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Hadronic Final States

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Abstract

A summary is given of the work which was presented in the working group C "Hadronic Final States" at the DIS04 workshop (Strbské Pleso, Slovakia , April 14-18, 2004). Progress in experimental tests and the theoretical development of perturbative and non-perturbative QCD is reported.

1 Introduction

One of the still open challenges in modern physics is to understand more completely the strong interaction. This is particularly important in light of the fact that many of the most important future discoveries in particle physics are expected to be made at the LHC, a machine that will collide strongly interacting particles at extremely high energies.

Hadronic final states produced in high-energy particle collisions have traditionally been used as a testing ground for the theory of the strong interactions, quantum chromodynamics (QCD). Within our working group, results on hadronic final states from ep, $p\bar{p}$, NN and e^+e^- induced final states were reported by 27 experimentalists and 11 theorists. The working group contained a vibrant atmosphere and was the forum for much useful discussion.

The breadth of topics included precision tests of perturbative QCD with jet and leading particles. Perturbative QCD is in good shape in the regions in which it is applicable. However, results from H1 and ZEUS on forward jets and azimuthal decorrelations between jets suggest that the DGLAP evolution approach may be failing and that calculations including small Bjorken x physics (BFKL/CCFM resummations) may be required. New measurements and theoretical predictions for event shapes, including new resummed calculations, have given improved consistency in the extraction of α_s and the non-perturbative parameter $\bar{\alpha}_0$. Amongst the main highlights of our working group were studies of exotic pentaquark states. In this working group, several experiments have reported their results on the search for pentaquark states with strangeness.

2 Jets and high P_T phenomena

2.1 Progress in experimental tests of perturbative QCD

The production of jets and leading particles provides a clean signature for probing perturbative QCD processes. At this workshop a number of measurements were presented from ep, $p\bar{p}$ and e^+e colliders.

Multi-jet production in DIS provides an important testing ground for QCD. At HERA, data are collected over a large range of the negative four-momentum transfer squared, Q^2, the Bjorken-x variable and the transverse energy E_T of the observed jets. HERA dijet data can be used to gain insight into the dynamics of the parton cascade in low x interactions.

ZEUS presented results on dijet and 3-jet production in DIS [1]. The data are described well by NLO calculations. The ratio of 3 and 2-jet production cross-sections is shown in Fig. 1. In principle, experimental and theoretical uncertainties should be minimised by taking this ratio. However, the theoretical uncertainty owing to the choice of parton distribution function (pdf) is clearly large and this requires further investigation.

Insight into low x dynamics can be gained from inclusive dijet data by studying the behaviour of events with a small azimuthal separation between the two hardest jets as measured in the hadronic centre-of-mass system. Fig. 2 shows measurements

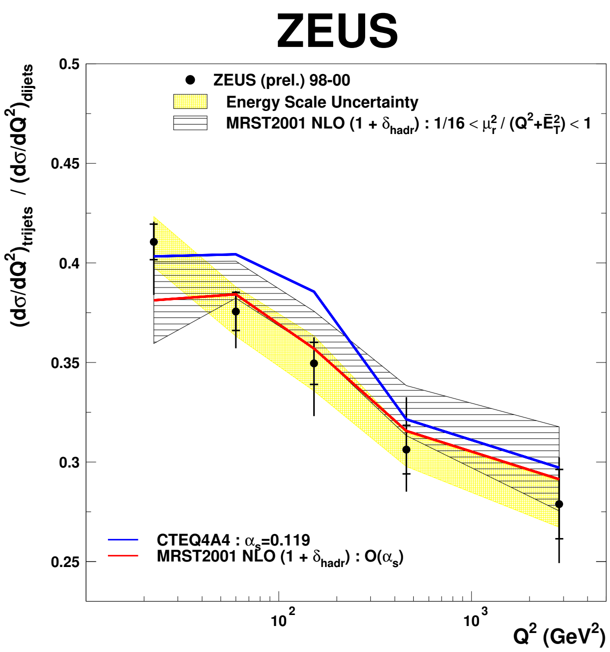

Figure 1: The 3/2 jet ratio in DIS as measured by ZEUS [1].

by H1 [2] of the S distribution, i.e. the fraction of fraction of dijet events with an azimuthal separation of less than 120° as a function of x for different Q^2 regions. NLO calculations for 3 and 2-jet processes are shown. Although the 3-jet calculation comes closest, neither calculation is able to reproduce the data at the lowest Q^2 and x values. In this region, higher order, small x, QCD evolution effects are expected to become important and the validity of the DGLAP approach is in doubt..

A further way to experimentally probe QCD evolution is to study events containing high momentum jets [3] and particles [4] in the forward region i.e. next to the proton direction. Fig. 3 shows the cross-section for forward π°-mesons produced at high transverse momentum as function of x. The data rise towards low x and a QCD prediction based on DGLAP evolution for proton structure (labelled DIR) fails to describe the data. Approaches based on a resolved virtual photon picture (labelled DIR+RES) and on CCFM evolution describe the data better. Analytical calculations based on the BFKL evolution equation also give a reasonable description of the data.

The structure of the photon at low Q^2 has been investigated by both the ZEUS [5] and H1 [6] experiments. Fig. 4 shows the dijet cross-section as a function of Q^2 for different regions of x_γ, the variable used to determine the fraction of the photon's momentum taking part in the hard sub-process. The data are described by the NLO calculations for $x_\gamma > 0.75$ although for $x_\gamma < 0.75$ the NLO prediction significantly underestimates the cross-section. This could be due to effects arising from the structure of the photon in this region.

Results from the CDF [7] and D0 [8, 9] showed encouraging progress in analysing

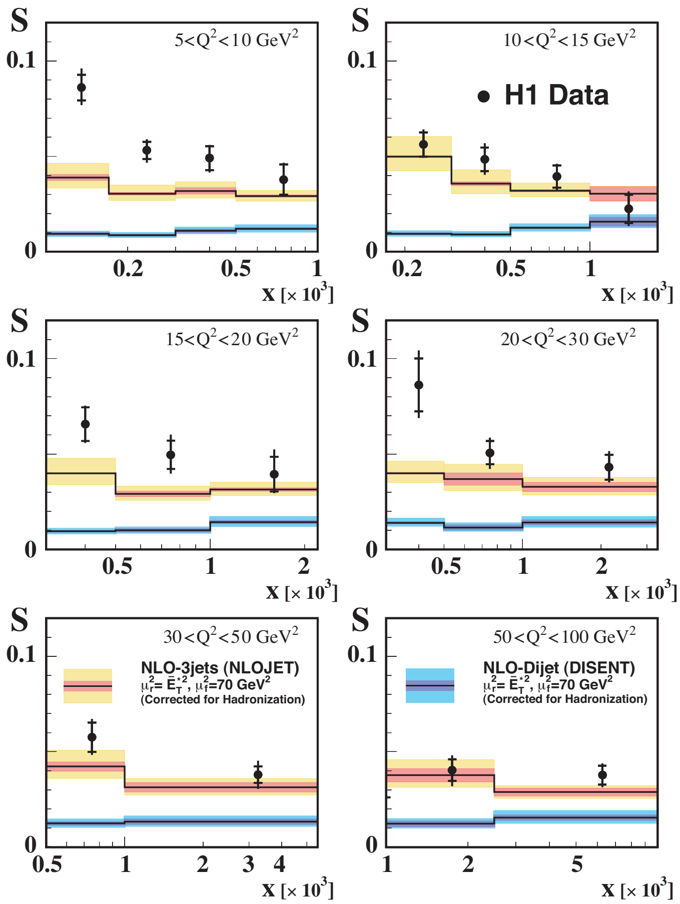

Figure 2: The S distribution for dijet events, as measured by H1 [2].

Run II data. The increased centre of mass energy to 1.96 GeV makes available a larger cross-section at the high values of jet transverse momentum. However, precision is severely limited due to calorimeter energy scale uncertainties for both experiments. The NLO predictions describe the data well although sensitivity is inhibited by the large energy scale uncertainty. In order to reduce the systematic effects from this source, D0 also presented results on the angular separation between the dijets, a variable which is highly sensitive to the higher order emissions. This is shown in Fig. 5. NLO calculations provide an excellent description except for the extremely large (small) regions of $\Delta\Phi^*$, where the available phase space for multi-jet emissions is limited.

In collisions between objects with extended structure, the final state of hard parton-parton scattering is characterised by high transverse momentum jets but also contains a number of soft particles which are collectively referred to as the "underlying event". This has been studied by CDF [10] in which back-to-back dijet events are analysed in order to isolate the $\eta - \phi$ regions which are sensitive to the underlying event and to analyse its properties. Fig. 6 shows the charged particle density in the "MIN", "MAX" and average transverse region of leading jet events. On an event-by-event basis the

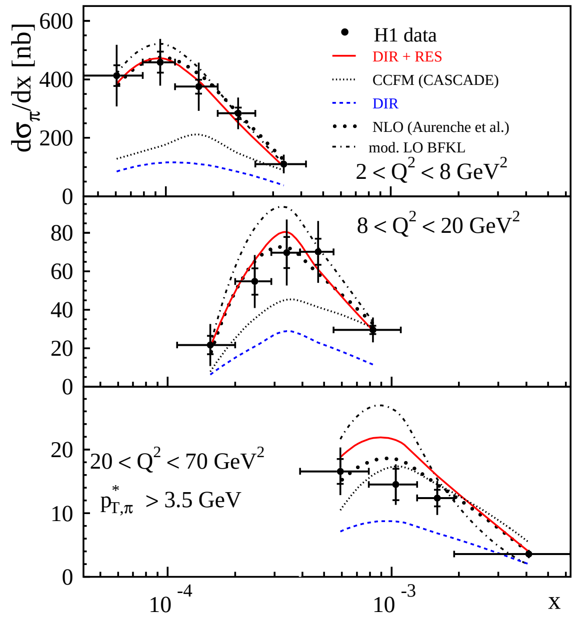

Figure 3: The forward jet cross-section, as measured by H1 [4].

"MAX" and "MIN" regions are defined to be the regions containing the largest and smallest, respectively, number of charged particles. The density increases with the leading jet's transverse momentum in the "MAX" region and decrease in the "MIN" region. The complete results of this study suggest that there is a jet structure in the underlying event even when initial and final state radiation is strongly suppressed. The techniques and results of this work will be of enormous benefit at the LHC.

2.2 Theoretical developments

Dijet data from H1 and ZEUS has been a significant source of information on quantities such as the pdfs. In such studies it has been commonly accepted that there is a need to impose asymmetric cuts on the transverse energy of the two highest E_t jets to avoid problems of infrared enhancements. This involves cutting out a significant fraction of events since in fact the measured dijet total rate is largest when one allows symmetric cuts to be placed. Moreover, there is accurate data in the region of symmetric cuts and it is only the NLO QCD theoretical calculation that breaks down in this region. An improved theoretical estimate can be obtained by resumming large logarithms in the E_t difference, Δ,[1] between the two highest E_t jets [11].This allows one to use the theoretical calculation in the entire range where there is data. Moreover it allows one to test the ideas behind multijet resummations (in a problem less contaminated by power corrections than several event shapes) by comparing the next-to–leading

[1] More precisely it is the difference in E_t cut values.

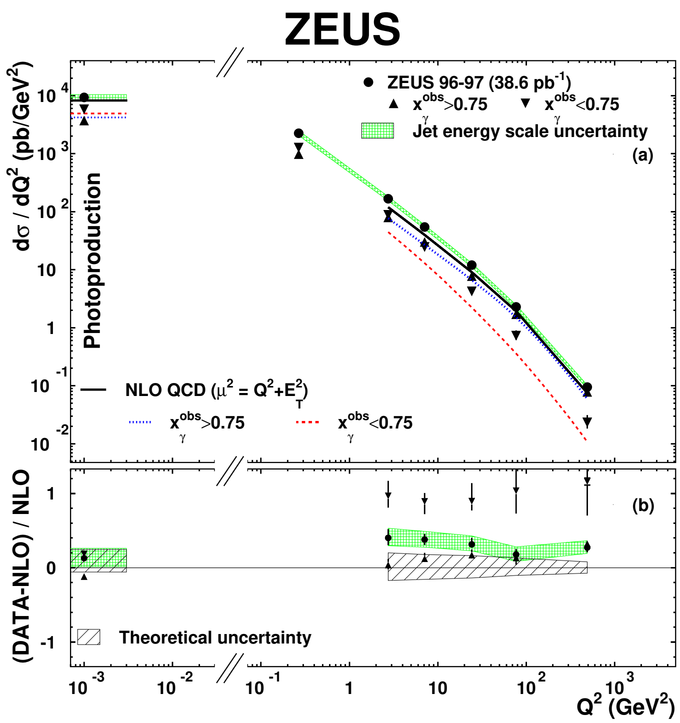

Figure 4: The differential dijet cross-section, as measured by ZEUS.

log (NLL) resummed theory to the experimental data. In the absence, thus far, of any detailed comparison of theory and data for resummations with more than two hard jets one would imagine that the calculation presented in [11] provides a good opportunity for the same. Such multijet configurations will be especially important in the context of hadron colliders such as the LHC. As far as results are concerned it was shown that after resummation the slope of the total rate $\sigma'(\Delta)$ was a linear function of Δ rather than a (double) logarithmically divergent one as indicated by NLO fixed-order computations. As a consequence the total rate itself rises monotonically with decreasing Δ instead of turning over as indicated by NLO alone. Future extensions involve extending the present cone algorithm results to the inclusive k_t algorithm and carrying out the matching to fixed-order estimates.

Jet and dijet production in photon-photon collisions is also a valuable source of information on the hadronic structure of the photon. While NLO calculations previously existed in the framework of the phase-space slicing method [12], results were presented here [13] for NLO computations employing the dipole subtraction method which is preferable, especially in the case of computing certain differential cross sections, from the point of view of numerical stability. The new method also allows a cross-check of the previous phase-space slicing results. At present the comparisons with OPAL data are very satisfactory for inclusive observables e.g E_t spectra in single inclusive jet production and the direct and single resolved dominated contributions to dijet production see Fig. 7. However one notes a discrepancy for the double resolved dominated region,

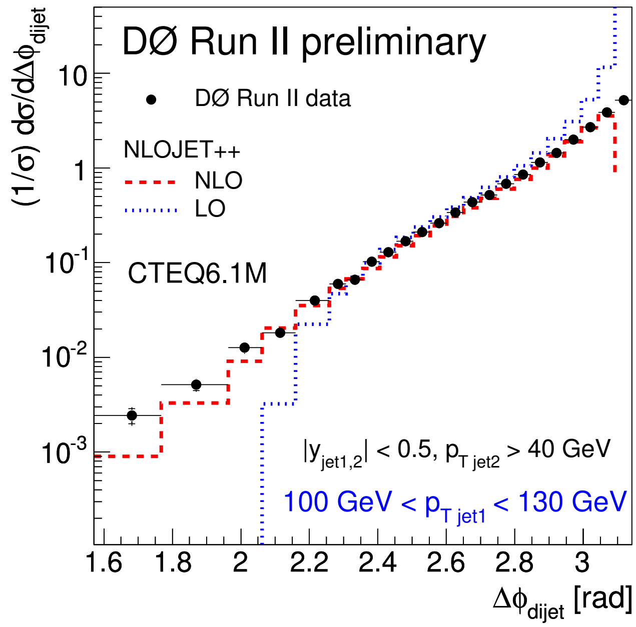

Figure 5: The azimuthal decorrelation between dijets, as measured by D0.

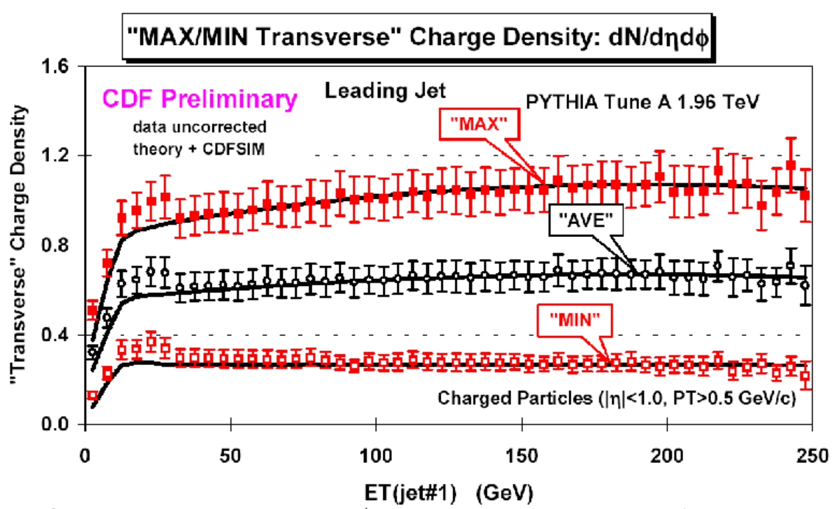

Figure 6: The charged particle density for different selected regions of phase in dijet events, as measured by CDF [10].

which is still outstanding.

Understanding the multiple collinear limit of QCD amplitudes is of great importance in several contexts. These include the development of subtraction terms for fixed higher order (NLO and beyond) computations, all order resummations, more accurate pdf

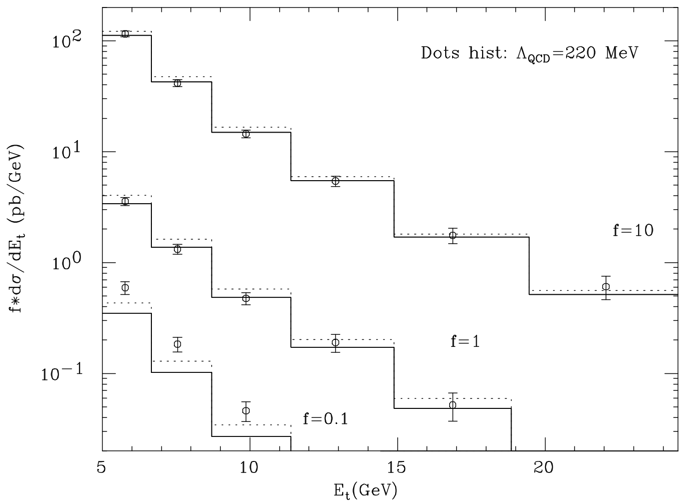

Figure 7: Comparison between theory [13] and OPAL data for dijet production in $\gamma\gamma$ collisions in three different x_γ regions.

evolution and improving the physics content of Monte Carlo event generators. For example the one loop correction to one to three collinear branchings is one of the ingredients in computing the full NNLO pdf evolution. Results were shown based on a new method that implements collinear factorisation directly in colour space thus retaining explicitly the colour matrix structure and resulting in the derivation of $1 \to m$ splitting amplitudes. The (divergent part of) one loop splitting matrix in the limit of m collinear partons reads (where $s_{1\ldots m}$ denotes $(p_1+p_2+\ldots p_m)^2$ and the p_i are collinear parton momenta:

$$
\begin{aligned}
\boldsymbol{Sp}^{(1)\,\mathrm{div.}}(p_1,\ldots,p_m) \;=\; & \frac{\Gamma(1+\epsilon)\,\Gamma^2(1-\epsilon)}{(4\pi)^{-\epsilon}\,\Gamma(1-2\epsilon)}\,\frac{1}{2}\left\{\frac{1}{\epsilon^2}\sum_{i,j=1(i\neq j)}^{m}\boldsymbol{T}_i\cdot\boldsymbol{T}_j\left(\frac{-s_{ij}-i0}{\mu^2}\right)^{-\epsilon}\right. \\
& + \left(\frac{-s_{1\ldots m}-i0}{\mu^2}\right)^{-\epsilon}\left[\frac{1}{\epsilon^2}\sum_{i,j=1}^{m}\boldsymbol{T}_i\cdot\boldsymbol{T}_j\,\left(2-(z_i)^{-\epsilon}-(z_j)^{-\epsilon}\right)\right. \\
& \left.\left. -\frac{1}{\epsilon}\left(\sum_{i=1}^{m}(\gamma_i-\epsilon\tilde{\gamma}_i^{\mathrm{R.S.}})-(\gamma_a-\epsilon\tilde{\gamma}_a^{\mathrm{R.S.}})-\frac{m-1}{2}\left(\beta_0-\epsilon\tilde{\beta}_0^{\mathrm{R.S.}}\right)\right)\right]\right\} \\
\times\;\; & \boldsymbol{Sp}^{(0)}(p_1,\ldots,p_m)\;, \qquad (1)
\end{aligned}
$$

which shows the infrared and ultraviolet ϵ pole structure. In the above the colour charge of the collinear parton with momentum p_i is denoted by $\boldsymbol{T}_i$, and from colour conservation one has $\sum_i \boldsymbol{T}_i\ \boldsymbol{Sp}^{(0)} = \boldsymbol{Sp}^{(0)}\ \boldsymbol{T}_a$ ($\boldsymbol{T}_a$ is the colour charge of the parent parton in the collinear splitting). The flavour coefficients γ_i and β_0 are $\gamma_q = \gamma_{\bar{q}} = 3C_F/2$ and $\gamma_g = \beta_0/2 = (11C_A - 2N_f)/6$. The flavour coefficients $\tilde{\gamma}_i^{\mathrm{R.S.}}$ and $\tilde{\beta}_0^{\mathrm{R.S.}}$ are renormalisation scheme dependent . $\boldsymbol{Sp}^{(0)}(p_1,\ldots,p_m)$ is the corresponding tree level quantity. From the above equation and the tree level result one can compute one loop splitting functions for the $1 \to m$ collinear branchings [14].

3 Event shape variables

A class of observables that are perhaps best suited for testing QCD are event shape variables (for a recent review see [15]). While the infrared and collinear safety of these observables allows one to make perturbative predictions, event shape distributions receive infrared and collinear enhancements, in the form of large logarithms, that require resummation. Resummation tools and predictions in turn follow from a sound understanding of QCD dynamics in the most important kinematic regions.

However, before one can confront resummed perturbative predictions with the accurate experimental data available for several event shapes, one usually has to account for power corrections. These are non-perturbative effects that, for most event shapes, scale as $1/Q$, Q being the hard scale involved in the reaction, and make a significant contribution to many event shape observables. Over the past decade this problematic aspect of event shapes has been turned into an advantage since theoretical ideas now exist that permit a description of power corrections based on renormalons (for a review see [18]). The sizable power corrections involved in event-shape studies make this a valuable testing ground for ideas on non-perturbative dynamics. Hence, event shapes allow one to test at once both perturbative and non-perturbative aspects of QCD.

Both the ZEUS [16] and H1 [17] experiments showed new results of event shape distributions in DIS, measured in the current region of the Breit frame. Fig. 8 shows the results of fits to event shape variable distributions, of resummed Next-to-leading logarithm (NLL) calculations matched to NLO calculations, with a power correction ansatz for the hadronisation step. The extracted values of $\bar{\alpha}_0$ and α_s are shown for a different range of event shape variables. Good consistency for the different variables is obtained except for the C variable. For this variable, there is much sensitivity to the choice of the fit range.

At this meeting there was a presentation on resumming Sudakov logarithms and power corrections for event shapes within the framework of dressed (i.e fake massive) gluon exponentiation (DGE) [19, 20]. The basic idea of DGE is to use a massive gluon as the kernel for exponentiation, with the gluon mass effectively accounting for resummation of renormalon bubbles diagrams on each gluon:

$$S(\nu, Q^2) = \int_0^\infty dv \left(e^{-\nu v} - 1\right) \left(\frac{1}{\sigma_{\rm tot}} \frac{d\sigma}{dv}\bigg|_{\rm SDG} \right) . \tag{2}$$

Here v is the event shape variable and ν is a Mellin variable conjugate to it while the suffix SDG denotes the single dressed gluon result. The above equation implies that the distribution for the emission of multiple independent dressed gluons can be obtained by 'exponentiating' the single dressed gluon result on the RHS of the above (in other words taking the inverse Mellin transform of $e^{S(\nu)}$). This result preserves all the information present in the resummed perturbative next-to-leading log (NLL) results that are known for several observables. It also resums [2] (due to the dressed gluon), certain sub-leading logarithms whose coefficients would grow as $n!$, for large n, at $n^{\rm th}$ perturbative order . Additionally on Borel transforming the running coupling

[2] In the leading power of β_0.

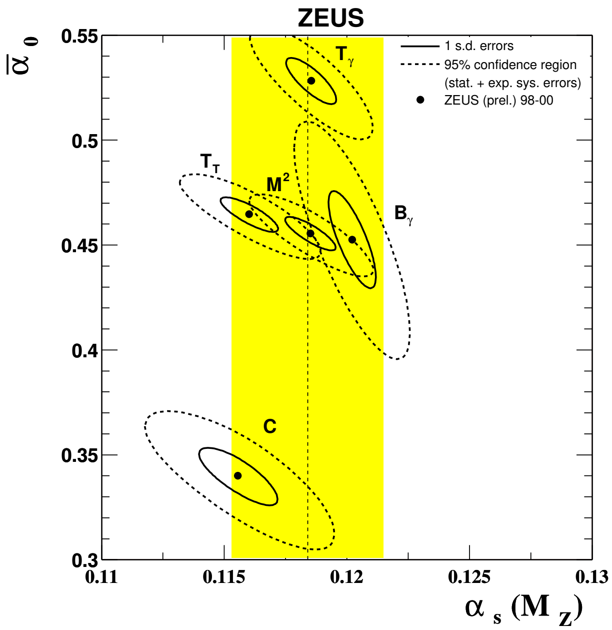

Figure 8: Fitted values of $\bar{\alpha}_0$ and α_s from event shape variable distributions, as measured by ZEUS.

$\alpha_s(k)$ in the expression for S, one generates singularities in the Borel plane, whose residues correspond to power corrections.

This is contrast to the Dokshitzer-Webber (DW) [21] approach in which one exponentiates the single massless gluon result and introduces a universal infrared finite extension of α_s to regulate the Landau singularity. In the DW approach the power correction then emerges as a shift of the perturbative distribution by an amount proportional to $1/Q$. While the shift has been known to be an excellent practical approximation for a wide range of values of v, it is well known that in the region of very small v, $v \sim \Lambda/Q$, the shift approximation breaks down due to increasing importance of higher-orders in the series of non perturbative terms Λ^n/v^nQ^n. The shift must then be replaced by a smearing of the perturbative spectrum with a shape function [22]. The dressed gluon exponentiation mimicks the shape function approach and, in fact, can be considered as a renormalon model for the full shape function. Phenomenological applications based on DGE can be found in [19]. For most recent results on the C parameter and a new class of event shapes (angularities) see [20].

It should be emphasised that the DGE, while attempting to maximise information obtained from renormalon resummed perturbation theory, is once again only a model. In particular it is well known that use of a massive gluon is not strictly appropriate, being too inclusive an approximation, for the case of event shapes. The DGE fails at present to address the issue of gluon decay, which is included for instance in the shift picture. However it is interesting to note that renormalons included via DGE can reproduce the basic features of the series of power corrections resummed into non-perturbative shape functions.

Regarding purely perturbative resummed results there have been significant developments in NLL resummations for observables such as event shapes. Results were presented, at this conference, on automated resummations for QCD final state observables [23]. The automation of resummation methods for generic observables in different processes is a big step forward since resummations done on a case-by–case basis were tedious and often error prone. This was in contrast to fixed order computations for event shapes where Monte Carlo programs exist that generate NLO results for several different observables without any laborious calculations required on the part of the user.

The approach encoded in the program CAESAR is a hybrid analytical and numerical method. The first step is to obtain the parametric dependence of the observable on final state soft and collinear particle momenta. This must be (and for the vast majority of interesting observables is) of the form :

$$V(p,k) = d_l \left(\frac{k_t}{Q}\right)^{a_l} e^{-b_l \eta} g_l(\phi) \tag{3}$$

where k_t, η and ϕ denote the transverse momentum, rapidity and azimuth wrt the hard (emitting) leg l and p the set of Born (hard) momenta. The parameters a_l, b_l and ϕ can be numerically obtained.

The next step is to determine whether the observable satisfies certain conditions, not previously available in the literature, which guarantee the validity of standard approximations that underly resummation methods. The most important condition is that of *recursive* infrared and collinear (IRC) safety which can be formulated as:

$$[\lim_{\epsilon\to 0}, \lim_{\epsilon'\to 0}]\, \frac{1}{\epsilon} V\left(p, \epsilon k_1, \epsilon' \epsilon k_2, ...\right) = 0. \tag{4}$$

In other words one probes the observable with two soft emissions (more precisely the commutator on the LHS of the above) rather than a single one (as for usual IRC safety) and checks that the scaling properties of the observable remain unaltered when one introduces the second soft emission. This condition being satisfied allows the exponentiation of the single gluon calculation (to NLL accuracy for global observables) with gluon branching merely reconstructing the running coupling in the exponent.

The final step is to insert the parameters determined above into an analytically computed master formula whose form depends on the number of hard legs in the Born configuration (e.g $n = 4$ for hadron–hadron dijet event shapes). The final results are numerically determined by a Monte Carlo algorithm. Results were presented (see [23] for the transverse thrust distribution at the Tevatron collider, as an example of the power of the automated resummation method.

LEP data continue to be an important source of information on event shapes as they are extracted in the cleanest possible environment for such studies. The LEP QCD working group has made important progress in quantifying and understanding better the theoretical uncertainties associated with event shape predictions. For details on recent progress made at this meeting see [24].

4 Particle production

The confinement transition from partons to the hadrons observed by experiments is poorly understood. Thus particle production phenomena cannot be explained in a systematic way solely from perturbative QCD. Studies of identified hadrons, inclusive hadronic multiplicities and particle flows allow to conduct detailed and sophisticated studies of many aspects of sort limit of QCD. At the same time, at this workshop we have seen how such observable can be used to tackle complicated problems related to perturbative QCD effects.

4.1 Conventional states

Identification of conventional baryons and mesons have received much attention in this working group. In particular, baryon-antibaryon production in two-photon processes in e^+e^- collisions has stable interest at LEP community. Agreements with the diquark and the handbag predictions were found in reasonable shape for the L3 studies [25], while the expectation from the three-quark model was clearly below the data.

Several results on the measurements of (anti)deutrons [26, 27] were presented by both PHENIX and H1 collaborations. In heavy ion collisions, the production of (anti)nuclei helps to understand the production size of the system and amount of radial expansion when the coalescence model is used to explain the production mechanism of (anti)deutrons [26]. In particularly, deuteron/antideuteron spectra at mid-rapidity probe the late stages of relativistic heavy ion collisions.

The measurements of (anti)deutrons are clearly a significant challenge for experimentalists, since these states can easily be produced by secondary scattering processes. This problem is less severe for antideutrons which were measured for the first time in ep collisions by the H1 collaboration [27]. The production mechanism of antideutrons in ep collisions is significantly less understood compared to heavy-ion collisions. The result of this interesting study was in the observation that the production rate of antideutrons in ep is by order of magnitude smaller than in heavy-ion collisions. Thus, in terms of the coalescence model, the size of the fireball at the thermal freeze out is expected to be much smaller for ep processes than for heavy-ion collisions.

4.2 Pentaquarks

This was the first DIS workshop at which the entire section was devoted to searches for pentaquarks, five-quark baryons which recently attracted tremendous attention of theorists and experimentalists. Let us remind that recent results from low-energy fixed-target experiments [28] gave evidence for the existence of a new narrow baryon resonance, Θ^+ with a mass of approximately 1530 MeV and positive strangeness. This state was seen in in the K^+n decay channel. These results have triggered new interest in baryon spectroscopy since this baryon is manifestly exotic; it cannot be composed of three quarks, but may be explained as a bound state of five quarks, i.e. as a pentaquark, $\Theta^+ = uudd\bar{s}$. A narrow baryonic resonance close to the observed mass is predicted in the chiral soliton model [29]. The quantum numbers of this state also permit decays to $K_S^0\, p$ and $K_S^0\, \bar{p}$, which can experimentally be measured using tracking detectors [30].

Two DESY experiments, HERMES [31] and ZEUS [32], reported observations of a possible pentaquark state in the decay mode $K_S^0 p(\bar{p})$, see Fig. 9. The masses and widths agreed rather well for both measurements. However, some discrepancies with the K^+n decay channel [28] may exist. This ether could mean that the particle decaying to $K_S^0\, p\, (\bar{p})$ is not the same state as that observed for the K^+n channel, or, unlike the well reconstructed $K_S^0\, p\, (\bar{p})$ final state, measurements involving detection of neutrons using missing mass could suffer from a significant systematic uncertainty which is not fully understood.

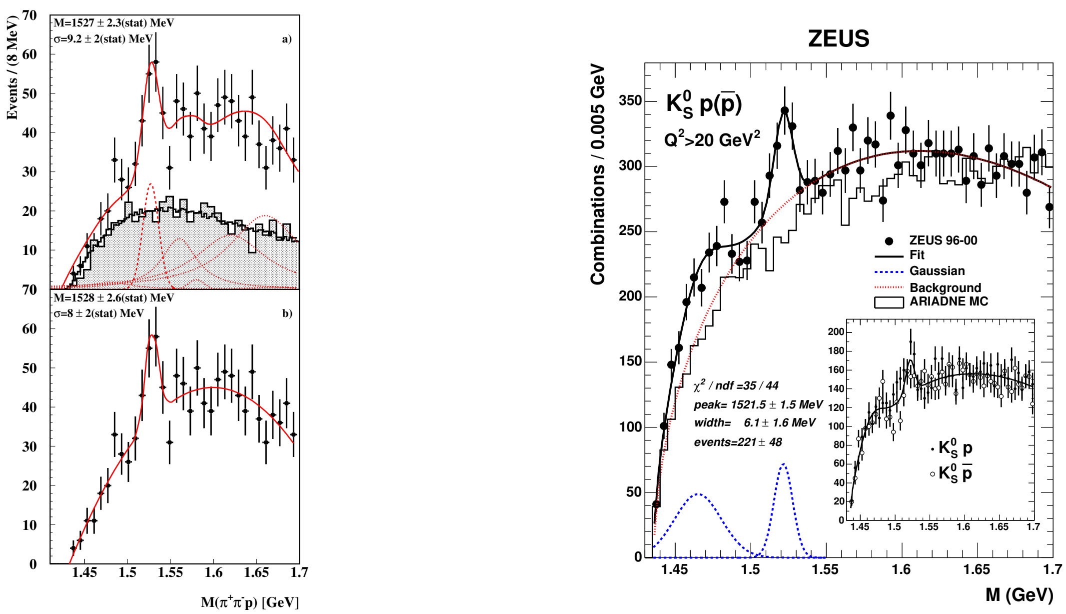

Figure 9: Invariant-mass spectra for the $K_S^0\, p\, (\bar{p})$ channel measured by HERMES [31] and ZEUS [32] experiments at DESY. The measurements were performed for photoproduction (HERMES) and DIS (ZEUS) data.

ALEPH reported negative results on the Θ^+ search [33]. Presently, other LEP experiments have also reported their negative results (see a recent review [34]). Does this related to the fact that e^+e^- experiments do not have a contribution from the proton remnant, i.e. from the net baryon number in the initial state? At this conference there was a full concensus that this question requires further studies and, at present, no definite answer can be given.

Note that ZEUS is the first high-energy experiment which made the observation of Θ^+ state in the central fragmentation region dominated by fragmentation of quarks and gluons. One should mention that, unlike fixed-target experiments, the contribution from the proton remnant is negligible in this region. Thus, if confirmed, this result needs to be understood in terms of present hadronisation models.

It is important to point out again that several high-energy experiments have reported their negative results (see references in [34]). Of course, each negative case should be considered very seriously. If the pentaquark does exist near $1520-1530$ MeV, possible reasons of such ZEUS success may lay in a good tracking resolution for $K_S^0\, p\, (\bar{p})$ combinations ($\simeq 2.5$ MeV) and a relatively small combinatorial background for DIS at $Q^2 > 20$ GeV^2 (compared to some heavy-ion and Tevatron experiments). Of course, differences in the production dynamics may also be important. One possible way to learn about instrumental and background differences between different experiments would be to use the PDG Λ_c baryon (which can also decay to $K_S^0\, p\, (\bar{p})$) as a reference. Both HERMES and ZEUS used this state to calibrate the mass measurements near the $K_S^0\, p\, (\bar{p})$ production threshold.

The Θ^+ lies at the apex of a hypothetical anti-decuplet of pentaquarks with spin 1/2. The baryonic states $\Xi_{3/2}^{--}$ and $\Xi_{3/2}^{0}$ at the bottom of this antidecuplet are also manifestly exotic. According to the predictions of Diakonov et al. [29], the members in the anti-decouplet with the isospin quartet of $S=-2$ baryons should have a mass of about 2070 MeV and partial decay width into $\Xi\pi$ of about 40 MeV. Recently, NA49 [35] at the CERN SPS made observation of exotic $\Xi_{3/2}^{--}$ member of the Ξ multiplet, with a mass of 1862 ± 2 MeV and width below the detector resolution of about 18 MeV. At this conference, several experiments, CDF, ALEPH and ZEUS reported their negative results on the search for $\Xi_{3/2}^{--}$ and $\Xi_{3/2}^{0}$. Some experiments have extremely competitive data with a large number of reconstructed Ξ states used for the searches of exotic $\Xi_{3/2}^{--}$ and $\Xi_{3/2}^{0}$.

4.3 Multiplicities and particle flows

The measurements of multihadronic final state allow detection of color coherence properties. A number of interesting results were shown by DELPHI collaboration [36] using hadron multiplicities: a competitive value for the color-factor ratio was obtained, a clear signature for the destructive gluon interference was seen, and finally, the ratio of gluon to quark multiplicities was obtained and compared to the 3NLO and MLLA calculations. Both predictions gave a reasonably good agreement to the data.

Particle flows were also used by DELPHI [37] to study color-reconnection effects between color singlets which take place in WW production. This phenomenon contributes to enhancement or depletion of soft particle multiplicity in some phase-space regions. The data might indicate that there is a small contribution from color reconnection effect, but generally, the predictions are doing rather well without extra contributions. A possible mass shift in the reconstructed W mass is expected to be rather small, by order of magnitude smaller than that expected in early days of the WW studies.

Clearly, particle flows can be used to test certain details of hard QCD without using the jet algorithms, as long as we understand contributions from soft physics to such observables. There has been considerable progress in studying azimuthal asymmetry attributed to hard QCD by using the energy flow method as reported by ZEUS [38]. It was shown that this method has several advantages compared to conventional multiplicity-based and jet-based experimental techniques. The results indicate a rather good agreement with the NLO calculations (corrected by Monte Carlo models to take into account hadronisation effects).

4.4 Theoretical developments in particle production

Results were also presented in this meeting, on NLO computations for inclusive and two photon production at hadron colliders [39]. Successful comparisons were shown of the NLO predictions from the program DIPHOX with data from CDF and D0 Run II data for quantities such as azimuthal angle, invariant mass and the transverse momentum p_t of the γ pair in two photon production. In regions requiring resummation (such as the region of small p_t of the pair), as expected the comparison with NLO is less meaningful. However it was clear that two photon production at the Tevatron is well understood theoretically while a need for more data was observed in the inclusive photon case.

5 Future measurements

With the LHC around the corner theoretical tools have to be improved to meet the challenge of making new discoveries in a very complex hadronic environment. Amongst the most prominent tools that will be employed in such searches for new physics will be Monte Carlo event generators.

Progress and developments concerning the new event generator SHERPA were presented in this conference [40]. This is an event generator that uses the matrix element (ME) package AMEGIC++ along with its own parton shower (PS) model and the CKKW procedure to merge the ME and PS. It also has an interface to the PYTHIA string fragmentation model for hadronization. Results from SHERPA for the jet p_t distribution in Z+jet production at the Tevatron were shown, which indicated that the CKKW procedure, for such spectra, gave very similar results to those obtained from full NLO calculations.

There was also a presentation on the THEPEG [41] which is a general and modular C++ framework for implementing event generator models. Both PYTHIA7 and HERWIG++ will be built on THEPEG which will unify aspects of the event generation and share the administrative overheads involved. In the same talk progress was also reported on the merging of matrix elements and parton showers for the ARIADNE Monte Carlo. Results obtained in the case of the p_t distribution in W+jet production at the Tevatron indicated that the matching procedure worked extremely well in the incoming quark channel and less well for the incoming gluon channel with a visible cut-off artifact. Work is in progress in this regard.

Results for event shapes, jet rates, heavy quark fragmentation functions etc. were also displayed from the new event generator HERWIG++ [42], which was shown to perform as well[3](and in some cases better) than the fortran HERWIG, with precision tuning to LEP data still to be carried out. It was emphasised that the C++ version is not merely a rewrite of the fortran HERWIG but there are some changes in the physics models. The most significant is perhaps the use of a new evolution variable $\tilde{q}$ inspired by the heavy quark splitting function :

$$P_{gq}(z, q^2, m^2) = \frac{C_F}{1-z}\left[1 + z^2 - \frac{2m^2}{z\tilde{q}^2}\right] \tag{5}$$

[3]Thus far only e^+e^- processes are implemented

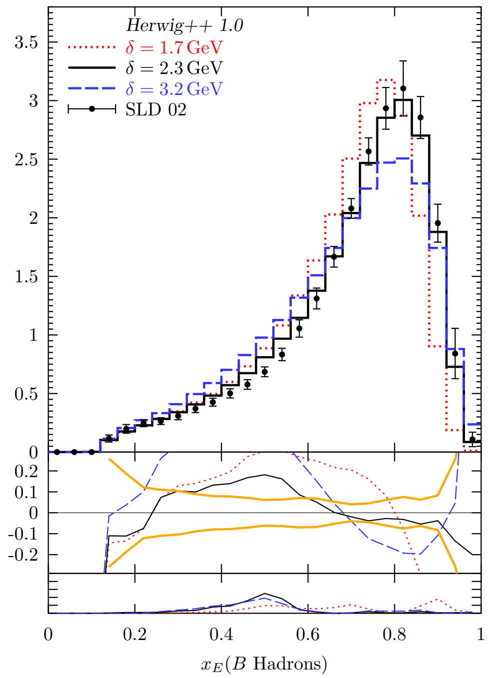

Figure 10. B fragmentation function from HERWIG++ compared to data for different values of the cut-off parameter δ.

Using $\tilde{q}$ as the evolution variable ensures a better coverage of the soft gluon phase space for emission off a heavy quark, in particular the description of the collinear (dead-cone) region. Evidence for the success of the new evolution can be seen in the excellent description of the B fragmentation function by varying just the parton shower parameters (see Fig. 10). There is also an improved cluster hadronization model employed in HERWIG++. Extensions to include *ep* and especially hadron-hadron processes are eagerly awaited.

6 Summary

A selected sample of presentations given at the DIS04 workshop (working group C) discussed different areas of hadronic final states phenomena has been summarized. The detailed comparisons of the experimental data with the latest theoretical developments show good agreement with QCD. In spite of all these successes of QCD theory, research in this direction is far from complete. We hope that the increase of the collected luminosity at HERA and Tevatron colliders, together with future experiments at LHC and a linear collider, as well as further progress in theoretical QCD calculations, will lead to new exciting results which would open up new areas where QCD theory can be confronted with greater challenges.

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References

[1] L. Li, these proceedings.

[2] R. Poeschl, these proceedings.

[3] A. Knutsson, these proceedings.

[4] L. Goerlich, these proceedings.

[5] M. Lightwood, these proceedings.

[6] K. Sedlak, these proceedings.

[7] A. Safonov, these proceedings.

[8] M. Kopal, these proceedings.

[9] P. Demine, these proceedings.

[10] N. Moggi, these proceedings.

[11] A. Banfi, these proceedings.
A. Banfi and M. Dasgupta, JHEP **0401** (2004) 027.

[12] M. Klasen, T. Kleinwort and G. Kramer, Eur. Phys. J.direct **C1** (1998) 1.

[13] L. Bertora, these proceedings.

[14] G. Rodrigo, these proceedings.
S. Catani, D. de Florian and G. Rodrigo, Phys. Lett. **B586** (2004) 323.

[15] M. Dasgupta and G.P. Salam J. Phys. G **30** (2004) R143.

[16] S. Hanlon, these proceedings.

[17] W. B. Yan, these proceedings.

[18] M. Beneke, Phys. Rept. **317** (1999) 1.

[19] E. Gardi and J. Rathsman, Nucl. Phys. **B638** (2002) 243.

[20] L. Magnea, these proceedings;
E. Gardi and L. Magnea JHEP 0308 (2003) 030.

[21] Yu.L. Dokshitzer and B.R. Webber, Phys. Lett.**B404** (1997) 321.

[22] G.P. Korchemsky and G. Sterman, Nucl. Phys **B555** (1999) 335.

[23] G.P. Salam, these proceedings.
A. Banfi, G.P. Salam,G. Zanderighi , Phys.Lett **B584** (2004) 298.

[24] M. Ford, these proceedings.
R.W.L. Jones, M. Ford, G.P. Salam, H. Stenzel and D. Wicke, JHEP **0312** (2003) 007.

[25] K. Freudenreich, these proceedings.

[26] J.Nystrand, these proceedings.

[27] T.Sloan, these proceedings.

[28] LEPS Collaboration, T. Nakano *et al.,* Phys. Rev. Lett. **91** (2003) 012002;
SAPHIR Collaboration, J. Barth *et al.,* Phys. Lett. **B 572** (2003) 127;
CLAS Collaboration, V. Kubarovsky *et al.,* Phys. Rev. Lett. **91** (2003) 252001;
CLAS Collaboration, V. Kubarovsky *et al.,* Phys. Rev. Lett. **92** (2004) 032001. Erratum; ibid, 049902.

[29] D. Diakonov, V. Petrov and M.V. Polyakov, Z. Phys. **A 359** (1997) 305.

[30] DIANA Collaboration, V.V. Barmin *et al.,* Phys. Atom. Nucl. **66** (2003) 1715;
A.E. Asratyan, A.G. Dolgolenko, M.A. Kubantsev, Preprint hep-ex/0309042, 2003;
SVD Collaboration, A. Aleev *et al.,* Preprint hep-ex/0401024, 2004;
COSY-TOF Collaboration, M. Abdel-Bary *et al.,* Preprint hep-ex/0403011, 2004.

[31] E.Aschenauer (HERMES Collab.), these proceedings;
see also: HERMES Collaboration, A. Airapetian *et al.,* Phys. Lett. **B 585** (2004) 213.

[32] S.Chekanov (ZEUS Collab.), these proceedings;
see also: ZEUS Collaboration, S. Chekanov *et al.,* Phys. Lett. **B591** (2004) 7.

[33] P. Hansen, (ALEPH Collab.) these proceedings.

[34] J. Pochodzally, Talk presented at 2nd Panda Physics Workshop (Frascati, May 17-19), 2004 `hep-ex/0406077`.

[35] NA49 Collaboration, C. Alt *et al.,* Phys. Rev. Lett. **92** (2004) 042003.

[36] M. Siebel, (DELPHI Collab), these proceedings.

[37] N. Anjos, (DELPHI Collab.), these proceedings.

[38] A. Ukleja (ZEUS Collab.), these proceedings.

[39] J.Ph. Guillet, these proceedings.
T. Binoth, J.Ph. Guillet, E. Pilon and M. Werlen, Phys. Rev. **D63** (2001) 114016.

[40] F. Krauss, these proceedings.

[41] L. Lonnblad, these proceedings.

[42] S. Gieseke, these proceedings.
S. Gieseke, A. Ribon, M.H. Seymour, P. Stevens and B.R. Webber, JHEP **0402** (2004) 005.