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New ideas for measurements and searches at the HL-LHC

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Abstract

The High-Luminosity Large Hadron Collider (HL-LHC) will operate at unprecedented luminosity, with substantial data boosts enhancing the search for new physics and precision measurements. This paper explores advancements in detector technology, novel search strategies, and cutting-edge analysis techniques aimed at maximizing the HL-LHC's physics potential. We focus on the challenges of high pileup, precision measurements of Higgs boson properties, searches for physics beyond the Standard Model, and improvements in handling complex data with machine learning. Through these innovations, the HL-LHC will push the boundaries of our understanding in particle physics.

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New ideas for measurements and searches at the HL-LHC

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The High-Luminosity Large Hadron Collider (HL-LHC) will operate at unprecedented luminosity, with substantial data boosts enhancing the search for new physics and precision measurements. This paper explores advancements in detector technology, novel search strategies, and cutting-edge analysis techniques aimed at maximizing the HL-LHC's physics potential. We focus on the challenges of high pileup, precision measurements of Higgs boson properties, searches for physics beyond the Standard Model, and improvements in handling complex data with machine learning. Through these innovations, the HL-LHC will push the boundaries of our understanding in particle physics.

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1. Introduction

The High-Luminosity Large Hadron Collider (HL-LHC) is poised to operate at an unprecedented peak luminosity of $L = 7.5 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$. This enhancement in luminosity will provide a substantial increase in the number of collisions, allowing the ATLAS [1] and CMS [2] experiments to collect datasets of up to 3000 fb^{-1} over the HL-LHC's operational period. Similarly, LHCb [3] and ALICE [4] will take advantage of this high-intensity environment to conduct heavy-ion collisions with a focus on studying the quark-gluon plasma (QGP) state and other complex nuclear phenomena.

The anticipated boost in data volume presents both significant opportunities and challenges for particle physics research. A larger dataset enables measurements with unprecedented statistical precision, opening doors to refined explorations of the Standard Model (SM). These include precision measurements of particle couplings, decay rates, and interaction cross-sections. Furthermore, the expanded dataset enhances the potential to observe rare processes, such as the production and decay of exotic particles, which could offer hints of physics beyond the Standard Model (BSM).

To harness this high data rate, extensive upgrades to the LHC detectors have been undertaken. These upgrades are designed to maintain the quality of data collection in a high-luminosity environment with significant pileup, where multiple interactions per bunch crossing create a challenging background. New developments in detector technology, such as high-granularity tracking, improved calorimetry, and advanced timing capabilities, will be essential for distinguishing signal from background. Moreover, the use of sophisticated machine learning algorithms will enable efficient real-time data processing and event selection, allowing physicists to identify and analyze rare events with increased sensitivity.

Overall, the upgrades at the HL-LHC will vastly extend the reach of current searches for new physics, while also enabling a range of innovative measurement techniques for both SM precision tests and BSM searches. This combination of advanced hardware and refined analytical methods will pave the way for groundbreaking discoveries and a deeper understanding of fundamental physics [6].

2. Challenges in High-Luminosity Operations and Upgrades

With the HL-LHC's high luminosity, collision rates will exceed current detector capacities, increasing pileup to as many as 200 interactions per bunch crossing. This pileup intensifies background noise, complicates particle identification, and impacts trigger efficiency. Enhancements in timing and spatial resolution of detectors, alongside new hardware and software trigger designs, will mitigate these challenges [6]. Advanced tracking detectors, calorimeters, and timing detectors are essential to maintain performance. For instance, CMS and ATLAS are introducing high-granularity timing detectors (HGTDs) and MIP Timing Detectors (MTDs), which improve particle identification and significantly reduce pileup. LHCb and ALICE benefit from similar high-precision upgrades to achieve efficient particle tracking under HL conditions [5, 7].

3. Precision Measurements

Precision measurement of the Higgs boson's properties and other SM particles is a cornerstone of the HL-LHC physics program. Such measurements will enable rigorous tests of the SM's self-consistency, probing the Higgs boson's role in electroweak symmetry breaking with unprecedented accuracy. With the vast dataset expected from the HL-LHC, researchers aim to achieve high precision in measuring Higgs couplings to other particles, the branching ratios of various decay channels, and the rates of rare decay modes. These precision studies will shed light on the fundamental mechanisms governing particle masses and interactions, providing potential avenues for new physics insights. As shown in Fig. 1, a key focus within this program is the measurement of rare decays like $H \to \mu\mu$ and $H \to Z\gamma$, which probe the Yukawa couplings of the Higgs boson to second-generation fermions. Since these processes have low branching fractions, they have remained elusive in lower-luminosity data. However, the larger dataset and upgraded detector capabilities at the HL-LHC make it possible to reach the sensitivity required for observing and analyzing these rare decays. Insights gained from such measurements will deepen our understanding of the SM's structure, specifically in regard to flavor physics and the universality of Yukawa couplings across fermion generations.

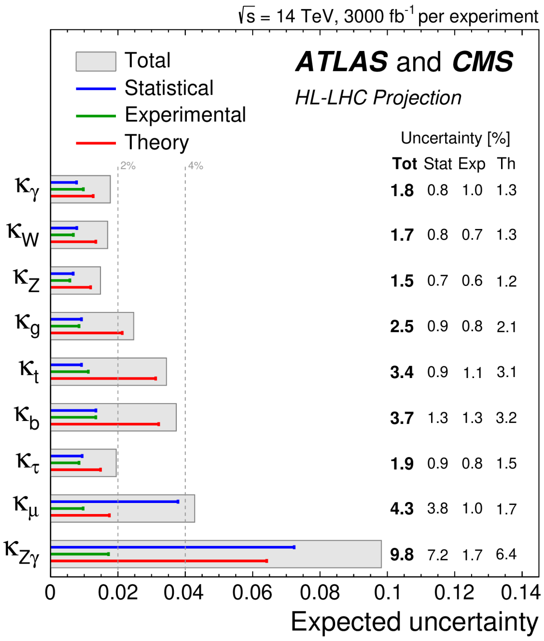

Figure 1: Summary plots showing the total expected uncertainties on the coupling modifier parameters (k), for the combination of ATLAS and CMS extrapolations at HL-LHC [9].

One of the most challenging but significant objectives at the HL-LHC is the direct measurement of the decay $H \to c\bar{c}$, which would offer a first look at the Higgs coupling to charm quarks. This process is exceptionally difficult to observe due to its low branching ratio and the overwhelming QCD background from processes producing charm jets. To address these challenges, researchers are developing advanced multivariate analysis techniques, such as machine learning classifiers and boosted decision trees, to isolate the $H \to c\bar{c}$ signal from the QCD background. Additionally,

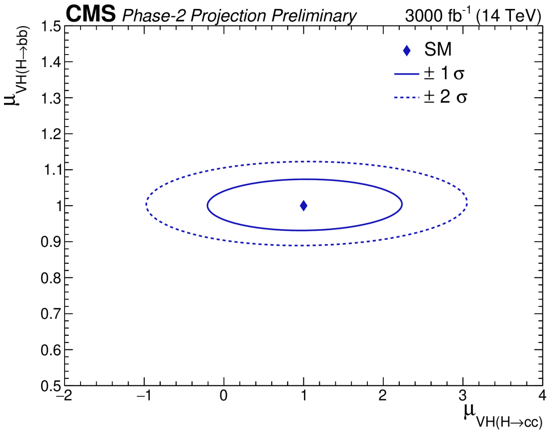

Figure 2: Profile likelihood scans as a function of $\mu_{VH(H\to c\bar{c})}$ and $\mu_{VH(H\to b\bar{b})}$. The black marker shows the SM expected best fit point. The solid and dashed lines show the expected one and two standard deviation contours [9].

simultaneous measurement approaches are being used to enhance sensitivity by combining multiple channels and observables within a single analysis framework.

At the HL-LHC, the ATLAS experiment aims to achieve sensitivity close to 6.4 times the SM prediction for processes such as $VH, H \to c\bar{c}$, as shown in Fig. 2. This represents a significant improvement over Run 2 results and brings the community closer to a direct observation of this decay mode. Such progress would mark an important milestone in validating the SM's predictions for Yukawa couplings, particularly for the second-generation quarks, and could hint at deviations that may signal new physics. Overall, the HL-LHC's precision measurements of the Higgs boson promise to provide insights into the fundamental forces and particles that constitute our universe[10][8].

4. Searches for New Physics

The search for BSM physics at the HL-LHC is an essential component of the scientific program, as it seeks to explore phenomena that could potentially extend or replace the current understanding provided by the SM. The HL-LHC will be particularly well-suited for investigating a variety of BSM theories, including supersymmetry (SUSY), which proposes partner particles for all SM particles and could provide solutions to the hierarchy problem. Additionally, the search for dark matter candidates is a priority, as these particles might interact only weakly with ordinary matter, making them challenging to detect. Finally, the HL-LHC will enable searches for other exotic particles, such as heavy resonances, axion-like particles, and new gauge bosons, which could indicate new fundamental forces or particles.

To maximize sensitivity to these rare processes, the HL-LHC will employ advanced triggering systems and sophisticated machine learning (ML) algorithms. These ML techniques will play a crucial role in real-time data processing, helping to filter and prioritize events of interest from the enormous volume of collision data. By leveraging the power of machine learning, the HL-LHC

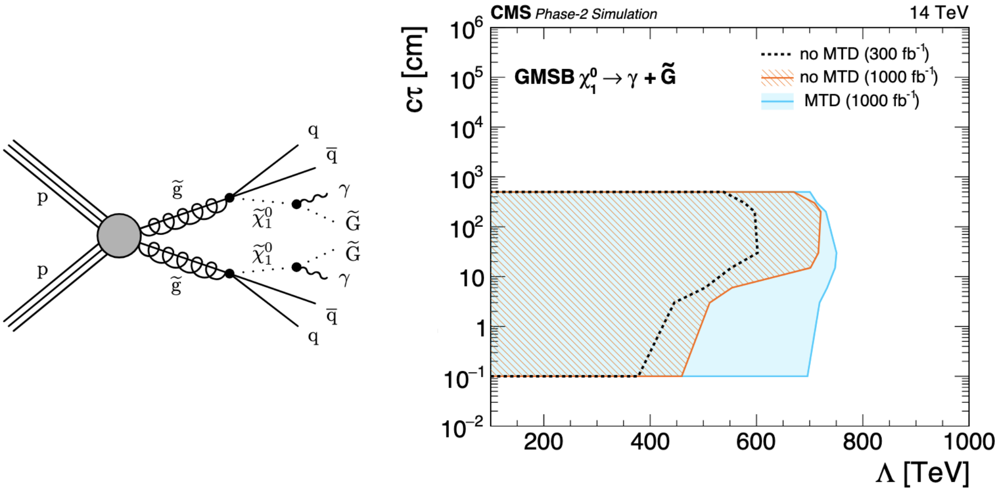

Figure 3: Left: Diagrams for a SUSY process that results in a diphoton final state through gluino production at the LHC. Right: Sensitivity to displaced neutralinos signals expressed in terms of neutralino lifetimes for 180 and 30 ps timing detector resolution, corresponding to the CMS Phase-2 detector with photon timing without MTD and with MTD, respectively [5].

will be able to improve the efficiency and accuracy of BSM searches, increasing the likelihood of identifying subtle signals that might otherwise be obscured by background noise [11].

Among the most intriguing BSM targets are new massive resonances decaying into Higgs boson pairs or long-lived particles (LLPs) decaying within the detector volume. Such LLPs, predicted by many BSM models, could have lifetimes long enough to travel significant distances before decaying, often producing unique signatures like displaced vertices or delayed photon signals. CMS's MTD and ATLAS's HGTD are pivotal in detecting these signatures. The high precision timing capabilities of the MTD and HGTD will allow for example for the identification of delayed photon events, a key signature of LLPs, by measuring the arrival time of photons with high accuracy, as shown for example in Fig. 3. These detectors also enhance the spatial resolution for rare decay products, enabling the HL-LHC experiments to distinguish between prompt and delayed signals. By providing these advanced detection capabilities, CMS and ATLAS are significantly improving their ability to explore new physics scenarios involving LLPs and other BSM phenomena [5].

5. Heavy Ion Physics and Rare Processes

The ALICE and LHCb experiments will play a critical role in exploring heavy-ion collisions at the HL-LHC, focusing on the study of the quark-gluon plasma (QGP) state and on precision measurements in rare flavor physics processes. These measurements will address crucial questions related to CP violation, flavor anomalies, and potential BSM physics by analyzing decays and interactions involving heavy-flavor hadrons, such as *b* and *c* quarks. The unprecedented luminosity and upgraded detectors at the HL-LHC will significantly increase the sensitivity to rare decay modes and flavor-changing neutral currents, enabling more accurate tests of theoretical predictions [12].

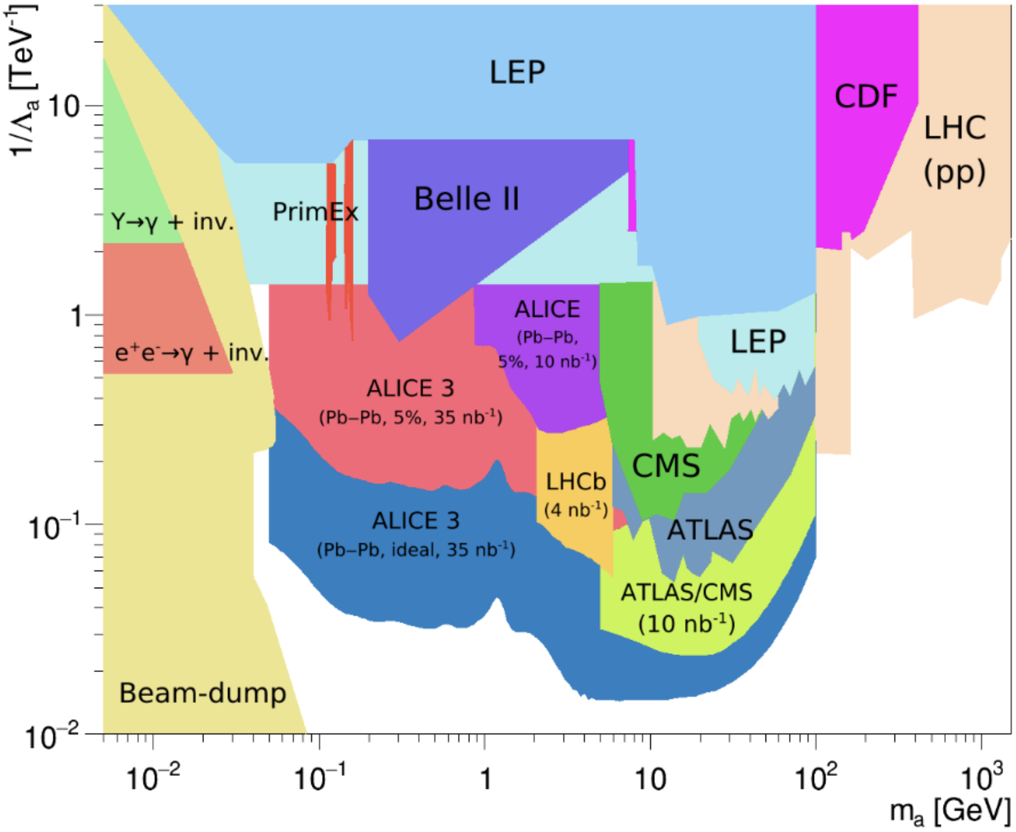

Figure 4: Bounds in the mass vs couplings plane from existing and future ALP searches [13].

A major component of this program is the ALICE-3 detector, which has been specifically designed to access low invariant masses in ultra-peripheral collisions (UPCs). This capability will allow ALICE-3 to probe processes sensitive to the muon anomalous magnetic moment, $g-2$, with unprecedented precision. By measuring light-by-light scattering and exploring potential contributions from axion-like particles (ALPs), as shown in Fig. 4, ALICE-3 is poised to make substantial contributions to precision physics. These results will complement efforts by other experiments to resolve the existing discrepancy in $g-2$, providing a comprehensive approach to understanding both SM and BSM effects in muon interactions [13].

6. Conclusion

HL-LHC will revolutionize particle physics with vast datasets, enabling precise SM tests and potentially discovering new physics. Detector upgrades, innovative search strategies, and advanced analysis techniques will be instrumental in addressing the challenges of high-luminosity conditions and maximizing the scientific output of the HL-LHC program.

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