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CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Action to be taken *Voting Procedure*

For endorsement	**SCIENTIFIC POLICY COMMITTEE** 280th Meeting **10-11 December 2012**	-
For information	**COUNCIL** 165th Session **13-14 December 2012**	-

Report on the question from Council to the SPC

The scientific significance of the observation of a particle consistent with the SM Higgs boson with a mass of around 126 GeV

At its meeting in September 2012, the CERN Council asked for an assessment by the Scientific Policy Committee of the scientific significance of the observation of a particle consistent with the SM Higgs boson with a mass of around 126 GeV. A working group of the SPC consisting of M.Diemoz, K.Ellis, H.Murayama, G. 't Hooft, K.Tokushuku, T.Wyatt (chair) and F.Zwirner was set up to carry out this assessment.

N.B. In preparing this document we have tried to distinguish material that uses language suitable for communication with the outside world (in standard font) from additional technical background for the Council scientific delegates as professional scientists *(in italic font).*

Answer to the Council Question

<u>Summary of the main points</u>

- **The discovery of a new particle consistent with the Higgs boson postulated in the Standard Model (SM) is a triumph for science.** Many factors were crucial for making this possible: the remarkable theoretical vision and insight that went into the construction of the SM, with its minimal realisation of the Brout-Englert-Higgs (BEH) symmetry-breaking mechanism; the long-term effort to characterize the direct and indirect signals of the Higgs boson and compute the relevant backgrounds; the skill and dedication of those who have designed, built and operated the CERN LHC accelerator, its two general purpose detectors ATLAS and CMS, and the related computing infrastructures; the persistence of CERN – across many DG terms – to realize the LHC project, and the sustained support of its member states.

- **Finding this new particle is just the start of a major programme of work to measure its properties with the highest possible precision, with the aim of establishing whether or not these are consistent with those expected for the SM Higgs boson.** This will require many years of operation of the LHC, accumulating the largest possible data set at the highest achievable energy, with upgraded detectors able to acquire good quality data during high luminosity operating conditions. A possible future electron-positron collider with adequate energy and luminosity would go further in this direction.

- **The wider aim of the LHC remains to explore thoroughly particle physics phenomena at the TeV energy scale and, in particular, to elucidate the nature of the mechanism of mass generation for elementary particles.** The discovery of a Higgs-like boson is only the first milestone in this direction. To obtain a more complete picture it is essential to check whether or not the Higgs boson is accompanied by other particles at the TeV scale. The negative results from initial searches have already yielded important constraints on models for physics beyond the SM (BSM). However, it should be remembered that this initial phase of LHC operations is at roughly half of the design energy and represents a tiny fraction of the integrated luminosity that will ultimately be collected. Whatever the eventual outcome of these additional investigations, they will deeply affect our view of the fundamental laws of nature and of the role of symmetries in nature.

Further Details

- In July 2012 the ATLAS and CMS experiments at the LHC announced the discovery of a new particle state with a mass of around 126 GeV. The most significant signals were seen in the channels that provide excellent mass resolution ($H\longrightarrow\gamma\gamma$ and $H\longrightarrow ZZ$). The observed rates in these and also in the other channels studied ($H\longrightarrow WW$, $H\longrightarrow\tau\tau$ and $H\longrightarrow bb$) were consistent, within the current experimental uncertainties, with expectations for a SM Higgs boson of the observed mass. Both experiments independently achieved a statistical significance of 5 standard deviations or more for a signal above the background expectation when combining the results in all channels. Around the same time, the CDF and DØ experiments at the Fermilab Tevatron presented evidence with a combined statistical significance of 3 standard deviations for a signal consistent with the production in association with a W or Z boson of a SM Higgs boson followed by the decay $H\longrightarrow bb$ for a mass of around 120-140 GeV. The existence of a SM Higgs boson with a mass of around 126 GeV is consistent also with the indirect evidence that comes from taking into account the expected effect of processes involving “virtual” Higgs bosons on a large number of precisely measured physical processes at the LEP, SLC and Tevatron colliders and elsewhere. Some updated results from the ATLAS and CMS Higgs analyses have been presented at the HCP conference in November 2012 and during the December Council Week. The analysis of the full 2011+2012 data set is expected in time for the winter 2013 conferences.

- This discovery requires extensive further experimental investigation at the LHC in at least three directions. Firstly, it will be checked with the greatest achievable precision whether or not the observed state has indeed the properties expected of a Higgs boson in the Standard Model: the mass will be measured with greater precision, and the spin, CP properties, couplings to the W, Z and fermions, and its self-coupling will all be determined. Secondly, evidence for other new particles will be searched for, not only additional resonances that might be evidence of an extended Higgs sector, but also other particles that may play a role in the global picture of electroweak symmetry breaking. Even with the reduced centre of mass energy and low integrated luminosity currently available, initial searches for new particles at the LHC already rule out or strongly constrain some simple possibilities for BSM physics. However, much discovery potential remains for the LHC at its design energy and luminosity. Thirdly, the study of the scattering of pairs of massive vector bosons (WW, WZ, ZZ) emitted by the colliding protons will be an important test that the observed boson at 126 GeV is really that predicted by the SM mechanism of electroweak symmetry breaking. Of particular relevance are the "longitudinal" components of these vector bosons. These arise due to their non-zero mass and are thus due to their coupling to the electroweak symmetry breaking sector. Departures of the amplitudes for longitudinal WW, WZ and ZZ scattering from those predicted by the SM at energy scales above 1 TeV would be a signature of new physics in the mechanism of electroweak symmetry breaking. All three of these programmes will require many years of operation of the LHC, accumulating the largest possible data set at the highest achievable energy.

- *In this document we use the term "SM Higgs" to refer to the simplest realisation of the BEH electroweak symmetry breaking mechanism, with a single scalar doublet. The LHC experiments have presented preliminary projections of the expected precision of their measurements of SM Higgs properties with integrated luminosities from 300 fb^{-1} (expected by around 2021) up to 3000 fb^{-1} (corresponding to that expected by around 2030 if the HL-LHC upgrade plans are carried out). These projections will be refined in the coming months, but already demonstrate that substantial improvements in precision can be expected from the HL-LHC running. In addition, having the data in hand will be a great spur to human ingenuity. From direct reconstruction of the final state particles the Higgs mass is expected to be determined to a* *precision of around 100 MeV. The determination of the Higgs couplings will require the measurement of the cross section times branching ratio into every observable final state. Within the SM, a Higgs mass of around 126 GeV is "optimal" in this regard because it provides sizeable branching ratios into many possible final states. With an integrated luminosity of around 3000 fb*$^{-1}$ *and upgraded detectors, single experiment precisions on cross section times branching ratios of around 5% or better are expected in some channels (e.g.,* $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$ *and* $H \rightarrow WW$*). However, achieving uncertainties at this level will require very significant progress in understanding experimental and theoretical systematic uncertainties. In other channels single experiment precisions may be limited by statistics or systematics: for example, in* $H \rightarrow \mu\mu$ *the precision will be around 15%. CP information can be derived, e.g., from angular distributions in the fully reconstructed ZZ decay mode and from the distributions of the tagging jets in vector boson fusion production. A possible future electron-positron collider could improve the precision of Higgs physics measurements and would be sensitive to Higgs decay modes that are inaccessible at HL-LHC .*

- The elementary particle masses and other properties of the vacuum depend on the effective coupling strength of the interactions of the Higgs field with itself. The discovery of a Higgs-like particle with mass near 126 GeV means that this coupling strength is positive and small at the energy scales explored so far by the LHC. When we extrapolate to higher energy scales, and thus back to the early history of the universe, we have to consider the possible variation (or "running") of the coupling strength of the Higgs field with itself. The empirical observation that the Universe we live in exists in its current state implies that this coupling strength has remained positive, or at least close to zero (if negative) along the way. *Technically speaking, we can deduce that the vacuum state of our Universe either is absolutely stable, or is "metastable" with a lifetime of the order of the current age of the Universe or larger.* It is remarkable that, with the measured value of the Higgs mass lying close to 126 GeV, the predictions of the SM agree with observations to an astonishing precision without the need for additional particles or forces. It is conceivable that the SM can be extrapolated to very high scales, possibly even up to the Planck scale of gravitational interactions; the observation of a Higgs boson with a mass of 126 GeV may be telling us something very profound about the laws of nature. *This extrapolation would lie close to the boundary between absolute stability and metastability of our vacuum, but in the latter case with a lifetime many orders of magnitude larger than the age of the Universe. In particular, according to the SM extrapolation, the effective*

Higgs self interaction could become negligibly small not far from the Planck scale; exploring the possible meaning of such a coincidence is an area of active theoretical research. The criterion of “vacuum stability” can also be used to constrain possible extensions of the SM.