Experimental tests of QCD

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Abstract. A brief review is presented of experimental tests of hard hadronic scattering processes at the high energy colliders HERA, LEP and TEVATRON The covered topics are: proton structure, determination of α_s, diffractive physics, underlying event and fragmentation studies.

1. Introduction

2007 is a special year for experimental tests of hard QCD: the HERA ep collider was finally shut down on June 30, after 15 years of operation. This marks the end of a unique machine for deep inelastic scattering at the high energy frontier. The final analysis of the almost 0.5 fb^{-1} of data recorded by each H1 and ZEUS will continue for at least for a couple of more years. The expected reward from this is an unprecedented precision for tests of QCD at hadron colliders, approaching the 1% level for proton structure function measurements in certain kinematic regions. HERA is also the main contributor of hard QCD results at this conference – in total 60 new measurements were presented by H1 and ZEUS. LEP, the 'grand dame' of QCD is still alive – in total about five new measurements were provided for this conference, e.g. the final ALEPH beauty production measurement in $\gamma\gamma$ collisions. Another key player is the TEVATRON, running in 2007 better than ever: the totally delivered integrated RUN II luminosity has now increased to about 3 fb^{-1}. The aim is to collect by 2009 in total about 8 fb^{-1}. CDF and D0 presented at this conference about 10 new measurements related to hard QCD, many of them involving the production of very high transverse momentum jets.

In the following new results obtained at the three colliders are presented. In the first part the review focuses on the determination of the quark and gluon densities in the proton which is mandatory for making precise Standard Model predictions for important processes at the LHC such as $gg \to H$ or $u\bar{d} \to W$. The review then continues with a discussion of the determination of the strong coupling constant α_s. Finally, the QCD sector which can be purely treated by means of perturbation theory is being left behind and the topics diffraction, underlying event, and fragmentation are briefly discussed.

Many new results on hard QCD cannot be included in this review, please have a look at the talks in the parallel session[1] and at the associated proceedings. For example new and interesting results were reported on the nucleon spin from COMPASS [2], HERMES [3] and RHIC [4]. The majority of results on charm and beauty production at HERA, LEP and the TEVATRON was covered in another plenary talk [5] as well as top production at the TEVATRON [6].

2. Proton structure

The main information on the proton structure has been obtained from deep inelastic scattering (DIS). In figure 1 the basic reaction is shown for DIS at HERA via photon exchange together with an exemplary event recorded with the H1 detector. The scattering of the electron off the
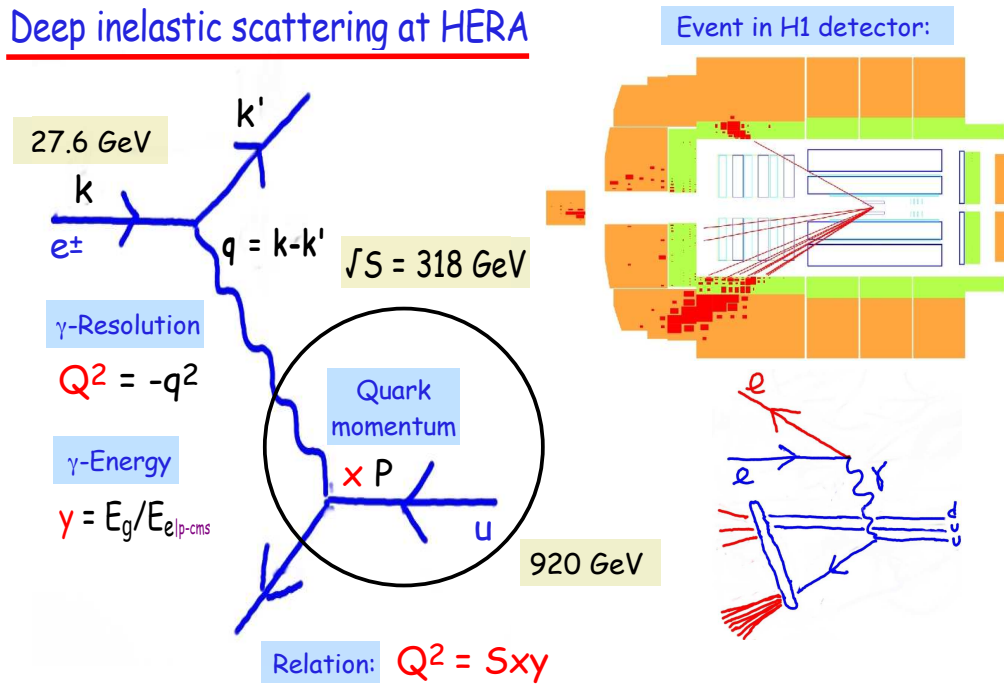
Figure 1. Sketch of deep inelastic ep scattering via photon exchange at HERA (left) and exemplary event as recorded with the H1 detector (right).

proton is characterised by three kinematic quantities: the four momentum transfer squared Q^2 of the exchanged photon; the inelasticity y, which is the fraction of the electron energy carried by the photon in the proton rest frame; and *Bjorken x*, which in the quark parton model gives the proton momentum fraction carried by the struck quark. Only two of these observables are independent, the third is determined by the relation $Q^2 = Sxy$, where S denotes the fixed ep centre-of-mass energy squared.

2.1. H1 and ZEUS combination of inclusive DIS cross sections

Precise densities of quarks and gluons in the proton (PDFs) down to very small $x \approx 0.0001$ have been determined from the HERA inclusive neutral current (NC) and charged current (CC) data. H1 and ZEUS very recently combined [7] the data collected in the HERA I phase (1992-2000) which were used separately by each experiment for their one PDF determinations. For the combination of the two datasets a method of weighted averaging was applied, where parameters representing experimental systematic uncertainties (e.g. calorimeter energy scales) are also fitted. This leads to an effective cross calibration of the two experiments, and finally to greatly reduced systematic errors. The obtained results for the NC reduced cross section,

defined as

$$\sigma_r(x, Q^2) = \frac{\mathrm{d}^2\sigma(ep \to eX)}{\mathrm{d}x\mathrm{d}Q^2} \frac{xQ^4}{2\pi\alpha^2(1 + (1-y)^2)},$$

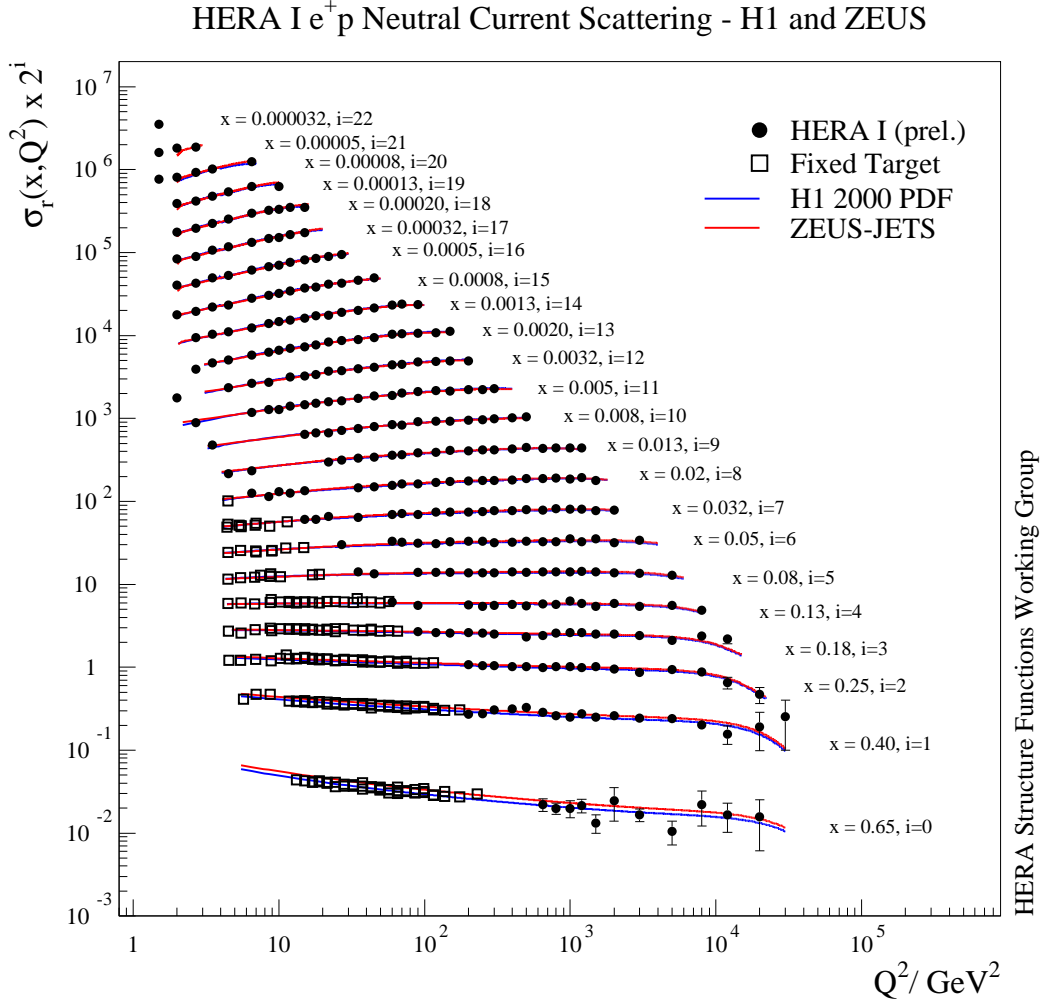are shown in figure 1, together with fixed target data and the previously obtained QCD fits. For

Figure 2. H1 and ZEUS combined neutral current e^+p reduced cross sections [7] (labelled HERA I (prel.)), based on the published HERA I data. The curves are NLO QCD fits as performed by H1 and ZEUS to their own data.

single data points a total uncertainty of less than 2% has been reached for the first time. These H1 and ZEUS combined datasets will be used for a new PDF fit by the two collaborations.

2.2. Last inclusive measurements at HERA at low Q^2

H1 presented at this conference probably the last inclusive ep measurement [8] from HERA reaching down to very low Q^2, i.e. $0.2\ \mathrm{GeV}^2 < Q^2 < 8.5\ \mathrm{GeV}^2$. Very small x values are probed, down to $x \sim 4 \cdot 10^{-6}$, a region which is highly relevant for many interesting sea-quark or gluon initiated processes at the LHC. The H1 inclusive cross section measurements have reached a precision of 2-3% in certain regions. They provide a wealth of information for QCD model builders for the transition into the non-perturbative region which begins approximately at $Q^2 < 2\ \mathrm{GeV}^2$.

2.3. **H1 and ZEUS analyses at high** y

H1 and ZEUS have presented new measurements [8, 9] of neutral current inclusive *ep* cross sections at the highest accessible photon energies corresponding to a large value of y, above ~ 0.6. Thus the quarks in the proton with a given momentum fraction x are probed at the highest available resolution scale Q^2. This will help to reduce the uncertainties of the quark density evolution to the much higher scales which will be relevant at the LHC. Furthermore; these data are highly sensitive to the longitudinal structure function F_L, whose contribution to the NC cross section becomes large only at high y. Both H1 and ZEUS analyses are based on the new data sets taken in the HERA II running period (2003-2007). The H1 results are shown in figure 3 together with the previously published data. Improvements in precision are clearly visible.
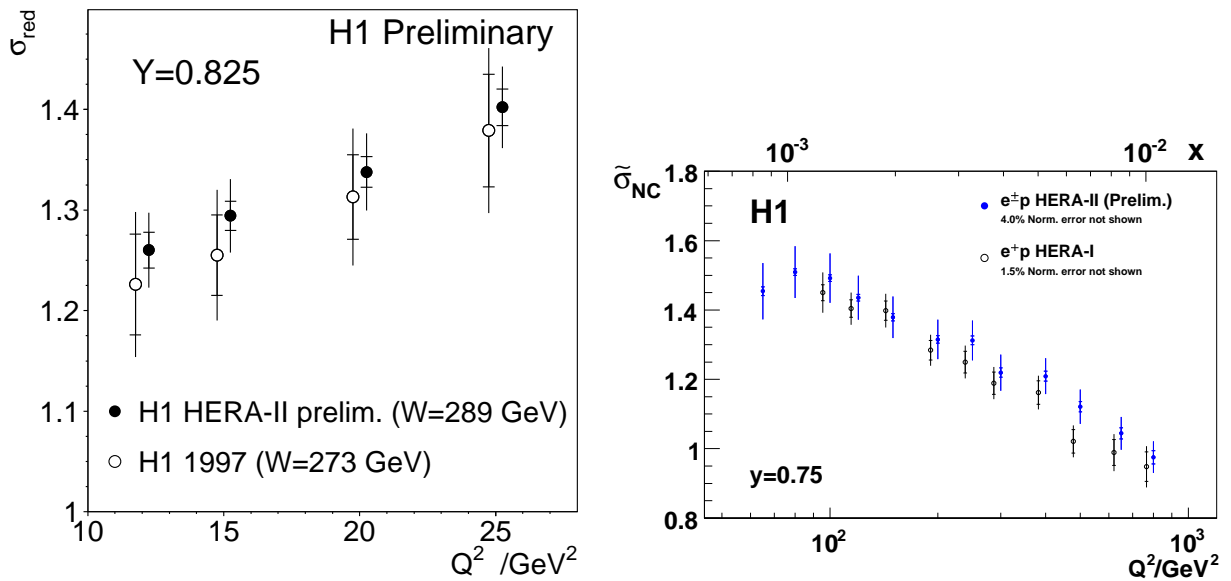

Figure 3. Neutral current reduced cross sections at high inelasticities y as a function of Q^2. The new H1 preliminary measurements [8] at lower Q^2 (left) and at higher Q^2 (right) are compared with the previously published results.

2.4. Further prospects from HERA for determination of sea- and valence quarks

The analysis of the double differential NC and CC cross sections at high $Q^2 > 150$ GeV^2 using the *full* HERA II statistics, roughly three times larger than the published HERA I data, is under way. Preliminary results [10] based on partial statistics have been released within the last year, e.g. the combined H1 and ZEUS measurement of the structure function $xF_3 \propto \sigma_{NC}^{e^+p} - \sigma_{NC}^{e^-p} \propto 2u_v + d_v$, which provides unique information on valence quarks over a wide range in x down to $x \sim 0.01$.

H1 is working on the analysis of the inclusive NC data in the range $10 < Q^2 < 150$ GeV^2, taken during the year 2000. This measurement is expected [11] to reach an unprecedented precision of $\sim 1.5\%$ in certain phase-space regions and will probably provide the most accurate data points from a single experiment for the determination of sea-quarks in the proton. For the exploitation of the corresponding data from the HERA II running period one would need to address the systematic errors at a new precision level.

2.5. Proton gluon density determination

The determination of the gluon density in the proton is of highest relevance for making predictions for important reactions at LHC such as $gg \rightarrow H$. The so far most statistically

precise, although indirect, determination is provided by the scaling violations of the structure function F_2 at HERA, which at low x can be approximated by $dF_2/dln(Q^2) \sim \alpha_s(Q^2)xg(x, Q^2)$. These scaling violations are clearly visible in figure 2, respecting that $\sigma_r \approx F_2$ for not so large y and Q^2. The improvements of the inclusive NC measurements discussed above will lead to similar improvements in the determination of the scaling violations and hence also of the gluon density. In the following subsections, 2.6 to 2.8, new or expected results are discussed for processes that are *directly sensitive* to the gluon density.

2.6. Jet Production at HERA and TEVATRON

Jet production at HERA is dominated over a large range in x by the boson gluon fusion (BGF) process (see figure 4 left) and thus provides direct access to the proton gluon density. A great
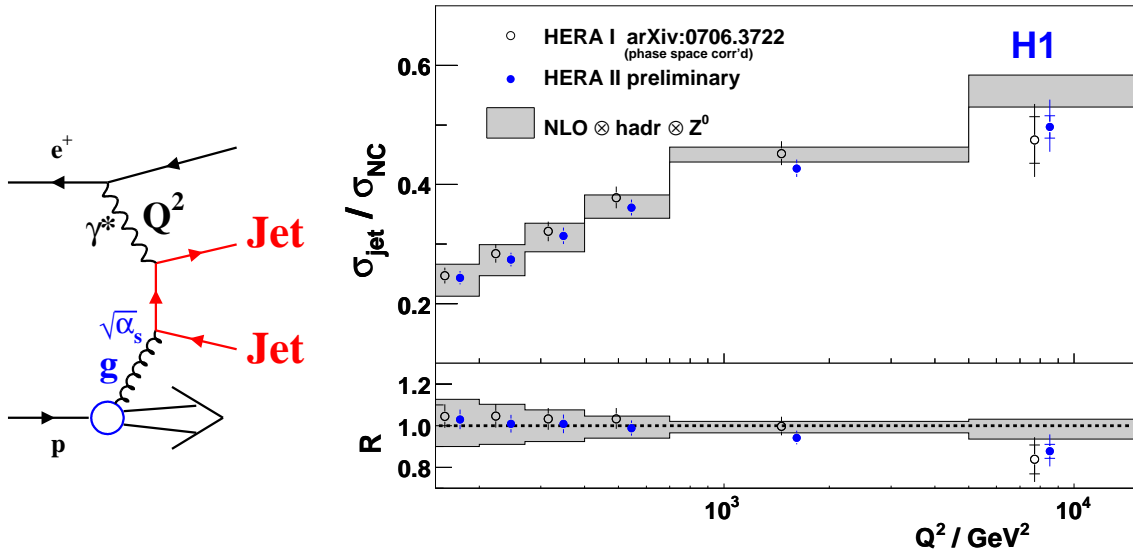

Figure 4. Left: Boson Gluon Fusion diagram leading to jet production at HERA. Right: H1 measurement [12] of inclusive jet cross sections normalised to the total DIS cross section, as a function of Q^2. The preliminary results based on HERA II data are compared to recently published HERA I data and to a NLO QCD prediction.

wealth of new jet measurements in DIS and photoproduction at HERA has been presented [12] at this conference. The right panel in figure 4 shows as one example the brand new H1 measurement [12] of inclusive jet production normalised to the total DIS cross section. This analysis is carried out at high Q^2 and exploits almost the full HERA II statistics. The new data is compared with the previously published HERA I analysis and a theory prediction. The improved precision is clearly visible. The HERA jet data will be mainly useful to further constrain the proton gluon density for proton momentum fractions in the range $0.01 < x < 0.2$, which is of high relevance for many LHC processes in the central rapidity of the CMS and ATLAS detectors such as $gg \rightarrow H$.

The production of very high energetic jets at the TEVATRON (with $gg \rightarrow gg$ being an important reaction channel) provides constraints on the proton gluon density up to the largest x close to unity, as reported by both CDF [13] and D0 [14] at this conference. New measurements can be expected with increased statistics: this necessitates for both detectors improvements in the precision understanding of the hadronic energy scale for jets of a few hundred GeV energy.

2.7. Charm and Beauty production at HERA and TEVATRON

Charm and beauty quarks are produced at HERA mainly in the BGF process $\gamma^* g \to c\bar{c}$ (or $b\bar{b}$), which is directly sensitive to the proton gluon density. Charm events are tagged at HERA using fully reconstructed D mesons or displaced track impact parameters, the latter exploiting the long lifetime of the charm quark. Theoretical analyses focus on the structure function $F_2^{c\bar{c}}$, which is defined as the part of F_2 due to events with charm quarks in the final state. Figure 5 (left) shows a compilation of the HERA $F_2^{c\bar{c}}$ results. This includes new preliminary ZEUS
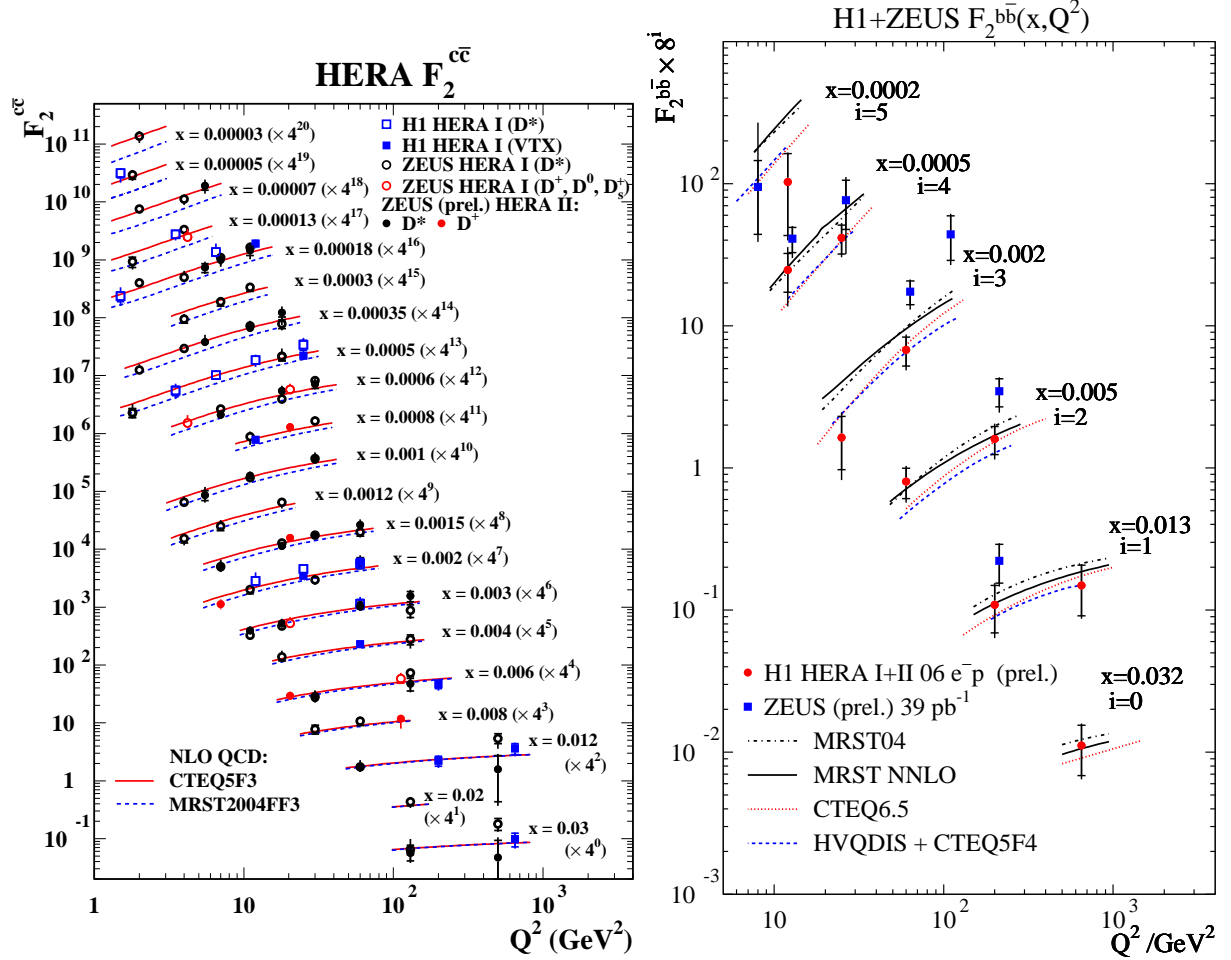

Figure 5. Compilation of the available HERA results [15, 16] for the contributions from charm and beauty events to F_2, the observables $F_2^{c\bar{c}}$ (left) and $F_2^{b\bar{b}}$ (right). The H1 and ZEUS data are compared to several QCD model predictions.

measurements [15] (based on partial sets of the recent HERA II data) using $D^{*\pm}$ mesons and for the first time $D^{\pm}$ mesons. Individual data points have reached a precision of better than 10% and there is good hope that the final analysis of the full HERA data set will reduce the uncertainties to the 5% level or even better. These data provide an important consistency check of the global QCD fits to the HERA inclusive data (such as those shown in figure 2) and to other data, especially for the highly non-trivial question of the charm quark mass treatment, which in turn influences the fitted gluon density. The usefulness of the $F_2^{c\bar{c}}$ data can be directly seen from the comparisons in figure 5 with two QCD calculations which differ in the used gluon density parameterisation and thus diverge toward small x and Q^2.

Beauty production at HERA probes the gluon density mainly at larger proton momentum fractions $x \sim 0.01$, where it is well known from the F_2 scaling violations. The available measurements [16] of the structure function $F_2^{b\bar{b}}$ are presented in the right panel of figure 5. This includes new measurements by ZEUS using semimuonic decays of beauty hadrons and a novel H1 analysis [16], using track impact parameters, which was released shortly after the HEP-2007 conference (also an update of $F_2^{c\bar{c}}$ was provided which is not included in figure 5 left). The full inclusion of the HERA II dataset will hopefully reduce the rather large uncertainties of the present measurements by at least a factor of two. These measurements may provide constraints for the effective beauty quark density in the proton (neglecting the beauty quark mass) which can then be used to make predictions at very large scales at the LHC for processes such as $b\bar{b} \to H$ or $b\bar{b} \to Z$. This effective beauty quark density is also investigated at the TEVATRON in $Z + b$ production (the main partonic reaction being $bg \to Zb$). CDF presented brand new results [17] at this conference with greatly improved precision.

2.8. Longitudinal structure function F_L

The proton structure function F_L provides another independent means to determine the gluon density. For a direct F_L determination, HERA operated over the last 3 months of its lifetime with protons of lower energies than the nominal $E_p = 920$ GeV. H1 and ZEUS have each recorded [8, 9] about 13 pb^{-1} and 7 pb^{-1} of data at $E_p = 460$ GeV and $E_p = 575$ GeV, respectively. These data may be used to measure F_L with sufficient precision to separate between extreme gluon density parameterisations, especially for small $x < 0.001$, where the gluon density is not so well known.

3. Determination of α_s

A precise determination of the strong coupling constant α_s is very important for the further exploration of the Standard Model and of theories beyond. Jet production at HERA is directly sensitive to α_s (see figure 4 left). At this conference H1 and ZEUS have released a new combined HERA α_s determination [18], based on DIS inclusive jet production measurements: $\alpha_s(M_Z) = 0.1198 \pm 0.0032$. Only very high Q^2 data were included in this determination in order to reduce the theoretical uncertainty and to obtain the smallest total error. Figure 6 shows the running of α_s versus the hard scale. The left plot shows HERA jet and event shape results together with a QCD curve using the world average value $\alpha_s(M_Z) = 0.1189 \pm 0.0001$ as compiled by Bethke [19]. The right plot [19] shows the same QCD curve together with a selection of the experimental results that were used for the world average value determination. From the high energy colliders the results from LEP (e.g. ~ 400 k four-jet events collected by OPAL [20]) still provide the statistically most accurate determinations. All HERA results shown in figure 6 are still based on the HERA I run period - the exploitation of the ~ 3 times larger HERA II data sample will allow for the reduction in the total error of the HERA data points by a factor two.

4. Diffraction

Hadron-hadron collisions proceed predominantly via soft interactions. In a sizeable fraction of these soft processes the colliding hadrons remain intact or merely dissociate to larger mass states with the same quantum numbers. These processes are called diffractive reactions. The parton composition of the diffractive exchange is not well known.

4.1. Diffractive parton densities

In QCD a hard scattering collinear factorisation theorem predicts that the cross section for diffractive deep-inelastic ep scattering (DIS) factorises into a set of universal diffractive parton distribution functions (DPDFs) of the proton and process-dependent hard scattering coefficients.
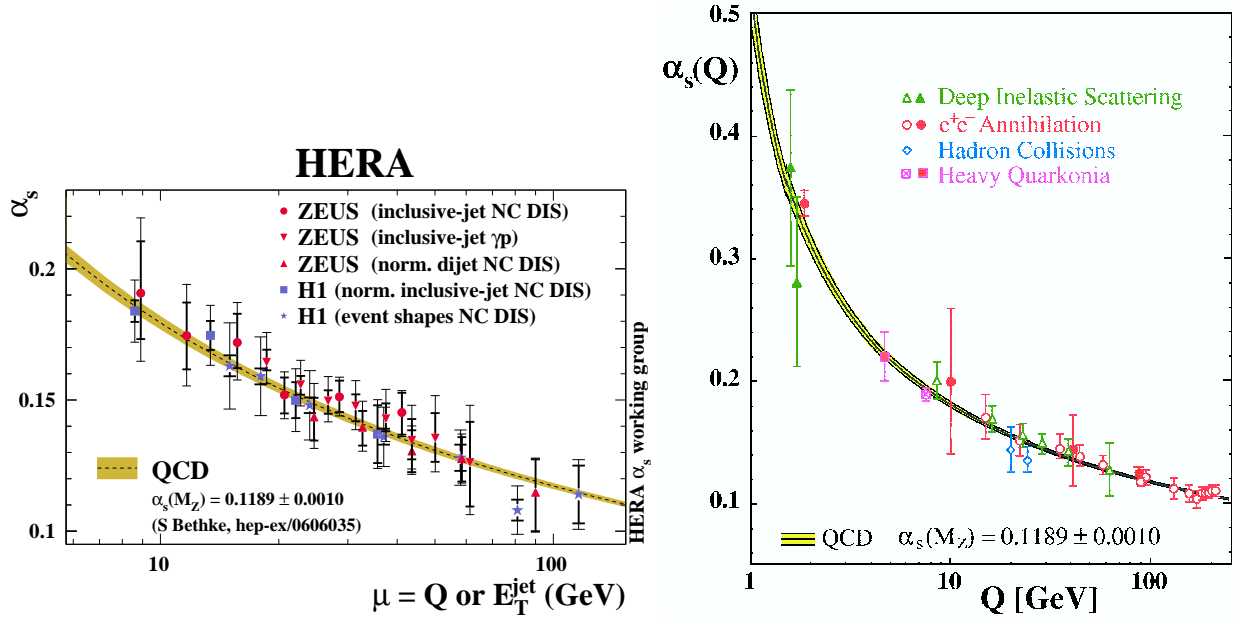
Figure 6. Running of α_s as a function of the hard scale. Recent HERA results [18] based on jet and event shape measurements are shown on the left, a selection of the results that were used by Bethke [19] to obtain the quoted world average value for $\alpha_s(M_Z)$ is shown on the right. In both plots the QCD curve based on this world average value is also shown.

At HERA DPDFs have been determined [21] from the measured cross sections of inclusive diffractive scattering $ep \rightarrow eXp$ in the DIS kinematic range (for Q^2 above ~ 8.5 GeV^2). At this conference, new sets of DPDFs have been presented by H1 [23] which were obtained through a simultaneous fit to the diffractive inclusive and dijet cross sections in DIS. The dijet cross sections make it possible to constrain, for the first time, the gluon density in the diffractive exchange up to large momentum fractions. The good consistency of the inclusive and dijet results support the validity of QCD factorisation. As has been known for long time, the factorisation appears to be strongly broken for diffractive dijet production in $p\bar{p}$ collisions at the TEVATRON [22], where the observed cross sections are roughly an order of magnitude below the predictions based on the HERA DPDFs. This discrepancy has been attributed to the presence of the additional beam hadron remnant, which leads to secondary interactions. At HERA this has been investigated in diffractive photoproduction of dijets, as reported in the talk [24]. The exchanged quasi real photon can fluctuate hadronically (so called resolved photon events in contrast to direct photon events), thus resembling the situation at the TEVATRON. H1 [25] observes a global suppression of the dijet cross sections by a factor ~ 0.5, with no indication for a different supresion in direct and resolved photon enhanced samples. A similar measurement by ZEUS [26], restricted to higher jet transverse momenta, sees a smaller suppression factor which could be still in agreement with no suppression.

4.2. Diffractive production of vector mesons

Diffractive production of vector mesons or real photons at HERA $\gamma^*p \rightarrow Vp$ or $\gamma^*p \rightarrow \gamma p$ provides a rich testing ground for QCD [27]. These processes are characterised by four scales (see also the diagram in the top left of figure 7): the four momentum transfer squared Q^2 of the virtual photon, the mass m_V of the produced vector meson, the photon-proton centre of mass energy $W_{\gamma p}$ and the four momentum transfer squared t at the proton verex. Detailed studies as a function of these variables allow a three-dimensional picture of the proton to be obtained, i.e.
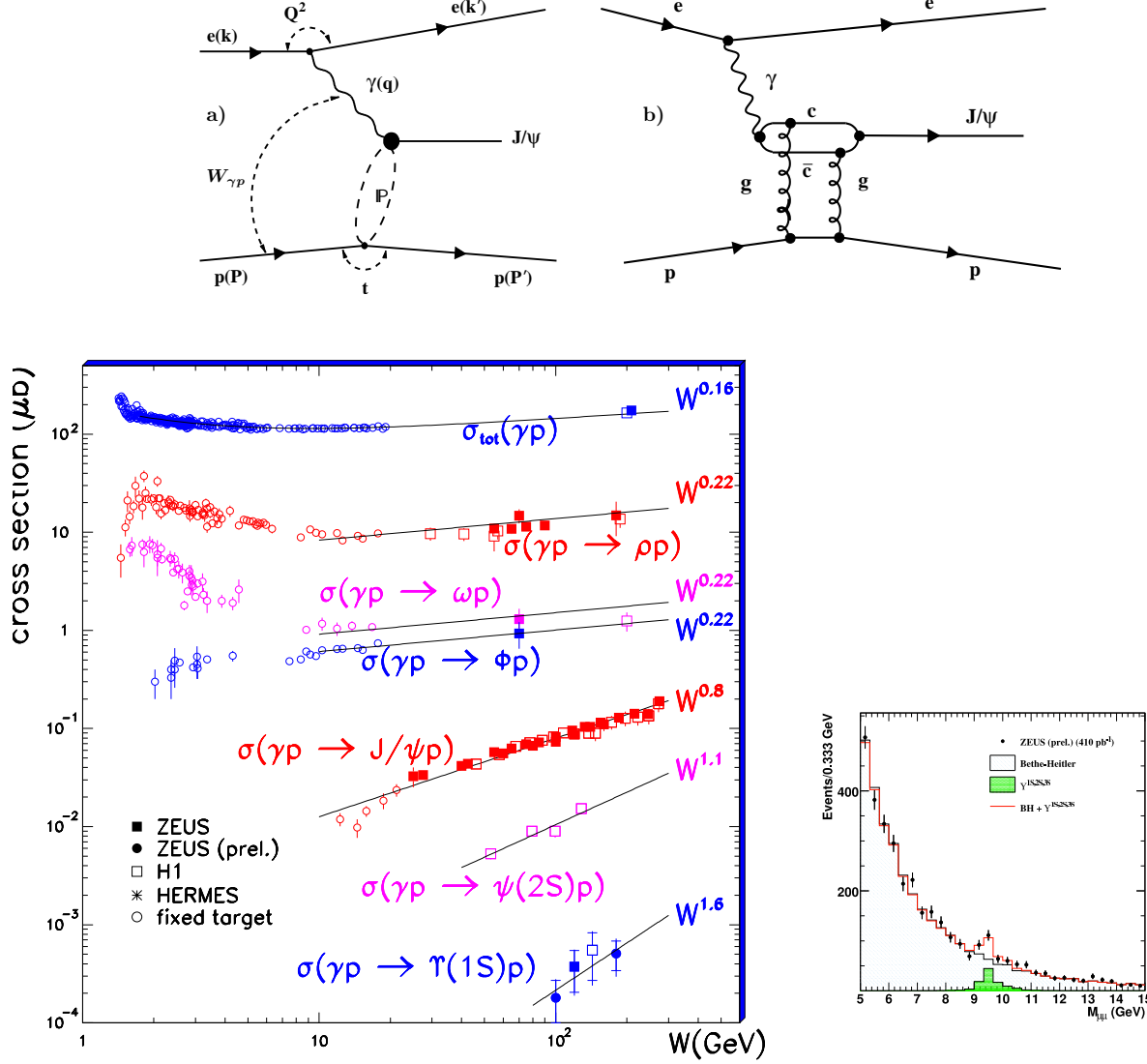
Figure 7. Diffractive vector meson production at HERA: Top-left: Diffractive vector meson production diagram for the exemplary case of J/Ψ production, in an approach based on Regge theory (Pomeron exachange), and introducing the kinematic variables Q^2, $W_{\gamma p}$ and t. Top-right: Diagram for J/Ψ production in the perturbative two gluon exchange picture. Left-bottom: HERA cross section results [27, 28] for diffractive vector meson production in the photoproduction kinematic regime ($Q^2 \sim 0$ GeV^2). The results for various vector mesons are shown as a function of $W_{\gamma p}$, together with fits of the form $W_{\gamma p}^{\delta}$. For the $\Upsilon(1S)$ the two brand new ZEUS [28] points (closed circles) are obtained from the analysis of a large part of the HERA statistics. The corresponding signal mass peak in the total HERA sample is shown in the right-bottom histogram.

of the distributions of partons in the proton (which are expected to be mostly gluons) that take part in the diffractive exchange. The study of the diffractive production of various vector mesons in photoproduction ($Q^2 \sim 0$ GeV^2) at HERA allows to observe the transition from the soft to the hard QCD regime. This is demonstrated in figure 7. For inclusive γp scattering and for light vector meson production such as for the ρ a soft rise of the cross section with W is observed

– this is the non perturbative domain which can be described by Regge-theory. The larger the mass of the vector meson, the steeper the cross section rises with $W_{\gamma p}$. This can be understood in the perturbative picture of hard QCD: the dominant production mechanism is the fluctuation of the photon into a quark-antiquark pair which scatters off two gluons in the proton and then annihilates into the vector meson. This reaction is shown for J/ψ production in the top right diagram of figure 7. The process is proportional to the squared gluon density $|g(x, \mu_f)|^2$. The rise with $W_{\gamma p} \sim 1/\sqrt{x}$ reflects the well known increase of the gluon density towards small x which becomes steeper for larger factorisation scales μ_f which are set by the mass of the vector meson. A brand new result presented at this conference is the ZEUS measurement [28] of the production of the heaviest accessible meson, the $\Upsilon(1S)$ resonance, as shown in figure 7. As expected, the rise with $W_{\gamma p}$ is in agreement with being very steep.

Amongst the other interesting results presented at this conference are analyses by H1 [29] of the first beam charge asymmetry measurement in deeply virtual compton scattering ($\gamma^* p \rightarrow \gamma p$) and a comprehensive study by ZEUS [30] of exclusive ρ production in DIS reaching up to high Q^2 and $|t|$.

5. Underlying event

The main physics interest in collider physics are hard primary interactions at the energy frontier such as the anticipated Higgs production at the LHC, e.g. in the channel $gg \rightarrow H$. However, in hadron hadron collisions secondary interactions occur (as depicted in figure 8 left) that can lead to a distortion of the reconstructed energies of particles and/or jets from the primary interactions. Thus a good understanding and modelling of these secondary interactions which
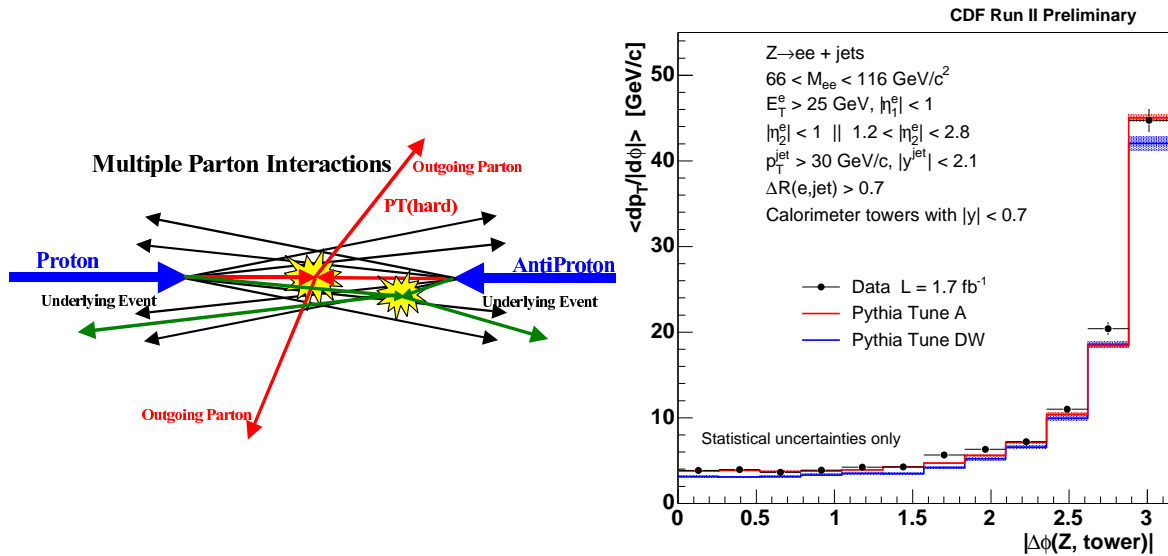

Figure 8. Left: Sketch of a $p\bar{p}$ event at the TEAVTRON with a hard primary and a secondary parton interaction, the latter creating an underlying event. Right: CDF measurement [31] of the energy flow in events containing a Z boson, reconstructed via $Z \rightarrow e^+e^-$, and a jet. The energy flow is sampled as a function of the azimuthal separation of the Z and the jet. The data are compared with PYTHIA Monte Carlo program predictions using two different tunes of the underlying event.

produce the so called *underlying event* is mandatory. Intense investigations of the underlying event are performed at the TEVATRON. As an example CDF [31] has recently performed a study of events with $Z + jet$ production. The energy flow between the jet and the Z is shown in figure 8 right. It is well described by the PYTHIA Monte Carlo prediction, where the underlying

event is modelled with the so called 'Tune A'. It remains however an intriguing question if these tuned models will work at the much greater LHC energies.

6. Fragmentation studies at HERA

It is an interesting question if the fragmentation of the outgoing quarks and gluons in hard scattering processes is independent of the production mechanism and especially of the colour configuration of the partons. This has been investigated recently in H1 and ZEUS analyses [32, 33] of the scaled momentum distribution of charged tracks in DIS events in the Breit frame. In the quark parton model picture (shown in the diagram in the left of figure 9), the scaled momentum gives directly the fraction of the quark momentum transferred to the charged track and this can be compared to the fraction of the quark energy taken by charged tracks in e^+e^- annihilation experiments. The results, which are shown in the right panel of figure 9, broadly
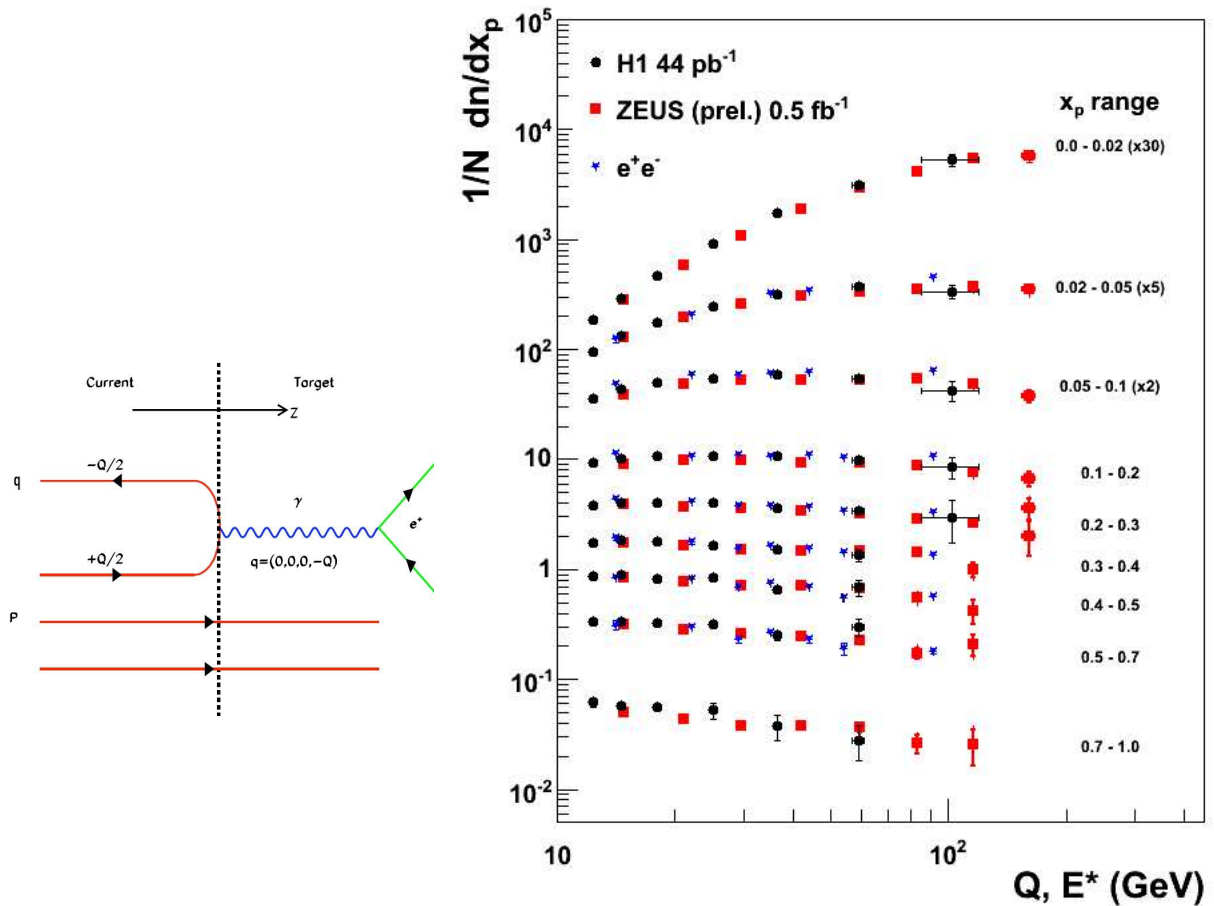

Figure 9. Left: Sketch of the quark parton model process in DIS at HERA in the Breit frame. Note the similarity of the hard scattering process with quark-antiquark production in $e^+e^- \to \gamma^* \to q\bar{q}$. Right: Normalised distributions of the charged track scaled momenta x_P. The observable x_P is a measure of the quark momentum fraction carried by charged tracks. The measurements [32, 33] obtained by H1 and ZEUS in DIS in the Breit frame are compared to results from e^+e^- experiments. The data are shown in bins of x_P as a function of the relevant hard scale, which is taken to be Q for HERA and the centre-of-mass energy E^* for e^+e^- reactions.

support the concept of quark fragmentation universality in ep collisions and e^+e^- annihilation.

7. Conclusion

Presented here is a highly personal selection taken from the great wealth of new measurements of hard hadronic scattering processes at the high energy colliders, HERA, LEP and TEVATRON. The major emphasis has been placed on results that are relevant for the LHC, such as the detailed exploration of the proton structure. In the future, the final analysis of the full HERA data sample is expected to make significant progress in the determination of the quark and gluon densities within the proton: typically by a factor of two or more. Significant improvements are also expected from the TEVATRON, where the data analysed so far (typically ~ 1.5 fb^{-1}) contribute only $\sim 20\%$ of the expected total integrated luminosity to be collected until 2009. One of the TEVATRON physics topics that will remain of high importance is the production of jets of the highest energies, since these data are not only sensitive to the not-so-well-known gluon density at highest proton momentum fractions, but also potentially to new phyiscs that may show up at the high energy frontier. Finally, when the LHC starts operation (hopefully in 2008), with its unprecedented centre of mass energy of 14 TeV, a new era will open for tests of hard QCD, presenting vast and splendid possibilities to learn more about the strongest force in nature.

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