QCD and Hadronic Final States

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Abstract. We give an overview of the experimental and theoretical results which were presented during the "QCD and Hadronic Final States" working group sessions at the DIS 2011 workshop.

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INTRODUCTION

In this document the current experimental and theoretical efforts presented at the "QCD and Hadronic Final States" working group at the 2011 DIS workshop in Newport News are summarised [1]. The subjects covered include jet production, particle spectra, prompt photons, and boson plus jets production. Of the 49 talks given in our sessions 13 were from theorists. The first significant results from the LHC experiments (ATLAS, ALICE, CMS and LHCb) were presented and discussed in detail. New results from experiments based at HERA, Tevatron, RHIC, JLab and CERN were also discussed.

The results presented show that our knowledge of QCD is generally able to account for a wide range of data from very different environments. However there are some important caveats that need to be taken into account:

- The small x data tends to favour unordered parton emission models of the parton shower.
- Monte Carlo tunes of data can have large degrees of freedom, especially when including data from more than one centre of mass energy.
- LHC measurements tend to be focused on central rapidities and high p_T, limiting the region in which they currently test QCD theory. The LHCb experiment with its forward rapidity coverage has proven able to extend the LHC experimental reach in minimum bias events.
- Next-to-leading order QCD predictions in many cases include large uncertainties from the PDF as well as the scale choice, suggesting that next-to-next-to leading order (NNLO) QCD calculations and predictions are needed!

With these observations noted we look forward to next year's new results which promise to test QCD even further.

JETS

Jet Cross Sections

Measurements of jet cross sections are fundamental measurements at the LHC. Both ATLAS and CMS presented new jet measurements of proton-proton collisions at a centre-of-mass energy of 7 TeV.

ATLAS (Ximo Poveda Torres) use the anti-kt algorithm with $R = 0.6$ or 0.4, with a minimum jet E_T of 20 GeV and a maximum rapidity of 4.4, to identify jets. Inclusive single-jet differential cross sections as functions of jet transverse momentum and rapidity and di-jet cross sections as functions of di-jet mass and angle were presented. The measurements extend the previously measured kinematic region to higher rapidities, and to both higher and lower values of transverse momentum. The results were compared to next-to-leading-order (NLO) QCD calculations matched to leading-logarithmic parton showers. Agreement between data and theory over several orders of magnitude is observed. A trend that measured cross sections are smaller than theory at large p_T and di-jet mass is noted.

ATLAS (Long Zhao) also presented measurements of multi-jet cross sections, the azimuthal correlation between di-jets, which are sensitive to higher order QCD effects, and di-jets separated by large intervals of rapidity ("jet veto"), which are sensitive to BFKL-like dynamics. The measurements were compared to NLO QCD and higher multiplicity LO QCD calculations matched to parton showers using leading-logarithmic approximations. The large rapidity-interval distributions were also compared to calculations using approximations based on resumming the leading-logarithmic terms in rapidity. In general, there is good agreement between theoretical predictions and data.

CMS (Cosmin Dragoiu) have measured various jet cross sections, such as the inclusive jet cross-section, the di-jet mass spectra and the di-jet angular distributions, using the anti-kt algorithm with $R = 0.7$ or 0.5, with a minimum jet E_T of 18 GeV and a maximum rapidity of 3.0, to identify jets. Good agreement with QCD predictions is observed. CMS (Joanna Weng) have also measured hadronic event shapes, thrust and thrust minor, and the ratio of the 3 jet to 2 jet production cross-sections, confronting QCD multi-jet dynamics in a previously unexplored kinematic regime. The data are compared to various QCD Monte Carlo models. For the event shapes PYTHIA6, PYTHIA8 and Herwig++ are close to the data while Alpgen, MadGraph show discrepancies (with CMS parameter choice) while the ratio is best described by Madgraph.

New theory predictions for event shapes are under development. Zhao Li presented the resummation effect on light quark and gluon jet functions and jet energy profiles based on first principles of perturbative QCD theory. The jet function provides a jet mass distribution for a given jet transverse momentum. Jet mass distributions including non-perturbative contributions agree with PYTHIA8 for different jet p_T and R, and with CDF data. The jet energy profile gives important information about the jet substructure, predictions for jet energy profile were found to agree with CDF and CMS data. The method can be further extended to HERA and RHIC results, and for heavy quark (top) jet analyses.

D0 (Zdenek Hubacek) presented analyses of inclusive di-jet and three-jet production

in a data set corresponding to an integrated luminosity of 0.7 fb^{-1} using the midpoint cone algorithm. The inclusive di-jet production double differential cross section as a function of di-jet invariant mass and the largest absolute rapidity of the two leading jets measurement was presented in six rapidity (y) regions up to $|y| = 2.4$ for the two jets with the largest transverse momentum in an event. NLO perturbative QCD predictions are found to be in agreement with the data. The measurement of the inclusive three-jet cross section was presented as a function of three-jet invariant mass in bins of softest jet transverse momenta and in bins of jet rapidities. The description of the data by NLO QCD theory was found to be sensitive to the choice of proton parton density function (PDF), with the MSTW2008 and NNPDFv2.1 Pt's giving the best description. These results were used in the D0 extraction of α_s.

ZEUS (Oleg Kuprash) presented new results of the di-jet cross sections in neutral current deep-inelastic scattering and photoproduction. For the di-jets the cross sections are described by NLO QCD predictions. The results for photoproduction were presented as a function of the average jet transverse energy and pseudorapidity, as a function of the fraction of the incoming photon momentum taken by the di-jet system, and as functions of the di-jet invariant mass, M_{jj}, and the scattering angle in the di-jet centre-of-mass system. NLO QCD calculations give a good description of the measurements. The cross sections have the potential to constrain the parton densities in the proton and the photon when included as input to fits to extract the parton distribution functions.

For high-p_T forward processes at the Large Hadron Collider (LHC), QCD logarithmic corrections in the hard transverse momentum and in the large rapidity interval may both be quantitatively significant. Michal Deak presented numerical Monte Carlo applications of high-energy factorisation, which are able to resum both types of corrections to final-state observables associated with production of one forward and one central jet. By computing jet correlations in rapidity and azimuth, the role of corrections to the parton-showering chain from large-angle gluon radiation was studied, and was discussed in relationship with Monte Carlo results modeling interactions due to multiple parton chains. Proposal of observables which allow for discrimination between different approaches were suggested such as measuring $\Delta\phi$ in different $\Delta\eta$ regions.

Christian Weiss presented a discussion on how the transverse nucleon structure is a key concept in the analysis of particle production in pp collision with hard processes at the LHC. Using information on the transverse spatial distribution of partons from hard exclusive processes in $ep/\gamma p$ scattering the impact parameter distribution of pp events with a hard inclusive parton-parton process as a function of the p_T and rapidity of the produced jets was calculated. The average pp impact parameters in such events was found to depend only weakly on the jet kinematics for $p_T > 2$ GeV and are much smaller than those in minimum-bias inelastic collisions. The impact parameter in turn determines underlying event characteristics such as the transverse multiplicity, forward energy flow and multi-jet rates. By measuring these event characteristics as functions of the "trigger" p_T one can decode the role of the pp impact parameter and perform detailed quantitative tests of the mechanism of particle production. First results from CMS and ATLAS fully support the proposed geometric picture. The approach exposes model independent properties of the final state that should serve as benchmarks for future detailed studies using MC generators.

Given the importance of double parton distributions for collider phenomenology,

Jochen Bartels discussed the non-trivial issue of the evolution of *double* parton distributions, which are central to the calculations discussed by C. Weiss. Approximating this with a double DGLAP evolution may not be enough, especially at small parton fractional momentum, where parton recombination leads to various kinds of reconnection of the DGLAP chains, leading, *e.g.*, to contributions to diffractive events. Several theoretical issues have been pointed out, including the most relevant evolution variable, and the pressing need for further theoretical investigations stressed.

Precise predictions for jet production cross sections require calculations through next-to-next-to-leading order (NNLO) in QCD perturbation theory. NNLO computations require a systematic procedure to extract infrared singularities from real radiation contributions. Radja Boughezal presented an overview of recent progress in subtraction methods developed to allow high-precision perturbative calculations of jet observables at hadron colliders. Results for a subset of the complete set of the needed integrated antennae were shown. In the near future the first physics applications should be available.

Jet production and particle correlations in heavy ion collisions

In heavy ion collision, partons that have undergone a hard scatter have to traverse through a hot dense medium which could alter the parton evolution leading to effects such as jet quenching. Understanding and chartering this effect is a hot topic and results from ALICE, PHENIX and STAR were presented. The presence of a large soft background in the heavy ion environment makes the use of traditional jet reconstruction algorithms non trivial.

The problem of jet reconstruction at heavy-ion colliders was discussed by Juan Rojo and the jet-area-based background subtraction tools as provided by FastJet was presented. Monte Carlo simulations with and without quenching were used to study the performance of several jet algorithms, including the option of filtering, under conditions corresponding to RHIC and LHC collisions. Most standard algorithms were shown to perform well, though the anti-kt and filtered Cambridge/Aachen algorithms have clear advantages in terms of the reconstructed transverse-momentum offset and dispersion.

The status of full jet reconstruction in ALICE was presented (Leticia Cunqueiro Mendez). In particular results on the inclusive charged jet cross section and the understanding of the underlying background and its fluctuations, which are the main source of uncertainty in the measurement, were discussed.

An alternative method of full jet reconstruction in pp and heavy-ion collisions was presented by the PHENIX experiment (Ali Hanks). The development of a new algorithm applying a Gaussian filter in combination with a sophisticated fake jet rejection scheme was shown to greatly improve the ability to measure real jets even in the high multiplicity environment of central *AuAu* collisions. Recent results using this new algorithm were presented for pp and *CuCu*, including jet spectra and the nuclear modification factor, di-jet correlations and the pp fragmentation function. The pp inclusive jet cross-section is consistent with that from STAR using the midpoint cone algorithm. Jet yields are seen to be strongly suppressed in central collisions in *CuCu* collisions compared to peripheral collisions.

The STAR experiment (Hua Pei) presented results from 2+1 correlations. Two back-to-back high p_T particles (charged hadrons or high energy photons) are used as proxies of di-jets to tag events. Then the distributions of low-pt charge hadrons correlated with these trigger pairs was studied. In contrast to the "ridge" and "hump" structures observed in di-hadron correlations with a single high p_T trigger, the correlation functions for 2+1, with the similar associated hadron p_T range, show clear peak structures even for central *AuAu* collisions in both $\Delta\phi$ and $\Delta\eta$. The asymmetry of the back-to-back triggers was varied, and the associated yields and trigger rates for such di-jets are studied as a function of the number of particles and associated p_T. A comparative study of this using *AuAu* and *dAu* systems has also been made. Results are compatible with the surface emission model (core/corona medium). Path-length dependent energy loss models are expected to show a relative difference between near and away side double ratio of $AuAu/dAu$, this was not observed in either symmetric or asymmetric trigger case and is under further study.

Jet Cross Sections and α_s

Jets measurements can be used to extract both an accurate measurement of α_s and demonstrate the running of the strong coupling. Several results were presented in a session dedicated to α_s.

The D0 experiment (Markus Wobisch) has determined the strong coupling constant and its energy dependence from the p_T dependence of the inclusive jet cross section. The strong coupling constant is determined over the transverse momentum range $50 < p_T < 145$ GeV. Using perturbative QCD calculations to order $O(\alpha_s^3)$ combined with $O(\alpha_s^4)$ contributions from threshold corrections, they obtained $\alpha_s(M_Z) = 0.1161\ ^{+0.0041}_{-0.0048}$. This is the most precise result obtained at a hadron-hadron collider to date. D0 also presented the first measurement of ratios of multi-jet cross sections in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Tevatron. The ratio of inclusive three-jet and di-jet cross sections was measured as a function of transverse jet momentum. NLO QCD calculations give a good description of the measurements.

The ZEUS experiment (Inna Makarenko) has measured the differential inclusive-jet cross sections in photoproduction for boson virtualities $Q^2 < 1$ GeV^2. Jets were identified in the laboratory using the k_t cluster algorithm in the longitudinally inclusive mode. Cross sections were presented as functions of the jet pseudorapidity, and the jet transverse energy. NLO QCD calculations give a good description of the measurements. The value of $\alpha_s(M_z)$ extracted from the measurements was found to be $\alpha_s(M_Z) = 0.1206\ ^{+0.0023}_{-0.0022}(\text{exp.})\ ^{+0.0042}_{-0.0033}(\text{th.})$.

The ZEUS experiment (Denys Lontkovskyi) also measured differential inclusive-jet cross sections in neutral current DIS for boson virtualities $Q^2 > 125$ GeV^2. Jets were identified in the Breit frame using the k_t cluster algorithm in the longitudinally inclusive mode. Single-differential cross sections were presented as functions of Q^2, the jet pseudorapidity and the jet transverse energy. In addition, measurements of double-differential inclusive-jet cross sections were presented as functions of jet transverse energy in different regions of Q^2. NLO QCD calculations give a good description of

the measurements. A value of $\alpha_s(M_Z)$ was extracted from the measurements of the single-differential cross-section $d\sigma/dQ^2$ for $Q^2 > 500\text{GeV}^2$ and found to be $\alpha_s(M_Z) = 0.1207\ ^{+0.0038}_{0.0036}(\text{exp.})\ ^{+0.0022}_{0.0023}(\text{th.})$. The dependency of the results on the choice of jet algorithm was by checked by repeating the measurements using the anti-kt and SIScone algorithms. The values were in general found to be consistent with each other and have similar precision for both DIS and photoproduction.

The H1 Experiment (Roman Kogler) has measured the inclusive-jet, di-jet and tri-jet differential cross sections in neutral current DIS for exchanged boson virtualities $150 < Q^2 < 15000$ GeV^2. Jet cross sections as well as ratios of jet cross sections to neutral current DIS cross sections have been measured. The cross sections were presented as a function of Q^2 and the transverse momentum of the jet (the mean transverse momentum for di-jets and tri-jets) and were compared to NLO QCD calculations and found to agree. The measurements were used to determine value of the strong coupling $\alpha_s(M_Z)$. The most precise experimental result came from the tri-jet cross section and was found to be $\alpha_s(M_Z) = 0.1196 \pm 0.0016(exp.) \pm 0.0010(pdf.)\ ^{+0.0055}_{0.0039}(th.)$.

PARTICLE PRODUCTION

Semi Inclusive with Protons

The LHCb experiment presented results on baryon number transport (Marco Adinolfi) and strangeness production studies (Jesko Merkel). Due to its large pseudorapidity coverage, excellent tracking capabilities and the possibility of extending the measurements to low transverse momenta the LHCb experiment provides uniquely useful results for the study of particle production. Measurements of the production cross-section of particles with strangeness (K^0_S, ϕ), the production ratios of $\bar{\Lambda}/\Lambda$ and $\bar{\Lambda}/K^0_S$ and the proton/antiproton production ratio as a function of rapidity at center-of-mass energies of 0.9 and 7 TeV were presented. The results are sensitive to baryon number transport from the beam to the final state particles, and to the various tunes of QCD model predictions. Preliminary results compared to current models indicate data has a: harder p_T distributions; higher baryon number transport; lower baryon/meson suppression than predicted.

The ATLAS experiment presented results on particle distributions and correlations in minimum bias and underlying event distributions and Monte Carlo generator tuning (Holger Schulz, Cristina Oropeza Barrera). Particle production in proton-proton collisions are a sensitive probe of non- and semi-perturbative QCD. Measurements of charged particle distributions were presented from proton-proton collisions at centre-of-mass energies of $\sqrt{(}s) = 0.9,\ 2.36$ and 7 TeV. Inclusive "minimum bias" distributions as well as measurements in regions defined with respect to the highest transverse energy particle in an event, which are sensitive to the underlying event, were presented. The data were compared to several Monte Carlo models, including models with parameters tuned to ATLAS data. New tunes of the general purpose MC generators PYTHIA6 and Herwig which improve upon previous ATLAS tunes, using a wider variety of measurements and higher precision data, were presented. It is of course impossible to describe all measurements at all energies at the same time, and compromises must be made al-

though more distributions are described in this set of tunes than previously. Inclusive two-particle correlations between charged particles, $\Delta\eta$ and $\Delta\phi$, was also presented for p_T inclusive minimum bias events. None of the models reproduce the strength of the correlations seen in data.

The CDF experiment (Seog Oh) reported on an extensive resonance production study with minimum bias events up to $p_T = 10$ GeV and in association with a high p_T jet. They measured the inclusive invariant transverse momentum differential cross sections of centrally produced hyperons (lambdas, cascades, and omegas) and light strange resonances (K^0_S, $K^{*\pm}(892)$ and $\phi^0(1020)$). Neither PYTHIA nor HERWIG is able to describe the data using the LEP tunes. The slopes of the differential cross sections of particles in the high transverse momentum region are very similar to each other indicating a universality in the particle production processes as the transverse momentum increases.

ZEUS (Ryuma Hori) have measured the scaled momentum distributions of identified particles, $K^0_S$and Λ, using an integrated luminosity of 290 pb^{-1} in the kinematic region $10 < Q^2 < 40000$ GeV^2. The distributions have been measured in the current region of the Breit frame. NLO QCD calculations including hadron-mass effects are compared to the data. Scaled momentum distributions clearly show scaling violations. Monte Carlo predictions (LEPTO and ARIADNE) give a good description of the data. NLO QCD calculations with 2 different theoretical approaches (AKK+CYCLOPS and DSS) reproduce the data reasonably well in the infrared safe regions.

k_t-factorization together with unintegrated parton distributions (TMD distributions) are very important theoretical tool for the analysis of semi-inclusive data and hadronic final states at the LHC. Emil Avsar presented a review of the concept of unintegrated gluon distributions which are widely used in phenomenology at small-x. Emphasis was placed on whether we actually understand what exactly the TMD distributions are, examining the used distributions in the literature, understanding their exact meanings and comparing these to novel definitions given for the TMD distributions which follows from TMD factorization theorems. The importance of obtaining exact and coherent definitions for these quantities, especially given that the applications to less inclusive hadronic data are numerous and widespread, was made.

Charge separated multiplicities for $\pi^\pm$ and $K^\pm$ production in semi-inclusive DIS were presented by the HERMES experiment (Sylvester Joosten) using the 27.6 GeV HERA electron/positron beam scattered off a hydrogen or deuterium gas target. The results were presented as a function of Bjorken x, Q^2, z and transverse momentum p_T. Comparison to NLO predictions, obtained from fits to e^+e^- data only, show there is room for improvement. The results represent a unique data set of identified hadrons which will significantly enhance our understanding of the fragmentation of quarks into final state hadrons in DIS.

Semi Inclusive with Nuclei

Nuclei in DIS can be used as femtometer scale detectors of the propagation and fragmentation of the quark struck by the virtual photon. CLAS (Taisiya Mineeva) presented results on a series of SIDIS measurements off D, C, Fe and Pb nuclei taken in Hall B at

JLab. This data set provides insights on parton fragmentation processes and the space-time development of in-medium hadronisation, respectively, via measurements of transverse momentum broadening and the hadron attenuation for different types of hadrons. In particular the high luminosity available at CLAS allows for multidimensional distributions in the hadron fractional energy z, scale Q^2, photon energy ν and hadron transverse momentum p_T to be measured. Several examples for charged and neutral pions, and the first world data on neutral kaon multiplicities have been discussed. The full interpretation of this preliminary data is in progress.

Jian Zhou presented theoretical results on nuclear modifications of azimuthal asymmetries in semi-inclusive DIS, which is yet another observable sensitive to parton propagation and hadronisation in nuclei. Taking into account multiple scatterings of the struck quark, he showed that at small Bjorken x (x_B), the $\cos\Phi$ asymmetry, where Φ is the angle between the hadron production plane and the lepton reaction plane, sensitive to the gluon saturation scale Q_s; specifically it is increasingly suppressed compared to proton targets as Q_S increases. At large x_B, the $\cos\Phi$ asymmetry is suppressed by transverse momentum broadening, and is thus a sensitive probe of in-medium parton dynamics.

Another way of addressing color confinement is by studying the hadronic spectrum. In particular, the number of nucleon resonances predicted by several theory models exceeds what is experimentally observed, indicating the need for a deeper understanding of the relevant effective degrees of freedom, and indirectly of QCD confinement. Sergio Anefalos Pereira presented a comprehensive set of data on the spectrum of photoproduction of excited nucleon states decaying in kaon-hyperon particles taken with the CLAS detector at JLab. He also showed preliminary data on deuteron targets, which will be useful to estimate hyperon-nucleon interactions.

PHYSICS WITH PHOTONS AND MEDIUM EFFECTS

Prompt photons in hadron colliders are mainly produced in parton hard scattering. They provide a test of perturbative QCD predictions without using jets. The dominant production process at the LHC involves gluons in the initial state and thus are a probe of the gluon content of the proton. They are also a possible background to new physics searches (e.g. $H \to \gamma\gamma$).

CMS (Andre David) made the first measurement of the differential cross section for the inclusive production of isolated prompt photons as a function of the photon transverse energy at the LHC. Shower shape and isolation requirements are applied and a minimum photon $E_T > 15$ GeV is required. Results are compared with NLO perturbative QCD calculations which are in good agreement with the data.

ATLAS (Giovanni Marchiori) have measured the cross section for the inclusive production of isolated prompt photons. Photon candidates are identified by combining information from the calorimeters and from the inner tracker and are required to have a minimum $E_T > 15$ GeV. Residual background in the selected sample was estimated from data based on the observed distribution of the transverse isolation energy in a narrow cone around the photon candidate. The results when compared to predictions from NLO perturbative QCD are generally in agreement but there are small discrepancies below 35 GeV.

Both ATLAS and CMS are extending these measurements to include γ+jets and di-photons measurements in the near future.

D0 (Dmitri Bandurin) have measured the single differential cross sections as a function of the di-photon mass, the transverse momentum of the di-photon system, the azimuthal angle between the two photons, and the polar scattering angle of the photons, as well as the double differential cross sections in three di-photon mass bins. Measurements were compared with latest theory predictions using RESBOS, DIPHOX and PYTHIA. None of the packages was able to describe data in the whole kinematic region. Most problematic are regions of small masses, large $p_{T,\gamma\gamma}$ and small $\Delta\Phi_{\gamma\gamma}$. RESBOS predictions are closest to data, with excellent agreement at di-photon Mass $>$ 80 GeV, which is the important phase space for $H \rightarrow \gamma\gamma$ searches.

ZEUS (Nataliia Zhmak) have made measurements of prompt-photon+jet cross sections as functions of the photon transverse energy and pseudorapidity and as a function of the jet transverse energy and pseudorapidity in neutral current DIS events using the full HERA data set (330 pb^{-1}). The photon transverse energy is in the range $4 < E_T < 15$ GeV. Monte Carlo models (PYTHIA), after appropriate scaling of the *QQ* component (where a photon is radiated from a quark), is able to describe the data. The next step will be to compare to NLO perturbative QCD calculations.

Direct photon tagged jets are an excellent probe of the quark gluon plasma, since photons do not interact via the strong force, they escape the medium unmodified. The PHENIX experiment (Megan Connors) measured the direct photon-hadron correlations in *pp* and *AuAu* collisions. By studying the yield opposite the photon in direct photon-hadron correlations, the quark fragmentation function in *pp* and *AuAu* collisions was obtained. It is then possible to quantify the effective modification to the fragmentation function in *AuAu* collisions due to energy loss and medium response. A statistical subtraction method, to remove the large contribution of decay photons from the inclusive photon sample, was used in the *AuAu* measurement, while for the *pp* collisions an event by event technique was also applied. The results were compared to data from e^+e^- annihilation events, medium modified MLLA predictions and fragmentation functions. At low ξ the yield in *AuAu* is suppressed but the shape of the fragmentation function appears to be unmodified. Moving towards high ξ the shape does change and an enhancement in particle production is observed.

D0 (Alexander Verkheev) have used a sample of γ+3-jet events to determine the fraction of events with double parton scattering, f_{DP}. The double parton fraction and effective cross section σ_{eff}, a process-independent scale parameter related to the parton density inside the nucleon, was measured in three intervals of the second (ordered in p_T) jet transverse momentum $p_{T,jet2}$ within the range $15 < p_{T,jet2} < 30$ GeV. In this range, f_{DP} varies between $0.23 < f_{DP} < 0.47$, while σ_{eff} has the average value $\sigma_{eff}^{ave} = 16.4 \pm 0.3(stat) \pm 2.3(syst)$ mb. The data indicate a contribution from events with double parton interactions that is described by predictions from the PYTHIA MPI model with Perugia P0 or S0 tunes and p_T-ordered showers and by SHERPA with the default MPI model.

PHYSICS WITH BOSONS

The D0 collaboration has introduced new variables (called a_T and ϕ^*) to accurately probe the low transverse momentum region of Z boson production at hadron colliders. The comparison of this data to perturbative QCD prediction is expected to give important information on the size of non-perturbative effects. Simone Marzani presented a state-of-the-art analytical calculation of these new variables that contains the resummation of large logarithms up to next-to-next-to leading logarithmic accuracy, matched to a full next-to leading order calculation. The theoretical result is performed accounting for the experimental cuts introduced by the D0 collaboration, and the theory prediction has been compared to data, however theoretical uncertainties have yet to be calculated.

Vector boson production in association with jets is an excellent probe of QCD and constitutes the main background to many small cross section processes, such as associated Higgs production. These measurements are crucial tests of the predictions of perturbative QCD and current event generators, which have varied success in describing the data. Using these measurements as inputs in tuning event generators will increase the experimental sensitivity to rare signals.

ATLAS (Stefan Ask) have Measured the inclusive W+jets and Z+jets cross sections, in both the electron and muon decay modes of the bosons. The results were presented as a function of jet multiplicity, the transverse momentum of the leading and next-to-leading jets in the event and as ratios of cross sections. The results show good agreement with NLO predictions, obtained from MCFM and Blackhat-Sherpa. Multi-jet results also show good agreement with predictions from multi-parton matrix element MC programs, Alpgen and Sherpa.

D0 (Darren Price) presented and extensive overview of their precise results relating to boson+jets measurements. They presented: the first measurements at a hadron collider of differential cross sections for $Z/\gamma^* + jet + X$ production in $\Delta\phi(Z, jet)$ and $|\Delta y(Z, jet)|$; The ratio of the cross section for Z boson and at least one b-quark jet to the inclusive Z+jet cross section ; and measurements of $W \to l\nu$ production in association with 1, 2, 3 or 4 jets. The shape of the $|\Delta y(Z, jet)|$ distributions are described by NLO pQCD and Sherpa, some tunes of PYTHIA also do a reasonable job, however $\Delta\phi(Z, j)$ is badly described by all. The $Z \to e^+e^-$ candidate events with at least one b-jet are discriminated from Z+charm and light jet events by a novel technique that exploits the properties of the tracks associated to the jet. The measured ratio is 0.019 ± 0.0027 for events having a jet with transverse momentum $p_T > 20$ GeV and pseudorapidity $|\eta| < 2.5$, which is the most precise to date and is consistent with theoretical predictions. W+1 and 2 jets distributions are described by NLO QCD predictions, W+3 jets show some disagreement in shape, although normalisation is well described, while W+4 jets predictions are only leading order and suffer from very large uncertainties. A variety of W/Z+jets measurements is expected to be published by D0 in the near future.

Anna Stasto pointed out that calculations of di-lepton pair production at forward rapidity at the LHC in the dipole model consistently underestimate their collinear factorization counterparts. Furthermore, the effects of power suppressed terms in Q_s^2/M^2 cannot be neglected for di-lepton mass $M < 6$ GeV due to the large saturation scale Q_s in this kinematics. It would be interesting to perform measurements in pA collisions to test this approach through the impact parameter or A dependence of the saturation scale.

SMALL X AND RAPIDITY GAPS (JOINT WITH THE SMALL-X WORKING GROUP)

At HERA studies of DIS at very small Bjorken-x (down to about 10^{-5}) have been made. At such small x_B, new parton dynamics beyond DGLAP are expected to become important. The LHC can access even smaller x_B processes, and an understanding of parton dynamics at small x_B is even more important if QCD predictions at the LHC are to be constrained.

H1 (Izabela Milcewicz) have measured DIS events at low Q^2 with a high transverse momentum jet. The $\Delta\phi$ dependence in events with a forward jet and an additional jet was measured in the central region of the laboratory frame. Differential cross sections and normalised distributions were presented as a function of the azimuthal angle difference, $\Delta\phi$, between the forward jet and the scattered electron. The measurements were then compared to predictions from Monte Carlo generators based on different QCD evolution schemes. At small x_B, models where the parton emission is not ordered in p_T, e.g. CCFM and CDM, describe the data better, while standard LO DGLAP models fail. Normalised shape distributions were found to be insensitive to different QCD evolution schemes and best described by the CDM model.

H1 (Anastasia Grebenyuk) also presented results from an analysis of charged particle spectra, measured at low Q^2, in different regions of pseudorapidity. Compared to previous analyses the measurement extends the coverage in pseudorapidity into the forward region (towards the proton remnant), where deviations from models based on DGLAP evolution are expected to be more pronounced. The measurements were compared to different Monte Carlo models based on different QCD evolution schemes. At low transverse momenta the results are primarily sensitive to hadronisation, whereas at large transverse momenta the results are sensitive to the different QCD evolution schemes.

Paolo Bolzoni presented small-x resummation for partonic cross sections in time-like kinematics, *i.e.*, for the $e^+e^- \to gluon$ process at NLO, relevant to the calculation of single inclusive hadron production cross sections for hadrons with small fractional momentum z. His results are expected to enable accurate NLO fits of parton fragmentation functions at small z. In particular he presented a simple rederivation of a formal calculation of double logarithmic singularities he previously obtained with his collaborators in the $\overline{\rm MS}$ regularization scheme. These are the largest logarithms appearing at small x, and determine all other partonic cross sections. They are also a key ingredient in the calculation of the subleading single logarithmic singularities, which he will tackle next.

Christophe Royon presented a model able to describe diffractive events in hadron-hadron collisions where a rapidity gap is surrounded by two jets. The hard color-singlet object exchanged in the t-channel, and responsible for the rapidity gap, is described by the pQCD Balitsky-Fadin-Kuraev-Lipatov Pomeron, including corrections due to next-to-leading logarithms. When the rapidity gap is smaller than the inter-jet rapidity interval, the corresponding soft radiation is modeled using the HERWIG Monte Carlo. The model is able to reproduce all Tevatron data, and predictions were made for the jet-gap-jet cross section at the LHC.

Simone Marzani presented progress of understanding physics of the di-jet cross-section with a jet veto as presented by ATLAS at this workshop. Understanding jet

vetoing in this context, with its large cross-section, is of great importance if in the future we want to successfully measure processes like Z plus two jets and eventually Higgs plus two jets with a jet veto. Progress on matching the resummation to tree level matrix elements and including the experimental cuts chosen by the ATLAS collaboration, so that we can compare to their results, were presented. Improvements to the parton shower modeling of HERWIG++ were implemented as a part of the studies undertaken.

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A wide selection of other topics were also discussed.

CDF (Arie Bodek) presented the first measurement of the angular coefficients of DY e^+e^- pairs in the Z mass region from $p\bar{p}$ collisions, which provides a detailed test of the production mechanism of gauge bosons with large p_T. The measurement is sensitive to the relative contribution of annihilation and Compton processes, and validates the gluon as a spin-1 boson.

ZEUS at HERA (Aharon Levy) presented measurements of the energy dependence of the total photon-proton cross section, which allows to experimentally constrain the transition from soft to hard degrees of freedom in DIS structure functions as Q^2 increases above 1 GeV^2.

The NA48 experiment at CERN (Sergio Giudici) presented precise measurements of $K^+ \to \pi^0\pi^0 e^+ \nu$ by the NA48 experiment CERN (Sergio Giudici) which allow detailed comparisons with predictions from chiral perturbation theory.

Nikolaos Kidonakis presented recent results for threshold resummation of soft gluon divergences at next-to-next-to leading logarithm accuracy. He presented the complete two-loop results for $t\bar{t}$ production, single top production in the s and t channels, direct photon and W production at large Q_T, among others. He demonstrated that the Tevatron and LHC single top results are consistent with the NNLO calculations.

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