FUTURE OF THE LHC

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Abstract

The future of the LHC is discussed, considering aspects related to the accelerator, experiments, and physics. This includes the recently-approved high luminosity upgrade, HL-LHC, and beyond.

1 Accelerator

The Large Hadron Collider (LHC) at CERN is the highest energy collider in the world, with 27 km circumference—it has been called the world’s largest scientific instrument. It is primarily a proton-proton collider (although heavier ions can also be accelerated), with design centre-of-mass energy of 14 TeV. The dipole magnets shown in Fig. 1 feature a two-in-one design to allow the acceleration of same-charged particles in both directions around the ring. The superconducting magnets use niobium titanium (NbTi) alloy cable, which gives 8.3 T
field in the main dipoles. They are cooled with liquid helium to a temperature of 1.9 K. The design luminosity is $10^{34} \text{cm}^{-2}\text{s}^{-1}$, achieved with 2808 circulating bunches, each with $\sim 10^{11}$ protons, and focussed at the high-luminosity interaction points with $\beta^* = 40 \text{cm}$, giving a transverse beam size of order $10 \mu\text{m}$. The bunches are spaced by 25 ns, corresponding to a collision rate of 40 MHz at each of the four interaction points.

The LHC was conceived in the early 1980s, and re-uses the tunnel of the previous machine, LEP ($e^+e^-$, 1989–2000). An incident during commissioning in 2008, due to failure of a magnet interconnect, delayed the start-up. The accelerator restarted at $\sqrt{s} = 7 \text{TeV}$ in 2010 then 8 TeV in 2012. The inte-
grated luminosity is illustrated in Fig. 2, and amounted to $5 + 24 \text{ fb}^{-1}$ at the high-luminosity experiments (Run 1). The discovery of the Higgs Boson was announced in 2012. This was followed by the first long shutdown (LS1) in 2013–14, during which consolidation was completed for all of the magnet interconnects. The machine restarted in 2015 at 13 TeV. This required a significant number of training quenches for the magnets: up to 50 in the most difficult sector. $4 \text{ fb}^{-1}$ had been integrated so far in Run 2.

2016 is intended to be a “luminosity production year”, aiming to reach the nominal luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (that has since been achieved). The accelerator complex had recently recovered from power failure during start-up, caused by a weasel. At the time of the conference $\sim 900$ bunches were circulating, and the machine was ramping up fast to higher luminosity. Pushing up the energy to 14 TeV would require many further training quenches, so it has been decided to stay at 13 TeV for this year (at least). The planned schedule is shown in Fig. 3.

1.1 HL-LHC

According to the European Strategy for Particle Physics, updated in 2013, “Europe’s top priority should be the exploitation of the full potential of the LHC,
High-luminosity LHC (HL-LHC) is a project to increase the peak luminosity by a factor 5 and integrate 3000 fb$^{-1}$ of data. The project is mostly focused on entirely renovating the insertion regions around the high-luminosity experiments (i.e. about 1.2 km of accelerator, as shown in Fig. 4). To achieve stronger focusing the low-beta triplet quadrupoles will be replaced with higher field and larger aperture versions. Low $\beta^*$ requires a larger crossing angle, which would reduce the luminosity by a geometrical factor, so crab cavities will be introduced to rotate bunches to collide head on. Overall this is a 1 BCHF-scale project. R&D on high-field magnets in progress using niobium-tin (Nb$_3$Sn) alloy as superconductor: in December 2015 a two-in-one dipole using this material (1.8 m long) reached 11.3 T without quench. This will allow space for extra collimation in dispersion suppressor region.

2 Experiments

There are four major experiments at the LHC. Two are general-purpose high-$p_T$ experiments, ATLAS and CMS, that perform precision studies of the Standard Model (including the new field of Higgs properties) and search for physics beyond the Standard Model. There is an enormous rate of b and c hadrons produced at LHC, dominantly in forward region, and the dedicated flavour experiment, LHCb, has exquisite proper-time resolution (40 fs). Luminosity is levelled for LHCb by adjusting the separation of the beams, as shown in Fig. 5; this technique will be important for HL-LHC. The LHC also accelerates heavy ions (Pb$^{82+}$). Typically it is run with Pb-Pb or Pb-p collisions for one month at the end of each year. The dedicated experiment for this physics is
ALICE, although by now all experiments participate. Such collisions allow the properties of matter to be studied at high temperature/density, with a total collision energy of over 1 PeV.

Other smaller experiments include MoEDAL, a monopole search experiment (at the LHCb IP) which surrounds the interaction region with plastic sheets that reveal tracks of highly-ionizing particles after etching. There are also experiments studying forward physics: LHCf (at the ATLAS IP) uses a zero-degree calorimeter to study neutral production, relevant for cosmic rays; TOTEM (at the CMS IP) uses silicon tracking detectors in Roman Pots to study elastic and diffractive scattering of protons.

2.1 Detector upgrades

The recent increase in energy brings less for LHCb and ALICE than high-\(p_T\) experiments, so they have major upgrades planned already for 2019 (during LS2), known as Phase 1. Major upgrades for ATLAS and CMS are foreseen to prepare for HL-LHC in LS3 (Phase 2), with an agreed funding scale of \(\sim 250\) MCHF for each experiment. LHCb and ALICE are also expected to continue during HL-LHC. The major challenges for the high-luminosity phase are the radiation dose, and occupancy/pile-up.

The increase in occupancy will be fought using higher granularity. All experiments will replace their silicon trackers, and CMS is preparing a High-
Granularity Calorimeter in the forward region. Another theme of the detector upgrades concerns increased speed: the ALICE TPC wire chamber readout currently limits their data-taking rate, and will be replaced with GEM end-plates allowing 50 kHz readout (i.e. 20× higher). The LHCb signal yield is currently limited for hadronic modes by their first-level trigger; for the upgrade they will remove the hardware trigger and read out the full detector at 40 MHz. This will give an enormous data rate ~ 5 TB/s, via 12,000 optical links to the CPU farm on the surface. Fast timing detectors are studied by all experiments to fight pile-up: since the beam-spot spreads over ~ 300 ps, if could be divided into O(25 ps) slices this would reduce the occupancy back to its current level.

3 Physics

The Higgs Boson was discovered in the $\gamma\gamma$ and ZZ decay modes. ATLAS and CMS results have now been combined, e.g. for the mass measurement: $125.09 \pm 0.21$ (stat) $\pm 0.11$ (syst) GeV. Alternative spin-parities are disfavoured at over 99.9%—it behaves like Standard Model Higgs, so far (see Fig. 6).

The major focus at the LHC is on the search for physics beyond the Standard Model. Some hints of anomalies were seen in the Run 1 data: in flavour physics, e.g. lepton-flavour violation in $B^0 \rightarrow D^{(*)}\tau\nu$, and the angular analysis
Figure 7: (left) Sensitivity to Supersymmetry in the plane of neutralino vs. chargino mass, for different integrated luminosities. (right) Predicted signal for $H \rightarrow \mu^+\mu^-$ at HL-LHC.

$(P_T')$ of $B \rightarrow K^{*}\mu\mu$ decays; and in the search for resonances in vector-boson pairs. These effects will be followed up with the new data. The latest excitement is an excess seen in diphoton mass spectrum in 13 TeV data by both ATLAS and CMS at around 750 GeV. This would clearly be new physics if confirmed, and over 200 papers on its interpretation have already been published. However, it may still be a statistical fluctuation, so this year’s data is eagerly awaited.

Assuming dark matter is made of particles that couple to quarks via a mediator, it may be produced at LHC. It would leave no trace in the detector, so to tag its production a particle is needed from initial state radiation, leading to a monojet search (with missing $E_T$). One can also expect that mediator would couple to quarks in the final state, leading to a dijet resonance search. This will continue to be a very active field at ATLAS and CMS.

LHCb integrated 3 fb$^{-1}$ of data in Run 1 with levelled luminosity of $4 \times 10^{32}$ cm$^{-2}$s$^{-1}$. Precision measurements were made of rare decays and CP violation for many $b$ and $c$ hadrons. In the LHCb upgrade the luminosity will be increased to a few $\times 10^{33}$ cm$^{-2}$s$^{-1}$, aiming to integrate 50 fb$^{-1}$. Examples of the precision expected include $\text{BR}(B_s \rightarrow \mu^+\mu^-)$ at the $10^{-10}$ level; $\phi_s$ (the phase of $B_s$ oscillation) $\pm 0.008$; and the unitarity angle $\gamma$ to $\pm 1^\circ$.

Another active field is the study of exotic spectroscopy, where there is a zoo of possible exotic hadron states: LHCb has established a pentaquark state.
$P_c(4450)^+ \to J/\psi p$ using a full angular analysis.

At HL-LHC, if new physics discovered in Run 2 or 3, its first detailed exploration will be possible with well-understood accelerator and experiments. Otherwise, the direct discovery potential will be extended by 20–30% in mass reach, as illustrated in Fig. 7. In either case over 100 million Higgs Bosons will be produced, allowing the Higgs couplings to be measured to a few percent, and including the 2nd generation via the observation of $H \to \mu^+\mu^-$.  

3.1 Far future

Results from Run 2 will hopefully clarify the best choice for the next energy-frontier machine in time for the next update of the European Strategy in 2019–20. One option is the Future Circular Collider (FCC): a 100 TeV-scale pp collider (with an $e^+e^-$ machine as a possible first step), for which the LHC is likely to be reused as injector. Key R&D for the FCC is to develop 16 T magnets to reach 100 TeV in a 80–100 km tunnel. Using such magnets in the existing tunnel would give $\sqrt{s} \sim 30$ TeV. Investigation of this possible High-Energy LHC (HE-LHC) is now included as part of the FCC study.

4 Conclusions

The LHC at CERN is the flag-ship facility of world-wide particle physics. It has been operating successfully over the last 5 years, providing the Higgs Boson discovery, as well as a vast array of other results: over 1500 scientific publications (and counting). This is a very exciting time for particle physics, as the recent increase in energy is the last such major step for some time, and there are strong hopes for discoveries over the coming years. An upgrade program is in preparation for both machine and experiments, to integrate over 100 times the current data-set, and exploit the LHC to its full potential over the next 20 years. Results from the LHC will play a key role in defining the future direction; the long lead time means that the choice of its successor will need to be made soon.

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