Proton Diffractive Dissociation at HERA. Studying the Proton Dissociation Using Forward Taggers or Calorimeters

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Abstract: The potential of the HERA colliding experiments for studies of diffractive proton dissociation is investigated. Two measurement methods are considered. The first one relies on a set of tagging devices detecting particles emitted from the proton dissociation, while the second one involves a calorimetric measurement. The possible accuracy of the measurement of the dissociated mass spectrum and the measurement of the fraction of diffractive events where the proton did not dissociate is estimated. The effect of lowering the proton beam energy is also studied.

1 Introduction

The processes under consideration are $ep \to eVY, eXY$, where V denotes a vector meson, X is a dissociated photon system and Y is the excited nucleonic state. They compete with reactions where the proton stays intact, namely $ep \to eVp, eXp$. An efficient way of separating the two classes of events is essential for the measurements of the elastic and photon dissociation cross sections. It is also of primary importance to test the factorization of the diffractive proton vertex, i.e. to verify whether the probability for the proton to dissociate to a system of a given mass, M_Y, is the same in ep as in pp collisions and whether it depends on Q^2 or M_X.

In a naive approach, it should be easiest to study the proton dissociation in processes involving the production of vector mesons which decay into charged particles. One could estimate the energy, momentum and the mass of the nucleonic system from the difference between that of the initial and scattered electron and the vector meson decay products measured in tracking devices. One could also distinguish events with an intact proton by means of a simple mass cut. Unfortunately, the kinematics at HERA strongly disfavors this method. The only other possibility is by measuring the particles from the proton dissociation or the protons that stayed intact in the scattering process. The scattered protons are already measured by ZEUS using a leading proton spectrometer [1]. The acceptance is limited for geometric reasons and the momentum range restricted. The leading proton spectrometer can be used to select events with intact protons or to describe qualitatively proton dissociation events, but it is not suitable as a tagger of proton dissociation.

In the following we investigate the potential accuracy that may be reached in measurements of the proton dissociation by recording the particles originating from the Y system in detectors installed in the proton fragmentation region. The fraction of the events where the proton stayed intact may be estimated by selecting the events where no particles were detected in these devices. The precision of such measurements is also analyzed.

2 Modelling the proton dissociation

The creation of the Y system may be modelled as a collision of the proton with the pomeron. Since the proton momentum is fixed the mass and the total momentum of the dissociated nucleonic state is determined by the energy and the momentum of the pomeron. The transverse momentum of the pomeron is practically zero compared to the longitudinal momenta involved, as $p_T^2 \approx t$, where t is the exponentially suppressed squared four momentum of the pomeron. Therefore in practice the kinematics of the nucleonic system is solely determined by the longitudinal momentum of the pomeron or equivalently by the mass $M_Y^2 \approx 4 \cdot p_p \cdot p_{I\!P}$.

The properties of the hadronization of the dissociated proton system depend mainly on the mass M_Y. Within the discussed model it corresponds to the centre–of–mass of the pomeron–proton collision. Fig. 1 shows the dependence of the average total transverse energy and the average charged multiplicity on the dissociated proton mass, according to PYTHIA 5.7 Monte Carlo program [2].

At HERA the particles from the proton dissociation are emitted under small angles in the direction of flight of the proton beam due to the strong Lorenz boost of the whole Y system. The angular distributions of final state hadrons, expressed in terms of pseudorapidity [1] for different intervals of the dissociated proton mass are shown in fig. 2. These distributions were obtained using the EPSOFT [3] MC program. It models the proton dissociation as a soft hadronic collision of the pomeron and the proton. The following assumptions define the properties of the final state:

- charged multiplicity according to the parametrization of $pp \to pN$ data;
- exponential suppression of transverse momenta with $\langle p_T \rangle \approx 300$ MeV;
- longitudinal momenta uniformly distributed in phase space.

Fig. 2 shows also how the distributions change if the average multiplicity is lowered by 30% or the average transverse momentum is increased by 30%. The reduction of the proton beam energy to $E_p = 450$ GeV shifts the distributions towards lower pseudorapidities which is equivalent to larger opening angles.

[1] The pseudorapidity, η, is derived from the relation $\eta = -log(tan(\theta/2))$, where θ is the polar angle calculated with respect to the proton beam direction

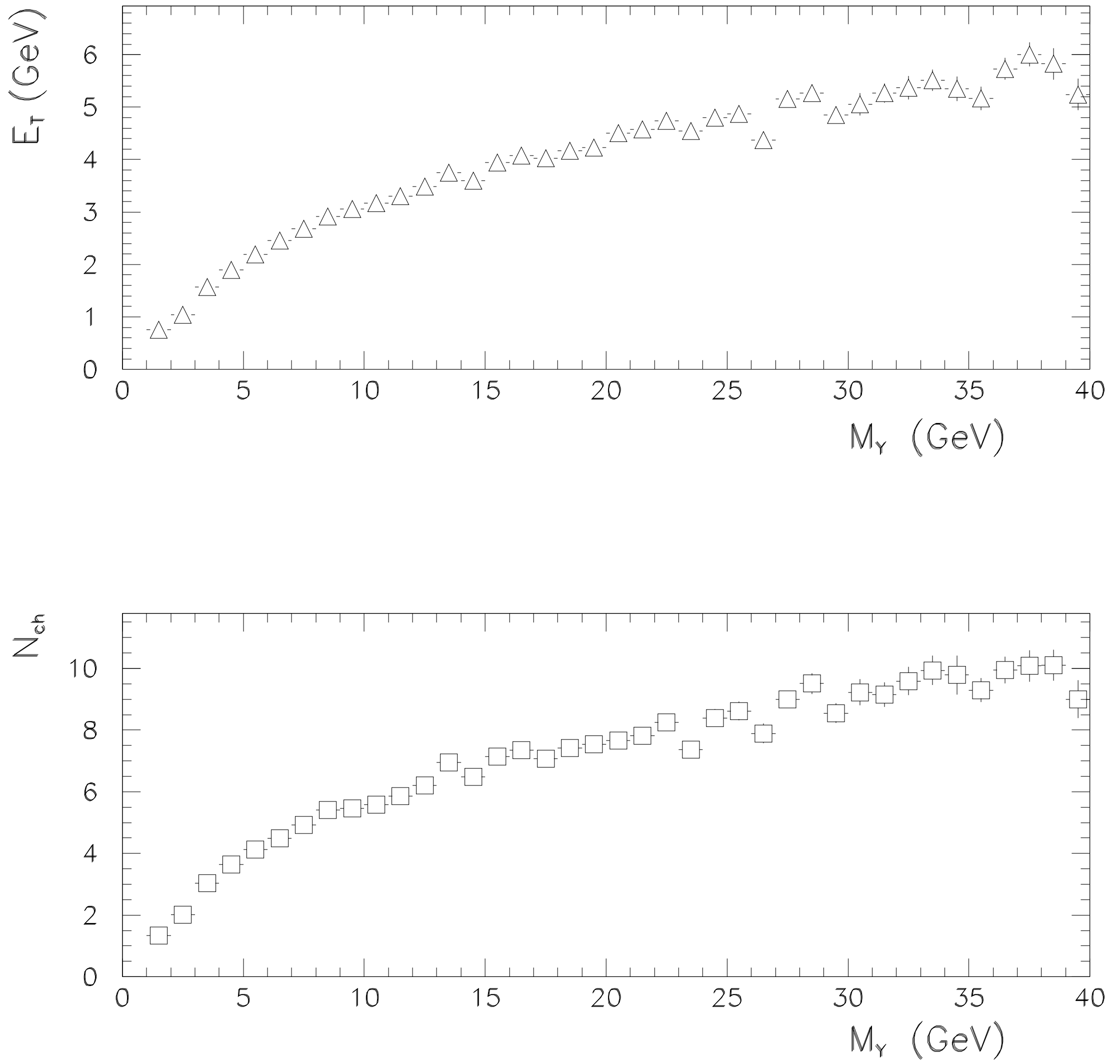

Figure 1: *Dependence of the average transverse energy (top) and the average charged multiplicity (bottom) on the dissociated proton mass in events generated with PYTHIA 5.7.*

3 Tagging the proton dissociation

In this section we investigate the possibility of tagging events with diffractive proton dissociation by detecting particles from the Y system with tagging devices installed in the forward region. For this study it was assumed that the central calorimeter, CAL, measures up to $\eta < 4$. The forward region was assumed to be instrumented with two counter rings symmetric around the beam axis covering the angles $4 < \eta < 4.9$ (tagger 1) and $4.9 < \eta < 5.9$ (tagger 2). There is a significant amount of inactive material in front of the taggers (up to one interaction length), concentrated mainly at $Z \approx 2.5$ m, where in the present design of the ZEUS interaction region the C4 collimator is installed. The preshowering effects may lead to significant distortions of the spectra in the taggers. This was simulated assuming that a shower of 7 cm radius may start

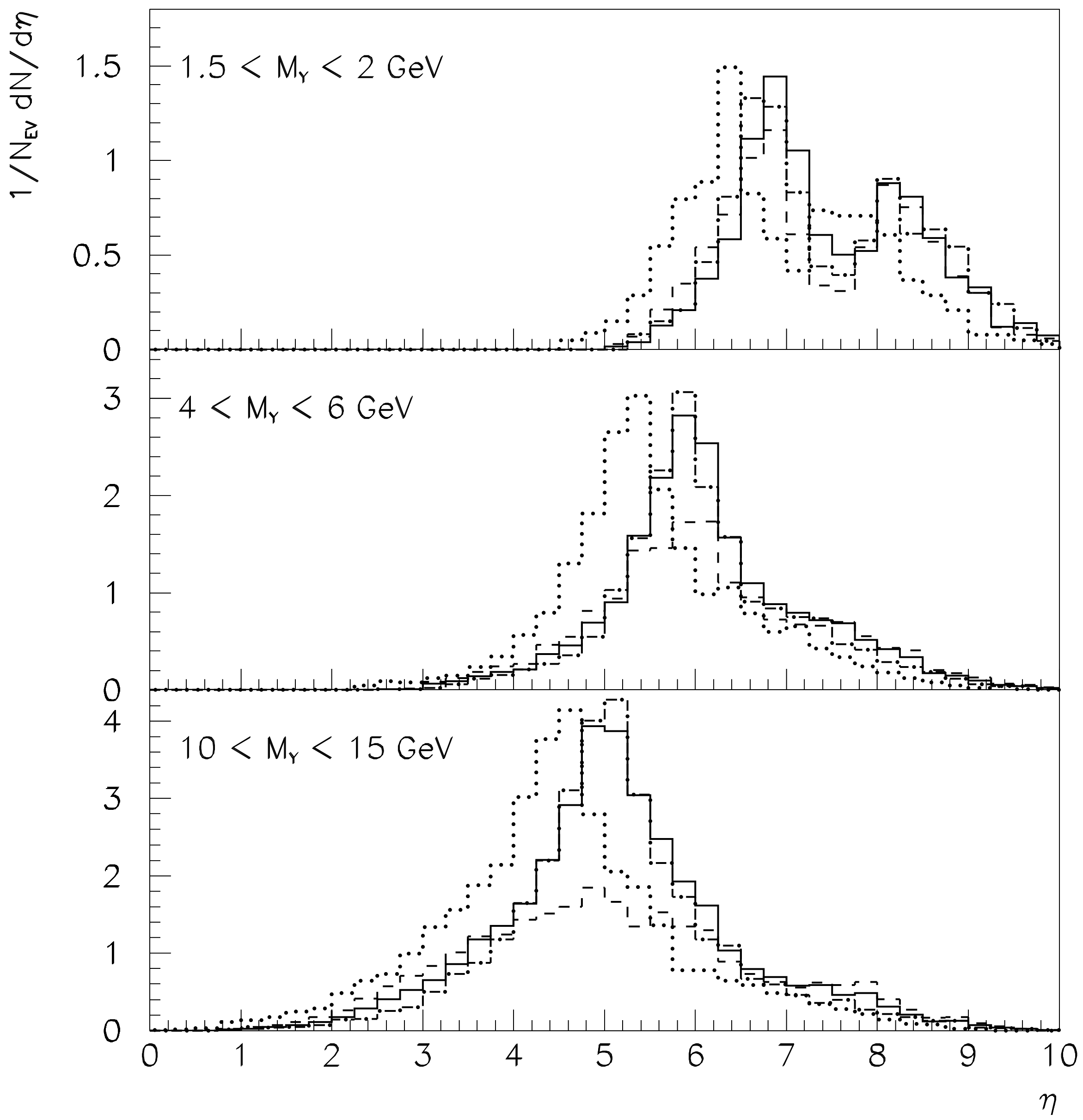

Figure 2: *Pseudorapidity distributions of particles from proton dissociation for different intervals of M_Y (solid histogram) according to EPSOFT. Dashed and dashed–dotted lines correspond to the distributions obtained if the charged multiplicities are reduced by 30 % or if the transverse momenta are increased by 30 %, respectively. The dotted line corresponds to lower proton beam energy, $E_p = 450$ GeV.*

at that place. Since the preshowering effect ensures high multiplicity of secondaries reaching the detectors, a 100 % efficiency for tagging such events was assumed. Fig. 3 shows the fraction of the proton dissociation events tagged by these devices as a function of the mass M_Y. Most of the events with $M_Y < 2$ GeV escape the detection in any of the devices, however masses $M_Y > 4$ GeV will almost certainly produce particles within the geometrical acceptance of the taggers.

The most straightforward application of forward taggers is the selection of diffractive processes where the proton stayed intact. This is done by rejecting all events with a signal in the

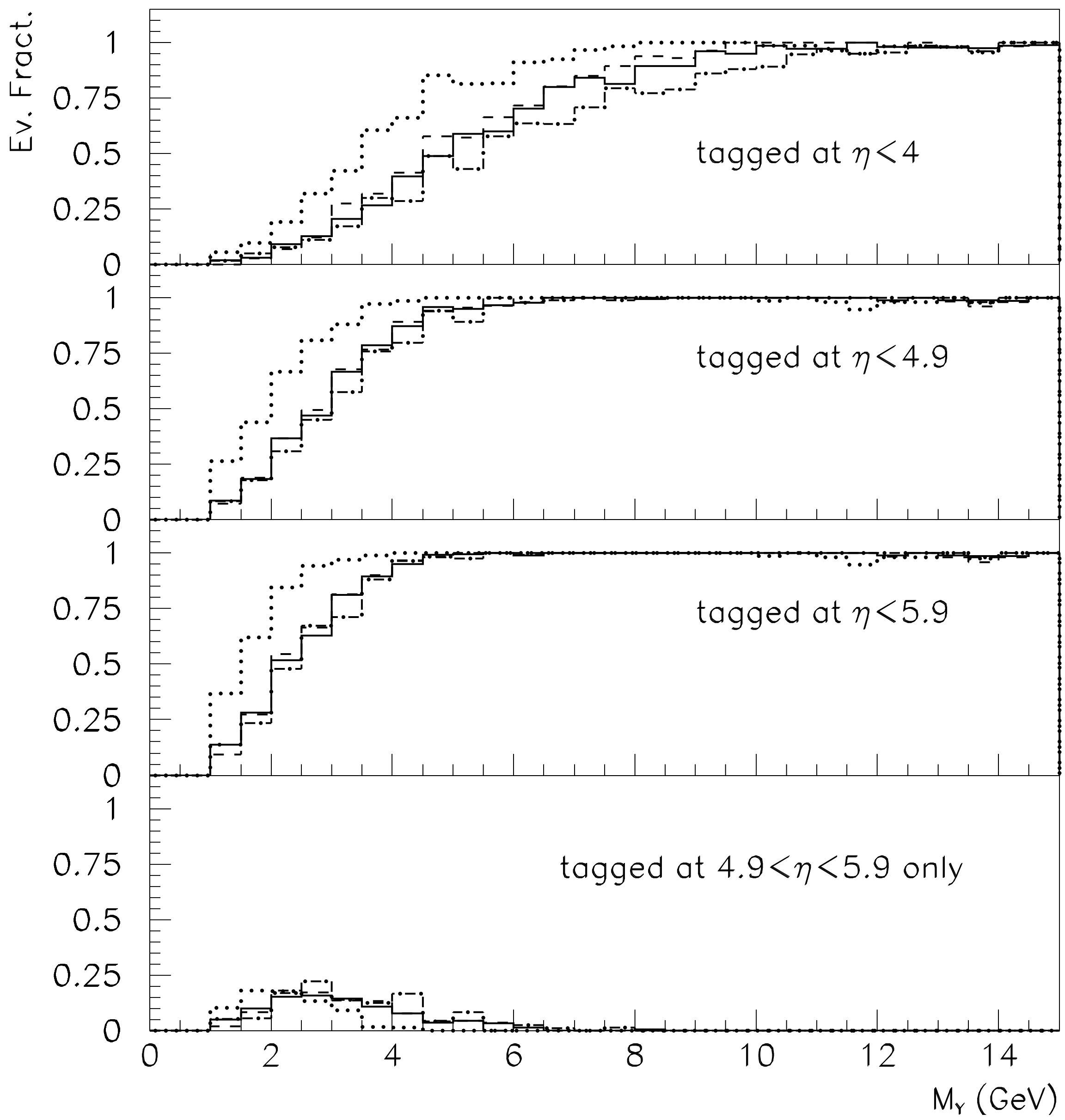

Figure 3: *The fraction of the proton dissociation events tagged by the counting devices covering different pseudorapidity regions as a function of the mass M_Y (solid histogram) according to EPSOFT. Dashed and dashed–dotted lines correspond to the distributions obtained if the charged multiplicities are reduced by 30 % or if the transverse momenta are increased by 30 %, respectively. The dotted line corresponds to lower proton beam energy, E_p = 450 GeV.*

forward detectors. Assuming that the probability for the proton in a diffractive ep interactions to stay intact or to dissociate to a given mass M_Y is the same as in the pp collisions one can estimate the fraction of the events with proton dissociation with no signal in the taggers. If only the central detector with $\eta < 4$ is used as veto, the contamination of single photon diffractive processes by proton dissociation is 16 $\pm$ 5 %. The error was estimated by varying the multiplicities and the transverse momenta assumed in the hadronization model by 30 %. The result is a large fraction known with a relatively poor precision. This uncertainty directly translates into a large error on the measured cross sections for the processes $ep \rightarrow eVp, eXp$.

The fraction of events with untagged proton dissociation may be reduced to 5.7 ± 1.4 %, if all the tagging devices at $\eta < 5.9$ are used. A significant reduction of the remaining proton dissociation fraction is possible only with devices reaching smaller polar angles, or by running with a lowered proton beam energy. The geometrical acceptance of the taggers for the beam energy of $E_p = 450$ GeV is also shown in fig. 3. In that case only 2.1 ± 0.6 % of the accepted events are accompanied by an untagged proton dissociation, allowing for very precise measurements of the cross sections for the single diffractive processes $ep \to eVp, eXp$.

To conclude, the fraction of single diffractive dissociation events contaminated by untagged double dissociation can be reduced by factor 3 by extending the forward tagging capabilities from $\eta = 4$ down to $\eta = 5.9$. A 30% uncertainty in the average multiplicity and transverse momenta of particles in proton dissociation results in similar uncertainty in the contamination.

4 Measuring the $d\sigma/dM_Y$ spectrum using taggers

It is also of interest to measure the mass spectrum of the diffractive proton dissociation in ep collisions at HERA and verify the factorization in diffractive process by comparing to pp interactions. Such a measurement is very difficult at HERA due to the strong forward boost of the whole Y system. Nevertheless one may attempt to estimate the behaviour of the M_Y spectrum even if only tagging devices are installed in the forward region. For example, one can measure the ratio of the number of proton dissociated events detected only in tagger 2 covering $4.9 < \eta < 5.9$ to the number of events tagged only in the main CAL, $\eta < 4$. As shown in fig. 3, the former cut selects events with c.a. $2 < M_Y < 5$ GeV, while the latter picks up those with roughly $M_Y > 8$ GeV. Assuming the distribution of the nucleonic mass in the form,

$$\frac{d\sigma}{dM_Y^2} \propto \left(\frac{1}{M_Y^2}\right)^a \tag{1}$$

it is possible to estimate the value of a from the measured ratio of the events. However, the region of Y masses selected by requiring signals in the tagging devices depends strongly on the assumptions of the fragmentation model. We have verified, that if the assumed average multiplicities are off by 30 %, the obtained value of a will be shifted by 0.11. This should be compared to 1.08, which is the absolute value expected for a from triple–pomeron phenomenology [4, 5]. The sensitivity of a to the p_T of the produced hadrons is similar. Therefore, considering the ideal case of 100 % efficient taggers the error on the measured value of a is $\sigma_a > 0.13$ due only to uncertainties in the hadronization process. If the energy of the proton beam is reduced to $E_p = 450$ GeV the acceptance of the tagging improves, but the uncertainty on a due to model assumptions does not.

5 Measuring the $d\sigma/dM_Y$ spectrum using calorimeters

The situation can be improved by installing calorimeters instead of the tagging devices in the forward region. To evaluate the potential of this solution we performed a MC study assuming that the region $4 < \eta < 5.9$ is instrumented with a calorimeter having a resolution of $\sigma_E/E = 60\ \%/\sqrt{E}$. The granularity is assumed to be such, that one cell corresponds to $\Delta\theta = 7$ mrad for angles $\theta < 28$ mrad and $\Delta\theta = 40$ mrad beyond that. Additionally, a position reconstruction

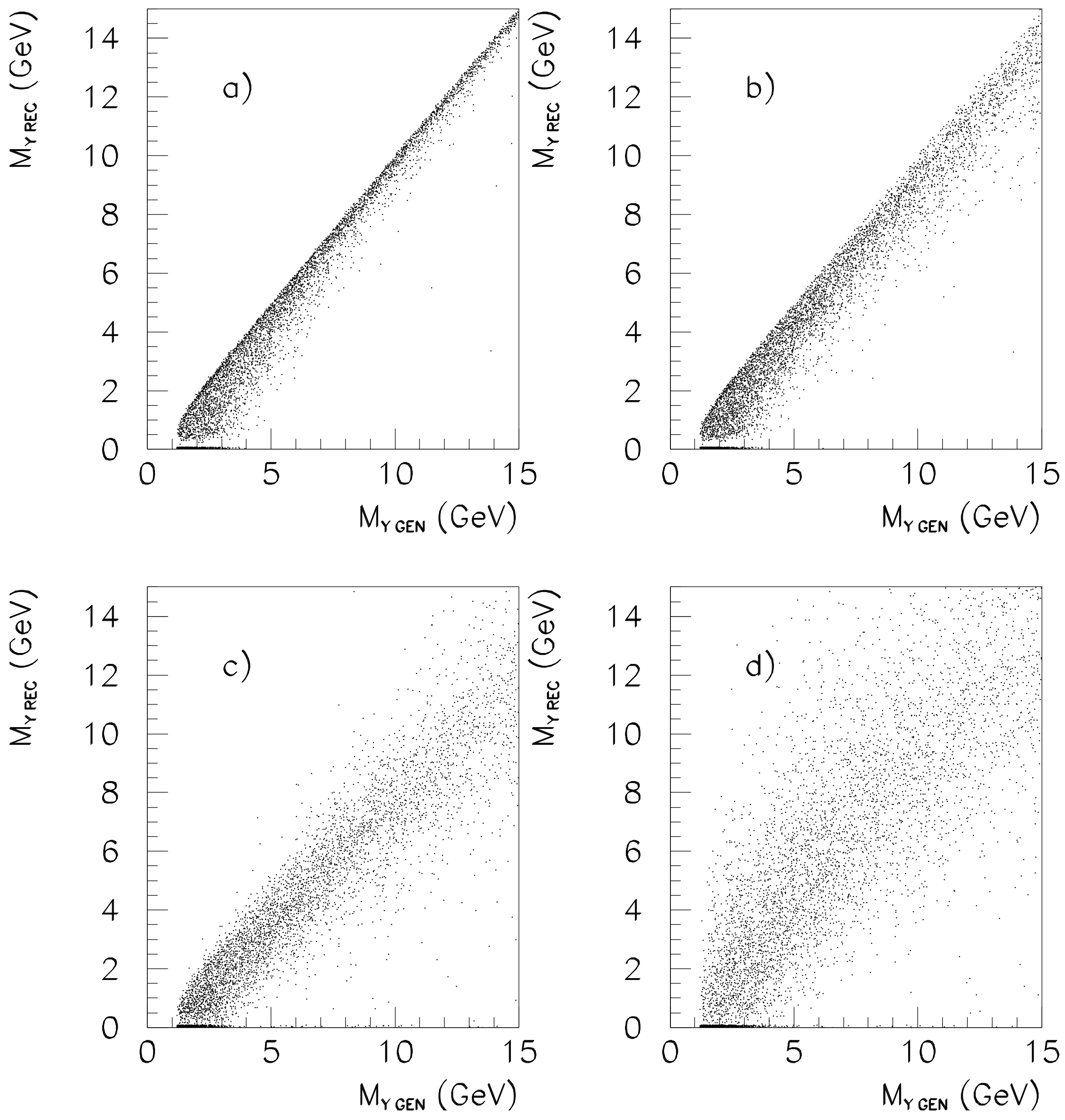

Figure 4: *Relation between the reconstructed and the true mass of the dissociated proton system according to EPSOFT MC program: a) taking into account only the effect of geometrical acceptance of the forward calorimeters, b) assuming in addition that particle momenta are approximated by their energy, c) after including the energy smearing due to losses in inactive material and calorimeter resolution, d) and after the position reconstruction smearing is also included.*

smearing due to the transverse size of the hadronic shower was included. The showers were assumed to begin at the C4 collimator at $Z \approx 2.5$ m and have a radius of 7 cm. The large amount of inactive material in the forward beam pipe region may also significantly distort the energy measurement. This was simulated assuming that every second particle may lose some energy before entering the calorimeter. This energy loss was generated from a flat distribution spanning from 0 to the particle energy. The rough estimate is based on the measurement of energy lost by hadrons in the EMC section of the ZEUS calorimeter [1]. The main calorimeter covering $\eta < 4$ was assumed to have a resolution of $\sigma_E/E = 40\ \%/\sqrt{E}$ and a granularity of $\Delta\theta = 40$ mrad. The following relation was used to reconstruct the invariant mass of the nucleonic system Y:

$$M_{Y\,REC} = \sqrt{E^2 - P^2} \approx \sqrt{(E - P_Z) \cdot (E + P_Z)} \approx \sqrt{\sum_i E_i(1 - cos\theta_i) \cdot 2E_p}, \tag{2}$$

where the summation runs over all the energy deposits measured in the forward region. Fig. 4 illustrates the expected quality of the dissociated proton mass reconstruction. The four plots show how the different factors degrade the mass resolution. Based on this simplified MC simulation one can estimate the resolution expected for the M_Y reconstruction of $\sigma_{M_Y}/M_Y \approx$ 100-120 $\%/\sqrt{M_Y}$. However, if the energy of the beam is reduced to $E_p = 450$ GeV the resolution can improve to about $\sigma_{M_Y}/M_Y \approx$ 70-80 $\%/\sqrt{M_Y}$, since the particles are emitted under larger angles.

Given this quality of the dissociated proton mass reconstruction we estimated the systematic precision one can achieve in measuring the mass spectrum. We assumed that the experimental method is similar to that considered for the case of taggers, namely by measuring the ratio of the number of events with mass $2 < M_Y < 5$ GeV and those with $M_Y > 8$ GeV. This time, the events were selected by requiring the reconstructed mass to fall into the intervals $0 < M_{Y\,REC} <$ 3 GeV and $M_{Y\,REC} > 7$ GeV. The thresholds applied on the reconstructed quantity are lower than what is expected for the true masses, since $M_{Y\,REC}$ is not corrected for energy lost in inactive material and carried by the particles that escaped the detection.

Assuming the form of Eq. 1 for the nucleonic mass spectrum we estimated the sensitivity of the measured value of a to the details of the hadronization of the Y system. Assuming that the average multiplicities and the transverse momenta are known to 30% the systematic uncertainty on a can not be smaller than 0.09. However, if the beam energy is reduced to $E_p =$ 450 GeV the precision on the measurement of a improves significantly, to about 0.03.

In this analysis we have not considered the uncertainties of the acceptance due to imprecise simulation of the effects of the dead material which may be large. Most probably, it is easier to control these effects if a calorimeter is installed in the forward region, as the calorimetric measurement is less sensitive to preshowering effects. A more realistic comparison of the two scenario would require further investigation of these aspects as well, as the questions of calibration, aging, radiation damage, etc.

6 Conclusions

We investigated the potential of forward detectors covering the pseudorapidities of $\eta < 5.9$ in the HERA colliding experiments for the studies of diffractive processes involving proton dissociation and those where the proton stays intact.

The processes with an elastically scattered proton, $ep \to eVp, eXp$, are measured by selecting events with no signal deposited in the forward detectors covering a range in η up to 5.9 units. Due to limited tagging acceptance, 5.7 $\pm$ 1.4 % of the events may still involve proton dissociation. If lower proton beam energy of $E_p = 450$ GeV was used the contribution from proton dissociation would reduce to 2.1 $\pm$ 0.6 %. For this type of studies the instrumentation of the forward region with tagging devices is as good as the calorimetric measurement since the geometrical acceptance is the decisive factor.

If the mass spectrum of the dissociated nucleonic states is to be measured, instrumenting the forward region with a calorimeter is preferable. The power a of the $d\sigma/dM_Y^2 \propto (1/M_Y^2)^a$ form of the mass spectrum may be measured with an error of 0.10 using calorimeters compared to that of 0.15 if tagging devices are used. The real potential of calorimetry with respect to tagging becomes apparent only if the beam energy is reduced. At $E_p = 450$ GeV the calorimetric resolution becomes $\sigma_{M_Y}/M_Y \approx$ 70-80 $\%/\sqrt{M_Y}$ instead of $100 - 120\%/\sqrt{M_Y}$ at the nominal beam energy and the systematic error on a may be reduced to roughly 0.03. The precision of the measurement using taggers does not significantly improve if the beam energy is reduced.

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