# PHYSICS AT LHC*

Grzegorz Wrochna

A. Soltan Institute for Nuclear Studies
Hoża 69, 00-681 Warsaw, Poland

(Received July 26, 2002)

The LHC discovery potential is briefly reviewed with an emphasis on hard processes studied by ATLAS and CMS. It covers the Standard Model Higgs, supersymmetry and many other models including those with extra spatial dimensions.

PACS numbers: 13.85.–t

## 1. Introduction

The Large Hadron Collider (LHC) is being build at the CERN laboratory near Geneva. Protons will be accelerated and collided with the CMS energy of $\sqrt{s} = 14\,\mathrm{TeV}$. It is expected that during the first year of running with luminosity of $10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ one can collect $10\,\mathrm{fb}^{-1}$. One year with the designed luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ would yield about $100\,\mathrm{fb}^{-1}$.

The collisions will be studied by two general purpose detectors ATLAS and CMS. LHC will also accelerate heavy ions to be studied by the ALICE detector. The LHC program will be completed with the LHC-$b$ experiment dedicated to the $b$-quark physics and with the TOTEM detector, designed for total cross section measurements, and for studying diffractive processes. In this paper we concentrate on hard processes in the ATLAS and CMS detectors. The Higgs boson and minimal supersymmetry are touched very briefly as they were widely explored in past years. Greater attention is given to more exotic models underlying recent developments.

* Presented at the X International Workshop on Deep Inelastic Scattering (DIS2002) Cracow, Poland, 30 April–4 May, 2002.

## 2. Standard model Higgs

Higgs particle — the last missing element of the Standard Model (SM), if exists, "must" be discovered at LHC. As shown in Fig. 1(left), the full range of Higgs masses allowed by theory (up to ~1 TeV) can be covered by various channels [1]. The most interesting is the region of low masses favored by fits to precise measurement of SM parameters [2]. Recent study [3] has shown that the channels where Higgs is produced by a vector boson fusion are important in this region (see Fig. 1(right)).

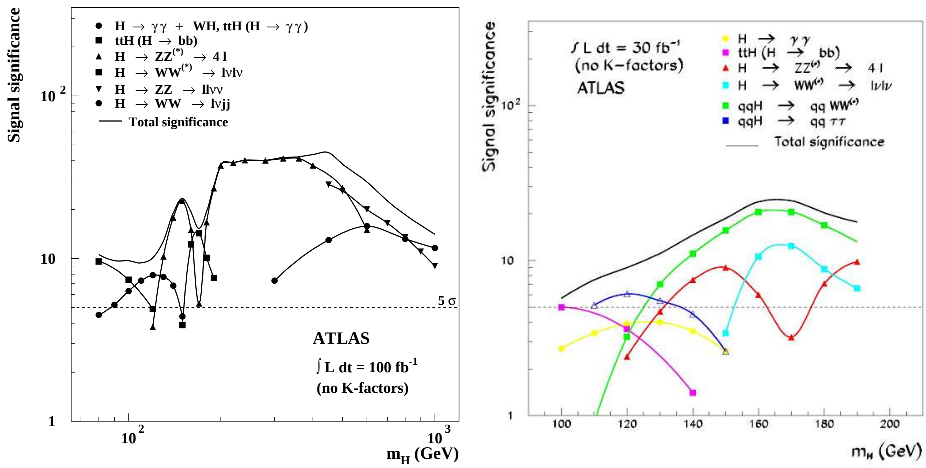


Fig. 1. (Left)SM Higgs search in various channels [1]. (Right) Low mass SM Higgs search in vector boson fusion channels [3].

## 3. Supersymmetry

Supersymmetric (SUSY) models assuming that each fermion has a boson counter-partner and vice versa, are "number one" on the list of alternatives to SM. Minimal Supersymmetric Standard Model (MSSM) assumes existence of two Higgs doublets resulting in five physical states: $h^0$, $A^0$, $H^0$, $H^+$, and $H^-$. The model can be characterised by two parameters: the mass of one of the Higgses, *e.g.* $m_A$ and the ratio of the two vacuum expectation values $\tan\beta = v_1/v_2$. The full parameter space can be covered after 3 years of LHC running, as shown in Fig. 2(left).

Discovery reach for squarks $\tilde{q}$ and gluinos $\tilde{g}$ is shown in Fig. 2(right). They are relatively easy to detect through spectacular cascade decays into lighter and lighter states down to the lightest SUSY particle (LSP), which typically escapes detection and results in the missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$. A number of leptons and jets produced in cascades facilitate triggering. In practice, one can detect $\tilde{q}$ and $\tilde{g}$ up to masses of 2–3 TeV [4].

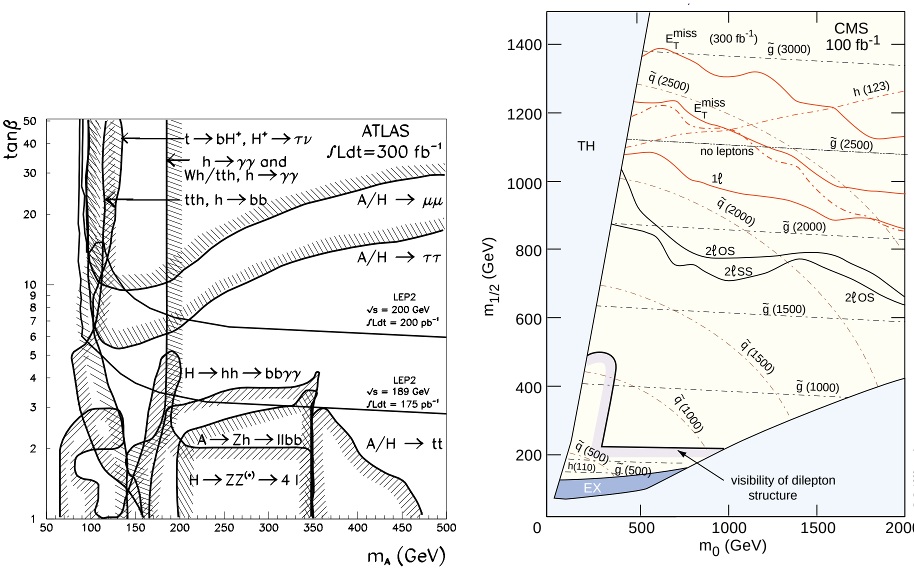


Fig. 2. (Left) MSSM Higgs search [1]. (Right) Limits for $\tilde{q}$ and $\tilde{g}$ in channels with leptons, $E_{\mathrm{T}}^{\mathrm{miss}}$ and >2 jets [4].

Among SUSY models, the Gauge Mediated Susy Breaking (GMSB) ones offer especially interesting signatures [5]. In those models graviton $G$ becomes the LSP. Neutralino $\tilde{N}$ or stau $\tilde{\tau}$ can be the "Next to LSP" and it can be stable or long lived. Such $\tilde{\tau}$ would look like a "heavy muon" traversing detector with velocity significantly lower than $c$. One can measure its time of flight, and hence, calculate the mass $m_{\tilde{\tau}}$. It was shown [5] that for $100\,\mathrm{fb}^{-1}$ one can measure $m_{\tilde{\tau}}$ from 90 to ∼700 GeV. The upper limit corresponds to $\sigma_{\mathrm{SUSY}} = 1$ fb and $\tilde{q}$ $\tilde{g}$ masses of ∼4 TeV — beyond the direct search limit.

Because of the finite $\tilde{N}$ lifetime, the $\tilde{N} \to G\gamma$ decay can happen far from the interaction point. It would be observed as an electromagnetic shower, starting somewhere inside a calorimeter or a muon system, non-pointing to the vertex. In the later case, the muon system can be used as a kind of poor man's sampling calorimeter ("$\mu$CAL"). Several methods have been developed to measure $\tilde{N}$ lifetime $\tau_{\tilde{N}}$. One can count events with the origin in electromagnetic calorimeter or a muon system ("ECAL or $\mu$CAL counting"), measure the impact parameter of the shower ("ECAL impact") or observe the slope of the $\tilde{N}$ flight path distribution. Resulting precision of $\tau_{\tilde{N}}$ measurement is shown in Fig. 3. For $\sigma_{\mathrm{SUSY}} > 100$ fb the $c\tau_{\tilde{N}}$ can be measured effectively in the range from 1 cm to 1 km [5].

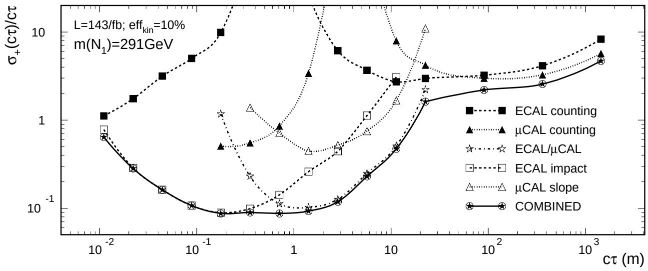


Fig. 3. Relative precision of neutralino lifetime measurement [5].

## 4. Exotica

An extention of the Standard Model symmetry group might introduce **new gauge bosons $W'$ and $Z'$** with a mass of several TeV. They can be discovered through bosonic or fermionic decay modes, as shown in Fig. 4(left). For $\mathrm{M}_{W'} > 0.5$ TeV the signal is well visible over the background [1].

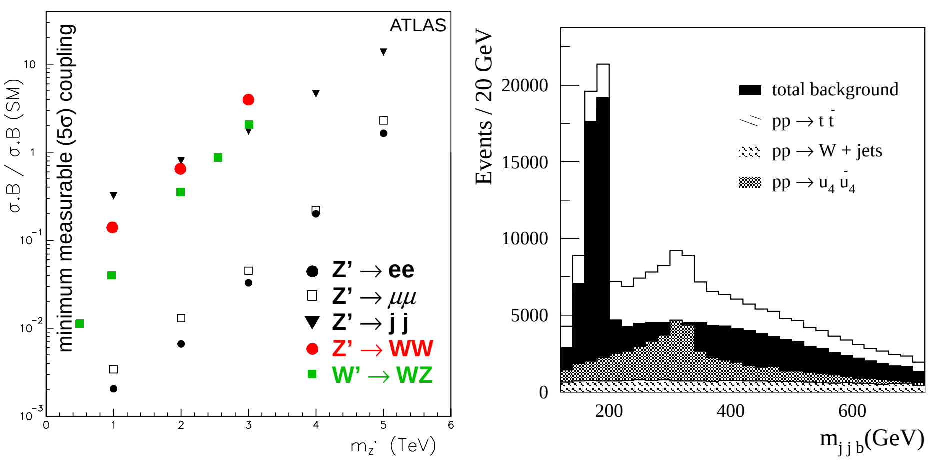


Fig. 4. (Left) Limits ($5\sigma$) on $W'$ and $Z'$ coupling for fermionic ($100\,\mathrm{fb}^{-1}$) and bosonic ($300\,\mathrm{fb}^{-1}$) decay modes [1]. (Right) Invariant mass distribution for 320 GeV forth generation quark $u_4 \to bW \to bjj$ [1].

So far three generations of quarks and leptons have been discovered, but there is not evident why there should be just three generation. Therefore, it is quite natural to consider models containing **fourth generation leptons and quarks** with higher masses. A forth generation quark $u_4$ would predominantly decay to $Wb$. An example of $u_4$ with 320 GeV mass is shown in Fig. 4(right). Integrated luminosity of $100\,\mathrm{fb}^{-1}$ is needed to see the signal over large $t\bar{t}$ and $Wj$ background [1].

**Monopoles** are particles with only one magnetic pole. Because the interaction of monopoles with photons is very strong one would expect that photon-photon rescattering with box diagram as shown in Fig. 5(left) is the most favorable way to observe monopoles at LHC [1]. Significance of possible discovery is given in Fig. 5(right).

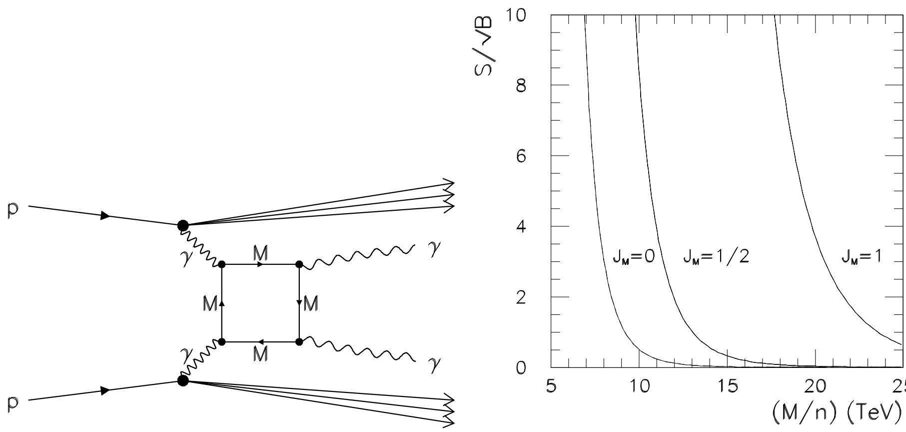


Fig. 5. (Left) Monopole production at LHC. (Right) Significance contours for monopoles of spin $J_M$, mass $M$ and charge $n$ ($100\,\mathrm{fb}^{-1}$) [1].

**Leptoquarks** (LQ) are particles carrying both leptonic and barionic number. At LHC they could be produced in pairs in the process $qq \to$ LQ LQ, or individually, by $qg \to$ LQ. They usually decay into lepton and quark (LQ $\to \ell q$) so the signature is a high $p_{\mathrm{T}}$ muon or electron plus an energetic jet. Major background comes from $t\bar{t}$ and $ZZ$ pairs. For leptoquark

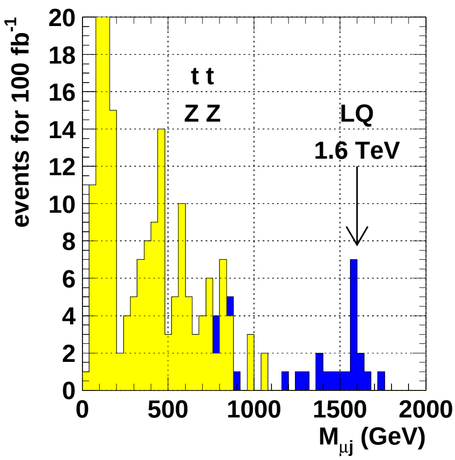


Fig. 6. Mass distribution for scalar, 2$^{\mathrm{nd}}$ generation leptoquarks of 1.6 TeV produced in pairs [6].

masses above 1 TeV the background is not important anymore and discovery rich is limited only by LQ cross section and statistics. Fig. 6 shows the result of a study of second generation scalar LQ. With $100\,\mathrm{fb}^{-1}$ one can observe LQ up to 1.6 TeV [6].

**Technicolor** is the name of a new strong interaction at high scale. It provides an alternative to Higgs mechanism of electroweak symmetry breaking by means of technipions (condensates of technifermions). Technicolor resonances could be observed at LHC. An example cascading decay $\rho_{\mathrm{T}}^{\pm} \to \pi_{\mathrm{T}}^{\pm} Z \to bq\,\ell^+\ell^-$ is shown in Fig. 7.

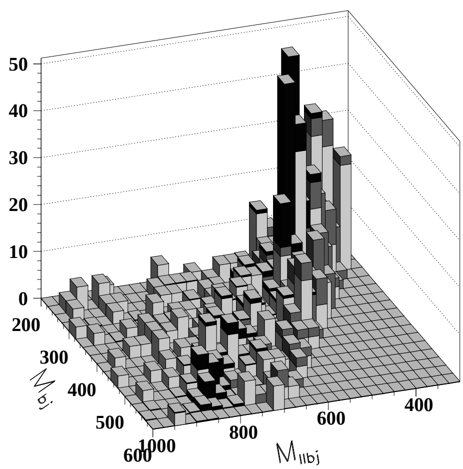


Fig. 7. Mass distribution for $\pi_{\mathrm{T}}^{\pm}$ of 300 GeV and $\rho_{\mathrm{T}}^{\pm}$ of 500 GeV in $\rho_{\mathrm{T}}^{\pm} \to \pi_{\mathrm{T}}^{\pm} Z \to bq\,\ell^+\ell^-$ ($30\,\mathrm{fb}^{-1}$) [1]. Signal in black, $t\bar{t}$ background in dark gray, $Zj$ — light gray.

## 5. Extra dimensions

Recently, models assuming existence of extra spacial dimensions were introduced in order to solve the problem of hierarchy between the electroweak scale and the Planck scale. The most popular one is the Randall–Sundrum model [7] in which the gravity lives in a five-dimensional bulk between the Planck brane and the SM brane. It predicts Kaluza–Klein type excitations of the graviton $G$. They are spaced according to roots of the Bessel function and the first could have a mass of the order of 1 TeV. They can decay into fermion pairs which could be a convenient signature at LHC.

Fig. 8(left) shows the interesting region of masses $m_G$ and couplings $c$. The upper limit represents divergences which would lead to violation of the Newton's low. The lower limit corresponds to the scale value of 10 TeV somewhat arbitrality chosen as a naturalness limit. The whole range can be cover by both $G \to e^+e^-$ and $G \to \mu^+\mu^-$ channels [8].

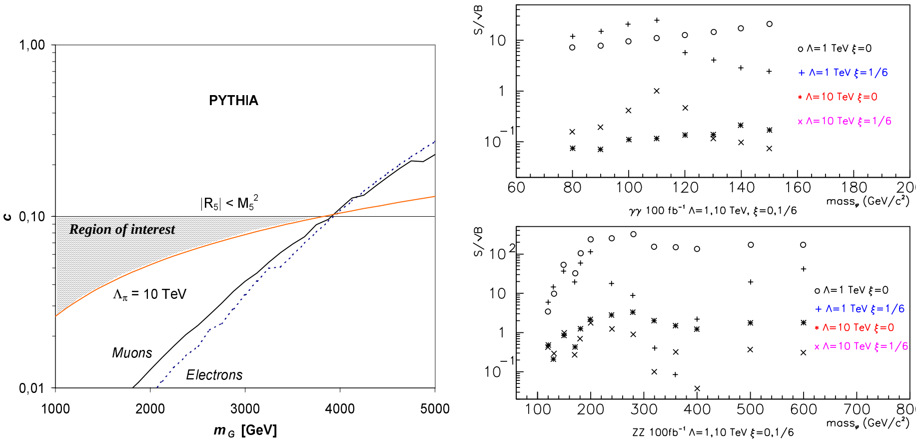


Fig. 8. (Left) Search for RS graviton $G \to \ell\ell$. Couplings $c > 0.01$–$0.1$ are accessible for masses $m_G > 2$–$4$ TeV respectively [8]. (Right) Significance for radion signal in $\phi \to \gamma\gamma$ (upper plot) and $\phi \to ZZ$ (lower plot) channels [9].

In order to stabilize the size of the fifth dimension without fine tuning one can introduce a new particle called radion and denoted as $\phi$. It has the same quantum numbers as Higgs, so it could be mixed with it. Radion is characterised by its mass $m_\phi$, vacuum expectation value (scale) $\Lambda_\phi$ and mixing with Higgs $\xi$. It can be searched at LHC in the following channels: $\phi \to \gamma\gamma$, $\phi \to ZZ \to 4\ell$, $\phi \to hh \to \gamma\gamma\, b\bar{b}$, $\phi \to hh \to b\bar{b}\,\tau\bar{\tau}$. It is seen from Fig. 8(right) that discovery limit of LHC is somewhere between $\Lambda_\phi = 1$ and 10 TeV [9].

## 6. Summary

Discovery potential of the LHC is very rich. It includes the SM Higgs, supersymmetry and many more exotic models including those with extra dimensions. New particles can be discovered up to masses of several TeV.

## REFERENCES


[1] ATLAS Collaboration, ATLAS Detector and Physics Performance Technical Design Report, CERN LHCC 98-16.

[2] T. Saeki, *Acta Phys. Pol.* **B33**, 3831 (2002).

[3] K. Jacobs, Higgs Boson Searches at the LHC Using Vector Boson Fusion, ECFA/DESY Workshop, St. Malo, April 2002.

[4] S. Abdullin *et al.,* Discovery Potential for Supersymmetry in CMS, CMS NOTE-1998/006.

[5] M. Kazana, G. Wrochna, P. Zalewski, Study of the NLSP from the GMSB Models in the CMS Detector at the LHC, CMS CR-1999/019 and Proceedings of the HEP 99 Conference, Tampere, Finland, July 15–21, 1999.

[6] G. Wrochna, First look at leptoquarks in CMS, CMS CR-1996/003 and and Proceedings of New Directions for High Energy Snowmass, Colorado, June 1996; S. Abdullin, F. Charles, F. Luckel, Study of Leptoquark Pair Production at the LHC with the CMS Detector, CMS NOTE-1999/027.

[7] L. Randall, R. Sundrum, *Phys. Rev. Lett.* **83**, 3370 (1999).

[8] P. Traczyk, G. Wrochna, Search for Randall–Sundrum Graviton Excitations in the CMS Experiment, CMS NOTE-2002/003.

[9] G. Azuelos *et al.*, Search for the Randall Sundrum Radion Using the ATLAS Detector in Report of the Beyond the Standard Model Working Group for the Workshop Physics at TeV Colliders, Les Houches, France, May 2001, hep-ph/0204031.