A review of the discovery potential of LHC for new phenomena beyond the Standard Model (BSM) other than Supersymmetry in the early phase of running is presented. Topics covered include searches for extra dimensions in different scenarios (ADD, Randall-Sundrum, black holes ...), resonance hunting in di-lepton, di-photon and di-jet final states, searches for contact interactions, heavy stable charged particles, technicolor, etc. The strategies of the ATLAS and CMS experiments to understand the detectors and prepare them for "search" mode and the prospects for discoveries using early data are described.

I. INTRODUCTION

At the dawn of the LHC era particle physics finds itself in a unique and paradoxical situation. On the credit side we have a Standard Model (SM) which could be the envy of many disciplines - tested to tantalizing detail and shown to explain well the vast expanse of often very precise experimental results, on the debit side no one seems to be happy with it. Of course there are weighty arguments like the unification of forces or the glaring omission of gravity, just to name a few, that point to new physics at higher energies. Moreover there are strong expectations that something new will happen at energies around a couple of TeV, the Terascale that LHC is about to start exploring. These enhanced expectations have led to the development of a flurry of models, and the hope is that the LHC will serve as Occam’s razor and point the way beyond the Standard Model.

The scope of this talk is to cover all other BSM searches except the 200 kg gorilla better known as Supersymmetry. This is a huge field, I will focus on “clean”, low background channels which can provide early discoveries once the machine, detectors and Standard Model contributions are understood in sufficient detail. Advance apologies for the omissions, unavoidable in a short review. Most results are for 14 TeV center-of-mass energy, but luminosities $\sim 40 \text{ pb}^{-1}$ at 10 TeV have interesting potential. And we better be ready from the start: the W and Z were discovered by UA1/UA2 with $\sim 20/55 \text{ nb}^{-1}$, of course they knew where to look.

II. BSM SEARCHES

The results are organized by experimental signatures, not by the models. For details the readers are referred to [1, 2, 3, 4, 5].

A. One Lepton

The channel with one lepton (electron or muon) and missing transverse energy, used to discover the W boson, is ideal search field for an additional charged gauge boson W’. Both collaborations have new results for the muon channel, showing that very little luminosity is needed in the case of the Sequential Standard Model (SSM), see e.g. Figure 1. While we are unable to reconstruct the full invariant mass, the transverse mass $M_T$ is a powerful discriminator. The SM backgrounds are the usual suspects which appear throughout this talk, I will list them once here and only mention additional background contributions for specific channels later:

- $W \rightarrow \mu \nu$
• $Z \rightarrow \mu\mu$
• Di-jet QCD
• $t\bar{t}$
• $WW, WZ, ZZ$.

B. LHC as Bump Hunting Factory

A primary early search field are simple final states where complete reconstruction of the invariant mass of new objects, in the ideal case “narrow” bumps, is feasible. Due to the large parton luminosity up to TeV masses the LHC is a di-{lepton, photon, jet} factory, able to test the SM up to the highest available momentum transfers and search for signals for many new physics scenarios: “easy” like resonances ($Z'$, Randall-Sundrum (RS) gravitons ...), or “not-so-easy”: non-resonant deviations from the SM or just tails like compositeness, extra dimensions in the ADD scenario, etc. In Figure 2 rough estimates for the rate of Drell-Yan events is shown, illustrating how fast the LHC will start probing masses unaccessible at the Tevatron. As a rule of thumb, at 10 TeV center-of-mass energy the dominant Drell-Yan background for 10 pb$^{-1}$ is negligible (less than one expected event per channel) above 500 GeV, for 100 pb$^{-1}$ above 1 TeV. Any statistically significant accumulation of events in these areas would signal new physics.

C. Two Leptons

The two lepton channel is the classical hunting field where $J/\psi, \Upsilon$ and $Z$ where discovered. An additional gauge boson $Z'$ decaying to di-electrons or di-muons appears in many scenarios. An example of the various backgrounds and their magnitude and the discovery reach for the two channels is shown in Figure 3 for CMS and different $Z'$ models. Numbers to keep in mind are that LEP2 has already excluded a SSM $Z'$ below 1.8 TeV and cut deeply into the LHC phase space, and the Tevatron is approaching the kinematic limit for several models.
FIG. 2: Cumulative plots for the expected number of events at the LHC above a given mass in a single Drell-Yan channel (di-electron or di-muon) for one experiment and comparison with the Tevatron (rough estimate). Left (2a): LHC at nominal energy. Right (2b): LHC at 10 TeV.

ATLAS has performed a study using the nearly model-independent CDDT parameterization. The results, shown in Figure 4, depend on three parameters: the mass of the gauge boson $M_{Z'}$, the global coupling strength $g_{Z'}$, and the relative coupling strength to different fermions $x$. Four classes of solutions are possible, denoted as B-xL, 10+x5, d-xu, q+xu. As can be seen the LEP limits will be superseded very fast.
D. Two Photons

The excellent resolution of the detectors makes searches with photons very competitive, as the physical backgrounds are typically smaller, the machine backgrounds and fakes need to be well under control. The large signal to noise ratio and the discovery reach for narrow Randall-Sundrum gravitons are illustrated in Figure 5.

FIG. 4: ATLAS Z' study.

FIG. 5: CMS di-photon study: Left (5a): example of invariant mass distribution. Right (5b): discovery reach for the Randall-Sundrum model as function of luminosity and coupling strength.
E. Two Jets

A more difficult channel with large discovery potential, the di-jet final state is sensitive to the jet energy scale and large QCD background, typical for a hadron collider. The parton density functions (PDF) have to be understood well to avoid being fooled by initial state effects. The invariant mass reconstruction and the early discovery potential are shown e.g. in Figure 6 for CMS.

![CMS Preliminary](image1)

FIG. 6: CMS di-jet study: Left (6a): example of invariant mass distribution before and after corrections. Right (6b): discovery reach for excited quarks and 100 pb$^{-1}$.

F. Three Leptons

This is a more tricky channel. It can be used to search e.g for technicolor models where the “walking” gauge coupling lowers the scale, and light almost degenerate vector technimesons can be observed. They decay

$$\rho_T/a_T \rightarrow WZ \rightarrow 3l + \nu.$$  \hspace{1cm} (1)

The three observed leptons together with the missing transverse energy and the W invariant mass constraint, a technique developed at the Tevatron, can be used successfully to reconstruct the full invariant mass of the final state, as shown in Figure 7(left) for ATLAS. Even close-by resonances can be resolved.

G. Two Leptons and Two Jets

This channel is ideal search field for pair-produced leptoquarks (LQ): hypothetical particles carrying both lepton and baryon numbers and decaying to a quark and lepton. Typical simplifying assumptions are that they couple to only one generation of quarks and leptons and that the interactions are chiral. Current limits from LEP2 and the Tevatron are $\sim 250–540$ GeV depending on the LQ type. An update by ATLAS produces a 95 % CL exclusion below 300 GeV with integrated luminosity of only 2.8 pb$^{-1}$ and below 800 GeV with 220 pb$^{-1}$, so this is clearly an early discovery channel.
H. Two Tops

Even a complex object like a resonance decaying to top-antitop quark pair is no barrier for the LHC detectors. The mass reconstruction when one W decays to hadrons, the second to electron or muon plus neutrino is shown in Figure 7(right). Such resonances can arise e.g. in TeV$^{-1}$ Kaluza-Klein extra dimensions models. The sensitivity will ultimately reach 3.3 TeV.

I. Contact Interactions: Two Leptons or Jets Revisited

So far we have basically described “bump-hunt” type of searches. A small digression are searches where we do not expect to see a resonance, but rather a gradual deviation from the SM expectation as function of invariant mass. In this subsection we will limit ourselves to di-leptons and di-jets. Clearly, in contrast to before where a not-too-wide bump provides an easy handle on the backgrounds e.g. from the side bands or ad-hoc fits of the background shape excluding the peak region, here a better understanding of the backgrounds is crucial. An important component is the uncertainty on the SM predictions originating from the PDF uncertainties. The modern library of PDFs LHAPDF provides convenient tools to estimate the size of these effects, as shown in Figure 8. Clearly a normalization to a standard candle like the Z peak helps to reduce many systematic effects, PDF uncertainties included.

Contact interactions offer a general approach for new interactions at a scale above the accessible center-of-mass energy. New phenomena can be observed through virtual effects and interference with the SM amplitudes. The constraints obtained this way are on the ratio of coupling divided by the scale. A very popular model searched for today is the ADD scenario for extra dimensions.

The most promising approach is to use ratios of data from signal enriched and depleted regions or double ratios of data and Monte Carlo, both normalized to a well described by the SM region, typically at lower masses, as illustrated by CMS studies, Figure 9. Scales above 15 TeV can be probed already with 1 fb$^{-1}$ in the di-muon channel.
FIG. 8: CMS PDF uncertainty study for Drell-Yan: Left (8a): uncertainties on the cross section in the CMS acceptance region for CTEQ6.1 and MRST2006nnlo as function of mass. Right (8b): the PDF uncertainties are reduced when using ratios to the Z peak when correlations are taken into account.

FIG. 9: CMS compositeness studies using ratios: Left (9a): di-muon study using double ratios of normalized data and Monte Carlo. If the SM is valid, the ratio is 1 independent of mass. Middle(9b): di-muon discovery reach. Right (9c): di-jet study using central/forward ratios.

J. “Slow” Particles

Most particles traverse the LHC detectors at speeds very close to the speed of light. But if a new particle is very heavy (hundreds of GeV) it can be slow (\(v < c\)) and hard with sizable momentum above 100 GeV. In this case it is possible to determine directly the mass of the particle if we can measure both the momentum and \(\beta\). E.g. in CMS \(\beta\) can be measured two times independently: using time-of-flight in the Drift Tube muon stations or specific ionization \(dE/dx\) in the tracker. This gives a powerful handle to extract the signal, making an early discovery
FIG. 10: CMS heavy stable charged particles (HSCP) study. Two measurements of $\beta^{-1}$ in the tracker and the muon drift tubes: Left (10a) - signal, Middle(10b) - background. Right (10c): discovery reach.

K. Unusual Event Shapes

So far we have looked at the best measured objects in collider experiments like leptons, photons, jets and missing transverse energy, which have fuelled many discoveries over the last decades. Given the large jump in energy, a closer look at the general event shape and charged or neutral particle multiplicities is certainly among the first topics and papers to come from the LHC. Besides testing the SM, the Monte Carlo generator tuning and the extrapolations from the Tevatron, new phenomena like TeV strings or mini blackholes can be produced copiously in extra dimensions models with a low enough Planck scale. The experimental signatures are striking. Mini blackholes for example will evaporate “democratically” through Hawking radiation producing high multiplicity “circular” events, much more spherical than the usual “jetty” events, as seen in Figure 11. This could open the prospect of studying quantum gravity at colliders. Scales up to 5 TeV can be probed with luminosity not even reaching 1 fb$^{-1}$.

III. OUTLOOK

The ATLAS and CMS collaborations are about to start exploring the Terascale - the culmination of long preparations and many thousands of man–years of hard work. This will open a reach search field for early discoveries: resonances first, hopefully enabling us to fix the scale for new physics. Many other searches like single photons, heavy Majorana neutrinos and right-handed bosons, little Higgs, doubly-charged scalars, isosinglet quarks, same sign top, WW scattering, etc. are not covered in the limited time available.

The experiments are concentrating their efforts to be ready when first collisions take place this fall: detectors, data acquisition systems and software are in place awaiting first LHC data. A lot of inspired work lies ahead to understand detectors of this scale and to avoid “discovering” detector features. The years ahead will be very exciting and the prospects are excellent for paper titles beginning with “Observation of” and not with “Search for”. And be prepared for the unexpected.
FIG. 11: Black hole studies: Left (11a): The striking difference in sphericity (CMS). Right (11b): ATLAS discovery reach for different luminosities as function of the number of extra dimensions.

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[1] ATLAS public results, https://twiki.cern.ch/twiki/bin/view/Atlas/AtlasPhysicsPublicResults
[2] ATLAS Exotica group, https://twiki.cern.ch/twiki/bin/view/Atlas/ExoticsWorkingGroup
[3] CMS Collaboration, “The CMS Physics Technical Design Report, Volume I,” CERN/LHCC 2006-001, CERN, Geneva, 2006.
[4] CMS Collaboration, “The CMS Physics Technical Design Report, Volume II,” CERN/LHCC 2006-021, CERN, Geneva, 2006 and references therein. Published in J. Phys. G: Nucl. Part. Phys. 34 995-1579.
[5] CMS public results of the Exotica group, https://twiki.cern.ch/twiki/bin/view/CMS/EXOTICApublicResults.