Searches for the standard model scalar boson in CMS and for new physics in ATLAS and CMS

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Latest LHC results are reported focussing on the search for the standard model scalar boson, as well as a selection of searches for new physics beyond the standard model.

1 Introduction

This proceeding reports on latest results on two of the main goals of the LHC : (i) searches for the standard model (SM) Brout-Englert-Higgs scalar boson performed by the CMS Collaboration (results from ATLAS are presented separately in this proceeding) and (ii) searches for physics beyond the standard model (BSM), with a selection of results from both CMS and ATLAS. The public CMS and ATLAS results are available on the web pages given in Refs. [1, 2].

The results are based on the LHC data taken during the year 2011 at the proton-proton center of mass energy $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity delivered of more than 5 fb^{-1}, with a peak instantaneous luminosity up to 3.5 10^{33} cm^{-2}s^{-1} as shown in Fig. 1, indicating the excellent performance of the machine in 2011. With such high instantaneous luminosity the number of proton-proton interactions in each bunch crossing is in average more than 10. CMS and ATLAS are multipurpose detectors described in detail in [3, 4].

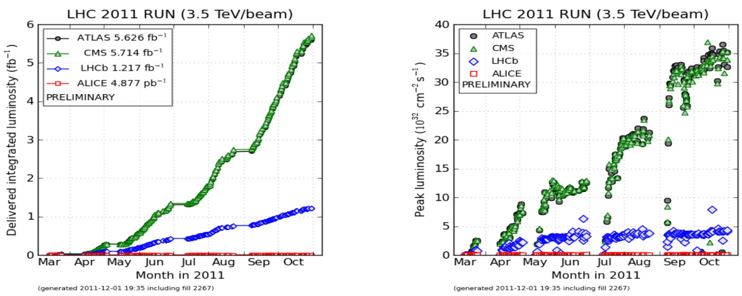
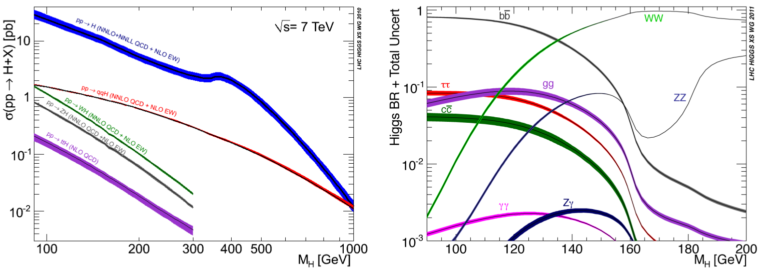


Figure 1: The integrated (left) and peak (right) luminosity delivered by the LHC machine in 2011.



	Channel	m_H range (GeV)	Luminosity (fb^{-1})	Sub-channels	m_H resolution
new	$H \to \gamma\gamma$	110–150	4.8	2	1–2%
	$H \to \tau\tau \to e\tau_h/\mu\tau_h/e\mu + X$	110–145	4.6	9	20%
new	$H \to \tau\tau \to \mu\mu + X$	110–140	4.5	3	20%
new	$WH \to e\mu\tau_h/\mu\mu\tau_h + \nu$'s	100–140	4.7	2	20%
	$(W/Z)H \to (e\nu/\mu\nu/ee/\mu\mu/\nu\nu)(bb)$	110–135	4.7	5	10%
	$H \to WW^* \to 2\ell 2\nu$	110–600	4.6	5	20%
new	$WH \to W(WW^*) \to 3\ell 3\nu$	110–200	4.6	1	20%
	$H \to ZZ^{(*)} \to 4\ell$	110–600	4.7	3	1–2%
	$H \to ZZ^{(*)} \to 2\ell 2q$	{ 130–164 200–600	4.6	6	3% 3%
	$H \to ZZ \to 2\ell 2\tau$	190–600	4.7	8	10–15%
	$H \to ZZ \to 2\ell 2\nu$	250–600	4.6	2	7%

Figure 2: SM scalar boson production cross sections at $\sqrt{s} = 7$ GeV (top left) and decay branching ratios (top right); the 11 decay channels analysed by CMS (bottom).

2 Searches for the standard model scalar boson in CMS

Since the introduction of a scalar field in the SM, proposed in 1964 [5, 6, 7], particle physicists have actively searched for a massive scalar (H) with no success yet. Direct searches at LEP lead to a lower limit on the scalar mass $m_H = 114.4$ GeV at 95% confidence level (CL) [8]. Latest results from indirect constraints from precision electroweak measurements give an upper limit $m_H < 152$ GeV at 95% CL [9], indicating that, if no new physics is introduced, the SM scalar boson is favored at low mass above the LEP limit. Search were also performed at the Tevatron and are reported separately in this proceeding.

The search of the scalar boson continues thanks to the LHC machine. Figure 2 presents the SM H boson production cross sections at $\sqrt{s} = 7$ GeV and the boson decay branching ratios, as a function of the boson mass. The main contributions to the production cross section come from gluon-gluon fusion and from Vector Boson Fusion (VBF). Different final state topologies are relevant for different H boson mass hypotheses. CMS studied and optimised 11 independent channels as detailed at the bottom of Fig. 2. For each channel, the table gives the corresponding m_H range, the luminosity, the number of subchannels considered and the m_H resolution.

2.1 Di-photon final state

Despite its small branching fraction, the $H \to \gamma\gamma$ channel is the most sensitive one for the low mass hypothesis (110-150 GeV). Events with two high pt photons are selected, with possibly two additional jets from outgoing quarks in the VBF production case [10]. The signature of this channel is a narrow mass peak over a large smoothly decreasing background coming from QCD production and γ+jet events. Thanks to the excellent performance of the electromagnetic

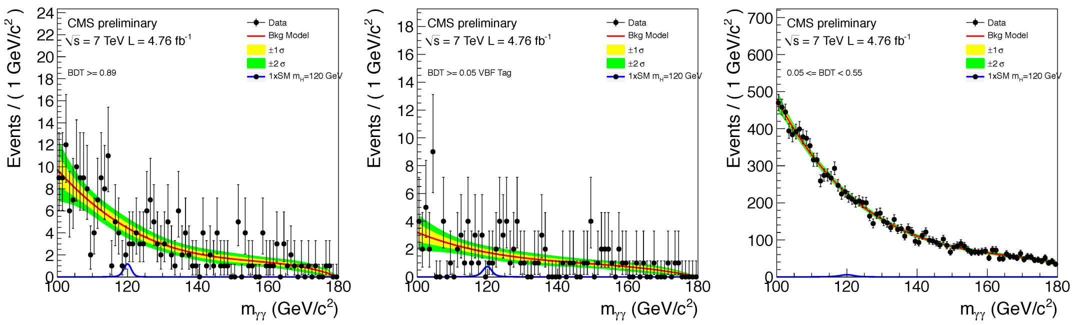


Figure 3: Background model fit to the $m_{\gamma\gamma}$ distribution for the best event class defined by a high BDT output value (left), the VBF event class (middle) and the sum of all the event classes (right). From [10].

calorimeter ECAL of CMS, a very good mass resolution of 1-2% is archieved. To improve the sensitivity of the search, selected diphoton events are subdivided into classes according to the output value of a diphoton Boosted Decision Tree (BDT) which classifies events with signal-like kinematic, good diphoton mass resolution, and good photon identification, with a high score. Five mutually exclusive event classes are defined, four defined by the diphoton BDT output, and a fifth one for the VBF candidate events. The background model is obtained by fitting polynomials to the observed diphoton mass distributions in each of the five event classes. Figure 3 presents the background model fit to the $m_{\gamma\gamma}$ distribution for different event classes, together with a simulated signal ($m_H = 120$ GeV). No significant excess is observed in the data. Figure 4 presents the exclusion limit on the cross section of a SM scalar boson decaying into two photons as a function of the boson mass and relative to the SM cross section, $\sigma/\sigma(SM)$, as well as the observed local p-values. The largest excess of events over the expected background is observed around 125 GeV. Taking into account the look-elsewhere effect in the search range 110-150 GeV, the excess has a global significance of 1.6 σ.

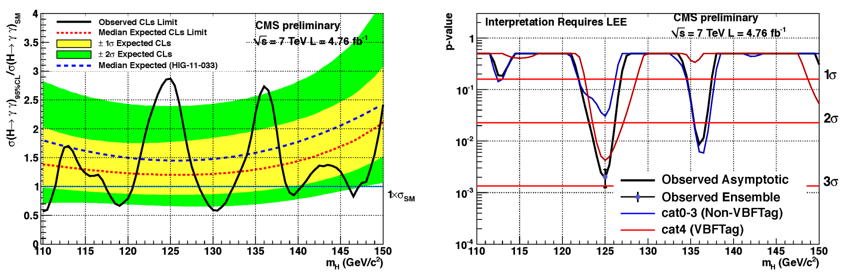


Figure 4: Exclusion limit at 95% CL on the cross section of a SM scalar boson decaying into two photons as a function of the boson mass and relative to the SM cross section, the theoretical uncertainties on the cross section have been included in the limit setting (left); the observed local p-values for the combined event class, the VBF and non-VBF classes (right). From [10].

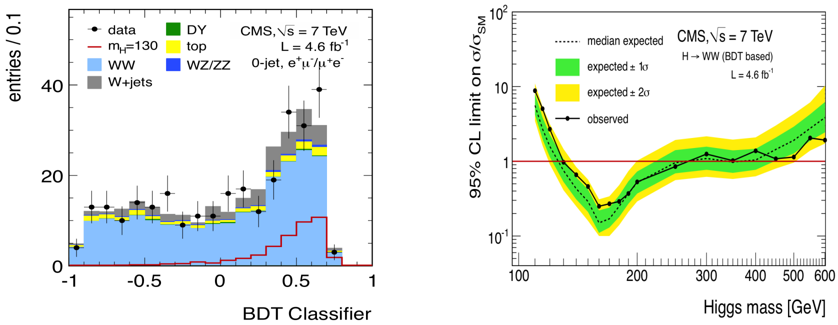


Figure 5: For the $H \to WW \to 2\ell 2\nu$ channel : BDT output in the 0-jet bin for opposite flavor final state (left) and exclusion limit at 95% CL on $\sigma/\sigma(SM)$ (right). From [11].

2.2 Di-boson final state : WW and ZZ

The $H \to WW \to 2\ell 2\nu$ channel is sensitive in a large m_H range, especially around twice the W boson mass. Events with two high pt isolated leptons are selected with additional requirement on the missing transverse energy variable (MET) in the events [11]. Due to the presence of neutrinos in the final state, the m_H resolution is poor, about 20%. Events are classified according to the exclusive jet multiplicity : 0, 1 and 2 (VBF). A multivariate (BDT) analysis is performed, optimized for each mass point. Figure 5(left) shows the BDT output in the 0-jet bin for opposite flavor final state. The main backgrounds (WW, $t\bar{t}$, Drell-Yan, W+jets) are estimated with data-driven techniques. The uncertainty on the background normalization represent the largest source of systematics of the analysis, together with the theoretical uncertainties on the scalar boson cross section. No evidence of the H boson is found and the results are interpreted as an exclusion of a wide m_H range, as shown in Fig. 5(right). Using the CLs approach, the expected exclusion mass range at 95% CL is between 127 and 270 GeV, while the observed one is 129-270 GeV.

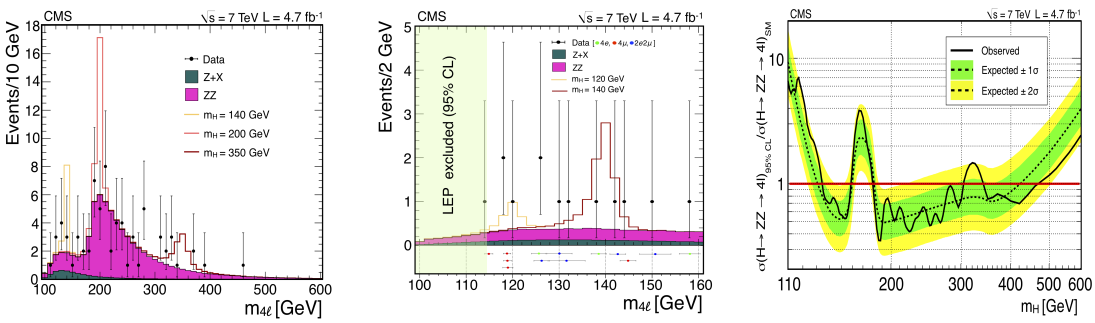


Figure 6: For the $H \to ZZ \to 4\ell$ channel : four-lepton reconstructed mass distribution (left) and a zoom at low mass (middle); exclusion limit at 95% CL on $\sigma/\sigma(SM)$(right). From [12].

The four-lepton decay channel $H \to ZZ \to 4\ell$ search [12] presents a very clear signature : two high mass pairs of isolated electrons or muons. The key point of the selection being a very good lepton identification and a selection down to low pt for the leptons, allowing a large m_H range coverage $110 < m_H < 600$ GeV. Figure 6 presents the four-lepton reconstructed mass distribution in the sum of the 4 lepton channels and a zoom at low mass. No significant excess is observed and upper limits at 95% CL exclude the SM scalar boson in the ranges 134-158 GeV, 180-305 GeV, and 340-465 GeV, see Fig. 6(right). Small excesses of events are observed around masses of 119, 126, and 320 GeV, making in these mass ranges the observed limits weaker than expected in the absence of a signal.

2.3 Channel combination

Five H boson decay modes : $\gamma\gamma$, $b\bar{b}$, $\tau\tau$, WW, and ZZ, with various final state topologies (see the bottom of Fig. 2) have been combined in the mass range 110-600 GeV [13]. The expected excluded mass range in the absence of the SM scalar boson is 114.5-543 GeV at 95% CL, and the observed exclusion mass range is 127.5-600 GeV, See Fig. 7. An excess of events above the expected SM background is observed at the low end of the explored mass range making the observed limits weaker than expected in the absence of a signal. The largest excess, with a local significance of 2.8 σ, is observed for a m_H hypothesis of 125 GeV. The global significance of observing an excess with a local significance greater than 2.8 σ anywhere in the search range 110-600 (110-145) GeV is estimated to be 0.8 σ (2.1 σ), see Fig. 7(right). More data are required to ascertain the origin of this excess.

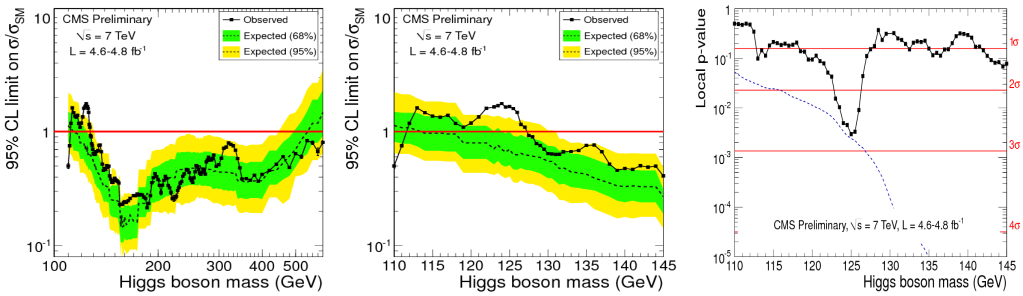


Figure 7: Combination of the 5 scalar boson decay modes : the 95% CL upper limits on the signal strength parameter $\sigma/\sigma(\mathrm{SM})$ for the SM H boson hypothesis as function of m_H (left) and a zoom at low mass (middle); the observed local p-value as a function of m_H (right). From [13].

3 Searches for scalar boson(s) beyond the standard model at the LHC

The SM scalar boson search results presented in previous section can be re-used and interpreted in the context of BSM models. For an extension of the SM including a fourth generation of fermions (SM4), the SM4 scalar boson is excluded in the mass range 120-600 GeV at 95% CL [13]. In the fermiophobic scalar boson scenario, using the $\gamma\gamma$, WW and ZZ decay channels,

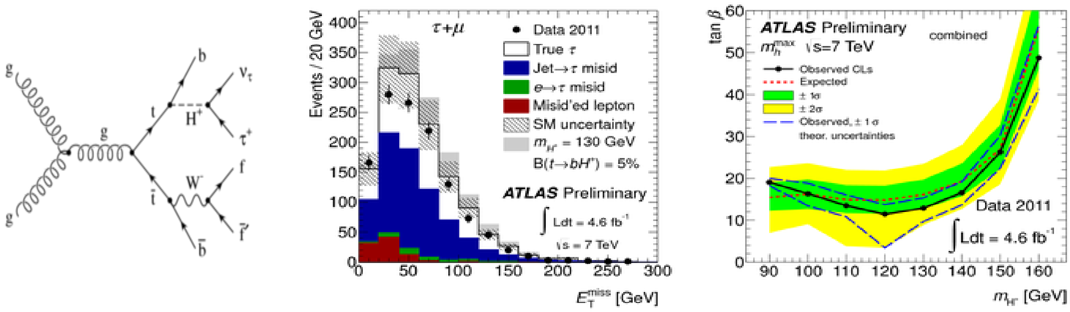


Figure 8: Example of a LO diagram for the production of a H^+ boson, followed by its decays into $\tau\nu$ (left); MET distribution in the $(b\bar{b}+\tau\nu+\mu\nu)$ final state (middle). The full line corresponds to the SM-only hypothesis and the hatched area around it shows the total uncertainty for the SM backgrounds. The predicted contribution of a 130 GeV charged scalar boson with BR$(t \to bH^+)$ = 5% and BR$(H^+ \to \tau^+\nu)$ = 100% is also indicated; 95% CL exclusion limits on $\tan\beta$ as a function of m_{H^+} (right), results are shown in the context of the MSSM scenario $m_h^{\max}$ for the combination of all channels considered. ATLAS results from [15].

a fermiophobic scalar boson is excluded by CMS in the mass range 110-192 GeV at 95% CL [13]. Searches are also performed by ATLAS using the $\gamma\gamma$ decay channel [14].

Supersymmetry is a well known extension to the SM. The minimal supersymmetric SM (MSSM) contains two scalar doublets, giving rise to five physical states : a light neutral CP-even state (h), a heavy neutral CP-even state (H), a neutral CP-odd state (A) and a pair of charged states (H^+, H^-). The mass relations between these particles depend in particular on the MSSM parameter $\tan\beta$, the ratio of the scalar fields vacuum expectation values. The main H^+ production mode at the LHC is through top quark decays, for m_{H^+} smaller than the top quark mass. Search for the H^+ boson in the range 90-160 GeV, is performed by ATLAS [15] and CMS [16] using $t\bar{t}$ events, $H^+ \to \tau\nu$, with a leptonically or hadronically decaying τ lepton in the final state, see Fig. 8(left). Figure 8 (middle) shows the MET distribution in the $(b\bar{b}+\tau\nu+\mu\nu)$ final state. The observed data are in agreement with the SM predictions. These results are interpreted in the context of the $m_h^{\max}$ scenario of the MSSM, and values of $\tan\beta$ above 13-26 are excluded in the mass range $90 < m_{H^+} < 150$ GeV, see Fig.8(right).

4 Searches for new physics in ATLAS and CMS

Complementary to the search for a possible scalar boson, LHC may also shed light on new physics beyond the SM. Indeed the SM is generally considered as a low energy effective model of a more fundamental theory. The motivations of new physics are numerous, one of it being the need of identification of new matter type, called the Dark Matter (DM), still unknown presently. DM candidates are proposed for example in some supersymmetry (SUSY) models. Another motivation is the wish of unification of the four fundamental interactions at high energy: the GUT (Grand Unify Theory), which generally implies the existence of new heavy resonances.

Searches are performed at the LHC to track possible new physics in many different final state topologies, see Refs. [1, 2] for a complete list. Here three recent specific searches will be presented : SUSY searches, heavy resonance searches and dark matter searches.

4.1 Search for SUSY particles

If SUSY exists at the TeV scale, the SUSY partners of quarks and gluons, squarks and gluinos, should be abundantly produced at the LHC thanks to their large cross section production. The most sensitive search is the multijet + MET final state, as for example produced by diagram shown in Fig. 9(left). CMS has performed a search for heavy particle pairs production, sensitive to generic SUSY models provided superpartner particles are kinematically accessible, with minimal assumptions on properties of the lightest superpartner particle [17]. The kinematic consistency of the selected events is tested against the hypothesis of heavy particle pair production using the dimensionless *razor* variable R, related to the MET. The new physics signal is characterized by a broad peak in the distribution of M_R, an event-by-event indicator of the heavy particle mass scale. As no significant excess of events is found beyond the SM expectations, results are interpreted in the context of the Constrained Minimal Supersymmetric Standard Model, see Fig. 9(right).

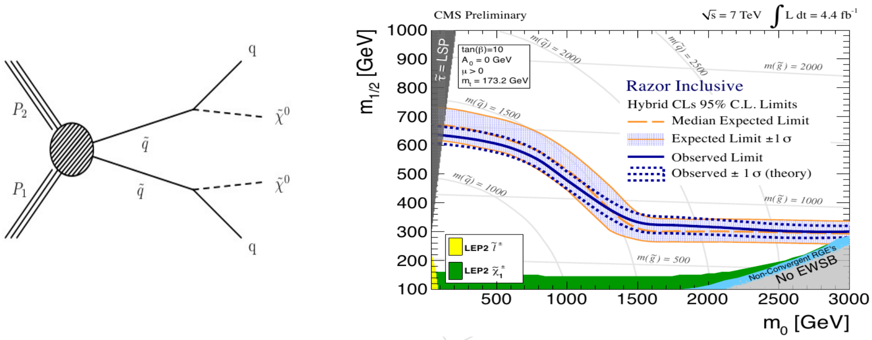


Figure 9: Example of diagram of heavy SUSY particle pair production (left); observed (solid blue curve) and median expected (dot-dashed curve) 95% CL limits in the $(m_0, m_{1/2})$ CMSSM plane with $\tan\beta = 10$, from the razor analysis. CMS results from [17].

With the large amount of luminosity collected in 2011, CMS and ATLAS become sensitive to more exclusive production modes, with lower cross section, as for example the electroweak chargino/neutralino production. Charginos $\tilde{\chi}_1^{\pm}$ and neutralinos $\tilde{\chi}_1^0$ are mass eigenstates formed from the linear superposition of the SUSY partners of the electroweak gauge bosons (W, Z, γ) and of the scalar bosons. In many SUSY models, $\tilde{\chi}_1^{\pm}$ are among the lightest SUSY particles and the $\tilde{\chi}_1^0$ is the lightest SUSY particle (LSP). Search for associated production and leptonic decays, of charginos and neutralinos are performed by ATLAS in the three lepton and MET final states [18], see Fig. 10(left). No significant excess of events is found in data. The results are interpreted in pMSSM [19] and in simplified models [20, 21]. For the simplified models, degenerate lightest chargino and next-to-lightest neutralino masses are excluded up to 300 GeV for mass differences to the lightest neutralino up to 250 GeV, see Fig. 10(right).

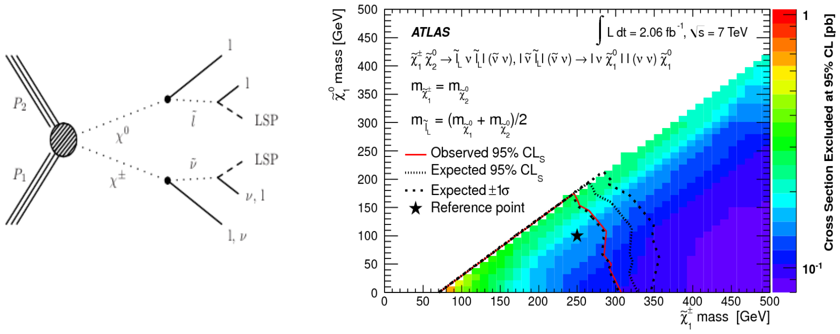


Figure 10: Example of a diagram pour chargino-neutralino production at the LHC (left); observed and expected 95% CL limit contours for chargino and neutralino production in the simplified model scenarios. ATLAS results from [18].

4.2 Search for heavy resonances

CMS and ATLAS are searching for new heavy resonances in the dilepton (ee and $\mu\mu$) decay channel. These new particles are typically predicted in GUT models (spin 1 boson noted Z'), or models proposing extra spatial dimension(s), as for example the Randall-Sundrum model (spin 2 boson noted G) [22]. Events with two isolated high pt leptons are selected [23, 24]. The dilepton mass spectrum is analysed in the high mass range, typically $M_{\ell\ell} > 500$ GeV. The main backgrounds come from Drell-Yan events (irreducible), from $t\bar{t}$ and multijet events. These later two backgrounds are estimated by data driven methods. Figure 11(left) presents the CMS dielectron invariant mass distribution, compared to the stacked sum of all expected backgrounds. Figure 11 (right) presents the expected and observed 95% CL upper limits obtained by ATLAS on $\sigma \times BR$ as a function of mass for various Z' models, with the combination of the electron and muon channels.

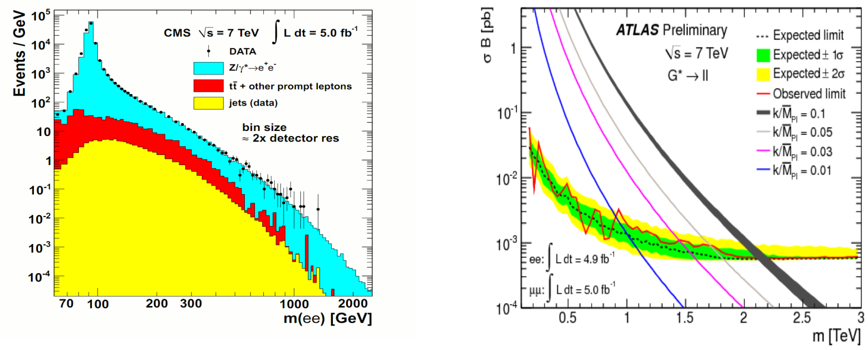


Figure 11: The CMS dielectron invariant mass distribution [23] (left); ATLAS expected and observed 95% CL upper limits on $\sigma \times BR$ as a function of mass for various Z' models (ee and $\mu\mu$ channels) combined [24].

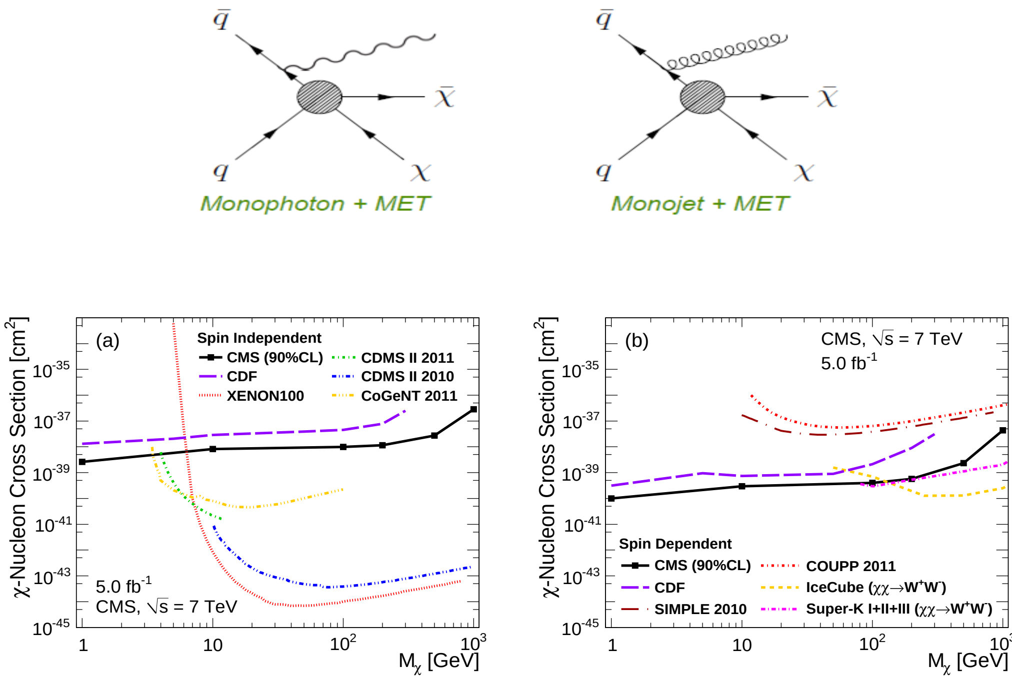


Figure 12: Diagram for mono-photon and mono-jet production with MET (top); comparison of the 90% CL upper limits on the dark matter-nucleon scattering cross section versus dark matter mass for the spin-independent (bottom left) and spin-dependent (bottom right) models, with results from various direct detection experiments. CMS results from [25].

4.3 Search for dark matter

A search for dark matter particles and large extra dimensions in events with an energetic jet or photon and an imbalance in transverse momentum is performed in CMS, the unique object in the event being the jet or the photon from ISR, see Fig. 12(top). The analyses are detailed in [25, 26]. The data are in good agreement with the expected contributions from SM processes. Using an effective operator (see Ref. [27]), constraints on the dark matter-nucleon scattering cross sections are determined, as shown in Fig. 12(bottom). For the spin-independent model, these are the best limits for a dark matter particle with mass below 3.5 GeV, a region unexplored by the direct detection experiments. For the spin-dependent model, these are the most stringent constraints over the entire 1-1000 GeV mass range studied.

5 Conclusions

This proceeding has presented the latest searches performed by CMS for the standard model scalar boson in 11 independent channels. No significant excess is found and the expected and observed 95% CL exclusion ranges in m_H are 114.5-543 and 127.5-600 GeV, respectively. A small excess of events around 125 GeV is observed, characterised by a local significance of 2.8 σ, the global significance in the 110-145 GeV mass range and in the full mass range are 2.1 σ and 0.8 σ, respectively. The small excess is compatible with both the presence of a minimal SM scalar boson signal and the background fluctuation.

Searches for new physics by the ATLAS and CMS experiments were also performed in many topologies, more exotic final states and more exclusion production were studied. No evidence for new physics so far have been observed and limits on new physics cross section production or on new particle mass have been significantly extended.

These impressive results were possible thanks to the excellent performance of the LHC machine in 2011. A total of 15 fb^{-1} of data is expected to be collected in year 2012, 3 times more than in 2011, at a center-of-mass energy of 8 TeV. At the end of 2012, the LHC will give a final answer on the existence of the minimal SM scalar boson, and will search for new physics in a larger phase space. The data that will be collected after 2014, at the design energy of 14 TeV, will identify and study the properties of any possible new signal hopefully.

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