EARLY LHC PHYSICS STUDIES: WHAT CAN BE OBTAINED BEFORE DISCOVERIES?

K. LASSILA-PERINI
Helsinki Institute of Physics, P.O.Box 64 (Gustaf Hällströmin katu 2), FIN-00014 University of Helsinki, Finland

The Large Hadron Collider will provide an unprecedented quantity of collision data right from the start-up. The challenge for the LHC experiments is the quick use of these data for the final commissioning of the detectors, including calibration, alignment, measuring of detector and trigger efficiencies. A new energy frontier will open up, and measurement of basic Standard Model processes will build a solid basement for any discovery studies.

1 Introduction

Apart from the well studied discovery potential for missing pieces in the Standard Model, supersymmetric particles and new physics, the Large Hadron Collider (LHC) will provide unprecedented opportunities to explore the frontier of high energy physics. Excellent reports have been presented considering the start-up strategy for the LHC experiments ATLAS and CMS, this note aims to concentrate on questions such as

1. what will the early LHC data consist of?
2. what will be the first physics publications of the LHC?
3. what is the work required before any results can be published?

These questions will be addressed by a hypothetical and speculative list of first LHC papers.

2 The context

The LHC is expected to provide collisions at nominal luminosity values of $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$ ("low luminosity") and $10^{34}$ cm$^{-2}$s$^{-1}$ ("high luminosity"). During the low luminosity running the
experiments are expected to collect 10-20 fb$^{-1}$ of data per year, whereas the high luminosity running will yield 100 fb$^{-1}$ of collected data yearly. The nominal values will be reached after a period of pilot runs during the accelerator and physics commissioning where the machine and detector conditions will be studied and understood. This note concentrates on these early periods of LHC running, and the following naming convention is used:

- **Pilot run**: machine development run interleaved with data-taking runs
- **First physics run**: run where the nominal machine parameters and the nominal low luminosity will be gradually reached, but the integrated luminosity is limited by the time needed to master the LHC operation.

With the present knowledge, the pilot run will start in 2007 and it can be estimated to take one month, the first physics run will follow the year after. For the pilot run, the integrated luminosity recorded per experiment is estimated to be of order of 10 pb$^{-1}$ if an average luminosity of $10^{31}$ cm$^{-2}$s$^{-1}$ is reached. The integrated luminosity of the first physics run is envisaged to be of order of some fb$^{-1}$.

The discovery potential of the LHC detectors has been thoroughly studied and will not be discussed in this note. It is useful to remember, however, that already with 1 fb$^{-1}$ of collected data a wide range of the possible Standard Model (SM) Higgs boson mass reach can be covered and that the experiments have a good sensitivity to supersymmetric particles, many of which can be discovered or excluded with the early data. In most discovery areas, nevertheless, a good understanding of the detector performance is required and the background processes need to be well understood before claiming discovery or exclusion, so it is most likely that such discovery papers are not among the earliest LHC publications, except if Nature has reserved surprises just over the high energy corner.

3 Start-up data

Due to the significant increase of the cross-sections of the hard processes as a function of collision energy, the event rates at the LHC start-up will be larger than other colliders even with a modest luminosity. To reach the before mentioned 10 pb$^{-1}$ of recorded data during the pilot run, a fairly low data taking efficiency of 20% (luminosity recorded/luminosity delivered) is assumed at the start-up. As a fictive example of the possible start-up rates, a selection efficiency of 20% (including the geometrical acceptance, $p_t$ cuts, and detector efficiency) is assumed for leptons from $W \rightarrow \ell \nu$ and $Z \rightarrow \ell \ell$ and 1.5% for $t \bar{t} \rightarrow \ell \nu + X$. Such selection efficiencies are much lower that foreseen in the two experiments and they are meant to be pessimistic including anything that can go wrong at the start-up. Possible event samples collected in one mont of a pilot run are shown in Table I. Even with these pessimistic assumptions, the very first LHC operation will provide a large statistics of interesting data at a completely new energy frontier. The challenge for the LHC experiments is to make best profit of these data and complete the mapping of the detector performance and make the very first physics measurements.

4 The experiments at the start-up

At the moment of writing, the construction of the LHC experiment is proceeding at full speed. The ATLAS experiment is being built in its final position in the experimental pit and the lowering of the large components of the CMS experiment from the construction hall at the surface to the experimental cavern is being prepared. At the start-up, the detectors will be fairly complete and ready enough for early physics. Some items, however, will not be present during the pilot run and they will be installed during the first long accelerator shut-down between the pilot run and the first physics run.
Table 1: Expected data samples from the pilot run.

| Process                  | $\sigma \times \text{BR}$ | $\varepsilon$ (estimate) | Events selected in 10 pb$^{-1}$ |
|--------------------------|-----------------------------|---------------------------|---------------------------------|
| $W \rightarrow \ell \nu$ | 20 nb                       | $\sim 20\%$              | $\sim 40000$                   |
| $Z \rightarrow \ell \ell$| 2 nb                        | $\sim 20\%$              | $\sim 4000$                    |
| $t\bar{t} \rightarrow \ell \nu + X$ | 370 pb | $\sim 1.5\%$ | $< 100$|
| Jet $E_T > 25$ GeV       | 3 mb                        | 100%                      | $\sim 3 \times 10^{10} \times$ prescale factor |
| Jet $E_T > 140$ GeV      | 440 nb                      | 100%                      | $\sim 4.4 \times 10^6$         |
| Minimum bias             | 100 mb                      |                           | $10^{12} \times$ prescale factor |

The final alignment and calibration will only take place with the real data and, therefore, at the very beginning, there are somewhat large uncertainties on the detector measurements, due to non optimal uniformity, $e/\gamma$ jet scale and track alignment.

5 The first publication: “Charged particle multiplicity in pp collision at $\sqrt{s} = 12$ TeV and $\sqrt{s} = 14$ TeV”

We report on a measurement of the mean charged particle multiplicity in minimum bias events, produced at the LHC in pp collisions with $\sqrt{s} = 12$ TeV and $\sqrt{s} = 14$ TeV, and recorded in the CMS experiment at CERN. The events have been selected by a minimum bias trigger, the charged tracks reconstructed in the silicon tracker and in the muon chambers. The track density is compared to the results of Monte Carlo programs and it is observed that none of the programs describe all features of the data.$^5$

5.1 Why?

The most common collisions — the so called minimum bias events — have large uncertainties, and being soft processes, it is hard to predict their structure at the high LHC collision energies. Their measurement is vital for understanding the detector backgrounds, energy scales and detector occupancy. Only when the minimum bias events are well known and understood, can the reconstruction algorithm details be fixed.

5.2 How to get there?

Counting the charged tracks is a fairly simple measurement and doable already with an only partly understood detector behaviour. Selecting the events can be done with a random trigger firing on non-empty bunch crossing which can be identified from a scintillator or electromagnetic calorimeter (ECAL) signal. Obviously, track reconstruction needs to be working, and to study the very first collisions, it needs to work without the possibly missing detector element, such as the inner pixel layers in the case of CMS.

Much of the work has already started before the first collisions. The experiments use cosmic muons to verify the functioning of the track reconstruction already before the final installation. Further on, in the operational position, the cosmic muons will be used to align and calibrate the detector in the barrel region. With the first LHC beam circulating, the beam halo muons — machine induced secondary particles crossing the detector horizontally — can be used for alignment and calibration in the endcap region. Still before the first collisions there will be beam...

$^5$All “abstracts” quoted in this note are purely fictive, speculative and not necessarily based on solid studies, and the phrasing may have been strongly influenced by existing publications.
gas interactions which produce collision like event structures with low $p_t$ tracks if interactions happen in the active detector volume. All such data collected before the start-up and during the single beam operation will be useful for gaining experience with data taking, studying dead channels, debugging readout among others.

The question to be asked for such an early measurement is how it is affected by the not yet optimal detector performance. As the quantity to be measured is the number of charged tracks rather than the track $p_t$, this study is fairly insensitive to the alignment errors. As an example, Figure 1 shows that inefficiency on the global track reconstruction induced by the rough alignment is negligible.

![Figure 1: The effect of non perfect alignment on the track reconstruction efficiency](image)

6 Then follows: “Measurement of inclusive jet cross section in pp collisions at $\sqrt{s} = 12$ TeV and $\sqrt{s} = 14$ TeV”?

We present results from the measurement of the inclusive jet cross section for jet transverse energies from 100 to 1500 GeV in the pseudorapidity range $0.1 < |\eta| < 1.4$. The results are based on 18 pb$^{-1}$ of data collected by the ATLAS Collaboration at the Large Hadron Collider at CERN. The data are consistent with previously published results. The data are also consistent with QCD predictions given the flexibility allowed from current knowledge of the proton parton distributions.

6.1 Why?

The pilot run will provide a large statistics of jet and single particle events at highest collision energies ever measured. The statistical uncertainties on many measurements are quickly smaller than experimental and theoretical systematic uncertainties. Studying jet events will yield information of perturbative QCD and it will provide the first occasion to test the accuracy of parton distribution function (PDF) whose uncertainty will influence many of the possible LHC measurements.

6.2 How to get there?

Quoting cross-sections requires knowledge of connected quantities:

$$\sigma = n_{\text{events}} / (\varepsilon_{\text{trigger}} \cdot \varepsilon_{\text{selection}} \cdot \int L)$$

(1)
where \( \int L \) is the integrated luminosity, \( \varepsilon_{\text{selection}} \) the offline event selection efficiency and \( \varepsilon_{\text{trigger}} \) the online trigger efficiency. The number of events \( n_{\text{events}} \) is measured.

To present inclusive jet cross sections as suggested in this publication, the luminosity measurement is therefore needed. The goal at the LHC is to have the uncertainty in this measurement lower that the theoretical uncertainty in cross-sections at the LHC start-up which is estimated to be approximately 5%. The luminosity measurement consists of two equally important components, the luminosity determination (the total p-p cross-section) and the luminosity monitoring (the instantaneous luminosity). The former can determined with a special measurement in the very forward region and extrapolating the total inelastic cross-section from the measured elastic cross-section according to the optical theorem. This can only be done with a special beam optics different from that of the normal running. Alternatively, the cross-section can be normalized to the SM predictions of the W and Z cross-sections which are computed with 1-2% precision. The latter, the instantaneous luminosity, can be monitored by counting simple structures in the detector, such as empty events or empty regions in the very forward calorimeter or counting tracks. It is obvious that the precision on the integrated luminosity at the start-up cannot be optimal, hardly any of the elements having been studied in detail right at the beginning. Therefore, the induced uncertainty on a total cross-section measurement will be large, but it should not prevent interesting studies on differential cross-sections as a function of jet energy and jet position.

While the offline event selection efficiency is thoroughly quantified in the preparatory studies on any physics signature, the trigger efficiency often draws less attention by physicists, at least in the preparational phase of the experiments as now. It is, however, one of the key factor in determining the cross-section, as shown in Equation 1. The trigger efficiency varies as a function of energy and position of the triggered objects, and it will be monitored by recording a fraction of rejected events and studying the causes of rejection, and by recording preselected trigger streams, i.e. recording one in N (prescale factor) events with low trigger thresholds, and studying the efficiency with which the events pass the higher threshold. The pilot run will provide enough statistics for studying the trigger efficiency.

The measurement of differential jet cross-section requires knowledge of the jet energy. The energy determination consists of three components: hadronic calorimeter (HCAL) calibration, jet energy scale, and jet energy corrections. The HCAL calibration assures that all elements give the same response to an equal signal. It can be achieved by a scan by a radioactive source and by test beam calibration in a single particle beam. A correct jet energy scale means that the measured jet energy corresponds to the energy of the originating parton. This scale can be set by using jet events where the jet energy is balanced by high \( p_t \) particle (such as \( \gamma \) or Z) in the opposite direction. The high \( t\bar{t} \) cross-section at the LHC allows \( t\bar{t} \rightarrow bWbW \rightarrow b\ell\nu jj \) events to be used to set the jet scale as W and top quark masses are known. Isolated charged tracks may also be used to connect the single particle beam calibration to the measured jet energy. The jet energy corrections are needed to have a jet energy response linear in energy and independent of jet coordinates. The corrections can be defined for example from di-jet events where one jet is in a well calibrated energy and coordinate region and the other jet is to be calibrated. While the pilot run will provide an excellent statistics for many jet studies, it is likely that achieving the complete jet energy calibration requires some time and detailed studies as many elements used in jet calibration need a calibration of their own.

One of the main issues of the jet energy spectrum measurement is to compare it with the SM predictions. There are many systematic uncertainties involved, as an example the long list studied by the experiments at Tevatron: high \( p_t \) and low \( p_t \) hadron response, energy scale stability, underlying event, calorimeter resolution, fragmentation of partons to stable hadrons, \( e/\gamma \) response. Large amount of work is needed to address all these issues which will be important at the LHC as well, and it may well be that before the publication on jets some single
particle spectrum measurements or measurement of Drell-Yan production of dileptons, and in particular \( Z \to \mu^+\mu^- \) may make their way through as publications.

7 And next: “Search for new high mass particles decaying to lepton pairs in pp collisions at \( \sqrt{s} = 14 \) TeV”

A search for new particles \((X)\) that decay to electron or muon pairs has been performed using approximately 800 pb\(^{-1}\) of pp collision data at \( \sqrt{s} = 14 \) TeV collected by the CMS experiment at the LHC at CERN. Limits on \( \sigma(pp \to X) \cdot BR(X \to \ell\ell) \) are presented as a function of dilepton invariant mass \( m(\ell\ell) > 150 \) GeV/c\(^2\), for different spin hypotheses (0, 1, or 2). Lower mass bounds for \( X \) from representative models beyond the Standard Model including heavy neutral gauge bosons are presented.

7.1 Why?

New resonance in the di-lepton spectrum may be seen — or excluded — very early, already at the beginning of the first physics run. There are many beyond SM scenarios which can produce a new heavy di-lepton resonance, and among the possible early-comers are new heavy vector bosons\(^4\) or Randall-Sundrum gravitons\(^5\). They form a spectacular peak in absence of SM backgrounds.

7.2 How to get there?

In the most favourable cases, observation of heavy di-lepton resonances does not pose particular problems. The measurement of a broad peak with low background is not sensitive to detector uncertainties, and is therefore feasible already with early data. However, when it comes to exclusion, more care is needed to quantify the systematic uncertainties. Due to the large event rate at the LHC, the statistical uncertainty in many measurements soon becomes negligible in comparison with the systematic uncertainties. The systematic uncertainties may come from theoretical predictions or from the event modelling, they may be purely experimental and be induced from the accelerator conditions.

8 And certainly: “Top quark mass measurement in pp collisions at \( \sqrt{s} = 14 \) TeV”

Preliminary results on the measurement of the top quark mass in the ATLAS experiment at the LHC are presented. In the lepton plus jets channel, the ATLAS Collaboration measures 178.2\(\pm 0.4\)(stat.)\(\pm 7.2\)(syst.) GeV/c\(^2\), using a sample of \( \sim 102 \) pb\(^{-1}\) at \( \sqrt{s} = 14 \) TeV. Events with an isolated electron or muon with \( p_t > 20 \) GeV/c and four jets with \( E_t > 40 \) GeV were selected. The mass is obtained from the invariant mass of the three highest \( E_t \) jets. The uncorrected mass shows a slight dependence on the jet energies, which has been taken into account in the energy scale corrections.

8.1 Why?

The LHC is a top factory: the \( t\bar{t} \) cross-section at the LHC energies is 833 pb while it is 7 pb at the Tevatron. In consequence, early LHC runs will provide high enough statistics to observe and measure top quark properties with simple analysis techniques.
8.2 How to get there?

The top quark mass at the LHC from can be first measured with a very simple and robust selection of the $t\bar{t} \rightarrow bWbW \rightarrow b\ell\nu jj$ channel. One isolated lepton ($e$ or $\mu$) is required and exactly 4 jets. No kinematic fits nor $b$-tagging is required to start with, whereas these techniques are of ultimate importance at the Tevatron due to the lower statistics. The mass peak can be obtained by plotting the invariant mass of the highest $E_t$ jets as shown in Fig. 2, and constraining two of the jets with the $W$ mass, the background can be further reduced.

![Figure 2: The reconstructed top mass, without $b$-tagging, for 150 pb$^{-1}$ of data. The $W + 4 \text{ jet}$ background is added to signal events and shown as a dashed line.](image)

Apart from being an important measurement on its own, the top mass measurement gives important feedback on detector performance even at the early stage when the mass precision is not yet competitive with earlier Tevatron studies. A wrong top mass indicates error in the energy scale. The top sample will also be useful to commission the $b$-tagging algorithms.

9 Conclusions

Even with a limited performance at the start-up, the LHC will provide a large quantity of data right from the beginning. Already the very first pilot run can provide 10 pb$^{-1}$. These data will come in a short period of order of one month and there will be very little time for fine-tuning. There are many unknowns and the machine operation will vary from single beam to close to nominal conditions. The experiments will need to make sure that as much useful data as possible will be recorded as the physics commissioning of the detectors rely mainly on real collision data.

The first physics run is expected to provide some fb$^{-1}$ of data. The data volumes are unprecedented and the collaborations will have to cope with data access, fast reconstruction and analysis code development cycle, and how to do all this worldwide, putting the grid computing in serious use.

Despite of the difficulties, many interesting studies can be made and will have to be made with the early data. Examples of possible early measurements have been shown, and to conclude — although beyond the scope of this note — yet another is suggested:
And perhaps: “Evidence for squark and gluino production in pp collisions at $\sqrt{s} = 14$ TeV”

Experimental evidence for squark and gluino production in pp collisions $\sqrt{s} = 14$ TeV with an integrated luminosity of 97 pb$^{-1}$ at the Large Hadron Collider at CERN is reported. The CMS experiment has collected 320 events of events with several high $E_T$ jets and large missing $E_T$, and the measured effective mass, i.e. the scalar sum of the four highest $P_T$ jets and the event $E_T$, is consistent with squark and gluino masses of the order of 650 GeV/$c^2$. The probability that the measured yield is consistent with the background is 0.26%.

Acknowledgments

This note relies on the work done by my CMS and ATLAS colleagues. Many excellent presentations have been shown on this topic, and I’m grateful to F. Gianotti, A. de Roeck, G. Rolandi and O. Buchmueller among others as I have learnt much on the subject from their lectures and presentations. Furthermore, special thanks go to A. de Roeck, P. Janot, D. Denegri, I. Tomalin and R. Tenchini for their comments and suggestions.

References

1. F. Gianotti and M. Mangano, hep-ph/0504221, CERN-PH-TH/2005-072
2. CMS Note 2006/029
3. CDF Collaboration: hep-ph/0102074
4. R. Cousins, J. Mumford and V. Valuev: CMS Note 2005/02
5. C. Collard and M.-Cl. Lemaire: CMS Note 2004/024
6. S. Bentvelsen and M. Cobal: ATL-PHYS-PUB-2005-024