$k_T$, anti-$k_T$ & SIScone jets and $\alpha_s \@ HERA$

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on behalf of the H1 and ZEUS collaborations

- introduction
- measurements of $k_T$ multijets at low $Q^2$
- measurement of inclusive $k_T$, anti-$k_T$ and SIScone jets at high $Q^2$
- comparison of data to NLO
- running $\alpha_s$ and $\alpha_s(M_Z)$ from jets
**HERA: ep collider, basic kinematics**

- \( \sqrt{s} = 318 \text{ GeV} \)
- \( E_e = 27.6 \text{ GeV} \quad E_p = 920 \text{ GeV} \)
- 2001/2002 luminosity upgrade \( \rightarrow \) HERA-2
- \( \sim 0.5 \text{ fb}^{-1} \) of data collected per experiment

- Virtuality of the exchanged boson:
  \[ Q^2 = -q^2 = -(k-k')^2 = sxy \]

- Bjorken scaling variable:
  \[ x = Q^2/2p \cdot q \]

- Inelasticity:
  \[ \gamma = p \cdot q/p \cdot k \]
Jet production in DIS @ HERA

2 large scales in DIS: $Q$ (2-125 GeV) & $P_{T_\text{jet}}$ (5-80 GeV)

typical choices for pQCD calculations are:

$\mu_f = Q$, $\mu_r = Q$ or $P_{T_\text{jet}}$ (ZEUS)

$\mu_r = \sqrt{[(Q^2 + (P_{T_\text{jet}})^2)/2]}$ (H1)
Jet production in DIS @ HERA

tracks and calorimetric energy deposits are measured in the laboratory

Jet finding is usually performed in the Breit frame (in analogy to e+e-)

QPM process generates no $p_T$

only QCD processes generate $p_T$
Jet finding: $k_T$, anti-$k_T$ & SIScone

Requirements for comparing jet cross sections with pQCD:
- factorization $\Rightarrow$ in DIS perform measurement in Breit frame
- collinear & infrared safe jet algorithm $\Rightarrow k_T$, anti-$k_T$ & SIScone

Sequential recombination algorithms:

\[ d_{ij} = \min(k_{T_i}, k_{T_j})^{2p} \frac{\Delta R^2}{R^2} \quad \text{and} \quad d_{IB} = k_{T_i}^{2p} \]

with \[ \Delta R^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2 \]

\[ p = 1 \Rightarrow k_T \]
\[ p = -1 \Rightarrow \text{anti-}k_T \]

at HERA typically $R=1.0$

SIScone:
- seedless iterative cone with split merge (0.75)
- finds stable cones, i.e. cone axis = momentum sum of particles
H1: Multijet cross sections at low $Q^2$

- arXiv:0911.5678, HERA-1 data, 44 pb$^{-1}$
- DIS phase space: $5 < Q^2 < 100$ GeV$^2$, $0.2 < y < 0.7$
- jet phase space: $-1.0 < \eta_{\text{jet,lab}} < 2.5$
  - incl. jets, 2-jet, 3-jet: $p_T > 5$ GeV (Breit)
  - 2-jet & 3-jet: $M_{1,2} > 18$ GeV
- cross sections are measured as function of $Q^2$, $p_T$ ($<p_T>$) and $\xi$
- main experimental uncertainties:
  - jet energy scale 2% $\Rightarrow \Delta \sigma/\sigma = 4\text{-}10\%$
  - uncertainty in acceptance $\Rightarrow \Delta \sigma/\sigma = 2\text{-}15\%$
- NLO calculation: NLOJET++
  - MSbar scheme for 5 massless quark flavors,
  - $\mu_f = \mu_r = \sqrt{(Q^2 + p_{T,\text{jet}}^2)/2}$
  - PDFs: CTEQ6.5M
Inclusive Jet, 2-Jet and 3-Jet Cross Sections

- Measurements are well described by NLO
- Exp. uncertainty 6-11%
- Theo. uncert., dominated by renorm. scale uncertainty: 30% (lowest $Q^2$ and $p_T$) to 10% (highest $Q^2$ and $p_T$)
- Pdf uncertainty: 6 to 2%
- Low predictive power of NLO at low $Q^2$ and/or low $p_T$ → orders beyond NLO are needed to match the precision of the data
H1: 3-jet/2-jet ratio in $Q^2$, <$p_T$>

- in ratio norm. errors cancel & other syst. uncertainties reduced by 50%
- reduced sensitivity to renorm. scale variation in theory
- good description of ratio by NLOjet++

analysis on 9 x stats of HERA-2 in progress
**H1: $\alpha_s$ from low & high $Q^2$ jets**

- **at low $Q^2$, extraction of $\alpha_s(M_Z)$** from double diff. incl. jet, 2 and 3-jet cross sections using the $k_T$ jet finder:
  
  \[
  \alpha_s(M_Z) = 0.1160 \pm 0.0014 \text{(exp.)} +0.0030 \underbrace{-0.0077}_{\text{(th.)}} \pm 0.0016 \text{(pdfs)}
  \]

- **at high $Q^2$, extraction of $\alpha_s(M_Z)$** from double diff. **normalized** incl. jet, 2 and 3-jet cross sections using the $k_T$ jet finder:
  
  \[
  \alpha_s(M_Z) = 0.1168 \pm 0.0007 \text{(exp.)} +0.0046 \underbrace{-0.0030}_{\text{(th.)}} \pm 0.0016 \text{(pdfs)}
  \]

  central value of $\alpha_s(M_Z)$ using anti-$k_T$ is within 0.6%

remarkable agreement between low and high $Q^2$ extraction & with QCD expectations

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ZEUS: Incl. $k_T$, anti-$k_T$, SIScone jets

- HERA-1 data, 82 pb$^{-1}$, DESY-10-034, arXiv:1003.2923
- DIS phase space: $Q^2 > 125$ GeV$^2$, $|\cos \gamma_h| < 0.65$
- jets are found in the Breit frame using anti-$k_T$ and SIScone
- jet phase space: at least one jet with $-2 < \eta < 1.5$, $E_T > 8$ GeV in Breit frame
- incl. jet cross sections are measured as a function of $Q^2$ and $E_T$
- main experimental uncertainties:
  - jet energy scale 1% ($E_{T,\text{lab}} > 10$ GeV) to 3% for lower $E_{T,\text{lab}} \Rightarrow \Delta \sigma / \sigma \approx 5$
  - uncertainty in acceptance $\Rightarrow \Delta \sigma / \sigma \approx 4$
- NLO calculations: DISENT & NLOjet++
  - MSbar scheme for 5 massless quark flavors
  - $\mu_f = Q$ and $\mu_r = E_T$
- PDFs: ZEUS-S parametrization
**ZEUS: Incl. $k_T$, anti-$k_T$, SIScone jets**

- **Data** and NLO are in good agreement.
- Hadronization corrections are smallest for $k_T$ and largest for SIScone.
**ZEUS: Incl. \( k_T \), anti-\( k_T \), SIScone jets**

- **Theoretical relative uncertainties**

![Graphs showing theoretical uncertainties vs. \( E_{T,B} \) and \( Q^2 \)]

- **Theory uncert. as a funct. of \( Q^2 \)** varies from 3-7% (3-10%) for the **anti-\( k_T \) (SIScone)**

- **NLO** using \( k_T \) and anti-\( k_T \) have similar precision, with SIScone slightly less precise
**Ratio of incl. jet cross sections based on different jet algorithms:**

- incl. jet cross sections currently calculated up to $O(\alpha_s^2)$

- differences of incl. jet cross sections using different jet algorithms can however be predicted up to $O(\alpha_s^3)$ using NLOjet++

\[
\frac{d\sigma_{\text{anti-}k_T}/dX}{d\sigma_{k_T}/dX} = 1 + \frac{d\sigma_{\text{anti-}k_T}/dX - d\sigma_{k_T}/dX}{d\sigma_{k_T}/dX} \approx 1 + \frac{C\alpha_s^3}{A\alpha_s + B\alpha_s^2}
\]

\[
\frac{d\sigma_{\text{SIScone}}/dX}{d\sigma_{k_T}/dX} = 1 + \frac{d\sigma_{\text{SIScone}}/dX - d\sigma_{k_T}/dX}{d\sigma_{k_T}/dX} \approx 1 + \frac{D\alpha_s^2 + E\alpha_s^3}{A\alpha_s + B\alpha_s^2}
\]

*note: for the cancellations to work, the differences are calculated on an event by event basis*
ZEUS: xsect ratios of data & of NLO

- In $E_T$ the ratios differ from unity by < 3.6%, except at highest $E_T$ (10%).
- In $Q^2$ they differ by < 3.2%.
- Data ratios are well described by predictions up to $O(\alpha_s^3)$.
- In ratio, theoretical uncertainty mainly due to hadronization uncertainty.
ZEUS: determination of $\alpha_s(M_Z)$

- use data on $d\sigma/dQ^2$ for $Q^2 > 500$ GeV$^2$ (to minimize error on $\alpha_s(M_Z)$)
- NLO calculation using DISENT
- PDFs: ZEUS-S parametrizations for five different values of $\alpha_s(M_Z)$
- main uncertainties on $\alpha_s(M_Z)$
  - jet energy scale $\rightarrow$ 1.9 to 2%
  - terms beyond NLO $\rightarrow$ 1.5% (method by Jones et al.)
  - pdfs $\rightarrow$ 0.7 to 0.8%
  - hadronization $\rightarrow$ 0.8% ($k_T$), 0.9% (anti-$k_T$), 1.2% (SIScone)

\[ k_T: \quad \alpha_s(M_Z) = 0.1207 \pm 0.0014 \text{ (stat.)}^{+0.0035}_{-0.0033} \text{ (exp.)}^{+0.0022}_{-0.0023} \text{ (th.)} \]

\[ \text{anti-}k_T: \quad \alpha_s(M_Z) = 0.1188 \pm 0.0014 \text{ (stat.)}^{+0.0033}_{-0.0032} \text{ (exp.)}^{+0.0022}_{-0.0022} \text{ (th.)} \]

\[ \text{SIScone}: \quad \alpha_s(M_Z) = 0.1186 \pm 0.0013 \text{ (stat.)}^{+0.0034}_{-0.0032} \text{ (exp.)}^{+0.0025}_{-0.0025} \text{ (th.)} \]

The values are very similar, differences comparable to terms beyond NLO
Summary

- Multijet cross sections for $Q^2 < 100$ GeV$^2$ in good agreement with expectations from NLO
- consistent $\alpha_s(M_Z)$ & running from low and high $Q^2$ multijet cross sections
- first measurements of incl. jet cross sections using anti-$k_T$ and SIScone
- the measured cross sections have similar shapes & normalization, and they agree well with NLO
- calculations have similar precision, only SIScone is slightly less precise
- $k_T$, anti-$k_T$ and SIScone lead to similar values of $\alpha_s(M_Z)$ with similar precision.

![Graph showing comparisons between measurements and calculations for $\alpha_s(M_Z)$ with error bars indicating experimental uncertainty and theoretical uncertainty.](image-url)
Thank you!

Further results from H1 & ZEUS:

http://www-h1.desy.de/publications/H1_sci_results.shtml
http://www-zeus.desy.de/zeus_papers/zeus_papers.html
Jet finding: $k_T$, anti-$k_T$ & SIScone
H1: 2-jets & $\alpha_s$

2-Jet Cross Section

$\frac{d^2\sigma}{dQdP_T}$ [pb/GeV]

- $5 < Q^2 < 7$ GeV$^2$
- $7 < Q^2 < 10$ GeV$^2$
- $10 < Q^2 < 15$ GeV$^2$
- $15 < Q^2 < 20$ GeV$^2$
- $20 < Q^2 < 30$ GeV$^2$
- $30 < Q^2 < 40$ GeV$^2$
- $40 < Q^2 < 100$ GeV$^2$

$\alpha_s$ from Inclusive Jet Cross Sections

- H1 data
- $\alpha_s$ fit to $c_{jet}$
- Theory+PDF

$\alpha_s$ from 2-Jet Cross Sections

- H1 data
- $\alpha_s$ fit to $c_{2-jet}$
- Theory+PDF
NLOjet++ provides also a good description of the 3-jet cross section in NLO, i.e. $O(\alpha_s^3)$. 
Jet multiplicity & Running $\alpha_s$

Normalized Inclusive Jet Cross Section

H1

$\alpha_s$ fit to $\sigma_{\text{jet}}/\sigma_{\text{NC}}$

$\mu_r = \sqrt{(Q^2 + P_T^2)/2}$

H1 data

H1

$\mu_r / \text{GeV}$

$10^2$
Theory uncertainty on $\alpha_s(M_Z)$

- method 1: the fit of $\alpha_s(M_Z)$ to the data is repeated with $\mu_r$ scaled by 0.5 and 2 in the NLO calc.; the difference to the result with the nominal scale is taken as uncertainty.
  - the theory uncertainty depends on the data
- method 2: only theory is used (Jones et al., JHEP 122003007), no refit to data
ZEUS: data/NLO for $k_T$ & SIScone

ZEUS

- ZEUS 82 pb$^{-1}$
- NLO uncertainty
- anti-$k_T$

$125 < Q^2 < 250$ GeV$^2$
$250 < Q^2 < 500$ GeV$^2$

$-2 < \eta_h^B < 1.5$
$|\cos \gamma_h| < 0.65$

jet energy scale uncertainty

$500 < Q^2 < 1000$ GeV$^2$
$1000 < Q^2 < 2000$ GeV$^2$

$2000 < Q^2 < 5000$ GeV$^2$
$Q^2 > 5000$ GeV$^2$

ratio to NLO

ZEUS

- ZEUS 82 pb$^{-1}$
- NLO uncertainty
- SIScone

$125 < Q^2 < 250$ GeV$^2$
$250 < Q^2 < 500$ GeV$^2$

$-2 < \eta_h^B < 1.5$
$|\cos \gamma_h| < 0.65$

jet energy scale uncertainty

$500 < Q^2 < 1000$ GeV$^2$
$1000 < Q^2 < 2000$ GeV$^2$

$2000 < Q^2 < 5000$ GeV$^2$
$Q^2 > 5000$ GeV$^2$

ratio to NLO

$E_{T,B}$ (GeV)

$E_{T,B}$ (GeV)
Fitting $\alpha_s(M_Z)$: $\chi^2$

Minimise $\chi^2(\alpha_s(M_Z))$ defined as:

$$\chi^2 = \vec{V}^T \cdot M^{-1} \cdot \vec{V} + \sum_k \varepsilon_k^2$$

- correlated version of $\sum$(difference/error)$^2$
- penalty term for fitted systematics
- "Hessian" method

$$M = M_{\text{stat.}} + M_{\text{uncor.}}$$

- correlated for some bins
- uncorrelated systematics

$$V_i = \sigma_i^{\text{exp.}} - \sigma_i^{\text{theo.}} (1 - \sum_k \Delta_{ik} \varepsilon_k)$$

- bin #
- correlated systematical error #k
- parameter in fit, pull "Hessian" method

Exp. uncertainty of fit defined as $\alpha_s$ interval upto minimum $\chi^2 + 1$