Precision Measurements at the LHC

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In addition to the large discovery potential for Higgs bosons and new physics phenomena, like for instance Supersymmetry, experiments at the LHC will also be able to perform precise measurements of many Standard Model processes. The huge cross sections and the high collision energy will allow the exploration of less well tested areas of the Standard Model and to improve significantly on the precision of many parameters. Therefore the detailed experimental study of known Standard Model processes at the LHC will not only prepare the anticipated discoveries but also complement their interpretation. This article describes some selected items on the perspectives of the two general purpose detectors ATLAS and CMS on the determination of parton distribution functions, tests of QCD and electroweak physics at the highest energies and the physics of the top quark.

1. Introduction

The Large Hadron Collider (LHC) under construction at CERN in Geneva combines the two most important virtues for high energy physics experiments. From the year 2007 it will provide proton-proton collisions at the highest centre-of-mass energy of 14 TeV and large luminosities in the range from $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ in the initial phase up to $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ at a later stage.

Cross sections of various Standard Model (SM) processes in $p\bar{p}$ and pp collisions as a function of the energy are compared in Fig. 1 [1]. For instance the production cross sections for the heavy gauge bosons W and Z and $t\bar{t}$ quark pairs are significantly larger at the LHC than at the Tevatron because of the higher energy. Already during the low luminosity phase of the LHC this results in large production rates as can be seen from the right scale of this plot. Approximately 200 W, 50 Z bosons and one $t\bar{t}$ pair will be produced every second. Even when taking into account reasonable values for selection efficiencies and the branching ratios into clean leptonic final states (electrons and muons) it is evident from these numbers that large data samples will be acquired shortly after the start-up of the collider. Besides providing excellent means to calibrate and understand the detectors these data samples will allow

many precision measurements.

2. The structure of the proton

Most of the interesting reactions at the LHC are hard scattering processes of the partons inside the protons. Therefore the accurate knowledge of the parton distribution functions (PDF) of quarks, anti-quarks and gluons is mandatory for the interpretation of the data. The region of the fractional parton momentum x and the momentum transfer Q^2 interesting for LHC physics is shown in Fig. 2. This is compared to the area investigated by fixed target experiments and at the electron-proton collider HERA. As the overlap of both regions is small theoretical models like the DGLAP evolution [2] are required to extrapolate from the experimentally tested regions of low Q^2 to the higher momentum transfers important for the LHC physics. It is therefore desirable to determine the PDFs for all parton species directly from LHC data, to test the extrapolation models and to improve the precision.

SM processes provide various means to measure and constrain the PDF through differential distributions like the distributions of transverse momentum p_T and pseudo-rapidity η .

Obvious examples are measurements of differential cross sections in W and Z production, but

Figure 1. Cross sections of various SM processes in (anti)proton-proton collision in the Tevatron and LHC energy ranges.

also quark gluon scattering processes like $gq \rightarrow q\gamma$. These reaction have a large cross section and thus lead to small statistical uncertainties already in the initial phase of the experiments. However the achievable precision of such analyses still has to be demonstrated taking into account full detector and background simulations. Because of the high cross section of these processes the analyses are particularly suited for the start-up phase at lower luminosities.

Another issue related to the composite structure of the proton is the so-called underlying event which is understood as the proton-proton interaction without the hard scattering process. The precise modelling of the underlying event is important for the experimental quantities like jet definition and resolution and therefore for the correct interpretation of the data. Experimental studies of the underlying event have been per-

Figure 2. LHC area of interest in the $x-Q^2$ -plane of the scattering partons compared to the regions accessible at HERA and fixed target experiments.

formed at the Tevatron [3] but their extrapolation to the LHC energy is rather uncertain [4]. Again, the initial LHC data will be important to perform experimental studies and to improve the theoretical description of this effect.

A new experimental problem at the LHC is the event pile-up due to the high instantaneous luminosity. Already at the design luminosity for the first LHC phase of $2 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ on average seven pp interactions per bunch collision will take place which will increase to 35 at high luminosities. Also these interactions must be, at least on a statistical basis, separated from the hard scattering process which requires experimental studies as well as a very good theoretical description.

3. QCD and Jet Physics

Hadron colliders are a predestined tool for probing strong interactions and the physics of

Figure 3. Differential jet cross section as a function of the transverse jet energy (ATLAS).

jets. The observable spectrum of transverse jet energies (E_T) ranges from about 200 GeV to several TeV with the corresponding cross sections varying over 11 orders of magnitude. This is illustrated in Fig. 3 showing the differential cross section $d\sigma/dE_T$ in various intervals of rapidity. Of particular interest are the jets at the highest energies. For an integrated luminosity of 300 fb^{-1} which corresponds to a few years of LHC operation at the highest instantaneous luminosity about 4 million jets with $E_T > 1 \text{ TeV}$ and still 400 with $E_T > 3 \text{ TeV}$ are expected per experiment [5]. These samples will allow to probe QCD at the smallest distance scales and provide information on a possible quark substructure.

4. Electroweak physics

The LHC will abundantly produce W and Z bosons which through their leptonic decays provide relatively clear signatures and are readily identifiable. The experiments will hence be able to study the properties of W and Z bosons and to complement and extend the tests of the electroweak theory performed so far at e^+e^- and $p\bar{p}$ -

colliders.

4.1. The mass of the W boson

An important parameter for precision tests of electroweak theory is the mass of the W boson. Techniques to measure this parameter at hadron colliders have been developed and already today the Tevatron experiments provide results competitive to the precision reached at LEP. At the LHC the overwhelming statistics on Z bosons can be used to experimentally constrain theoretical uncertainties on the production and to determine accurately the detector response. This will minimise the dependence on Monte Carlo simulations and the corresponding uncertainties.

Figure 4. Expected transverse energy spectrum of electrons scaled to the W mass in the channel $W \rightarrow e\nu$ together with the contributions from background sources (CMS).

Fig. 4 shows the expected experimental distribution of the electron transverse energy in selected $W \rightarrow e\nu$ decays. The background contributions from other processes are small and already with 1 fb^{-1} of integrated luminosity large

statistics can be accumulated. The determination of the W mass from this and other distributions will be limited by experimental and theoretical systematic uncertainties. Detailed studies [6,7] show that the LHC experiment have the potential to further improve the error on m_W beyond the anticipated uncertainty of about 20 MeV from final LEP and Tevatron Run II data. A very good understanding of the detector and improved theoretical calculation are required to achieve this goal.

4.2. Drell-Yan process

Figure 5. Mass spectrum of Drell-Yan lepton pairs in 50 GeV bins.

Drell-Yan production of lepton pairs $q\bar{q} \rightarrow e^+e^-, \mu^+\mu^-$ is the equivalent of the reaction $e^+e^- \rightarrow \text{hadrons}$ which was extensively studied at LEP and SLC. This process is not only an important tool to constrain the PDFs but also the

discovery channels for heavy new particles decaying into leptons, e.g. a Z' boson. Fig. 5 shows the expected number of events per di-lepton channel and experiment as a function of the mass for a total luminosity of 100 fb^{-1} in comparison to the expectation at the Tevatron Run II (10 fb^{-1}) [1]. The higher luminosity and energy at the LHC will extend the sensitivity well beyond the reach of the Tevatron into the TeV range. Already with the modest integrated luminosity of approximately 1 fb^{-1} which is expected to be available in 2008 the sensitivity of the LHC will extend beyond the reach of the Tevatron experiments.

4.3. Boson gauge couplings

The high energy makes the LHC also an ideal place to study di-boson production from which information on the triple gauge boson vertices can be deduced. In the SM two such vertices, $WW\gamma$ and WWZ exist whereas all others, in particular those involving only the neutral bosons γ and Z , do not.

The $WW\gamma$ vertex is tested in $W\gamma$ final states and a sensitive variable is the transverse momentum of the photon of which an example is shown in Fig. 6. Deviations from the SM are described by the parameters λ and $\Delta\kappa$ which have been found to be consistent with zero at the percent level at LEP from studies of W pair production ($e^+e^- \rightarrow W^+W^-$). From an analysis of $W\gamma$ events at the LHC limits on the coupling parameters can be derived as shown in Fig. 7. In particular the sensitivity to λ is much higher at the LHC because deviations from the SM induced by this coupling parameter scale with the square of the centre-of-mass energy. In a similar way $Z\gamma$ events will be used to observe anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings.

Final states with two heavy gauge bosons have not yet been doubtlessly observed at the Tevatron. Again, owing to the high energy and luminosity final states like WZ and ZZ will be copiously produced at the LHC and their leptonic decays will allow a clean event selection. This is illustrated in Fig. 8 which shows the mass distribution of the Z candidate in selected WZ events together with the background. It has been shown that less than 1 fb^{-1} are required to firmly estab-

Figure 6. Photon p_T spectrum in selected $W\gamma$ final states for SM couplings (filled histogram) and for coupling parameters λ and $\Delta\kappa$ consistent with current limits [8].

lish the SM signal of WZ and ZZ production [9]. The analysis of these events will then contribute to tests of triple gauge couplings.

In the SM also vertices with four gauge bosons exist. These quartic couplings contribute to final states with three bosons. However, final states of three heavy bosons are difficult to observe due to several neutrinos from leptonic W decays, e.g. $pp \rightarrow WWW + X$, or because of low cross sections like for $pp \rightarrow ZZW + X$ [10,11]. Therefore the easiest channel to observe quartic gauge boson couplings is $pp \rightarrow W\gamma\gamma + X$. Fig. 9 shows the expected transverse momentum spectrum for the SM signal and background proving that the quartic $WW\gamma\gamma$ coupling is observable. Anomalous contributions to it would be observable as an increase in the cross section at high p_T values (see Fig. 10).

Figure 7. Limits in the plane $\lambda - \Delta\kappa$ obtainable for various integrated luminosities from studies of $W\gamma$ final states.

5. Physics of the top Quark

The LHC is also a real top quark factory which will permit precision measurements of the properties of the heaviest SM fermion. Contrary to the Tevatron the dominant production process for top quark pairs is gluon fusion $gg \rightarrow t\bar{t}$ contributing with about 87% much more than quark annihilation $q\bar{q} \rightarrow t\bar{t}$. The top quark decays to almost 100% into a b quark and a W boson such that the signature of a $t\bar{t}$ pair is given by the decay topology of the W pair in addition to the two b quarks in the final state. The experimentally cleanest modes are characterised by the leptonic (electron or muon) decay of one or both W bosons which are referred to as semi-leptonic and di-lepton channel, respectively.

The experiments will be able to establish a $t\bar{t}$ signal very quickly with relatively low integrated luminosity. As an example Fig. 11 shows the result of a selection for di-leptonic events for 1 fb^{-1} [13]. After removing the contribution of $Z + \text{jets}$ events with a cut on the invariant mass

Figure 8. Selection of leptonic WZ final states in 1 fb^{-1} : The di-lepton mass closest to the Z hypothesis is shown for signal and background.

of the lepton pair the only significant background remaining are other $t\bar{t}$ final states.

5.1. Measurement of the top mass

An important measurement is the precise determination of the top quark mass which is a crucial quantity for precision tests of the SM as it enters quadratically in quantum corrections. The most evident channel for a precise top mass measurement is the semi-leptonic final state which provides a clear signature from the high momentum lepton together with a high branching ratio and full mass information from the hadronically decaying top quark. The top mass is then reconstructed from the two light quark jets exploiting a W mass constraint and one b-quark jet.

Fig. 12 shows a mass distributions obtained from kinematic reconstruction of the semi-leptonic events [14]. Very clean top samples can be obtained in this channel where the signal to background ratio can be adjusted by the selection criteria. This offers the possibility to optimise the analysis for the available integrated luminosity,

Figure 9. ATLAS simulation for the SM expectation of the transverse momentum spectrum in selected $W\gamma\gamma$ final states for 30 fb^{-1} .

balancing statistical and systematic errors and to obtain a significant result for the top mass rather quickly. The achievable ultimate precision from this channel is expected to be $\Delta m_t \approx 1 \text{ GeV}$ where the knowledge of the energy scale of b-quark jets and of final state radiation will be the main limiting factors.

Also the other $t\bar{t}$ decay modes will contribute to the top mass determination. The fully hadronic decay mode has a large branching ratio of 45% but the large QCD background and the six jets in the final state create a difficult environment and ambiguities. Even though the two neutrinos present in the di-lepton channel lead to kinematically underconstraint events methods have been developed and applied to exploit this channel for the top mass measurement [13].

Another interesting mode for the mass measurement are top decays where a J/Ψ meson emerges from the b fragmentation and the W decays into an electron or muon. The J/Ψ is readily identifiable by its decay into two leptons and the invariant mass of the J/Ψ and the lepton from the W decay is rather sensitive to m_t [15]. The partially reconstructed top mass is independent of the b jet energy scale, thus circumventing the problem limiting the precision of the inclusive semi-leptonic channel.

Figure 10. Impact of anomalous quartic coupling constants on the photon spectrum in $W\gamma\gamma$ events [12].

5.2. Spin correlation in $t\bar{t}$ production

The production of top pairs at the LHC offers the opportunity to study the spin of a quark at production. Because of its high mass the lifetime of the top is very short such that no bound hadron states form and the information on the top quark spin is preserved until its decay. The $t\bar{t}$ spin correlation A is defined as the asymmetry of finding top and anti-top in the same or in different polarisation states:

$$A = \frac{N(t_L\bar{t}_L + t_R\bar{t}_R) - N(t_L\bar{t}_R + t_R\bar{t}_L)}{N(t_L\bar{t}_L + t_R\bar{t}_R) + N(t_L\bar{t}_R + t_R\bar{t}_L)}.$$

This quantity is sensitive to the production mechanism because different spin correlations are expected for the t -channel gluon fusion process ($A = +0.43$) and the s -channel quark annihilation ($A = -0.47$) [16]. Since the gluon fusion dominates, a combined value of $A = 0.32$ is predicted at the LHC [17].

The angle of the charged lepton in the (anti)-top rest frame can be used as spin analyzer. The double differential distribution of $\theta_{\pm}^*$ for the pos-

Figure 11. Mass distribution of the lepton pair in di-lepton $t\bar{t}$ candidates corresponding to 1 fb^{-1} (CMS). The broken lines indicate the mass window used to remove $Z + \text{jets}$ events.

itive and negative lepton in di-lepton events as shown in Fig. 13 is obtained. From di-leptonic $t\bar{t}$ events in 30 fb^{-1} a precision of $\Delta A \approx 0.04$ can be obtained.

5.3. Total and differential cross sections

Evidently the determination of the total cross section $pp \rightarrow t\bar{t}$ at 14 TeV is an important and interesting measurement in itself. Moreover as it depends strongly on m_t it can provide another handle on the top mass provided that the experimental, namely on the luminosity, and theoretical uncertainties can be controlled to the percent level. Also precise measurements of differential cross sections as $d\sigma_{t\bar{t}}/dp_T$ and $d\sigma_{t\bar{t}}/d\eta$ are very valuable as they constrain quark and gluon PDFs at high Q^2 values and help to reduce uncertainties on discovery channels like Higgs and SUSY production channels.

Of particular interest is also the invariant mass distribution of the $t\bar{t}$ system. A hypothetical particle decaying preferentially into the heaviest SM

Figure 12. Top mass distribution in the semi-leptonic channel obtained from a kinematic fit and using 1 fb (CMS).

particle would show up as a resonance in the differential cross section $d\sigma_{t\bar{t}}/dm_{t\bar{t}}$. The result of an ATLAS simulation is shown in the left part of Fig. 14 for a 1.6 TeV particle [7]. In the absence of such a resonance stringent limits can be set.

The large available statistics at the LHC will allow to search for rare decays of the top quark. Such analyses comprise rare SM decays such as the CKM suppressed modes $t \rightarrow W^+s$, W^+d and the higher order processes $t \rightarrow W^+Zb$, $t \rightarrow W^+W^-c$ as well as flavour changing neutral current decays like $t \rightarrow cZ$.

6. Search for the Higgs boson

The experimental search for Higgs bosons will be a central point of the LHC programme and the experiments will definitely answer the question if a Higgs boson exists. The sensitivity of the experiments covers the allowed mass range from the experimental limit of 114 GeV [18] to the largest theoretically allowed value of 1 TeV.

The most difficult Higgs mass values are just

Figure 13. Determination of the $t\bar{t}$ spin correlation in the di-lepton channel: Double differential distribution of the lepton angles in the top quark rest frames after detector simulation and acceptance corrections.

above the experimental limit because here the dominant decay channel $H \rightarrow b\bar{b}$ cannot be exploited due to the enormous b-quark background from QCD production. The most promising channel is $H \rightarrow \gamma\gamma$ which however has a low branching order of only about 10^{-3} and thus requires larger integrated luminosity. At around 140 GeV Higgs decays into heavy gauge bosons become dominant which provide clean signatures through their leptonic decays resulting in lower luminosities required to establish a Higgs signal. This is illustrated in Fig. 15 which summarises the achievable statistical significance as a function of m_H . An integrated luminosity of 30 fb^{-1} , corresponding to three years operation at $10^{33} \text{ cm}^{-2}\text{s}^{-1}$, is sufficient to discover the SM Higgs with a significance of five standard deviations independent of its mass. Large parts of the allowed mass region can be explored with significantly less luminosity.

Figure 14. Invariant mass distribution of the top quark pair in the presence of a hypothetical resonance at 1.6 TeV decaying into $t\bar{t}$ [7].

7. Conclusions

The general purpose experiments ATLAS and CMS will have a large physics potential not only for discovery of new physics phenomena but also for precise test of the SM in known channels. The high energy and luminosity of the LHC will offer the possibility to explore a new energy domain and to acquire large data sets of processes which today lack of statistics.

In particular in the initial phase of the experimental programme the investigation of SM processes will be indispensable to understand the sophisticated detectors, to reduce at the relevant energy scale the theoretical uncertainties on QCD and PDF and this way prepare the basis for the anticipated discoveries. Careful studies of SM reactions can be used to understand and normalize Monte Carlo generators which are needed in combination with data to understand the backgrounds to new physics.

Beyond that the LHC opens many possibilities for precise tests of the SM of which important examples are discussed above and which are completing its discovery potential. Because of the large event rates most of the SM analyses will be

Figure 15. Statistical significance for the observation of the SM Higgs boson as a function of its mass using 30 fb^{-1} and various decay channels. The horizontal lines indicate 5σ significances at different integrated luminosities.

limited by systematic uncertainties. To achieve the optimum precision it will be important to develop and to explore different techniques for the measurements.

The measurements discussed here are complementary to the experiments at the International Linear Collider (ILC) which will allow to further improve on precision test of today's Standard Model and further enlight discoveries made at the LHC [20].

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