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Discovery potential for the Standard Model Higgs at ATLAS

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Summary. — The potential of the ATLAS experiment to discover or exclude the Standard Model Higgs boson is reviewed. Several important decay channels are considered, and more will be included in the future. The statistical treatment used here to combine the channels relies on a large sample approximation that is expected to be valid for an integrated luminosity of at least $2\,\text{fb}^{-1}$. Results are presented for the expected statistical significance of discovery and expected exclusion limits.

PACS `14.80.Bn` – Standard model Higgs bosons.

1. – Introduction

The search for the Higgs boson is one of the primary physics goals of the Large Hadron Collider. The LHC will provide colliding proton beams with a design centre-of-mass energy of 14 TeV and a luminosity of $10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$, after an initial phase at lower CM energy planned for 2009/10. Here we review the prospects for discovery or exclusion of the Standard Model Higgs boson by the ATLAS detector, considering the period of 14 TeV running with a data sample achievable within the first several years (up to $30\,\text{fb}^{-1}$).

The ability to discover and study the Standard Model Higgs boson over a wide range of masses was an important design criterion of the ATLAS detector. This has led to a detector with excellent tracking and calorimetry as well as lepton identification over a wide angular range. Details on the ATLAS experiment can be found in ref. [1].

Standard Model Higgs boson production and decay are reviewed briefly in sect. **2**. The present study uses the decay modes $\text{H} \to \text{ZZ}^{(*)} \to 4l$ ($l = \text{e}, \mu$), $\text{H} \to \tau^+\tau^-$, $\text{H} \to \gamma\gamma$ and $\text{H} \to \text{W}^+\text{W}^- \to \text{e}\nu\mu\nu$. Including additional decay channels, *e.g.*, $\text{H} \to \text{W}^+\text{W}^-$ with the W-bosons decaying to $\text{e}\nu\text{e}\nu$ or $\mu\nu\mu\nu$, will improve the sensitivity beyond what is reported here. The searches based on individual channels are described in sect. **3**.

Section **4** describes the statistical combination of the channels into a single statement of discovery significance or exclusion limits. The approach taken here uses the profile likelihood ratio, where effects of systematic uncertainties are incorporated by use of appropriate nuisance parameters. Results are shown in sect. **5**; more information can be found in ref. [2]. These studies represent updates of previous investigations reported in ref. [3].

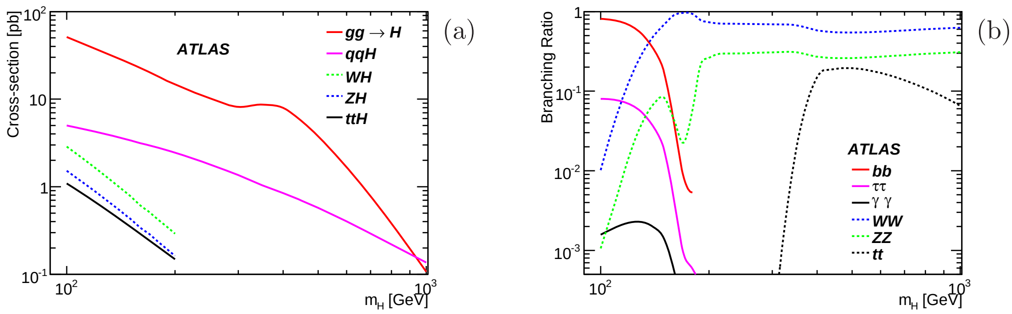

Fig. 1. – (a) The production cross-sections and (b) branching ratios for decays to several important final states for the Standard Model Higgs boson as a function of its mass (from ref. [2]).

2. – Properties of the Standard Model Higgs boson

The cross-section for production of a Standard Model Higgs in pp collisions is shown in fig. 1(a) as a function of the Higgs mass for several production modes. Gluon fusion has by far the largest cross-section for the relevant mass range. The Vector Boson Fusion (VBF, *i.e.* $qq \to qq\mathrm{H}$) cross-section is lower by an order of magnitude, but these events are characterized by two jets separated by a large-rapidity gap with no hadronic activity in the central region, and this helps distinguish them from background events. The cross-sections for a Higgs produced with a vector boson or heavy quark pair are much smaller and therefore in the present study we focus on gluon fusion and VBF production.

The branching ratios for different Higgs decay modes depend strongly on its mass m_H, as can be seen in fig. 1(b). The decay $\mathrm{H} \to b\bar{b}$ dominates at low mass, but the resulting b-jets are swamped by the QCD background. Although the branching ratio for $\mathrm{H} \to \gamma\gamma$ is only around 2×10^{-3} in the low-mass range, the signature of these events is distinctive and the mode is important for discovery. The rate for $\mathrm{H} \to \tau^+\tau^-$ lies between that of $\gamma\gamma$ and $b\bar{b}$ for low mass, and this mode is also important for low m_H despite the difficulties in reconstructing tau-leptons. At higher m_H the decay $\mathrm{H} \to \mathrm{W}^+\mathrm{W}^-$ grows in importance, dominating for m_H near $2M_\mathrm{W}$. Although the branching ratio for ZZ stays a factor of two below that of WW even above its kinematic threshold of $2M_\mathrm{Z}$, it quickly becomes the dominant channel in terms of discovery potential because of its clear signature when both Z-bosons decay to electron or muon pairs.

3. – Overview of Higgs channels studied

3·1. $\mathrm{H} \to \mathrm{ZZ}^{(*)} \to 4l$ ($l = \mathrm{e}, \mu$). – The decay channel $\mathrm{H} \to \mathrm{ZZ}^{(*)} \to 4l$, where here l indicates either an electron or muon, is effective in the Higgs search for masses in the range $130 < m_\mathrm{H} < 1000\,\mathrm{GeV}$, with the exception of the small gap around $m_\mathrm{H} \approx 2M_\mathrm{W}$ where the dominant decay $\mathrm{H} \to \mathrm{W}^+\mathrm{W}^-$ suppresses all other modes.

Successful reconstruction of a Higgs boson in this mode requires excellent lepton efficiency, since four of them must be found. At least one of the Z bosons is required to be on shell, which suppresses $t\bar{t}$ background. The remaining dominant background is from continuum $\mathrm{ZZ}^{(*)}$ production, the level of which is fitted from the sidebands of the four-lepton mass distribution. The expected shape of this distribution for $m_\mathrm{H} = 130\,\mathrm{GeV}$ is shown in fig. 2(a), which is normalized to an integrated luminosity of $30\,\mathrm{fb}^{-1}$.

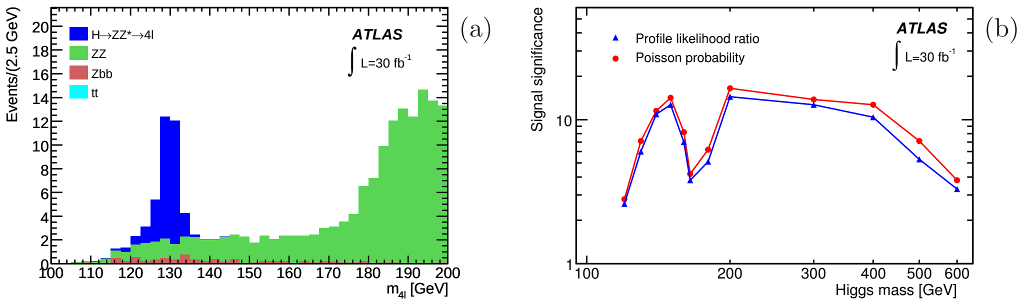

Fig. 2. – (a) The four-lepton invariant-mass distribution expected for an integrated luminosity of $30\,\mathrm{fb}^{-1}$. (b) The expected signal significance *versus* Higgs mass for the $\mathrm{H} \to \mathrm{ZZ}^{(*)} \to 4l$ channel based on $30\,\mathrm{fb}^{-1}$.

Figure 2(b) shows the expected discovery significance (number of standard deviations) based on this mode alone for an integrated luminosity of $30\,\mathrm{fb}^{-1}$, and it is well above the 5σ discovery threshold for a broad mass range. The upper points in the plot show the significance based on counting events in a mass window around the Higgs mass being tested, without consideration of the systematic uncertainty in the background shape of the four-lepton mass distribution. The lower points (triangles) includes this systematic uncertainty by modeling the shape with a sufficiently flexible parametric function that is fitted to the data.

3·2. $\mathrm{H} \to \tau^+\tau^-$. – The decay $\mathrm{H} \to \tau^+\tau^-$ is investigated for the case where the Higgs is produced together with two forward jets (VBF production). Events are considered where either both taus decay to e or μ (the ll-channel) or where one decays to leptons and the other to hadrons (lh-channel). In both cases one has missing neutrinos, and thus the invariant mass of the visible decay products does not give the Higgs mass. However, as the tau-leptons typically have very high momenta compared to the tau mass, their decay products are highly boosted and almost collinear with the direction of the taus. Using this approximation and by measuring the missing transverse energy in the event, one can reconstruct the invariant mass of the $\tau^+\tau^-$ system.

The expected $\tau^+\tau^-$ mass distribution is shown in fig. 3(a), which is scaled to an integrated luminosity of $30\,\mathrm{fb}^{-1}$. The dominant background is from events with two jets plus a Z which decays to $\tau^+\tau^-$, resulting in the large peak at M_Z. This background is estimated by selecting events with two jets plus a Z decaying to either $\mu^+\mu^-$ or $\mathrm{e}^+\mathrm{e}^-$. The leptons are then replaced with simulated tau-decays. The uncertainty in the background related to the jet production is thus measured directly from data.

The expected significance (number of standard deviations) for $\mathrm{H} \to \tau^+\tau^-$ alone is shown in fig. 3(b) as a function of the Higgs mass for an integrated luminosity of $30\,\mathrm{fb}^{-1}$. Although the lh-channel gives the most sensitivity, the ll-channel also makes an important contribution and thus both are used in the combined search.

3·3. $H \to \gamma\gamma$. – The decay $H \to \gamma\gamma$ is comparatively rare with a branching ratio around 2×10^{-3} for $110 < m_\mathrm{H} < 140\,\mathrm{GeV}$. Nevertheless, the events are sufficiently distinct from the background to make this channel important for the discovery of a Higgs boson in this mass range. Although backgrounds from direct photons as well as

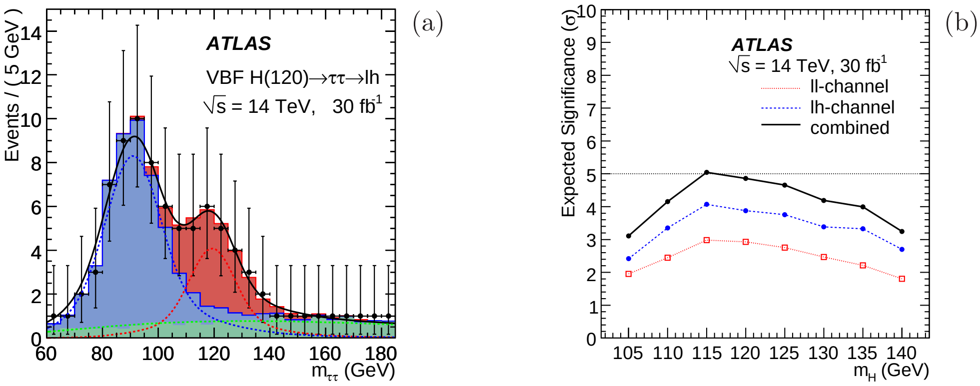

Fig. 3. – (a) The di-tau invariant-mass distribution expected for an integrated luminosity of $30\,\mathrm{fb}^{-1}$. The error bars shown are to indicate the level of statistical fluctuation one would expect in such a sample. (b) The expected signal significance *versus* Higgs mass for the $\mathrm{H} \to \tau^+\tau^-$ channel based on $30\,\mathrm{fb}^{-1}$.

neutral pions from hadronic jets are difficult to predict in absolute terms, they can be assumed to give a smooth diphoton mass distribution, and thus can be measured directly from the sidebands around the Higgs signal peak. An example is shown in fig. 4(a).

The expected signal significance from the $\gamma\gamma$ channel is shown as a function of m_{H} in fig. 4(b). This is shown for fixed m_{H} and also for the case where m_{H} is regarded as a free parameter, which accounts for the so-called "look-elsewhere effect" (see sect. **4**). For purposes of the combination done here, the fixed-mass result based on the inclusive analysis is used, which only uses the diphoton mass in a one-dimensional fit. Exclusive analyses where a photon pair is found with 0, 1, or 2 jets have also been carried out, and in this case, the diphoton mass and other kinematic variables are used in a multivariate analysis. The combination of exclusive analyses is found to have the highest sensitivity, and it is planned to use this instead of the inclusive analysis at a later stage.

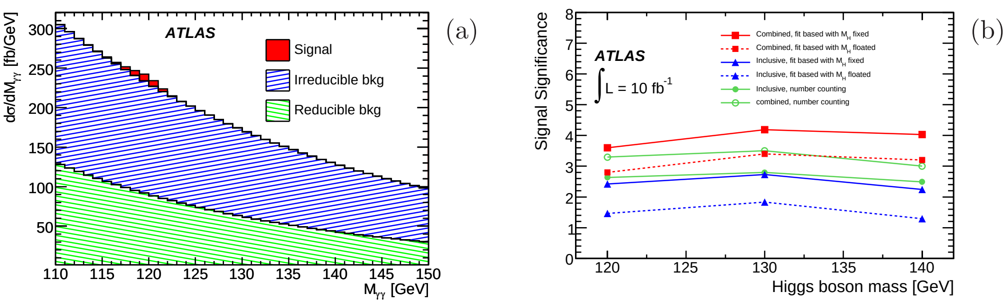

Fig. 4. – (a) The di-photon invariant-mass distribution $\mathrm{d}\sigma/\mathrm{d}M_{\gamma\gamma}$ in fb/GeV. The irreducible background refers to pairs of prompt photons; the reducible background is the case where one or both photons are faked by hadronic jets containing a high-energy π^0. (b) The expected signal significance *versus* Higgs mass for the $\mathrm{H} \to \gamma\gamma$ channel based on $10\,\mathrm{fb}^{-1}$.

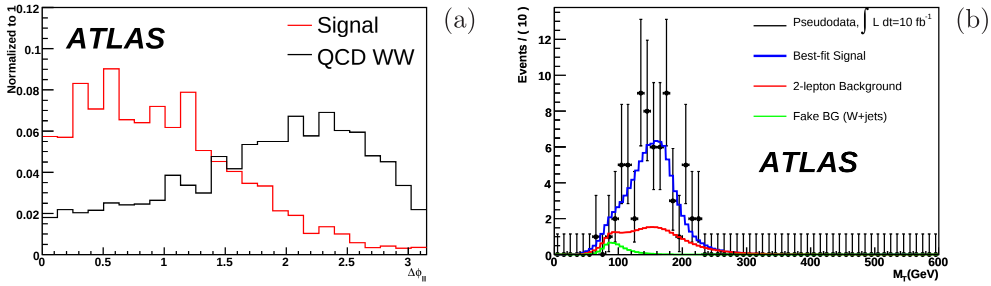

Fig. 5. – (a) The expected distributions of $\Delta\phi_{ll}$ for signal and background for the W^+W^- channel with no hard jets (normalized to unit area). (b) The transverse mass distribution expected for the W^+W^- channel with two hard jets for an integrated luminosity of $10\,\text{fb}^{-1}$. Both plots assume a true Higgs mass of 170 GeV.

3˙4. $H \to W^+W^- \to e\nu\mu\nu$. – The decay channel $H \to W^+W^-$ is most important for the Higgs mass range from somewhat below $2M_W$, where its branching ratio becomes dominant, up to about $2M_Z$, above which the ZZ mode takes over as the most significant. The analysis of this mode includes two separate searches: one where a W^+W^- pair is found with no additional high-p_T hadron jets, where the Higgs signal would come primarily from gluon fusion, and the other where one finds two additional hard jets, which is sensitive to VBF production. In both cases, the W pairs are found using only the decay channel $e\nu\mu\nu$. Other possibilities, *e.g.*, $e\nu e\nu$, $\mu\nu\mu\nu$ and $l\nu qq$, are under study and will be included later.

Because of the missing neutrinos in the W decays, one is unable to reconstruct the Higgs candidate's mass. Instead, an effective variable for separating signal from background is the transverse mass, defined by

$$m_T = \sqrt{(E_{T,\text{miss}} + E_{T,ll})^2 - (\vec{p}_{T,\text{miss}} + \vec{p}_{T,ll})^2}, \tag{1}$$

where $E_{T,ll} = \sqrt{p^2_{T,ll} + m^2_{ll}}$ and $E_{T,\text{miss}} = \sqrt{p^2_{T,\text{miss}} + m^2_{ll}}$. Another important variable is $\Delta\phi_{ll}$, the opening angle between the two leptons in the transverse plane. The distribution of $\Delta\phi_{ll}$ is enhanced at low angles for Higgs events, which results from the spins of the two W bosons being antiparallel. The distributions of the transverse mass and $\Delta\phi_{ll}$ for signal and background are shown in fig. 5.

The main background for the W^+W^- channel with no hard jets is from continuum WW events. The Higgs search for this channel uses the transverse mass, the p_T of the WW system, and the angle $\Delta\phi_{ll}$. For the two-jet analysis the main background comes from $t\bar{t}$ events. Here events are selected in a range of the angular variables $\Delta\phi_{ll}$ and the rapidity $\Delta\eta_{ll}$, and then the distributions of the transverse mass and a neural network based on jet activity are used in a simultaneous fit. Further details on the sensitivity achievable with the WW channel alone can be found in ref. [2].

4. – Statistical combination of channels

To obtain the maximum discovery sensitivity for the Higgs boson one wishes to exploit all of information available from each channel. Here this is done using a statistical formalism based on the *profile likelihood ratio*. Other approaches, for example, methods similar to those used at LEP [4] or Bayesian methods, are also being considered.

Here we report the discovery significance based on a search for a Higgs boson of a fixed mass m_{H}. If one tests a large range of mass values, however, then there is an increased probability that a fluctuation will lead to an apparent signal for some mass in the range considered (the so-called "look-elsewhere-effect"). This can be taken into account either by regarding m_{H} as a free parameter in the search or by adjusting the fixed-mass result with a correction factor derived from Monte Carlo. These corrections are not considered for the combined result here, although both the fixed and floating-mass approaches have been studied for several of the channels individually (see ref. [2]).

For the analysis of a given channel one measures for each event a set of kinematic variables such as the invariant mass of the Higgs candidate. Here we describe the procedure for a binned analysis, but the extension to the unbinned case is straightforward. The number of entries found in bin i of a kinematic variable is a number n_i assumed to follow a Poisson distribution with an expectation value $E[n_i] = \mu s_i + b_i$, where s_i is the expected number of signal events assuming a Standard Model Higgs and b_i is the expected number of background events, here taken to mean the prediction of the Standard Model without real Higgs production. The quantity μ is a global strength parameter common to all channels designed such that $\mu = 0$ is the background-only hypothesis and $\mu = 1$ corresponds to a Standard Model Higgs.

The expected number of signal and background events in a bin of a kinematic variable x can be written as

$$s_i = s_{\mathrm{tot}} \int_{\mathrm{bin}\, i} f_s(x; \vec{\theta}_s)\, \mathrm{d}x, \tag{2}$$

$$b_i = b_{\mathrm{tot}} \int_{\mathrm{bin}\, i} f_b(x; \vec{\theta}_b)\, \mathrm{d}x, \tag{3}$$

where b_{tot} is the total background and $\vec{\theta}_s$ and $\vec{\theta}_b$ represent shape parameters needed to describe the distributions of x for the signal and background, respectively. These quantities, collectively referred to as $\boldsymbol{\theta}$, are treated as nuisance parameters, and μ is thus the only parameter of interest.

The single-channel likelihood can be written as the product of Poisson terms for the number of entries in each bin. Some channels also use subsidiary measurements of distributions that provide information on the background rate and possibly also shape. The numbers of entries in the bins of these distribution are also included in the likelihood as independent Poisson variables. The i-th decay channel is thus described by a likelihood function $L_i(\mu; \vec{\theta}_i)$, and since the data samples for each channel are disjoint, the full likelihood can be written as a product over the channels: $L(\mu, \boldsymbol{\theta}) = \prod_i L_i(\mu; \vec{\theta}_i)$. Here the vector $\boldsymbol{\theta}$ represents all of the parameters of the problem except the single parameter of interest μ, which is assumed to be common to all channels.

To test a hypothesized value of the strength parameter μ one constructs the profile likelihood ratio

$$\lambda(\mu) = \frac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}\,. \tag{4}$$

Here $\hat{\mu}$ and $\hat{\boldsymbol{\theta}}$ in the denominator indicate the values of the parameters that maximize the likelihood, and $\hat{\hat{\boldsymbol{\theta}}}$ in the numerator maximizes the likelihood for the specified value

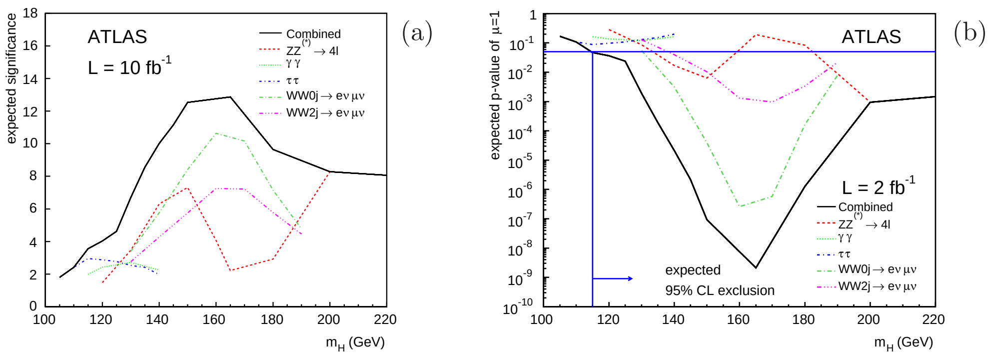

Fig. 6. – (a) The median discovery significance and (b) the median p-value of the Standard Model Higgs hypothesis *versus* the Higgs boson mass m_{H} based on the combination of all channels considered here for an integrated luminosity of $10\,\mathrm{fb}^{-1}$.

of μ. If the data are in good agreement with the hypothesized μ, then one will find $\hat{\mu}$ close to μ and $\lambda(\mu)$ close to one.

For purposes of establishing discovery, we define $q_\mu = -2\ln\lambda(\mu)$, and one is specifically interested in excluding the case $\mu = 0$. For setting upper limits on μ, it is more appropriate to define $q_\mu = -2\ln\lambda(\mu)$ for $\hat{\mu} < \mu$ and zero otherwise; further discussion can be found in ref. [2].

For both discovery and upper limits, larger values of q_μ indicate that the data are in increasing disagreement with the hypothesized μ. The level of disagreement is quantified by giving the p-value, which is the probability, assuming μ, to see data with equal or less compatibility with μ, *i.e.*, it is the integral of $f(q_\mu|\mu)$ from the observed value $q_{\mu,\mathrm{obs}}$ to infinity. This is usually converted to an equivalent significance, Z, defined as the number of standard deviations of a Gaussian variable giving an upper-tail area equal to p, *i.e.*, $Z = \Phi^{-1}(1-p)$ where Φ is the Standard Gaussian cumulative distribution.

Thus to find the p-value one requires the distribution, assuming data generated with a given value μ, of the statistic q_μ. For a sufficiently large data sample this can be related to a chi-square distribution for one degree of freedom. In this case the relation between the observed value of q_μ and the significance Z is simply $Z = \sqrt{q_\mu}$ (this holds for both discovery and upper limits). From Monte Carlo studies described in ref. [2] it was found that this approximation should be valid for an integrated luminosity of at least $2\,\mathrm{fb}^{-1}$.

5. – Results

By "discovery" of the Higgs boson here one means rejecting the $\mu = 0$ hypothesis using the statistic q_0 with a high significance, usually taken to mean $Z \geq 5$. Naturally one would still need to investigate further properties of the observed signal before one could establish whether it really is a Standard Model Higgs boson. To characterize the sensitivity of the experiment, we give the median discovery significance (Z value based on a test of $\mu = 0$) where the median corresponds to a Standard Model Higgs signal. This is shown in fig. 6(a) as a function of the hypothesized Higgs mass for an integrated luminosity of $10\,\mathrm{fb}^{-1}$.

To quantify the expected limits one expects to set if the Higgs signal is absent, we compute the p-value of the $\mu = 1$ hypothesis, where the median corresponds to data generated with no signal present. This is shown in fig. 6(b) for the individual channels and for the combination. Values of m_{H} for which the combined p-value is less than 0.05 are regarded as excluded at 95% CL. For $2\,\mathrm{fb}^{-1}$, one expects to exclude m_{H} down to 115 GeV, essentially closing the gap with the 114.4 GeV lower limit set by LEP [4].

6. – Conclusions

Several decay channels of the Standard Model Higgs boson have been studied and their combined sensitivity for discovery and limits has been investigated. Future inclusion of additional channels, such as the $\mu\nu\mu\nu$, $e\nu e\nu$ and $l\nu qq$ decays for the $\mathrm{H} \to \mathrm{W}^+\mathrm{W}^-$ mode, and use of combined exclusive channels for the $\mathrm{H} \to \gamma\gamma$ mode, will lead to greater sensitivity.

The statistical procedure for combination is based on the profile likelihood ratio, which accounts for systematic uncertainties by use of sufficiently flexible parametric models. Other statistical approaches, such as those used at LEP and Bayesian methods, are also under study.

The median discovery significance under assumption of a Standard Model Higgs signal and the median upper limits assuming data with no Higgs signal have been shown. These results use approximations expected to be valid for a data sample of at least $2\,\mathrm{fb}^{-1}$; below this the results are expected to be conservative. For an integrated luminosity of $2\,\mathrm{fb}^{-1}$, we expect discovery at 5σ or more for $143 < m_{\mathrm{H}} < 179$ GeV, and if the Higgs signal is absent, the expected upper limit on m_{H} at 95% CL is 115 GeV.

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