A New Routine for Analysing 3-jet Events in *ep*-collisions at HERA

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Abstract: A new C++ routine is written and used for comparing Monte Carlo predictions for *ep* deep inelastic scattering at low x to data from HERA. 3-jet events that fulfill several phase cuts are selected and cross sections of kinematic and jet variables are estimated. Events with foward jets and events with jets with high transverse momentum are analysed. Predictions of RAPGAP and CASCADE are compared to the data and to each other. Also the sensitivity to different PDF is examined. In addition, foward jet data is compared to MC prediction by using an existing analysis routine.

Contents

1 Introduction

During its runtime from 1990 to 2007, HERA has provided deep insights in the structure of the proton. Owing to a high center of mass energy of up to 319 GeV, deep inelastic scattering events between electrons and protons could resolve highly the inner structure of the proton so that we now have a good percepton of its parton density function at different scales. But still from the experiments of H1 and ZEUS there is data left to analyse, which will further incease our knowledge about the proton's structure.

Besides, Monte Carlo event generators were developed that can simulate arbitrary events for verifying the experimental setup as well as the underlying theory. Because of the rapidly increasing computer performance, Monte Carlo generators have become an indispensible tool in high energy physics. With the right theoretical input, the predictions of Monte Carlo generators match the data stemming from HERA measurements pretty well. Since the Monte Carlo generators simulate the physics, i.e. the kinematics and the produced particles that form jets and particle showers, one has to select event corresponding to the phase space that is accessible by the detector and for which the measurement will be reliable. Furhermore, if one is interested in special events, that give rise to certain physics discussed later, one has to apply further phase cuts.

Here, I will describe a routine in C++ processing deep inelastic scattering events at the H1 detector and filtering out events with at least three jets. With it, one can compare measured data to Monte Carlo predictions based on different physics, like evolution schemes and PDFs, which will be done at the end of this report.

2 Physics

2.1 Deep Inelastic Scattering

Deep inelastic scattering (DIS) is the process from which we mainly learn about the proton's inner structure. Most generally, it is a scattering event between a lepton and a hadron, which are in our case the electron with 4-momentum e (later a positron denoted also by e)) and the proton with 4-momentum p. Since, as far as we know, the electron has no inner structure, we know its state before the collision very well. Therefore we can use it as a probe particle to explore the proton, similar to the photon in the Rutherford experiment. In the dynamic quark model, the proton consists of not only of two up and one down quark called valence quarks, but also of an unspecified number of sea quarks and gluons. These latter virtual particles have very short lifetimes and are permanently created and annihilated. The constituents of the proton are called partons.

In DIS, the electron will scatter on one of these partons and exchange a photon $q = e - e'$ [1]. Because of energy conservation, this has to be a virtual photon with negative mass. One often is interested in the positive quantity $Q^2 = -q^2$, which is called virtuality. Roughly speaking, the higher the virtuality of the photon is, the better one can resolve the inner structure of the proton. To reach high virtualities, one needs high center of mass energies. Therefore both, the proton and the electron are accelerated and shot head to head on each other. The direction of the proton, that has the higher energy before the collision, is then called forward.

While the photon can couple directly to a quark, a gluon can do this just via producing another quark-antiquark pair before, which is called photon gluon fusion. From perturbative quantum field theory we know that every allowed Feynman diagram, e.g. with additional loops or radiated gluons and photons, will contribute to this scattering event. The probability of a special event to occur depends on the number of vertices in the belonging diagram, where every vertex gives a factor of the coupling constant α_e for electromagnetic and α_s for strong interactions. As long as the coupling constant is much smaller than one, which will be the case for electromagnetic interactions and strong interactions with low distances or high energies, we can neglect higher order diagrams and concentrate on the simple ones, that have few vertices.

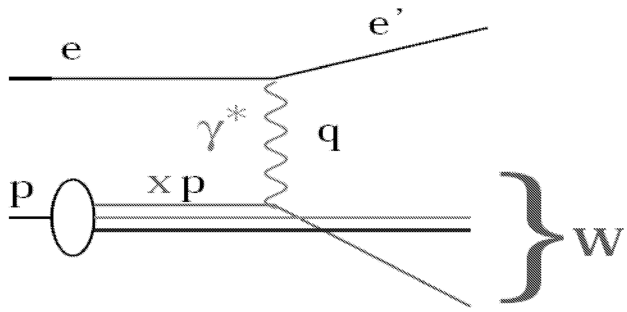

Figure 1: Feynman diagram of deep inelastic scattering in lowest order

Figure 1 shows schematically the DIS, where an electron scatters in lowest order ($O(\alpha_e)$,$O(\alpha_s^0)$) on a valence quark. Here, no gluon is involved. After the collision, the electron will have

[1] We don't consider the exchange of a Z-Boson and exclude it later by a phase cut.

a different 4-momentum e'. The scattered quark will, most likely, because of a high transmitted energy, be kicked out of the proton, so that the scattering actually is inelastic. Because of confinement in Quantum chromodynamics, the kicked out quark as well as the other remnants of the proton, that are no longer neutral charged, will create new quarks and gluons, which combine to new hadrons. The procedure will continue till all remaining quarks again form neutral hadrons. This is called hadronization. In general, the particles that stem from one inital radiated parton will fly in a certain solid angle and are called a jet. As a whole, we denote the energy of the hadronic final stage by W. Because the proton has much more energy than the electron in the laboratory frame, their momenta will be pointing strongly in the forward direction.

Since a parton is not fixed in the proton, it could carry any fraction of the protons momentum, which we denote by x. In DIS, the fraction of the protons energy of the quark that interacts with the photon is called Bjorken variable x_{Bj}. In an idealized picture, where this quark carries no momentum transverse to the proton beam, for x_{Bj} [2] it holds [1]:

$$x_{Bj} = \frac{Q^2}{2p \cdot q} \tag{1}$$

Another important variable is the inelasticity y of the process:

$$y = \frac{q \cdot p}{e \cdot p} \tag{2}$$

By measuring the angle θ, one can calculate the virtuality ($m_e \approx 0$):

$$Q^2 = -(e - e')^2 = -e^2 + 2e \cdot e' - e'^2 \approx e_0 e_{sc,0}(1 - \cos\theta) \tag{3}$$

These variables have the advantage that they are Lorentz invariant. Two independent of these variables are enough to describe to reconstruct the scattering.

Beside the total energy, which in high energy physics is essentially the kinetic energy, also the transverse energy p_T, perpendicular to the proton beam, will be important. As usual, we are defining the proton beam line as the z-axis of our coordinate system. So the x- and y-coordinates of all measured particles should in the end sum to zero. Of interest is also the pseudorapidity η of a particle, for which one needs the angle ϑ between its four momentum and the beam light (z-axis):

$$\eta = -\ln\left[\tan\left(\frac{\vartheta}{2}\right)\right] \tag{4}$$

[2] Later we will just use x for the Bjorken variable. It will be clear from the context if it is the momentum fraction of the interacting particle or for example of a parton in the evolution scheme.

[1] Here and hence we are using just 4-momentum vectors in energy units, usually GeV.

So, particles that are very forward have a high pseudorapidity, transverse directed particles none and backward particles a negative one.

2.2 Cross Sections

In collision experiments, one describes the likelihood of an event to happen by its cross section σ. The total cross section σ_{tot} is defined as the area around the target particle that will induce some event if the probe particle hits this area. No event means here no disturbance of the probe particle. The total cross section is directly proportional to the probability that an event will occur but independet of the whole experimental setup. The differential cross section is a function of a continious variable A that specifies the event and is denoted by $\mathrm{d}\sigma/\mathrm{d}A$. It is similar to the probability density that the variable will take a certain value [3]. If we are interested in the probability of a special phase space region, we have to integrate the differential cross section over this region.

The differential cross section is the variable of interest and is calculated by cutting the variable space in i pieces, called bins. The bin counts N_i, that depend on the variable value, have to be divided by the total number of events $N = \sum_i N_i$, to get the probability of this phase region to occur. To get an estimation of differential cross section, one then divides by the bin width μ_i and multiplies with the total cross section σ_{tot} measured in the laboratory by including all tries. After all, we got the important formula:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}A}(A) \approx \frac{N_i(A) \cdot \sigma_{tot}}{\mu_i \cdot N_{tot}} \tag{5}$$

The more bins one uses and the more events one induces, the better the differential cross section will be resolved. Usually, one depicts the differential cross section in histograms that can be produced with the help of ROOT.

2.3 Proton Structure Function and Evolution Equations

The most important quantity describing the proton's structure is the parton density function (PDF) $f_i(x, Q^2)$ [4]. In DIS, it describes the probability that one detects a parton of type i that has Bjorken x while the resolution in the event is Q^2. To detect

[3] Mathematically, we can get the differential cross section by differentiating a scale depending cross section $\sigma(A)$, which is proportional to the cumulative distribution function and is the total cross section for the maximal scale. But this picture is very confusing and the procedure is not very helpful because we don't know $\sigma(A)$.

[4] It could also be a function of two other independent scale variables.

also gluons, that do not couple with photons, one has to define the PDF in DIS at least in first order α_s. This means, either a gluon is in the proton that splits up in a quark-antiquark pair that then interacts with the photon, or a quark is in the proton that radiates a gluon before the interaction. Generally, it describes the probability to find any parton in the proton, also gluons, but these can not measured directly in DIS. By summing the PDFs weighted with the charges of the particles due to their coupling and the momentum fraction x, one gets the structure function F_2 of the proton that combines all this information:

$$F_2(x, Q^2) = x \sum_i C_i^2 f_i(x, Q^2) \tag{6}$$

Calulating pertubatively the PDFs is very tough in QCD. Because of the large value of the strong coupling, one really needs to calculate higher orders. But one has not yet managed to perform these calculations for $O(\alpha_s^3)$. Therefore one uses schemes that combine experimental results with approximations to the usual pertubative calculations. These are called evolution schemes. The key idea is always that one considers the PDF at a low starting scale μ_0 that is determined by inclusive measurements. From a proton described by the starting PDF, a chain of n partons radiate/split up in hard processes. The partons in the chain are numbered, having virtualities k_i and momentum fractions x_i, where the parton "1" was radiated at first, near the proton. In the DIS, the last parton in the chain has to be a quark that scatters with the photon. Calculating these radiation processes pertubatively, one can predict the probability for finding a certain particle at the end of the chain. From that calculations, one can derive a differential equation in the scale μ for the PDF, the so called evolution equation. In DIS, one chooses Q^2, the virtuality of the photon, as a scale variable. Therefore, with DIS one can check the PDF or, respectively, the evolution scheme by measuring the cross section of the quarks interacting with the probe electron via the photon. The total cross section will be almost [5] proportinal to the structure function $F_2(x, Q^2)$.

A certain scheme sums up only certain matrix elements, i.e. Feynman diagrams, of these processes while restricting to a phase space area where these matrix elements are dominant. For (in total) small x, gluon splitting becomes the dominating process and one can neglect the other splittings. In figure 2 we see, a DIS event with several gluons radiated before the "‘hard"’ scattering between the photon and the quark takes place. This process is also called initial state gluon radiation. For the gluons, there is a always a simple ordering in x_i:

[5] Actually, one also has to take care of the polarisation of the photon

$$x_{i+1} < x_i. \tag{7}$$

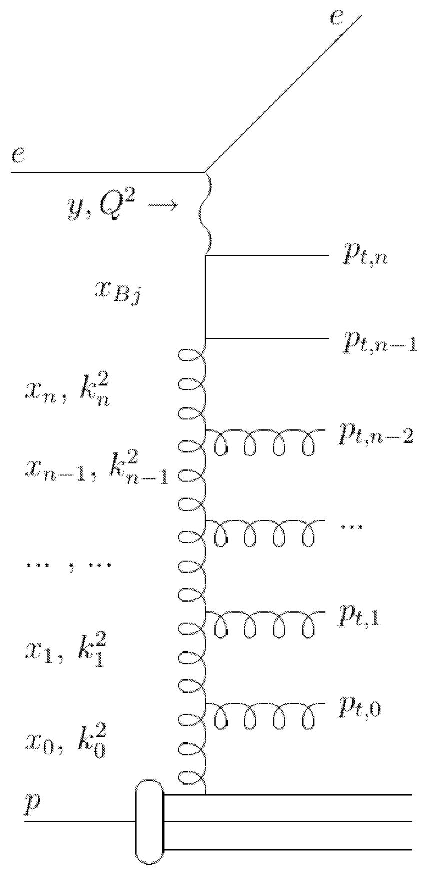

Figure 2: Feynman diagram of deep inelastic scattering with initial state gluon radiation

One famous evolution scheme is the DGLAP and was developed by Dokshitzer, Gribov, Lipatov, Alarelli and Parisi. It sums up terms with a factor of $\alpha_s^m \ln(Q^2)^n$ while neglecting terms with $\alpha^m \ln \frac{1}{x}$. So it will be valid for high Q^2 and relatively large x_{Bj}. The DGLAP schemes comes along with a strong ordering in the virtualities

$$Q^2 \gg k_n^2 \gg ... \gg k_i^2 \gg ... \gg k_1^2 \tag{8}$$

which is correlated to a similar ordering in the $p_{T,i}$. Because of the strong k_i ordering, the masses of the partons in the chain are very low and can be neglected. The DGLAP evolution equation then is:

$$\frac{\mathrm{d}}{\mathrm{d}\ln Q^2} f_i(x,Q^2) = \frac{\alpha_s Q^2}{2\pi} \sum_j \int_x^1 \frac{\mathrm{d}x'}{x'} f_i(x',Q^2) P_{ij}\left(\frac{x}{x'}\right) \tag{9}$$

Here $P_{ij}\left(\frac{x}{x'}\right)$ is the probability kernel for a parton i to radiate a parton j and is called splitting function. So, by measuring $f_i(x,Q^2)$ at a starting scale Q^2 one can "evolve" the PDF to different scales.

Another evolution scheme is the BFKL (Balitsky, Fadin, Kuraev, Lipatov). In contrast to the DGLAP scheme, it sums terms with factors of $\alpha_s^m \ln\frac{1}{x}$ and ignores those with $\alpha_s^m (\ln Q^2)^n$. So it will be valid when x is relativlely small such that. $\ln Q^2 \ll \ln\frac{1}{x}$. Assuming here that x is very small, the scheme just considers gluon splitting. BFKL corresponds to a strong ordering in the fractions

$$x_{Bj} \ll x_{n-1} \ll ... \ll x_0 \alpha^m \ln\frac{1}{x_{Bj}} \tag{10}$$

and randomly distributed virtualities k_i that no longer can be neglected. Due to the possible high transverse momenta k_T of the chain gluons (not the radiated ones), the respective evolution equation is expressed in the so called unintegrated gluon density $A(x,k_T^2)$ that is connected to the gluon density by:

$$x f_{gluon}(x,Q^2) \approx \int_0^{\mu} \frac{\mathrm{d}k_T^2}{k_T^2} A(x,k_T^2) \tag{11}$$

The BFKL evolution equation is:

$$\frac{\mathrm{d}A(x,k_T)}{\mathrm{d}\log(\frac{1}{x})} = \int \mathrm{d}k_T'^2 A(x,k_T'^2) K(k_T^2,k_T'^2) \tag{12}$$

Here $K(k_T^2,k_T'^2)$ is the gluon splitting function in terms of k_T, so it is the probability that a gluon with virtuality k_T will radiate another gluon with virtuality k_T'. For the integrated PDFs, this k_T dependence is integrated out.

Finally, the evolution scheme CCFM (Catani, Ciafaloni, Fiorani, Marchesini) sums up terms in $\ln Q^2$ as well as terms in $\ln\frac{1}{x}$. There will be again no ordering in k_i but in the angles of the radiated gluons:

$$\theta_n > ... > \theta_i \tag{13}$$

3 Tools

3.1 Event generators

During my work, I used the event generators CASCADE and RAPGAP, which generate randomly DIS events according to a chosen starting scale PDF, a evolution scheme and certain splitting functions. The hard scattering between electron, photon and the quark-antiquark pair is calculated with full pertubative QCD methods, while the high order processes are calculated using the evolution schemes. This means, the evolution scheme predicts the cross sections of the quark in the hard process and the cross sections of all beforehand radiated partons. For CASCADE, only gluons are considered in the evolution and in the radiation. For my simulations, I used four different unintegrated gluon densities: "CCFM J2003 set 1" ("set1"), "CCFM J2003 set 2" ("set2"), "CCFM J2003 set 3" ("set 3") and "CCFM set A0" ("set A0"). All these gluon density functions $A($ are determined by making the Ansatz

$$xA(x, k_T) = N \cdot x^{-b} \cdot (1-x)^C \cdot \exp\left(-\frac{(k_T - \mu)^2}{2\sigma^2}\right) \tag{14}$$

where N, B, C, and σ are fitting parameters that have to be determined by comparing the simulated data to measurements. The different sets also use different gluon splitting functions

For both generators, the starting PDF is defined at a low scale $Q^2 \approx 1\text{GeV}^2$, s.t. the pertubative terms converge. RAPGAP uses the DGLAP evolution scheme whereas CASCADE works with CCFM. Therefore one expects less forward jets with a high transverse momentum when running RAPGAP because they have ordered $p_{T,i}$ beginning at the gluon that is radiated first.

After the scattering, the hadronisation is randomly simulated, but I will not describe this step.

In the steering file, all needed information from outside is saved, like number of events to process, the 4-momenta of the incoming particles, the used set containing splitting functions and PDFs, the jet finding algorithm, other physical processes etc. . This is then the input file of the compiled event generator program. After each event has been generated, the output information, i.e. the 4-momenta of the produced particles, is saved in a common block. Then, the actual routine containing phase cuts, calculations, booking and histogramming is run. This procedure recurs till the last event has processed. Then the routine is run for a last time for terminating jobs, for example error checking and the normalising of the histogram. Also histograms with the measured data will be filed. This data is stored in the routine.

3.2 HzTool

HzTool is a library of routines and functions mostly written in Fortran to analyse data of simulated scattering experiments given by Monte Carlo generators and to compare it to measured data from the laboratory that is also stored in the library. It has been developed at DESY within the workshop "'Future physics at HERA"' in 1995 and has been extended steadily from then on. With a wrapper the it is also possible to use the routines in other programming languages. All the used HzTool routines have been included to the C++ wrapper. I will describe the most important routines that I used.

Many of the routines are used to extract special information out of the bulk that is provided by the generator. This can be the 4-momenta of the incoming or the outgoing particles or just the place where they are stored in the common block. Others are computing variables like angles of the particles w.r.t. the beam line (HZPHMANG), their rapidities (HZETA) or the kinematic quantities x, y, Q^2 (HZDISKIN).

As already mentioned, radiated quarks and gluons create jets, i.e. sprays of particles whose 4-momenta ideally sum up to the 4-momentum of their mother particle. The daughter particles are confined to a cone. But the more jets there are and the closer they are together, the harder their distinction will be. On the other hand, it depends on the definition of a jet, how many of them we will find. Restriction to special conditions, like the radius around the center of mass of the clustered particles, will make jet finding sensible, but this procedure is rather arbitrary. There are several jet algorithms that peform the distinction. They are not described here. In HzTool, the routine HZJTFIND performs the jet finding for different algorithms and modes. For my analysis, I used the KTCLUS algorithm. The jet finder works not in the laboratory frame, but in the hadronic center of mass (HCM) frame. In DIS, this is the inertial system, where the momenta of the quark and the photon cancel each other. The term hadronic just means the absence of the lepton in the calculation. To boost in the HCM frame and back again, I used the routine HZHCMTOL.

3.3 ROOT

The histograms in this report have been plotted with ROOT. ROOT is a graphical software to plot and to analyse statistical data. It was developed by CERN originally to evaluate scattering experiments and many parts are licensed publicly. ROOT is written in C++ and is object oriented by itself using almost completely the C++ language. It contains also a big library of routines supporting the analysis. With ROOT functions implemented in the event routine it is easy to fill a histogram, to weight entries and to scale and normalise it afterwards.

For plotting the histograms, I wrote different plotting routines, that automate loading of the root files created by the event routine, labeling the histograms, setting the ranges, coulors, symbols and eventually plotting the histograms. Here one can combine different histograms in the same plot and several plots in the same graphic.

4 The New Routine

The routine I wrote in C++ works as follows: First, the 4-momenta of the scattering particles and other important variables like (q, θ etc.) and the kinematics (Q^2, x, y) are defined. While the four momenta are loaded directly from the common block, other variables have to be calculated from them, partly with the help of HzTool. The next step is then the event selection. The phase space cuts are based on collisions with 920 GeV protons and 26.5 GeV positrons recorded at HERA in the years 1999 to 2000, so that it can be compared to measured data. To match the scattered positron to the calorimeter acceptance, one demands that its energy $e_{sc,0}$ should be above 9 GeV. The range of the calorimeter confines the scattered angle to $156° < \theta < 175°$. To take care of the high energy limit of the calorimeter and to avoid photoproduction, one also restricts to $5 < \mathrm{Q}^2 < 80\mathrm{GeV}^2$ and $0.1 < y < 0.7$. To have the desired low x for the evolution schemes, one requires $0.0001 < x < 0.01$. In table 1, the cuts for the event selection are summarised.

For the jet selection, the particles in the common block have to be boosted to the hadronic center of mass frame because this is the frame the jet finder is defined. The jet finder then clusters the particles according to the so called k_T-clustering algorithm. The 4-momenta ($E_j, p_{1,j}, p_{2,j}, p_{3,j}$), the mass m_j (Lorentz invariant), the transverse energies $p^*_{T,j}$, the pseudorapidities η^*_j and the angle to the proton beam ϑ^*_j of the jets are stored in an array. The jets are ordered due to their transverse energy. After the jet finding, the common block has to be boosted back, s.t. also other routines running at the same event loop can use it. Additionally, one has to boost back the four momenta of the jets to the laboratory frame to calculate η_j. This is because cuts of the pseudorapidities of the jets $-1 < \eta_j < 2.5$ have to be made, again match the calorimeter acceptance.

For the jet selection, one requires also every jet to have a minimum transverse energy of $p^*_{T,j} > 4\text{GeV}$ to make sure that they are well defined and stem from the partons involved in the initial gluon radiation. At least three jets should fulfill these cuts. The first two jets we want to associate with the radiated quark-antiquark pair of the hard process. To ensure this, the sum of $p_{T,j}$ of the two leading jets should exceed 9 GeV. The other jets fulfilling these constraints then can be identified with radiated gluons in initial state gluon radiation. The last cut requires one of the three leading jets to have a pseudorapidity of less then 1.3 which ensures a good trigger efficiency in the measurment. In table 2 all jet constraints are listed.

$5\text{GeV}^2 < Q^2 < 80\text{GeV}^2$
$0.0001 < x < 0.01$
$0.1 < y < 0.7$
$156° < \theta < 175°$
$e_{sc,0} > 9\text{GeV}$

Table 1: Event selection

$N_{jet} > 3$
$p^*_{T,1} > 4$ GeV
$p^*_{T,1} + p^*_{T,2} > 9$ GeV
$-1 < \eta_i < 2.5$, $i = 1, 2, 3$
$\eta_i < 1.3$, for one $i \in \{1, 2, 3\}$

Table 2: Jet selection

For the events that pass all these requirements, the following variables are filled in histograms:

- virtuality of the photon Q^2
- Bjorken variable x
- inelasticity y
- number N_j of jets fulfilling the jet selection
- transverse energy $p^*_{T,1}$ of the leading jet
- pseudorapidities η_j of the three leading jets
- difference of pseudo-rapidities $\eta^*_{T,1} - \eta^*_{T,2}$ of first two leading jets

Next, one is interested in events with one forward jet. This will be interesting in the comparison of the different evolution schemes. Therefore, one requires one of the leading jets to have a high pseudorapidity of $\eta_j > 1.73$ and a high fraction of the protons energy of $\frac{E_j}{p_0} > 0.035$. The other to leading jets should either be central, i.e. having pseudorapidities $-1 < \eta_j < 1$ or just one of them has to be central while the other is also more forward with $\eta_j > 1$. For both subsamples, two and one central jets, the Bjorken x, the pseudorapidities of the three leading jets and the transverse energy of the leading jet are stored in histograms.

A last case is the observation of events with at least one jet of very high transverse energy of $p^*_{T,j} > 20$ GeV. In this case, two more histograms with x and η_j of the leading jet are filled.

After all events have been processed, the histograms contain the number of the specific events happened. Also the statistical errors are stored. Histogram entries are then, according to equation 5, normalised to the bin width, divided by the number of events N and muliplied by the total cross section σ that one can from the common block. The resulting cross sections are saved in new Root files, as well as the data, to be loaded later by the plotting scripts.

5 Comparison of RAPGAP to CASCADE

Here and for all further analysis, in total $N = 2500000$ events have been processed. The measured data that is compared to the Monte Carlo predictions, including statistical errors, stems from [2].

We will now compare the results for the event simulations of RAPGAP and CASCADE, both processed by the routine. As already mentioned, RAPGAP uses the DGLAP evolution scheme while CASCADE is based on CCFM. In this run, CASCADE worked with the unintegrated gluon density "CCFM JET2003 set 2". Because of the properties of the evolution schemes described in section 2.3, we expect RAPGAP to describe the upper x regime whereas CASCADE should be more similar to the data for lower x. This is precisely confirmed by the cross section as a function of x in figure 3 and figure 4. Due to the fact that the cross section is statistically dominated by events at low x, the RAPGAP predictions are too low for all variables, mostly by a factor of about 2. This is also a good cross-check for my routine since this factor of 2 has been predicted already by other publications [2].

Especially the forward jet subsample is interesting to consider: Here, the RAPGAP predictions deviate very drastically. This is, because of the strong ordering in k_i that comes along with an ordering in $p_{T,i}$ for the radiated gluons, one would not expect energetically high gluon radiations in the forward direction due to DGLAP. For CCFM, there is no contradiction to energetic forward gluon radiations and the data is described much better.

In general, one sees that the CASCADE predictions describe the data very well. One also has to keep in mind that in the regions, where the statistics is very low, the statistical error is very high and a few events can change the shape of the histogram. So we find a pretty good matching of the theoretical prediction of the CCFM evolution scheme and the chosen gluon density function with the data in these special phase regions.

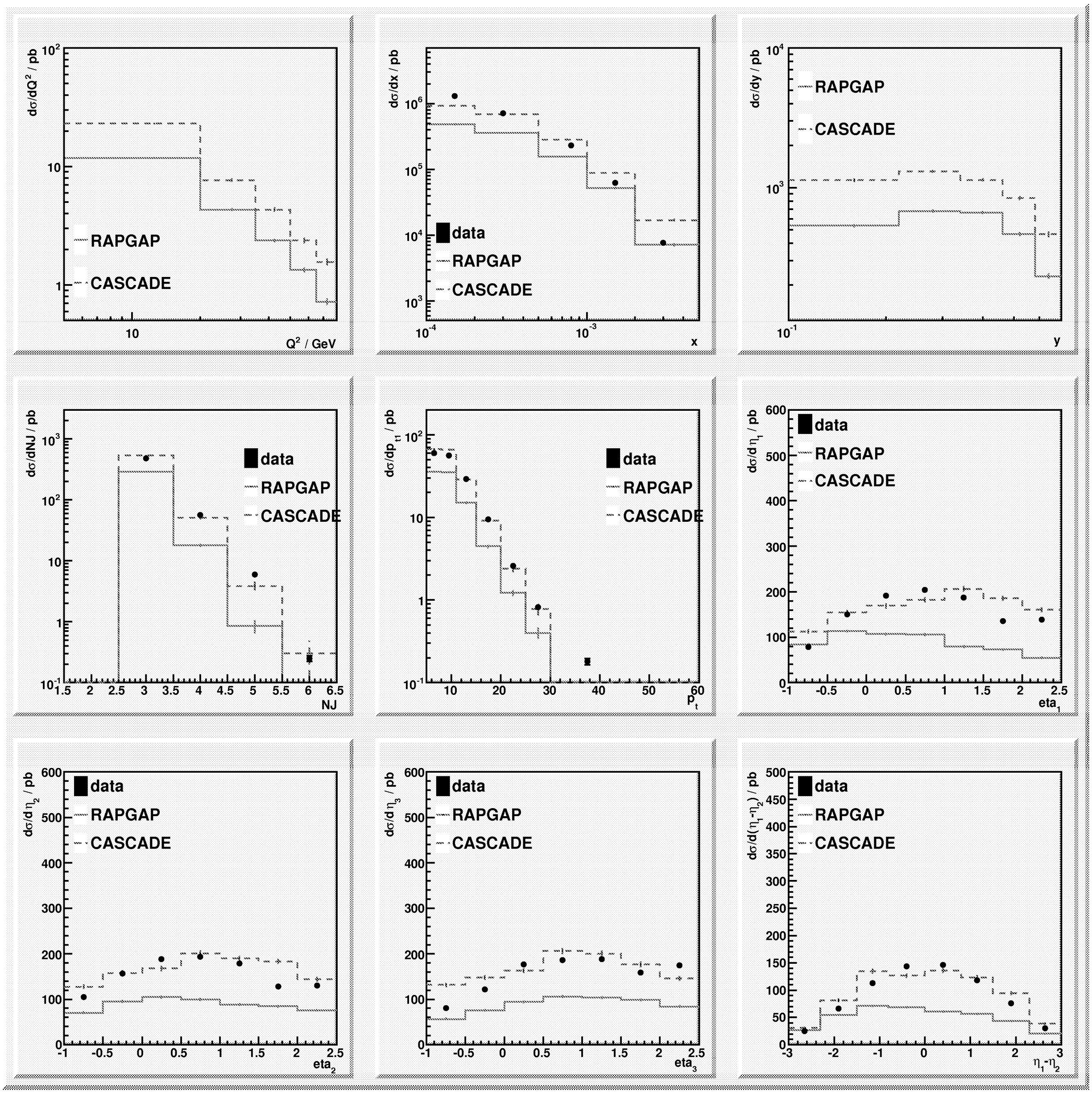

Figure 3: Cross sections of different variables for 3-jet production, comparison of RAPGAP- and CASCADE-predictions; for Q^2 and y there is no data because there was no direct measurement

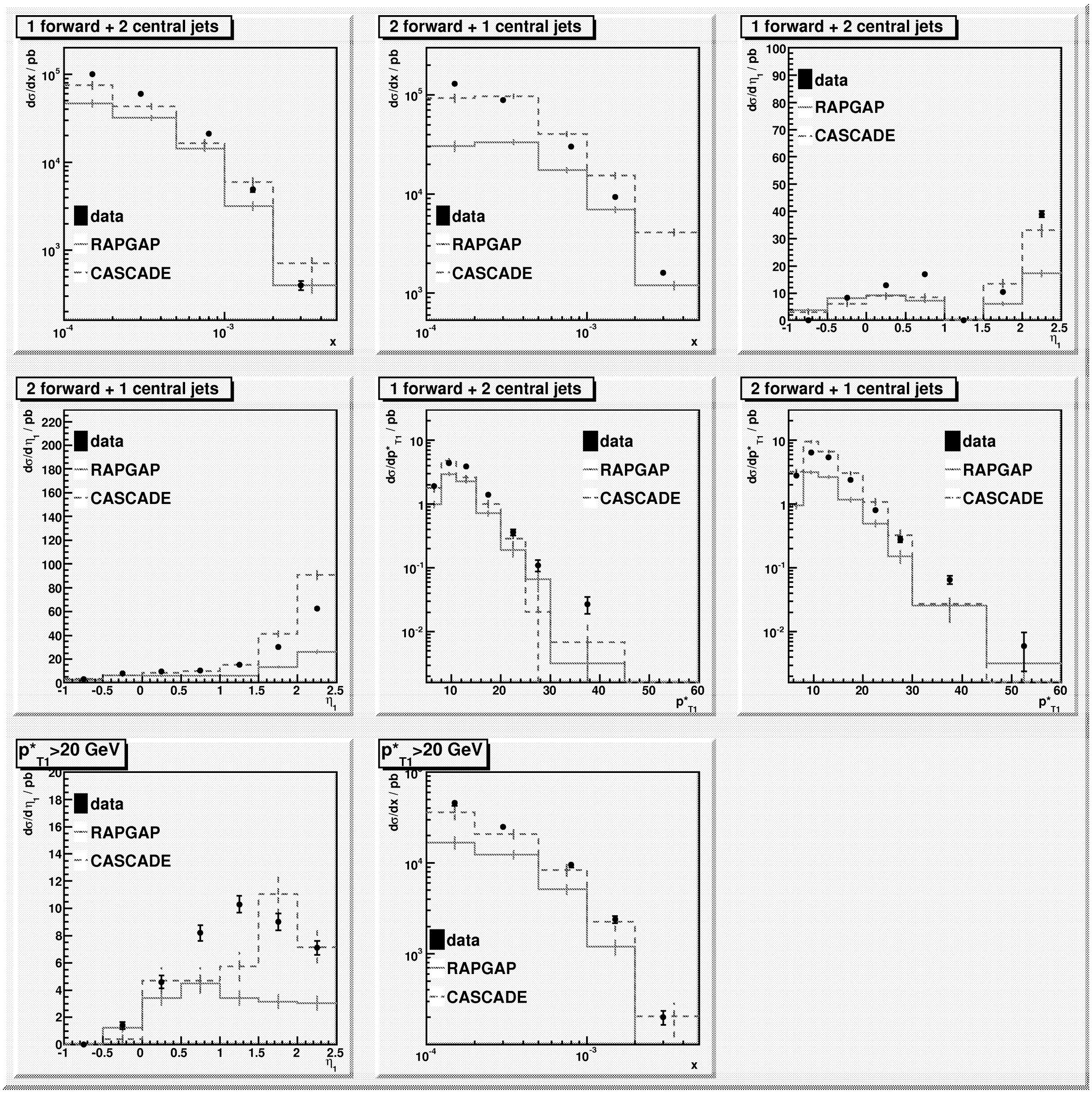

Figure 4: Cross sections of different variables for 3-jet production, comparison of RAPGAP and CASCADE predictions

6 Comparison of Different PDFs

As already seen in the previous section, the gluon density function set 2 leads to pretty good Monte Carlo predicions. Now we also want to consider other unintegrated PDFs, set 1, set 3, set A0, and compare them. In figures 5 and 6 all histograms are shown for these four gluon density functions. Obviously, there are higher deviations for the other PDFs. Roughly, the predictions are a factor of 2 too high while the shape is described pretty well. The reason is that the fitting parameters of the unintegrated PDFs are different. Even though they have been optimised according to the same data, they used different splitting functions in the evolution scheme.

For high p_T of the leading jet, the domination of set2 decreases and the other sets are describing the data better.

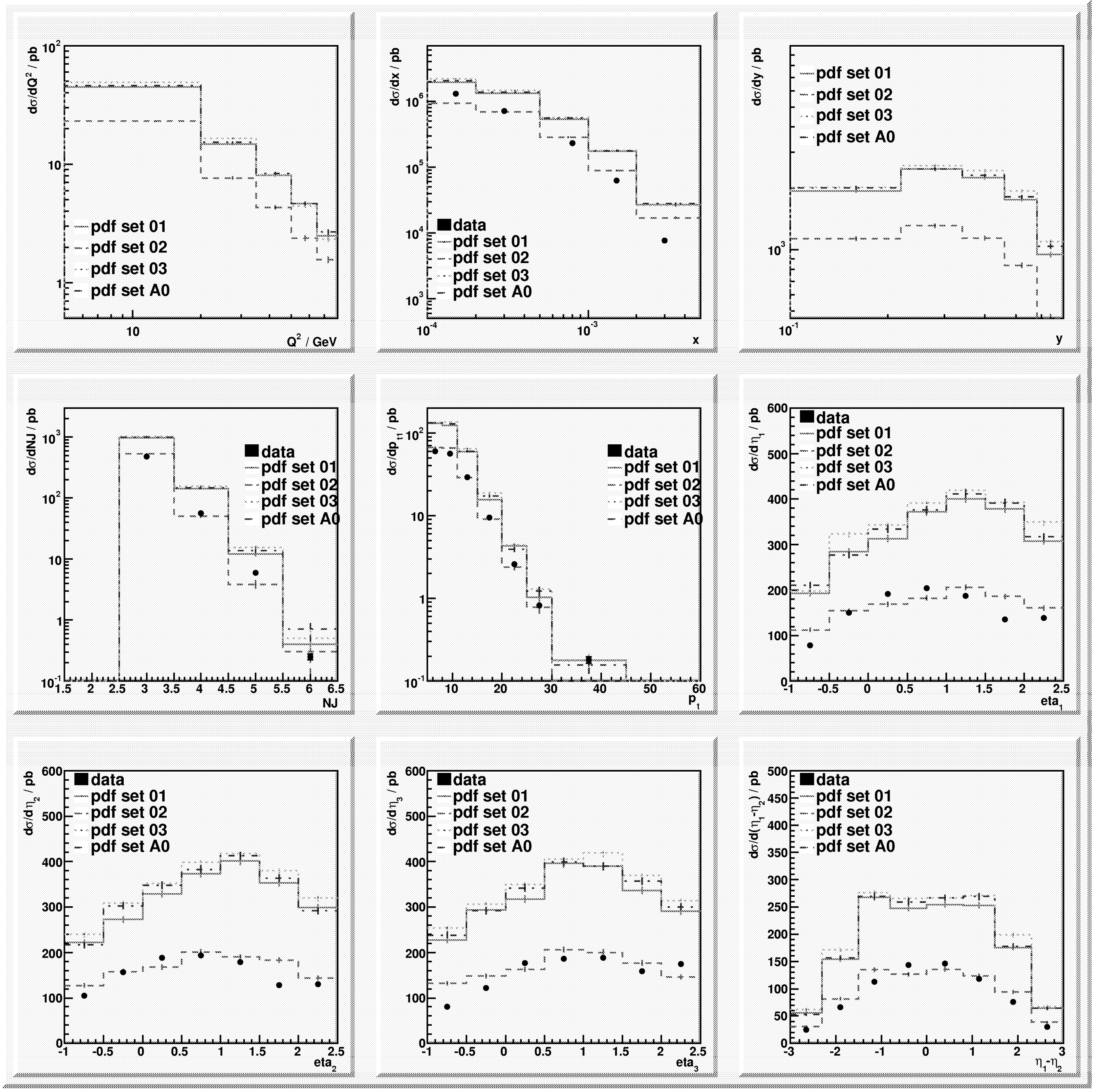

Figure 5: Cross sections of different variables for 3-jet production, comparison of different PDFs; for Q^2 and y there is no data because there was no direct measurement

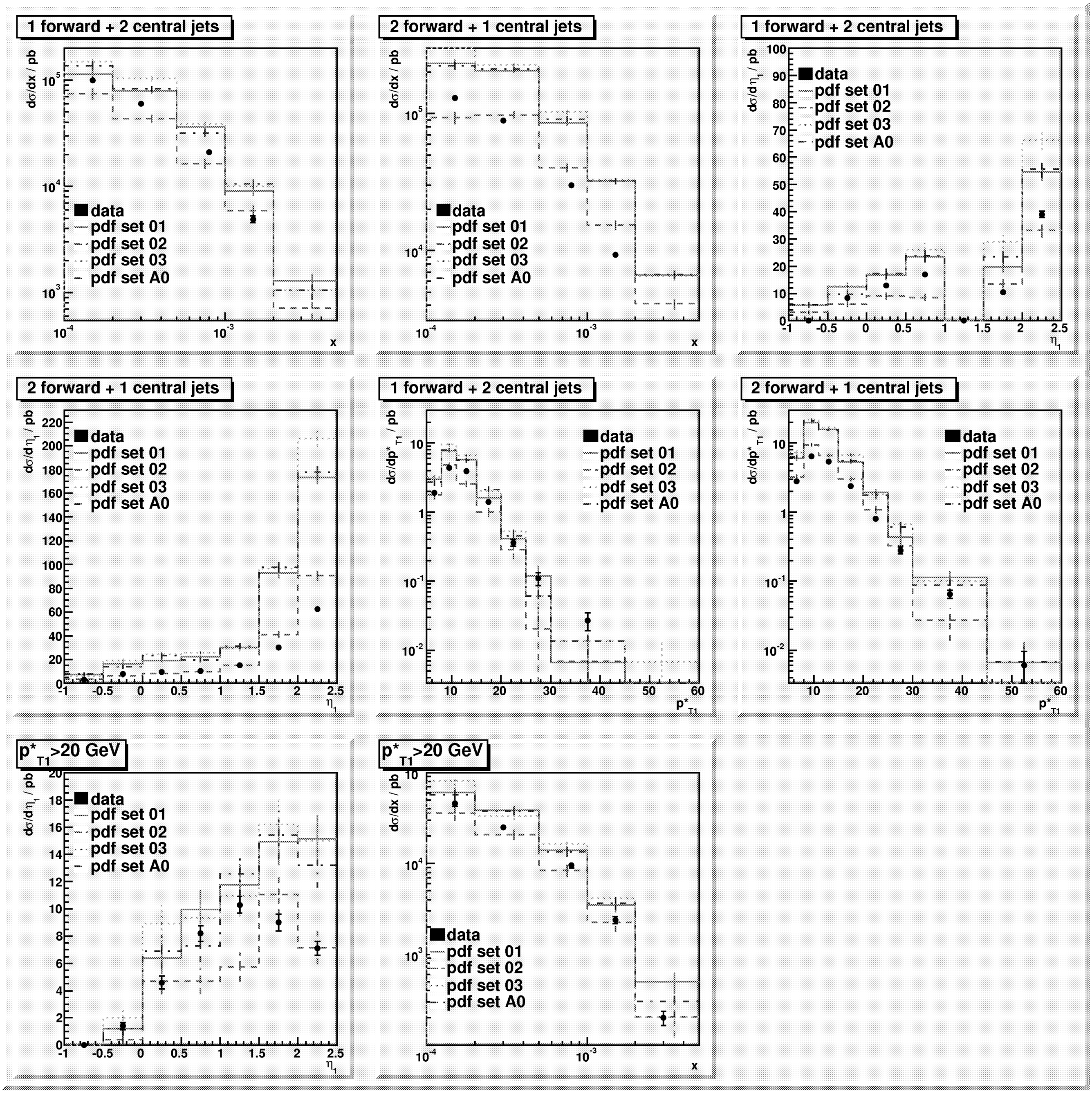

Figure 6: Cross sections of different variables for 3-jet production, comparison of different PDFs

7 Forward Jet Events

Now, I will compare foward jet predictions of my routine to Monte Carlo predictions run with another routine, called HZ05135. HZ05135 is based on earlier measurements with 820 GeV protons and has been more exclusive than the data that has been used for the comparison up to now. In figure 7 the cross section as a function of x is shown for both routines. The statistics is by a factor of 1000 lower for HZ05135 because of another cut in the energy regime. Even though one can not directly compare these two plots, one can compare how well the PDFs are matching the respective data. The conclusion from comparing CASCADE predictions are consistent: CASCADE does not describe the shape of the data and the uncertainty from the uncertainty stemming from the choice of the PDF is very large, especially for very low x. To get not tricked by the logarithmic scale, the some plots are shown with linear y-axis in figure 8.

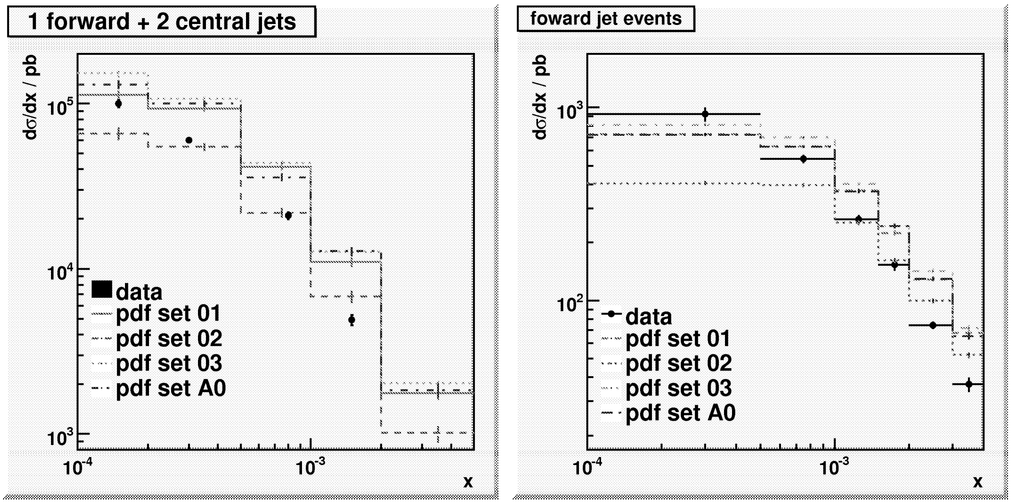

Figure 7: Cross sections over Bjorken x for very forward jet events; left: the new routine, right: HZ05135; logarithmic scale

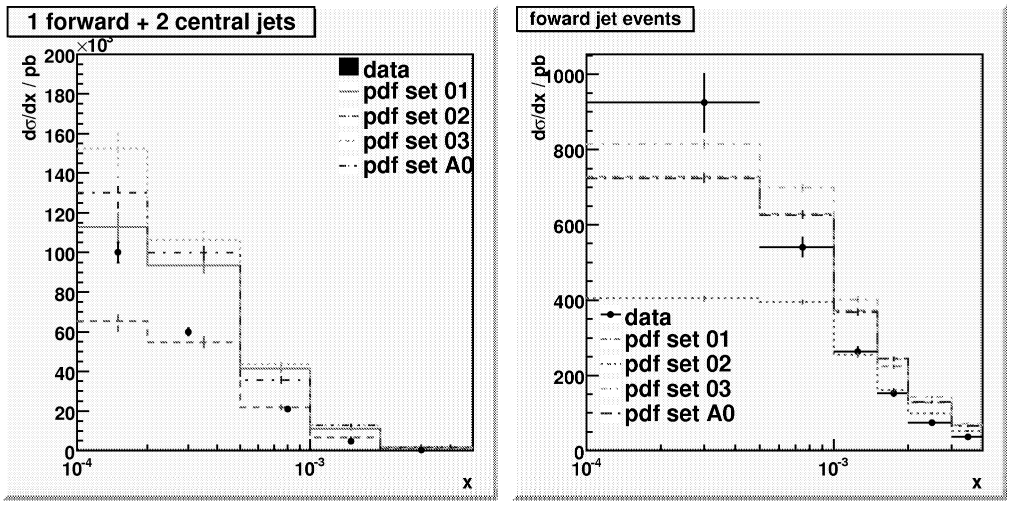

Figure 8: Cross sections over Bjorken x for very forward jet events; left: the new routine, right: HZ05135; linear scale

8 Review

Now I want to give a short review about the results, difficulities and gains the work has yielded. First of all, it took quite a long time to get used to the underlying physics and the used programs. It took me a while to understand the idea behind evolution schemes and PDFs. I find it very difficult to find good literature to these topics and many people are just giving a superficial introduction them. To come to the technical part: Even with a few experiences in programming, I did a lot of mistakes during the coding that imlicated a long time of debugging. But this really improved over the weeks. Whereas writing the routine was a very clear and straightforward aim, physical results getting from it raised rather unexpected and sudden. For example, the statistics my routine produced where a factor of 2 to high in the beginning. So I spent a lot of time searching for mistakes in the routine or forgotten factors. I actually found a few smaller bugs but they were not responsible for significant deviations. After that, I tried to change many input variables to locate the problem. When I changed the PDFs, the predictions suddenly agreed with the data. From that, the idea arised to compare the PDFs. Altogether, I really learned a lot about scattering physics, event generators and I improved my technical skills in programming and plotting enourmosly.

I want to thank my supervisor Albert Knutsson for spending so much time helping me, answering my question and providing me with suitable literature. He did a great job.

This is also true for the entire H1 group that always supported me. I never felt any pressure of producing new or better results, unless it came from myself. These weeks have been very productive for me. Thank you.

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