# Physics at the LHC

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## 1 Introduction

The LHC will be the first accelerator to explore directly the TeV scale. Any new energy range takes us deeper into the structure of matter, but there are good reasons to expect the TeV range to be particularly interesting, since there are several indications that it might reveal new physics. One is that we expect it to reveal the *origin of particle masses*, which are presumably due to the Higgs mechanism [1] but possibly with the aid of additional particles beyond the single Higgs boson of the minimal Standard Model, such as *supersymmetry* [2]. These seem to be required, for example, to stabilize the energy scale of the weak interactions below 1 TeV [3]. Another indication of new physics at the TeV scale may be provided by attempts to unify the fundamental gauge interactions, which fail if only Standard Model particles are included in the calculations, but work well if supersymmetric particles appear at the TeV scale [4]. Another hint of new physics at the TeV scale is provided by the astrophysical evidence for *dark matter*, which is naturally explained by new weakly-interacting particles weighing less than a TeV [5]. Finally, the muon anomalous magnetic moment [6] provides evanescent suggestions of new physics at the TeV scale.

As seen in Fig. 1, the LHC is designed to provide high collision rates that should be ample to produce the Higgs boson and supersymmetric particles if they exist in the TeV energy range. In addition, the LHC will yield plenty of bread-and-butter Standard Model physics. For example, its large sample of W bosons will enable the $W$ mass to be measured with an accuracy of about 15 MeV, and its large sample of top quarks will enable the top mass to be measured with an accuracy of about 1 GeV [7,8]. In addition to these bread-and-butter topics, the LHC will be able to explore dense hadronic matter in relativistic heavy-ion collisions, where the quark–gluon plasma may be created. The LHC will also provide a good opportunity to study matter–antimatter asymmetry via $CP$ violation in $B$ system. Each of these LHC opportunities is reviewed in the following.



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Many of the most interesting aspects of LHC physics touch on the interface between particle physics and cosmology: the Higgs boson may be a prototype for the inflaton, supersymmetry may provide the dark matter in the Universe, heavy-ion collisions may reproduce conditions in the first microseconds in the life of the Universe, and $CP$ studies may help understand the origin of the matter in the Universe.

## 2 The quest for the Higgs boson

Generating the masses of the electroweak vector bosons requires breaking gauge symmetry spontaneously, i.e., there must be a field $X$ with non-zero isospin $I$ that has a non-zero vacuum expectation value:

$$m_{W,Z} \neq 0 \Leftrightarrow \langle 0 \,|X_I|\, 0 \rangle \neq 0$$

In addition, the relation:

$$m_W^2 = m_Z^2 \times \cos^2 \theta_{\mathrm{W}}$$

implies that $I = 1/2$ is preferred. Moreover, the value $I = 1/2$ is also needed to give masses to the fermions of the Standard Model.
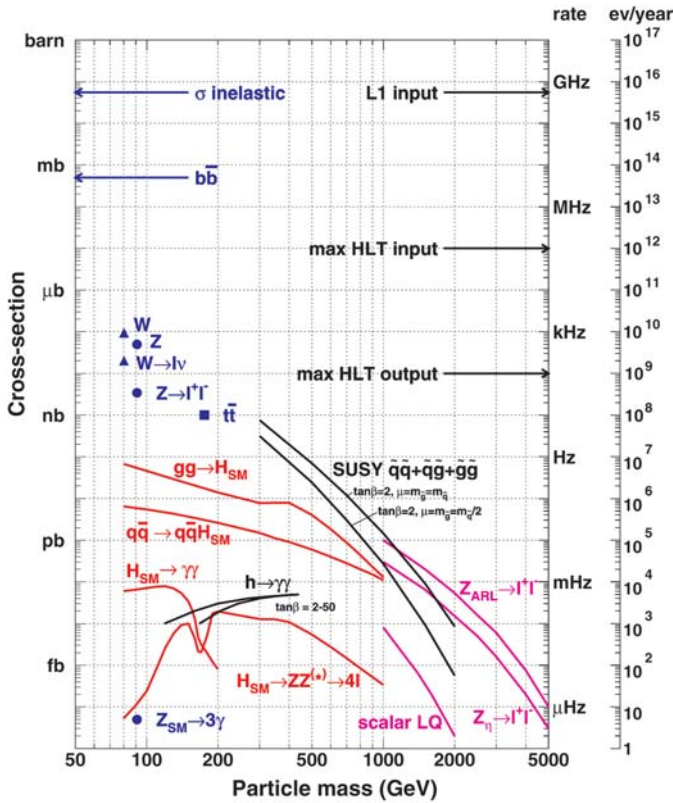
**Fig. 1.** Typical cross sections and event rates at the LHC, at $\sqrt{s} = 14$ TeV, assuming a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$

The next question concerns the nature of the field X: is it elementary or is it composite? The option used in the original formulation of the Standard Model was an elementary Higgs field: $\langle 0|H|0\rangle \neq 0$ [1]. However, this option is subject to large quantum (loop) corrections:

$$\delta m^2_{H,W} = O\left(\frac{\alpha}{\pi}\right)\Lambda^2$$
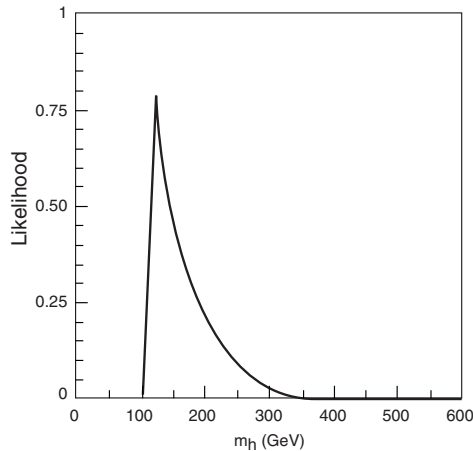


**Fig. 2.** The likelihood function for the mass of the Higgs boson obtained by combining information from direct searches at LEP and precision electroweak measurements
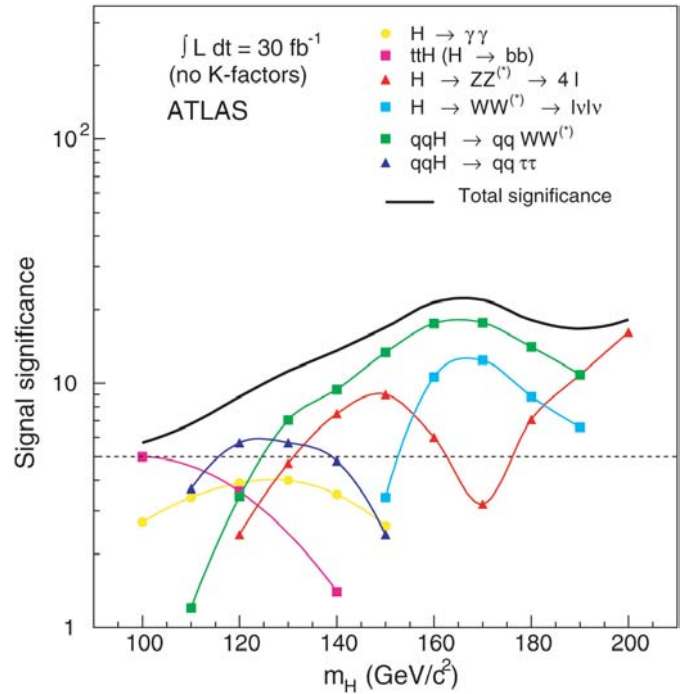


**Fig. 3.** Signal-to-background ratios for Higgs detection in various channels at the LHC

where $\Lambda$ is a cut-off representing the energy scale at which new physics beyond the Standard Model appears. One of the favoured origins for this cut-off is supersymmetry [2]. If the loop corrections to the Higgs and $W$ masses are to be naturally small, the cut-off $\Lambda$ should be less than about 1 TeV. In particular, sparticles should appear below this scale, if they are to stabilize the electroweak scale [3].

An alternative to an elementary Higgs field $H$ is a condensate of fermion pairs, as happens in the BCS theory of superconductivity – where electron pairs condense – and in QCD – where quark–antiquark pairs condense in the vacuum. One of the theories studied was that top quark–antiquark pairs might condense and replace the elementary Higgs field [9], but the simplest examples of this type would have required the top quark to have weighed above 200 GeV, so these models are excluded. An alternative theory postulated a new strong technicolour force binding together new technifermions [10]. However, simple examples of this type are inconsistent with precision electroweak data [11]. In the absence of a viable alternative for the moment, in the following we concentrate on the elementary Higgs option.

Precision electroweak measurements at LEP, SLC, etc., predicted successfully that the top quark would be found with mass in the range 160 to 180 GeV, and it was indeed found with a mass $\sim$ 175 GeV [12]. The precision electroweak experiments are also sensitive to the mass of the Higgs boson and, when combined with the measurement of the top mass, suggest that m$_H$ < 200 GeV [13]. Direct searches for the Higgs boson at LEP using the reaction $e^+e^- \rightarrow Z + H$ saw a hint in late 2000, whose significance is now estimated to be < $2\sigma$. Finally, they
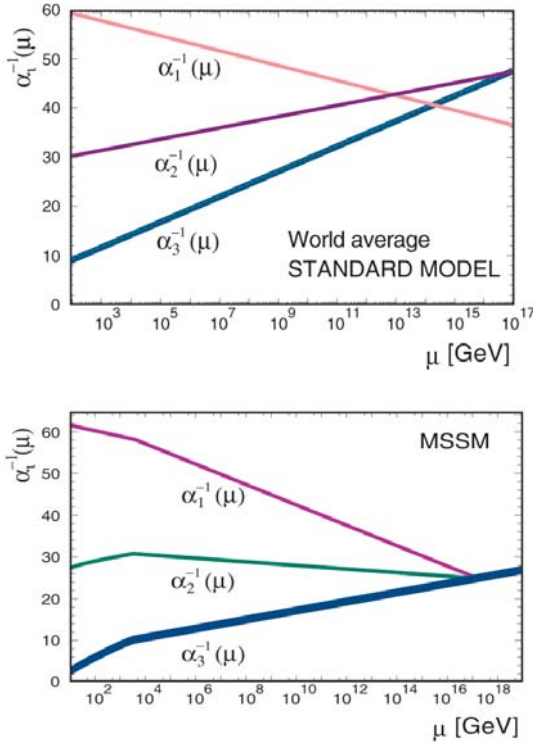
**Fig. 4.** Unification of the strong and electroweak interactions is not possible without supersymmetric particles (*top graph*) but is possible with supersymmetric particles (*bottom graph*)

only provide the lower limit $m_H > 114.4$ GeV [14]. The likelihood function obtained by combining the direct and indirect information on the Higgs boson is shown in Fig. 2: it is peaked sharply around 120 GeV, suggesting that the Higgs boson may not be far away.

The most important Higgs decays vary rapidly as the Higgs mass increases from 120 to 200 GeV, so the LHC experiments must be prepared for a range of different signatures. These include $H \rightarrow$ bottom–antibottom pairs in association with top or bottom quarks, $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4$ leptons, $H \rightarrow WW$ and $H \rightarrow \tau\tau$ [7,8]. Combining these channels, it seems certain that a Standard Model Higgs boson can be found at the LHC, whatever its mass, and potentially quite quickly if the Higgs

mass is about 150 GeV or more, as seen in Fig. 3. Most difficult to find would be a Higgs boson weighing about 115 GeV. The Higgs mass could be measured with a precision of the order of $1°/\!\!\circ\!\circ$ if it weighs less than about 400 GeV, and a number of ratios of its couplings could be measured at the $\sim 10$ to 20% level [7, 8].

## 3 The quest for supersymmetry

As already mentioned, the primary motivation for supersymmetry in the TeV range is the hierarchy problem [3]: why is $m_W \ll m_P$? where $m_P$ is the Planck mass of about $10^{19}$ GeV, the energy where gravitational forces become as strong as the other interactions, and the only known candidate for a fundamental energy scale in physics. Alternatively, why is $G_N = 1/m_P^2 \ll G_F = 1/m_W^2$? Or why is the Newton potential inside an atom so much smaller than the Coulomb potential: $G_N m^2/r \ll e^2/r$? Supersymmetry does not by itself explain the origin of this hierarchy, but it can stabilize the hierarchy if supersymmetric particles appear with masses below about 1 TeV. Other reasons for liking accessible supersymmetry include the help it provides to enable the gauge couplings to be unified as shown in Fig. 4 [4], its prediction of a relatively light Higgs boson [15], and the fact that it stabilizes the effective Higgs potential for small Higgs masses [16].

There are important constraints on supersymmetry from the non-observation of supersymmetric particles at LEP and the Tevatron, the absence of the Higgs boson at LEP, the agreement of $b \rightarrow s\gamma$ measurements with the Standard Model and measurements of the anomalous magnetic moment of the muon [6]. Also very important is the relic density $\Omega_\chi h^2$ of the lightest supersymmetric particle $\chi$ [5], which has recently been constrained more strongly by the WMAP satellite [17]: $0.094 < \Omega_\chi h^2 < 0.124$, assuming that it constitutes most of the dark matter in the Universe.

As seen in Fig. 5, narrow lines in the supersymmetric parameter space are allowed [18] by the accelerator constraints and the WMAP data, and the detectability of sparticles along one of these WMAP lines is shown in Fig. 6 [19]. In typical supersymmetric scenarios, the LHC discovers many sparticles and one or more Higgs bosons,
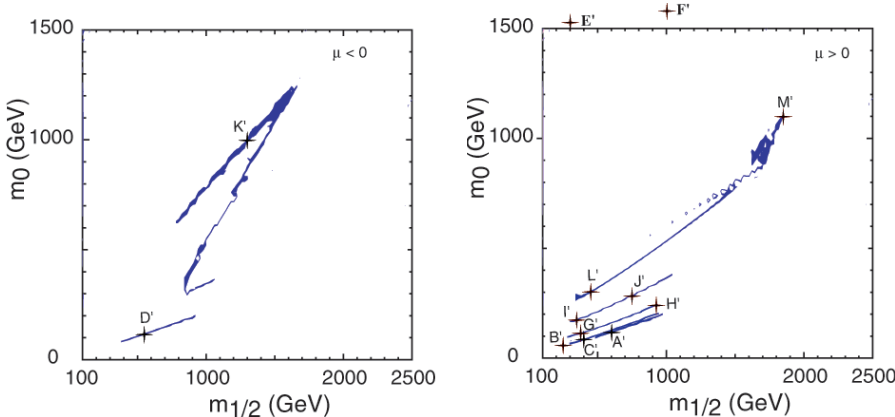


**Fig. 5.** The strips of supersymmetric parameter space allowed by WMAP for different values of $\tan\beta$. The crosses indicate specific benchmark scenarios that have been studied in more detail [18, 19]
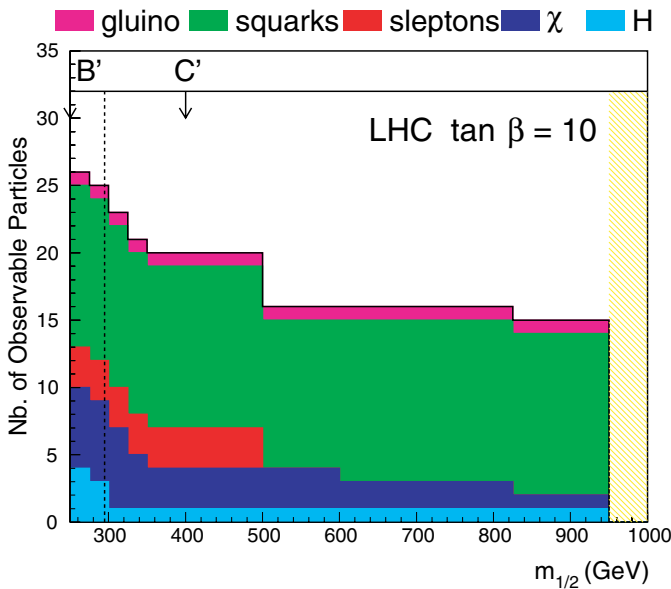
**Fig. 6.** The numbers of sparticles detectable along a WMAP line, as a function of an input supersymmetric fermion mass, $m_{1/2}$, which is about 2.4 times larger than the mass of the lightest supersymmetric particle

via cascade decays of heavy sparticles [20] such as that simulated in Fig. 7. In suitable cases, the decay chain can be reconstructed and several of the sparticle masses measured. The quality of LHC measurements at specific benchmark [21] points located along these WMAP lines has been explored in more detail, and it seems they would provide inputs sufficient to calculate the relic density with
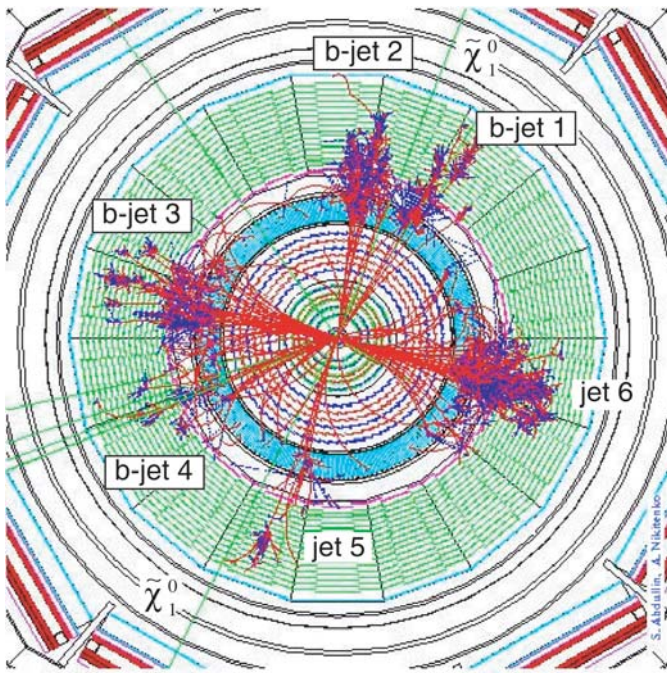


**Fig. 7.** Simulation of a "typical" supersymmetric event in the CMS detector

an error comparable to the WMAP estimate, at least in some cases. The LHC is almost "guaranteed" to discover supersymmetry if it is relevant to the hierarchy and dark matter problems.

## 4 The quest for extra dimensions

These were suggested originally by Kaluza and Klein in attempts to unify gravity and electromagnetism. More recently, it has been realized that extra dimensions are required for the consistency of string theory, and could help unify the strong, weak and electromagnetic forces with gravity if they are much larger than the Planck length [22]. In other scenarios, extra dimensions could originate the breaking of supersymmetry [23], or enable a reformulation of the hierarchy problem [24].
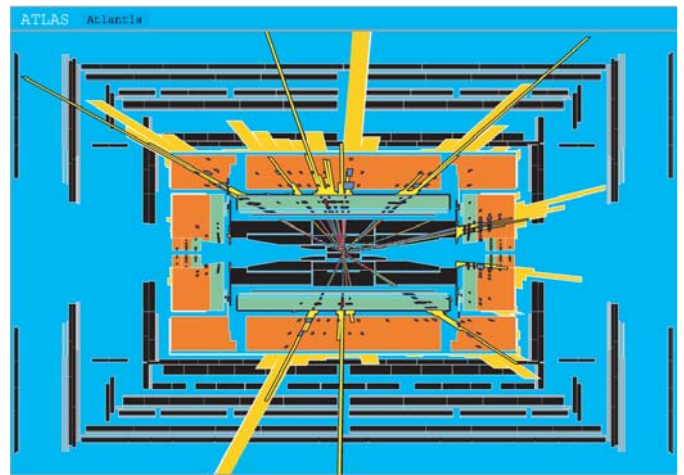


**Fig. 8.** An ATLAS simulation of a black hole production event at LHC

Possible signatures of extra dimensions could include a diphoton graviton resonance, if gravity "feels" the extra dimensions, or a dilepton $Z$ boson resonance, if the electroweak gauge interactions feel them. In some scenarios with extra dimensions, gravity becomes strong at the TeV scale and black hole formation may form and then decay via Hawking radiation, emitting many jets and leptons, as seen in Fig. 8.

The LHC also has great capabilities for finding the new strongly-interacting particles predicted by some composite "technicolour" models of electroweak symmetry breaking, or of detecting composite structure inside quarks. All in all, the LHC has unparalleled reach for finding new physics at the TeV scale, as shown in Fig. 9.

## 5 The quest for the quark–gluon plasma

Relativistic heavy-ion collisions at the LHC are expected to create effective temperatures of the order of 600 MeV, which are far above the critical temperature of about 170
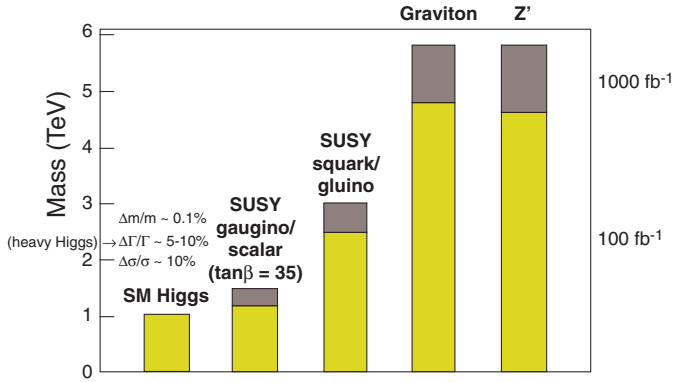
**Fig. 9.** CMS estimates of the reach for new particles at the LHC. The LHC luminosity upgrade extends the mass reach by about 20%. For the SM Higgs there is complete coverage of the mass range up to 1 TeV

tion temperature [26], $J/\psi$ production – that is sensitive to Debye screening in a plasma [27], and jet quenching – that could be due to parton energy dissipation during propagation through a plasma. All these signatures are to be explored in a hostile environment where thousands of particles are produced in each collision.

ALICE plans to measure $J/\psi$ and $\Upsilon$ production in both the central region (using $e^+e^-$ decays) and towards the forward direction (using $\mu^+\mu^-$ decays), and to compare the $J/\psi$ production with open charm production, to see whether there is any significant suppression. ATLAS and CMS may also contribute to the studies of heavy-ion collisions: for example, CMS can study $Z$ bosons produced with large transverse momenta, and look whether there is a jet on the opposite side, or whether it has been quenched [8].

MeV for the quark–hadron phase transition that has been found in lattice calculations.

Previous experiments at the CERN SPS and RHIC have already found evidence that hadronic matter changes its nature around 170 MeV, and the LHC should be able to tell us what lies beyond the quark–hadron phase transition, recreating conditions in the first microsecond of the Universe with "Little Bangs".

As seen in Fig. 10, among the signatures that the dedicated experiment ALICE [25] plans to explore are $\pi\pi$ interferometry – that can determine the size and expansion rate of the little fireball, the abundances of strange particles – that are expected to increase near the transi-

# 6 The quest for $CP$ violation beyond the Standard Model

So far, measurements of quark mixing angles and $CP$ violation in the decays of $K$ and $B$ mesons agree well with the Standard Model and its Kobayashi–Maskawa mechanism, though there are some puzzles, notably in B $\rightarrow \Phi$K and $\pi\pi$ decays. In 2007, when the LHC comes into operation, not all the angles of the $CP$-violating unitarity triangle will have been measured accurately. It will fall to the LHC to carry further these tests of the Standard Model, and perhaps provide a glimpse beyond it. There have been many suggestions how new physics, such as su-
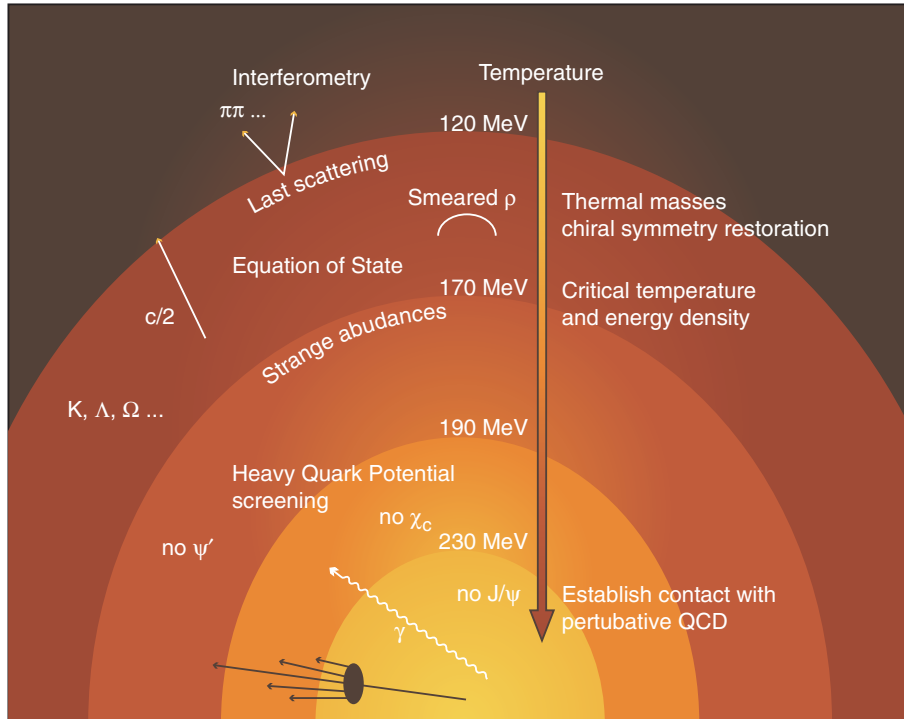


**Fig. 10.** Possible signatures of the quark–gluon plasma in relativistic heavy ion collisions
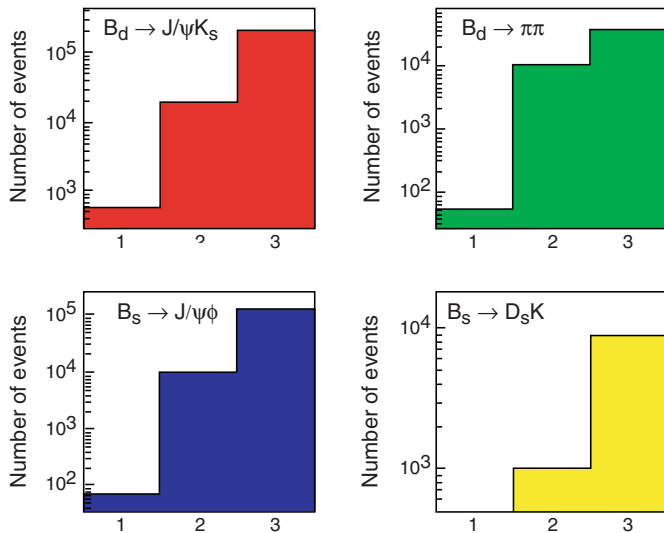
**Fig. 11.** Present, pre- and post-LHC statistics for interesting $CP$-violating decays of B mesons, shown respectively in bins 1, 2 and 3 of the histograms

persymmetry, might show up in studies of $CP$ violation in mesons containing $b$ quarks [28].

These possibilities will be explored at the LHC by a dedicated experiment, LHCb [29], as well as by ATLAS and CMS. There are some channels where the LHC will provide a significant increase in the available statistics, such as $B \to J/\psi K$ and $\pi^+\pi^-$ decays, as seen in Fig. 11. There are other channels where LHCb may be able to make the first measurements, such as $B_s \to D_s K$ decays, enabling the unitarity triangle to be overconstrained. The stakes are high: the $CP$ violation present in the Standard Model is apparently unable to explain the origin of the matter in the Universe. This would require some extension of the Standard Model, which might be found at the LHC.

# 7 The LHC will explore new dimensions of physics

The LHC will explore a new dimension in *energy*, up to the TeV scale [30]. There are good reasons to think that the origin of particle masses, a Higgs boson or its replacement, will be revealed in this energy range. The LHC will also explore new dimensions of *space*. These might be additional curled-up versions of the more familiar *bosonic* dimensions, or they might be more novel *fermionic* "quantum" dimensions, that appear in the formulation of supersymmetry in "superspace". The LHC will also explore a new dimension of *time*, recreating particles and events that occurred just $10^{-12}$ sec after the beginning of the Big Bang. This time travel should reveal to us the nature of the primordial "soup" that filled the Universe before nuclear particles were born. It may also reveal the nature of dark matter, and perhaps also hints about the origin of matter itself.

# References

1. P.W. Higgs, Phys. Rev. Lett. **13**, 508 (1964)
2. J. Wess, B. Zumino, Phys. Lett. B **49**, 52 (1974)
3. L. Maiani, Proceedings of the 1979 Gif-sur-Yvette Summer School on Particle Physics, 1; G. 't Hooft, Recent Developments in Gauge Theories, Proceedings of the NATO Advanced Study Institute, Cargese, 1979, eds. G. 't Hooft et al., (Plenum Press, NY, 1980); E. Witten, Phys. Lett. B **105**, 267 (1981)
4. J. Ellis, S. Kelley, D.V. Nanopoulos, Phys. Lett. B **260**, 131 (1991); U. Amaldi, W. de Boer, H. Furstenau, Phys. Lett. B **260**, 447 (1991); P. Langacker, M.-X. Luo, Phys. Rev. D **44**, 817 (1991); C. Giunti, C.W. Kim, U.W. Lee, Mod. Phys. Lett. A **6**, 1745 (1991)
5. J. Ellis, J.S. Hagelin, D.V. Nanopoulos, K.A. Olive, M. Srednicki, Nucl. Phys. B **238**, 453 (1984)
6. G.W. Bennett et al., Muon g – 2 Collaboration, Phys. Rev. Lett. **89**, 101804 (2002)
7. ATLAS Collaboration, http://atlas.web.cern.ch/Atlas/internal/Welcome.html
8. CMS Collaboration, http://cmsinfo.cern.ch/Welcome.html/
9. See, for example: C.T. Hill, Phys. Lett. B **266**, 419 (1991)
10. For a review, see: E. Farhi, L. Susskind, Phys. Rept. **74**, 277 (1981)
11. See, for example: J. Ellis, G.L. Fogli, E. Lisi, Phys. Lett. B **343**, 282 (1995)
12. F. Abe et al., CDF Collaboration, Phys. Rev. D **50**, 2966 (1994); S. Abachi et al., Phys. Rev. Lett. **74**, 2632 (1995)
13. LEP Electroweak Working Group, http://lepewwg.web.cern.ch/LEPEWWG/
14. LEP Higgs Working Group, http://lephiggs.web.cern.ch /LEPHIGGS /www /Welcome.html/
15. Y. Okada, M. Yamaguchi, T. Yanagida, Prog. Theor. Phys. **85**, 1 (1991); J. Ellis, G. Ridolfi, F. Zwirner, Phys. Lett. B **257**, 83 (1991); H.E. Haber, R. Hempfling, Phys. Rev. Lett. **66**, 1815 (1991)
16. J. Ellis, D.A. Ross, Phys. Lett. B **506**, 331 (2001)
17. C.L. Bennett et al., WMAP Collaboration, Astrophys. J. Suppl. **148**, 1 (2003)
18. J. Ellis, K.A. Olive, Y. Santoso, V.C. Spanos, Phys. Lett. B **565**, 176 (2003)
19. M. Battaglia, A. De Roeck, J. Ellis, F. Gianotti, K.A. Olive, L. Pape, hep-ph/0306219
20. I. Hinchliffe, F.E. Paige, M.D. Shapiro, J. Soderqvist, W. Yao, Phys. Rev. D **55**, 5520 (1997)
21. M. Battaglia, A. De Roeck, J. Ellis, F. Gianotti, K.A. Matchev, K.A. Olive, L. Pape, G. Wilson, Eur. Phys. J. C **22**, 535 (2001)
22. P. Horava, E. Witten, Nucl. Phys. B **460**, 506 (1996)
23. I. Antoniadis, Phys. Lett. B **246**, 377 (1990)
24. I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, Phys. Lett. B **436**, 257 (1998)
25. ALICE Collaboration, http://alice.web.cern.ch/Alice/-AliceNew/collaboration
26. J. Rafelski, B. Muller, Phys. Rev. Lett. **48**, 1066 (1982)
27. T. Matsui, H. Satz, Phys. Lett. B **178**, 416 (1986)
28. See, for example: M. Ciuchini, E. Franco, A. Masiero, L. Silvestrini, Phys. Rev. D **67**, 075016 (2003)
29. LHCb Collaboration, http://lhcb.web.cern.ch/lhcb/
30. In addition to the above topics, elastic scattering will be explored by the TOTEM Collaboration, http://totem.web.cern.ch/Totem/