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QCD UNCERTAINTIES AT THE LHC AND THE IMPLICATIONS OF HERA

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Strong interaction physics will be ubiquitous at the Large Hadron Collider since the colliding beams consist of confined quarks and gluons. Although the main purpose of the LHC is to study the mechanism of electroweak symmetry breaking and to search for physics beyond the Standard Model, to maximise the precision and sensitivity of such analyses it is necessary to understand in detail various perturbative, semi-perturbative and non-perturbative QCD effects. Many of these effects have been extensively studied at HERA and will be studied further at HERA II. We discuss the impact of the knowledge thus gained on physics at the LHC.

1 Introduction

The large hadron collider (LHC), currently under construction at CERN, will collide protons on protons with an energy of 7 TeV, extending the available centre-of-mass energy ($\sqrt{s}$) by an order of magnitude compared to existing colliders. Together with its high collision rate, corresponding to an expected integrated luminosity of $10 - 100$ fb^{-1}/year, these energies give access to particles with high masses, or at high transverse momentum, which have low production cross-sections. The LHC can search for new interactions at very short distances and for new particles beyond the Standard Model (SM) of particle physics.

One year of data taking at LHC energies can produce jets with transverse energies of up to $E_T^{\rm jet} = 3$ TeV, probing the structure of matter at the smallest distances ever accessed. About 20 (2) $W^{\pm}$- (Z^0)-bosons will be produced per second. These large data samples allow their production cross-sections, and the $W^{\pm}$-mass, to be measured with a precision of up to 1%. Their rate provides a luminosity monitor, limited only by the precision of the theoretical predictions. Moreover, each second about one top quark pair will be produced. Precise determination of the top quark mass and of the top decay modes will be a key challenge to the SM.

In all these cases, a good understanding of particle production and decay in a hadronic environment is needed. The large phase space and the large cross-section of strongly interacting particles makes it necessary to test and extend our understanding of strong interactions in the early phase of LHC data taking. This requires not only an experimental program to measure basic SM processes over a wide range, but also the development of "tuneable" models implementing the correct underlying physics processes, and of tools to calculate higher order cross-

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sections. Examples are models for soft hadron-hadron collisions (minimum bias and underlying events), simulation of events with many particles and many jets and their correlations, and the production mechanism for weakly interacting particles and heavy quarks. It will also be necessary to validate the QCD input parameters, the strong coupling constant and the parton density functions, extrapolated to high momentum transfers, and to constrain their uncertainties with LHC data.

Thus, studying QCD in high energy collisions is interesting now, and also vital for the future of high energy physics. The ability of the Tevatron and earlier hadron-hadron machines to have an impact in this area is clear, and is the subject of ongoing study [1]. The focus of this contribution, however, is the impact of data from the HERA lepton-proton collider at DESY. HERA is a precision QCD machine, as well as a QCD "discovery" machine. We argue that data from HERA are needed to fully exploit the LHC. The areas we discuss can be split into three general categories: the precision measurement of QCD input parameters; the testing of calculational techniques; and the testing of non- or semi-perturbative models. In all these areas, HERA data can help us gain a quantitative understanding of hadronic production mechanisms at high energies.

2 Precision measurement of QCD inputs

2.1 The Strong Coupling Constant

One yardstick by which the present understanding of the strong interaction can be judged is the precision of measurements of the strong coupling constant α_s, the fundamental parameter of QCD. A summary of such measurements made at HERA [2] is shown in Fig. 1.

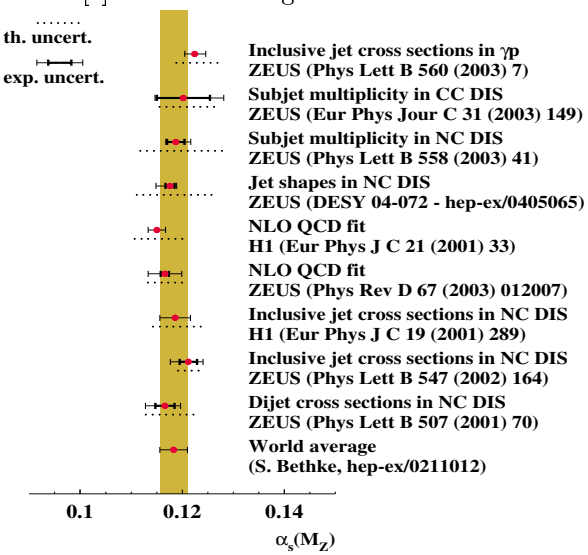

Figure 1. α_s measurements from HERA I [2].

The majority of the measurements shown are made using jet cross-sections and event shape properties in the final state. To make them, many technical advances in QCD calculations have been exploited, and a calibration of the calorimeter energy response to around the 1% level was required. The parameter α_s itself is perhaps not such a critical number for the LHC. However, measuring α_s at the high scales uniquely accessible at the LHC is an essential measurement which probes QCD at very small distance scales and is hence sensitive to physics beyond the SM (see also Section 2.2).

The HERA measurements demonstrate the ability to do precise QCD physics in the final state of hadronic collisions. This ability has a significant impact in several areas of more direct relevance to the LHC.

2.2 Parton Distributions

The most obvious area where HERA data have an impact at the LHC is the parton distribution functions (PDFs) in the proton. These distributions parameterise the probability of resolving, at a given energy scale Q^2, a quark or gluon in the proton carrying a fraction x of the proton's momentum. They are thus crucial inputs to all hard cross-section predictions at the LHC. They are determined using fits to deep inelastic scattering data and other processes; the HERA data [3] are a dominant input to these fits, particularly in driving the rise of the gluon density as x decreases.

However, when one translates the parton kinematics to the x, Q^2 plane (see the well known illustration in [4], and Fig. 2a) it is clear that there is in fact only a small overlap between the HERA and LHC regions. The DGLAP [5] equations are therefore used to evolve the parton densities up in Q^2 and obtain predictions for the LHC. In addition the LHC, by profiting from the techniques developed for the hadronic final state analyses at HERA, will itself be able to constrain PDFs using a variety of SM processes.

The limitations due to the present PDF uncertainties can be illustrated with the example of inclusive jet production at LHC. The measurement of the single inclusive jet cross-section as a function of $E_T^{\rm jet}$ is a clean way to demonstrate our understanding of α_s and of the PDFs at very short distances, and in addition a promising way to search for new physics. At central rapidity $0 < |y| < 1$ an uncertainty of 100% is found at $E_T^{\rm jet} \approx 5$ TeV. For forward jets $2 < |y| < 3$ this large uncertainty, which is mainly due to the limited knowledge on the gluon distribution at large x, is already present at $E_T^{\rm jet} \approx 2$ TeV [6]. By measuring the inclusive jet cross-section in different rapidity bins, it should be possible to disentangle possible new physics from other, more mundane, effects. However, the PDF uncertainties do reduce the ability of the LHC experiments to discover new physics in what is a relatively simple channel, where due to the inclusive nature of the measurement the background calculations should be in principle very reliable.

For instance, the dijet cross-section are sensitive to possible effects due to extra space-time dimensions. In contrast to the SM, where the electroweak symmetry breaking scale, the GUT scale and the Planck scale are very different, models with extra space-time dimensions, compactified at a scale M_c, need only one fundamental scale, which may be of the order of a few TeV. If bosons can propagate in these extra-dimensions, a modification of the energy dependence of the strong coupling is expected [7]. In principle the dijet cross-sections at LHC give a sensitivity to compactification scales up to $5 - 10$ TeV [8]. However, PDF uncertainties reduce this sensitivity to $2 - 3$ TeV [9].

There remain several issues with the above:

1. The HERA and fixed-target data are primarily sensitive to the quark distributions; the gluon is at least equally important at the LHC. The gluon is constrained in the global fits mainly via scaling violations. However, this means

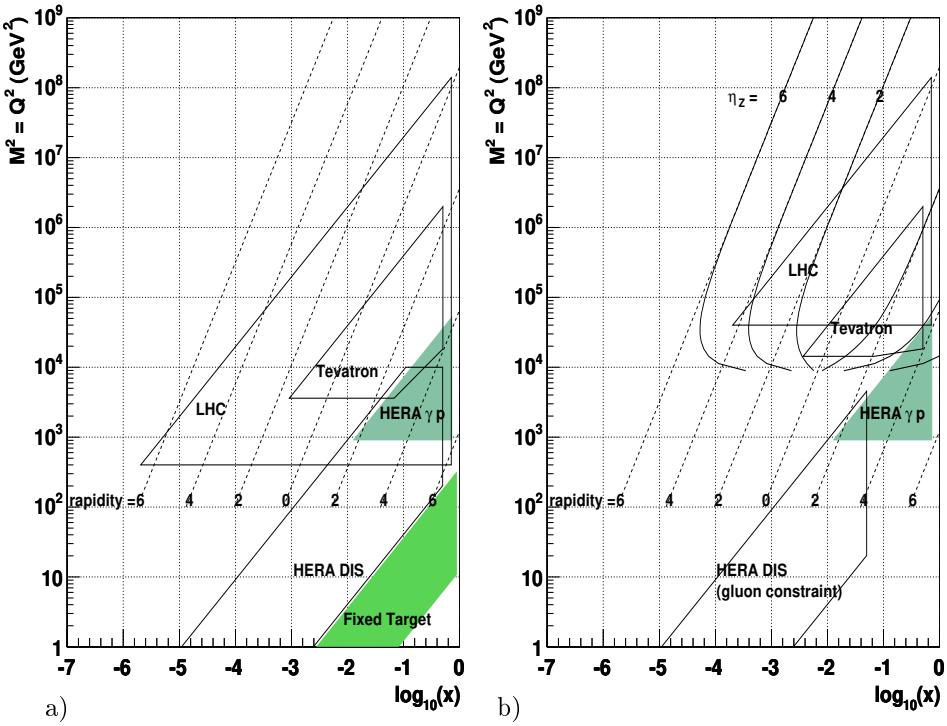

Figure 2. The parton kinematic plane. In (a), the approximate region of LHC sensitivity to the PDFs is shown, along with the regions where pre-LHC measurements either constrain or are expected to constrain them. In (b), the regions in which LHC, HERA and Tevatron constrain (or can constrain) the gluon PDF are shown. The assumption is that jets below 100 GeV (60 GeV) at LHC (Tevatron) cannot be used to get precise constraints. The diagonal lines show the rapidity of the system with mass M at LHC, and the curves show the approximate corresponding pseudo-rapidity for a Z boson produced at such a rapidity (see text). The HERA photoproduction region is taken from [10].

that if the quark is measured in some x range, this will determine the gluon distribution in a region of lower x. Deep inelastic scattering data provide little effective constraint on the gluon for x $\geq$ 0.1 (see Fig. 2b), and there are significant uncertainties even below this. This situation will not be improved by any measurement of F_L at HERA II [11]. Some information can be obtained from jet data at the Tevatron, but the precision is not competitive with structure function measurements. Furthermore, some of this data represents the highest energy parton-parton collisions ever measured, and new physics possibilities cannot be excluded. The net result is - the knowledge of the gluon density at high and intermediate x is poor.

2. The LHC will have difficulty constraining the parton distributions at high x. At

the highest Q^2, the problem is the same as that currently faced at the Tevatron - these will be the highest energy parton-parton collisions ever, where new physics may arise (see above). What is required is a constraint at intermediate Q^2 and high x. To achieve this, it is necessary to use boosted events, where one x value is high and the other low. If one considers Z+jet production in the region of interest, say at rapidity of 2 and a Z+jet mass of 600 GeV, the x values probed are 3.2×10^{-3} and 0.58. The rapidity and pseudorapidity lines for Z bosons are shown on Fig. 2b. The detector acceptance will drop between pseudorapidities of 3 and 4. Detailed MC studies are required to see where the LHC will really provide good information.

3. It is far from certain that DGLAP evolution is valid over the required x range. The current fits show good agreement down to $x \approx 10^{-4}$, but the amount of data at low x for $Q^2 \gtrsim 4\ \mathrm{GeV}^2$, where fits can be made, is small. Hence the level of confirmation of the validity of the evolution in this region is weak. The low x parton in the example above ($x = 3.2 \times 10^{-3}$) is already in a region where a more stringent validation of the applicability DGLAP evolution is desirable before predictions are made with confidence. Here, more measurements at HERA, including F_L, together with charm and beauty quark cross-section measurements in DIS and photoproduction, as well as measurements in the early days of LHC, will be very important.

It should be obvious that anything more HERA can say about the high x region will be very valuable. One under-exploited process with potential to help here is dijet photoproduction. The kinematic reach of this process, which is directly sensitive to the gluon density, is shown in Fig. 2. The ZEUS collaboration has already included jet data (from DIS and photoproduction [10,12]) in their new fits [13]. The impact is considerable, particularly in the region $x > 10^{-2}$ (Fig 3). The data set used is ZEUS 1996-1997 data, which is statistically limited at high E_T^{jet}, corresponding to high x. Several possibilities for improvement include optimising the cross-section for sensitivity to the high x gluon by (for example) extending to the forward region, including the rest of ZEUS and H1 HERA I data, and eventually HERA II data. An illustration of the potential of HERA II data in this area is shown Fig. 4. It is important that these possibilities are vigorously pursued, not just by the collaborations, but by the other global fitting groups.

Another area where there has been impressive progress recently is in the full calculation of the DGLAP splitting functions to next-to-NLO [15]. These calculations show that the perturbative series is stable over a wide kinematic range (for $x > 10^{-3}$ the NNLO corrections are around eight times smaller than the NLO terms). This gives more confidence and accuracy in the use of the evolution from the HERA regime, and (coupled with NNLO matrix elements for key process) will allow the LHC to more accurately constrain the PDFs.

2.3 Fragmentation Parameters

Another set of parameters which may be measured at HERA and used at LHC are those governing fragmentation, in particular the one of charm and beauty quarks.

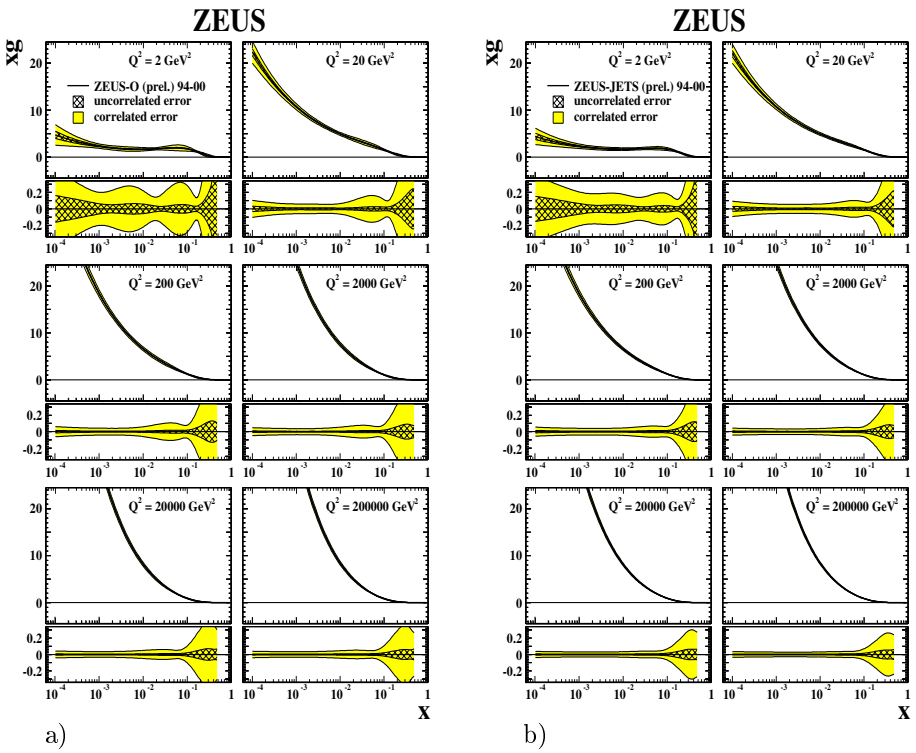

Figure 3. ZEUS fits [13]. In (a), only ZEUS DIS jet data are used. In (b), ZEUS jet data [10,12] are added to the fit. The yellow band shows the total uncertainty, which at high x and high Q^2 is reduced from around 40% to around 25%.

For example, HERA can measure the charm fragmentation function directly in hadronic events [16]. The same should also be possible for b-quarks with HERA II data, and precise measurements of such parameters would be an important input to predictions for b-jet rates, and important process at LHC. The fragmentation fractions for charmed particles measured at HERA also measured with precision comparable to the combined LEP results, and give confidence in the portability of such numbers between different processes [17].

3 Testing ground for calculational techniques

The LHC will operate at energies where processes with multiple hard scales ($M_W, M_{\rm top}, E_T^{\rm jet}$) are commonplace. Such an environment is a new challenge for the established techniques of perturbative calculation. At HERA, the scales involved are lower (e.g. $Q^2, E_T^{\rm jet}, M_c, M_b$) but the experiments have unique control over them and the data provide an equally challenging arena for QCD predictions.

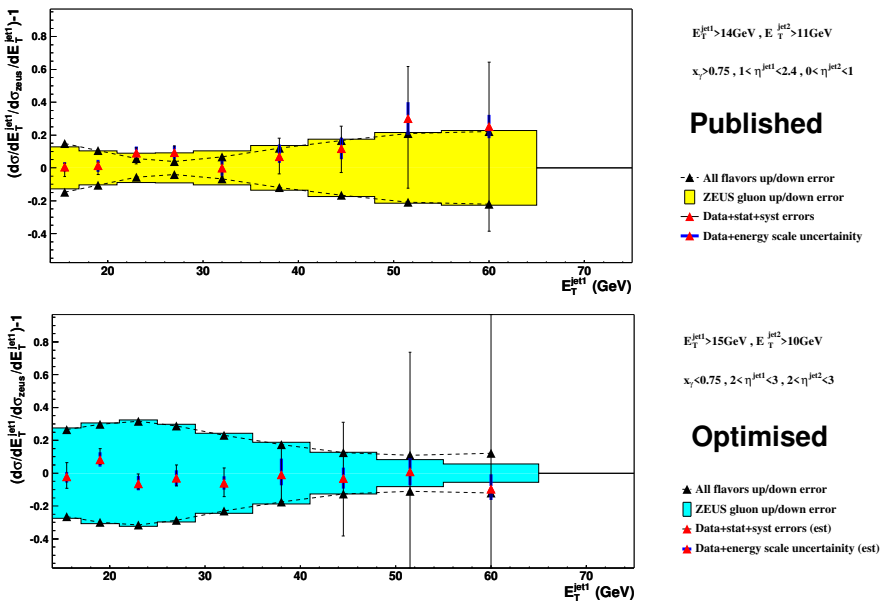

Figure 4. The potential of HERA II jet photoproduction data [14]. The upper plot compares the uncertainties on the ZEUS-O [13] fit to the relevant published jet photoproduction data [10]. The lower plot compares the uncertainties from the same fits, but now for a cross-section optimised to constrain the gluon. The data in the lower plot are faked, but give an indication of the experimental uncertainties expected for 500 pb^{-1} of HERA II data.

3.1 Very forward jets

At the LHC, forward jets ($2 < \eta^{\rm jet} < 4$) are of interest for several reasons. In general, extending the acceptance as far forward as possible will enhance search channels, and is also important for determining the PDFs (see Section 2.2). They may also be useful for triggering purposes at LHCb [18]. But perhaps the most important application is their role in tagging vector-boson fusion events [19], a key SM process and Higgs search channel.

Forward jets are also sensitive to low-x physics [20]. Although the jet itself is at high-x, the QCD evolution between two high-$E_T^{\rm jet}$ jets at widely differing rapidities is sensitive to non-DGLAP evolution [21]. A similar kinematic configuration is achieved in forward jet production in DIS at HERA [22]. There has been much study of these processes at HERA [23], and a general feature is that the agreement with fixed order QCD calculations degrades, and the theoretical uncertainties in such calculations increase, as the jet moves into the forward region. This may be a

sign that low-x effects are becoming important. It certainly means that predictions of rates at LHC need careful study. Fixed-order calculations of the signal [24] show that the uncertainties are around the 5% level. However, the uncertainties from QCD in the backgrounds to these processes may be much higher and will be hard to evaluate. They may be a dominant effect in the measurement of the WW-fusion cross-section. Studying such effects at HERA is therefore important for improving the phenomenology in this area.

3.2 Multijets

In many searches for physics beyond the SM, multi-jet events are an important background, *e.g.* for SUSY searches. The correct modeling of the correlation between the jets is therefore crucial to maintain the optimal sensitivity of the LHC experiments. Another example where the multi-particle final state has to be correctly modeled is the production of top quark pairs at LHC. One of the most promising channels for the accurate determination of $M_{\rm top}$ has four jets in the final state: $pp \to t_1 t_2 \to W^{\pm}W^{\pm}b_1 b_2 \to b_1 \nu_l l b_2 q q$. Using the PYTHIA and HERWIG simulation programs, the modeling of the higher order final-state parton radiation is expected to give the largest systematic error [25]. It limits the error on $M_{\rm top}$ to about 1 GeV. In view of the potential to discover new physics through a mismatch in the correlation of the $W^{\pm}$, the top quark and the Higgs mass, efforts to improve our understanding and ability to simulate higher order QCD radiation have recently intensified.

These efforts mainly focus on simulation of the final state in pp collisions via Monte Carlo (MC) simulations and/or automatic resummed calculations [26]. One of the most important developments is the consistent implementation of higher order parton radiation in full MC event generators. Here, two different possibilities have been explored: the matching of NLO matrix elements (ME) to parton showers (PS) in programs like MC@NLO [27,28] and the matching of n-parton tree level ME with PS.

In the MC@NLO approach the analytic form of the real parton emissions and the virtual corrections is subtracted from the NLO ME. Then the singularity connected to soft and collinear parton emissions is handled by the PS algorithm and absorbed in the Sudakov form factor. The NLO corrections are used to describe the n-body kinematics. Since negative and positive event weights are bounded, an unweighting procedure can be performed. This procedure has been successfully implemented for many processes, including heavy quark, Higgs, Drell-Yan and $W^{\pm}$ and Z^0 production. It can in principle be extended to any process known to NLO accuracy. The inclusion of NLO corrections guarantees that the total cross-section generated by the MC has the correct normalisation, and its renormalisation- and factorisation-scale dependencies are reduced.

This procedure leads to a correct description of the one extra parton from the Born LO processes. If fails, however, for events with high jet multiplicities, since hard radiation at large angles is suppressed by the angular ordering in the PS. To solve this problem the n-parton tree-level ME can be merged with the PS. Double counting can be avoided with the CKKW prescription [29]. This approach is being

implemented in the next generation of MC event generators [30]. Presently, ME up to $2 \to 8$ parton processes can be treated.

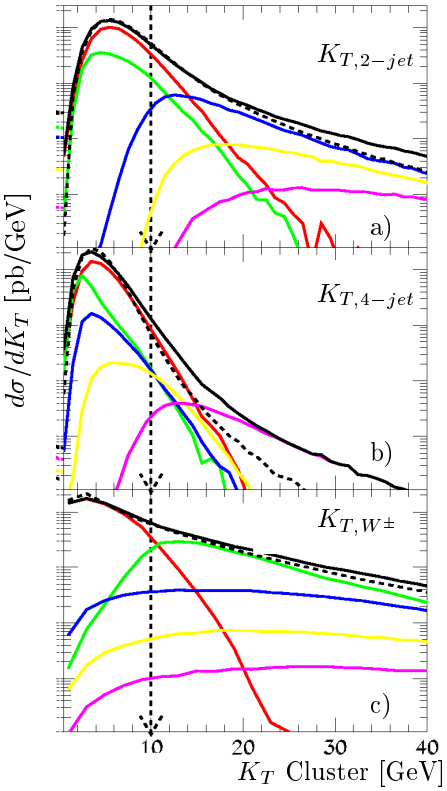

Figure 5. Differential jet cross-section for $W^\pm$ and $n-jets$ events as a function of the transverse energy of the second (a) and forth (b) jet and of the $W^\pm$ (c). The result of a matching procedure of the n-parton tree level MEs and PS is shown as solid line. The dotted line shows the HERWIG default. From [31].

As an example [31], we show the matching of PS to the n-parton tree level ME for events with $W^\pm$-bosons and n-jets in pp-collisions at $\sqrt{s} = 1.96$ TeV. The differential jet cross-section with respect to the K_T-jet cluster algorithm in hadron-hadron collisions [32] is shown in Fig. 5. The matching has been performed at $K_T = 10$ GeV (vertical dotted line). The quantity K_T, closely related to the transverse momentum, is shown for the second (a) and the fourth (b) highest K_T jet and the $W^\pm$-boson (c) for the matching of the n-parton tree level ME with the PS[a] and for the default HERWIG ME matching procedure [33] (dashed line). For low K_T, the new matching procedure and the HERWIG default agree. Towards high K_T the new matching procedure leads to a significantly harder distribution. This is quite dramatic for the forth jet where the 6-parton ME gives the main contribution. Obviously the PS as implemented in HERWIG is not a good approximation in this region. Since at LHC there is a much larger phase space for parton radiation, the correct simulation of multi-parton final states will be even more important.

Since the above procedure is based on a LO calculation, the absolute normalisation is arbitrary and has to be determined from the data. However, the shape of the distributions and the correlation between the final state particles should be well described. For multi-particle final states these calculations should also be better than NLO calculations of lower multiplicity diagrams.

The validation of these ideas using Tevatron data is presently on-going. For HERA, these new ideas have not yet been made available. However, the clean event topology, the controllable kinematics and the large phase space for hadron production in the low-x regime mean that HERA data could make decisive contributions in this field. For instance, it was the first time at HERA that NLO corrections for $2 \to 3$ parton processes have been calculated for collisions with hadrons in the initial state [34]. After the successful experimental test [35] of the 3-

[a] Also shown as coloured solid lines are the individual n-parton ME components: 2 partons as red, 3 as green, 4 as blue, 5 as yellow, 6 as magenta solid line.

jet cross-sections $ep \to jjj$ in DIS it has also been made available for proton proton collisions $pp \to jjj$ [36]. A number of other processes [37] have been made available since then: $pp \to V + jj$, $pp \to \gamma\gamma j$, $pp \to Hjj$. These calculations represent the current frontier of our capabilities.

Furthermore, comparisons of fixed-order ME programs and leading-logarithmic PS simulations to current HERA jet data already show interesting features. For example, the dijet cross section for hadronic photon events as a function of the leading jet transverse energy is in excellent agreement with NLO QCD calculations [10,38]. There is also good agreement with HERWIG, if a normalisation factor of 1.6 is applied. However, these dijet cross-sections are defined in terms of highest $E_T^{\rm jet}$ jet and the rapidities of the two highest $E_T^{\rm jet}$ jet. If the $E_T^{\rm jet}$ of the second jet is varied, this is formally a sub-leading effect. However, there is a significant dependence of the cross-section on this variable, and the shape of the dependence is well modeled by HERWIG, but not by fixed order NLO [10]. Furthermore, three-jet cross-sections for $M_{\rm 3jet} > 50$ GeV [40], which are sensitive to colour coherence in initial and final state radiation, are described by HERWIG in both shape and normalisation if the same factor of 1.6, determined from the high $E_T^{\rm jet}$ dijet data, is applied [39]. Such studies indicate the successes and limitations of the technology and should be extended to test the newer techniques described above.

3.3 NNLO calculations

NLO QCD calculations are able to describe $2 \to 2$ and $2 \to 3$ processes in most phase space regions in both pp and ep collisions. However, the predictions are in many cases still insufficient for precision analyses. Typical residual scale dependences on the renormalisation and factorisation scales are of the order of $10-20\%$. This uncertainty on the absolute cross-section normalisation presently limits, e.g., the precision extraction of α_s at hadron colliders.

At LHC, about 10^5 $W^{\pm}$-boson and about 10^4 Z^0-bosons with transverse momenta bigger than 400 GeV will be produced for an integrated luminosity of $30\,{\rm fb}^{-1}$. This huge data sample can be used for detector calibration and to monitor our understanding of pp collisions. One of the obvious applications is the quasi-online measurement of the LHC luminosity needed for the determination of couplings within the SM (e.g. α_s, Higgs or triple gauge couplings), or beyond it (once new interactions have been discovered). A precise cross-section prediction is therefore needed. For those processes and for the Drell-Yan process $pp \to \gamma^* X$, the NNLO corrections have been recently been calculated [41] for Tevatron and LHC energies. The NNLO cross-section is a bit smaller in NLO, but it remains within the NLO uncertainties. The residual scale dependence is reduced to 1% in NNLO and the shape of the rapidity distribution of the bosons is unchanged. Therefore, it will probably be possible to simulate these processes with NLO QCD programs like MC@NLO and apply a normalisation factor (K-factor). One has to see, however, if this conclusion still holds once the detector acceptance is folded in. Together with the recent calculations of the NNLO DGLAP splitting functions [15] these calculations will allow to include these data in future NNLO QCD fits to HERA, Tevatron and LHC data.

3.4 Beauty and charm production

One area of much recent phenomenological activity where HERA and Tevatron data have both played an important role is the question of how charm and beauty are produced in hadronic collisions. It is obviously important to understand these processes for LHC, since b-tagging is a vital tool in many searches. After an interesting history in which some large discrepancies were reported, the latest data on beauty production at HERA and Tevatron are reasonably well described by perturbative QCD (see [42] for an entertaining and informative review). Nevertheless, this is often within fairly large uncertainties, and more precise data from HERA II, in particular using the improved tagging capabilities of the experiments' new vertex detectors (demonstrated by H1 at this meeting [43]) should be able to provide further and more stringent tests of the phenomenology.

4 Testing ground for non- or semi-perturbative models

The almost on-shell photons which come along with the electron beam at HERA collide with protons, and these photons can fluctuate to acquire a hadron-like structure. Therefore HERA can look like a hadron-hadron machine (*i.e* hadronic photon vs proton), but can also do "simpler" measurements with a pointlike photon (for example in DIS, or direct photoproduction). This ability to turn on and off the hadronic nature of the photon gives HERA unique handle for testing non- and semi-perturbative models of remnant-remnant interactions.

Such interactions are an inevitable property of hadronic collisions, and have an impact on jet energies and profiles, energy flow and the isolation of photons. They are a natural consequence of eikonalisation of the parton model in high density PDF region [44], and as such are also responsible for unitarising the total cross-section. They are also related to diffractive factorisation breaking and rapidity gap survival probability, as well as to absorption/rescattering corrections to forward proton and neutron production.

4.1 The underlying event and minimum bias physics

Multiparton interaction models [44,45,46] have been shown [39,47,48] to give the best description of the final state in $p\bar{p}$ and γp interactions, and also do well in $\gamma\gamma \to$ jets. The extrapolation of such models to the LHC inevitably involves very large uncertainties. Studying data from several experiments and processes at existing experiments allows us to learn about the energy dependence and target particle dependence of models and at least reduce the "phase-space" of possible models.

As an illustration, the average charged particle multiplicity in the event hemisphere not containing the hard jets in a pp collision is shown as a function of the leading jet transverse energy in Fig. 6a. Shown is the prediction from a multi-parton interaction model implemented in PYTHIA and from a multi-pomeron exchange model based on the dual parton model for soft and semi-hard particles as implemented in PHOJET [46]. The PYTHIA model was tuned to a variety of hadronic final state data at SPS and Tevatron [48]. For PHOJET no tuning was needed. While both models describe the data at low $\sqrt{s}$, they give predictions which differ

by a factor of 3 at LHC. The dependence of the charged particle multiplicity at the central rapidity is illustrated in Fig. 6b. Large differences are found in the predictions at high $\sqrt{s}$.

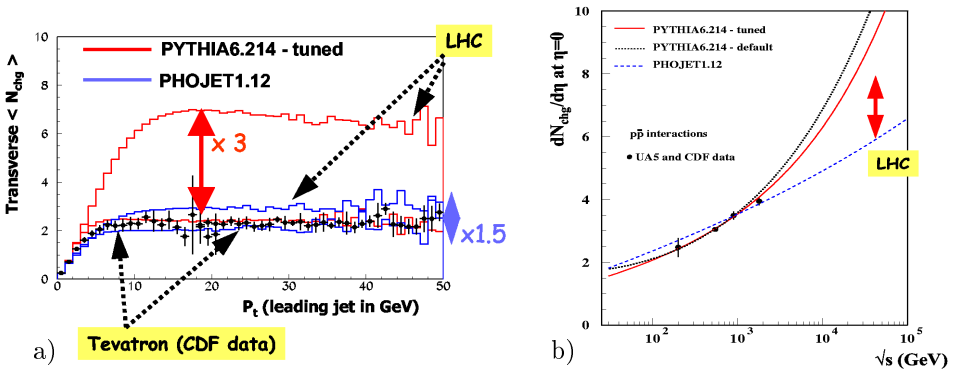

Figure 6. a) Average charged particle multiplicity in the hemisphere not containing the hard jets as a function of the leading jet transverse momentum. b) Average charged particle multiplicity in the central rapidity region as a function of the $\sqrt{s}$. Figure taken from [49].

Early data from the LHC will of course be the best way to improve the models; however, even this is not fool-proof, as the correlations between the hard subprocess and the underlying event are non-trivial, meaning that minimum bias events, while useful, are not a 100% reliable guide. It remains important to have a physically consistent and well-motivated model which is tuned to the widest selection of relevant data. The impact of uncertainties on, for example, the minijet vetoes proposed for identifying vector-boson fusion processes [50,51] is large [52].

New ideas to describe soft hadron collisions and the interplay between soft and hard contributions, developed at HERA, might help to develop new and better models. Such models could make use of k_T-factorisation, of skewed parton distribution describing the correlation of partons at different momentum fraction in the protons or of the dipole model to describe the transition between soft and hard scattering.

Another area where HERA data are relevant is in the determination of the proton PDFs at low x, since these are an important input to multiparton interaction models. In fact, present tunings of the minimum bias event models are only valid for a given PDF. If the $\hat{p}_T^{\min}$ for hard scatters is around $1.0 - 3.0$ GeV or so, the range of values favoured by several of the studies mentioned above, then the models are sensitive to values of x down to 5×10^{-6}. This is a region where the effects of saturation (gluon recombination) may be important.

Possibilities which have not been fully explored yet with HERA data include detailed studies of the behaviour of jet-finding algorithms in the same $E_T^{\rm jet}$ and $\eta^{\rm jet}$ region both with without an underlying event. It may also be possible to test models which predict both minimum bias and underlying event by using the electron-tagged photoproduction samples to obtain "zero-bias" events.

4.2 Leading baryon production

The physics which leads to the enhanced activity in the central region known as the underlying event is closely related to the rescattering (or absorptive) effects which have an impact of leading baryon rates. In models for these processes, a leading proton or neutron is initially present due to a low-t pomeron or pion exchange, but is rescattered and destroyed by remnant-remnant interactions. Such effects can be rather directly investigated at HERA by appealing once again to the ability to switch between pointlike (in DIS or direct photoproduction) photons and the hadronic photons which dominate the photoproduction cross-section.

The leading neutron energy spectrum at HERA has been shown to be well described by pion exchange. In inclusive photoproduction [53] there is no hard scale, the photon is dominantly hadronic,and the forward neutron rate is expected to be affected by rescattering. However, in DIS [53,54], there is a hard scale present. In addition, the photon is pointlike and therefore has no remnant to undergo rescattering. The forward neutron rate is correspondingly higher. In charm photoproduction [55], there is again a hard scale, provided by the charm mass. Some contribution from the hadronic photon is expected to be present, but this is suppressed with respect to the inclusive case, at least for inclusive dijet charm events [56]. There is no evidence for rescattering in these events, with the measured neutron fraction of $9 \pm 1\%$ being in good agreement with the DIS rate, and inconsistent with the rate for inclusive photoproduction. Finally one can consider dijet photoproduction. Here a hard scale is present, but one can select between hadronic and pointlike photons using the $x_\gamma^{\rm OBS}$ variable [57]. There is no acceptance-corrected measurement of the ratio available as a function of $x_\gamma^{\rm OBS}$, but both ZEUS and H1 uncorrected data exhibit a trend which indicates that absorptive effects are reduced as $x_\gamma^{\rm OBS}$ increases [58].

4.3 Diffractive particle production as a search channel

One major source of interest in the measurements of forward neutron production, discussed above, is their relation to rates for leading proton production. This is an area of increasing interest for LHC experimentalists, and there as been much phenomenological progress in the past year or so, reflected by several talks in the diffractive session at the workshop [59]. This may be the cleanest way to discover a low-mass Higgs at the LHC, and other exotic neutral particles may also be accessible. Experimentally the technique requires leading-proton tagging to provide excellent resolution on the energy of the central system. A proton spectrometer designed to achieve this must be triggered in conjunction with the central detector, and would also do some excellent diffractive QCD physics. The phenomenological predictions require a good understanding of diffractive processes, particularly diffractive PDFs and factorization breaking.

At HERA, along the lines of the leading neutron discussion in the previous section, one expects the leading proton (and associated rapidity gap) to be destroyed by rescattering, with a probability which is higher for hadronic photons than for pointlike photons. Dijet photoproduction in association with a forward rapidity gap has been measured [60] and compared to LO Monte Carlo models as well as NLO

QCD calculations [61]. Interestingly, the LO Monte Carlo's, which in this case do not include any remnant-remnant interactions, describe the data well without any need for a rescattering correction. However, in the NLO calculations, agreement is only seen if a rescattering correction of around 0.34 [62] is applied to the hadronic photon component.

If the substantial investment of effort and money required for leading proton spectrometry is to be made, it is obviously vital to gain as much confidence as possible in the cross-section predictions for LHC. Demonstrating a phenomenology which can accurately accommodate the rescattering effects in leading proton and leading neutron production in photoproduction and DIS, as well as describing underlying events, would be a major step towards this. Away from HERA, crucial input is also required from the from measurements at the Tevatron of diffractive jet and particle production [63].

5 Summary

HERA is a great lab for testing the standard model, particularly QCD. Good data are already available on the hadroproduction of jets, of photons and of rapidity gaps. There is further precise heavy flavour data to come from the HERA II program. Systematic efforts to make best use of this data are underway and should intensify.

Uncertainties from QCD effects are expected to be the limiting factor in many key measurements and searches at the LHC. Working out what we need to know from current colliders should be a priority now for those interested in LHC data, while new measurements can still be proposed.

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