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Perspectives at LHC with 300 fb^{-1} at 14 TeV

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In the next future LHC will be operated at the design energy of about 14 TeV. Two distinct physics runs will allow the collection of about 300 fb^{-1} by 2018. The physics reach and the experimental challenge of this phase of LHC will be discussed.

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Introduction

The multipurpose ATLAS [1] and CMS [2] detectors allow experiments aiming at the observation of new phenomena at the CERN Large Hadron Collider (LHC). The two experiments have the same physics goals but the detection techniques chosen to meet these goals are significantly different. Both experiments are built guided by their magnetic field scheme. Thanks to a 0.6 T toroidal magnet in air ATLAS can perform stand alone measurement of high p$_T$ muons in the external muon chamber system. In order to mesure the momentum of charged particles and reconstruct the primary vertices in the inner tracking system a second 2 T solenoidal magnet is placed in front of the calorimeters.

The 3.8 T solenoidal magnet of CMS allows a precise measurement of the high p$_T$ muons by combining the information from the inner tracking system with that from the external muon chamber system placed in the iron yoke. The limited radius of the solenoid fixes significant space constraints to the calorimeters and the inner tracking.

These constraints drove ATLAS and CMS to identify diverse solutions and the reconstruction of physics objects in the two experiments are subject to different kinds of systematic errors. The experimental observations made by ATLAS and CMS, when in agreement, have an undeniable strength. The first major one, the discovery of a Higgs boson, was announced by ATLAS [4] and CMS [3] on the 4th of July 2012.

1. The next ten years

The LHC first physics run lasted three years ending after the delivery of 30 fb^{-1} in March 2013. For about 18 months (LS1) the collider will be subject to technical repairs in order to reach the design energy of 13-14 TeV and the design luminosity of 10^{34} cm^{-2}s^{-1}. The main technical interventions during LS1 will be the repair of faulty interconnects between the accelerator superconducting magnets and the consolidations of all these interconnects with a new design. ATLAS and CMS will perform a set of initial upgrades, design detector completions (parts foreseen in the original project that were then staged) and maintenance operations. The second period of data taking will start in mid 2015 and will allow the collection of about 75-100 fb^{-1} with an average of 25 pile-up events (μ = 25) if the machine will be operated at 25 ns bunch crossing. It is also possible that LHC will run with a 50 ns bunch crossing as already tested in 2012, this choice will depend upon technical considerations. While this scheme of operation will supply more luminosity (higher number of protons per bunch) with respect to the design one will also result in a higher average of 50 pile-up events.

A one-year long shutdown is foreseen in 2018 (LS2) to maintain and upgrade LHC equipment in order to double the design instantaneous luminosity. An integrated luminosity around 300 fb^{-1} should be reached around 2021. During LS2 ATLAS and CMS will perform major Phase-1 upgrades mainly related to trigger and pixel systems to cope with the increase of luminosity and pile-up ($\mu = 50$ (80) for 25 (50) ns bunch crossing) not foreseen by the original accelerator design. In years 2022-2023 (LS3) a further step to achieve a luminosity of 5×10^{34} cm^{-2}s^{-1} with a nominal pile-up of 140 events per bunch crossing, HL-LHC, will entail a substantial upgrade of the LHC as well as of ATLAS and CMS. The plan is to collect of the order of 3000 fb^{-1} by 2035.

The experiments will have to upgrade their detectors significantly, in particular their entire tracking systems. Studies of detector technical capabilities in HL-LHC conditions to assess what is needed to maintain physics performances and R&D on detector components are ongoing.

After LS1 LHC will provide collisions at about 14 TeV. The gain in physics reach given by the energy increase can be seen in Fig. 1. The ratio 14 TeV over 8 TeV of the gluon-gluon parton luminosities for the production of masses between 1 and 2 TeV ranges from 7 to 20. At 14 TeV ATLAS and CMS will reach the current sensitivity for masses of 1-2 TeV (typical limits in SUSY searches) after the collection of 1-3 fb^{-1}. Assuming the first year of run (2015) will follow the same integrated luminosity time profile of the 2012 run, it will take about two months of data-taking to achieve the present mass limits and enter in a new territory.

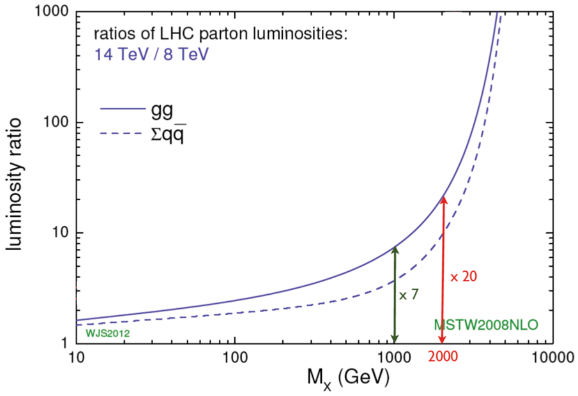

Figure 1: Ratio of parton luminosities [5] for the production of an object of mass M_X; the dashed curve corresponds to different parton beams as indicated in the key. The black and the red arrows indicate the value of the gluon-gluon luminosities ratio for M_X 1 TeV and 2 TeV respectively.

Based on the current experience ATLAS [6] and CMS [7] have produced projections of the physics reach achievable by a substantial increase in the collected luminosity at 14 TeV. These studies were performed for the update of the European Strategy for Particle Physics [8] and should be considered as very preliminary. Nevertheless they give an indication of the attainable results. These studies assume that the detectors will be adequately upgraded in order to maintain the present physics performances.

2. The physics reach with 300 fb^{-1}

An integrated luminosity of 300 fb^{-1} will allow important progress in the Higgs boson characterisation. Quantum numbers can be precisely determined and CP nature can be clarified (for non-mixed states) excluding CP violating state with a significance of more than 5σ. Signal strengths compatibility with SM can be tested to a precision of 5–10%. In a general approach deviations of Higgs couplings to photons, vector bosons, gluons, bottom quarks, top quarks, and τ leptons from SM predictions are probed in the six corresponding scale factors κ_γ, κ_V, κ_g, κ_b, κ_t and κ_τ. CMS expected results for the coupling scale factors are shown in Table 1 for a collected luminosity of 300 fb^{-1} and 3000 fb^{-1} assuming two scenarios for the projected uncertainities. In the first one (current) the systematic errors are kept at their current values, the gain in precision comes only from the scaling of the statistical error. In the second one (scaled) the systematic experimental error is scaled with statistics and the theoretical uncertainty is assumed to improve by a factor of two. The first scenario is probably too pessimistic while the second might be somewhat optimistic. Already with 300 fb^{-1} values not far from 5% are expected for the couplings uncertainities measured by a single experiment.

coupling	300 fb^{-1}		3000 fb^{-1}	
	syst. (%)		syst. (%)	
	current	scaled	current	scaled
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

Table 1: Expected precision in % attainable by CMS with 300 fb^{-1} and 3000 fb^{-1} keeping the present systematic errors or scaling both experimental and theoretical errors as described in the text.

Further significant improvements require higher statistics. The completion of the Higgs caracterization program needs about 3000 fb^{-1} to detect rare Higgs production and decay channels, to study the Higgs self coupling and to investigate Vector Boson Scattering.

Supersymmetry (SUSY) has been the subject of many dedicated searches. A number of SUSY models exists. The experimental strategy is to look for strongly produced heavy superpartners which then develop long decay chains characterised by several high p_T jets, and missing transverse energy (MET) due to a stable Lightest Supersymmetric Particle (LSP) escaping detection, with the possible additional presence of leptons and photons. A solid knowledge of the background estimates, derived using data-driven approach, and a precise control of the detector response is needed in order to detect SUSY events. Current results (Moriond 2013), interpreted in the context of simplified MSSM, set exclusion limits at 95% CL on squarks and gluinos at 1.4 TeV and 1.2 TeV respectively. Natural MSSM scenarios favour a 3rd generation of light squarks. The search is in this case focused on direct or gluino mediated production of stop/sbottom by adding to the generic citeria a specific search looking for $t\bar{t}$ pairs in presence of high MET. In this framework limits on the gluinos mass are typically reduced to 800 GeV for masses of LSP below 400 GeV and on masses of 3rd generation squark in the range 300-500 GeV for masses of LSP below 200 GeV. In scenarios with heavy squarks and gluinos, direct pair-production of weak gauginos (EWKinos) may dominate SUSY production. Representative limits exclude charginos with masses between 50 and 600 GeV but strongly depend on the assumptions about the intermediate states of the decay chain and on the value of the LSP mass. The increase in the energy of the collisions significantly improve the new states searches mass reach as shown in Fig. 1. An integrated luminosity of 300 fb^{-1} at 14 TeV would allow SUSY searches to extend the present limits for generic squarks and gluinos up to 2.7 TeV. The sensitivity to direct stop/sbottom production will reach 1.2 TeV and EWKinos might be excluded up to about 800 GeV. ATLAS expectation for stop discovery reach at

5 σ with 300 fb^{-1} is shown in Figure 2, depending on the decay channel (BR 100%) considered, a discovery might be possible up to around 700-800 GeV for masses of the LSP below 300 GeV. To extend the 95% exclusion limits to 1 TeV irrespectively of the LSP mass it is necessary to collect 3000 fb^{-1} of data.

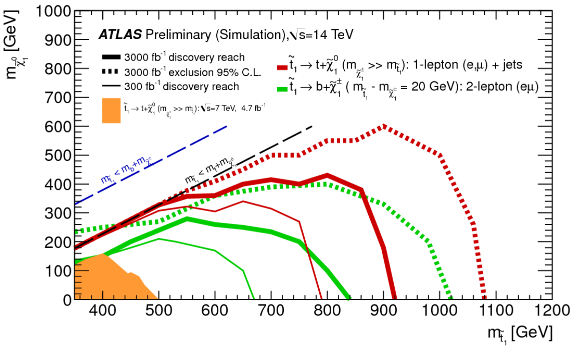

Figure 2: ATLAS projections for 5σ discovery reach and 95% CL exclusion limits in the stop-LSP mass plane for two decay channels, as indicated, for direct stop pair production.

Figure 3 shows that with 300 fb^{-1} a potential discovery of charginos may happen with ATLAS for masses below 350 GeV if the LSP is lighter than 250 GeV.

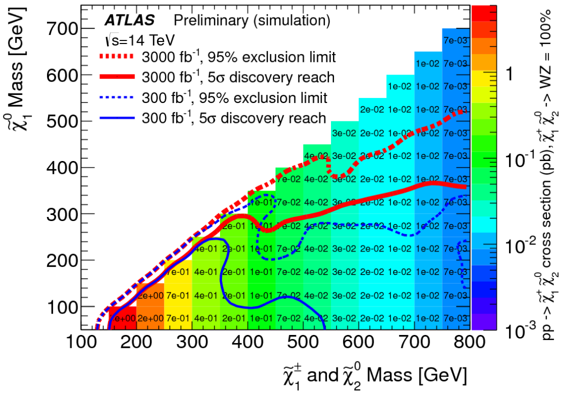

Figure 3: ATLAS 95% CL exclusion limits (dashed lines) and 5σ discovery reach (solid lines) for charginos and neutralinos undergoing $\tilde{\chi}_1^{\pm}$ $\tilde{\chi}_2^{0}$ –> W(*)$\tilde{\chi}_1^{0}$ Z(*)$\tilde{\chi}_1^{0}$ decays with BR=100%. The 300 fb^{-1} and 3000 fb^{-1} cases are reported.

The so-called Exotica area collects all BSM models which are not based on minimal SUSY or its extensions. A non-exhaustive list includes searches for heavy resonances, composite objects, 4th generation quarks, long-lived particles, leptoquarks, black holes as well as limits on contact interaction scales. A number of models have been ruled out, exclusions of heavy objects range from 0.5 TeV to 5 TeV (Moriond 2013). As a reference looking at heavy narrow resonances, ZâĂŹs limits range from 1.5 TeV to 3 TeV depending on the theoretical model.

This sector will gain substantially from the increase of LHC energy (see Fig. 1). With 300 fb^{-1} heavy narrow resonances such as sequential Z' with SM couplings will be probed up to typical values of 6.5 TeV. More complex topologies deriving from the decay in $t\bar{t}$ pairs of an heavy resonance like the Kaluza-Klein gluon can be investigated up to about 4 TeV.

With an integrated luminosity of 300 fb^{-1} many important SM studies can be performed. In particular the evidence of the production mechanism ttH can be obtained with about $50 fb^{-1}$. Top physics studies will benefit from the collection (after trigger) of about 50M $t\bar{t}$ in lepton+jet final states, 10M $t\bar{t}$ in di-leptons final states and 15M single top in leptonic final states. Top quark FCNC rare decays (as $t \to q\gamma$) may happen in the SM with a BR of the order of 10^{-14}, many models of new physics foresees an enhancement of these BR which can become as large as 10^{-4}. This level of sensitivity will be reached by ATLAS and CMS and open an additional window on new physics.

3. The experimental challenge

The first physics run of LHC has been a real challenge for ATLAS and CMS due to the frequent changes in the accelerator running coonditions and an average pile-up higher than what was expected in the original scheme with 25 ns bunch crossing. In 2012 a maximum peak luminosity of 7.7 10^{33} cm^{-2}s^{-1} was achieved, the experiments were confronted with an average μ of about 20 events and 30-40 peak interactions per crossing have been handled. The tracking resolution, the granularity and smart and sophisticated algorithms are the key elements to mitigate the pile-up effects. The "pile-up activity" indicating the average energy per solid angle is measured per event as a function of the number of primary vertices and subtracted as an energy offset from the jet energy and from the energy measurements for isolation pourposes. Figure 4 shows the p_T offest added to a CMS jet in the central region $|\eta| < 0.5$ as a function of the number of primary vertices reconstructed in the event. The behaviour of the offset is basically linear and tens of GeV will add to a jet p_T in a future situation where the number of primary vertices may exceed 100. Of-course high pile-up will have an even stronger impact on MET determination. Beside jet and MET also the electromagnetic objects energy scale will suffer in high pile-up conditions.

Other challanges due to the increase of luminosity beyond the design value of 10^{34} cm^{-2}s^{-1} will be the higher irradiation levels and the rise of event rate (which will be 6 times the current one after LS2 and 15 times in the running of HL-LHC) can not be controlled just by increasing the trigger thresholds without compromising the physics output. To cope with these problems the experiments are planning a set of upgrades mainly concerning tracking and trigger systems, some of which have to be operative by 2018 (Phase-1 upgrades) and are well established (Technical Design Report are in preparation). Taking as a reference the cost of the construction of the current detectors the Phase-1 upgrades will represent a fraction of about 10-15%. The upgrades needed for phase-2 (HL-LHC) are more demanding, as both experiments are planning to replace the tracking systems (Technical Proposals are on the way) which by that time will be exhausted by many years of irradiation and evaluating possible longevity problems of the whole system. Roughly the phase-2 upgrade of the experiments will require an investement of at least 50% in units of "cost of the present detectors".

Conclusions

The physics perspectives of the next LHC run with 300 fb^{-1} are of exceptional interest. A

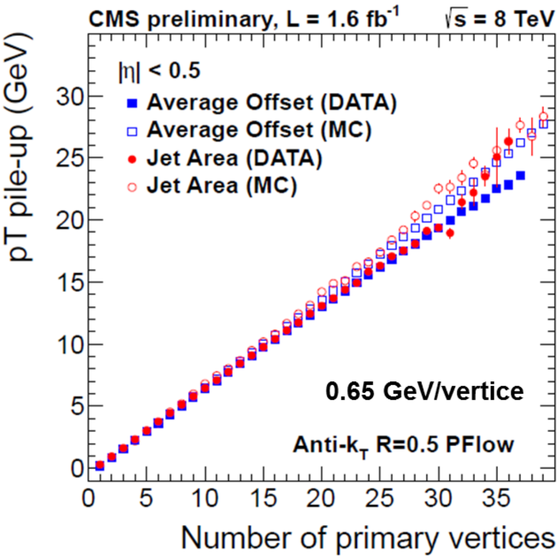

Figure 4: p_T offset for CMS central jets, average offset and jet area methods compared for data and MC as a function of the number of primary vertices.

final challenge to the most popular new physics theories is within the reach of ATLAS and CMS. A 5% – 15% precision is achievable in the comparison of Higgs couplings to SM expectations, and this is already sufficient to highlight possible contributions from new physics. Meanwhile a lot of thinking and a lot of R&D work is needed to design the next generation of these experiments.

References

[1] ATLAS Collaboration, The ATLAS experiment at the CERN LHC, J. Instrum., 3 S08003 (2008)

[2] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum 3 S08004 (2008)

[3] CMS Collaboration, Phys. Lett. B716 (2012)

[4] ATLAS Collaboration, Phys. Lett. B716 (2012)

[5] http://www.hep.phy.cam.ac.uk/ wjs/plots/plots.html

[6] ATLAS Collaboration, ATL-PHYS-PUB-2012-001; ATLAS Collaboration, ATL-PHYS-PUB-2012-004

[7] CMS Collaboration, CMS Note 2012/006

[8] CERN-ESG-005

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