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Physics reach of LHC with 1 fb^{-1} at $\sqrt{s} = 7$ TeV

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Summary. — The physics reach of the ATLAS and CMS experiments for $\sqrt{s} = 7$ TeV at LHC is reviewed. In particular the measurement of Standard Model processes, the search for the Higgs boson as well as the discovery potential for various Beyond the Standard models are discussed.

PACS 10.00 – The physics of elementary particles and fields.

1. – Introduction

LHC began operation at 7 TeV in March 2010, and is expected to collect up to 1 fb^{-1} before the end of 2011. The plan is to continue the run until ATLAS and CMS experiments collect at least this amount of data at 7 TeV. The perspectives of the physics at LHC with 7 TeV will be discussed in this paper.

A brief perspective of the physics at 7 TeV can be estimated by using the ratio of parton luminosity. In general, the gain is expected to be a factor 10 or more compared to the Tevatron. In other words, the LHC can reach the same sensitivity with a factor of 10 less integrated luminosity than the Tevatron, approximately.

In the next section, the perspectives for the LHC physics at 7 TeV will be discussed in three different areas: the Standard Model (SM), the Higgs searches, and Beyond the Standard Model (BSM) searches.

2. – Standard Model

2·1. *Heavy flavor measurement.* – Heavy flavour physics is one of the things which can be measured with very early data. For example, fig. 1 shows the results from ATLAS (left) and CMS (right) on heavy flavor measurements with small amount of early data. The left plot in the figure shows the mass difference between D^* and D^0, which are low mass resonances. The fit result is close to the PDG value. The right plot in fig. 1 shows the observation of the J/ψ signal with 1 nb^{-1} with the CMS.

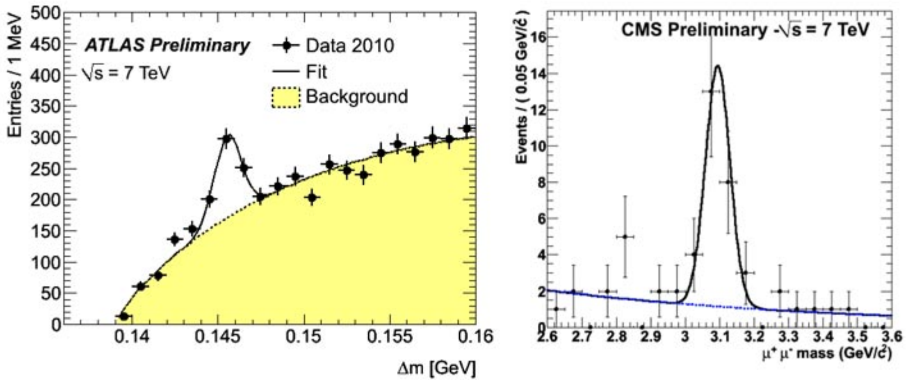

Fig. 1. – Left: mass difference between D^* and D^0 with early data from ATLAS. Right: J/ψ peak observed with $1\,\mathrm{nb}^{-1}$ at CMS.

Υ and $b\bar{b}$ cross section studies can be also performed with only 1 to $5\,\mathrm{pb}^{-1}$ data. These heavy flavor measurement studies are done using data from the tracking system, and are very useful to understand the dectector.

2˙2. *W and Z measurement*. – Measurement of the W and Z is also a very important analysis with early data. The W and Z are higher mass resonances than the heavy flavor resonances, and have very large cross sections. ATLAS and CMS expect about 250000 W candidates and 25000 Z candidates per $100\,\mathrm{pb}^{-1}$ in the semileptonic decay channels. The W and Z cross sections are predicted by the SM and the measurement of W and Z production is an important tool for understanding the detector performance.

For the expectation in this measurement at 7 TeV with $1\,\mathrm{fb}^{-1}$ data, the systematic uncertainty is dominant in the cross section measurement. Table I shows the expectation for the statistical and systematic uncertainties in both ATLAS and CMS. One of the main contributions to the systematic uncertainty is the uncertainty on the Parton Distribution Function (PDF), and one possibility to constrain the PDF uncertainty is W charge asymmetry. According to ref. [1], the W charge asymmetry result at 10 TeV with $100\,\mathrm{pb}^{-1}$ using MC simulation has comparable total uncertainty to the PDF uncertainty. At 7 TeV, about $150\,\mathrm{pb}^{-1}$ data is needed to get the same W yield as at 10 TeV.

2˙3. *Top quark measurements*. – The production cross section for top pair increases dramatically with energy. In 2010 ATLAS and CMS expect to collect about 100–200 pb^{-1}

Table I. – *Expected uncertainty for the W/Z cross section measurements with* $1\,\mathrm{fb}^{-1}$.

W cross section	ATLAS	CMS
Statistical uncertainty	0.04%	0.04%
Systematic uncertainty	2.4%	3.3%
Z cross section	**ATLAS**	**CMS**
Statistical uncertainty	0.2%	0.13%
Systematic uncertainty	1.3%	2.3%

TABLE II. – *Comparison between the Tevatron and the LHC for $t\bar{t}$ cross section.*

	Tevatron	LHC at 7 TeV	Ratio
$\sigma_{t\bar{t}}$ (NLO)	5.5 pb	160 pb	30
Luminosity for evidence	20 pb^{-1}	1 pb^{-1}	1/20
Main background (W+jets)	6.5 pb	240 pb	37

data, therefore by the end of 2010, the LHC experiments expect to collect samples comparable to the Tevatron experiments.

Table II shows more detailed comparison between the Tevatron and the LHC. The NLO cross section for $t\bar{t}$ is 30 times higher in the LHC. However, the main background, W+jets will be 37 times higher at the LHC with 7 TeV. The main challenge is to suppress this background. With 1 fb^{-1}, each experiment expects to collect more than 150000 $t\bar{t}$ pairs, but this estimation is very dependent on the event selection.

The dilepton channel has very clean signal and the W+jets background is not so significant. Therefore, the first channel is the most likely to be observed at the LHC. With 10 pb^{-1} data, about 30 events are expected including 5 or 6 background events. The lepton+jets channel has about 35% branching fraction, and will yield more than the dilepton channel for the same integrated luminosity, however with a much higher W+jets background. B-tagging will be very useful to suppress the backgrounds. With 10 pb^{-1} 100 candidates are expected including 40 background events. In fig. 2, the left plot shows the 10 TeV expectation in dilepton channel ($e\mu$) with 200 pb^{-1} data from ATLAS [2]. The dominant background contribution is the W+jets process, however the top signal is very significant. The right plot shows 10 TeV expectation in lepton+jets channel with 20 pb^{-1}, as a function of jet multiplicity from CMS [3].

For the single top analysis, more data is needed. The single top is already observed at the Tevatron [4,5]. The production cross section of the single top is much smaller than $t\bar{t}$ pairs, and it is not expected to reach the 5σ discovery level sensitivity with 1 fb^{-1} data at 7 TeV. About 1.4 fb^{-1} data is needed for this sensitivity.

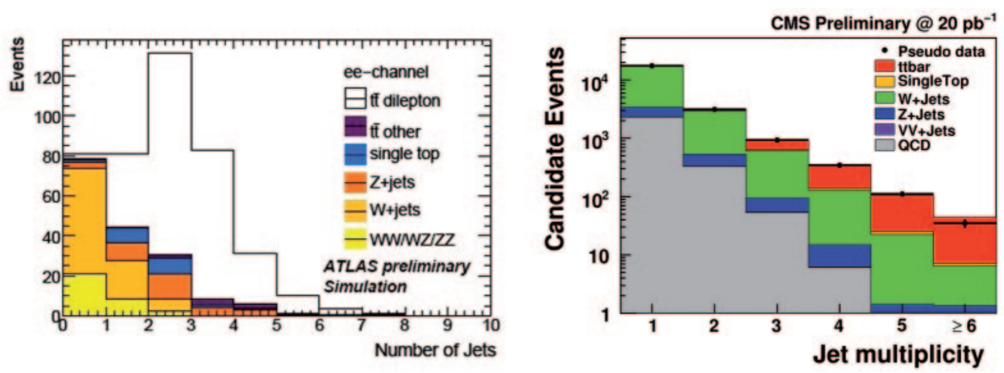

Fig. 2. – Left: 10 TeV expectation in the dilepton channel with 200 pb^{-1} data from ATLAS. Right: 10 TeV expectation in the lepton+jets channel with 20 pb^{-1} as a function of jet multiplicity from CMS.

3. – Higgs boson searches

The Higgs boson is the last missing particle in the Standard Model. At the LHC it is expected to be produced mainly via gluon-gluon fusion with the cross section around 10 pb for 7 TeV centre-of-mass energy, but also via vector-boson fusion (VBF) with a cross section about an order of magnitude lower. The Higgs boson decay can proceed via various decay channels, which strongly depend on the Higgs boson mass. For Higgs masses below 140 GeV the $b\bar{b}$ and $\tau^+\tau^-$ final states are important, whereas for Higgs masses above 140 GeV WW and ZZ final states become important. Hence several analyses with focus on different decay channels have to be carried out in order to cover effectively the full Higgs mass range.

One of the most sensitive channels is the $H \to WW \to l\nu l\nu$ ($l = e/\mu$). This dileptonic final state can occur with or without additional hadronic activity (jets). The 0-jet final state has large statistics but rather small signal-to-background ratio, where the dominant background is WW and top pair production. The final state with additional jets has a more favorable signal-to-background ratio, but smaller statistics due to the small VBF production cross section. Both ATLAS and CMS experiments used the control sample techniques to estimate the background normalization in the signal region. The CMS analysis [6] requires no jets while the ATLAS analysis [7] takes into account also the 2jet final states. For $\sqrt{\hat{s}} = 7$ TeV and an integrated luminosity $1\,\text{fb}^{-1}$ the CMS can exclude the mass range $150 < m_H < 185$ GeV. Both CMS and ATLAS approach the discovery level sensitivity ($4 - 5\sigma$) for the mass range $160 < m_H < 170$ GeV.

The $H \to ZZ \to 4l$ ($l = e/\mu$) is the cleanest decay channel to search for the Higgs. In contrast to the previous channel the Higgs invariant mass can be here directly reconstructed, resulting in a narrow peak with a smooth SM background originating predominantly from ZZ processes. The CMS results [6] include all three final states—4μ, $4e$, $2e2\mu$, where simple event counting in the $4l$ mass window is performed. With an integrated luminosity of $1\,\text{fb}^{-1}$ the SM Higgs cannot be excluded. However, the $H \to ZZ$ search should be strong enough to exclude the existence of Higgs boson up to 500 GeV in the four-generation scenario.

Although the $H \to \gamma\gamma$ channel has small branching ratio of order of few per mill, it has a high experimental relevance for discovery if the Higgs mass is between 120 and 140 GeV. The SM background consists here of two prompt-photon production (irreducible background), and from the di-jets and γ-jets which fake the di-photon signature. First the di-photon invariant mass $M_{\gamma\gamma}$ is reconstructed, then simple counting of events in the optimal $M_{\gamma\gamma}$ window is performed. The CMS analysis results [6] show that for $\sqrt{\hat{s}} = 7$ TeV and an integrated luminosity $1\,\text{fb}^{-1}$ the Standard Model Higgs cannot be excluded.

Combining all three decay channels ($H \to WW$, $H \to ZZ$ and $H \to \gamma\gamma$) one can achieve the best coverage for the full range of possible SM Higgs boson masses. The expected CMS 95% CL exclusion limits are shown in fig. 3 left, the mass range $145 < m_H < 190$ GeV can be excluded.

In the Minimal Supersymmetric extension of the Standard Model (MSSM) the existence of two charged ($H^{\pm}$) and three neutral (h, H and A) Higgs bosons is predicted. The CMS results [6] for a heavy neutral Higgs boson search at $\sqrt{\hat{s}} = 7$ TeV and integrated luminosity of $1\,\text{fb}^{-1}$ are shown in fig. 3 right. The neutral Higgs boson production in association with b jets ($gg \to b\bar{b}/H/A$) is studied, using the decay channel $A/H \to \tau^+\tau^-$ which yields the highest sensitivity. The analysis strategy is based on b-jets tagging, reconstructing the $\tau\tau$ final states and counting events in the $M_{\tau\tau}$ window. In the absence

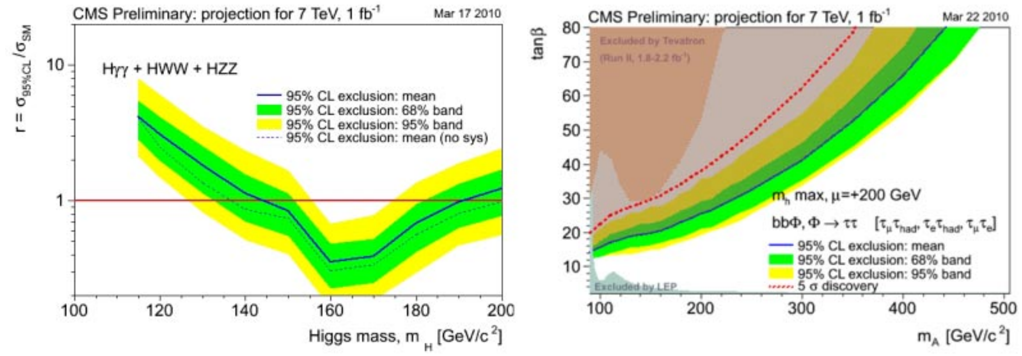

Fig. 3. – Left: expected 95% CL exclusion limits for the SM Higgs boson production cross section normalized to the cross section predicted by the Standard Model. Results are obtained from combining three decay channels: $H \to WW$, $H \to ZZ$ and $H \to \gamma\gamma$. Right: expected sensitivity to the MSSM Higgs bosons (the generic Higgs boson is denoted by Φ). The dotted line denotes the 5σ discovery reach, whereas the continuous line denotes the exclusion limits at 95% CL.

of a signal it is possible to exclude in the $(m_A, \tan\beta)$ MSSM parameter space down to a $\tan\beta$ 15 at low M_A region.

4. – Beyond the Standard Model searches

Many CMS and ATLAS analyses focused on beyond the Standard model searches have been recently updated to 7 TeV centre-of-mass energy, *e.g.*, leptoquarks, 4th-generation quarks, large extra dimensions, Randall-Sundrum gravitons, new gauge bosons, SUSY, etc... Since it is not possible to cover all analyses within these proceedings, we discuss only some of them.

4·1. *4th-generation quarks.* – One of the possible extensions of the SM is the existence of 4th generation quarks. At the LHC are the heavy b-like 4th-generation quarks (b') expected to be produced in pairs via gluon-gluon fusion. If they are heavy enough they are kinematically allowed to decay to a top quark and W boson ($b' \to tW$ being the dominant decay channel). This results in final states containing same-sign dileptons or trileptons with multiple jets, which makes the search powerful since SM backgrounds for these channels are expected to be very small. At $\sqrt{\hat{s}} = 7\,\mathrm{TeV}$ the CMS experiment [6] can exclude b' quarks with masses up to 400 GeV (450 GeV) with a data sample of $200\,\mathrm{pb}^{-1}$ ($600\,\mathrm{pb}^{-1}$) integrated luminosity and thus surpass the current Tevatron limit of 325 GeV.

4·2. *New gauge bosons.* – Several models predict the existence of additional gauge bosons Z' and W', for instance the Sequential Standard Model (SSM), Left-Right Symmetric models, Little Higgs, etc... Generally there are no predictions for the mass of these particles.

The dimuon decay is considered to be the golden channel for Z' discovery. The dominant background arises from the Drell-Yan lepton pair channel. Although the resolution is expected to be significantly poorer compared with dielectron channel, the reducible backgrounds are expected to be lower which makes this channel preferable. The exclusion

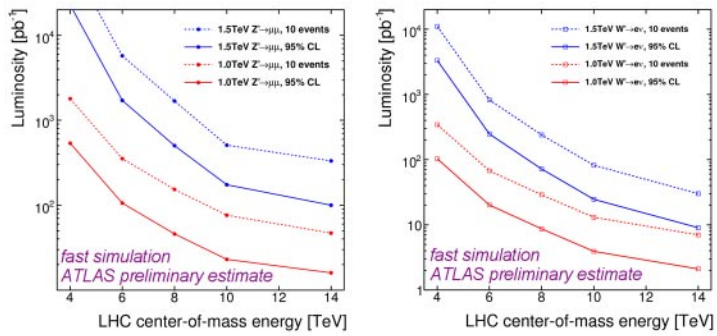

Fig. 4. – Left: expected sensitivity for the production of a Sequential Standard Model-like Z' boson for Z' masses of 1 and 1.5 TeV, as a function of centre-of-mass energy. Right: expected sensitivity for the production of a Sequential Standard Model-like W' boson for W' masses of 1 and 1.5 TeV, as a function of centre-of-mass energy. The discovery potential shown corresponds to a signal of at least ten events, which is expected to be somewhat more significant than 5 sigma.

limits derived by the ATLAS experiment [7] as a function of the LHC centre-of-mass energy are shown in fig. 4 left. The Z' mass of 1 TeV can be excluded already with 70 pb^{-1}. The W' bosons exclusion limits for $W' \to e\nu$ channel as a function of LHC centre-of-mass energy are shown in fig. 4 right.

4·3. *Supersymmetry*. – Supersymmetry [8] (SUSY) is one of the favoured candidates for physics beyond the SM. At the LHC the SUSY production is dominated by strongly interacting squarks and gluinos, which have long decay cascades involving multiple jets and eventually leptons. At the end of the decay chain is the lightest SUSY particle (LSP), which according to cosmological arguments should be stable, neutral, weakly interacting and thus would escape the detection. Hence, in order to cover various SUSY scenarios and event topologies, a generic search in channels with multiple jets, leptons and large missing transverse momentum is performed.

ATLAS and CMS did study the discovery potential in the framework of minimal Supergravity model [9] (mSUGRA) with only 5 free parameters: common boson mass m_0 and fermion mass $m_{1/2}$ at GUT scale, the trilinear coupling A_0, the Higgs sector parameters $\tan\beta$ and μ. The R-parity is assumed to be conserved, *i.e.* the SUSY particles are produced always in pairs.

The 0-lepton channel has the highest efficiency for many SUSY models, but suffers from high SM backgrounds like Z, W and top pair production, as well as QCD which might be challenging to understand for the early LHC data analysis. In the 1-lepton and 2-lepton channels the top background dominates. The CMS exclusion limits [6] for 0-lepton channel and the ATLAS discovery potential [7] for 1-lepton channel are shown in fig. 5. A 50% (100%) systematic error on SM background was assumed by CMS (ATLAS). The sensitivity is significantly better than in previous experiments.

Besides of mSUGRA, there exist numerous SUSY scenarios which predict specific final states, such as long-lived stable massive particles, which may not be observed in generic search. In the Split-SUSY [10] model the lifetime of the gluino is very long such that it can hadronize into so-called R-hadrons. A significant fraction of the R-hadrons can stop inside the detector and decay seconds, days or even weeks later. This will produce

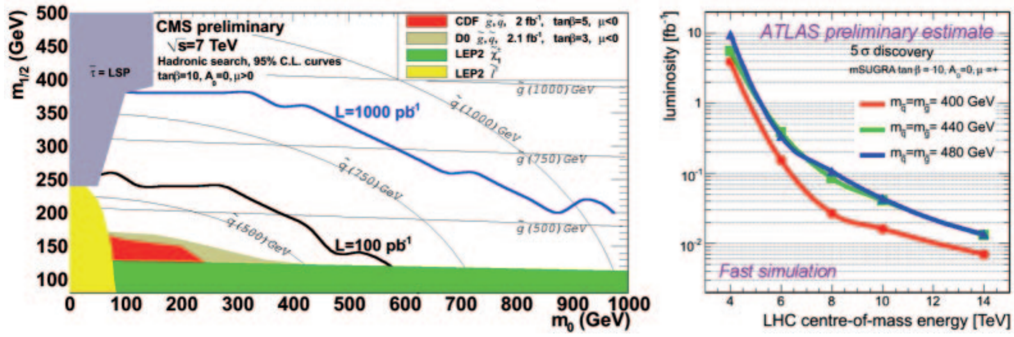

Fig. 5. – Left: the mSUGRA exclusion limits in the m_0-$m_{1/2}$ plane estimated by CMS for 0-lepton channel. Right: the discovery sensitivity for mSUGRA model with equal mass squarks and gluinos estimated by ATLAS for various LHC centre-of-mass energy. The significance is calculated for 1-lepton channel.

a signal in the detector which is out-of-time with respect to the LHC collisions. Therefore, it is essential to have a dedicated trigger operating in gaps between the bunch crossings or during the period without beams. For the offline analysis hadronic activity in the central pseudorapidity region with reconstructed jet energy above 50 GeV is required. In contrast to the usual analysis the background (mainly cosmics) does not depend on an instantaneous luminosity whereas the signal does. Assuming instantaneous luminosity of 10^{32} cm^{-2} s^{-1} and $\sqrt{\hat{s}} = 7$ TeV the CMS [6] can discover long-lived gluinos with masses of 300 GeV (just beyond the Tevatron limit) with lifetimes in the range from 1 μs up to 1 week within a couple of weeks of data taking.

5. – Conclusions

With the 2010-2011 LHC data at 7 TeV centre-of-mass energy, both the ATLAS and CMS experiments can explore the energy regime well beyond the Tevatron limits and search for new particles. With the full integrated luminosity of 1 fb^{-1} precision measurements of top quark properties can be achieved, and the exclusion limits for the SM Higgs mass can be extended up to a range of $145 < m_H < 190$ GeV if no Higgs signal is observed.

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