUS collaboration has pioneered a fast calculation method (basically putting the cross-sections on a grid) which enables the use of jet data to be put rigorously into a NLO fit.
- This makes possible, for the first time, a rigorous use of jet data in NLOQCD fits to parton distributions of the proton.
- This enables, for example, a consistent simultaneous extraction of precision $\alpha_s$ (mainly based on jets) and pdfs taking all correlated uncertainties into account.
ZEUS-JETS QCDNLO fit results
ZEUS-JETS NLOQCD fit results

Jet data constrain the medium x gluon

Gluon improvement

NC and CC constrain quarks
ZEUS-JETS simultaneous fit to pdf and $\alpha_s$

Gluon does not become unconstrained when $\alpha_s$ freed.
HERALHC workshop

Predictions of LHC jet cross-sections

Improvement due to inclusion of ZEUS jet data

Prediction for LHC Inclusive jet production using ZEUS-ONLY 2004 and ZEUS-JETS 2004 PDFs in the JETRAD programme-uncertainties in the prediction are smaller using the PDFs which include HERA jet information

work by: K. Nagano, KEK
ZEUS-JETS fit: possible extensions

- **Use charm production data:** still has some theoretical issues; also experimental systematic uncertainties are a little too large.
- **Use other jet data:** use e.g. 2 to 3 jet ratio, subjet multiplicity etc.
- Use “resolved” photoproduction jet data and constrain photon pdfs simultaneously.
- ...
Impact of HERA II

- HERA II (x5 increase in luminosity compared to HERA I)
- Planned to run to middle of 2007
- 500-1000 pb-1 data using both e+ and e-beams. (also e polarization)
- Currently taking data
- Impact on these fits?
HERALHC workshop

Impact on d-valence distribution

- Maximum uncertainty reduced from over 200% to 100%

(C. Gwenlan, Oxford)
Impact on $x F_3 \sim \Sigma x(q-q\bar{q})$

- Significant improvement in $x F_3$ uncertainties (max. uncert. goes from ~60-20%)

(C. Gwenlan, Oxford)
Impact on the gluon distribution

- Impact at mid-to-high-\(x\), uncertainties are further reduced

(C. Gwenlan, Oxford)
Conclusions

• HERA jet measurements are precision data (~5% uncertainty).
• $\alpha_s$ has been measured at HERA from jets, running, over an order of magnitude in scale, and at a precision at the level of the world average. The uncertainties are dominated by theoretical ones.
• ZEUS has developed a method to do a rigorous combined fit at NLO with structure function and jet measurements to extract pdfs and $\alpha_s$. The precision of the gluon determination improve markedly; a precision $\alpha_s$ is extracted.
• The new HERA II data will lead to much improved pdfs at high $x$. 
Extras
HERALHC workshop

**Impact on the LHC (an example)**

$W^\pm$ production (plots from Kunihiro Nagano)

- $pp \rightarrow W + X$
- $\sqrt{s} = 140$ TeV
- $|\eta_{lepton}| < 2.5$
- $p_T > 20$ GeV
- $E_T > 20$ GeV
- DYRAD
- PDF: ZEUS-D (ZMVFN)

**Before:** no jet data

**After:** with jet data

- Smaller uncertainties from improved knowledge of gluon from jet data

(K. Nagano, KEK)
Triumph of perturbative QCD

A part of Wilczek’s comments upon the Nobel Prize announcement

proposed specific experimental tests of our ideas. In the fourth paper some technical objections to the theory were cleared up, and in the fifth and sixth papers further experimental consequences, regarding the pointwise evolution of structure functions, were derived. The most dramatic of these, that protons viewed at ever higher resolution would appear more and more as field energy (soft glue), was only clearly verified at HERA twenty years later.
## HERALHC workshop

### 2. Comparison of ZEUS/H1 public analyses

Both ZEUS (2004) and H1 (2003) now make PDF fits to their own data. Where does the information come from in a HERA only fit compared to a global fit?

<table>
<thead>
<tr>
<th></th>
<th>Global</th>
<th>HERA Only</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Valence</strong></td>
<td>Predominantly fixed target data ((\nu\text{-Fe} \text{ and } \mu\text{D}/\mu\text{p}))</td>
<td>High (Q^2) NC/CC (e^+e^-) cross sections</td>
</tr>
<tr>
<td><strong>Sea</strong></td>
<td>Low-x from NC DIS</td>
<td>Low-x from NC DIS</td>
</tr>
<tr>
<td></td>
<td>High-x from fixed target</td>
<td>High-x less precise</td>
</tr>
<tr>
<td></td>
<td>Flavour from fixed target</td>
<td>Flavour ? (need assumptions)</td>
</tr>
<tr>
<td><strong>Gluon</strong></td>
<td>Low-x from HERA (dF_2/d\ln Q^2)</td>
<td>Low-x from HERA (dF_2/d\ln Q^2)</td>
</tr>
<tr>
<td></td>
<td>High-x from momentum sum</td>
<td>High-x from momentum sum</td>
</tr>
</tbody>
</table>

**ANALYSES FROM HERA ONLY ...**
- Systematics well understood
  - measurements from our own experiments !!!
- No complications from heavy target Fe or D corrections

(A. Cooper-Sarkar, Oxford)
Both collaborations include model errors – variations on assumptions at $Q^2_0$. These are large compared to the HESSIAN exp. errors of H1, and small compared to the OFFSET exp. errors of ZEUS. Comparison with model errors included gives similar size of errors.

But valence PDFs cannot really be compared this way because H1 do not fit in terms of valence PDFs and model errors cannot be easily evaluated- recall that the H1 parametrization puts a strong constraint on the shape of the valence PDF

(A. Cooper-Sarkar, Oxford)
I have also made predictions for CDF jet data.
- And I obtain $\chi^2$ of 63 for 31 data points for MRST2002 PDFs.
- Whereas I obtain $\chi^2$ of 51 for 31 data points for ZEUS-S 2002 central PDFs.
I.e., we are actually BETTER at predicting CDF jets!

This figure shows $(data-theory)/theory$.
And the error bars represent the size of the experimental error.
Whereas the shaded area represents the PDF error larger than exp error until high ET.
IF the PDF error is included in the $\chi^2$ we get $\chi^2 = 13$ for 31 d.p.

(A. Cooper-Sarkar, Oxford)
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We would also like to investigate these things for the ZEUS PDFs 2004 both the ZEUS-ONLY (no jets) PDFs and the ZEUS-JETS PDFs

(ZEUS-ONLY no jets
\[\chi^2 = 122\] for central PDF \[\chi^2 = 26\] if PDF error accounted

(ZEUS-ONLY no jets
\[\chi^2 = 49\] for central PDF \[\chi^2 = 8\] if PDF error accounted

(ZEUS-JETS \[\chi^2 = 118\] for central PDF \[\chi^2 = 34\] if PDF error accounted

(ZEUS-JETS \[\chi^2 = 49\] for central PDF \[\chi^2 = 10\] if PDF error accounted

(A. Cooper-Sarkar, Oxford)

Note: CDF and D0 data have large (up to 60%) systematic uncertainties not shown on the plots: in case of the CDF data systematics are “shifted” to optimal values in the course of the fit. This is not possible for the D0 data since the relevant information is not available.