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HERA AND THE LHC*

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This report summarises some of the main results of the one year long workshop on the impact of HERA data on the physics program of the LHC.

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1. Introduction

This conference deals with studies which will be made at the LHC: precision measurements of Standard Model processes and, what we all hope, discoveries like the Higgs or physics beyond the Standard Model. 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. 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.

2. The HERA/LHC workshop

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

- To identify and prioritise 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;

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- 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: (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'04 (250 participants), and the final meeting was held at DESY in April'05 (150 participants). More information can be found on the web page [1]. Proceedings have been completed and can be found on [2]. After the proceedings were completed, it was felt that the momentum of the collaboration between the LHC and HERA community should be kept and a second phase of the workshop was launched, with a first meeting in June'06 at CERN [1].

3. 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 to improve the region of large x and Q^2 which is still statistically limited.

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 [6]. The message for the workshop is clear: we have to do better than that.

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, $\gamma+$ 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?

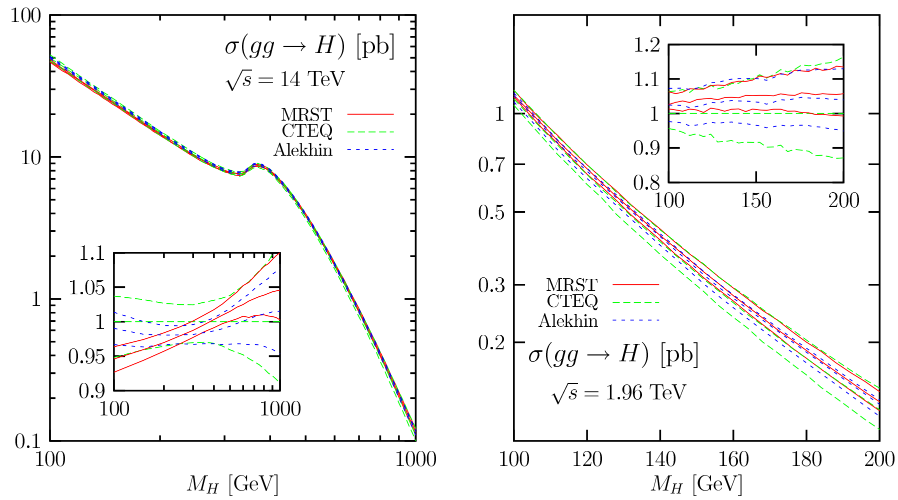


Fig. 1. The CTEQ [3], MRST [4] and Alekhin [5] PDF uncertainty bands for the NLO cross sections for the production of the Higgs boson at the LHC (left) and Tevatron (right) for the process $gg \to$ Higgs [6]. The insert shows the spread of the predictions when the NLO cross sections are normalised to the prediction of the reference CTEQ6M set.

The systematic study of well measurable LHC final states is ongoing. As an example the uncertainties for W, Z and dibosons production with experimental cuts, for the parton distributions and perturbative scales, are 4–5% and 4–9%, respectively, [7].

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. 2 shows the plane in x, Q^2 covered presently by HERA and the part that will be covered by the LHC [8]. 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 [10], so full NNLO fits can be made soon. Low-x resummation is important and it was shown that it can lead to differences of about 20% at

$x = 10^{-3}$ and low Q^2 for the gluon distribution extracted by global fits [11]. On the high x side, $x > 0.7$, resummations can lead to 15% changes in the quark distributions [12].

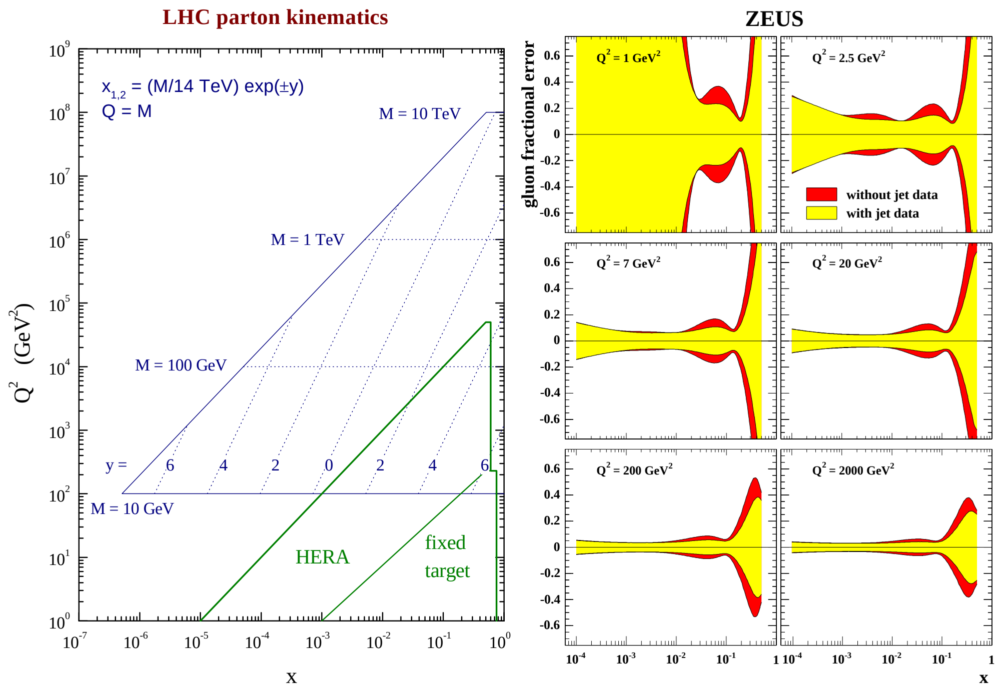


Fig. 2. Left: The kinematic plane (x, Q^2) and the reach of the LHC, together with that of the existing data (HERA, fixed target). Lines of constant pseudo-rapidity are shown to indicate the kinematics of the produced objects in the LHC centre of mass frame [8]. Right: The total experimental uncertainty 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 [9], for several values of Q^2.

The key issues nowadays for the global fits are the selection of data, a consistent treatment 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 treatment, 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 an encouraging study on a combined PDF study using F_2 data and jet cross sections. Fig. 2 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. 3 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. 3. 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

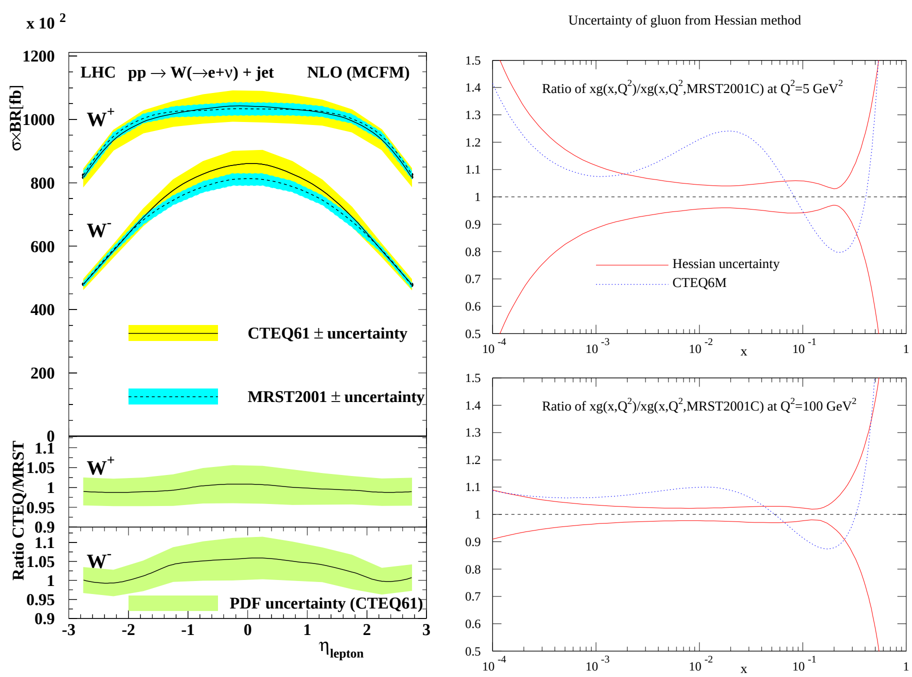


Fig. 3. Left: The PDF uncertainties for W^+ and W^- production [7]. Right: The gluon distribution uncertainty [11] from MRST, compared with the CTEQ central values.

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. HERA is a unique machine and if these measurements do NOT happen at HERA, they would not happen for at least a very long time to come.

4. 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/Parton Shower matching;
- Resummation of event shape variables;
- Future parton shower developments, such as unintegrated parton correlation functions and QED$\times$QCD exponentiation.

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. The effect of the (importance of) underlying event is demonstrated in Fig. 4 (left) for different underlying event models. Results in Fig. 4 (left) show that there is a 10% variation in the selection efficiency, depending on the model chosen 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

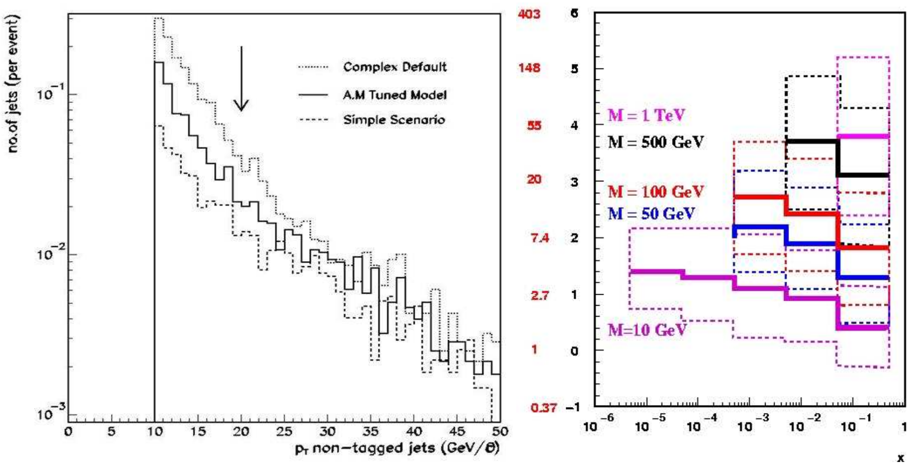


Fig. 4. Left: Number of central jets per event in an analysis of $H \to WW^* \to 2l$ for different models/assumptions of the underlying event. The study was performed with ATLFAST. Right: The k_{T} from QCD evolution for different values of the mass of a produced system M in $gg \to M$.

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 initial 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. 4 (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.

5. 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 interest 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. 5 shows recent results of a measurement of F_2^{b} from H1 based on HERA-I data [13]. The HERA-II data could reduce the errors by a factor of 4.

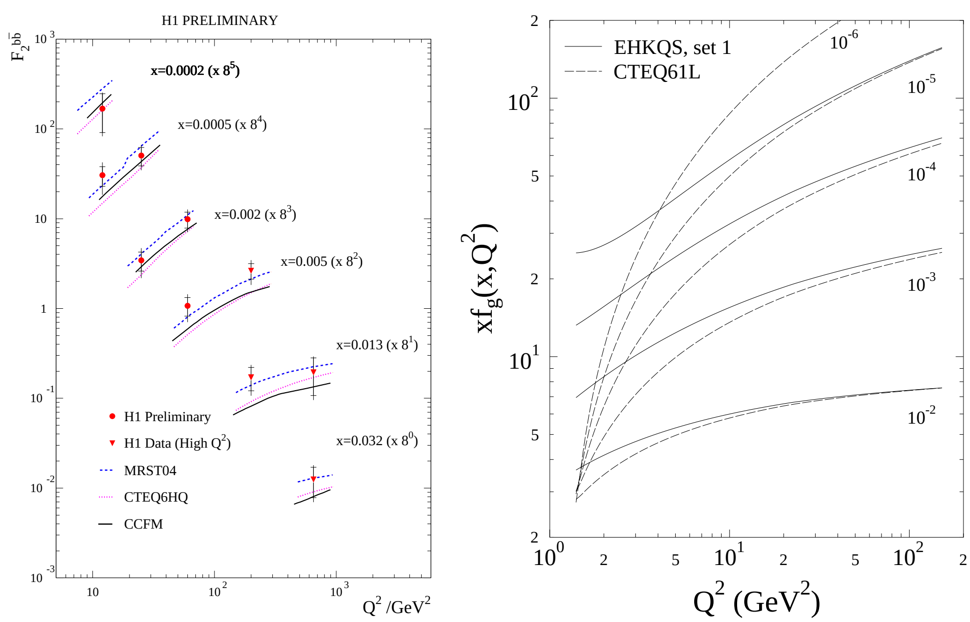


Fig. 5. Left: Data on $F_2^{\mathrm{b}}(x,Q^2)$ from the H1 experiment, compared to QCD predictions. Right: Comparison of EHKQS set 1 (solid line) and CTEQ1l (dashed line) gluon distributions as a function of Q^2 for various x values.

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. 5 [14]. This will lead to more charm production at low

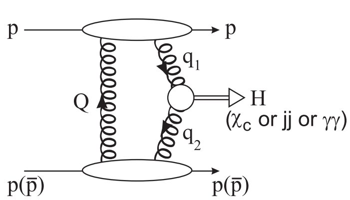
$p_{\rm T}$ [15]. The effects will become visible at the LHC for $p_{\rm T}$ values below about 2 GeV. ALICE will be best placed to measure these effects in the LHC data, since they can measure $p_{\rm T}$ values down to almost zero.

6. WG4: diffraction

This working group studied the following topics

- Diffractive Higgs production;
- Backgrounds to diffractive Higgs;
- Diffractive factorisation breaking in dijet, charm and leading neutron production;
- Rapidity gap survival;
- New measurements *e.g.* $F_{\rm L}^{D}$;
- Exclusive diffractive dijets;
- 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.



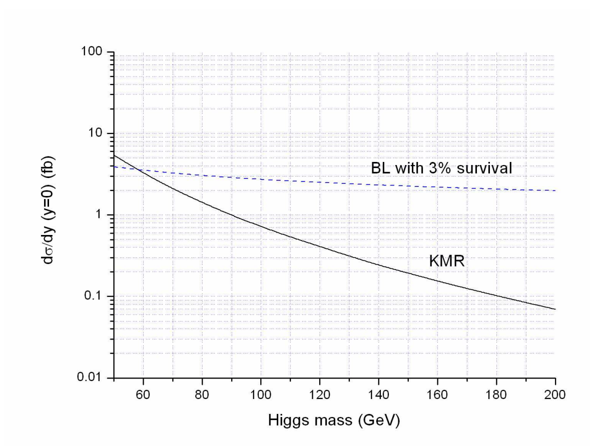


Fig. 6. Left: Diagram for exclusive Higgs production. Right: Evolution of the cross section for KMR [18] and the model proposed in [19] as function of mass.

A topic of recent strong interest is the possibility to produce central diffractive Higgs particles in *pp* collisions, see Fig. 6. The advantages of this channel are [16]: a good missing mass resolution, of order 1–2 GeV via the protons for the Higgs, and low 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 [17] program is considered to give the more natural expected η behaviour. The KMR [18] 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. 5 (right) shows the different energy dependence in the KMR and the model proposed in [19]. It is not excluded that the total exclusive cross section could be larger than the one calculated in [18] 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 re-scattering effects in collisions. It has been suggested to look into events with jets and a leading neutron at HERA [20] and study *e.g.* x–$p_{\rm T}$ correlations.

An input used in the exclusive Higgs cross section calculations are the generalised 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 tuning 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.

7. 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 parametrisations 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 pp?

- Discussions on RAPGAP and CASCADE Monte Carlo programs for inclusive and diffractive pp;

- Plenty of exchange on other Monte Carlo tools, leading to new Monte Carlo tools and comparisons with ep where possible;

- Continuation of the MC@LHC workshop, concerning validation of Monte Carlo programs.

8. 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 during the second phase of this workshop which started recently and will continue in 2007/2008. The meeting in 2007 will be at DESY in the week of the 12th March.

Some of the goals of the continuing workshop are as follows.

- PDF determination: Best possible PDFs. What is the ultimate expected precision and impact on LHC measurements? Finalise uncertainties on the PDF and QCD evolution. Determination of special PDFs, such as diffractive, unintegrated, generalised, and their uncertainties;

- Event topologies: Multiple interactions and underlying events: try to understand the physics and uncertainties. Higher order corrections: verify using HERA data;

- Reliable simulations, theory and models: tuning of free parameters to many different measurements. Use improved calculations and NLO libraries. Test alternative approaches (*e.g.* SCET?).

In short the keywords are: tools, phenomenological progress, and quantitative estimates for the impact of HERA on LHC measurements.

It is a pleasure to thank all participants of the workshop for their work, and especially Hannes Jung for the co-organization. My thanks go also to the organizers of LHC06 conference for this kind invitation.

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