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New Physics summary

S. Gennai([1]) and I. Masina([2])

([1]) *Scuola Normale Superiore - Pisa, Italy*
([2]) *Università di Ferrara - Ferrera, Italy*

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Summary. — We introduce the various contributions to the New Physics Session by identifying four main areas: Higgs-like signatures, supersymmetry, exotica and lepton flavour violation searches.

PACS 14.80.Da – Supersymmetric Higgs bosons.
PACS 14.80.Ly – Supersymmetric partners of known particles.
PACS 14.80.Rt – Kaluza-Klein excitations.

1. – Introduction

Physics beyond the Standard Model (SM) is a broad field covering several established frameworks (like supersymmetry, technicolour, extra-dimensions, etc.) but also new models of electroweak symmetry breaking (like Higgsless models) and neutrino mass models. It is clearly impossible to cover all these items in a few days, so that we have tried to focus on the most common models and well-established analysis, in order to have a panoramic view of the present state of the searches for new physics signals. Most of the searches at the Large Hadron Collider (LHC) presented in these proceedings consider 14 TeV as a center-of-mass energy. After the machine accident of the past September, it is very likely that the LHC will start with a center-of-mass energy below 10 TeV (most probably 6 or 8 TeV). Clearly all the results shown here must be rescaled to the new energy profile. New updated results would be published soon.

When looking for the unknown, one of the most famous composition by D. Rumsfeld came to our mind:
"As we know,
There are known knowns.
There are things we know we know.
We also know
There are known unknowns.
That is to say
We know there are some things
we do not know.
But there are also unknown unknowns,
The ones we don't know We don't know."

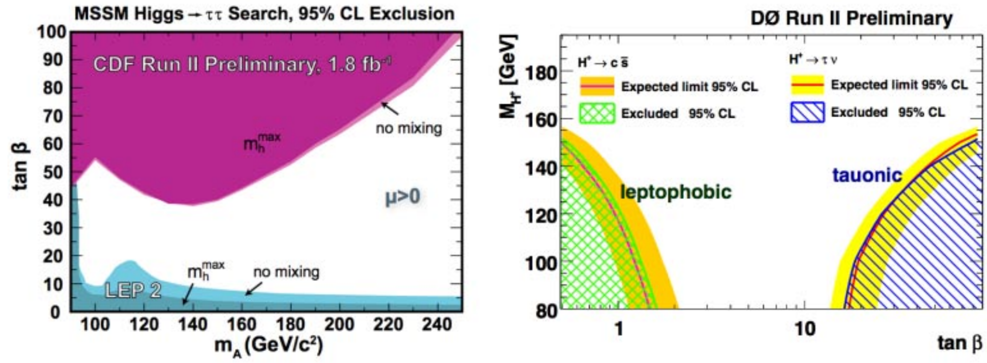

Fig. 1. – Exclusion plots for neutral (left) and charged Higgs (right) bosons in the MSSM, from Tevatron analysis.

To summarize, there is a full zoology of theories that predict New Physics, waiting for an experimental proof (which unfortunately is late to appear); collaborations of general purpose experiments like CDF, D0, ATLAS and CMS are developing strategies and tools to be ready to any possibility, as the unknown can be hidden in any signature.

2. – Higgs-like signatures

The crucial goal of particle physics today is the full understanding of the Higgs sector. We actually know that the electroweak symmetry has to be spontaneously broken, but we ignore the underlying mechanism responsible for this. Since the SM Higgs sector is plagued by the well-known hierarchy problem, the primary objective of any theory beyond the SM is to solve it or, at least, to postpone it at energies higher than the TeV. Clearly, the key to understand the Higgs sector is provided by the identification of Higgs-like signatures at colliders, and its successive theoretical interpretation.

The most explored extension of the SM is the supersymmetric one, in which for each SM particle a supersymmetric partner—a sparticle—is foreseen. When supersymmetry is exact, the stabilization of the scalar Higgs mass is thus provided by the interplay with its fermionic partner, the higgsino. However, as no sparticles have been discovered so far, supersymmetry has to be broken at some energy, shifting the mass of the sparticles to higher values with respect to those of the SM. The Minimal Supersymmetric Standard Model (MSSM) is the most famous extension of the Higgs sector. The model introduces two Higgs doublets that after the symmetry breaking give birth to 5 Higgs bosons: two neutral scalar (h and H), one neutral pseudo-scalar (A) and two charged Higgses ($H^\pm$). At tree level all the couplings of these five bosons to the other particles can be calculated with the use of two parameters: $\tan\beta$ and m_A. The H and A bosons are nearly degenerate in mass, and are usually considered as a unique particle named Φ.

The main production mechanisms at hadron colliders are through gluon fusion or associated production with one or two b-quarks. Figure 1 (left) shows the excluded regions in terms of m_A, being β from the Tevatron analysis. At high values of $\tan\beta$, the couplings to the third fermion family are enhanced, and hence the preferred decay channels are: $\Phi \to \tau\tau$ and $b\bar{b}$. The former is considered as a cleaner signature due to the lower background, however at Tevatron final states with up to three b-jets have been considered. For $H^\pm$ masses below the top mass, the main production mechanism is via

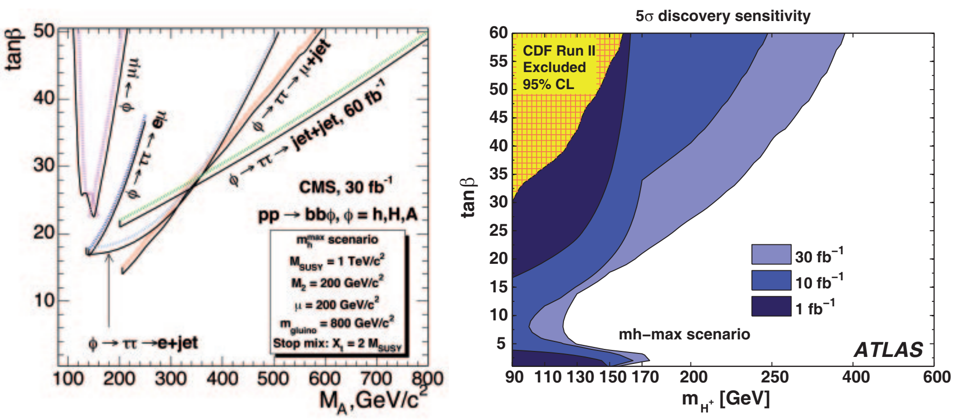

Fig. 2. – Exclusion plots for neutral (left) and charged Higgs (right) bosons in the MSSM, from LHC analysis.

top decay: $t \to H^+b$. Two possible final states have been considered at Tevatron: $c\bar{s}$ and $\tau\nu$. Figure 1 (right) shows the excluded regions for the two different decay channels. More details can be found in [1]. At LHC, analysis concentrates on the final states with leptons, as it has been proven to give better coverage in the parameter phase space. Figure 2 shows the excluded regions for the neutral (left) and charged (right) bosons [2]. Some details on the tau identification techniques used in CMS can be found in [3].

The scalar sector of theories beyond the SM includes prediction of several other possible particles, like, *e.g.*, axions. Some supersymmetric models indeed predict the existence of an axion-like particle, in addition to the five Higgs bosons of the MSSM, with masses up to a few GeV/c^2. These light particles can have couplings similar to those of the Higgs bosons and can populate final states not considered in the MSSM. The Babar Collaboration has searched this kind of particles up to masses of 10 GeV/c^2 through the υ decay into γA^0, $A^0 \to \mu\mu$ or in the invisible channel. The limits on the Branching Ratio ($\Upsilon \to \gamma A^0$, $A^0 \to \mu\mu$ or invisible) fluctuate depending on the central value of the signal yield returned by a particular fit, and range between 0.25×10^{-6} to 5.2×10^{-6} for the decay into muons, and between 0.7×10^{-6} to 31×10^{-6} for the decay into invisible particles [4].

Clearly the supersymmetric framework is not the only possibility of extending the Higgs sector. While dealing with modifications of the Higgs sector of the SM in order to stabilize the electroweak symmetry-breaking scale, the most important symmetry one has to consider is the custodial symmetry. The latter follows from the fact that the scalar sector of the SM has an approximate $SO(4)$ symmetry, violated only by the $U(1)_Y$ and Yukawa couplings. It is wise to require that models have an enlarged invariance group with respect to $SO(4)$. Attempts along this line, in which the SM Higgs emerges as a pseudo-Goldstone boson of some extended symmetry, have been recently proposed [5].

3. – Supersymmetry

As sparticles have not yet been discovered, the symmetry between SM particles and their super-partners must be broken at some scale. The most studied supersymmetry breaking models are: the gravity mediated symmetry breaking (mSUGRA) and the gauge-mediated symmetry breaking (GMSB). Each particle has a quantum number called

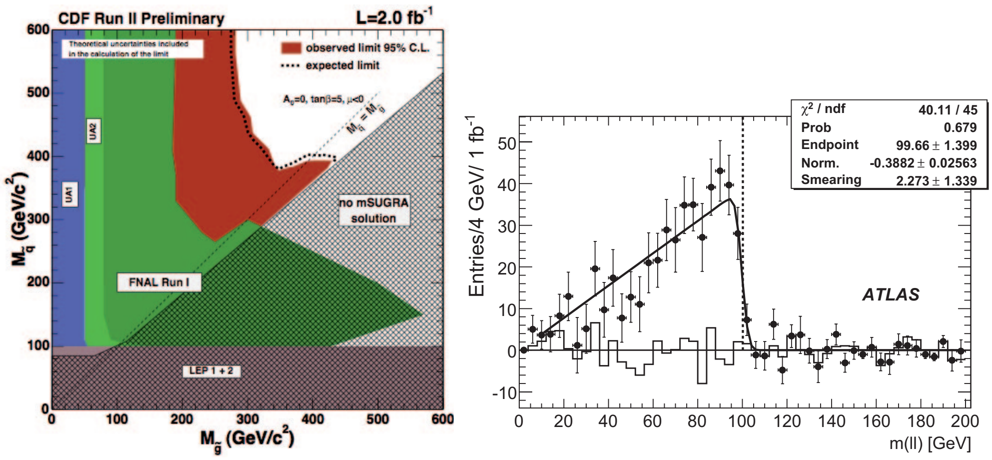

Fig. 3. – Left: exclusion plane for squark and gluino masses at 95% CL from CDF searches. Right: simultaneous fit of dielectron and dimuon masses, after having subtracted the background events, for 1 fb^{-1} of integrated luminosity. On the x-axis, units are in GeV/c^2.

R-parity which is assumed to be 1 for the SM particles and -1 for the sparticles. R-parity is supposed to be conserved in most of the physics scenario considered in the various searches at Tevatron and LHC. This means that sparticles are always produced in pairs (sparticle/anti-sparticle) and they decay in long chains passing through several heavy sparticles up to the lightest supersymmetric particle of the model (LSP). The latter is stable and (in most models) weakly interacting, hence escaping the possibility to be detected.

Depending on the particles involved in these long decay channels, the final state can present several jets, leptons and large missing energy. The cleaner signatures are given by squarks and gluinos production, since SM backgrounds are very small in comparison to the high squark/gluinos production cross-sections. Figure 3 (left) shows the excluded regions in the mSUGRA parameter space from searches at Tevatron [6]. Since every supersymmetric decay chain ends with the LSP particle that escapes the detection, no invariant mass peak can be reconstructed. However the invariant mass distribution of the particles in the final states presents endpoints (minimum and maxima) as shown in fig. 3 (right) for a $\tilde{\chi}_2^0 \to \ell\tilde{\ell} \to \ell\ell\tilde{\chi}_1^0$ (where $\ell =$ electrons or muons). These endpoints carry information about the mass differences of the sparticles involved in the decay chain. From these endpoints (provided that enough decay chains can be studied) it would be possible to extract the spectrum of the supersymmetric partners. More details on the supersymmetry searches at LHC can be found in [7].

From the theory point of view, a natural solution of the hierarchy problem is required in order for supersymmetry to be visible at LHC. The well-known fine-tuning problem of the Higgs sector of the MSSM can be ameliorated within next to minimal versions of the MSSM.

4. – Exotica searches

With the term exotica is commonly intended all the new physics signals not covered in the supersymmetric models, like: technicolour, extra-dimensions, seesaw, black holes, etc.

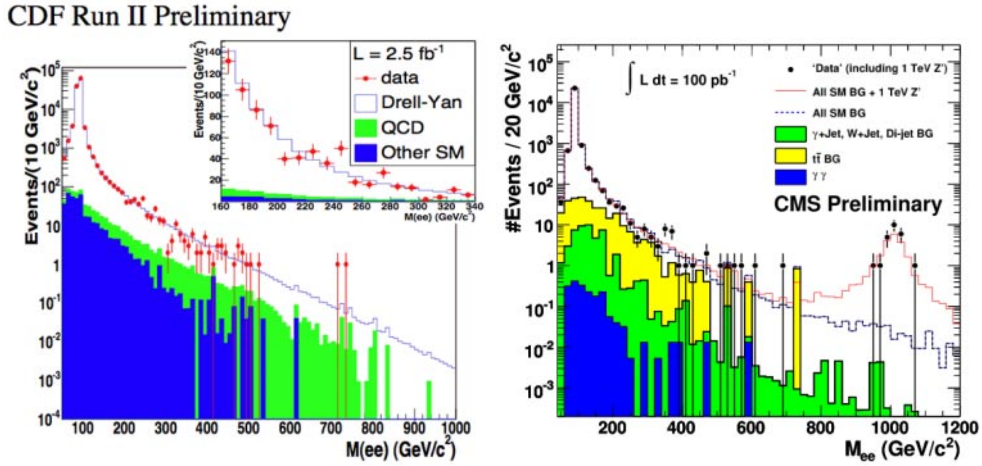

Fig. 4. – Left: CDF di-lepton resonances searches: the di-electron invariant mass. Right: CMS di-electron invariant mass spectrum for a $100\,\text{pb}^{-1}$, compared to SM background estimates.

Due to the huge number of possible models describing similar final states, the searches approach is different from what used for the supersymmetric models. Well-defined final states like: di-lepton/photon resonances, di-boson resonances, jets plus missing transverse energy are commonly studied, and the results are interpreted in terms of specific models only at the end of the analysis.

Historically the di-lepton resonances have been a leading discovery channel, so that it is natural to think that new physics may appear at present and future colliders under the signature of a heavy resonance decaying into a pair of electrons or muons [8]. This kind of searches are very similar between Tevatron and LHC as shown in fig. 4.

A completely different approach is required for analysis involving long-lived charged particles, *e.g.*, exotic particles that are heavy (mass of hundreds of GeV/c^2), long-lived (enough to decay outside of the detector) and charged. Such particles can be distinguished from SM particles by exploiting their unique signature: a low velocity ($\beta = p/E$) associated with a high momentum (few hundreds of GeV/c). Some of them (called R-hadrons) undergo "charge flipping" when they pass through the detector, making the measurement of their momentum particularly difficult [9]. In order to secure interesting events to the tape, ATLAS and CMS are developing refined trigger strategies, some of which are described in [10,11] For example extreme low β particles may miss the trigger requirement on being in sync with the bunch crossing and hence failed the selection. Special triggers are needed to recover the efficiency for these exotica events. In some other cases the heavy particle may be stopped inside the detector (without leaving any signal at all) and may decay with times ranging from μs to months, depending on the model. The CMS Collaboration has developed a dedicated trigger for this peculiar scenario, based on a calorimeter trigger looking at particles trapped in the CMS HCAL during periods of no proton-proton collisions.

In order to explain neutrino masses and mixings, the SM has to be extended. Probably, the most natural way to account for neutrino masses is via the seesaw mechanism. In general the heavy particles to be integrated out (those breaking the $B - L$ global symmetry) are considered to be heavy, with masses a few orders of magnitude below the unification scale. However, by properly suppressing the Yukawa couplings and/or introducing some fine tuning, it is possible to lower the mass of these particles down to the TeV scale. In this case, the phenomenology of their production and decay would give rise to interesting signatures at colliders. The LHC production and decay of $SU(2)_L$ triplets responsible for the generation of neutrino masses through type-III seesaw is discussed in [12].

Abelian extensions of the SM represent an economical but yet profound modification of the gauge structure of the electroweak sector, which can be tested at the LHC. Since $U(1)$ interactions abound in effective theories derived from grand-unified theories and string theories, establishing the origin of these extensions, if found at the future colliders, would be of paramount importance. The problem of unitarity and gauge restoration in effective anomalous models resulting from an extension of the SM in the presence of extra Abelian anomalous factors $U(1)$ is addressed in [13].

If gravity effects are relevant at TeV energy, quantum black holes can form at LHC. Far from inducing apocalyptic events, it seems that quantum black holes could decay leaving as signatures back to back final states of two particles [14].

5. – Lepton Flavour Violation

Searches for Lepton Flavour Violation (LFV) are carried out in several laboratories all over the world. The Babar Collaboration is looking at the τ decays into three leptons [4], while the MEG Collaboration is focused in the decay $\mu \to e\gamma$ [15]. The NA62 Collaboration is also active in these kinds of searches [16].

LFV searches are very interesting because, being the SM background negligible in many cases, a detection of such a signature would unambiguously represent a discovery of new physics. If no signal is detected, the results can nevertheless be used to limit the parameter space of models beyond the SM. Indeed, even if they are considered as indirect signals of new physics, LFV searches are complementary with respect to direct ones in constraining the parameter space of many models, like for instance supersymmetric models.

Indeed, like the SM, also the MSSM does not explain neutrino masses and mixing. In order to account for them, the seesaw mechanism is usually implemented in the MSSM framework, by adding right-handed neutrinos. Compared to the MSSM, the main novelty now is the presence of lepton flavor violation (LFV), which arises both in the gauge interactions (through lepton-slepton-gaugino couplings) and in the Yukawa interactions. Processes extremely suppressed in the SM, like $\mu \to e\gamma$, could thus be enhanced at the level to be probed by experiments; the literature about the constraints on seesaw models coming from the present bounds on $\mu \to e\gamma$ is indeed pretty wide. Since LFV Yukawa interactions are greatly enhanced at large $\tan\beta$, there could also be the possibility of detecting LFV decays of the Higgs bosons at LHC and ILC; in [17], a new mechanism of lepton flavor violation at the photon collider is discussed.

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