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LHC PHYSICS — WHAT CAN BE DONE IN THE FIRST YEARS*

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The current status of construction of the Large Hadron Collider LHC and the two multi-purpose detectors ATLAS and CMS is reported. The steps necessary to be ready for taking and understanding the first data expected in the second half of 2007 are briefly explained. Examples for early measurements of Standard Model processes are given. The perspectives for discovery of new phenomena in the fields of Higgs bosons, Supersymmetry, and Extra Space Dimensions are summarized.

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1. Introduction

The Large Hadron Collider LHC currently under construction at CERN will come into operation in less than two years from now. It will provide proton–proton collisions at a center-of-mass energy $\sqrt{s} = 14$ TeV at a design luminosity of 10^{34} cm^{-2}s^{-1}. It will thus extend the mass reach for the discovery of new particles by almost an order of magnitude compared to previous colliders and allow for the first broad-band survey of new phenomena at the TeV energy scale. While it is difficult to predict how fast the design luminosity will be reached, it is clear that this will not happen immediately after turn-on. This talk will mainly address the question what physics can be expected in the first years after LHC turn-on. The physics outcome in this phase does not only depend on the integrated luminosity (several fb^{-1} may be expected by the end of 2008) but also on the understanding of the detectors as well as of the instrumental and physics backgrounds. The commissioning and calibration of the detectors will be undertaken in steps, some of which are starting already now. In addition to test-beam and cosmic data,

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understanding the detector and the backgrounds will need collision data as well as most advanced theoretical calculations and Monte Carlo generators.

This talk is organized as follows: first the status of the LHC and the two multi-purpose detectors ATLAS and CMS is summarized. Then the strategy for detector commissioning is explained followed by a description of early measurements of Standard Model (SM) process. Finally, the potential for discovery of new phenomena is summarized, focusing on those cases which require only moderate integrated luminosity.

2. The LHC and the experiments ATLAS and CMS

The LHC is constructed in the former LEP tunnel at CERN. The 27 km ring will host 1232 superconducting dipole magnets each of 15 m length providing a 8.33 T bending magnetic field for the 7 TeV proton beams. To achieve design luminosity, 2808 bunches of 10^{11} protons each have to be stored. The bunch crossing interval will be 25 ns and the total energy stored per beam will be 350 MJ. After initial problems with the production of superconducting cables and recent problems in the installation of the cryogenic support lines have been overcome, the installation of the LHC machine is now progressing very well. The production of the dipoles is almost finished (see Fig. 1) and their installation in the tunnel has started. The dipole installation schedule is on the critical path to be ready for beams in July 2007 [2].

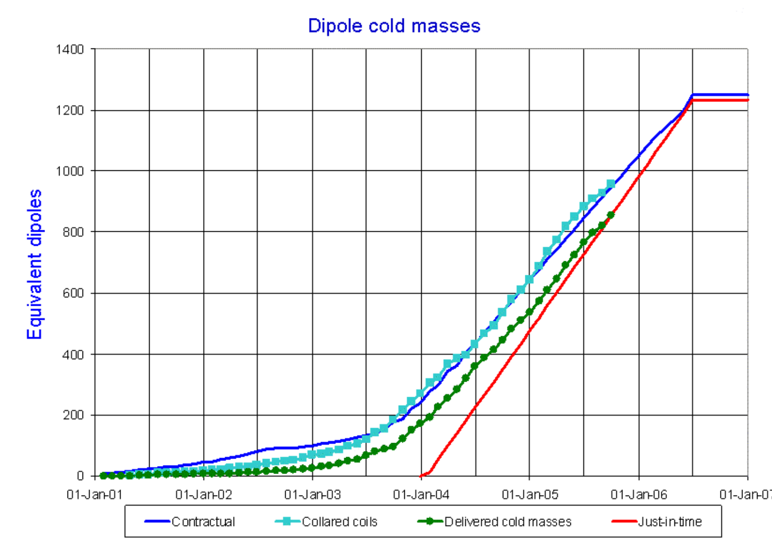

Fig. 1. Number of produced and delivered dipole cold masses for the LHC ring as of 30/09/2005 (from Ref. [1]).

At the LHC, four interaction regions are constructed which will host the experiments ATLAS [3] and CMS [4], designed for *pp* collisions at high luminosity. A specialized detector for heavy ion collisions (ALICE) and a spectrometer for *B*-physics (LHCb) are also under construction. Both ATLAS and CMS are typical multi-component collider detectors. Charged particle detection consists of silicon pixel vertex detectors, silicon strip detectors and (in the case of ATLAS) a straw tube transition radiation tracker (TRT). In ATLAS, a 2 T solenoidal magnet surrounds the tracking detectors in front of the calorimeter. In CMS a large volume 4 T magnet also surrounds the calorimeter. Both calorimetry and muon detection differ considerably between ATLAS and CMS. In ATLAS, a fine-grained liquid argon(LAr)–lead electromagnetic calorimeter is surrounded by a scintillator-iron Tile-Calorimeter and LAr–Cu calorimeters in the forward region. CMS relies on lead-tungstate crystals for electromagnetic shower detection surrounded by a brass-scintillator hadronic calorimeter. Muon detection in ATLAS proceeds through a huge air-core toroid magnet consisting of eight superconducting coils instrumented with monitored drift tubes (MDT) and cathode strip chambers (CSC) for momentum measurement and resistive plate chambers (RPC) for triggering. In CMS the muon detection proceeds in the return yoke of the 4 T superconducting solenoid, instrumented also with MDTs, RPCs and CSCs. The construction of most sub-detectors for ATLAS and CMS is finished or in its final phase. While ATLAS is assembled in the underground hall, CMS is built in a surface building. The detector will be lowered in five huge pieces in 2006. Installation is advancing very well for both detectors. For CMS, delays in the crystal production require that the end-caps will be installed after the pilot run during the shutdown in winter 2007/08. According to current schedule it can be expected that both detectors will be fully operational for the first physics run in 2008 although in both experiments the construction of some parts had to be deferred to a later time.

3. Commissioning of the detectors

Commissioning of the detectors has the goal to achieve the best possible day-1 performance and to improve this performance further with the help of real collision data. The main tasks in commissioning are alignment of tracking detectors to a precision of several μm, response calibration of the calorimeter cells, mapping of dead channels, commissioning of the data acquisition and trigger electronics and software, commissioning of the GRID-based world-wide data reconstruction and analysis chain.

This goal is approached in a multi-step procedure:

(i) Tight fabrication tolerances: differences between the initial and design performance often arise from material variations within their fabrication tolerances, *e.g.* the thickness of absorber plates in the sampling calorimeters.

It is the general strategy in the fabrication of the subdetectors to keep such tolerances as small as possible. As an example, the distribution of the thickness of ATLAS ECAL absorber plates has a r.m.s. of only 11 μm at an average of 2.2 mm.
(ii) Test-beam program: an extensive test-beam program was carried out in order to test modules of the individual subdetectors as well as their interplay. Furthermore, test beam data can be used to verify both simulation and reconstruction algorithms.
(iii) Cosmic muon calibration: once the detectors are completely installed, during the cool-down of the machine a cosmic run of approximately three months duration will be carried out. As an example, with these data the inter-calibration of the ECAL cells in ATLAS can be performed to 0.5% precision, the timing can be adjusted to better than 1 ns and alignment w.r.t. to other components can be carried out to about 1 mm precision.

After this commissioning program it is expected that the electromagnetic energy uniformity is calibrated to 1% (ATLAS) and 4% (CMS) and the absolute e/γ scale will be known to 1–2%. Hadronic energy uniformity will be 2–3% and the absolute hadronic energy scale will be known to better than 10%. Tracking point resolution is expected to be between 20–500 μm [5].

Further improvement towards the final detector design goals can only be achieved using physics samples from real collisions. In particular the absolute electromagnetic energy scale can be obtained from $Z \to e^+e^-$ events. Various approaches to improve the hadronic energy scale exist. Full reconstruction of hadronic W decays in $t\bar{t}$ events appears most promising. Tracker alignment and momentum resolution can be improved with $Z \to \mu^+\mu^-$, but also in general with high-momentum isolated tracks.

4. Early measurements of standard model processes

The initial measurements aim primarily at a better understanding of the general properties of pp collisions at 14 TeV such as properties of minimum bias events, charged multiplicity, and rapidity distribution. Immediately after turn on of the machine, the charged particle multiplicity can be determined, significantly constraining current extrapolations from the Tevatron which differ by almost one order of magnitude as can be seen in Fig. 2.

Furthermore, hard SM processes such as Z-, W- and top-production have to be established for various reasons. First, as mentioned above, they serve as important calibration tools. Second, SM gauge boson and top quark production are the most important backgrounds to many new physics channels. The measurement of differential distributions of these processes, such as the p_{T} distribution of gauge bosons is of utmost importance in order to estimate backgrounds to discovery channels, compare to higher-order theoretical cal-

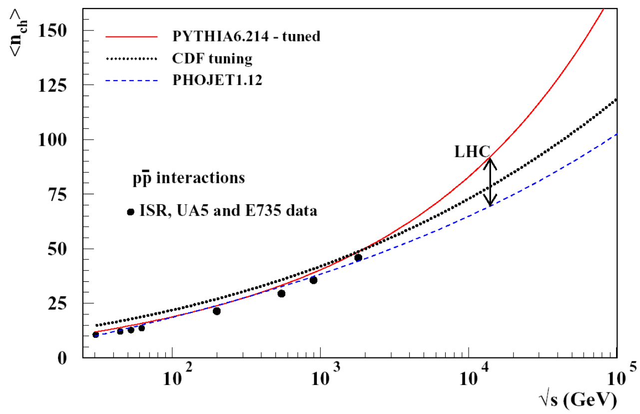

Fig. 2. Measured mean charged particle multiplicity at center-of-mass energies from 300 to 2000 GeV and extrapolations to LHC as a function of the pseudorapidity (from Ref. [6]).

culations and tune Monte Carlo simulation. The number of recorded SM events is tremendous already in a 1 sample corresponding to fb^{-1} of integrated luminosity. As examples, $10^7 W \to e\nu$, $10^6 Z \to ee$ and $10^5 t\bar{t}$ events will recorded. In Fig. 3, a full simulation of the reconstructed top mass in ATLAS is shown [7]. Signal events originate from $tt \to b\ell\nu bqq$ events. The invariant mass of the hardest three jets is plotted. Already without any b-tagging a clear signal can be seen. The statistical error on m_{top} is expected to be below 500 MeV for 150 pb^{-1} of data thus allowing immediately to improve on the hadronic energy scale from comparison of the observed peak posi-

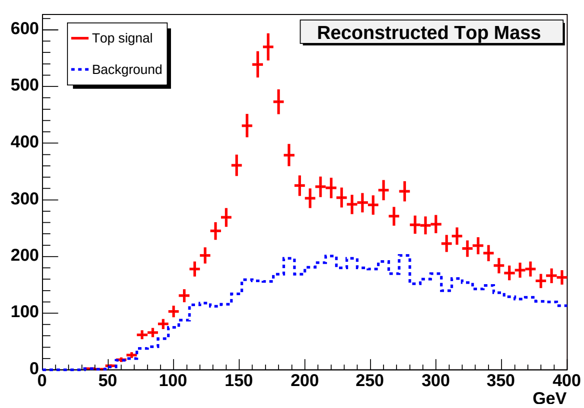

Fig. 3. Reconstructed three-jet invariant mass for semi-leptonic $t\bar{t}$ events and expected background from $W+4$ jet events passed through a simulation of the ATLAS detector. The integrated luminosity is 150 pb^{-1} and no b-tagging is applied (from Ref. [7]).

tion with the known top-mass from the Tevatron. Furthermore, the two jets from the hadronically decaying W-boson can be reconstructed allowing for improved calibration independent of $m_{\rm top}$. Requiring only one b-tagged jet immediately removes most of the combinatoric background. The $t\bar{t}$ sample will be also essential to commission b-tagging and determine the b-tagging efficiency from the single- to double-b-tag ratio. In addition, the p_t of the $t\bar{t}$ system can be studied and compared to NLO Monte Carlo calculations.

5. The road to discovery

Once the main SM processes have been observed and an initial calibration of the detector has been performed, the search for new phenomena can start. While the ultimate reach of the LHC experiments will mainly depend on the integrated luminosity, early sensitivity will also depend on the achieved accuracy in calibration and on the complexity of the final states under search.

5.1. The SM Higgs boson

One of the main motivations for the construction of the LHC is its potential to discover the SM Higgs boson if it is realized in Nature. Higgs production at the LHC predominantly proceeds through the loop-induced process $gg \to H$, with additional contributions from vector boson fusion, $qq \to Hqq$, and associated production modes WH, ZH, ttH. Due to the strong mass-dependence of the Higgs boson branching ratios, the strategy for Higgs discovery also depends crucially on the mass. For $m_H > 180\,\mathrm{GeV}$, the $H \to ZZ \to \ell\ell\ell\ell$ decay provides a robust and clean signature for Higgs production. Should the Higgs boson mass lie between 180 and 600 GeV, an early discovery with a few fb^{-1} is very likely. As an example, an expected signal in the four-lepton channel is shown for $m_H = 300\,\mathrm{GeV}$ in Fig. 4 (left).

For a lighter Higgs boson, as it is preferred by electro-weak precision data, the situation is more complex. Due to the huge QCD background, the dominant $H \to b\bar{b}$ decay cannot be seen in an inclusive search. Therefore, one has to rely on rarer but cleaner final states. These are the inclusive $H \to \gamma\gamma$ channel, the vector boson fusion modes $qqH \to qq\tau^+\tau^-$ and $qqH \to qqW^+W^-$ and $t\bar{t}H \to t\bar{t}b\bar{b}$. With 10 fb^{-1} of data for $m_H < 130\,\mathrm{GeV}$, a 5σ discovery can only be established when these three modes are combined. While at a later stage with more luminosity the complementarity of these different channels is beneficial as it provides robustness and allows for tests of Higgs boson properties, at an early stage their combination will certainly be difficult. In Fig. 4 (right) the signal significance for ATLAS at $30\,\mathrm{fb}^{-1}$ is shown for the individual channels and their combination.

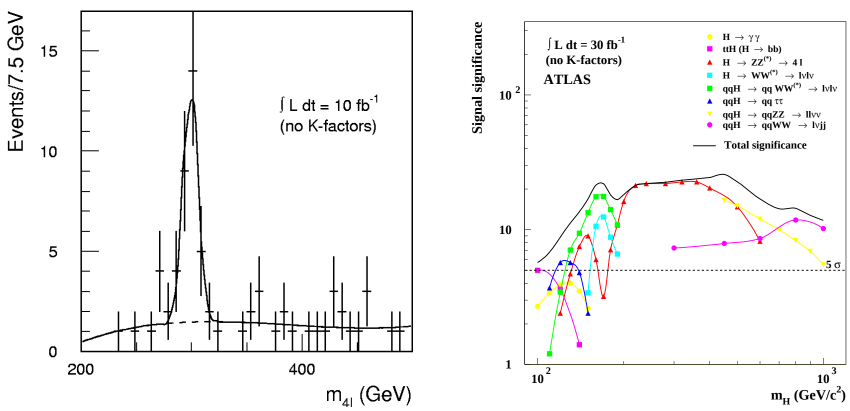

Fig. 4. Right: Expected signal and background in the $H \to 4\ell$ channel for $m_H =$ 300 GeV (from Ref. [8]). Left: Expected signal significance in ATLAS for the SM Higgs boson as a function of its mass assuming an integrated luminosity of 30 fb^{-1} (from Ref. [9]).

5.2. Supersymmetry

If low-energy Supersymmetry (SUSY) is realized in Nature, the LHC will be sensitive to the largest part of the theoretically preferred region of its parameter space. Previous studies have shown that SUSY signals can be established for various assumptions on the SUSY breaking mechanism and independent of whether R-parity is broken or not [8]. Here the focus is on the best-studied scenarios with conserved R-parity and gravity-mediated SUSY breaking as it proceeds in mSugra models. In these scenarios, SUSY particles are mainly produced through the strong interaction via $gg \to \tilde{g}\tilde{g}$, $gg \to \tilde{q}\tilde{q}$, $gq \to \tilde{g}\tilde{q}$ and similar processes. These colored superpartners typically decay through long decay chains to the lightest SUSY particle (LSP) which is stable and here assumed to be the lightest neutralino, $\tilde{\chi}_1^0$. The signatures from these decay chains are a high multiplicity of high-p_{T} jets, leptons and large missing transverse energy from the escaping LSP. Before individual production processes and decay modes will be analyzed, the search for SUSY at the LHC proceeds via a highly inclusive strategy, both in order to keep the analyses simple and to remain as model-independent as possible.

The most inclusive search simply requires a certain number of high-p_{T} objects (jets and/or leptons) and large missing transverse energy. A particular simple analysis proceeds via the calculation of the so-called *effective mass*, M_{eff}, which is defined as the sum of the transverse energies of the four highest p_{T} jets and the missing transverse energy. Studies, *e.g.* in Ref. [8], have shown that SUSY events will lead to a significant excess at high values of M_{eff} (Fig. 5, upper left). With 1 (10) fb^{-1} of data, a $>5\sigma$ excess is expected for squark/gluino masses up to 1(2) TeV. Recently, background estimations to this inclusive search are being re-evaluated with newer Monte Carlo generators such as ALPGEN [10], SHERPA [11] which match multi-parton matrix-element calculations to parton shower emission as well as the full next-to-leading generator MC@NLO [12]. Preliminary results indicate that backgrounds, in particular from $Z+$ jets, have longer tails in M_{eff} than previously estimated from LO+parton shower generators, thus reducing the mass reach for the inclusive search somewhat. It should be noted, however, that this inclusive SUSY search heavily relies on a well-understood calibration of the missing transverse energy which requires full control over the entire calorimeter response. This calibration will certainly take some time before a signal can be claimed.

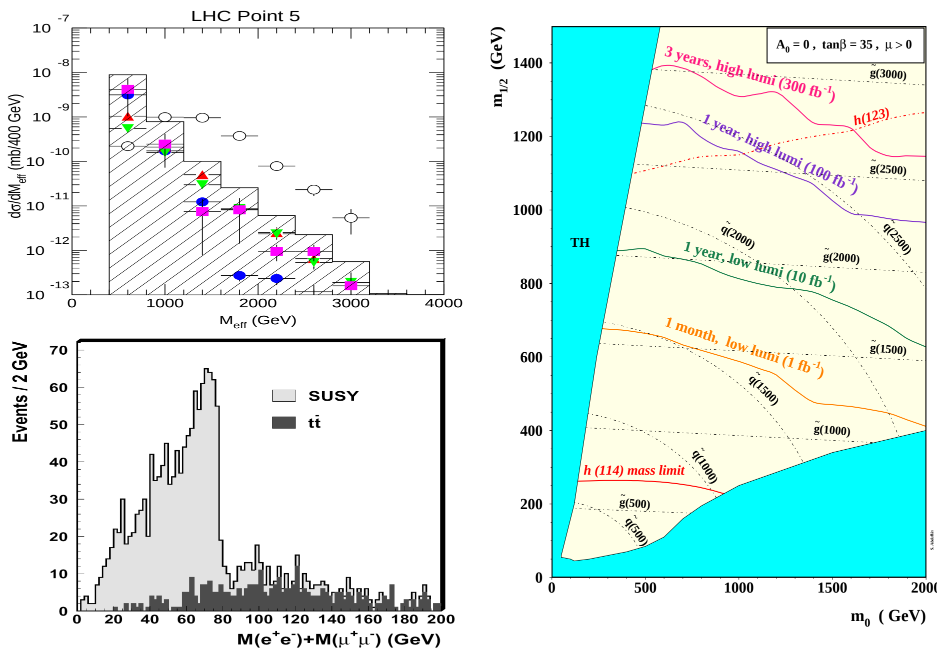

Fig. 5. Upper left: M_{eff} distribution for a mSugra benchmark point ($m_0 = 100\,\text{GeV}$, $m_{1/2} = 300\,\text{GeV}$, $A_0 = 0$, $\tan\beta = 2$, $\text{sgn}(\mu) = +$) signal and background obtained from a simulation of the ATLAS detector (from Ref. [8]). Lower left: invariant mass spectrum of two opposite-sign, same-flavor leptons from the decay $\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0$ for $10\,\text{fb}^{-1}$ of data simulated in the CMS detector (from Ref. [13]). Right: discovery region for the inclusive SUSY search in the $(m_0, m_{1/2})$-plane of mSugra for integrated luminosities from 1 to $300\,\text{fb}^{-1}$ (from Ref. [4]).

Search topologies, which explicitely require the presence of high-p_T leptons in addition to large missing transverse energy, are less vulnerable to uncertainties in SM background estimates. In particular, the presence of kinematic endpoints in di-lepton mass spectra, as they occur in significant parts of the SUSY parameter space from $\tilde{\chi}_2^0$ decays, provide a smoking gun signature for SUSY (Fig. 5, lower left). The discovery potential for the inclusive missing transverse energy signature in the $(m_0, m_{1/2})$-plane of the mSugra model is shown in Fig. 5 (right).

Another signature of SUSY is the presence of five physical Higgs bosons stemming from the Two-Higgs-Doublet structure of minimal SUSY. In particular, the lightest CP-even Higgs boson h is predicted to be lighter than $\sim 140\,\mathrm{GeV}$. This Higgs boson has similar properties as the SM Higgs. Its discovery has been shown to be possible over the whole parameter plane of $(m_A, \tan\beta)$ for various benchmark scenarios [14, 15] with $30\,\mathrm{fb}^{-1}$.

5.3. Extra dimensions

Models with additional compactified spatial dimensions can provide a viable alternative solution to the hierarchy problem. The ADD model [16] postulates large extra dimensions of up to few $100\,\mu\mathrm{m}$. In this model, at the LHC a structureless excess of events with missing transverse energy from the emission of a quasi-continuous tower of Kaluza–Klein(KK) graviton excitations is expected. In order to establish this signal, a very detailed understanding of the tails of the SM background and an excellent calibration of the detector are necessary. Furthermore, significant integrated luminosity in excess of $100\,\mathrm{fb}^{-1}$ may be required. Most likely, ADD signatures will not be visible in the first few fb^{-1} of data.

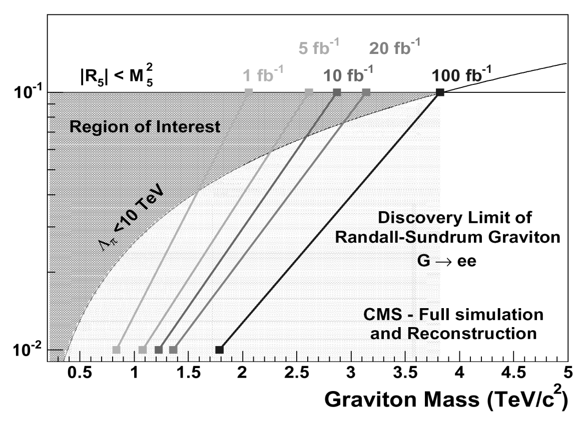

Fig. 6. Discovery reach in the parameter space of the Randall–Sundrum model of warped extra dimensions (from Ref. [19]).

On the other hand, in the Randall–Sundrum (RS) model [17] of warped extra dimensions, the KK excitations appear as narrow resonances, which can (partially) decay into charged di-lepton pairs. Such resonances [18, 19] as well as new vector boson resonances [20], can be observed up to masses around 3 TeV with $10\,\mathrm{fb}^{-1}$. In Fig. 6, the sensitivity of CMS in the parameter space of the RS model is shown. Already with $1\,\mathrm{fb}^{-1}$, a significant part of the theoretically allowed parameter space can be covered.

6. Summary and conclusions

The construction of the LHC and the two experiments ATLAS and CMS is advancing very well. First collisions are expected for the second half of 2007 with both experiments being ready to take first data. The commissioning process of the experiments has started and will continue with the aim of being able to understand the first data as fast as possible. Understanding the detectors is, however, not a simple task and will require significant effort and time even when the first data arrived. Once an initial understanding of the detectors has been established and major SM processes have been measured, the road to discovery is opened. The prospects for major discoveries already with the first 10–30 fb^{-1} are very good. In particular, the SM Higgs boson can be discovered with $10\,\mathrm{fb}^{-1}$ for $m_H > 120\,\mathrm{GeV}$. Also first signals from SUSY may be observed, depending mainly on what the scale of SUSY breaking is. Narrow di-lepton resonances from Z' bosons or RS resonances can also be observed in the first $10\,\mathrm{fb}^{-1}$ of data if their masses are below $\sim$3 TeV. Thus, already at the beginning the LHC program may lead to a major breakthrough in our view of Nature.

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