

MULTI-HADRON FINAL STATES*

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This summary aims to highlight major results and insights gained from recent studies of hadronic final states in ep , $p\bar{p}$, e^+e^- , as well as relevant theoretical developments, presented in the *Multi-Hadron Final States* parallel sessions of the DIS2002 workshop held in Kraków, Poland in May 2002.

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1. Introduction

Presentations at the *Multi-Hadron Final States* sessions covered a wealth of recent results on jet production characteristics and jet properties, heavy flavor production and decays, dimuon photoproduction, instanton searches, small- x final states, studies of hadronization, and theoretical progress in resummation and parton shower formalisms, providing new insights into and sensitivity to a broad range of physics aspects. Due to space limitation, we refer the interested reader to individual papers in these proceedings for exact definitions of variables, experimental selections, plots, and further references.

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2. Physics of jets

Jet production processes in ep , e^+e^- and hadronic interactions continue to be primary tools for studies of parton dynamics and for testing specific theoretical descriptions and Monte Carlo models (MC) based on QCD.

While results from HERA on inclusive, dijet, and multi-jet reactions, induced by real and virtual photons, dominated the discussion, they were complemented by recent multi-jet measurements at LEP that directly probe the color structure and the coupling constant of strong interactions, and by a variety of jet studies at the Tevatron, covering a large range of jet E_T and probing QCD aspects from the hardest partonic scatter to the properties of the soft underlying and minimum bias events.

2.1. Inclusive and dijet results from HERA, plus some photons

The results presented in the sessions were generally in an impressive agreement with theoretical predictions, for many kinematic variables, and for several orders of magnitude of cross sections. Here, we will attempt to highlight hints of disagreements, which may point to weaknesses in the description of particular aspects of the underlying physics. Most of the measurements used versions of the k_T algorithm and were carried out in the Breit frame. In general, the veracity of next-to-leading order (NLO) matrix elements is confirmed by good agreement with the angular distributions in the data ($\cos\theta^*$ in dijet photoproduction, especially for high dijet mass; $\cos\theta_3$, ψ_3 in 3-jet DIS and in 4-jet photoproduction at high 4-jet mass.)

The photoproduction data from both H1 and ZEUS probe the photon parton distribution functions (PDFs); the GRV-HO set provides predictions 10–15% above those from AFG-HO (and seems to be in better agreement with the data).

Jacek Turnau [1] presented an H1 measurement of the single inclusive jet cross section in photoproduction ($Q^2 < 1 \text{ GeV}^2$) at high E_T (21–75 GeV), where the sensitivity to soft physics is reduced. The data agree very well with NLO QCD and with previous ZEUS results, but because of the large uncertainty in the jet energy scale, the preference for the GRV PDF is only marginal; this uncertainty needs to be reduced to take advantage of the high luminosity measurements at HERA II.

Maria Krawczyk [2] discussed theoretical issues in the inclusive direct-photon production. There are two different approaches to counting the powers of α_s in NLO calculations, leading to different sets of subprocesses being included; other authors considered the $\log Q^2$ factor present in the photon F_2 function as an inverse of α_s . The ZEUS data currently have errors too large to discriminate between these calculations, or between the

photon PDFs, but are in rough agreement with expectations (although none of them describe the data for rapidities below 0.1).

Dijet photoproduction probes direct and resolved photon components in more detail and is sensitive, already at lowest order, to the gluon content of the photon. At HERA, the photon structure can be probed at higher scales than at LEP. Theoretical calculations are available at NLO.

Dijet photoproduction cross sections from ZEUS, presented by **Anna Lupi** [3], are sensitive to the photon PDFs, but neither GRV-HO or AFG-HO fully describe all features of the data. In particular, the predictions do not track the data when compared as function of the cut on the lower energy jet, $E_T^{\text{jet}2}$. For the cut value used by ZEUS, $E_T^{\text{jet}2} > 11$ GeV, there is a significant difference between data and theory for $x_\gamma < 0.8$, x_γ being the momentum fraction of the photon partaking in the hard interaction. The H1 comparisons, presented by **Gilles Frising** [4], show a better agreement with theory, which may be related to the higher cut value ($E_T^{\text{jet}2} > 15$ GeV) used by H1. Frising pointed to significant NLO scale uncertainty, and sizable hadronization corrections at high x_γ . Both speakers concluded that HERA data can constrain and should be included in fits to PDFs; the constraints could be made more stringent if improved higher-order or resummed calculations were available. The H1 analysis also exhibits some sensitivity to the proton PDFs; this could be exploited with the high-statistics HERA II data.

Up a step in Q^2 , the region $\Lambda_{\text{QCD}}^2 \ll Q^2 < E_T^2$ is the place to investigate contributions from longitudinally polarized photon interactions, which vanish in the photoproduction limit. The analysis of H1 data, presented by **Kamil Sedlak** [5], demonstrated the importance of the resolved transverse component even in this Q^2 region; however, addition of longitudinal resolved photon contributions (within the HERWIG framework) further improves the agreement with data. Based on a study of y -distributions, such a longitudinal component is preferred to a pure enhancement of the transverse part. Interestingly, the predictions of the CASCADE MC, based on the CCFM evolution, describe the data almost as well, without explicitly introducing a resolved component (however, the Q^2 dependence at low x_γ is poorly described.)

The above analysis neglected the possibility of interference between transverse and longitudinal components, which was found to be important in some cases studied at LEP. **Urszula Jezuita-Dąbrowska** [6] investigated theoretical aspects of such interference effects in the semi-inclusive Compton process in ep collisions. She found that at HERA energies the interference term is of similar magnitude as the longitudinal term, but of the opposite sign! The extension of this study to dijet production at low Q^2 would be certainly interesting.

The partonic content of the virtual photon is suppressed when Q^2 increases, leading to a corresponding suppression of the ratio R between cross sections for $x_\gamma < 0.75$ (dominated by the resolved component) and for $x_\gamma > 0.75$ (dominated by the direct component). **Matthew Lightwood** [7] investigated this behavior (as seen in the ZEUS data) in the case when the dijets were identified as originating from charm quarks. The charm events were tagged by reconstructing a high- p_T $D^{*+} \rightarrow K^- \pi^+ \pi_s^+$ decay. After correcting for the D^* kinematic selections, the Q^2 suppression of R for charm events was significantly weaker than for the all-flavors case — clearly a consequence of the charm-quark mass. Again, CASCADE described the charm data well.

A novel approach to the analysis of H1 dijet data in the DIS regime ($150 < Q^2 < 35000 \text{ GeV}^2$) was discussed by **Günter Grindhammer** [8], using a modified Durham algorithm. The traditional DIS analyses require a large inter-jet separation, with only $\approx 10\%$ of the inclusive sample classified as dijet events. H1 investigated the minimum separation required for an adequate agreement with NLO calculation in terms of the variable $y_2 = \min k_{Tij}^2 / \text{scale}^2$ (with *scale* chosen either as W or Q). For $y_2 > 0.001$ the agreement with NLO was excellent, and the sample retained a third of all DIS events. Detailed studies of several variables in this expanded sample showed a very good agreement with NLO calculations, for two choices of the renormalization scale. Interestingly, a LO+parton-shower (PS) MC *sc* Rapgap describes the y_2 -distribution down to 10^{-5} , and reproduces other data well, while ARIADNE, HERWIG and LEPTO fail at places.

Sonja Hillert [9] reviewed ZEUS studies of internal structure of jets in neutral-current, charged-current and photoproduction data. Such studies provide insights into the transition from partons to the observed jets of hadrons and are sensitive to emission of gluons, thus allowing a determination of the strong coupling constant. The jet substructure is studied through the measurement of the mean subjet multiplicity; subjets are resolved by reapplying the k_T -clustering algorithm to particles within the jet while using a smaller resolution parameter y_{cut} . Using $y_{\text{cut}} = 10^{-2}$, and for both NC and CC data, the mean subjet multiplicity was compared to NLO calculations with the α_s -dependent A-series of CTEQ4 PDFs, yielding fits to α_s in good agreement with the PDG value, and with other ZEUS determinations; the errors are dominated by the theoretical uncertainty. Results were also presented for both integrated and differential energy-density distributions as function of the distance from the jet axis. The quark-initiated jet shapes determined in DIS events are in good agreement with NLO expectations and are consistent between CC and NC samples. In photoproduction, however, one finds a somewhat different shape, which is expected because of the contributions from gluon initiated jets. A quark-enriched sample has

been selected by the D^* charm-tagging technique; these jets have shape distributions similar to DIS jets. By taking the fractional contributions of quark and gluon jets in photoproduction data from LO MC, and assuming the measured shape for the quark jets, ZEUS solved for the shape of gluon jets and found that PYTHIA provides a good representation.

2.2. Multi-jet studies at HERA and LEP

A direct sensitivity to higher-order effects is obtained through investigations of multi-jet events. Using ZEUS data **Claire Gwenlan** [10] presented the first four-jet photoproduction cross section measurement. Multi-jet production in the photoproduction regime is also sensitive to the photon structure and to the ensuing multiple parton interactions. The distribution of x_γ^{OBS} agrees well with PYTHIA for high mass events, $m_{4J} > 50$ GeV, but requires a large contribution of multiple parton interactions (MPI) at lower masses and low x_γ^{OBS} . Angular distributions $\cos\theta_3$ and ψ_3 have been compared to the MC expectations. While HERWIG alone, and HERWIG + SUE (a soft underlying event model) fail, HERWIG + JIMMY (a multi-parton interaction model) work fine, as does PYTHIA + MPI; at high mass the soft effects are much reduced and the LO+PS generators alone provide a satisfactory description of the data.

In the DIS regime, extra jets are produced primarily through hard gluon emission, prodding enhanced sensitivity to α_s and allowing more stringent test of NLO theory. **Christian Schwanenberger** [11] presented H1 measurements of the 3-jet cross section *versus* several variables, for $5 < Q^2 < 5000$ GeV². At lowest Q^2 the dominant theoretical uncertainty is related to the choice of scales, but at the high- Q^2 end this uncertainty is reduced, thus providing sensitivity to α_s . This sensitivity is enhanced in the ratio of 2-jet and 3-jet cross sections, as the scale and some other theoretical and experimental uncertainties tend to cancel. The data are in good agreement with NLO (but not LO) using the world average for α_s . It is notable that the angular $\cos\theta_3$ and ψ_3 distributions are well described by NLO, but not by phase space, confirming the expectation for QCD radiation patterns.

Data from e^+e^- annihilation into hadrons provide a particularly clean environment to study characteristics of multi-jet events. **Pablo Tortosa** [12] presented results from LEP measurements of 4-jet events. The underlying theoretical description assumes only a non-abelian gauge symmetry and standard hadronization models, thus allowing determinations of the strong coupling constant and the SU(3) color factors by comparison of the measured 4-jet production rate and four different angular correlations between jets to NLO perturbative predictions. The measurements are in agreement with SU(3) expectations and with the world average value of $\alpha_s(M_Z)$; the

uncertainties on the extracted parameters depend on the number of free parameters in the fits. Flavor tagging has been used to enhance the sensitivity to color factors by identifying quark *versus* gluon jets. The results exclude the existence of a massless gluino at more than 95% confidence level (it would modify the factors by adding light fermion degrees of freedom).

2.3. Selected jet results from the Tevatron

Traditionally, the Tevatron jet measurements have been based on the cone algorithm, and were aimed primarily at the highest transverse energies. In recent years, however, more attention has been paid to alternative algorithms and to studies of jet and event structure issues at low energies.

Iain Bertram [13] reviewed several recent analyses from DØ based on the Ellis–Soper version of the k_T algorithm. DØ recently published the inclusive k_T jet cross section, the first such measurement at the hadron collider. The measurement includes a study of hadronization effects, usually neglected for cone jets. The agreement with NLO theory is not as good as previously obtained with the cone algorithm — a behavior that can be partially traced to energy differences between jets reconstructed with these algorithms. The probability of agreement with NLO (JETRAD) is fair (44%), but the possibility of some discrepancy reinvigorated investigations of issues, such as hadronization, influence of the underlying event, and properties of the algorithms. With the k_T algorithm, DØ studied the jet substructure, similarly to the discussion above by Hillert. The quark and gluon subjet multiplicities have been disentangled by comparing the measurements at $\sqrt{s} = 630$ GeV and 1800 GeV and by assuming that the respective fractions of quark and gluon initiated jets are known from the MCs. The result for the ratio between quark and gluon subjet multiplicities has been found to be in good agreement with HERWIG. A very recent analysis, based on the k_T algorithm, investigated the event-shape thrust variable T , defined here using only the transverse momenta of the two leading jets; despite of this simplification, T remains sensitive to extra jets (radiation) in the event through the imbalance of the leading jets in the azimuthal plane. The measurement disagrees with the NLO JETRAD description at the very low values of $1 - T$, where resummation effects are expected to be important, and at high values of $1 - T$, where the lowest order is $\mathcal{O}(\alpha_s^4)$. Thus, this measurement provides an excellent opportunity for testing future resummed and higher order calculations. Using the cone algorithm, DØ investigated the production of multi-jet events at low $E_T \approx 20$ GeV (for inclusive $\geq 1, 2, 3$ and 4 jets), compared to expectations from PYTHIA and HERWIG. Both MCs can be tuned to reproduce the data in E_T and in various angular distributions, but fail to do so with the default parameters. The sensitive parameter in PYTHIA is the

fraction of core region of hadronic matter distribution (PARP(83)), which controls the rate of multiple parton interactions; in HERWIG the sensitive parameter is the minimum p_T of the hard process.

Christina Mesropian [14] discussed recent analyses from CDF focused on jet fragmentation properties, jet evolution from minimum bias events to higher E_T , and studies of properties of the underlying event (UE) in jet and minimum bias events. These analyses were performed using variations of the cone algorithm, and utilized both calorimeter and tracking information. Fragmentation into charged particles of well-balanced high-mass central dijet events was studied within the MLLA formalism combined with the LPHD hadronization prescription. The inclusive momentum distribution of charged particles in the jet was found to agree well with theoretical predictions, allowing extraction of the effective momentum cutoff Q_{eff} at which partons undergo hadronization; a value of order Λ_{QCD} was obtained. The ratio of hadron multiplicities in quark and gluon jets was also extracted. For studies of the development and evolution of jets from low (0.5 GeV/c) to high (50 GeV/c) transverse momenta charged jets were defined using only charged particles of $p_T > 0.5$ GeV/c in a cone clustering algorithm. Evidence of charged jets has been observed in minimum bias data already around 1–2 GeV/c, and their properties join smoothly these for jets observed in regular jet-triggered data (> 20 GeV/c). This charged jet technique was also employed for investigating properties of the UE and of minimum bias events. The analysis required a reconstructed charged jet, and the phase space was divided into angular regions “toward”, “away” and “transverse” to the jet, the latter being of primary interest here. While the two former regions were fairly well described by PYTHIA and HERWIG, none of the MCs examined described correctly all the properties of the UE (*i.e.* the “transverse” region). The influence of the UE on jet energies was also studied in the high- E_T calorimeter-jet data by defining two cones at the same η , but at $\pm 90^\circ$ in azimuth from the leading jet. The lower energy (*min*) cone was used to estimate the contribution from UE, while the higher (*max*) cone also receives contributions from perturbative radiation (thus measured by the *max-min* difference). The study concluded that the UE in hard scattering events is more active than in soft collisions. In general, these results will be useful for tuning the MC generators.

3. Heavy Flavor Production and decay

With the observation of large discrepancies between data and theory Heavy Flavor Production is currently one of the most interesting topics of High Energy Physics. At this workshop new results concerning charm, beauty and charmonium production at HERA and LEP were reported. From

the experimental point of view, the improvement in background reduction for the measurement of charm mesons, as obtained by the application of a decay length cut using the H1 Central Silicon Detector, is particularly impressive, see the talk [15] by **Jeannine Wagner**. On the theoretical side, applications of the saturation model and the k_T factorization model to heavy flavor production, as presented during this workshop, are particularly noteworthy.

3.1. Charm production

In general, the agreement between theory and measurement of open charm production is satisfactory. NLO calculations of charm production in deep inelastic scattering are able to reproduce the measured rates of D^* production [16]. In photoproduction the predictions [17] to fixed-order plus next-to-leading logarithms agree with measurements of H1 at two different γp center of mass energies, but lie a factor 1.5 to 2 below measurements of the ZEUS collaboration. As of now, there are no published measurements of open charm production cross sections available from the Tevatron collider. Given the large differences between measurement and calculation for beauty and charmonium production at the Tevatron, measurements of charm production cross sections in $p\bar{p}$ are eagerly awaited.

With the large sample of charm mesons collected at HERA it is possible to extract charm fragmentation factors and parameters with a precision comparable to e^+e^- experiments. **Jeannine Wagner** presented [15] new measurements by H1 of the fragmentation factors $f(c \rightarrow D)$ for D^+ , D^0 , D_s and D^* mesons. The results are in excellent agreement with the values obtained elsewhere and can be used to extract various charm fragmentation parameters, such as P_v (the fraction of vector mesons), $R_{u/d}$ (the ratio of u and d quarks) and γ_s (the strangeness suppression factor). For instance, assuming isospin invariance the fraction of vector mesons is determined to be $P_v = 0.613 \pm 0.061(\text{stat}) \pm 0.033(\text{syst}) \pm 0.008(\text{theo})$. **Sanjay Padhi** reported on a similar determination based on ZEUS data, quoting $P_v = 0.546 \pm 0.045(\text{stat}) \pm 0.028(\text{syst})$ [18]. Both results are in excellent agreement with the world average of $P_v = 0.601 \pm 0.032$.

Various processes contribute to the photoproduction of charm quarks: in direct photoproduction the dominant process is $\gamma - g$ fusion with a quark exchange, in resolved photoproduction charm excitation with a gluon exchange is expected to dominate. Due to the different spins of quarks and gluons, the angular distribution of the two processes differ, leading to an excess of events in the γ -direction for resolved events. A study [18] of the angular distribution of dijet events with an identified D^* meson based on ZEUS data was presented by **Sanjay Padhi**. The angular distributions for the direct and

resolved photon enriched samples are observed to be significantly different. A significant excess of events is observed in the γ direction for the sample enriched in resolved photoproduction events. This may be interpreted as the first convincing evidence for charm excitation in the photon.

Stephen Robins presented new measurements of D^* production cross sections in deep inelastic scattering by the ZEUS collaboration. The results [19] are based on the large data sets collected in the 1998-2000 running periods, corresponding to 82 pb^{-1} . Overall the data exhibit the features expected from NLO pQCD predictions based on recent parton density functions, such as CTEQ5F3. However, the data for electron- and positron-proton scattering show a statistically somewhat significant difference: the ratio of e^- and e^+ events increases with momentum transferred, from about 1.25 at $Q^2 = 30 \text{ GeV}^2$ to 2.25 at $Q^2 = 450 \text{ GeV}^2$. Detailed systematic checks have been performed to exclude differences in the acceptance of e^-p and e^+p collision events. No plausible physics reason for the observed difference has yet been proposed.

A wealth of results on charm production in $\gamma\gamma$ interaction is emerging from the LEP II data. **Armin Böhrer** reported on D^* rates *versus* pseudorapidity, η , transverse momentum of the D^* , $p_T^{D^*}$, momentum fraction of the photon partaking in the hard interaction, x_γ , visible $\gamma\gamma$ center-of-mass energy, W_{vis} and e^+e^- center-of-mass energy, $\sqrt{s}$ [20]. The agreement with NLO pQCD predictions is very good, apart from the differential cross section *versus* x_γ , as measured by OPAL, which shows an excess at a low value of $x_\gamma = 0.03$. The excess might be explained by additional hadron like contributions not included in standard parton density functions of the photon.

Motivated by the success of the Saturation Model in describing the proton structure function in the transition region between photoproduction and deep inelastic scattering and inclusive diffractive scattering in deep inelastic scattering, **Antoni Szczurek** extended the formalism to include heavy quark production in γ -nucleon and $\gamma\gamma$ scattering [21]. The saturation model describes the scattering of photons with the nucleon as convolution of a perturbatively calculable transverse photon wave function with a dipole-nucleon cross section parametrized in fits to proton structure function data. In its extension to describe heavy flavor production, particular care was devoted to the effects of the kinematical threshold and the phase-space limitations in the region of large x_γ . The calculations are able to describe measurements at low $W_{\gamma p}$, but lay significantly below the measurements from HERA with $W_{\gamma p} > 100 \text{ GeV}$. The situation for charm production in $\gamma\gamma$ collisions is somewhat better. The calculations are able to reproduce the shape of the rising cross section with $W_{\gamma\gamma}$, however the absolute normalization appears to be about 30% below the data.

Traditionally, inclusive DIS is analyzed within the framework of the DGLAP evolution scheme [22–25]. In a different formalism, the k_T factorization scheme, terms proportional to $\alpha_s \log(\mu/\Lambda)^2 \log(1/x))^n$ are resummed to all orders and give rise to a so-called unintegrated gluon momentum distribution, $A(x, k_T^2, \mu^2)$. The latter is dependent on x , the momentum fraction of the gluon in the proton, the probing scale μ and the transverse momentum k_T of the gluon. **Nikolaj Zotov** presented a calculation [26] of charm production cross sections based on three different choices of unintegrated gluon momentum distributions: (a) by J. Blümlein [27], based on the leading order solution of the BFKL [28, 29] equation; (b) by J. Jung and G. Salam [30], based on a numerical solution to the CCFM [31] equation; and (c) by M. Kimber *et al.* [32], based on a combination of the BFKL and DGLAP equations.

Despite large differences among the three choices of unintegrated gluon distributions, the corresponding predictions for the charm production cross sections in both photoproduction and DIS are remarkably similar and agree well with measurements by the HERA collider experiments.

3.2. Beauty production

Production of beauty quarks is an area where the predictions of pQCD are expected to be accurate and reliable. Beauty production cross sections have been measured in $\gamma\gamma$, γp , $\gamma^* p$, and $p\bar{p}$ collisions. Strikingly, in all these environments the experimental results lie factors of 3–5 [33, 34] above next-to-leading order pQCD predictions.

In order to understand the reasons for the failure of the calculations, the experiments are devoting large efforts to cross check their measurements, using *e.g.* other detection methods, and/or to extend the kinematical range of their measurements. In this context **Monica Turcato** presented a recent analysis [35] of photoproduction events by the ZEUS collaboration. The events containing b -quarks are identified through the measurement of the relative momentum of the decay μ with respect to the axis of its associated jet. The analysis makes use of the forward muon chambers, thus extending the angular coverage to pseudorapidities of 2.3. The results compare well to leading-order MC, such as PYTHIA. Measurements of the differential cross sections and comparison to NLO pQCD calculations are forthcoming.

Another way to obtain a handle on the b -quark production cross section was presented by **Jeannine Wagner**. The analysis [15] investigates the angular correlation of D^* mesons and μ 's in events containing both particles. The event sample is subdivided in four subsamples with either same/opposite charge and same/opposite side D^* 's and μ 's. The sample of same side and same charge particles is almost entirely originating from

B meson decays, with only a small contamination of charm quarks and ‘fake’ μ ’s. The extracted visible b -quark production cross section $\sigma_{\text{vis}}(ep \rightarrow e'D^*\mu X) = (380 \pm 120 \pm 130)$ pb is significantly above the predictions of 106 pb by the AROMA leading-order MC.

The situation is very similar in the $\gamma\gamma$ environment [20]. **Arnim Böhrer** presented recent measurement by L3 and OPAL of the inclusive beauty cross section. The measurements are based on an analysis of the relative momentum of either an electron or muon with respect to the axis of an associated jet. The measurements cluster around 13 pb and are about a factor three above the NLO pQCD prediction, a difference which corresponds to four standard deviations.

Given the many significant discrepancies between experiment and theory in beauty production, one would expect a large theoretical effort aiming at resolving these differences. Disappointingly, the workshop received only one contribution in which **Antoni Szczurek** applied [21] the saturation model (see above) to beauty photoproduction. Similarly to the collinear approach, his results are about a factor 2–3 below the recent HERA measurements at $W_{\gamma p} \sim 190$ GeV. To help resolve this discrepancy, measurements at different $W_{\gamma p}$ would be particularly useful.

3.3. Charmonium production

Jungil Lee presented a comprehensive overview of the status of theoretical calculations of J/ψ - meson production. He reviewed [36] the physics of the non-relativistic QCD factorization approach and the contributions of color-singlet (CS) and color-octet (CO) processes. Due to their different dependences on the transverse momentum p_T of the J/ψ meson the sum of these processes is able to describe the differential cross section *versus* p_T , as measured by CDF at the Tevatron. The strength of the CO contribution is described by universal matrix elements which can not (yet) be calculated theoretically, but have to be determined by experiment.

Katja Krüger presented new results [37] from the H1 collaboration concerning inelastic J/ψ photo- and electroproduction. The measurements span a large region of z , the inelasticity of the J/ψ mesons, defined as the ratio of the energies of the J/ψ meson and the photon in the proton rest frame. The results in photoproduction are well described by NLO pQCD calculation and the CS model. The importance of NLO corrections is particularly evident in the description of the $p_{T,\psi}^2$, where a leading order calculation fails to describe the shape of the cross section. Unfortunately, the NLO calculations suffer from a large uncertainty due to the wide range of allowable masses of the charm quark. When compared to leading order calculations, the differential cross sections are compatible with small values of the CO

matrix element, but do not appear to be in contradiction with the values determined from the Tevatron data. Clearly, a rigorous calculation to NLO including both CS and CO contributions is needed for both the HERA and Tevatron environment before firm conclusions about the universality of the matrix element can be drawn.

The measurement of the helicity distribution of J/ψ mesons *versus* z in photoproduction shows a different trend than LO calculations including CS or CS+CO contributions. The data tend to go from a full transverse polarization at low z to no polarization at high z , whereas the calculations seem to do the inverse. However, one has to keep in mind that the calculations are to leading order and do not resum soft gluon emissions. This may be an important shortcoming of the calculations, since each emitted gluon carries away one unit of spin.

Arnim Böhrer reported on recent calculations [38] of the differential cross section *versus* p_T^2 for inelastic J/ψ production in the $\gamma\gamma$ environment [20]. The calculations use the matrix elements determined by Tevatron data to estimate the CO contribution and is in good agreement with the data. However, the data are not precise enough to unambiguously establish the presence of CO contributions. Furthermore, the calculations are to LO only and large NLO corrections may affect the present results.

4. Dimuon photoproduction

H1 measured [39] di-muon photoproduction in search of deviations from Standard Model expectations. **Boris Leissner** presented the measured differential cross section *versus* the mass of the dimuon system. No obvious deviation from expectations, calculated with the GRAPE MC, are observed. The visible cross section, both inclusive and for the inelastic subsample, are in excellent agreement with the predictions.

5. Instanton searches at HERA

Instanton induced events are expected [40–42] to leave a distinct signature: high multiplicity of tracks in the forward region, flavor symmetry, large muon content etc. **Birger Koblitz** applied a multi-variant discrimination method to obtain limits on instanton induced processes. The analysis is performed in a corner of phase space where backgrounds from non-instanton induced events are minimized. Based on H1 data, exclusion limits of 55 to 80 pb are obtained if backgrounds from non-instanton induced processes, as predicted by standard LO MCs, are subtracted. Under the assumption that all selected events are instanton induced, the limit is degraded to 255 pb.

6. Small- x final states

As measurements from HERA of small- x final states have accumulated, it has become very clear that we do not understand the details of partonic evolution in this region of phase space. Even though NLO DGLAP [22–25] evolution is able to reproduce the increase of F_2 with decreasing x , it is clear from final-state data that parton evolution is more complicated. The alternative, BFKL [28,29] evolution, has turned out to suffer from huge NLO corrections [43] and there does not seem to be any completely satisfactory model available for small- x final states today (see *e.g.* [44] for a recent review).

One problem with the BFKL formalism is that it does not conserve energy and momentum. Although this may formally not be a problem at asymptotically large energies, in the real world it may make a very large difference. This was clearly demonstrated in the presentation by **Jeppe Andersen** [45]. By implementing BFKL evolution in an event generator where energy and momentum is conserved exactly in each vertex, he showed that the predicted BFKL enhancement of di-jet cross sections with the rapidity difference between the jets, actually transforms into a suppression. The reason is that if you take into account the energy needed to emit the gluons responsible for the increase of the partonic cross section, you will find that the parton densities are probed at correspondingly higher x -values. And since the gluon density decreases steeply with x , the total effect is a suppression. Andersen also suggested measurements which involved incoming quarks, the densities of which do not decrease as much with x .

When going to next-to-leading order in the evolution [43], some energy-momentum conservation effects are taken into account. But to get reliable predictions it is necessary to also calculate the so-called impact factors (or off-shell matrix elements) to next-to-leading order. This has previously been done for the γ^* impact factors [46], but to describe di-jets at large rapidity differences one needs to calculate the jet impact factors to NLO. **Gian Paolo Vacca** presented a first calculation for this [47]. For the γ^* impact factors one must treat carefully the cancellation between real and virtual diagrams in the ladder and the corresponding ones from the scattered $q\bar{q}$ system. For the jet impact factors there is the additional complication of also considering real and virtual diagrams in the parton densities. At the time of the presentation, the calculations were not quite ready and no predictions were presented, but since then the calculation has been completed [48].

Further theoretical progress in understanding small- x evolution was presented in the *Structure Functions* parallel sessions [49]. Also some new measurements were presented. Relevant for this summary was the report from **Lidia Goerlich** on forward pion production at HERA [50]. The ad-

vantage of looking at π^0 production rather than at jets, is that it is possible to go further forward and hence be more sensitive to small- x dynamics. The downside is, of course, that one needs to understand the fragmentation of partons into pions. The presented measurement is an update of a previous measurement [51] with increased statistics and a more detailed study of the event structure. The result is that, similar to forward jet measurements, it is impossible to describe the rate and distribution of forward π^0 with standard DGLAP based Event Generators, while adding a resolved virtual photon component does quite well. To some surprise, the CASCADE program [52], which is able to describe forward jets, is not able to describe forward pions. The problem may be that the program does not include quarks in the evolution. The investigation into the distribution of particle flow in events with a forward pion was also presented, but no additional discrimination power between models was obtained.

7. Hadronization

One problem with small- x evolution is that it balances on the border between perturbative and non-perturbative QCD, and our understanding of the latter is very poor. For the hadronization process we have a couple of models, string [53] and cluster [54] fragmentation, which are able to describe most features of the hadronic final-states in e^+e^- , but it is not entirely clear if these models can be used without modification in collisions involving incoming hadrons.

Dimitry Ozerov presented an investigation of the fragmentation parameters in the PYTHIA program [55] and found that he needed a smaller value of the parameter controlling the di-quark production in the string braking to reproduce the production of (anti-)protons in photoproduction events at HERA as compared to the value fitted to LEP data [56]. It was noted, however, that he had only been looking at minimum bias events, which are known to be notoriously difficult to model. Ozerov also noted an interesting scaling property when looking at the $m_\perp = m + p_\perp$ distribution scaled with the number of spin states, which seemed to be independent of particle species.

Looking at high- E_T jets and DIS events, where there is a hard scale present, the fragmentation of jets are assumed to be more similar to the e^+e^- case. Indeed, contrary to the minimum bias case above, there does not seem to be any need for a very different di-quark suppression in string fragmentation. At least not when comparing the production of kaons and lambdas in photo-production as presented by **Stewart Boogert** [57]. On the other hand, he finds a need for stronger strangeness suppression in the string fragmentation (again compared to LEP data) when looking at $\phi(1020)$

production in DIS, although there were some questions raised about the normalization uncertainties. Since the $\phi(1020)$ is a pure $s\bar{s}$ state, Boogert also showed that he can use such particles with very large fraction of the virtual photon momentum to directly probe the strange sea distribution.

Erika Garutti presented an interesting investigation of the formation time of hadrons [58]. Looking at pions, kaons and protons produced in DIS on heavy nuclei at HERMES, and comparing the attenuation in different nuclei as a function of their speed, she showed that protons seem to have a longer formation time than pions and kaons. Although there may still be some model dependency in the conclusions, these findings will be important for *e.g.* finding evidence for quark-gluon plasma.

Another result from HERMES was presented by **Volodymyr Uleshchenko** [59]. Looking at particles carrying a large fraction of the virtual photon momentum, one would expect that the ratio of charged to uncharged pions would be constant, if one only considered the naïve parton model. This is, however, not what has been found at HERMES. Uleshchenko showed that the discrepancy can be explained by adding a diffractively produced ρ^0 decaying into $\pi^+\pi^-$. He also noted that this may influence previously published results on the flavour asymmetry of the light sea quarks [60].

Another way of getting insight into the particle production mechanism is to look at particle correlations. It is well known that the production of identical bosons should be enhanced if the particles are close in phase space. This so-called Bose–Einstein correlation depends on the size of the production region and can thus tell us about how particles are produced. **Edward Sarkisyan-Grinbaum** reviewed some results on multi-particle correlations from LEP [61]. He showed that the size of the production region, as obtained from Bose–Einstein correlations, seems to depend on the mass of the produced hadron, which casts some doubt on whether we really understand what is measured. He also showed results on genuine 3- and 4-particle correlations which are consistent with an incoherent source of particles. An interesting fact is that in fully hadronic W^+W^- events, where we expect the hadronization region from the two W 's to overlap, there seems to be no *cross-talk* whatsoever between the W 's. Note that even if particles are produced completely independent from the W 's we still expect Bose–Einstein correlations, but none has been found.

Malcolm Derrick reported on Bose–Einstein correlations at HERA [62]. Here one could imagine a decreasing size of the production region with increasing Q^2 , but no such dependence was found. In photo-production there does, however, seem to be a larger size of the production region.

8. Resummation and parton showers

By looking at infrared safe event shapes it is possible to avoid event generator based hadronization models altogether and still be able to obtain reliable QCD predictions. This is done by careful resummation of perturbative diagrams, together with a simple perturbatively inspired model to take *power corrections* from hadronization effects into account. **Gavin Salam** gave a brief overview of the results for wide range of event shapes measured at LEP, where it is possible to obtain a consistent fit to the two parameters, α_s and α_0 [63]. The main part of his presentation was aimed towards DIS, where one naïvely would expect the current hemisphere of the Breit frame to look like half an e^+e^- event. There are, however large spill-over effects from the target hemisphere, the phase space of which becomes very large at small x , and Salam presented a way to overcome these problems. He also presented a new program called DISPATCH with a common interface to the DISENT [64] and DISASTER [65] NLO programs.

Giulia Zanderighi also presented results on event shapes in DIS, but while most such investigations so far have dealt with two-jet shapes, she has been looking at the three-jet related K_{out} shape [66]. This measures the momenta out of the plane defined by the $\gamma^* - p$ and thrust-major axis. The calculation involves resummation of large single and double logarithms of K_{out}/Q which depend on the geometry of two outgoing jets, the colour structure, the parton densities and the experimental acceptance in the forward region. She also presented an effort to produce a MC program to semi-automatically calculate resummed power-corrected event shape predictions for any hard interaction in e^+e^- , DIS and hadronic collisions.

Another three-jet related event shape in DIS was discussed by **Andrea Banfi** [67]. He presented a calculation of the azimuthal correlations in DIS, which is similar to the energy-energy correlations in e^+e^- , but uses transverse momenta in the Breit frame rather than energies. One peculiarity of this event shape is that it does not go to zero with the azimuthal angle, which results in a non-integer power correction. This event shape has not yet been measured at HERA, but now that a prediction exists, such a measurement is surely called for.

There were two presentation about new algorithms for combining fixed order matrix elements with parton showers. Fixed order matrix can be used to describe the production of a handful well separated partons, but cannot be used to describe the soft and collinear inter- and intra-jet partons. For the parton shower models, the situation is reversed, which is why algorithms combining the two are very useful. Such algorithms are, however, not trivially constructed.

The first of these presentations, by **Frank Krauss** [68], described an algorithm based on the angular ordered parton shower in HERWIG [69]. Using a 2-, 3-, ..., n -jet matrix element generator for e^+e^- , the events obtained are reweighted with the relevant Sudakov form factors from the parton shower. To do this he needs to use the $k_\perp$ -algorithm [70] to reconstruct the emission scales. After this, a special *vetoed* version of the parton shower is added before hadronization can be performed. In this way the dependence on the regularization scale in the matrix element is canceled to next-to-leading logarithmic accuracy [71]. Krauss also presented a strategy for extending this algorithm to hadronic collisions [72].

Leif Lönnblad presented a similar algorithm [73,74] also based on the ideas in [71]. The main difference was that the Colour Dipole Model as implemented in ARIADNE [75] was used for the partonic cascade rather than the HERWIG parton shower. Also a modified version of the DCLUS algorithm [76] was used to reconstruct, not only emission scales, but complete dipole cascade histories of the matrix element generated states. The Sudakov form factors are then generated from within the dipole cascade with a special veto algorithm.

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