Jet substructure at HERA

from

C Glasman
Universidad Autónoma de Madrid

ZEUS Collab.

H1 Collab.

at

HERA

$e$ (E$_e$ = 27.5 GeV) \quad p$ (E$_p$ = 920 GeV)

$\sqrt{s} = 318$ GeV

\[ s = 318 \text{ GeV} \]
Perturbative calculations lead to partonic final states which are not directly accessible to the experimentalist

→ hadrons and not partons are observed in the final state
→ the observed hadrons are the result of the fragmentation of the coloured partons
→ all hadrons originating from a parton are contained in a narrow region around the original parton direction of motion, forming a “jet”

→ The first step in comparing experimental results with theoretical calculations is to group hadrons into jets to recover the parton topology (jet algorithms)

Jet structure:

→ the $p_L$ distribution of the hadrons in a jet scales with jet energy
→ the $p_T$ distribution of the hadrons in a jet has a mean value of $\sim 300$ MeV
→ $p_T/p_L$ (mean angle between a hadron and the jet axis) should decrease with jet energy → the size of a cone which contains a constant fraction of jet energy decreases with the jet energy
→ at high energies, gluon emission dominates and fragmentation effects become negligible → structure of jets driven by radiation and calculable in pQCD
Jet substructure

- The investigation of the internal structure of jets gives insight into the transition between a parton produced in a hard process and the experimentally observable jet of hadrons.

- QCD predictions:
  - Jet substructure driven by gluon emission off primary partons (at sufficiently high $E_T$, fragmentation effects negligible).
  - Gluon jets are broader than quark jets (larger colour charge of the gluon).
  - Jet substructure depends mainly on flavour of primary parton from which the jet originated and to a lesser extent on the hard scattering process.
Jet substructure: integrated jet shape

- $\psi(r)$: fraction of the jet transverse energy that lies inside a cone in the $\eta - \varphi$ plane of radius $r$, concentric with the jet axis

\[
\psi(r) = \frac{E_T(r)}{E_T^{\text{jet}}}
\]

\[
\langle \psi(r) \rangle = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{E_T(r)}{E_T^{\text{jet}}}
\]

mean integrated jet shape

Jet substructure: subjet multiplicity

- subjets: are resolved within a jet by reapplying the $k_T$ cluster algorithm until for every pair of particles $i, j$

\[
d_{ij} = \min(E_{Ti}, E_{Tj})^2[(\eta_i - \eta_j)^2 + (\varphi_i - \varphi_j)^2]
\]

is above $y_{\text{cut}} \cdot (E_T^{\text{jet}})^2$

\[
\langle n_{\text{sbj}}(y_{\text{cut}}) \rangle = \frac{1}{N_{\text{jets}}} \sum_{i=1}^{N_{\text{jets}}} n_{\text{sbj}}^i(y_{\text{cut}})
\]

mean subjet multiplicity
QCD calculations of jet substructure

- **QCD-based Monte Carlo models:**
  - \textbf{Pythia, Herwig, Ariadne, Lepto} approximate the substructure of jets with parton showers

- **Fixed-order QCD calculations:**
  - at lowest order, a jet consists of one parton (no structure)
  - higher-order terms give the non-trivial contributions
  - NLO calculations in NC DIS are possible in LAB frame from $\mathcal{O}(\alpha_s^2)$ predictions since three partons can be inside one jet

- **Measurements of jet substructure provide a stringent test of pQCD calculations directly beyond LO**

- **pQCD calculations of jet shapes:**
  \[
  \langle 1 - \psi(r) \rangle = \frac{\int_R^R dE_T \left( E_T / E_T^{\text{jet}} \right) [d\sigma(ep \to 2\text{partons})/dE_T]}{\sigma_{\text{jet}}(E_T^{\text{jet}})}
  \]

- **pQCD calculations of subjet multiplicities:**
  \[
  \langle n_{\text{sbj}}(y_{\text{cut}}) \rangle = 1 + \frac{1}{\sigma_{\text{jet}}} \sum_{j=2}^{\infty} (j - 1) \cdot \sigma_{\text{sbj},j}(y_{\text{cut}}) = 1 + C_1 \alpha_s + C_2 \alpha_s^2
  \]
Jet substructure and QCD predictions

- **QCD predictions:**
  - jet substructure driven by *gluon emission* off primary partons (at sufficiently high $E_T^{\text{jet}}$, fragmentation effects negligible)

  → Adequate description of data by $O(\alpha_s^3)$ theory and QCD-based MC models
  → QCD prediction confirmed!
QCD predictions:

- Gluon jets are broader than quark jets (larger colour charge of the gluon)

→ Gluon jets are seen to be substantially broader than quark jets
→ QCD prediction confirmed!
Tests of pQCD using jet substructure at HERA
Jet production at HERA

- Jet production in photoproduction up to \( \mathcal{O}(\alpha_s) \):

\[
x^{\text{obs}}_{\gamma} = \frac{1}{E_{\gamma}} \left( \sum_{\text{jets}} E_{\text{jet}}^\gamma e^{-\eta_{\text{jet}}} \right)
\]

- Resolved processes give rise to quark and gluon jets through \( q\gamma g_p \to qg, g\gamma g_p \to gg, \ldots \)

- Direct processes give rise mostly to quark jets through \( \gamma g \to q\bar{q} \)

- \( \eta_{\text{jet}} \) dependence of jet substructure expected to show quark-like jets for \( \eta_{\text{jet}} < 0 \) and gluon-like jets in forward direction due to HERA dynamics
Jet production in neutral and charged current deep inelastic $ep$ scattering up to $\mathcal{O}(\alpha_s)$:

- **Quark-parton model**
  
  \[ e + p \rightarrow q + q + \gamma/Z (W) + \text{proton remnant} \]

- **Boson-gluon fusion**
  
  \[ e + p \rightarrow e (v) + \bar{q} + \gamma/Z (W) + \text{Jet} \]

- **QCD Compton**
  
  \[ e + p \rightarrow e (v) + g + q + \gamma/Z (W) + \text{Jet} \]

→ Inclusive-jet sample expected to be dominated by quark jets

→ no dependence of jet substructure on $\eta_{jet}$ expected

→ Dijet sample expected to contain a larger fraction of gluon jets

→ jets expected to become broader as $\eta_{jet}$ increases
Mean integrated jet shape in photoproduction

- $\eta^{\text{jet}}$ dependence of $\langle \psi (r) \rangle$ in photoproduction
  - Jets searched using the cone algorithm
  - Kinematic region: $0.2 < y < 0.85$ and $Q^2 \leq 4$ GeV$^2$
  - At least one jet with $E_T^{\text{jet}} > 14$ GeV and $-1 < \eta^{\text{jet}} < 2$

- $\langle \psi (r) \rangle$ vs $r$ in different $\eta^{\text{jet}}$ regions:
  - Jets become broader as $\eta^{\text{jet}}$ increases

- Comparison to QCD predictions:
  - Models with only fragmentation predict jets too narrow
  - Models including initial- and final-state QCD radiation give a good description of the data for $-1 < \eta^{\text{jet}} < 1$
  - Parton radiation dominant mechanism responsible for jet shape
• $\eta^{\text{jet}}$ dependence of $\langle \psi(r) \rangle$ in photoproduction
  
  - Jets searched using the cone algorithm
  - Kinematic region: $0.2 < y < 0.85$ and $Q^2 \leq 4 \text{ GeV}^2$
  - At least one jet with $E_T^{\text{jet}} > 14 \text{ GeV}$ and $-1 < \eta^{\text{jet}} < 2$

• $\langle \psi(r) \rangle$ vs $r$ in different $\eta^{\text{jet}}$ regions:
  → jets become broader as $\eta^{\text{jet}}$ increases

• Comparison to QCD predictions:
  → predictions for gluon and quark jets show that the measured jets are
    → quark-like for $-1 < \eta^{\text{jet}} < 0$
    → gluon-like for $1 < \eta^{\text{jet}} < 2$
Mean integrated jet shape in photoproduction

- $\eta^{\text{jet}}$ and $E_T^{\text{jet}}$ dependence of $\langle \psi (r = 0.5) \rangle$ in photoproduction
  - Jets searched using the $k_T$ cluster algorithm
  - Kinematic region: $0.2 < y < 0.85$ and $Q^2 \leq 1 \text{ GeV}^2$
  - At least one jet with $E_T^{\text{jet}} > 17$ GeV and $-1 < \eta^{\text{jet}} < 2.5$

- The measured $\langle \psi (r = 0.5) \rangle$ decreases with $\eta^{\text{jet}}$
  $\rightarrow$ the jets become broader as $\eta^{\text{jet}}$ increases

- The measured $\langle \psi (r = 0.5) \rangle$ increases with $E_T^{\text{jet}}$
  $\rightarrow$ the jets become narrower as $E_T^{\text{jet}}$ increases

- Comparison with the predictions for gluon and quark jets:
  $\rightarrow$ the broadening of the jets is consistent with an increasing fraction of gluon jets as $\eta^{\text{jet}}$ increases
Mean integrated jet shape in photoproduction

- $x_\gamma^{\text{obs}}$ and $\eta^{\text{jet}}$ dependence of $\langle \psi(r) \rangle$ in photoproduction:
  - Jets searched using the $k_T$ cluster algorithm
  - Kinematic region: $0.2 < y < 0.8$ and $Q^2 \leq 1 \text{ GeV}^2$
  - At least two jets with $E_T^{\text{jet}} > 7, 6 \text{ GeV}$ and $-0.75 < \eta^{\text{jet}} < 1.5$

- $\langle \psi(r) \rangle$ vs $r$ in different $x_\gamma^{\text{obs}}$ regions:
  - Jets for $x_\gamma^{\text{obs}} \leq 0.75$ are broader than for $x_\gamma^{\text{obs}} > 0.75$

- $\langle \psi(r=0.5) \rangle$ decreases with $\eta^{\text{jet}}$
  - Jets become broader as $\eta^{\text{jet}}$ increases

- $\langle \psi(r=0.5) \rangle$ increases with $x_\gamma^{\text{obs}}$
  - Jets become narrower as $x_\gamma^{\text{obs}}$ increases

- Comparison to QCD predictions for resolved and direct:
  - Good description of data by predictions
  - Data consistent with being dominated by resolved for $x_\gamma^{\text{obs}} \leq 0.75$ and by direct for $x_\gamma^{\text{obs}} > 0.75$
Mean integrated jet shape in NC DIS

- $r$, $\eta^\text{jet}_B$ and $E_{T,B}^\text{jet}$ dependence of $\langle \psi(r) \rangle$ in NC DIS
  - Jets searched using the $k_T$ cluster algorithm in Breit frame
  - Kinematic region: $10 < Q^2 < 120 \text{ GeV}^2$
  - At least two jets with $E_{T,B}^\text{jet} > 5 \text{ GeV}$ and $-1 < \eta^\text{jet}_{LAB} < 2$

- The measured $\langle \psi(r = 0.5) \rangle$ decreases with $\eta^\text{jet}_B$
  → the jets become broader towards proton direction
  → effect more pronounced at low $E_{T,B}^\text{jet}$

- The measured $\langle \psi(r = 0.5) \rangle$ increases with $E_{T,B}^\text{jet}$
  → the jets become narrower as $E_{T,B}^\text{jet}$ increases

- Comparison to QCD predictions:
  → the data are well described by the QCD-based MC models
  → MC models predict jet sample dominated by quark-initiated jets
  → observed jet substructure compatible with that of quark-initiated jets
Mean integrated jet shape in NC DIS

- $\eta^{\text{jet}}$ dependence of $\langle \psi(r) \rangle$ in NC DIS
  - Jets searched using the $k_T$ cluster algorithm in LAB frame
  - Kinematic region: $Q^2 > 125$ GeV$^2$
  - At least one jet with $E_T^{\text{jet}} > 17$ GeV and $-1 < \eta^{\text{jet}} < 2.5$

- $\langle \psi(r) \rangle$ vs $r$ in different $\eta^{\text{jet}}$ regions:
  → no significant variation with $\eta^{\text{jet}}$ is observed

- Comparison to QCD predictions:
  → NLO predictions in NC DIS are possible in LAB frame from $\mathcal{O}(\alpha_s^2)$ calculations since three partons can be inside one jet

→ the data are well described by the NLO QCD calculations for $r > 0.1$
Mean integrated jet shape in NC DIS

- $E_T^{\text{jet}}$ dependence of $\langle \psi(r) \rangle$ in NC DIS
  - Jets searched using the $k_T$ cluster algorithm in LAB frame
  - Kinematic region: $Q^2 > 125$ GeV$^2$
  - At least one jet with $E_T^{\text{jet}} > 17$ GeV and $-1 < \eta^{\text{jet}} < 2.5$

- $\langle \psi(r) \rangle$ vs $r$ in different $E_T^{\text{jet}}$ regions:
  → the jets become narrower as $E_T^{\text{jet}}$ increases

- Comparison to QCD predictions:
  → NLO predictions in NC DIS are possible in LAB frame from $\mathcal{O}(\alpha_s^2)$ calculations since three partons can be inside one jet

→ the data are well described by the NLO QCD calculations for $r > 0.1$
Mean integrated jet shape in NC DIS

- \( \eta^{\text{jet}} \) and \( E_T^{\text{jet}} \) dependence of \( \langle \psi(r = 0.5) \rangle \) in NC DIS
  - Jets searched using the \( k_T \) cluster algorithm in LAB frame
  - Kinematic region: \( Q^2 > 125 \text{ GeV}^2 \)
  - At least one jet with \( E_T^{\text{jet}} > 17 \text{ GeV} \) and \(-1 < \eta^{\text{jet}} < 2.5\)

- The measured \( \langle \psi(r = 0.5) \rangle \) shows no significant variation with \( \eta^{\text{jet}} \)
- The measured \( \langle \psi(r = 0.5) \rangle \) increases with \( E_T^{\text{jet}} \) → the jets become narrower as \( E_T^{\text{jet}} \) increases
- Comparison with NLO QCD calculations → the calculations provide a good description of the data and show sensitivity to the value of \( \alpha_s(M_Z) \)
- From the measured \( \langle \psi(r = 0.5) \rangle \) for \( E_T^{\text{jet}} > 21 \text{ GeV} \) a value of \( \alpha_s(M_Z) \) has been extracted:

\[
\alpha_s(M_Z) = 0.1176 \pm 0.0009 \text{ (stat.)}^{+0.0009}_{-0.0026} \text{ (exp.)}^{+0.0091}_{-0.0072} \text{ (th.)}
\]
Mean subjet multiplicity in photoproduction and NC DIS

- $y_{\text{cut}}$, $\eta_{\text{jet}}$ and $E_{\text{T}}^{\text{jet}}$ dependence of $\langle \psi (r = 0.5) \rangle$ in photoproduction and NC DIS:
  - same conclusions as for the integrated jet shape

**PHP ZEUS**

**ZEUS NC DIS**

- From the measured $\langle n_{\text{subj}} (y_{\text{cut}} = 10^{-2}) \rangle$ for $E_{\text{T}}^{\text{jet}} > 25$ GeV a value of $\alpha_{S}(M_{Z})$

$$\alpha_{S}(M_{Z}) = 0.1187 \pm 0.0017 \text{ (stat.)} \pm 0.0024 \text{ (exp.)} \pm 0.0093 \text{ (th.)}$$
Jet properties in different environments
Comparison of jet shapes in photoproduction and NC DIS

- $r$ dependence: jets in NC DIS are
  - narrower than in $\gamma p$ with $x_{\gamma}^{\text{obs}} < 0.75$ → resolved dominated by gluon jets
  - similar to $\gamma p$ with $x_{\gamma}^{\text{obs}} > 0.75$ → direct dominated by quark jets
- $\eta^\text{jet}$ dependence:
  - inclusive jets in $\gamma p$: the fraction of gluons increases as $\eta^\text{jet}$ increases
  - $\gamma p$ with $x_{\gamma}^{\text{obs}} > 0.75$
  - inclusive jets in DIS
    - mainly quarks
    - no $\eta^\text{jet}$ dependence
Comparison of jet shapes in photoproduction and NC DIS

- $\eta^{\text{jet}}$ dependence:
  - $\gamma p$: jets become broader as $\eta^{\text{jet}}$ increases
  - DIS: no significant dependence

- Comparison with QCD:
  - $\gamma p$: broadening of data consistent with increase of fraction of gluon-initiated jets
  - DIS: consistent with being dominated by quark-initiated jets

- $E_T^{\text{jet}}$ dependence:
  - DIS and $\gamma p$: jets become narrower as $E_T^{\text{jet}}$ increases

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Comparison of subjet multiplicities in NC and CC DIS

- $E_T^{\text{jet}}$ and $Q^2$ dependence of $\langle n_{\text{sbj}}(y_{\text{cut}} = 10^{-2}) \rangle$ in CC DIS
  - Jets searched using the $k_T$ cluster algorithm in LAB frame
  - Kinematic region: $Q^2 > 200$ GeV$^2$ and $y < 0.9$
  - At least one jet with $E_T^{\text{jet}} > 14$ GeV and $-1 < \eta^{\text{jet}} < 2$

- The measured $\langle n_{\text{sbj}}(y_{\text{cut}} = 10^{-2}) \rangle$ decreases with $E_T^{\text{jet}}$ or $Q^2$
  - Jets get narrower as $E_T^{\text{jet}}$ or $Q^2$ increase

- Comparison with NLO QCD calculations
  - The calculations provide a good description of the data

- Comparison with NC DIS data
  - $E_T^{\text{jet}}$ dependence: $\langle n_{\text{sbj}} \rangle$ slightly larger in NC than in CC
  - $Q^2$ dependence of $\langle n_{\text{sbj}} \rangle$ similar in NC and CC
  - Differences in $E_T^{\text{jet}}$ dependence can be attributed to different $Q^2$ spectra in NC and CC
**Comparison of jet shapes in** $ep$, $e^+e^-$ and $p\bar{p}$

- **Jets in** $ep$ and $e^+e^-$ **are:**
  - → similar: jets in $ep$ and $e^+e^-$ come predominantly from quarks
  - → pattern of QCD radiation within a quark jet is to a large extent independent of hard scattering process
  - → narrower than those in $p\bar{p}$: jets in $p\bar{p}$ come predominantly from gluons

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**Diagram:**
- **HERA** $eq \rightarrow eq$
- **LEP** $e^+e^- \rightarrow q\bar{q}$
- **TEVATRON** $gg \rightarrow gg$

**Graph:**
- **ZEUS 1995+1996**
  - **ZEUS NC DIS** $(e^+p)$ $(37<\xi^m<45$ GeV)
  - **ZEUS CC DIS** $(e^+p)$ $(37<\xi^m<45$ GeV)
  - **OPAL** $(e^+e^-)$ $(\xi^m>35$ GeV)
  - **CDF** $(pp)$ $(40<\xi^m<60$ GeV)
  - **D0** $(pp)$ $(45<\xi^m<70$ GeV)
Quark and gluon jets properties
Charm photoproduction provides a handle to identify quark and gluon jets by selecting dijet events with one jet tagged as the charmed jet and measuring the substructure of the other ("untagged") jet in the event: enriched and unbiased sample of charm jets

**In photoproduction:**

→ in direct processes, the "untagged" jet is also a charm quark

→ in resolved processes, there are several contributing processes:
  → gluon-gluon fusion ("untagged" jet: also charm)
  → charm-excitation processes ("untagged" jet: gluon or quark)
Substructure of quark and gluon jets

- \( \langle \psi(r) \rangle \) in photoproduction with charm jets
  - Jets searched using the \( k_T \) cluster algorithm
  - Kinematic region: \( 0.2 < y < 0.85 \) and \( Q^2 \leq 1 \text{ GeV}^2 \)
  - At least two jets with \( E_T^{\text{jet}} > 7, 6 \text{ GeV} \) and \( -1 < \eta^{\text{jet}} < 2 \)

- Subsample of dijet events with a \( D^{*\pm} \) meson matched to one of the jets

- The other jet in the event ("untagged" charm jet) provides an enriched and unbiased sample of charm jets

→ Model predictions for charm jets and light-quark jets describe the data well
Substructure of quark and gluon jets

- Characterization of the substructure of gluon jets:
  - extraction of $O_{\text{gluon}}$ from
  
  $$O_{\text{dijet}} = f_q \cdot O_{\text{quark}} + f_g \cdot O_{\text{gluon}}$$

  - $O_{\text{dijet}}$ is the measured observable
  - $O_{\text{quark}}$ is approximated by $O_{\text{charm}}$
  - $f_q (f_g = 1 - f_q)$ is estimated using the MC models

- Extraction of gluon properties for $E_T^{\text{jet}} > 15$ GeV
  - gluon jets are broader than quark jets

  --> Model predictions for quark and gluon jets describe the measurements well
Substructure of quark and gluon jets

- $\langle \psi(r) \rangle$ in photoproduction with charm jets
  - Jets searched using the $k_T$ cluster algorithm
  - Kinematic region: $0.2 < y < 0.8$ and $Q^2 \leq 1 \text{ GeV}^2$
  - At least two jets with $E_T^{\text{jet}} > 7, 6 \text{ GeV}$ and $-0.75 < \eta^{\text{jet}} < 1.5$
- Subsample of dijet events with a $\mu$ matched to one of the jets
- The other jet in the event ("untagged" charm jet) provides an enriched and unbiased sample of charm jets
  → purity of the tagged jet: 71 – 73%
- The predictions of PYTHIA (including charm-excitation) describe the data well for $x_\gamma^{\text{obs}} > 0.75$
- Differences are observed for $x_\gamma^{\text{obs}} \leq 0.75$
  → the data suggest a smaller fraction of gluon jets at low $x_\gamma^{\text{obs}}$ than predicted by PYTHIA

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Substructure of quark and gluon jets

- Differences between quark and gluon jets were investigated by exploiting the different type of parton content in the final state for one-jet and dijet events in NC DIS in LAB frame.

- Jets searched using the $k_T$ cluster algorithm in LAB frame.
- Kinematic region: $Q^2 > 125 \text{ GeV}^2$.
- At least one (two) jet(s) with $E_T^{\text{jet}} > 17 \text{ GeV}$ and $-1 < \eta^{\text{jet}} < 2.5$.

→ In the dijet sample, the lowest-$E_T^{\text{jet}}$ jet is considered if distance jet-jet = $\sqrt{\Delta\eta^2 + \Delta\phi^2} \leq D = 2$.

→ The lowest-$E_T^{\text{jet}}$ jet in the two-jet sample is broader than the one-jet sample.
NLO QCD calculations for one-jet production

\[ \langle 1 - \Psi(r) \rangle = \frac{b_1 \cdot \alpha_s^1 + b_2 \cdot \alpha_s^2}{a_0 \cdot \alpha_s^0 + a_1 \cdot \alpha_s^1} \]

DISENT program
S. Catani and M.H. Seymour

• DISENT program: \( \alpha_s(M_Z) = 0.118; \mu_R = \mu_F = Q; \) CTEQ6 proton PDFs

→ Dominant theoretical uncertainty: terms beyond NLO, < 5\% for \( r \geq 0.2 \)
\[
\langle 1 - \Psi(r) \rangle = \frac{d_2 \cdot \alpha_s^2 + d_3 \cdot \alpha_s^3}{c_1 \cdot \alpha_s^1 + c_2 \cdot \alpha_s^2}
\]

NLOJET++ program
Z. Nagy and Z. Trocsanyi

- NLOJET++ program: \( \alpha_s(M_Z) = 0.118; \mu_R = \mu_F = Q; \) CTEQ6 proton PDFs
Substructure of quark and gluon jets

- Differences between quark and gluon jets were investigated by exploiting the different type of parton content in the final state for one-jet and dijet events in NC DIS in LAB frame.

\[ \text{one-jet events} \quad \text{enriched in quark jets} \]

\[ \text{two-jet events} \quad \text{higher content of gluon jets} \]

\[ \rightarrow \text{The lowest-} E_T^{\text{jet}} \text{ jet in the two-jet sample is broader than the one-jet sample: consistent with a higher gluon content in dijet events, as predicted by pQCD} \]
Identification of quark and gluon jets

- The Monte Carlo predictions of $\psi(r)$ for quark- and gluon-initiated jets show the expected differences.

- Statistical identification of quark and gluon jets assuming:
  - Gluon jets $\leftrightarrow$ “broad” jets
  - Quark jets $\leftrightarrow$ “narrow” jets

→ Samples enriched in gluon-like (“broad”) jets: $\psi(r = 0.3) < 0.6$

are obtained by requiring $\psi(r = 0.3) > 0.8$

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Substructure dependence of jet cross sections

- $d\sigma/d\eta^{\text{jet}}$ for broad and narrow jets in photoproduction
  - Jets searched using the $k_T$ cluster algorithm
  - Kinematic region: $0.2 < y < 0.85$ and $Q^2 < 1\text{ GeV}^2$
  - At least one jet with $E_T^{\text{jet}} > 17\text{ GeV}$ and $-1 < \eta^{\text{jet}} < 2.5$

- $d\sigma/d\eta^{\text{jet}}$ for “broad” and “narrow” jets show different shape

- Comparison with leading-logarithm parton shower MC calculations:
  - Same jet-shape cuts as the data
  - MC area normalised to data
  - Good description of the shape of the data

- Parton content of the final state from MC calculations of PYTHIA (HERWIG):
  - “broad” jets: $17(15)% \, gg$, $58(54)% \, gq$ and $25(31)% \, qq$
  - “narrow” jets: $54(56)% \, qq$, $41(41)% \, qg$ and $5(3)% \, gg$
Substructure dependence of jet cross sections

- $d\sigma/d|\cos \theta^*|$ for samples of two “broad”-jet events and two “narrow”-jet events exhibit a different slope:
  - Data and MC normalised to unity at $|\cos \theta^*| = 0.1$
  - $d\sigma/d|\cos \theta^*|$ at $|\cos \theta^*| = 0.7$ for “broad-broad” ("narrow-narrow") events is more than seven (only two) times larger than at 0.1

- Comparison with MC:
  - Same selection cuts as the data for “broad”/“narrow” sample
  - PYTHIA gives a reasonable description of the shape of the data

→ Different slope understood in terms of the dominant two-body processes:
  - $qg \rightarrow qg$ (dominant in “broad-broad” sample) rises more steeply than $\gamma g \rightarrow q\bar{q}$ (dominant in “narrow-narrow” sample) due to different spin of exchanged particle

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C Glasman (Universidad Autónoma de Madrid)
Substructure dependence of jet cross sections

- $d\sigma / d\cos \theta^*$ for a sample of events with one "broad" jet and one "narrow" jet measured wrt the "broad" jet shows different behaviour on the negative and positive sides:
  * data and MC normalised to unity at $\cos \theta^* = 0.1$
  $d\sigma / d\cos \theta^*$ at 0.7 is $\approx$ two times larger than at $-0.7$

- Comparison with MC:
  * same "broad-narrow" selection as for the data
  $\rightarrow$ PYTHIA gives a reasonable description of the shape of the data

$\rightarrow$ Observed asymmetry understood in terms of the dominant resolved subprocess: $q\gamma g_p \rightarrow qg$

$\rightarrow$ The asymmetry is due to the different dominant diagrams for $\cos \theta^* \rightarrow \pm 1$:
  * $t$—channel gluon exchange at $\cos \theta^* = +1$
  * $u$—channel quark exchange at $\cos \theta^* = -1$
Pattern of parton radiation
Subjet distributions

Subjet distributions can be used to study:

- pattern of parton radiation from a primary parton
- direct test of splitting functions $P_{ab}(z, \mu)$ and their scale dependence
- colour coherence
- soft gluon radiation tends to be emitted towards proton direction

Measurements of normalised cross sections as functions of

$$\frac{E_{T}^{\text{subj}}}{E_{T}^{\text{jet}}}, \eta^{\text{subj}} - \eta^{\text{jet}}, |\phi^{\text{subj}} - \phi^{\text{jet}}| \text{ and } \alpha^{\text{subj}}$$

and their dependence with $E_{T}^{\text{jet}}, Q^2$ and $x$

- Jets searched using the $k_T$ cluster algorithm in LAB frame
- Kinematic region: $Q^2 > 125 \text{ GeV}^2$
- At least one jet with $E_{T}^{\text{jet}} > 14 \text{ GeV}$ and $-1 < \eta^{\text{jet}} < 2.5$
- Final sample: jets that have two subjets for $y_{\text{cut}} = 0.05$
Normalised subjet cross sections compared with NLO calculations:

- $E_{T}^{sbj} / E_{T}^{jet}$: the two subjets tend to have similar $E_{T}^{sbj}$
- $\eta^{sbj} - \eta^{jet}$: asymmetric two-peak structure
- $|\phi^{sbj} - \phi^{jet}|$: suppression around 0 because the two subjets cannot be resolved when close
- $\alpha^{sbj}$: higher $E_{T}^{sbj}$ subjet tends to be in rear direction
  → consistent with asymmetric peaks of $\eta^{sbj} - \eta^{jet}$

→ The NLO predictions, which contain these diagrams describe the data adequately
Subjet distributions

- $\eta^{\text{subj}} - \eta^{\text{jet}}$ normalised cross section for $E_{T,\text{low}}^{\text{subj}} / E_T^{\text{jet}} < 0.4$

$\rightarrow$ The higher (lower) $E_T^{\text{subj}}$ subjet tends to be in the rear (forward) direction

$\rightarrow$ colour-coherence effects between the initial and final states

$\rightarrow$ subjet with lower $E_T^{\text{subj}}$ emitted predominantly towards proton beam direction

ZEUS Collab, 2008
Comparison with predictions for quark- and gluon-induced processes

- NLO prediction:
  81% of q-induced and 19% of g-induced

- Predictions for these two types of processes are different:
  - the two subjets in q-induced have more similar $E_{T}^{sbf}$ and are closer to each other than in g-induced
  - The data are better described by the calculations for jets arising from the splitting of a quark into a quark-gluon pair
Conclusions

Jet substructure has been extensively studied at HERA in terms of jet shapes and subjet multiplicities and distributions in DIS and photoproduction.

Measurements allowed

- stringent tests of pQCD directly beyond LO
- comparison of quark- and gluon-jet properties
- comparison of pattern of QCD radiation in different hard scattering processes
- determinations of $\alpha_s(M_Z)$
- study of underlying subprocess dynamics
- study of pattern of parton radiation

Jet substructure: a powerful tool to test QCD