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Prospect for Electroweak Measurements at the LHC

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Abstract

The prospects for electroweak measurements at the Large Hadron Collider (LHC) are discussed. In addition to high-luminosity results, special emphasis is placed on early start-up measurements with a total luminosity ranging from 10/pb to 100/pb, using the general-purpose detectors ATLAS and CMS and their initially larger calibration and alignment uncertainties. Topics discussed here include inclusive W and Z production, W-boson mass, Z forward-backward asymmetry, Z-plus-jets production and di-boson production, the latter constraining trilinear electroweak gauge couplings.

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Prospects for Electroweak Measurements at the LHC

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The prospects for electroweak measurements at the Large Hadron Collider (LHC) are discussed. In addition to high-luminosity results, special emphasis is placed on early start-up measurements with a total luminosity ranging from 10/pb to 100/pb, using the general-purpose detectors ATLAS and CMS and their initially larger calibration and alignment uncertainties. Topics discussed here include inclusive W and Z production, W-boson mass, Z forward-backward asymmetry, Z-plus-jets production and di-boson production, the latter constraining trilinear electroweak gauge couplings. (Invited talk at the 34th ICHEP, Philadelphia, USA, July/August 2008)

1. INTRODUCTION

After more than a decade of construction, the LHC has successfully been turned on in September of 2008. Following the end-of-year shutdown, 2009 will see first proton-proton collisions, at centre-of-mass energies of perhaps 900 GeV (injection), 10 TeV and 14 TeV, with a total luminosity reaching 1/fb or more. This paper summarises the prospects for electroweak measurements at the LHC with the two general-purpose detectors ATLAS and CMS.

Both ATLAS and CMS are built for high-pt physics at the LHC. Their most visible difference is in their size and magnetic field arrangement: while ATLAS is dominated by a 2.5-3.5 Tesla toroid combined with a central 2 Tesla solenoid, CMS uses a large superconducting solenoid of 4 Tesla, with the outer return flux instrumented with muon chambers. The muon systems of the detectors provide a coverage of 2.7 (ATLAS) and 2.4 (CMS) in pseudo-rapidity $|\eta|$. The momentum resolution for muons of 1 TeV transverse momentum (pt) is 8% in ATLAS and 5% in CMS. The central tracking system of both detectors covers $|\eta| < 2.5$, providing resolutions of 3.7% (ATLAS) and 1.5% (CMS) for tracks with pt of 100 GeV. The electromagnetic crystal calorimeter of CMS provides a superior energy resolution for electromagnetic showers, $3\%/\sqrt{E} \oplus 0.25\%$ within $|\eta| < 3.0$, versus $10\%/\sqrt{E} \oplus 0.5\%$ within $|\eta| < 3.2$ for the ATLAS calorimeter. Conversely, the ATLAS hadronic calorimeter ($|\eta| < 4.9$) provides for a better energy resolution compared to CMS ($|\eta| < 5.2$). For jets and combining the electromagnetic and hadronic calorimeter response, energy resolutions of $60\%/\sqrt{E} \oplus 3\%$ (ATLAS) and $70\%/\sqrt{E} \oplus 8\%$ (CMS) are expected. The resolutions vary strongly with η; more details can be found in [1].

Compared to the Tevatron centre-of-mass energy of 2 TeV, the factor 7 higher energy of the LHC results in cross sections for the production of heavy particles to increase by up to one or two orders of magnitude. With an instantaneous luminosity of $10^{33}/cm^2/sec$, the typical LHC event rates are 150 Hz W, 50 Hz Z and 1 Hz $t\bar{t}$. In an initial luminosity of 10/pb, we expect 150000 $W \to e\nu$ events, 15000 $Z \to ee$ events and 10000 $t\bar{t}$ events. Hence very soon after LHC start-up, event statistics of electroweak final states will not limit the measurements.

The signature of $W \to \ell\nu$ events is given by a high-energy lepton, missing (transverse) energy due to the neutrino, and a hadronic system recoiling against the decaying W boson. Inclusive $Z \to \ell^+\ell^-$ events contain a pair of high-energy leptons of opposite electric charge, no missing energy but again a hadronic recoil system. In both cases, the hadronic recoil spans the region from being very soft to hard, possibly even leading to one or more jets.

2. INCLUSIVE W/Z PRODUCTION

Inclusive W/Z production is considered as a fundamental benchmark process, also at the LHC, where it will be measured in the new regime of 10 TeV and 14 TeV center-of-mass energy. The cross section at 14 TeV is about 180nb and 60nb for W and Z production, respectively, and is theoretically one of the best understood cross sections at hadron colliders, especially concerning uncertainties due to radiative corrections and parton distribution functions (PDFs). The W/Z process has the potential to become a high-pt reaction for the determination of the luminosity at the few % uncertainty level. Further, inclusive W/Z production serves as the starting point for more detailed analyses, such as measuring the boson pt spectrum, looking for additional jets, or measurements of the Z-decay asymmetry and W-boson mass and width. In particular, Z events provide a crucial calibration source, given the precise knowledge of the Z mass and width as measured at LEP.

As an example, the ATLAS lepton identification and event selections designed for the LHC start-up, for 50/pb of luminosity, are listed here [2]: electrons are identified within $|\eta| < 2.4$ and muons within $|\eta| < 2.5$. Quality criteria on electron candidates are assigned, such as "loose" (using the calorimetric showershape), "medium" (adding track and track matching requirements), and "tight" (sharpening these requirements). For muon candidates, isolation, the amount of activity in a cone around the muon, is used.

The selection of $W \to \ell\nu$ events requires either a medium-quality electron or an isolated muon. The transverse energy of the lepton and the missing transverse energy must both be larger than 25 GeV, and the transverse mass of the lepton-missing energy system must be larger than 40 GeV. In $Z \to \ell^+\ell^-$, two charged leptons are present so that the lepton identification is relaxed: either two loose isolated electrons or two isolated muons of opposite charge. In case of electrons, the transverse energy must be larger than 15 GeV and the invariant di-electron mass must be in the range from 80 to 100 GeV. In case of muons, the transverse momentum must be larger than 20 GeV, and the di-muon mass be in a ± 20 GeV window around the Z mass value. The selection and trigger efficiencies range from 60% to 90%. Both experiments exploit data-driven determinations using tag-and-probe on Z decays.

The expected statistical and systematic uncertainties on the event numbers (rate) are as follows, using ATLAS 50/pb, ATLAS 1/fb and CMS 1/fb selections [2–4]: For W events, the statistical uncertainties are 0.2%, 0.04% and 0.04%, while the systematic uncertainties are projected as 3.1-5.2%, 2.4% and 3.3%. The systematic uncertainty is dominated by the missing energy determination. For the Z rate, the corresponding numbers are 0.8%, 0.2% and 0.13% statistical uncertainty, and 3.2-3.6%, 1.3% and 2.3% systematic uncertainty. The theoretical systematic uncertainty is dominated by PDFs and the underlying boson pt distribution. Thus even with a small amount of luminosity at LHC start-up, the rate measurements are dominated by systematic uncertainties. The systematic uncertainties will decrease with improved understanding of the detectors, but slower than the statistical uncertainty.

In order to turn the rate into a cross section, a luminosity determination is needed, typically obtained by measuring forward scattering. The uncertainty on the luminosity from this method is estimated to be 10% initially, decreasing to about 5% in the long term. It is thus attractive to use W/Z production as an alternative luminosity reaction, because a smaller uncertainty can be achieved. Further, using a high-pt process similar to other signal processes, e.g., $t\bar{t}$ production, theoretical uncertainties due to PDFs and other issues partially cancel in the ratio.

2.1. W Mass

The mass of the W boson is a fundamental parameter of the electroweak Standard Model; in particular, together with the mass of the top quark, it constrains the mass of the as yet undiscovered Higgs boson [5]. The W-boson mass and width is measured precisely at LEP-2 [5] and by the Tevatron experiments CDF and DØ [6]. The measurement requires a clean sample of W decays, thus tighter quality criteria on the lepton identification are imposed. In case of ATLAS [7], one requires for $W \to e\nu$ exactly one isolated tight electron candidate, and for $W \to \mu\nu$ one isolated muon candidate. The transverse energy of the lepton and the missing transverse energy must both exceed 20 GeV.

Already in 15/pb of luminosity, 67000 $W \to e\nu$ and 120000 $W \to \mu\nu$ events will be selected, together with 3000 $Z \to ee$ and 10000 $Z \to \mu\mu$ events. The W mass will be extracted from the Jacobian peak observed in the transverse mass of the lepton-neutrino system, or the transverse energy of the charged lepton. The Z events are a crucial source of calibration for the lepton energy scale (known Z mass) and energy resolution (known Z width), and used as well in the determination of the differential lepton reconstruction efficiency. The low-luminosity ATLAS study shows how well the energy scale and resolution can be monitored through Z events as a function of pseudo rapidity, for example the required corrections due to transition effects between central and endcap calorimeters. For 15/pb of luminosity, a W-mass uncertainty ranging from 160 to 240 MeV is expected. While this is not meant to be competitive with current measurements at LEP-2 and the Tevatron, it serves to establish the W-mass analysis at the LHC.

Requiring higher luminosities, novel techniques were studied by the CMS collaboration to measure the W-boson mass through templates generated from data (Z events), thus no longer relying on MC simulations [8]. Two possibilities are studied [9]: (i) an event-by-event transformation to change a Z event into a W event corresponding to a trial value of the W boson mass: one takes a $Z \to \ell\ell$ event, boosts it to the Z rest-system, rescales the lepton momenta by the ratio $M_W(trial)/M_Z(LEP)$, removes one lepton to mimic a neutrino, and boosts back to the detector system; and (ii) transformation of distributions, such as the lepton pt distribution [9]. The advantage of these methods lies in the fact that Z events from data rather than MC simulations are used, so that many systematic errors disappear and only the residual W-Z differences need to be studied. These methods require high luminosity as Z events from data are used. For 1/fb and 10/fb of luminosity, CMS expects statistical uncertainties of 40 and 15 MeV, with experimental systematic errors of 40 and 20 MeV, and PDF uncertainties of 20 and 10 MeV, respectively.

2.2. Z Forward-Backward Asymmetry

Even in Z production in proton-proton collisions, a forward-backward asymmetry of the Z decay products is expected. The Z is formed by a quark-antiquark pair; while the anti-quark always arises from the sea, the quark may also be a valence quark which on average carries a higher momentum than sea quarks. Thus the boost direction indicates the quark direction at high rapidities. In a sample of high-rapidity electron pairs, an asymmetry is observed which can be interpreted as a measurement of the effective electroweak mixing angle, $\sin^2\theta_{eff}$, similar to the asymmetries measured at LEP and at the Tevatron. With 100/fb of luminosity, ATLAS [10] expects a measurements of $\sin^2\theta_{eff}$ with a statistical precision of 0.00015 and a systematic uncertainty of 0.00024, comparable to the uncertainty of the world average dominated by LEP and SLD [5]. The DØ experiment at the Tevatron has made a measurement with a statistical precision of 0.0018 and systematic uncertainty of 0.0006 using 1.1/fb [11]. The systematic uncertainties are by far dominated by PDF-related uncertainties, but the knowledge of PDFs is expected to improve through measurements at the Tevatron, HERA, and also LHC (e.g., W asymmetry measurements).

3. Z PLUS JETS

Z production accompanied by jets serves as a test of perturbative QCD but is also a major background in searches for new physics, thus a good understanding of this process is required. The ATLAS [12] selection designed for a luminosity of 1/fb uses the standard $Z \to ee$ selection, while jets are clustered in a cone of $R = 0.4$ and considered within the fiducial volume of $|\eta| < 3$. Jets are required to have a pt larger than 40 GeV. The lepton-jet separation must exceed $R = 0.4$. The background from heavy-particle final states ($Z \to \tau\tau$, W, $t\bar{t}$) is taken from MC, while the QCD multi-jet background is derived from data, where MC simulations indicate that the expected multi-jet background fraction is independent of the jet pt. With 1/fb of luminosity, up to 4 jets can be observed in rate and pt spectrum, allowing to test MC models. A CMS study [13] specifically investigates $Z + b\bar{b}$ production resulting in a signature of two leptons and two b-jets. The background consists of Drell-Yan production plus light jets, $Z + c\bar{c}$ and $t\bar{t}$ production. The selection requires two isolated leptons of opposite charge and pt larger than 20 GeV, and at least two b-tagged jets within $|\eta| < 2.4$ and pt larger than 30 GeV. In order to reject $t\bar{t}$ events the missing energy must be smaller than 50 GeV. Within 100/pb, this results in a cross section determination with a statistical (systematic) uncertainty of 15% (23%), the latter dominated by the jet energy scale and missing energy systematic.

4. DI-BOSON PRODUCTION

Pair-production of electroweak gauge bosons tests the triple gauge boson couplings of the electroweak Standard Model. Within the SM, the trilinear vertices $WW\gamma$ and WWZ occur, while those involving only neutral gauge bosons, γ and Z, are absent. The charged triple gauge couplings (TGCs) are usually taken as g_1^V, κ^V and λ^V for $V = \gamma, Z$; they are related, for $V = \gamma$, to the magnetic dipole and electric quadrupole moment of the W boson.

Within the SM, their values are $g_1 = \kappa = 1$ and $\lambda = 0$. Di-boson production leads to final states containing charged leptons from W/Z decay and phtons. The photon identification is similar to the electron identification except for a veto on charged tracks matching the calorimetric cluster of the photon candidate.

CMS is using a cut-based analyses [8] while ATLAS studied in addition a boosted decision tree with improved sensitivity compared to their cut-based analysis [14]. The number of selected events for signal (background) obtained using the ATLAS boosted-decision-tree selections on a total luminosity of 1/fb are: $W\gamma$: 3770 (2525) and $Z\gamma$ 1118 (616), with the background dominated by W/Z plus fake photons; WW: 469 (92) yielding a signal significance of 10 standard deviations already with 0.1/fb of luminosity and a 20% background uncertainty; WZ: 128 (16) yielding a 5.8 sigma significance for 0.1/fb and a 20% background uncertainty; $ZZ \to 4\ell$ 13.3 (0.2) for a signal significance of 6.8 sigma in 1/fb, and $ZZ \to 2\ell 2\nu$ 10.2 (5.2 ± 2.6). Anomalous TGCs lead to increased cross sections especially at high boson pt and di-boson transverse mass, allowing to set limits. Systematic uncertainties in 95% CL limits on anomalous TGCs become relevant only for luminosities of 30/fb or higher.

5. CONCLUSION

The LHC will provide proton-proton collisions in 2009. The four detectors ATLAS, CMS, LHCb and ALICE are eagerly awaiting collision data. Both luminosity and cross sections at the LHC are much higher compared to earlier experiments, hence there will be no lack of statistics and sensitivity to rare processes such as ZZ production. The prospects of electroweak measurements are exciting due to high-performance detectors, allowing to place tight constraints on the electroweak Standard Model, through measurements of production rates, masses and couplings of the electroweak gauge bosons. To exploit the data it is important to understand the early data and detectors quickly.

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