Summary of the Hadronic Final State Working Group

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Abstract. Talks given during the Hadronic Final State sessions of the DIS 2005 workshop are summarized. Recent experimental studies on many topics ranging from perturbative and non-perturbative QCD effects in high-energy hadroproduction to hadron spectroscopy and high-energy nuclear matter were presented. Considerable progress achieved in higher-order QCD calculations, development of parton showers, resummations, and other theoretical areas was also reviewed.

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INTRODUCTION

The study of hadronic final states at particle colliders is one of the most active areas of research, as demonstrated by 38 talks presented during the sessions of this working group. Tests of perturbative QCD (pQCD), studies of non-perturbative QCD models, fragmentation effects, baryon and meson spectroscopy, search for exotic particles (e.g. pentaquarks), study of the photon structure and high-energy nuclear matter are some of the topics discussed during the workshop. The results presented constitute significant progress since the last conference in this series (DIS2004, Slovakia).

JET PHYSICS

Jet physics provides a testing ground for pQCD as well as the possibility of determining the strong coupling constant α_s and QCD colour factors. High-precision measurements of jet cross sections at HERA and Tevatron help constrain nonperturbative QCD inputs (e.g., gluon densities in the proton) and reduce uncertainties in signal and background cross sections in searches for Higgs bosons and other new particles at future accelerators, like LHC. Understanding of jet algorithms, multiparticle interactions and underlying events is a key issue on the experimental side. New experimental results comprise:

- Inclusive jet cross sections in neutral current deep inelastic scattering (ZEUS, J. Standage): measurements in a new kinematic regime show good agreement with next-to-leading-order (NLO) QCD calculations. The calculations present small uncertainties in the region of phase space spanned by the measurements.
- Multijet production in neutral current deep inelastic scattering (H1, T. Kluge): three-jet cross sections in deep inelastic scattering (DIS) are directly sensitive to

QCD radiation and the gluon density in the proton. Measurements of dijet and three-jet cross sections were presented at high Q^2. In this kinematic regime, the $\mathcal{O}(\alpha_s^3)$ corrections are suppressed by the small QCD coupling strength α_s. The calculations from NLOJET++ give a good description of the data. The ratio of the three-jet to the dijet cross sections as a function of Q^2 was used to make a determination of α_s with accuracy competitive with other more inclusive measurements.

- Color dynamics in photoproduction of jets (ZEUS, J. Terrón): three-jet production in direct photoproduction provides a means of testing the underlying gauge symmetry group of the strong interactions. The observables studied show a sensitivity to the color components. The data are consistent with the mixture of different color configurations predicted by SU(3) color symmetry; the contribution from diagrams with a triple-gluon vertex is $\sim 42\%$ and, thus, these measurements have a potential for extraction of color factors.
- Precision measurements of α_s at HERA (C. Glasman): an average value of $\alpha_s(M_Z)$ from several measurements by the H1 and ZEUS Collaborations was presented. The experimental uncertainty in the combined value is below 1%, whereas the theoretical uncertainty is $\sim 4\%$. Thus, further theoretical work is needed to obtain more precise determinations of α_s from HERA data. The combination of the measurements of α_s at different energies allows one to demonstrate the running of the QCD coupling by using the HERA jet data alone.
- Latest jet results from the DØ Collaboration (B. Davies): new cross sections for high transverse-energy jets in Run II show agreement with NLO QCD calculations within the uncertainties. The experimental uncertainty arising from the absolute energy scale of the jets ($\sim 5\%$) dominates. The azimuthal decorrelation between jets in multijet events also shows good agreement with the theoretical expectations. First measurements of tagged jet cross sections were also presented.
- Jet physics in Run II at CDF (R. Field): jet cross sections in Run II from CDF using the k_T cluster algorithm were presented. Good agreement between data and theory is observed. Measurements of *b*-tagged jet cross sections also show a good agreement with QCD calculations. Detailed studies of the effects of the "underlying event" were presented. Aside from Tevatron applications and constraints on parton densities, these studies may help understand the "underlying event" at the LHC, which may be quite different from that at the Tevatron as a consequence of the absence of KNO scaling. Hadronization models in the present Monte-Carlo showering programs may be inadequate ("still sort of plug and pray", to use S. Frixione's expression) at the LHC. Consequently substantial re-tuning of Monte-Carlo generators in the first few years at LHC may be needed. Alternatively, data from low energies at RHIC ($\sqrt{s}$ = 200 GeV) may be possibly utilized to determine the energy dependence of the underlying event. The relevant data is already becoming available from the RHIC measurements (see J. Jia's talk).

PERTURBATIVE QCD, MONTE-CARLO GENERATORS, AND RESUMMATIONS

Successful theory predictions are obtained in quantum chromodynamics by combining systematic calculations for hard-scattering processes with all-order resummation of semi-hard hadronic activity and reliable modeling of nonperturbative contributions. Each of these three aspects of perturbative QCD theory was amply presented during this workshop.

The status of calculations for hard-scattering processes was reviewed by M. Klasen. Significant advances are being made in computations of two- and three-loop QCD matrix elements, improving accuracy of theory predictions up to next-to-next-to-leading-order (NNLO). The latest NNLO results of relevance to hadroproduction include complete expressions for 3-loop DIS structure functions and anomalous dimensions, qq helicity amplitudes for $pp \to 2$ jets, partial 2-loop expression for the average thrust in e^+e^- hadroproduction, fully differential distributions for Higgs + 2 jets, and 2-loop vertex corrections in e^+e^- heavy-quark production. Two-loop cross sections for semi-inclusive DIS hadroproduction at high p_T have been computed by several groups (see below). The soft and collinear limits of NNLO hard cross sections, where extra care is needed in dealing with kinematical singularities, are also being studied.

The progress in perturbative calculations is based, in part, on the development of efficient methods for evaluation of complex Feynman integrals: color and helicity decomposition, recursive relations suggested by graph topology and unitarity, integration by parts, sector decomposition, etc. An intriguing new connection has been established between the structures of massless multi-leg QCD diagrams and string representations in twistor space, which opens the door for more efficient calculations at tree and one-loop level. Besides our working group session, the technical aspects of QCD calculations and connections to the twistor formalism were covered in the plenary talk by L. Dixon.

With the exception of the simplest one-scale observables [such as the ratio $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$], the hard cross sections cannot be immediately accessed in experiments without also including effects of multiple parton radiation and long-distance nonperturbative dynamics. Resummation of large logarithms from emissions of partons in a wide span of energies can be realized by solving evolution equations (such as the DGLAP equations for parton densities and fragmentation functions), or numerically by Monte-Carlo showering programs. A presentation by S. Frixione (complementary to the plenary talk by P. Skands) described the latest achievements in the development of next-to-leading order (NLO) Monte-Carlo generators. The Monte-Carlo programs for leading-logarithm resummation are ubiquitously applied in experimental analyses because of their capability to simulate exclusive final states and flexibility. Until recently, the Monte-Carlo generators included only the leading-order hard-scattering cross sections and did not properly describe high-p_T and multi-jet configurations, or the total rate. On the other hand, fixed-order calculations properly account for hard emissions, estimate reliably the total rates, and can be systematically improved to reduce dependence on arbitrary factorization scales. The powerful features of the higher-order and Monte-Carlo computations are complementary, and significant effort is being dedicated to the combination of the two approaches in one calculation. The talk compared

two promising methods for such a merging (matrix element corrections and NLO with parton showers) and presented examples of successful applications in each hybrid approach.

In contrast to the Monte-Carlo methods, analytical resummation often preserves desirable features of the finite-order calculations, including systematical factorization of short- and long-distance scattering, order-by-order expansion in series of α_s, controlled total rates and scale dependence. Analogously to the finite-order calculations, resummation is applicable to limited classes of sufficiently inclusive observables, so that distinct types of resummation must be applied under different circumstances. Resummation issues were discussed in the following contributed talks:

- Soft-gluon expansions through NNNLO (N. Kidonakis): large logarithms enhance QCD cross sections when the scattering energy is barely above the threshold in the considered particle production channel. The leading threshold effects are process-independent, so that a master formula can be devised to describe such effects in a variety of reactions. The master formula has now been derived up to NNNLO, and its application to charged Higgs boson production was described.
- Transverse momentum resummation at small x (F. Olness): logarithms arising at small transverse momenta in Drell-Yan-like processes and semi-inclusive DIS are described by a generalized factorization formalism (Collins-Soper-Sterman resummation). Higher-order corrections will modify this formalism at small momentum fractions x, where Catani-Ciafaloni-Fiorani-Marchesini (CCFM) or Balitsky-Fadin-Kuraev-Lipatov (BFKL) small-x resummations are more appropriate. The talk pointed out that small-x modifications of logarithmic or other nature may have already been observed in q_T resummation for SIDIS at HERA, which would also imply observable modifications in q_T distributions in the comparable x range at the Tevatron and LHC. Possible effects on electroweak boson production at hadron-hadron colliders suggested by the HERA SIDIS data and opportunities to experimentally measure them in the Tevatron Run-2 were discussed.
- The high energy limit of QCD as described by the NNL BFKL equation (J. Andersen): an iterative method for solving the small-x BFKL resummation equation at full NNL accuracy directly in the space of physical rapidity and transverse momentum was described. The method has the advantage of being unaffected by instabilities arising when the NNL BFKL equation is solved in an approximate analytical form, and it gives stable predictions for the gluon Green function and effective intercept at large rapidity gaps. The instabilities in the analytical solution can be traced to the wrong choice of NNL kernel eigenfunctions and remedied by selecting an NNL eigenbasis with correct renormalization scale dependence.
- Gaps between jets in the high energy limit (A. Kyrieleis): dependence of the cross section for production of two jets on the jet separation in rapidity was considered. A combination of leading-log-Q_0 and BFKL resummations, applicable at small and large rapidity gaps respectively,was discussed. Several all-order schemes for interpolation between the leading-log-Q_0 and BFKL resummed cross sections in the whole rapidity range without double counting were worked out, and differences between the interpolation schemes were analyzed. This work contributes to the development of a unified formalism describing the “jet-gap-jet” process at all

rapidity separations, with resummations included in the appropriate kinematical limits.

SMALL X AND FORWARD PARTICLE PRODUCTION

Structure function data from HERA and fixed-target experiments have allowed a good determination of the proton PDFs over a large region in phase space. The evolution of the structure function data with Q^2 is successfully described by the DGLAP equations. Measurements of jet production have provided accurate tests of pQCD. At high Q^2 or $E_T^{\rm jet}$, where $E_T^{\rm jet}$ is the jet transverse energy, NLO calculations using the DGLAP evolution equations have been found to give a good description of the jet data. However, in production of forward, close to the proton direction, jets with $E_T^{\rm jet} \sim Q$ at low x, discrepancies with NLO DGLAP calculations may have been observed. In some cases, the NLO DGLAP cross section agrees with the data only after a large renormalization scale uncertainty (up to 100%) is taken into account. This indicates importance of higher-order corrections at low x and Q^2, possibly arising from small-x effects associated with CCFM or BFKL dynamics. An improved description of the data can alternatively be obtained by assigning a partonic structure to the exchanged virtual photon. New results on forward-jet production from H1 and ZEUS, as well as new theoretical calculations have been presented in the course of this workshop. The contributed talks include:

- Measurement of forward jet production at low x in DIS (H1, A. Knutsson): forward jet cross sections were measured and compared with the predictions of perturbative QCD of $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_s^2)$. The predictions using DISENT at NLO give a reasonable description of the data at high $x_{\rm Bj}$, but fail at low values. For dijet production, the predictions of NLOJET++ describe the data within the experimental and theoretical uncertainties. The data were also compared to the predictions of several leading-logarithm parton-shower models. Those models include a color-dipole treatment of the parton shower, which mimics the BFKL regime, or a resolved component for the virtual photon, which adds a second DGLAP evolution ladder on the photon side. They give a good description of the data.
- Forward jet production in DIS (ZEUS, N. Vlasov): inclusive forward jet measurements were presented and compared with theory predictions in different pseudorapidity regions. The leading-logarithm color-dipole parton shower ARIADNE gives the best overall description of the cross sections, while LO DGLAP parton showers fail to describe the forward data. NLO QCD predictions by DISENT give a good description of the measured transverse energy dependence of the jet cross section. The data are well described by DISENT at low pseudorapidity, but some discrepancies are seen in the most forward region, where a large renormalization scale uncertainty is also present. Discrepancies are also observed with the showering program CASCADE in the CCFM k_T-factorization approach, suggesting that adjustments in parameters of unintegrated parton distributions are necessary.
- QCD corrections to the electroproduction of hadrons with high p_T (R. Sassot); DIS production of inclusive hadrons with large p_T at NLO (B. Kniehl): NLO, or $\mathcal{O}(\alpha_s^2)$, cross sections for hadron electroproduction at large p_T were independently

computed by two groups (A. Daleo, D. de Florian, and R. Sassot; B. A. Kniehl, G. Kramer, and M. Maniatis). The NLO calculation describes well most of the HERA phase space, in contrast to the LO predictions, which typically fall below the HERA data. The NLO/LO K-factor is moderate at higher x, p_T and Q^2, but grows up to 10-25 toward the lowest reachable x and Q^2, including the forward production region. A new hadroproduction channel $\gamma^* g \to q\bar{q}g$ opens up at NLO and contributes a rate several times higher in forward π^0 production compared to the other channels (Sassot). Large renormalization scale uncertainty suggests that the NNLO analysis will ultimately be required for reliable interpretation of the forward production data (Kniehl). Reduction of other uncertainties, *e.g.* arising from substantial dependence on the choice of fragmentation functions, may also be needed.

- Small x effects in forward jet production at HERA (C. Marquet): an alternative interpretation of the forward jet data can be made in the BFKL framework, designed to resum the $\ln(1/x)$ logarithms from multiple $g \to g$ splittings as $x \to 0$. Such an analysis was performed in the leading-logarithm BFKL approximation, and the possibility of saturation effects at HERA energies was also considered. Both small and large saturation energy scales were found to be compatible with the forward jet data, suggesting that these data alone cannot distinguish between the weak saturation (essentially a pure BFKL regime) and strong saturation (with the BFKL cross section growth tamed by unitarity). Consequently, more data has to be included in the fit to help discriminate between the different saturation models.

As can be seen from the review of the talks, interpretation of the forward production data remains unsettled, with different (sometimes complementary) explanations presented by many authors. Further experimental and theoretical studies are clearly needed to work out a consistent point of view on the nature of QCD radiative corrections in the HERA forward region, especially given that the relevant region of x will be routinely probed at the LHC.

PARTICLE PRODUCTION

Studies of particle production have become increasingly detailed and flavour specific, providing stringent tests of QCD and our understanding of the hadronisation process. New and improved measurements of azimuthal asymmetries, polarisation in the $\Lambda(\bar{\Lambda})$ system and of Bose-Einstein correlations in kaon production were shown. A puzzling discrepancy between two determinations of electric and magnetic dipole moments of protons may have an explanation, and heavy particle production at the LHC may be modified by onset of the "black body" limit:

- Predictions for azimuthal asymmetries (T. Tymieniecka): the energy flow method for studying azimuthal asymmetries was presented, with the goal of measuring contributions from subleading angular functions in semi-inclusive deep inelastic scattering. This method is more reliable than multiplicity methods, as it is not sensitive to details of fragmentation in the final state.

- Azimuthal asymmetry using energy flow method (ZEUS, A. Ukleja): measurements of azimuthal asymmetries of hadronic energy flow, charged and neutral hadrons in neutral current deep inelastic scattering were presented. Next-to-leading-order QCD calculations show a reasonable description of the asymmetry as a function of the pseudorapidity in the hadronic center-of-mass frame.
- Polarization and asymmetries in neutral strange particle production (ZEUS, A. Cottrell): new measurements of $\Lambda(\Lambda)$ polarization were presented. The transverse and longitudinal polarizations are consistent with zero. Results on baryon asymmetry and the baryon-meson ratio were also presented. No significant asymmetry was observed. The data give a higher baryon to meson ratio at low p_T than the predictions. This ratio rises steeply as x decreases.
- New possible insight into JLab proton polarization data puzzle by DIS (A. Dubnickova): the talk discussed a disagreement between the ratios of the electric and magnetic form factors determined in polarized ep scattering at JLab and by Rosenbluth technique. The disagreement between the two measurements is explained by different behaviour of the electric form factor, which is known with less certainty than the magnetic form factor as a result of its kinematical suppression in the Rosenbluth method. A new sum rule was proposed to independently constrain the electric form factor from measurement of the difference of proton and neutron differential distributions $d\sigma/dQ^2$ (with x integrated out) in DIS.
- Neutral and charged kaon Bose-Einstein correlations in DIS (ZEUS, A. Galas): results on Bose-Einstein correlations for charged kaons show an r value similar to pions, but a somewhat smaller λ value. The results for r are in good agreement with the results from LEP, but the λ value is smaller. For neutral kaons, the value of r is in good agreement with that for charged kaons and similar to that of pions, and is also in good agreement with the measurements of LEP. The value of λ extracted for neutral kaons is rather large.
- Black body limit in central pp/pA collisions at the LHC (C. Weiss): massive electroweak bosons and other heavy particles will be frequently produced at the LHC in central proton-proton or proton-nucleus collisions. Production of very forward hadrons in such collisions may saturate the "black-body" (unitarity) limit, which will modify properties of the hadronic final state at very large rapidities. Signatures of the "black-body" limit were analyzed in the dipole approximation for DGLAP evolution, and kinematical regions where the "black-body" limit may be reached were identified based on the HERA data.

NON-PERTURBATIVE EFFECTS

Event-shape variables are particularly sensitive to details of the non-perturbative effects of hadronization and can be used to test the models for these effects. Recently, new developments with regard to power-law corrections have prompted a revived interest in the understanding of hadronization from first principles. In this type of analysis, the data are compared to model predictions which combine NLO calculations and theoretical expectations for the power corrections, characterized in this case by an effective coupling

$\bar{\alpha}_0$. Previous results supported the concept of power corrections in the approach of Dokshitzer et al., but a large spread of the results suggested that higher-order corrections were needed. Now, resummed next-to-leading-logarithm calculations matched to NLO are available, and so it is possible to study event-shape distributions instead of only their mean values. New results from ZEUS were presented:

- Event shapes at HERA (ZEUS, A. Everett): measurements of event-shape variables in neutral current deep inelastic scattering were presented both as mean values and differential distributions. The results were used to test the model of power corrections for the hadronization process. This model uses only one universal non-perturbative parameter, $\bar{\alpha}_0$, in addition to α_s to describe fragmentation. For the differential distributions, the NLO calculations compared to the data were complemented by resummed calculations. This led to a good description of the data and extraction of values for α_s and $\bar{\alpha}_0$, which are consistent with measurements in other experiments. New variables based on event shapes with jets were also discussed.

FRAGMENTATION EFFECTS

Studies of the fragmentation process through measurement of particle multiplicities have been expanded at HERA. Tests of the universality of the fragmentation process were extended to higher energy scales, and HERMES presented a detailed and careful analysis of flavour-separated multiplicities at lower energies.

- Recent results on multiplicity from ZEUS (M. Rosin): charged particle multiplicities were measured in the current regions of Breit and hadronic center-of-mass frames at a higher energy scale than in previous ep measurements. The results were compared to hadron multiplicities in e^+e^- and pp collisions. Similarity between the energy dependences of multiplicities in ep, ee, and ep scattering was found, if the energy scale in ep collisions was equated to twice the energy in the current region of the Breit frame.
- The fragmentation process at HERMES (B. Maiheu): the fragmentation function was studied at HERMES, with the focus on flavor separation of multiplicities in semi-inclusive deep inelastic scattering. Cross sections as a function of Q^2 and x_{Bj} were presented. The results obtained are model-independent, and much effort was invested in a proper treatment of uncertainties. No signs of strong factorization breaking were found.

PENTAQUARKS

The experimental status of pentaquarks remains ambiguous, with observation and non-observation of the various states being reported in roughly equal numbers of experiments. Careful comparison of superficially contradictory results can sometimes show that the differences are not really significant (see talks from H1 and ZEUS on the strange

pentaquark), and the new results from CLAS show that apparently "solid" observations can sometimes evaporate in the light of higher statistics. The results presented are:

- Search for pentaquarks at HERMES (A. Airapetian): HERMES has searched for Θ^+ and Ξ^{--} states in the decay channels of $\Theta^+ \to K^0_s p$ and $\Xi^{--} \to \Xi^- \pi^- \to \Lambda^0 \pi^- \pi^-$. A signal with a significance of 3.7σ is observed at $M = 1528 \pm 2.6$ MeV in the $\pi^+ \pi^- p$ mass spectrum. No signal for $\Theta^{++} \to pK^+$ is observed, thus Θ^+ cannot be an isotensor state. No signal is observed for a Ξ^{--} state; a limit on the production cross section of 2.1 nb was set at 90% CL.
- Pentaquarks at JLab: new results from CLAS (M. Battaglieri): CLAS has searched the Θ^+ state in high-statistics dedicated runs in exclusive photoproduction on protons. The process studied is $\gamma p \to \Theta^+ \bar{K}^0 \to (nK^+)(K_s \to \pi^+ \pi^-)$. Preliminary results with only 1% of the collected data were presented. The observed nK^+ spectrum is smooth; no signal is observed at masses of ~ 1540 MeV. An upper limit of $1-4$ nb at 95% CL was derived for the production cross section of the process $\gamma p \to \Theta^+ \bar{K}^0$, in contrast to the SAPHIR results.
- Analysis of the anti-charmed baryon state at H1 (K. Daum): a report on the observation and analysis of the $D^* p(3100)$ state by the H1 collaboration was made. The corrected fraction of $D^* p(3100)$ to D^* was measured to be $1.59 \pm 0.33^{+0.33}_{-0.45}\%$, whereas the ratio of the production cross section is $\sigma(D^* p(3100))/\sigma(D^*) = 2.48 \pm 0.52^{+0.85}_{-0.64}\%$. The kinematics of the $D^* p(3100)$ state were studied: D^* mesons from $D^* p(3100)$ decay are significantly softer than normal D^*s, and $D^* p(3100)$ production at central pseudorapidities $\eta_{\rm LAB}$ is suppressed. A simple fragmentation approach with isotropic decay for the $D^* p(3100)$ state describes the W and Q^2 spectra, but does not describe the properties of the D^* mesons produced in the $D^* p(3100)$ decay.
- Searches for pentaquarks at BaBar (E. Eckhart): the Θ^+, Ξ^{--}, Ξ^0, and Θ^{*++} states have been searched for by BaBar. No enhancement was observed in electroproduction, hadroproduction, or e^+e^- $K_s p$ mass spectrum at masses of about 1540 MeV corresponding to the Θ^+ state. Also, no enhancement in the $\Xi^- \pi^+$ or $\Xi^- \pi^-$ spectrum was observed at masses corresponding to the $\Xi(1860)$ state. No evidence was found for a Θ^{*++} signal in the pK^+ decay mode.
- The experimental search for charm pentaquarks at ZEUS (Y. Eisenberg): ZEUS has searched for decays of charmed pentaquarks into $D^* p$ using 127 pb^{-1} of integrated luminosity. The D^* mesons were searched for in the $D^{*+} \to D^0 \pi^+_s \to (K^- \pi^+)\pi^+_s + (c.c.)$ and $D^{*+} \to D^0 \pi^+_s \to (K^- \pi^+ \pi^+ \pi^-)\pi^+_s + (c.c.)$ decay channels. No evidence for a signal at 3.1 GeV, as reported by H1, was observed in the $D^* p$ spectra studied, even when using a very similar selection to that of H1. An upper limit on the fraction of D^* mesons originating from Θ^0_c decays was set to 0.37% (full sample) and 0.51% (a sample from deep inelastic scattering at $Q^2 > 1$ GeV^2) at 95% CL.
- Strange pentaquark search with ZEUS (Z. Ren): ZEUS observes the Θ^+ state in the $K^0_s p(\bar{p})$ decay channel at a mass of 1521.5 ± 1.5 (stat.) $^{+1.28}_{-1.7}$ (syst.) MeV with 4.6σ significance in deep inelastic scattering events with $Q^2 > 20$ GeV^2. The production cross section is $\sigma(ep \to e\Theta + X) = 125 \pm 27(\text{stat.})^{+36}_{-28}(\text{syst.})$ pb. New results on production mechanisms of various states were presented: the production

of $\Lambda(1520)$ is consistent with a pure fragmentation origin; the production of Λ_c can be attributed to boson-gluon fusion processes; the production of Θ^+ may favor a proton-remnant fragmentation origin.

- H1 search for a narrow baryonic resonance decaying to $K_s^0 p(\bar{p})$ (C. Risler): H1 has searched for the Θ^+ state in the $K_s^0 p(\bar{p})$ decay channel. No significant signal was found in the region of $1.48 - 1.7$ GeV of the decay-products mass spectrum in different regions of Q^2. An upper limit of $40 - 120$ pb at 95% CL was set. This limit is not incompatible with the measured production cross section of ZEUS.
- Theoretical aspects of pentaquark searches (A. Szczepaniak): a detailed review on experimental pentaquark results was presented. Most pentaquark sightings seem to come from low statistics, low resolution, low-energy experiments with kinematically constrained final states and complicated cuts. On the other hand, it seems that high-resolution, high-statistics experiments with low- or high-particles multiplicity do not report signals.

PHOTON STRUCTURE AND PROMPT PHOTONS

The photon, being the gauge particle of QED, can couple directly to $q\bar{q}$ pairs. In this light, a hard photon observed in the final state can give direct insight into the mechanism of the hard interaction with the advantage of not undergoing a fragmentation process. Thus, measurements of final-state photons are less affected by the experimental and theoretical uncertainties of hadronization. On the other hand, softer photons in the initial state can also interact via their resolved partonic structure, and photon PDFs are needed to describe these processes. The PDFs of the photon are less constrained at present than the proton PDFs, especially the gluon densities. Inclusion of data directly sensitive to the gluonic content in the photon, such as HERA photoproduction jet data, in principle helps to constrain the gluon density in the PDF fits. Results on these two topics were presented:

- Measurement of prompt photon cross sections in photoproduction at H1 (J. Ferencei): new measurements of prompt photon inclusive cross sections and those accompanied by jets were presented using a method with a likelihood discriminator to isolate the signal. The measured cross sections are reasonably well described by NLO QCD calculations, whereas leading-logarithm parton-shower Monte Carlo models describe the shape, but underestimate the normalization of the data.
- Next-to-leading-order photon PDF (A. Levy): new parametrizations for the photon parton distribution functions at NLO were presented. Analysis of experimental PDF uncertainties with the error matrix method was performed. Several data sets, including measurements of F_2^γ, low-x F_2^p and dijets in photoproduction, were used in the fits. A good description of the data is obtained with these parametrizations. Although the dijet data receives a contribution from the gluon photon density, this contribution is kinematically suppressed compared to the gluon proton density in the region covered by HERA. Consequently, inclusion of the dijet data did not substantially reduce uncertainties in the gluon photon density, contrary to the original anticipations.

HIGH-ENERGY HEAVY-ION COLLISIONS

Analysis of the hadronic final state in RHIC experiments is providing insight into the existence and properties of the hadronic matter produced in the aftermath of heavy-ion collisions. New results provide strong evidence that the observed suppression in hadron yields indeed arises from propagation through a dense hadronic medium and is not caused by intrinsic properties of the colliding nuclei or production mechanism. Experimental tools for analysing jets in this new environment are being developed and tested.

- π, η and direct photon production in pp and *AuAu* collisions (PHENIX, T. Awes): measurements of high-p_T π^0 and γ cross sections were presented and compared with pQCD calculations. The data on photon production agrees well with the pQCD calculation, in contrast to π^0 production, which is strongly suppressed compared to the perturbative prediction. Direct photons do not interact with the hadronic matter after the hard scattering occurs. The difference between the γ and π^0 yields therefore indicates presence of a dense hadronic medium in the final state, and is not likely to be caused by an initial-state effect.
- Jet properties from di-hadron correlation in pp and *dAu* (PHENIX, J. Jia): two-particle correlations were described as a useful characteristic of the jets produced in pp and *dAu* collisions at RHIC. The comparison of proton-proton and deuteron-gold data provides useful information about the impact of the nuclear matter on formation of the jets. Transverse momentum distributions of hadrons in the jets are very similar between *dAu* and pp collisions, *i.e.* presence of a cold nuclear medium (*dAu*) does not cause significant broadening of the jets comparatively to pp scattering. The jet-yield distribution is also very similar between these two reactions, thus, no significant increase in jet multiplicity occurs for *dAu* with respect to pp. The underlying event is larger at small p_T in *dAu*, but essentially coincides with the pp underlying event at large p_T. Assuming that hard-scattering events in the *dAu* system happen in independent nucleon-nucleon collisions, the underlying event rates in pp and *dAu* are related by a simple function depending on the pp minimum bias yield, number of collisions, and *dAu* nuclear modification factor.

SUMMARY

This short article does not attempt to give more than a flavour of the diverse topics presented during the Hadronic Final State sessions of the conference. The reader can find the full details of each presentation within the individual contributions. Several conclusions can be drawn from this overview, which of course do not cover the whole span of important topics discussed in many interesting talks.

High-Q^2 data now arriving from HERA become increasingly suited to precision studies of QCD: accurate determination of the QCD coupling, color factors, parton densities, etc. Further developments in QCD theory must also be pursued to match the experimental accuracy. For example, percent-level precision in the measurement of the fundamental parameter of QCD, the strong coupling constant, has been achieved at

HERA. Further theoretical work, namely NNLO calculations, is needed to reduce theory uncertainties for this observable to a level comparable with experimental errors.

Despite substantial recent progress, interpretation of the low-x scattering at HERA remains challenging, with none of the existing theoretical frameworks adequately explaining all features of forward hadroproduction. Future precision data may provide additional clues about the mechanisms involved. Improvements in the theoretical frameworks for the large- and small-x limits (DGLAP and BFKL) and development of specialized methods for moderately small x (e.g., CCFM) are required to explain the whole range of x and Q^2 covered by HERA measurements. Both inclusive and exclusive observables must be well understood as a function of x, given that many new physics searches at the LHC will rely on observation of multi-particle final states in the x range accessible at HERA and/or at forward rapidities.

The evidence for pentaquarks is dwindling; high-statistics experiments will be able to provide decisive information on the pentaquark existence or absence in the near future. Remarkable progress is being observed in higher-order QCD computations, development of Monte-Carlo showering programs, and resummations, with combined methods comprising several theoretical approaches (parton showers with NLO; joint resummations) gradually emerging. Details of high-energy hadronic scattering (angular momentum and spin dependence; partonic structure; power-suppressed contributions; fragmentation, hadron multiplicities, and jet formation; underlying event; ...) are systematically explored. Examination of hadronic interactions in heavy-nucleus collisions provides telling clues about properties of nuclear matter at high energies. Taken together, the results presented demonstrate that the physics of hadronic final states remains a leading area of particle research, with many new discoveries awaiting in the future.

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