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Measurement of the 1-jettiness event shape observable in deep inelastic electron-proton scattering at HERA

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The H1 Collaboration reports the first measurement of the 1-jettiness event shape observable τ_1^b in neutral-current deep-inelastic electron-proton scattering. The analysis is based on data recorded in 2003-2007 by the H1 detector at the HERA collider for ep collisions at $\sqrt{s} = 319$ GeV, with integrated luminosity of 351.1 pb^{-1}. The observable τ_1^b is equivalent to a thrust observable defined in the Breit frame. The triple differential cross section is presented as a function of τ_1^b, event virtuality Q^2, and inelasticity y, in the kinematic region $Q^2 > 150$ GeV. The data are compared to predictions from Monte Carlo event generators and fixed-order calculations in next-to-next-to-leading order in perturbative Quantum Chromodynamics. These comparisons reveal sensitivity of the observable to parton shower and resummation effects, the magnitude of the strong coupling constant, and proton parton distribution functions, as well as the modeling of hadronization and fragmentation.

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1. Introduction

Measurements of event shape observables in high-energy lepton-proton deep-inelastic scattering (DIS) provide a rigorous test of perturbative Quantum Chromodynamics (pQCD). This analysis [1] presents the first measurement of the 1-jettiness event shape observable τ_1^b [2] in ep collisions. This observable is infrared safe, allows for analytical or automatized resummation and is free of non-global logarithms [3]. It can be thus be theoretically calculated with high precision. It is defined as

$$\tau_1^b = \frac{2}{Q^2} \sum_{i \in \mathrm{HFS}} \min\{xP \cdot p_i, (q + xP) \cdot p_i\} \,. \tag{1}$$

The 4-momentum of the exchanged boson q defines the virtuality $Q^2 = -q^2$ in the denominator. All particles in the hadronic final state (HFS) contribute to the observable. The 4-momenta of the single HFS particles are denoted with p_i, while P describes the incoming proton. The quantity x denotes the Bjorken scaling variable. An alternative expression for τ_1^b can be derived [4]

$$\tau_Q = 1 - \frac{2}{Q} \sum_{i \in \mathcal{H}_C} P_{z,i}^{\mathrm{Breit}} \,. \tag{2}$$

It measures the sum of longitudinal momenta of the HFS particles in the Breit frame. Only particles in the current hemisphere $\mathcal{H}_C$ defined by $\eta < 0$ contribute to the sum. This expression corresponds to the DIS thrust normalized to $Q/2$. The 1-jettiness ranges from zero to unity, with $\tau_1^b \approx 0$ indicating an event structure with a single collimated jet emitted along the scattered parton. At low x_{Bj}, configurations can occur with $\tau_1^b = 1$, corresponding to events with empty current hemisphere [5]. A value for τ_1^b can be calculated for each event in neutral-current DIS.
The data were taken by the H1 experiment at HERA in the years 2003 to 2007. They include electron-proton and positron-proton collision events at a center of mass energy of $\sqrt{s} = 319$ GeV. The integrated luminosity amounts to $\mathcal{L} = 361\ \mathrm{pb}^{-1}$. The DIS kinematic variables virtuality Q^2, inelasticity y and Bjorken-x are defined with the IΣ reconstruction method [6]:

$$y_\Sigma = \frac{\Sigma_h}{\Sigma_h + \Sigma_e} \quad Q^2_\Sigma = \frac{P^2_{T,e}}{1 - y_\Sigma} \,, \quad \text{and} \;\; x_{I\Sigma} = \frac{E_{e'}}{E_p} \frac{\cos^2(\theta_{e'}/2)}{y_\Sigma} \tag{3}$$

where Σ_i is defined as $\Sigma_i = E_i - P_{z,i}$ for $i = e, h$, the polar angle of the scattered electron is denoted $\theta_{e'}$, and $E_p = 920\,\mathrm{GeV}$ is the proton beam energy. Since the electron beam energy does not enter the equations, the effect of QED initial state radiation (ISR) is small. For Q^2 dependent measurements, the electron method is used instead

$$Q^2_e = \frac{P^2_{T,e}}{1 - y_e} \,, \quad \text{with} \quad y_e = 1 - \frac{\Sigma_e}{2E_{e_0}} . \tag{4}$$

A variety of cuts is applied in the event selection to achieve a high resolution and to reduce ISR effects of the incoming electron arising from Quantum Electrodynamics (QED).

2. Cross section results

The data are corrected for detector effects, background processes, and higher-order QED effects using regularized unfolding. The detector response matrix A is determined using the two signal Monte Carlo (MC) event generators Djangoh 1.4 [7] and Rapgap 3.1 [8] in combination with a detailed detector simulation based on GEANT3. The TUnfold package is used to calculate the regularized inverse matrix A^+ and to propagate its uncertainties. The cross section $d\sigma/d\tau_1^b(Q^2, y)$ in one measurement bin i is defined as

$$\frac{d\sigma_i}{d\tau_1^b} = \frac{(A^+(\vec{n}_{\text{data}} - \vec{n}_{\text{Bkg}}))_i}{\mathcal{L} \cdot \Delta_{\tau_1^b,i}} \cdot c_{\text{QED,i}}\,, \tag{5}$$

where $\vec{n}_{\text{data}}$ denotes the vector of data event counts, $\vec{n}_{\text{Bkg}}$ is the corresponding vector with the estimated number of background events (processes other than high-Q^2 neutral-current DIS) and Δ_τ denotes the width of single τ_1^b bins. The integrated luminosity $\mathcal{L}$ amounts to $\mathcal{L} = 351.1$ pb^{-1}, consisting of electron (160.1 pb^{-1}) and positron (190 pb^{-1}) runs.
The c_{QED} are multiplicative factors correcting for QED radiative effects of the electron. They are obtained from Djangoh where higher order QED effects are implemented with Heracles [9]. Corrections for the positron charge are included, allowing us to report the cross sections for e^-p scattering. Single differential cross sections are reported, as well as results in adjacent (Q^2,y)-bins denoted as triple differential cross sections.
The normalization uncertainty is found to be 2.7% where the largest contribution comes from the uncertainty associated to the integrated luminosity. Other uncertainty sources that are taken into account include the energy measurement of the scattered lepton and the polar-angle position of the liquid argon calorimeter with respect to the central tracking detector. Scale factors for the energy of all clusters and tracks are derived from a dedicated jet energy calibration.
The measured cross sections are compared to a large number of theoretical predictions, including the DIS MC event generators Djangoh 1.4 and Rapgap 3.1. To study the sensitivity of the data to different parton shower models, the MC event generator Pythia 8.303 [10] is used together with the 'default' shower, the Vincia parton shower [11] and the Dire [12] parton shower. Further models that are considered are Powheg predictions [13] interfaced with the Pythia parton shower, Herwig 7.2 [14], Sherpa 2.2 [15], as well as pre-release Sherpa 3.0 [16] predictions. The effect of transverse-momentum-dependent parton distribution functions (PDFs) is investigated with KaTie+Cascade predictions. Next-to-next-to-leading order (NNLO) predictions in perturbative QCD for the process $ep \to e + 2\text{jets} + X$ are obtained with the program NNLOJET [17] up to order $O(\alpha_s^3)$. Correction factors for non-perturbative effects are obtained from Djangoh and Rapgap. The NNLO predictions are valid only in the region $\tau_1^b \gtrsim 0.22$ and $\tau_1^b \neq 1$. Resummed predictions at next-to-leading-log (NLL) accuracy are matched to fixed-order predictions at $O(\alpha_s^2)$. Dedicated hadronization corrections are applied as a multiplicative correction matrix obtained from Sherpa 3.0
Figure 1 displays the single differential cross section $\frac{d\sigma}{d\tau_1^b}$ in the kinematic range $200 \leq Q^2 < 1700$ GeV^2 and $0.2 \leq y < 0.7$. The data are corrected to e^-p scattering. The statistical uncertainties are commonly smaller than the marker size in the range of 2 – 4%. Systematical uncertainties are in the range of 4%. The so-called peak region with $\tau_1^b \lesssim 0.3$ is populated by DIS

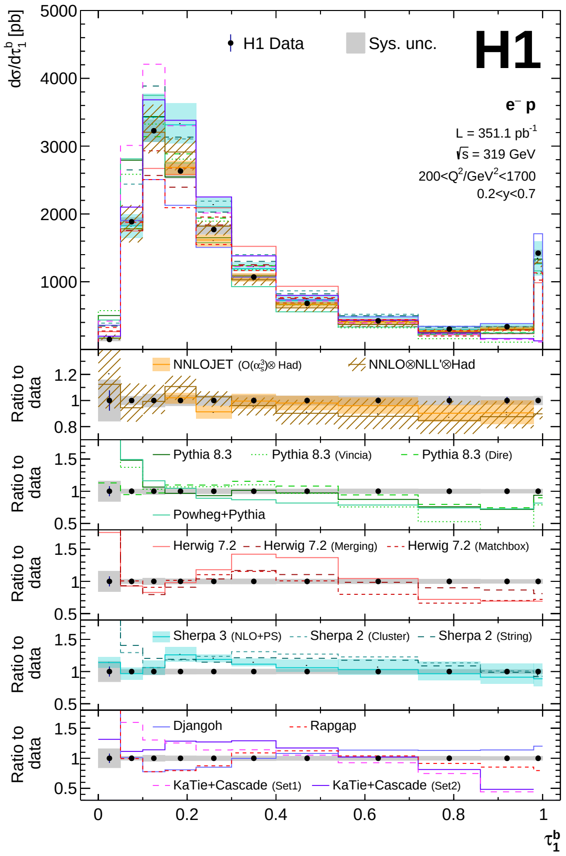

Figure 1: Single differential cross section $d\sigma/d\tau_1^b$. A comparison of the data to numerous different predictions is shown, including fixed-order predictions as well as a comparison of various parton shower and hadronization models.

one-jet events. It is sensitive to resummation and hadronization effects. Towards higher values of τ_1^b (denoted as tail region) the cross section decreases. These events are characterized by additional hard radiation, including two jet topologies. At next-to-leading order in QCD an event configuration with empty current hemisphere can occur DIS. The 1-jettiness takes the value $\tau_1^b = 1$ for these so-called Empty Hemisphere Events (EHEs). This type of event has a sizable cross section and populates the last bin of the distribution. It is studied in detail in [18]. The predictions from NNLOJET provide a good description of the data in the range of validity. Since they describe a dijet final state, they cannot describe the peak region. The correction factors for non-perturbative effects can become sizable and hinder a more quantitave comparison. The resummed prediction at NNLO⊗NLL accuracy provides an accurate description of the entire τ_1^b range within their uncertainty. The recent MC event generators Pythia 8.3, Powheg+Pythia, Herwig 7.2, Sherpa 2 and Sherpa 3 provide a good description of the data. Differences between the employed parton shower and hadronization models can be observed. The best description of the data is provided by Sherpa 3. The DIS event generator KaTie+Cascade provides a reasonable description of the peak region, but fails to describe the data towards high τ_1^b. This is probably related to the absence of $eg \to eq(\bar{q})$ processes in the hard matrix elements. Djangoh tends to overestimate the data in the tail region, while Rapgap is a bit too low. Triple differential cross sections are presented in figure 2 in adjacent bins of Q^2 and y. They are presented in the kinematic range $150 \leq Q^2 < 20000$ GeV^2 and $0.05 < y < 0.94$ as a function of τ_1^b. Phase space regions that are kinematically forbidden or experimentally inaccessible are omitted. Events with a harder virtuality Q produce more collimated particles, effectively shifting the DIS peak towards lower values of τ_1^b. Simultaneously, the tail region is lowered, due to a reduced phase space for hard radiation at high Q^2. For a fixed Q^2, the relative contribution of EHEs increases with y, which corresponds to a lowering of x_{Bj}.

3. Summary and conclusion

A first measurement of the 1-jettiness event shape observable τ_1^b in deep-inelastic electron proton scattering at HERA is presented. The data were taken with the H1 experiment. The cross sections were presented single differentially as well as in adjacent regions of (y, Q^2) in the phase space $Q^2 > 150$ GeV^2. The data are compared to numerous MC event generators, as well as fixed order calculations at $O(\alpha_s^3)$ and resummed calculations at $O(\alpha_s^2)$. Overall, a satisfactory description of the data by the various models could be observed. The data will be valuable for the improvement of MC event generators and hadronization and parton shower models.

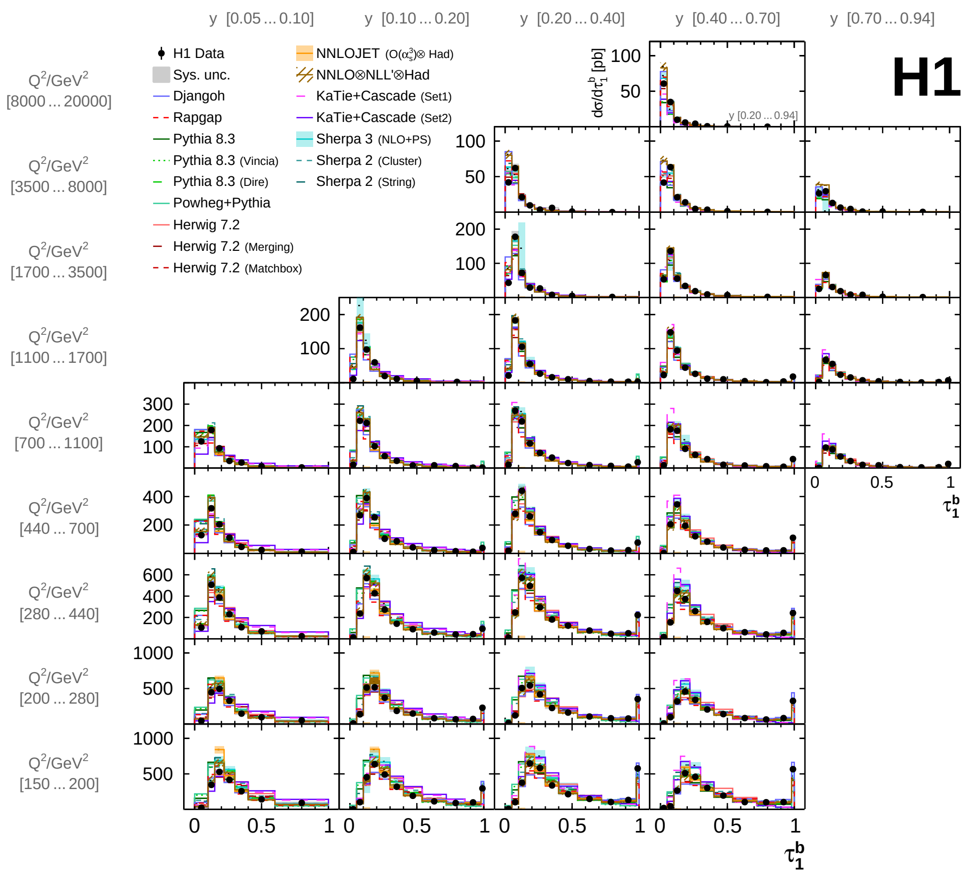

Figure 2: The differential cross section $d\sigma/d\tau_1^b$ for adjacent regions in Q^2 and y. Every panel displays the differential cross section $d\sigma/d\tau_1^b$ in a given phase space which is indicated on the left and top for Q^2 and y, respectively. The vertical error bars indicate statistical uncertainties, while systematic uncertainties are displayed as shaded area. The data are compared to a large number of predictions described in the text. The ratios of the data and predictions to the Sherpa 3 predictions are shown in [1].

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