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RESULTS OF SEARCHES FOR HIGGS BOSON AND NEW PHYSICS AT LHC

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An overview is given of the recent results from the LHC experiments on the searches for a Higgs Boson and New Physics with $\sqrt{s} = 7$ and 8 TeV data. Studies of Standard Model processes, including polarization measurements, are also presented.

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INTRODUCTION

The Large Hadron Collider (LHC) has delivered proton–proton collisions since the end of 2009, initially at a center-of-mass energy $\sqrt{s} = 7$ TeV, and then in 2012 at $\sqrt{s} = 8$ TeV. An integrated delivered luminosity of 23 fb^{-1} was obtained in the 2012 run and around 6 fb^{-1} in the 2011 run [1].

The general-purpose detectors at LHC — ATLAS (A Toroidal LHC Apparatus) [2] and CMS (Compact Muon Solenoid) [3] detectors — have performed the search for the Higgs boson, where several channels have reached the sensitivity of the Standard Model (SM) and an evidence of a new boson with a mass around 125 GeV has been presented [4, 5]. The physics program [6, 7] has also involved tests of the SM in various areas and searches for new physics beyond the SM [8, 9]. The ALICE detector (A Large Ion Collider Experiment) is mainly specialized for studies of heavy-ion collisions [10] which are not the topic of this report, but it has additionally obtained pp-collisions data with 10 pb^{-1} [1] also used to measure quarkonia polarization described below.

1. STANDARD MODEL

The measurements of electroweak, top, QCD, etc., processes are necessary for testing the SM itself and making its phenomenological aspects more precise (e.g., parton distribution functions).

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One of the first studies in the field of the electroweak physics is the measurement of the inclusive W- and Z-boson cross sections, the measured values are consistent within the electron and muon channels, and agree with the theoretical next-to-next-to-leading order (NNLO) calculations. Other studies of electroweak physics included measurements of differential cross sections of Z production with respect to transverse momentum and rapidity, as well as the differential Drell–Yan cross section $d\sigma/dM$, and the double-differential cross section $d^2\sigma/dMdY$ in the dimuon channel, using the full 2011 dataset at $\sqrt{s} = 7$ TeV [11–13]. In general, the results are in good agreement with the NNLO theoretical predictions required for a correct description of the $d\sigma/dM$ results at low dilepton invariant masses,

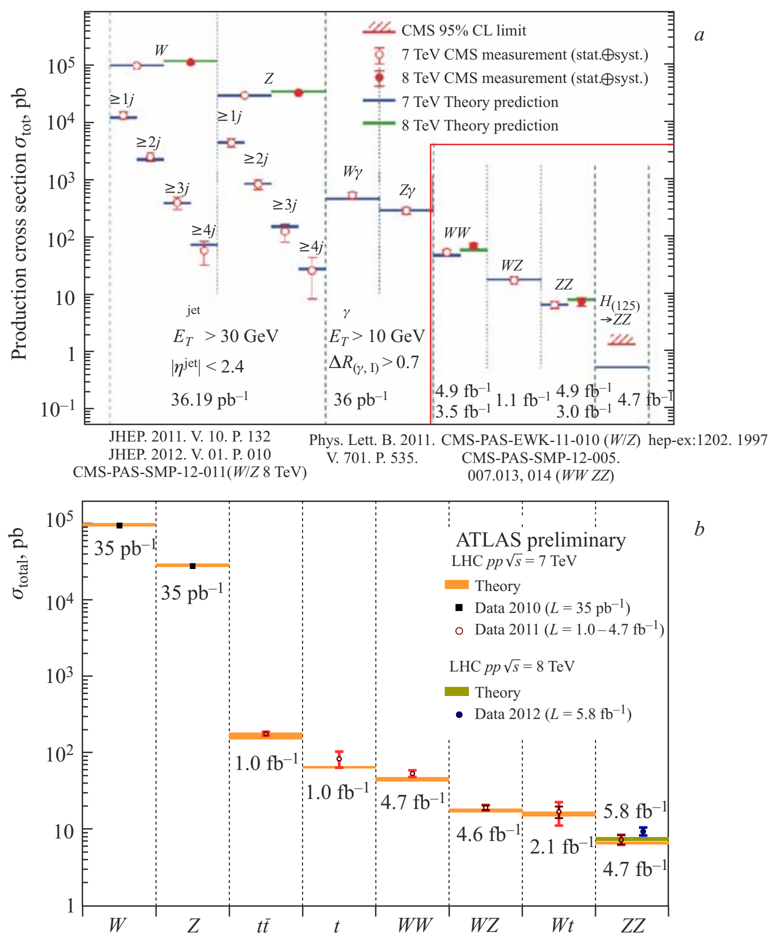


Fig. 1. Summaries of the main electroweak results of ATLAS and CMS

extending our knowledge of the partonic contents of the proton. The forward–backward asymmetry of Drell–Yan pair production and Weinberg weak mixing angle $\sin\theta_W^2$ have been measured, and found to be consistent with SM predictions [14–16] (details for the CMS study were given in the talk by I. N. Gorbunov in these Proceedings).

Summaries of the main electroweak physics measurements by ATLAS and CMS are shown in Fig. 1. No deviations of the measured values from SM predictions have been found.

ATLAS and CMS have presented the combined results for the top quark mass at $\sqrt{s} = 7$ TeV $m_t = (173.3 \pm 0.5(\text{stat.}) \pm 1.3\ (\text{syst.}))$ GeV [17] using the combination of lepton+jets, dilepton and all-jets channels. The cross sections of $t\bar{t}$ production were measured at $\sqrt{s} = 7$ and 8 TeV, as well as the single top production cross sections; their precision approaches that of the Fermilab experiments.

QCD and jet physics were studied, and no deviations from the SM have been found. These measurements are used to improve the currently available models of QCD production and fits of the collider data. Studies of jets included the measurement of the inclusive jet cross sections [18, 19] giving results in a good agreement with NLO QCD until $p_T^{\text{jet}} \approx 2$ TeV. Dijet studies included the measurements of differential dijet cross sections up to the invariant dijet mass of 5 TeV [18, 20], angular distributions, and other studies.

2. SEARCH FOR THE HIGGS BOSON

The Standard Model is based on the mechanism of spontaneous symmetry breaking by introducing a scalar field with a nonzero vacuum expectation value, leading to existence of a Higgs boson [21, 22]. By the beginning of 2012, a SM Higgs boson had already been excluded for masses less than 114.4 GeV and the range of 127.5–600 GeV. On July 4, 2012, a dedicated seminar was held at CERN, where the ATLAS and CMS collaborations each reported an approximate five standard deviation observations of a new boson with a mass about 125 GeV consistent with the SM Higgs boson. The following section describes the results reported by both the collaborations in the subsequent publications [4, 5] that have used around 5 fb^{-1} at $\sqrt{s} = 7$ TeV and 5–6 fb^{-1} at $\sqrt{s} = 8$ TeV.

The search for Higgs boson was performed in the five channels with the largest expected significance at the LHC: $\gamma\gamma$, $ZZ^* \to 4\ell$, $WW \to l\nu\, l\nu$, $\tau\tau$, $b\bar{b}$. The first two channels provide the best significance and separation from the background due to a good mass resolution of 1–2%, the other channels have the largest production cross sections.

The ZZ^* channel is a clean channel where two high-mass pairs of opposite-sign isolated muons or electrons coming from the primary vertex were required.

The SM branching ratio of $H \to ZZ^*$ is of the order of 10^{-3} at 125 GeV [23], therefore CMS used a specialized method utilizing the difference of matrix elements for the SM Higgs boson and the background to enhance the analysis sensitivity: Matrix Element Likelihood Approach (MELA) [24, 25] that uses all the available angles and masses of four leptons to construct a kinematic discriminant $K_D = P_{\rm sig}/(P_{\rm sig} + P_{\rm bkg})$ based on the probability ratio of the signal and background hypotheses, to increase the expected significance by 15–20%. The plots of Fig. 2 show the 2D distributions for the expected background and SM Higgs signal, respectively; one can see that the experimental points are well described by the SM Higgs signal hypothesis, especially for the large values of MELA discriminant K_D.

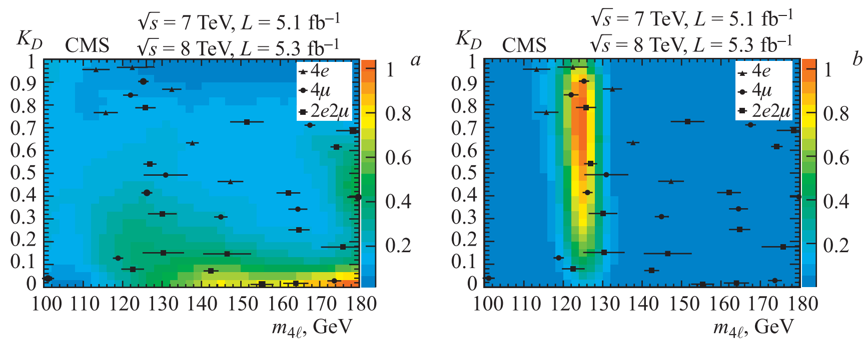


Fig. 2. Distribution of events $ZZ^* \to 4\ell$ for the kinematic discriminant K_D versus m_{4l}, the color-coded regions show the event density expected from the background (*a*) and a SM Higgs boson (*b*)

Expected and observed significance values of the SM Higgs boson search in terms of standard deviations for different channels and their combinations [4, 5]

Decay mode/combination	CMS		ATLAS	
	Expected	Observed	Expected	Observed
$\gamma\gamma$	2.8	4.1	2.5	4.5
ZZ^*	3.6	3.1	2.7	3.6
$\tau\tau + bb$	2.4	0.4	2.3	2.8
$\gamma\gamma + ZZ^*$	4.7	5.0		
$\gamma\gamma + ZZ^* + WW$	5.2	5.1	4.9	5.9
$\gamma\gamma + ZZ^* + WW + \tau\tau + bb$	5.8	5.0		

The combination of all channels yielded a local significance of 5.0σ and 5.9σ, for CMS and ATLAS, respectively (see the Table and Fig. 3). The signal strength (ratio of the fitted cross section of the excess to the SM cross section) is consistent with the SM scalar boson expectation: $\sigma/\sigma_{\rm SM} = 0.87 \pm 0.23$ and

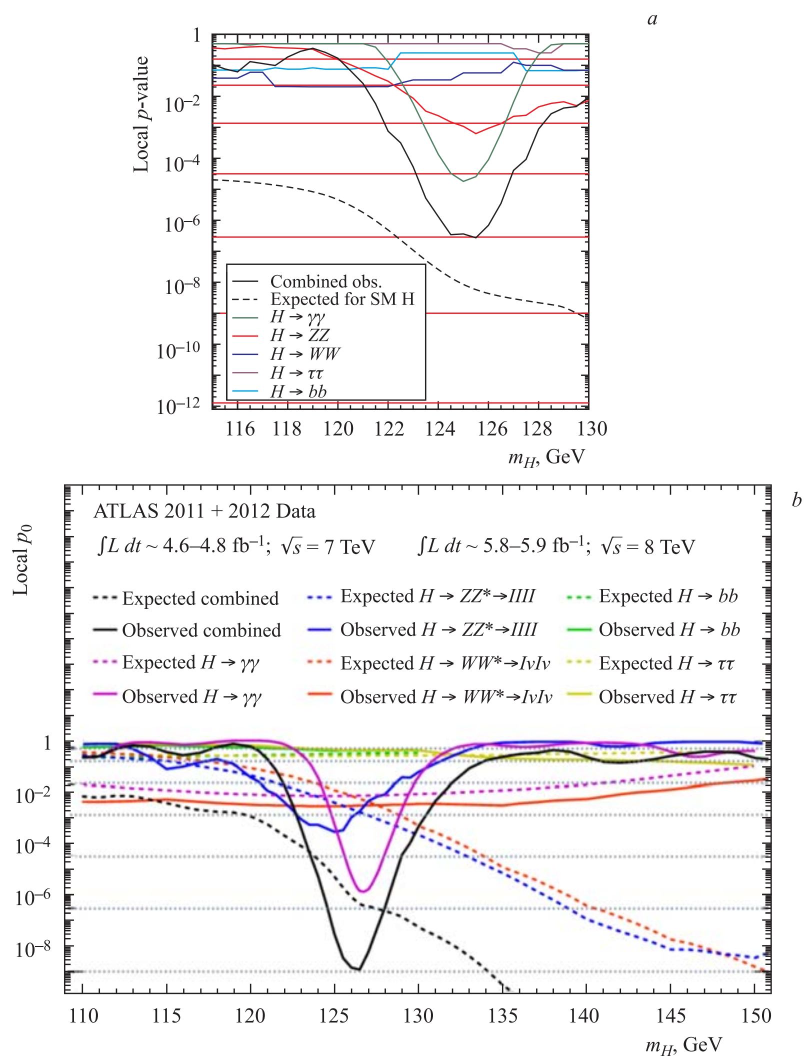


Fig. 3. Combination of all channels for Higgs boson search

1.4 ± 0.3. The signal strength for each channel is shown in Fig. 4. The measurement of the mass of the new boson yielded value of $M_X = (125.3 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.}))$ GeV and $(126.0 \pm 0.4(\text{stat.}) \pm 0.4(\text{syst.}))$ GeV.

First measurements of the scaling of vector vs. fermion couplings of the new boson $c_V \approx 1$ and 1.2, $c_F \approx 0.5$ and 1 were consistent with the SM Higgs boson hypothesis. The detailed study of the boson couplings will continue as the data

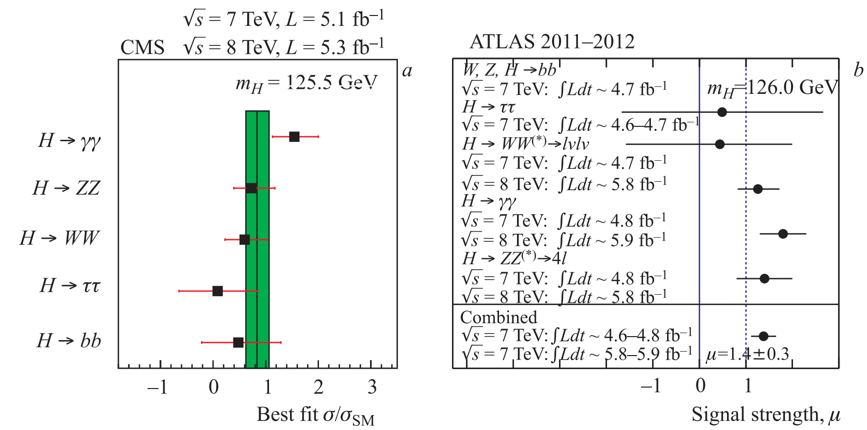


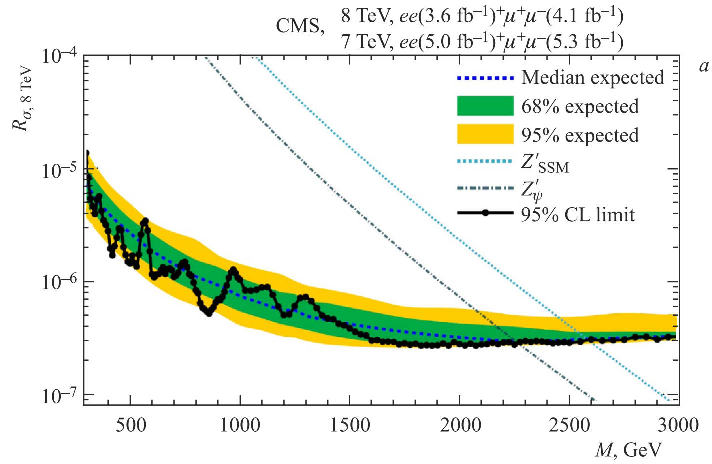
Fig. 4. Signal strength for each channel of Higgs boson search

are accumulated in the future [26, 27]. The spin and parity of the new boson could be probed using angular distributions [28, 29]. The collection of future data will enable a more rigorous test of the properties of the new boson and an investigation whether the properties of the new particle might imply physics beyond SM.

3. SEARCH FOR NEW PHYSICS

The search for new physics at ATLAS and CMS is performed in various channels for different theoretical models predicting deviations from the SM. One of the important directions is the search for heavy narrow resonances predicted by many models of new physics, in particular, extended gauge models [30], and Kaluza–Klein graviton measured excitations arising in the Randall–Sundrum (RS) scenario [31]. The spectra were consistent with expectations from the SM and the upper limits have been determined on the product of the cross section and branching fraction for Z' into lepton pairs relative to the SM Z-boson production [32, 33] (Fig. 5). CMS and ATLAS have put 95% confidence level (CL) lower limits on the mass of Z' resonances from the combinations of the data obtained at $\sqrt{s} = 7$ and 8 TeV (details for the ATLAS study were given in the talk by I. V. Eletskikh in these Proceedings). Similarly, searches in other Z' channels were performed ($\tau\tau$, ZZ, $t\bar{t}$, anomalous production of highly boosted Z bosons decaying to dimuons) and W' channels ($l\nu$, WZ, bt). Narrow resonances in the dijet channel have also been studied and the lower limits on the mass for various models have been set in 1–4.7 TeV range [20, 34–36].

The production of right-handed W_R bosons and heavy neutrinos N_ℓ ($\ell = e, \mu$) arisen naturally in the left-right symmetric extension to the SM was excluded up to masses of 2–3 TeV [37, 38].



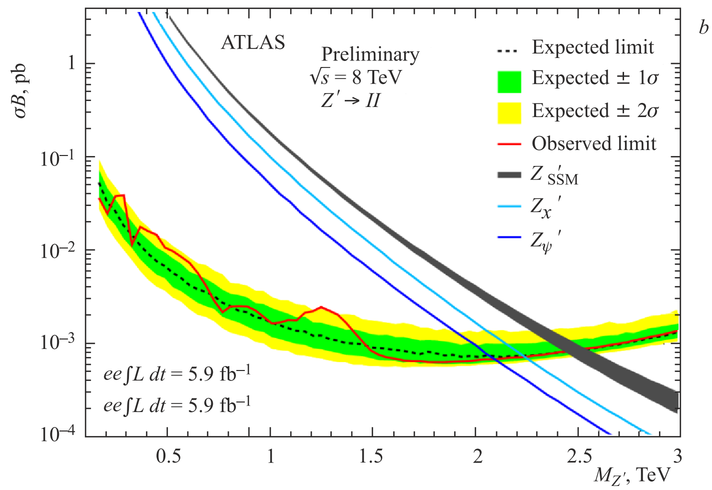


Fig. 5. Obtained 95% CL limits for the ratio of Z' cross section in the dilepton channel to that of Z

Theories with low-scale quantum gravity motivated by the large difference between the electroweak scale and the Planck scale (hierarchy problem) have predicted microscopic black-hole production in pp collisions at the LHC energies, which can manifest themselves by events with the large total transverse energy having multiple energetic jets, leptons, and photons. The agreement of the observed rate of such events with the expected SM backgrounds dominated by QCD multijet production, allowed one to put limits on new physics processes producing energetic final states with high multiplicity excluding semiclassical black holes with masses below 4.1 to 6.1 TeV [39, 40].

Many other searches for deviations from SM were carried out including the searches for supersymmetry leading to improved experimental limits [8, 9].

4. SPIN PHYSICS

Quarkonium production in hadronic collisions is not yet understood, despite recent progress: differential cross sections are well described by various models, but quarkonium polarization remains puzzling and new measurements are needed. Quarkonia polarization can be measured via anisotropies in the angular distributions of dilepton decay products: $W(\theta, \phi) \propto (1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi)$. ALICE produced first measurements of quarkonia polarization in pp collisions [41] which showed that the polarization for $p_T < 5$ GeV was small (Fig. 6, a), consistent with NLO NRQCD prediction [42]. CMS published the results for $\Upsilon(1S$–$3S)$ polarization [43] extending the measurements beyond the p_T

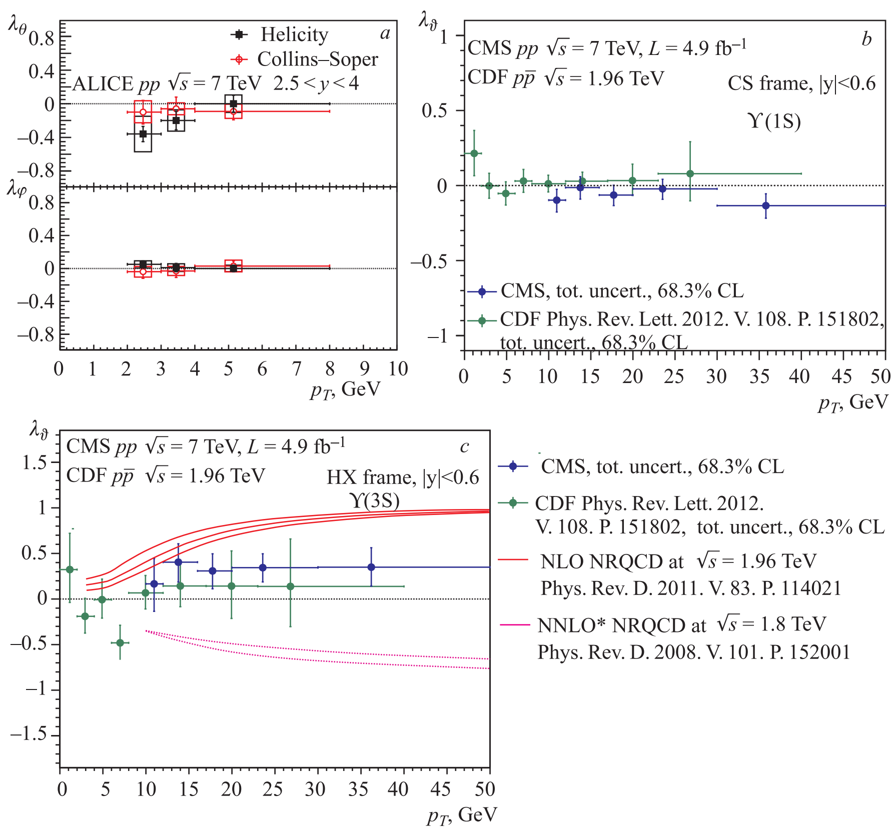


Fig. 6. Measurements of quarkonia polarization for J/ψ (ALICE (a)) and Υ (CMS (b, c))

and rapidity ranges probed by CDF and D0. Comparison with predictions from NRQCD and color-single models is shown in Fig. 6, *c* for $\Upsilon(3S)$, where polarization can be estimated more reliably, while $\Upsilon(1S)$ (Fig. 6, *b*) suffers from the large χ_b feed-down contribution with unknown polarization. Theoretical predictions are needed for λ_ϕ and $\lambda_{\theta\phi}$ [44]. Other polarization measurements by ATLAS and CMS included the measurement of τ polarization in $W \to \tau\nu$ decays [45] and W polarization in $W \to \mu\nu$ [46,47] and semileptonic $t\bar{t}$ decays [48,49].

According to SM, the top and antitop quarks are unpolarized in $t\bar{t}$ pair production. Measurements have confirmed that the top quark polarization is consistent with zero [50,51]. However, the quarks in $t\bar{t}$ pairs are correlated due to the production process. Spin correlations have been measured from fits to the angular distribution between leptons in the dilepton events. The resulting helicity asymmetries extracted $A_{\text{helicity}} = 0.24 \pm 0.02$ (stat.) $\pm\, 0.08$ (syst.) [52] and $A_{\text{helicity}} = 0.40 \pm 0.04$ (stat.) $\pm^{+0.08}_{-0.07}$ (syst.) [53] which are compatible with SM prediction $A^{\text{SM}}_{\text{helicity}} = 0.31$.

CONCLUSIONS

Excellent performance of LHC and its experiments has provided a large dataset of pp collisions at $\sqrt{s} = 7$ and 8 TeV. In the search for the SM Higgs boson, a new boson with a mass around 125 GeV has been found in the analysis of several channels. Its properties are compatible with the properties of the SM Higgs boson within the present experimental uncertainties. The studies of the processes in the Standard Model and searches for new physics beyond the Standard Model have been performed. By now, the LHC experiment has published several hundred papers in scientific journals [8, 9, 54]. The analysis of the whole dataset taken in 2012 and the planned transition to the full design LHC center-of-mass energy of 13–14 TeV will provide answers to the burning questions of particle physics.

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REFERENCES

1. LHC Programme Coordination. web pages. http://lpc.web.cern.ch/lpc/.
2. *ATLAS Collab.* // JINST. 2008. V. 3. P. S08003.
3. *CMS Collab.* // Ibid. P. S08004.
4. *CMS Collab.* // Phys. Lett. B. 2012. V. 716. P. 30; arXiv:1207.7235.
5. *ATLAS Collab.* // Ibid. P. 1; arXiv:1207.7214.
6. *CMS Collab.* // J. Phys. G. 2007. V. 34. P. 995.

7. *ATLAS Collab.* arXiv:0901.0512.
8. https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
9. https://twiki.cern.ch/twiki/bin/view/AtlasPublic
10. *ALICE Collab.* // JINST. 2008. V. 3. P. S08002.
11. *CMS Collab.* CMS-PAS-EWK-11-007.
12. *CMS Collab.* // JHEP. 2011. V. 1110. P. 007; 1108.0566
13. *ATLAS Collab.* ATLAS-CONF-2012-159.
14. *CMS Collab.* // Phys. Lett. B. 2013. V. 718. P. 699; arXiv:1207.3973.
15. *CMS Collab.* // Phys. Rev. D. 2011. V. 84. P. 112002; arXiv:1110.2682.
16. *ATLAS Collab.* arXiv:1211.6899.
17. *CMS Collab.* CMS-PAS-TOP-12-001, ATLAS-CONF-2012-095.
18. *CMS Collab.* CMS-PAS-QCD-11-004.
19. *ATLAS Collab.* // Phys. Rev. D. 2012. V. 86. P. 014022; arXiv:1112.6297.
20. *ATLAS Collab.* ATLAS-CONF-2012-088.
21. *Okun L. B.* // Proc. of the 1981 Intern. Symp. on Lepton and Photon Interactions at High Energy, Bonn, Germany, 1981. P. 1018.
22. *Rubakov V. A.* // Usp. Fiz. Nauk. 2012. V. 182, No. 10. P. 1017.
23. *Dittmaier S. et al.* arXiv:1101.0593.
24. *CMS Collab.* // JHEP. 2012. V. 1204. P. 036; arXiv:1202.1416.
25. *Bolognesi S. et al.* // Phys. Rev. D. 2012. V. 86. P. 095031; arXiv:1208.4018.
26. *CMS Collab.* CMS Note 2012-006, Oct 2012.
27. *ATLAS Collab.* ATLAS-CONF-2012-127.
28. *CMS Collab.* // Phys. Rev. Lett. 2013. V. 110. P. 081803; arXiv:1212.6639.
29. *ATLAS Collab.* ATLAS-CONF-2012-170.
30. *Leike A.* // Phys. Rep. 1999. V. 317. P. 143; arXiv:hep-ph/9805494.
31. *Randall L., Sundrum R.* // Phys. Rev. Lett. 1999. V. 83. P. 3370.
32. *CMS Collab.* // Phys. Lett. B. 2013. V. 2. P. 3; arXiv:1212.6175.
33. *ATLAS Collab.* ATLAS-CONF-2012-129.
34. *CMS Collab.* CMS-PAS-EXO-12-016.
35. *CMS Collab.* // Phys. Lett. B. 2011. V. 704. P. 123; arXiv:1107.4771.
36. *CMS Collab.* // JHEP. 2013. V. 1301. P. 013; arXiv:1210.2387.
37. *CMS Collab.* CMS-PAS-EXO-12-017.
38. *ATLAS Collab.* ATLAS-CONF-2012-139.
39. *CMS Collab.* CMS-PAS-EXO-12-009.

40. *ATLAS Collab.* // Phys. Lett. B. 2012. V. 709. P. 322; arXiv:1111.0080.
41. *ALICE Collab.* // Phys. Rev. Lett. 2012. V. 108. P. 082001.
42. *Butenschön M., Kniehl B. A.* // Nucl. Phys. Proc. Suppl. 2012. V. 222–224. P. 151.
43. *CMS Collab.* // Phys. Rev. Lett. 2013. V. 110. P. 081802; arXiv:1209.2922.
44. *Faccioli P.* // Mod. Phys. Lett. A. 2012. V. 27. P. 1230022; arXiv:1207.2050.
45. *ATLAS Collab.* // Eur. Phys. J. C. 2012. V. 72. P. 2062; arXiv:1204.6720.
46. *CMS Collab.* // Phys. Rev. Lett. 2011. V. 107. P. 021802; arXiv:1104.3829.
47. *ATLAS Collab.* // Eur. Phys. J. C. 2012. V. 72. P. 2001; arXiv:1203.2165.
48. *CMS Collab.* CMS-PAS-TOP-11-020.
49. *ATLAS Collab.* // JHEP. 2012. V. 1206. P. 088; arXiv:1205.2484.
50. *CMS Collab.* CMS-PAS-TOP-12-016.
51. *ATLAS Collab.* ATLAS-CONF-2012-133.
52. *CMS Collab.* CMS-PAS-TOP-12-004.
53. *ATLAS Collab.* // Phys. Rev. Lett. 2012. V. 108. P. 212001.
54. http://aliceinfo.cern.ch/ArtSubmission