Summary of the HERA/LHC workshop

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Abstract. This report summarizes some of the main results of the one year long workshop on HERA and the LHC.

Keywords: Parton distributions, hadronic final states, LHC, HERA, diffraction, heavy flavors

INTRODUCTION

In roughly two years time from this writing, i.e. in the second half of the year 2007, the Large Hadron Collider (LHC), presently under construction at CERN, Geneva, will come into operation. This collider will produce proton-proton interactions at a centre of mass system (CMS) energy of 14 TeV. Present experimental and theoretical indications are that this energy range, also called the TeV-scale or Terascale, will break new ground in the understanding of particle physics and even the Universe [1].

Specifically, the LHC will unveil the mystery of electro-weak symmetry breaking, either by discovering the Higgs bosons, or otherwise. Furthermore the chances are extremely high that new physics will be discovered, such as supersymmetry, extra dimensions or other. The LHC will also be a precision instrument, allowing for a measurement of the masses of the top quark and W boson to respectively 1 GeV and 15 MeV[2].

However the LHC will also allow for e.g. new measurements in the field of QCD, b and c physics, diffraction etc., in this new energy regime. Many of these measurements will need to be made and understood early on, in order to allow to estimate backgrounds correctly for searches of new phenomena. Precision measurements will also need a good understanding of QCD, both in the perturbative range (parton showering, jets,...) and the nonperturbative range (fragmentation, underlying events, minimum bias event cross sections,...). Since the protons are composite particles, consisting of gluons and quarks, the pp cross sections of hard scattering processes depend on the parton distributions in the proton. The LHC can make some measurements of these quantities, but will rely to a large extend on precision data collected at other colliders, in particular data from HERA.

The HERA ep collider has proven itself in the past years as a precision instrument for QCD measurements. A plethora of precision measurements on jet physics, diffraction, soft scattering and on particular the structure functions of the proton has been released by the two experiments H1 and ZEUS since HERA's start of operation in 1992. The experiments have collected about 100 pb^{-1} of data each during the first run which ended in 2000. Then a luminosity upgrade was initiated which should lead to an additional 500 pb^{-1} per experiment by the middle of 2007, when the HERA data taking program is scheduled to terminate. Given that the end of HERA may be near, and that the physics requirements at the LHC are by now sufficiently understood, it seemed like an excellent opportunity to launch a workshop to bring these two communities in direct dialog with each other, to make sure one can extract the maximum information from the HERA data to help the future analyses at the LHC[3]. This workshop will be described here. Another workshop with a similar program, but for the Tevatron-LHC combination, called TeV4LHC[4], was launched as well in 2004.

THE HERA/LHC WORKSHOP

The seeds of the idea to organize this workshop came from two other workshops organized in the year 2003. At CERN a one month workshop took place during the early part of the summer on "Monte Carlo Tools for the LHC" [5], and in Binn (Switzerland) there was a small but very topical workshop on "precision measurements" [6] in the Fall. Both workshops brought –among others– the HERA community in direct contact with the LHC community. These workshops were received enthusiastically, but could only scratch the top of the iceberg and something on longer term was needed to work out the ideas that were generated. Hence the idea for a full fletched one-year long workshop was born.

The goals of the HERA-LHC workshop have been defined as follows

- To identify and prioritize those measurements to be made at HERA which have an impact on the physics reach of the LHC.
- To encourage and stimulate the transfer of knowledge between the HERA and LHC communities and establish an ongoing interaction.
- To encourage and stimulate theory and phenomenological efforts related to the above goals.
- To examine and improve theoretical and experimental tools related to the above goals
- To increase the quantitative understanding of the implications of HERA measurements on LHC physics.

Five working groups have been formed to accomplish these tasks: (WG1) Parton Densities; (WG2) Multi-jet Final States; (WG3) Heavy Quarks; (WG4) Diffraction; (WG5) MC-Tools. The first meeting took place in CERN in March 03 (250 participants), and the final meeting was held at DESY (150 participants).

WG1 PARTON DISTRIBUTIONS

Parton distribution functions are the prime measurements that are made at HERA. The charged weighted quark distributions are measured directly via the structure function F_2. The gluon distributions can be measured indirectly via QCD evolution fits of F_2 or semi-directly in e.g. jet and charm cross section measurements.

The F_2 structure functions at HERA are now measured with a precision of typically 2% or better in large kinematic regions, and are basically limited by systematics. The Run-II high statistics HERA data is expected in particular to improve the region of large

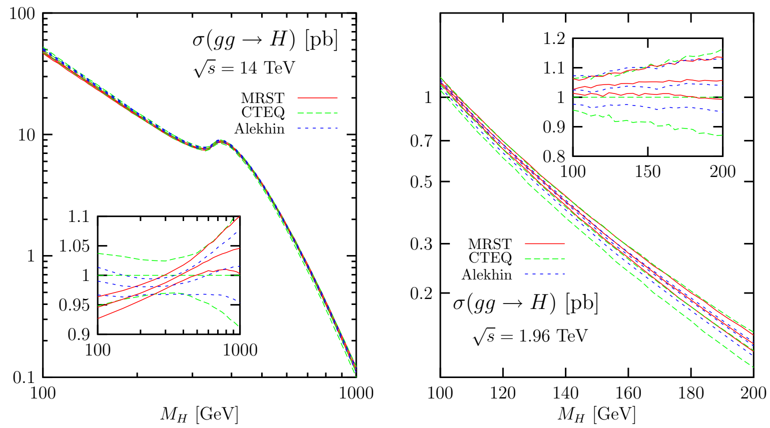

FIGURE 1. The CTEQ, MRST and Alekhin PDF uncertainty bands for the NLO cross sections for the production of the Higgs boson at the LHC (left) and Tevatron (right) for the process $gg \to$ Higgs. The insert shows the spread of the predictions when the NLO cross sections are normalized to the prediction of the reference CTEQ6M set [10].

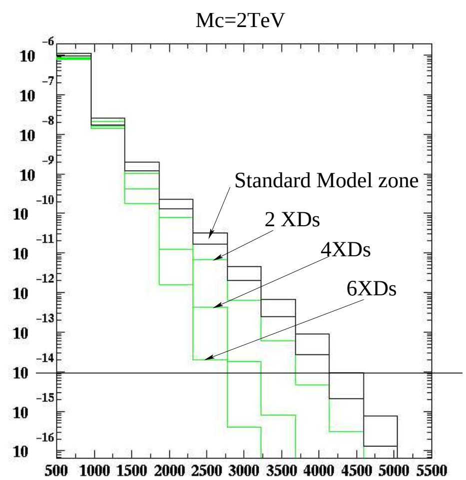

FIGURE 2. The dijet cross section in ADD extra dimensions with compactification scale $M_c = 2$ TeV. The Standard Model zone includes the uncertainties of the PDFs on the cross section prediction.

x and Q^2 which is still statistically limited. The results of HERA are used in PDF fits by either the collaborations themselves or in global fits by groups that try to include as much PDF sensitive data as possible. The current popular PDF sets are the MRST[7], CTEQ[8] and Alekhin[9] ones. The latter differ from the two former sets in that it includes only DIS data. The fits performed by the experimental collaborations themselves include less data but allow for a more easy determination of the error band as the errors and their correlations are often fully under control.

Taking naively the simple spread of the existing PDFs gives up to a 10% uncertainty in the SM Higgs cross section, as demonstrated in Fig. 1 [10]. The message for the workshop is clear: ultimately we have to do better than that. Another example is shown in Fig. 2: the sensitivity of the reach in discovery of ADD extra dimensions can be significantly reduced due to the parton density uncertainties [11]. The example is for virtual graviton exchange in a two jet final state. The two-jet cross section at the LHC gets reduced due to the interference of signal with SM QCD background. However the observation of the effect can be partially blurred by the PDF uncertainties: if one would know the SM di-jet cross section precisely, the sensitivity would be up to 5 TeV, but gets reduced to 2 (3,4) TeV for 2 (4,6) extra dimensions, due to the cross section uncertainty resulting from the PDF uncertainties.

The working group has defined the following program to be studied

- Study and document the potential experimental and theoretical accuracy for various LHC processes (Drell-Yan, W, Z, WW, γ+ jet production...) How can these be used for precision measurements at the LHC and e.g for luminosity determination? Cross sections and distributions will be studied and benchmarked with LHC detector simulation.
- Study of the impact of PDFs on LHC measurements. Here one will try to make the most of the HERA data. Is there a need for F_L and/or *eD* scattering? Can one judge which PDF is preferred? If so, what are the most precise PDFs and their errors?
- On the more theoretical side: what is the impact of small x and large x resummation and saturation corrections on PDFs? How well is the QCD evolution validated in the different kinematic regimes? How can we verify this at HERA and what is the impact on the LHC?

The systematic study of well measurable LHC final states is ongoing. As an example Table1 shows the summary of the uncertainties for W,Z and di-bosons production with experimental cuts, for the parton distributions and perturbative scale [12].

TABLE 1. Summary of uncertainties for measurments including experimental cuts, for the PDFs and scale of the perturbative calculation.

	W/Z	W/Z+jet	WW/ZZ
Δ_{PDF}(%)	$\pm$5.3	$\pm$4.3	$\pm$3.7
Δ_{Pert}(%)	$\pm$5.4	$\pm$9.1	$\pm$3.8

Many of the processes in this study can be used for the extraction of information on the PDFs, but it needs still to be quantified to what precision this can be done.

Fig. 3 shows the plane in x, Q^2 covered presently by HERA and the part that will be covered by the LHC [13]. Extrapolation or rather QCD evolution of the PDFs will be required over about 3 orders of magnitude. Clearly we need to understand as good as we can the evolution in the region where we have precise data at present, to check the uncertainty which is 'tolerated' by these data (e.g. the amount of non-linear effects). In the course of this workshop the NNLO splitting functions for the DGLAP evolution became available [14], so full NNLO fits can be made soon. Low-x resummation is important and was shown that it can lead to differences of about 20% at $x = 10^{-3}$ and

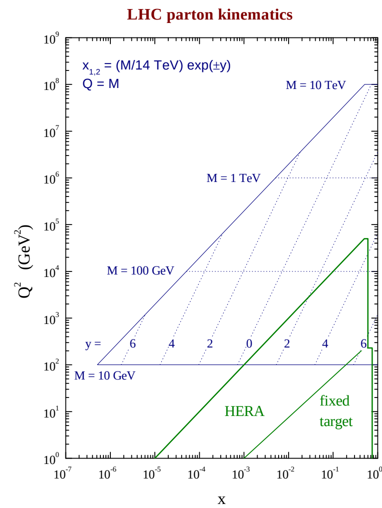

FIGURE 3. The kinematic plane (x, Q^2) and the reach of the LHC, together with that of the existing data (HERA, fixed target). Lines of constant pseudo-rapidity are shown to indicate the kinematics of the produced objects in the LHC centre of mass frame [13].

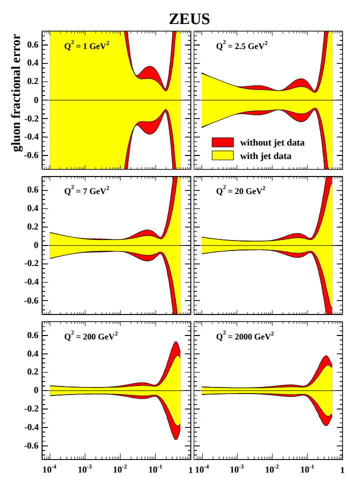

FIGURE 4. The total experimental uncertainty on the gluon PDF for a fit including the jets, compared to a fit not including jet data (outer error bands). The uncertainties are shown as fractional differences from the central values of the fits, for several values of Q^2 [17].

low Q^2 for the gluon distribution extracted by global fits [15]. On the high x side, $x > 0.7$, resummations can lead to 15% changes in the quark distributions [16].

The key issues nowadays for the global fits are the selection of data, a consistent treatement of errors and calculation of error bands. There are some tensions observed between data sets which need to be understood. While several prescriptions are being tried out for the error treatement, one radical way to approach this is to take data of one experiment only, but try to include as much as possible information. ZEUS presented and encouraging study on a combined PDF study using F_2 data and jet cross sections.

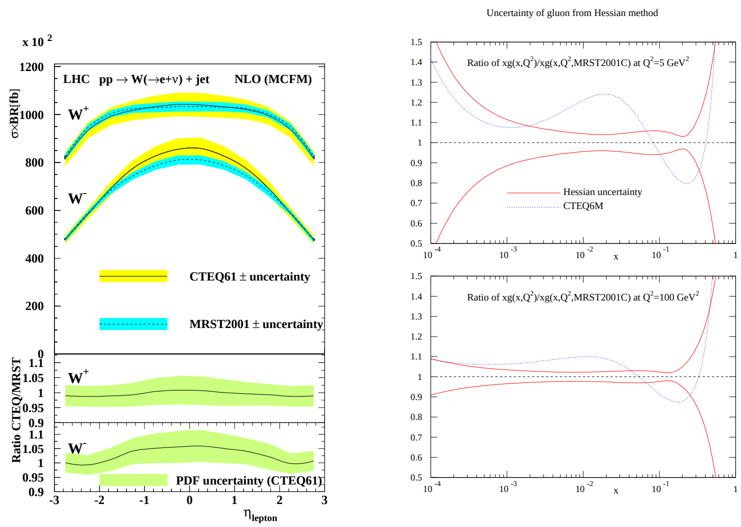

FIGURE 5. (Left) The PDF uncertainties for W^+ and W^- production [12]. (Right) The gluon distribution uncertainty from MRST, compared with the CTEQ central values [15]

Fig. 4 shows the potential gain in the uncertainty of the gluon distribution. Particularly at medium-x one can gain of order of 30% in precision in the gluon determination.

A new initiative that started during this workshop are the first steps towards a creation of combined data sets from HERA, i.e. really combining the experimental data points, rather than using the sets as two independent ones in the fit. The first results are very encouraging: they show that the extracted PDF fit from the combined data set can be much better than the fit to the sum of all the data points. What happens in practice is that one experiment 'calibrates' the other during the combining procedure. Similar improvements have been noted at LEP in combining measurements.

Turning back for a moment to the present PDF uncertainty: Fig. 5 shows the PDF error bands one gets using the present prescriptions of the PDF uncertainties, for W+jet production at the LHC. One notes that the error band of one PDF does not cover the central value of the other. One of the main reasons is the low-x behaviour of the parton distributions which is presently very different for the two sets of PDFs shown in Fig. 5. Both PDFs however are consistent with the HERA low-x data. Clearly nature may have chosen one or the other way, so how can one make progress here? What is needed are measurements that are more directly sensitive to the gluon in that region. The measurement of the longitudinal structure function F_L could do the trick, if it can reach the necessary precision. Better than the F_2^{charm}, F_L is as fundamental as F_2 with little theoretical ambiguity. To make a clean measurement of F_L HERA will have to operate some time at lower energies, and this is not yet on the program. Similarly for a good flavour separation and non-singlet structure function extraction, electron scattering on Deuterons would be needed. This option will however need some modifications in the HERA injection scheme. HERA is a unique machine and if these measurements do NOT happen at HERA, they won't happen for at least a very long time to come. Hence, the physics case should be made and discussed in all detail now, before it becomes irreversibly too late.

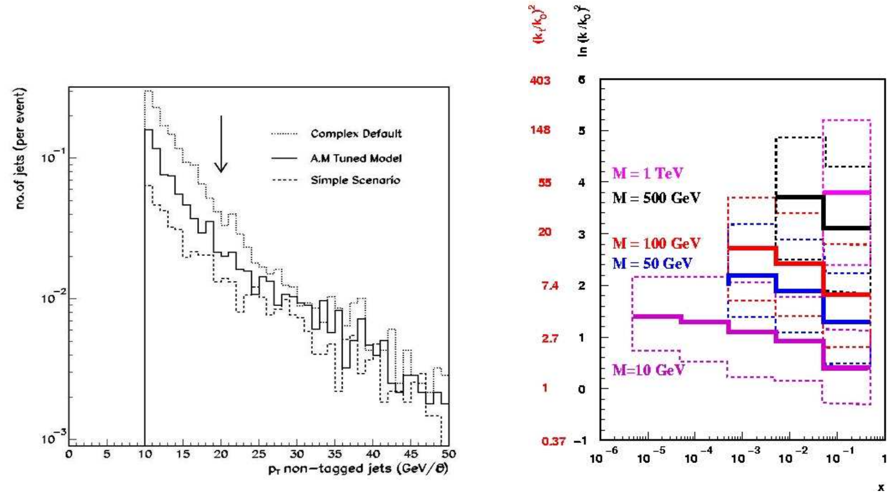

FIGURE 6. (left) Number of central jets per event in an analysis of $H \to WW^* \to 2l$ for different models/assumptions of the underlying event. The study was performed with ATLFAST. (Right) the k_T from QCD evolution for different values of the mass of a produced system M in $gg \to M$.

WG2: MULTI-JET FINAL STATES AND ENERGY FLOW

The following topics were studied by WG2

- The study of the structure of the underlying event, and of minimum bias events. New models were proposed and tested during the workshop. Tunes to existing data were discussed. A task force was installed to study similar observables in ep as done in pp for the tuning.
- The gap survival probability. The dynamics of gaps void of particles in pp and the consequences for the LHC are still poorly understood. New measurements were suggested to make further progress.
- A study of the phenomenology related to the CASCADE Monte Carlo, which shows differences with other QCD generators at the LHC at low-x
- Unintegrated PDFs and their importance e.g. on p_T distributions of the Higgs particle.
- Issues connected with Matrix Element and Parton Shower matching.
- Resummation of event shape variables.
- Future parton shower developments, such as unintegrated parton correlation functions and QEDxQCD exponentation.

Certainly one of the unknowns for studies at the LHC at present is the control of the underlying event and the event shape and number of minimum bias events which will be added to hard scattering event as pile-up: we expect about 4 interactions per bunch crossing on average at the first years luminosity of $2.10^{33}\text{cm}^{-2}\text{s}^{-1}$. Studies of tunes of PYTHIA and to some extend also HERWIG have been made using Tevatron and even lower energy data. These tunes should be validated next with the plethora of available HERA data. New models are now available: a new PYTHIA version,

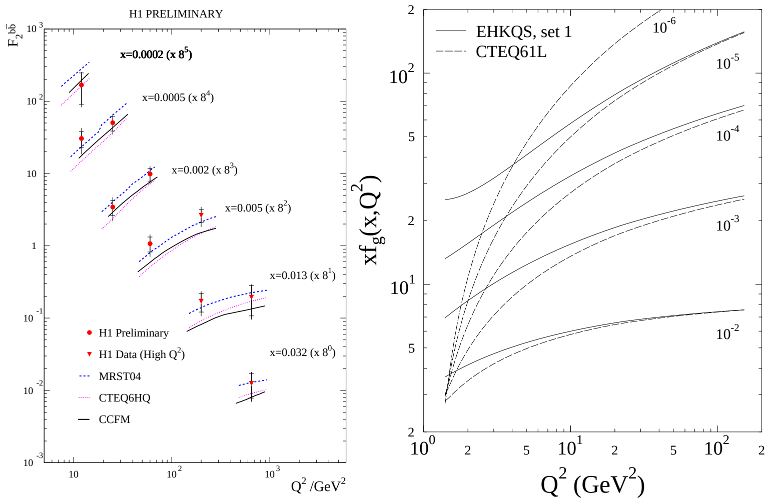

FIGURE 7. (Left) Data on $F_2^b(x,Q^2)$ from the H1 experiment, compared to QCD predictions. (Right) Comparison of EHKQS set 1 (solid line) and CTEQ1l (Dashed line) gluon distributions as a function of Q^2 for various x values.

Jimmy for HERWIG, and the SHERPA underlying event. All these need tuning and validating. The effect of the (importance of) underlying event was demonstrated with the vector boson fusion channel for Higgs production. In this process two forward jets are produced, plus the Higgs, choosen to decay in two W's, which in turn decay leptonically. Hence there is no color flow and hadron activity in the central region, except from the underlying event. To select these events over background a central jet veto is introduced, the efficiency of which will be affected and dependent on the underlying event model. Results in Fig. 6(left) show that there is a 10% variation in the selection efficiency, depending on the model choosen for the underlying event.

A challenge for final state studies will be to predict cross sections and topologies for many-jet events at the LHC, e.g. 8-jets or more. Certain SUSY cascades can lead to such number of jets, and a pure event counting technique will need a solid prediction of the QCD background. This needs good matching between matrix elements and parton showers. Such matching algorithms have been developed over the past year, in particular for *ee* and *pp* scattering, and are now being extended to *ep* such that these can be used to test on HERA multi-jet data.

A very important aspect is the intial k_T in the hard scattering, built up during the parton evolution before, say, the gluon enters in the hard scattering to produce a Higgs in the process $gg \to$ Higgs. The growth in k_T can be large as shown in Fig. 6(right) for a CASCADE calculation, for massive systems, thus affecting the p_T distribution of the produced particle. This means that for such production processes the unintegrated partons will be needed to correctly follow this evolution and provide the expected k_T in the scattering. HERA can test these k_T predictions and their effects with its data, and will allow to measure the unintegrated PDFs via final state measurements.

WG3: HEAVY FLAVOURS

Follows a list of measurements to be done at HERA, proposed by WG3

- The charm and bottom structure functions F_2^c and F_2^b
- Charm exclusive final states in γp and DIS: cross sections, fragmentation universality, contributions from higher charm resonances.
- Charm exclusive final states with jets
- Bottom exclusive final states
- Double quark tags
- Charm and bottom in charged current events
- Quarkonia
- Diffractive production of charm

To have significant impact and improve the already available data, at least 400 pb^{-1} will be needed at HERA-II. The topics listed are of general interst for the study of heavy flavour physics, but several have direct impact on the LHC. A clear case is the measurements of F_2^b, which is important for $bb \to$ Higgs production contribution. This needs a measurement of F_2^b at a scale of $m_H/2$. Fig. 7 shows recent results of a measurement of F_2^b from H1 based on HERA-I data [18]. The HERA-II data could reduce the errors by a factor of 4.

Heavy flavour measurements are also very sensitive to non-linear QCD evolution effects in the parton distributions. Fits to the HERA F_2 data at small x and small Q^2 improve by adding non-linear terms to the gluon evolution, see Fig. 7 [19]. This will lead to more charm production at low p_T [20]. The effects will become visible at the LHC for p_T values below about 2 GeV. ALICE will be best placed to measure these effects in the LHC data, since they can measure p_T values down to almost zero.

WG4: DIFFRACTION

This working group studied the following topics

- Diffractive Higgs production
- Backgrounds to diffractive Higgs
- Diffractive factorization breaking in di-jet, charm and leading neutron production
- Rapidity gap survival
- New measurements eg. F_L^D
- Exclusive diffractive di-jets
- Saturation effects and relation to multiple interactions and the gap survival

A large part of the activities was the transfer of experience and knowledge and design and operation of the detectors for forward physics from HERA to the LHC.

A topic of recent strong interest is the possibility to produce central diffractive Higgs particles in pp collisions, see Fig. 8. The advantages of this channel are [21]: a good missing mass resolution, of order 1-2 GeV via the protons for the Higgs, and low

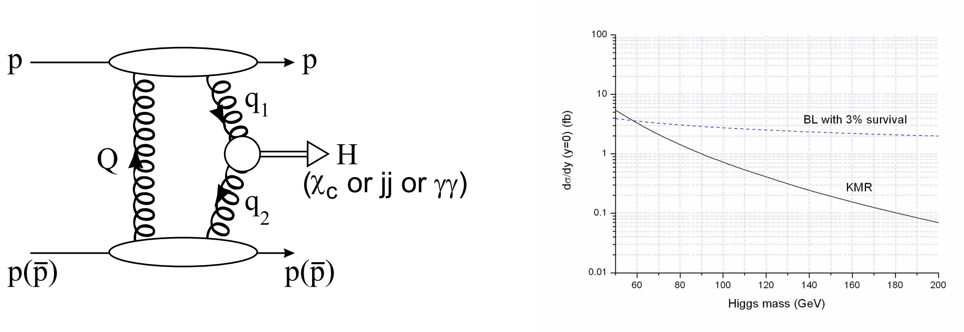

FIGURE 8. (Left) Diagram for exclusive Higgs production. (Right) Evolution of the cross section as function of mass for KMR[23] and the model as proposed in [24].

backgrounds. The cross sections are generally of the order of femtobarns and there has been quite some discussion on the validity of certain calculations. Also Monte Carlo models have been compared with one another in detail. The differences are basically understood as due to Sudakov suppression factors and parton distributions. In particular the Exhume[22] program is considered to give the more natural expected η behaviour. The KMR[23] calculation has been checked by independent groups and found to be ok. In all it means that the perturbative cross section for the Standard Model exclusive Higgs production is likely to stay below 10 fb. There are however alternative model predictions, based on non-perturbative calculations. Fig. 7(right) shows the different energy dependence in the KMR and the model proposed in [24]. It is not excluded that the total exclusive cross section could be larger than the one calculated in [23] if an additional soft component would be present.

It will be important in the coming year to test and measure the ingredients that go in that calculation. An example is the rescattering effects in collisions. It has been suggested to look into events with jets and a leading neutron at HERA [25] and study eg. $x - p_T$ correlations.

An input used in the exclusive Higgs cross section calculations are the generalized unintegrated parton distributions. HERA can measure these distributions via in exclusive J/ψ production. The double pomeron process itself can be measured at HERA in the reaction $\gamma p \to V + X + p$ with V a vector meson and X the centrally produced system. Finally the leading proton spectra as measured at HERA are found not to be described with standard Monte Carlo generators. This has an effect on the background studies to diffractive processes at the LHC, and some tunning based on the HERA leading baryon measurements will be essential.

Diffraction and low-x is part of the LHC physics program and there are plans to equip the central detectors with detectors in the forward region, which also offers new opportunities for groups to join in this activity.

WG5: TOOLS

WG5 had the following program

- Parton distribution library: LHAPDF is now the official carrier of the PDFs. It is used by the LHC experiments in generators. The HERA PDFs have been added recently. LHAPDF allows for uncertainty estimates. The Pion and Photon PDFs have been added to the library. Should the F_2^D parametrizations also be added?
- NLOLIB framework for NLO QCD programs. A uniform user interface is being developed, as well as an interface to HZTOOL. e^+e^-/ep have been included but pp still needs to be added.
- HZTOOL/JetWeb/RunMC/Cedar tools for Monte Carlo tuning. All HERA results have been included, some e^+e^- results. Include more pp data?
- Discussions on RAPGAP and CASCADE monte carlo programs for inclusive and diffractive pp
- Plenty of exchange on other MC tools, leading to new MC tools and comparisons with ep where possible.
- Continuation of the MC@LHC workshop, concerning validation of MC programs.

THE VERDICT AND OUTLOOK

Coming back to the goals that were set at the start of the workshop, one can say items $(1) \rightarrow (4)$ have been achieved. For item (5) many studies are still ongoing, and more quantitative examples/results are expected for the proceedings end of summer ’05.

The final meeting is not the end of the workshop, however. The link between the communities is now strong and should not fade away. Therefore it was unanimously decided to continue the workshop but on a "one meeting per year basis". The next meeting will be in March 2006 at CERN. Everybody is invited to continue (or start) participating in the workshop.

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