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Some Properties of the Very High Q^2 Events of HERA

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Abstract

The kinematic reconstruction of neutral current high Q^2 events at HERA is discussed in detail using as an example the recently published events of the H1 and ZEUS collaborations at $Q^2 > 15000$ GeV^2 and M > 180 GeV, which are more numerous than expected from Standard Model predictions. Taking into account the complete information of these events, the mass reconstruction is improved and the difference between the average mass of the samples of the two experiments is reduced from 26±10 GeV to 17±7 GeV, but remains different enough to render unlikely an interpretation of the excess observed by the two collaborations as originating from the decay of a single narrow resonance.

1 Introduction

At the electron-proton (ep) HERA collider, the study of DIS is performed in an unique and optimal way up to values of the squared momentum transfer Q^2 of 10^5 GeV^2. Recently, the two HERA collaborations H1 and ZEUS have reported [1, 2] an excess of events at *very high* Q^2 (defined in the following as $Q^2 > 15000$ GeV^2) compared to standard model expectations. This observation has triggered an important activity on "Beyond the Standard Model" theories which might explain the effect [3]. The most favoured solution involves the production of a new resonance, which after its decay is kinematically similar to a standard deep inelastic scattering (DIS) event.

Indeed, in the naive quark-parton model (QPM), a parton carrying a fraction x of the momentum of the proton scatters elastically against an electron and in the Standard Model, this interaction is representing a t-channel scattering occuring via the exchange of a gauge boson such as a photon or a Z°. Beyond the Standard Model, the naive QPM picture can represent the formation of an s-channel resonance (generically called "leptoquark") subsequently followed by a two-body decay. While in the first interpretation the Bjorken x variable is one of the two relevant variables to characterize the scattering, in the second case the invariant mass M of the system formed is the physical quantity of interest. This mass is related to x in the naive QPM by $M = \sqrt{xs}$, s being the squared center of mass energy. In "real" interactions, the quantum chromodynamics (QCD) effects do not spoil much this picture at large Q^2, which is characterized in DIS by the dominance of one electron + one partonic jet + one remnant jet in the final state. At high Q^2 the remnant jet has only a small influence on the DIS kinematic variables. So, when looking at high Q^2 deep inelastic scattering (DIS) in an inclusive way it is possible to distinguish between these two scenarios by comparing the event rates in different x or M intervals: the smooth evolution of the DIS cross-section as a function of x can be opposed to the appearance of a sharp resonnant peak in the invariant mass distribution, characteristic of a leptoquark.

The HERA effect is complicated by the fact that the invariant mass distributions of the event samples of the two collaborations differ: at a mass greater than 180 GeV, the 7 H1 events appear clustered around a mass of 200 GeV, while the 5 ZEUS events are broadly distributed between 191 and 253 GeV. It is the subject of this paper to understand how significant is this difference and to provide a combined mass spectrum using the complete available information of these events in order to give an interpretation of the effect.

At HERA the kinematic reconstruction does not need to rely on the scattered lepton only, since the most important part of the hadronic system is visible in the almost 4π detectors H1 and ZEUS. This redundancy allows for an experimental control of the systematic errors and the radiative corrections, hence to determine in a more precise way the usual DIS kinematic variables x, y and Q^2 which are defined as:

$$x = Q^2/(2P.q) \qquad y = (P.q)/(P.k) \qquad Q^2 = -(k-k')^2 = -q^2 = xys$$

P, k being the 4-vectors of the incident proton and lepton, k' the scattered lepton one.

In this report we briefly review in section 2 the methods used at HERA to determine the kinematics of the high Q^2 events. In section 3 we characterize the high Q^2 region and introduce a new method which optimizes the kinematic reconstruction by determining the measurement errors on an event by event basis. Section 4 is devoted to the detailed study of the very high Q^2 HERA events and discusses the mass distributions obtained.

2 Kinematic Reconstruction at HERA

In order to introduce the kinematic methods used at HERA in the high Q^2 region let us start by a few definitions. The initial electron and proton (beam) energies are labeled $E_\circ$ and $P_\circ$. The energy and polar angle[1] of the scattered electron (or positron) are E and θ. After identification of the scattered electron, we can reconstruct the following independent hadronic quantities: Σ, obtained as the sum of the scalar quantities $E_h - p_{z,h}$ of each particle belonging to the hadronic final state, $p_{T,h}$ as its total transverse momentum and define the inclusive angle γ of the hadronic system:

$$\Sigma = \sum_h (E_h - p_{z,h}) \qquad p_{T,h} = \sqrt{(\sum_h p_{x,h})^2 + (\sum_h p_{y,h})^2} \qquad \tan\frac{\gamma}{2} = \frac{\Sigma}{p_{T,h}} \tag{1}$$

$E_h, p_{x,h}, p_{y,h}, p_{z,h}$ are the four-momentum vector components of each hadronic final state particle. The corresponding quantities for the scattered electron are

$$\Sigma_e = E\ (1 - \cos\theta) \qquad p_{T,e} = E\sin\theta \qquad \text{i.e.} \qquad \tan\frac{\theta}{2} = \frac{\Sigma_e}{p_{T,e}} \tag{2}$$

Out of these variables, it is possible to write the four methods which have been used to determine the invariant mass of the very high Q^2 events (the formulae are given in the appendix).

- The electron only method (e) based on E and θ.
- The hadrons only method (h) based on Σ and $p_{T,h}$ [4].
- The double angle method (DA) based on θ and γ [5].
- The Sigma method (Σ) based on E, θ and Σ [6].

The e method is precise at high y but becomes less precise in x, y or M at low y. The h method is the only one available for charged current events, but is less precise than the three others in neutral currents, so it will be ignored in the following. The DA method is precise at high Q^2 both at high and low y. The Σ method is similar to the e method at high y and to the DA at low y apart from Q^2 which is less precise. However it is insensitive to ISR in M, y and Q^2. See [7] for a detailed discussion of the properties of these methods and [8] for their behaviour in presence of initial state QED radiation (ISR).

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[1] The positive z axis is defined at HERA as the incident proton beam direction.

3 Treatment at High Q^2

At *high* Q^2 (defined in the following as $Q^2 > 2500$ GeV^2) the kinematic reconstruction is in general more precise than at low Q^2 and indeed the differences between the results obtained with the methods seen above are small. However since the number of events drops rapidly with increasing Q^2 it is still crucial to optimize the reconstruction by making a full use of all the observables of these events.

The improvements on the reconstruction at high Q^2 come mainly from the better measurement of the hadronic final state. This is due to the fact that i) the individual hadron energy is on average greater; ii) the losses in the beam pipe and in the material in front of the calorimeter are in proportion smaller than at low Q^2, i.e. Σ, $p_{T,h}$ and γ are less affected by these losses; iii) the hadronic final state displays more often a (single) collimated jet configuration. This is due both to kinematics (events are in average at higher x), and to the smaller gluon radiation and power corrections (α_S is smaller).

All these characteristics enable a precise measurement of the hadronic angle, and thus are particularly favourable to the DA method which indeed becomes more accurate with increasing Q^2. This method has however the drawback to be very sensitive to ISR and thus difficult to use on a small number of events. For instance, the ISR of a 2.75 GeV photon, if not taken into account produces a shift of 10% on the reconstructed mass and 20% on Q^2. In order to overcome this drawback we introduce a new method which, by making use of the precision on γ, estimates *from the data* on an event by event basis the error on E and Σ, denoted in the following $\delta X/X \equiv (X_{true} - X_{reconstructed})/X_{reconstructed}$) with $X = E$ or Σ. These errors allow i) the Σ method to be corrected; ii) the presence of an unseen initial state photon (down to an energy of about 2 GeV) to be recognized with high efficiency, and therefore to correct for it.

3.1 The ω Method

We start by assuming that there is no ISR, and that θ and γ are precisely measured (implying $\delta\Sigma/\Sigma = \delta p_{T,h}/p_{T,h}$). From energy momentum conservation the two following equations can be derived:

$$(1-y_e)\,\frac{\delta E}{E} + y_h\,\frac{\delta\Sigma}{\Sigma} = y_e - y_h \tag{3}$$

$$-p_{T,e}\,\frac{\delta E}{E} + p_{T,h}\,\frac{\delta\Sigma}{\Sigma} = p_{T,e} - p_{T,h} \tag{4}$$

Under these assumptions $\delta E/E$ and $\delta\Sigma/\Sigma$ are determined on an event by event basis. Varying θ and γ within their typical errors[2] (5 and 40 mrad (r.m.s.) respectively, at high Q^2) we can obtain the errors arising from the angular measurements on $\delta E/E$ and

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[2] At very high Q^2, the γ resolution improves to 30 mrad. We stress here the need to use the r.m.s. to take into account non-gaussian tails which contribute in the propagation of the systematic errors.

$\delta\Sigma/\Sigma$. A more direct way to see the uncertainties arising from this determination is illustrated in fig.1, in which the error on E and Σ reconstructed using equations 3 and 4 are compared to their "true" value, which is known for the reconstructed simulated events. For a given event, the error on $(\delta E/E)_{rec}$, which is defined as $\Delta(\delta E/E) \equiv (\delta E/E)_{rec} - (\delta E/E)_{true}$, is of the same order as the r.m.s. (denoted $< \delta E/E >$) of the $\delta E/E$ distribution obtained from a large sample (fig.1b), showing that its use will not bring an improvement on an event by event basis. On the other side, the relative error on $(\delta\Sigma/\Sigma)_{rec}$ is smaller, about 30% of $< \delta\Sigma/\Sigma >$, and diminishes at high y (compare fig.1e to 1f, and 1b to 1c) implying that correcting Σ will provide a better kinematic measurement, in particular at high y. The ω kinematic variables are thus derived from the Σ ones by including the effect of $\delta\Sigma/\Sigma$, i.e.

$$y_\omega \equiv \frac{\Sigma + \delta\Sigma}{\Sigma + \delta\Sigma + \Sigma_e} \qquad\qquad Q^2_\omega \equiv \frac{p^2_{T,e}}{1 - y_\omega}$$

The comparison of the ω and Σ reconstruction of M, y and Q^2 for high Q^2 events fully simulated in the H1 detector is shown in fig.2. The improvement obtained by the recalibration of Σ is clearly visible, allowing this method to be compared favourably to the original ones. This comparison is shown in fig.3 for high Q^2 events (in all the high Q^2 section, an $E - p_z$ cut against hard initial state radiation is applied, see next section) both at high y and at low y. At high y ($y_e > 0.4$), the e and the ω methods are comparable in M and y and slightly better than the DA one (fig.3a,b). In Q^2, the

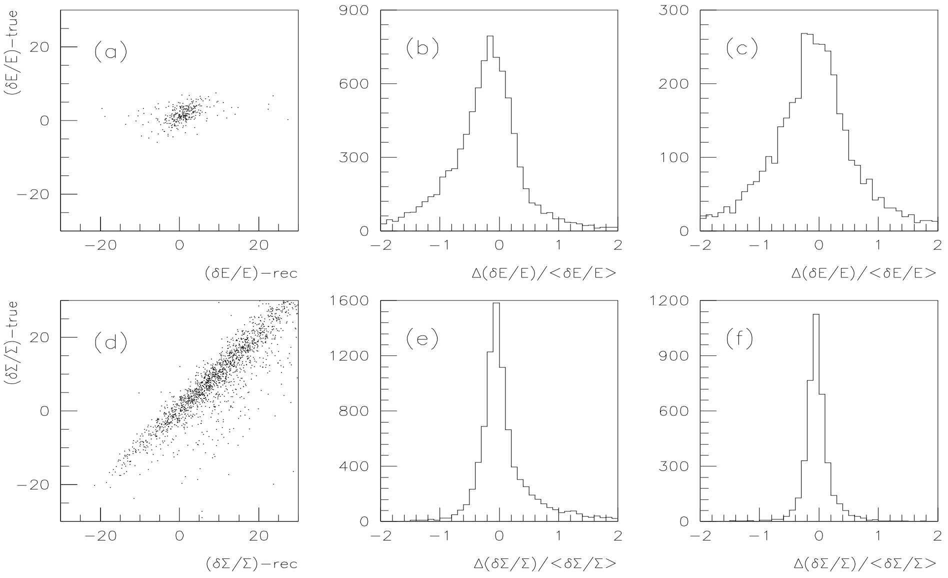

Figure 1: *a) shows the correlation between true reconstruction errors on E and those obtained from eqs. 3 and 4, on a full simulation in the H1 detector of high Q^2 events. b) (c) shows the projection of this correlation (at high $y, y > 0.4$). In b,c) we use $\Delta(\frac{\delta E}{E}) \equiv (\frac{\delta E}{E})_{rec} - (\frac{\delta E}{E})_{true}$, and $< \frac{\delta E}{E} > \equiv$ r.m.s. of the $\frac{\delta E}{E}$ distribution = 3%. d,e,f) show the same plots but for Σ instead of E, with $< \frac{\delta\Sigma}{\Sigma} > = 10\%$.*

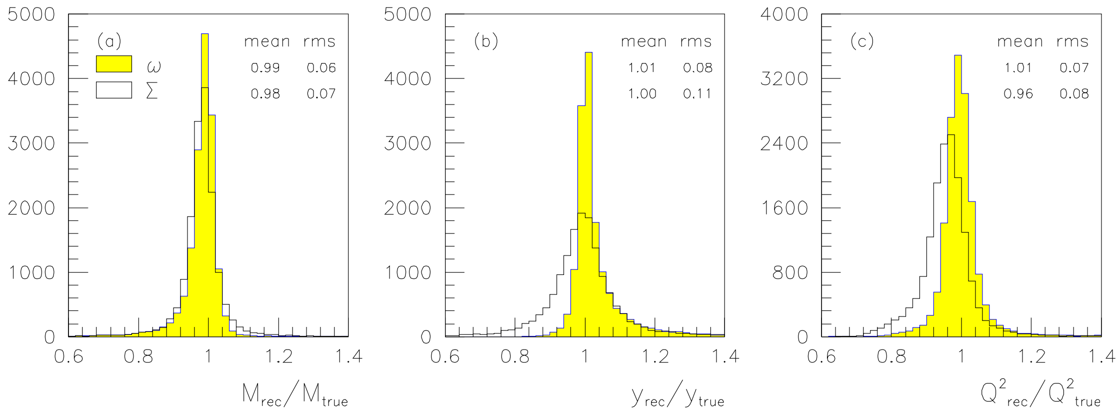

Figure 2: *Improvement on the M (5a), y(5b) and Q^2(5c) reconstruction at high Q^2, using the ω method compared to the Σ method.*

DA displays the narrowest peak both at high and low y (fig.3c,f), but its high sentivity to ISR induces tails in the distribution which renders its r.m.s. larger than the ω and e ones. At low y ($y_e < 0.25$) the e method has a relatively poor resolution in M, much worse than the ω one which is slightly better than the DA one. In conclusion, for the high Q^2 events the ω method is similar or slightly better than the e and DA method.

3.2 Treatment of QED Initial State Radiation

The influence of ISR is taken into account in the simulation programs used by the HERA experiments, but on a small number of events it is difficult to control the migration due to an unseen ISR photon when using the e and DA methods. Both H1 and ZEUS use an experimental cut on the total $E-p_z$ of the event (Σ_{he}) or equivalently on the normalized $E-p_z$ called hereafter σ_{he}[3] and defined as

$$\sigma_{he} \equiv \frac{\Sigma_{he}}{2E_\circ} \equiv \frac{\Sigma + \Sigma_e}{2E_\circ} \equiv \sigma_h + \sigma_e$$

The $E-p_z$ cuts used in H1 and ZEUS correspond to good approximation to $\sigma_{he} > 0.75$ and prevent an ISR photon from carrying away more than about 25% of the incident electron energy. Such a photon can induce a large shift to the reconstructed mass [8] of $1-\sqrt{(0.75y_e)/(y_e-0.25)}$ for M_e (i.e. -18% at $y_e = 0.75$) and of 25% on M_{DA} at any y. On M_Σ the shift is zero since the method is independent of colinear ISR for M, y and Q^2. A more stringent cut on σ_{he} is difficult to implement due to the experimental resolutions on y_h and y_e.

The ω method allows ISR photons to be recognized with high efficiency for σ_{he} as high as ~ 0.93. It makes use of the simple fact that depending on the origin of the

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[3] The normalized E-p$_z$ for the electron and for the hadronic final state satisfy: $\sigma_e = 1-y_e$; $\sigma_h = y_h$.

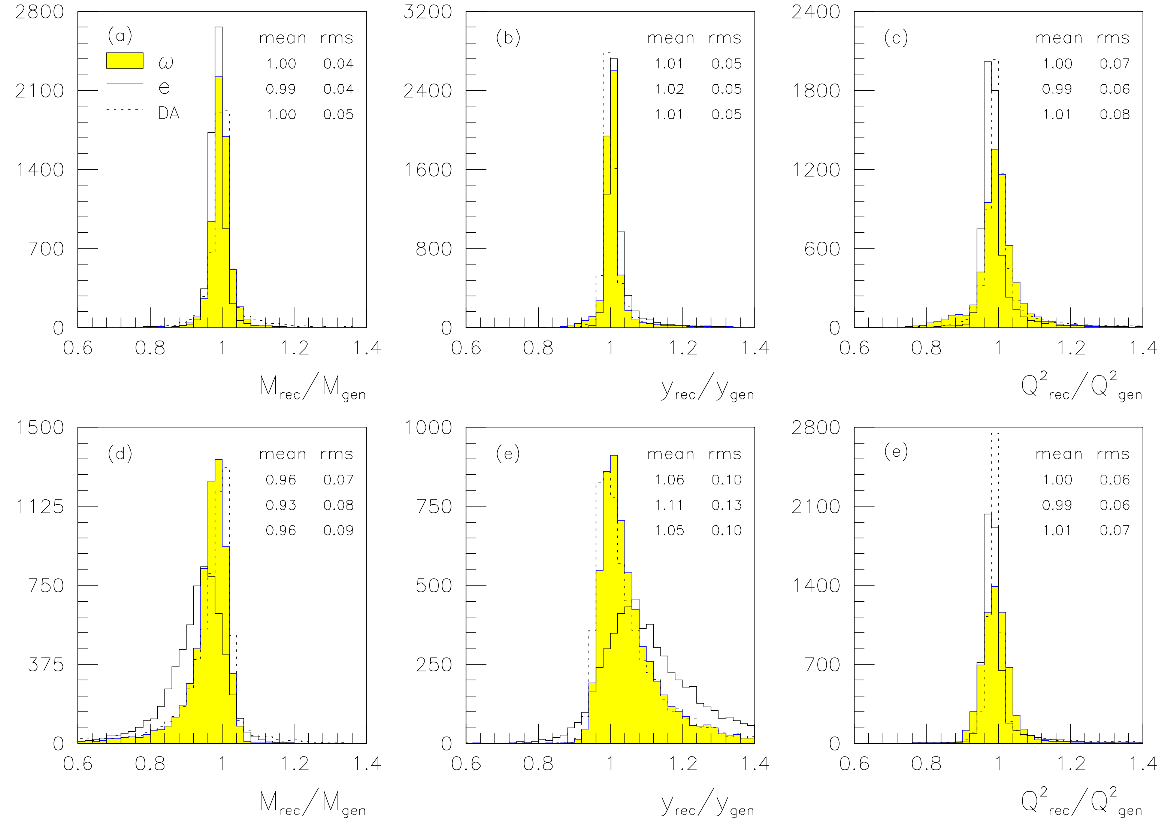

Figure 3: *Comparison on high Q^2 events, at high y ($y_e > 0.4$) of the ω, DA and e reconstruction of the mass*