Highlights in High-Energy Physics
https://www.sciltp.com/journals/hihep

Review

Precision Physics in the Era of (HL)LHC

Maurizio Pierini

The European Organization for Nuclear Research (CERN), 1217 Geneva, Switzerland; maurizio.pierini@cern.ch

How To Cite: Pierini, M. Precision physics in the era of (HL)LHC. *Highlights in High-Energy Physics* **2025**, *1*(1), 11. https://doi.org/10.53941/hihep.2025.100011.

Received: 5 April 2025
Revised: 20 June 2025
Accepted: 28 June 2025
Published: 30 June 2025

Abstract: The LHC was conceived as the ultimate discovery machine, designed mainly to find the Higgs boson and extensively search for SUSY and its alternatives at the electroweak (EW) energy scale. After a decade of operation, thanks to improved detector performance and advanced algorithms, the LHC experiments entered a precision era, surpassing LEP and Tevatron in many areas. Innovations such as deep learning and new data-taking methods have further extended their reach, beyond assumed limitations such as the trigger bandwidth. The luminosity upgrade of LHC, HL-LHC, promises even greater precision with upgraded detectors. The LHC experiments will remain leading in high-energy physics for the foreseeable future, leaving a lasting impact on various fronts.

Keywords: hadron collider physics; new physics searches; higgs boson

1. The Initial Mission

Our modern understanding of high energy physics before the Large Hadron Collider (LHC) has long rested on two central theoretical pillars: the Higgs mechanism for EW symmetry breaking and the expectation of EW-scale supersymmetry (SUSY) as a natural solution to stabilize the Higgs vacuum expectation value. On the experimental side, progress has been driven along two major fronts: precision measurements at e^+e^- colliders to indirectly probe signs of new physics, and direct searches for new phenomena at hadron colliders.

There have been notable exceptions that blurred the line between these approaches, such as EW SUSY searches at LEP and the precise measurement of the W boson mass at the Tevatron. However, it was the construction of the Large Hadron Collider (LHC) that marked a transformative step forward. Designed as the ultimate discovery machine, the LHC exceeded expectations early in its run. ATLAS and CMS discovered the Higgs boson [1,2] sooner than anticipated—with only about half the design energy and a fraction of the projected dataset. Furthermore, large portions of the EW-scale natural SUSY parameter space have been excluded. In particular, gluino searches have ruled out all models in which the gluino is accessible at LHC energies, and even when the gluino is assumed to decouple, most of the viable SUSY parameter space remains tightly constrained.

A key strength of the LHC lay in its unprecedented collision energy and luminosity, enabling the collection of enormous datasets. This, however, introduced significant computing and data handling challenges, addressed by novel High-Level Trigger systems and the globally distributed LHC Computing Grid. The LHC environment also posed harsh experimental conditions, characterized by high particle multiplicity and event pileup. Remarkably, many of these initially daunting challenges are now considered routine, thanks to substantial progress in detector performance and analysis techniques. The LHC experiments are then capable to still deliver outstanding results, having transitioned into a new era of precision physics, something that was far from obvious when the LHC started.

2. The Rise in Precision

The transition of the LHC from a discovery machine to a precision instrument has been driven by two complementary developments: improved data quality and access to increasingly larger datasets in addition to high performance detectors. Together, these advancements have enabled a new class of precision measurements that were previously beyond reach.

The effort to achieve the ambitious goals of the LHC program, along with the extensive exploitation of Run 2 data, led to numerous experimental breakthroughs. Among these are advanced event processing techniques such as sophisticated pileup subtraction schemes, and enhanced reconstruction algorithms including state-of-the-art jet tagging methods. Since around 2015, the adoption of deep learning algorithms has significantly accelerated progress in many of these areas. These methods have been deployed across a wide range of tasks, from object identification to regression and classification problems central to event reconstruction.

These developments, shown in Figure 1, allowed physicists to extract precise measurements from increasingly complex data. This has paved the way for the LHC's growing role in the domain of precision physics.

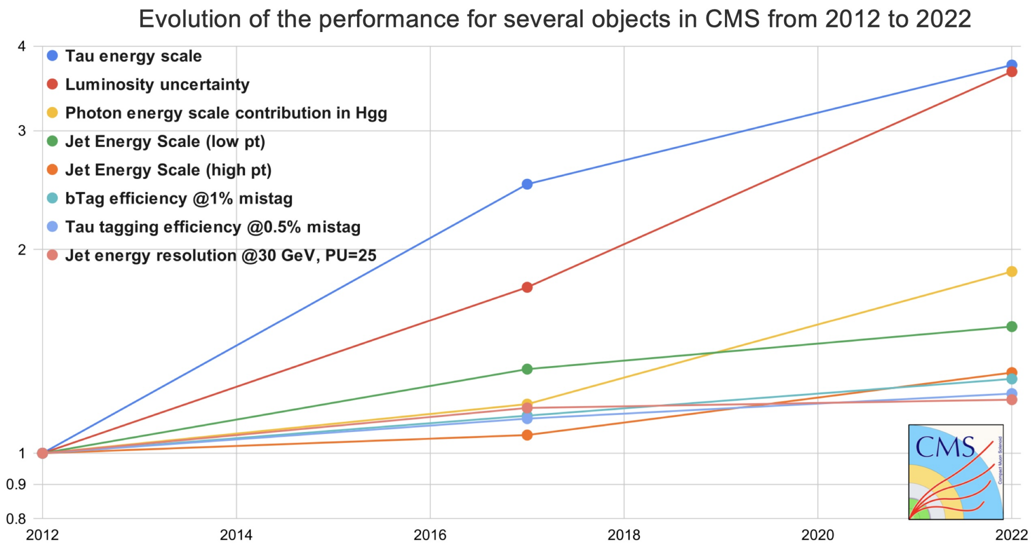

Figure 1. Evolution of experimental performance vs. time for the CMS experiment, quantified quoting the ratio of the efficiency or of the inverse of the uncertainty over the corresponding 2012 value, for various inputs to physics analyses. Plot extracted from Ref. [3] .

The LHC has consistently delivered more collisions than the experiments were originally designed to process in real-time. By design, this should have been a problem: traditionally, detectors were configured to record only a subset of "interesting" events, constrained by bandwidth and computing limits. To overcome this bottleneck, LHC experiments began breaking this paradigm as early as Run 1, turning the problem into an opportunity. One notable strategy is the use of parking [4] (knows in ATLAS as delayed reconstruction), wherein more events than can be promptly processed are recorded to tape and analyzed later, typically during accelerator shutdowns when computing resources are more readily available. Another complementary approach is the use of trigger-level reconstruction for physics analysis. The strategy consists in maximizing the number of triggered events by reducing the event data format to the minimum required to perform physics studies (as opposed to store the whole event in so-called RAW format). This approach opens new frontiers for both discovery and precision measurements without exceeding real-time processing limits. This approach was pioneered by CMS already in Run 1 with the introduction of the so-called data scouting stream, and since Run 2 it is exploited also in LHCb's turbo stream [5] and ATLAS' trigger-level analyses [6].

Machine learning (ML), particularly deep learning (DL) techniques, has played a transformative role in enhancing the sensitivity of the LHC experiments beyond initial expectations. One notable advancement has been the development of novel DL-based taggers, which have obtained improved tagging capabilities on traditional tasks such as b-jet tagging (see Figure 2) and extended the reach of experiments to probe previously unexplored topologies, such as c, bb, and cc jets. These advances have enabled incredible progress in the study of Higgs physics, as discussed in Section 3. In particular, the application of DL to boosted topologies has been instrumental in analyzing events with high transverse momentum, a challenging regime for standard reconstruction techniques [7,8]. The study of resolved topologies, which involve lower momentum objects and more complex event structures, have also seen improvements due to better identification of b-jets [9,10] and hadronic tau decays [11,12]. These developments have collectively led to an unprecedented level of precision in measurements.

In addition, the use of ML algorithms created unexpected opportunities. For instance, CMS managed to compensate for the absence of a dedicated particle identification (PID) for flavor physics system with cutting-edge DL techniques, developing the most accurate b-flavor tagger at hadron colliders, exploiting both same-side and opposite-side topologies in dedicated binary classifiers based on DeepSets, an architecture designed to handle sets of particles and their relationships. The b-flavor tagging power was reached an impressive 5.6%, increased by a factor of four over previous methods.

These are only a few examples to highlight the indispensable role of ML in pushing the boundaries of precision physics at the LHC, opening new avenues for exploring both Standard Model (SM) processes and potential new physics.

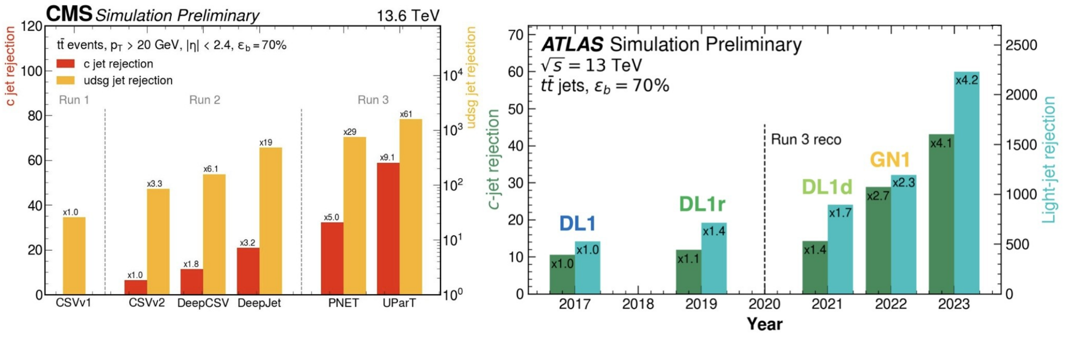

Figure 2. Evolution of b-jet tagging efficiency for CMS (**left**) and ATLAS (**right**), from the Run-1 algorithms to the DL architectures.

3. Physics Highlights from LHC Run 1 and Run 2

The precision in Higgs boson coupling measurements has seen remarkable progress in Run 2, with current uncertainties already below 10% for most couplings—despite exploiting only about 5% of the total dataset expected from the HL-LHC program. This rapid advancement reflects not only the quantity of data collected but also significant improvements in analysis techniques. These innovations have extended the sensitivity of the LHC experiments well beyond initial expectations, enabling, for instance, the probing of second-generation fermions through decays such as $H \to \mu\mu$ and $H \to c\bar{c}$ [13,14] (see the top row of Figure 3).

The search for double Higgs boson (HH) production has made remarkable progress since the first round of analyses. Initially a highly challenging measurement, recent developments have significantly improved sensitivity (see section 2). By the end of Run 2, the precision achieved in HH searches matched the expectations originally set for an integrated luminosity of 1000 fb^{-1} at the HL-LHC [15], highlighting the power of experimental innovation and analysis improvements in pushing the limits of what is experimentally achievable (see the bottom row of Figure 3).

The status of the global EW fit as of 2023 reflects a landscape shaped by EW precision observables (EWPO) measured at lepton colliders, complemented increasingly by contributions from hadron colliders. While hadron colliders have historically played a secondary role in measuring EWPO, the high precision reached by the LHC experiments has inverted this tendency. For instance, CMS recently measured the branching ratios of hadronic W decays [16], outperforming LEP-era results and marking a clear step forward in the precision EW program at hadron colliders.

A recent full Run 2 (2015-2018) measurement of the effective EW mixing angle ($\sin^2\theta_{\text{eff}}$) was performed by the CMS Collaboration using the forward-backward asymmetry (A_{FB}) in Drell–Yan events [17]. This result achieves a precision greater than that of the LEP combination for the same quantity and is now comparable to the most precise determinations from LEP A^b_{FB} and SLD A_{LR}. The extracted value, $\sin^2\theta_{\text{eff}} = 0.23157 \pm 0.00010$ (stat) $\pm$ 0.00015 (syst)± 0.00009 (theory)± 0.00027 (PDF), sits between the LEP and SLD measurements and is in excellent agreement with the SM prediction. This result contributes valuable insight into a long-standing tension among EW precision measurements and showcases the growing impact of hadron collider data in this domain.

Last summer, LHCb released its own precise determination of $\sin^2\theta_{\text{eff}}$, also obtained through a measurement of A_{FB} in Drell–Yan events [18]. The result, $\sin^2\theta_{\text{eff}} = 0.23152 \pm 0.00044$ (stat)± 0.00005 (syst)± 0.00022 (theory), is remarkably competitive despite a significantly larger statistical uncertainty (due to the lower integrated luminosity at LHCb, owing to the beam separation necessary to keep pileup under control). This result stands out because of its notably smaller theoretical uncertainty—especially with respect to parton distribution functions (PDFs)—thanks to the unique forward phase space probed by the LHCb detector. This complementary approach enhances the global picture of EW precision and underscores the value of diverse experimental environments at the LHC.

In addition, hadron colliders traditionally provide unique inputs to the EW fit, such as the W boson mass (m_W), the top quark mass (m_t), and the Higgs boson mass (m_H). However, these contributions have not come without controversy. Notable tensions include discrepancies between m_t measurements from the Tevatron and the LHC, and the striking difference between the CDF measurement of m_W and the global average from other experiments.

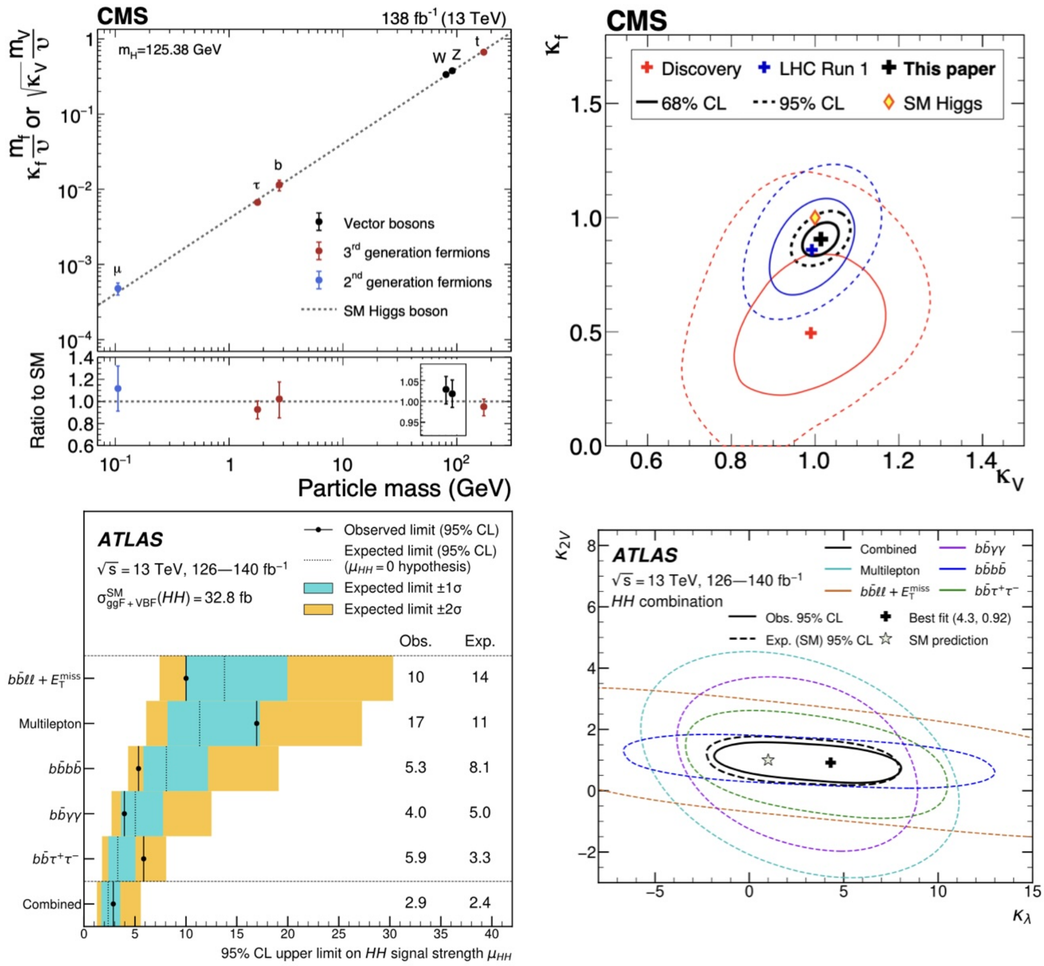

Figure 3. (**Top-left**): CMS measurements of the Higgs couplings to bosons and fermions as a quadratic and linear function of the mass, respectively. (**Top-right**): extraction of the universal fermion and boson coupling modifiers from a combined fit to the CMS coupling measurements. (**Bottom-left**): 95% CL upper limit on the HH signal strength (normalized to the SM prediction) from ATLAS searches to various final states. (**Bottom-right**): Two-dimensional bounds on κ_{2V} and κ_λ coupling modifiers, obtained from ATLAS HH searches.

The precision reached by the LHC experiments has been crucial to solve these issues. ATLAS utilized the low-pileup dataset collected in Run 1 (2010–2012) to perform a high-precision measurement of both m_W and the W width [19]. The analysis leveraged decays to both muons and electrons, extracting information from the transverse mass (m_T) and lepton transverse momentum (p_T^ℓ) distributions to maximize sensitivity. More recently, CMS released the most precise determination of m_W at the LHC to date [20]. This measurement was based on approximately half of the 2016 dataset and focused exclusively on the muon decay channel, using the p_T^μ distribution to minimize sensitivity to pileup effects. In addition to the main result, CMS provided a complementary analysis using relaxed theoretical assumptions, which yielded a consistent outcome. Overall, the CMS measurement is in agreement with previous LHC results and aligns well with SM predictions, reinforcing the robustness of the LHC's EW precision program.

In parallel, a comprehensive program exists to determine m_t, employing multiple techniques across different final states (leptonic and hadronic), production processes (cross-section based vs. kinematic reconstructions), and event topologies (resolved vs. boosted) [21]. The most precise determination to date comes from a combined Run 1 ATLAS and CMS analysis [22]. Run 2 measurements, enhanced by modern statistical techniques such as full profiling of systematics (similar to the Higgs discovery strategy), have independently achieved comparable precision.

At the LHC, m_H has been precisely measured using the two golden decay channels: $H \to \gamma\gamma$, which exploits the excellent electromagnetic calorimeter resolutions, and $H \to ZZ^* \to 4\ell$, which leverages the high-precision tracking system. ATLAS has achieved the most precise determination on m_H, combining the two channels ($m_H = 125.11 \pm 0.11$ GeV) [23]. CMS has delivered the best single-channel measurement so far

($m_H = 125.04 \pm 0.12$ GeV) [24].

Besides providing valuable inputs to the EW fit, these measurements give a unique hint on the history of our Universe [25]. Assuming the validity of the SM up to the Planck scale, the values of m_H and m_t are crucial inputs for determining the stability of the EW vacuum. Current best-fit values for m_H and m_t place the vacuum at the boundary between stability and metastability [26]. However, a definitive statement requires a further improvement in precision, both on the input masses and on the strong coupling constant, α_s.

The knowledge of α_s has significantly improved at the LHC. CMS recently performed a combined analysis of inclusive jet production across four center-of-mass energies—2.76, 7, 8, and 13 TeV—yielding the most precise determination of α_s from jet events to date. The analysis was carried out at next-to-next-to-leading order (NNLO) in perturbative QCD and simultaneously constrained the parton distribution functions (PDFs) in situ, further reducing systematic uncertainties [27]. Despite this achievement, the ultimate precision still falls short of that obtained from measurements based on the Z boson transverse momentum (p_T^Z), which are less sensitive to jet energy scale uncertainties. In this context, ATLAS has released the most precise determination of α_s at the LHC, based on the p_T^Z spectrum [28]. While discussions are ongoing regarding whether this measurement qualifies as N^{3}LO, the improvement in experimental precision is unquestionable and marks a significant leap forward in the determination of one of the fundamental parameters of the SM.

One of the most remarkable achievements in precision flavor physics has come from LHCb's improved determination of the CKM unitarity triangle (UT) angle γ [29]. Historically, γ was the least precisely known angle of the UT, but it is now measured with an uncertainty of only a few degrees. This represents a significant step forward in our understanding of the CKM matrix, as γ is determined from tree-level processes and is therefore largely insensitive to potential new physics contributions. As such, it provides a clean SM reference point for testing consistency with indirect measurements affected by possible beyond-the-SM (BSM) effects. With this improvement, the precision of tree-level determinations of the CKM parameters has reached a level comparable to that of the full pre-LHCb global fits. For instance, the tree-level analysis now yields $|\bar{\rho}| = 0.158 \pm 0.026$ and $|\bar{\eta}| = 0.358 \pm 0.012$ [30], illustrating how the CKM matrix can now be reliably determined from purely SM-safe observables. In addition, further precision measurements such as CP violation in neutral meson mixing provide stringent bounds on potential new physics amplitudes in $|\Delta F| = 2$ processes, further constraining the BSM landscape.

CP violation measurements in neutral meson mixing have now reached an astonishing level of precision, with the three main LHC experiments—ATLAS, CMS, and LHCb—contributing results at comparable precision. The field has now entered the regime of $\mathcal{O}(10^{-3})$ sensitivity, enabling clear evidence of CP violation in the B_s system [31].

The first phase of the LHC physics program is nearing completion. By the end of 2025, both ATLAS and CMS aim to have collected over 300 fb^{-1} of integrated luminosity EACH, combining Run 2 and Run 3 (2022–2026) data. This milestone is expected to be achieved within the current year, marking a successful conclusion to the initial exploration and precision program of the LHC.

4. A Look into the Future

Preparations are already well underway for the HL-LHC phase. The upgraded machine, together with substantially enhanced detectors, is targeted to deliver an integrated luminosity of 3000 fb^{-1} by 2041. In the meantime, both experiments are already pushing their current detectors far beyond their original design. For instance, CMS has operated stably while recording events with up to 63 simultaneous proton-proton collisions—2.5 times its original design tolerance and 45% of what is expected during HL-LHC conditions. Data-taking rates have also ramped up significantly, with CMS reaching 7 kHz, which corresponds to 70% of HL-LHC targets and nearly 7 times the standard operational rate during Run 2. In practice, many HL-LHC challenges—particularly related to pileup—are already being addressed during Run 3 operations.

Looking ahead to Run 4 and beyond, further increases in data throughput will come at the cost of even more intense pileup environments, potentially reaching an average of 140 simultaneous collisions per bunch crossing. This is substantially larger than the original LHC design, which anticipated tolerances around 20 pileup events. However, both ATLAS and CMS have already demonstrated their ability to handle pileup levels around 60 in routine operations, thanks to rapid algorithmic developments and advanced reconstruction techniques. In addition, the upcoming detector upgrades are designed precisely with these challenges in mind. Key improvements include:

- Larger angular coverage, especially in tracking detectors, enabling robust reconstruction in the forward regions.
- Higher granularity in calorimeters and trackers, facilitating a better tracking and vertexing accuracy, an improved pileup suppression, and more precise jet and lepton identification.

- Precision timing layers, providing time-of-flight information for vertex separation and PID, crucial in mitigating pileup effects and for flavor and heavy ion physics.
- Particle-flow algorithms extended to the forward region, enhancing object reconstruction and energy resolution.
- Hardware-based *Track Triggers*, allowing tracking information to be used directly at the earliest stages of the trigger system.

Thanks to these improvements, the HL-LHC era will not only deliver more data, but also higher quality data, enabling continued exploration of the SM and extending our reach into potential new physics territories.

Currently, ATLAS and CMS work along two independent but complementary fronts to search for new physics at the LHC. The first, *direct searches for new physics*, involves assuming a specific new physics model and searching for it through hypothesis testing. This approach relies heavily on data-driven models of background processes, using techniques such as template fits for bump hunting, where an excess in the invariant mass spectrum would point to new particles or resonances. These searches are highly model-dependent, assuming particular signatures of new physics such as new particles or interactions, and they provide direct evidence or exclusion of these models.

The second front, *indirect bounds from measurements*, focuses on precise measurements of SM processes. By measuring absolute and differential cross-sections for SM processes and comparing them to theoretical predictions, experiments can constrain new physics models by ensuring that no significant deviations from the SM predictions are observed. This is where the growing interest in Effective Field Theory (EFT) plays a crucial role. EFT allows for a systematic framework to encode potential new physics effects as higher-dimensional operators in the Lagrangian, offering a way to probe deviations from the SM in a model-independent manner. In this context, EFT analyses effectively combine both direct searches and precision measurements, as they search for discrepancies between the data and the SM predictions that might signal new physics beyond the SM. A key challenge in this area is minimizing systematic uncertainties, especially those arising from theoretical uncertainties in the calculation of SM processes.

The increasing interest in EFT and its application to high-energy processes has blurred the lines between direct searches and indirect measurements. For example, searches for large extra dimensions or broad resonances can be interpreted within the EFT framework. Similarly, high-precision measurements of differential cross-sections can provide sensitivity to new physics in a similar way to direct searches for new particles. On the timescale of the HL-LHC, the direct and indirect search programs will likely merge, with EFT analyses becoming a central tool for interpreting deviations from the SM across a wide range of processes. Recasting studies [32]—where the same experimental data is analyzed under different new physics scenarios—will be crucial in understanding the full implications of the data.

Looking ahead, the Higgs factory will improve precision by a factor of 2–3 for coupling measurements involving the W, Z, and g bosons, with a particular focus on third-generation quarks. However, it is important to note that the Higgs factory will not improve LHC measurements for rare decays, as these are primarily loop-mediated processes. The LHC will remain the primary probe for rare Higgs decays and serve as an indirect tool for new physics searches. Assuming no other hadron collider before 2070, the LHC will remain the only machine capable of probing this and other crucial aspects of SM physics at the highest energies. Additionally, the study of Higgs boson pair (HH) production and its implication on the shape of the Higgs potential will be even more central, providing a unique opportunity to probe new physics scenarios related to baryogenesis and other aspects of the physics of the early universe [33]. The top quark Yukawa coupling, which can be probed in several processes (such as $t\bar{t}H$ production), is another important target for precision measurements. The LHC will also continue to offer crucial insights into multi-top production, vector boson scattering (VBS), and other precision measurements of SM couplings. Before the advent of a dedicated Higgs factory, the LHC is poised to deliver precise measurements of these couplings [33].

Historically, new physics searches were focused on processes with small SM amplitudes. With the HL-LHC, however, we expect to see an unprecedented improvement in precision, particularly in the determination of the Unitarity Triangle (UT) parameters, with LHCb's precision step-up pushing the UT analysis below 1% precision [34]. This will set a new milestone for the SM and provide stringent constraints for beyond-the-SM model building. Further efforts from CMS to contribute to this area are expected, though the long-term implications of new parking strategies are still under active assessment.

5. Conclusions

The LHC began its journey as the ultimate discovery machine, tasked with probing the deepest open questions of particle physics. Its early successes, such as the landmark discovery of the Higgs boson, marked a monumental achievement for the SM. The LHC also provided a unique platform for exploring the potential existence of new physics, including the search for supersymmetry (SUSY) and its various alternatives. These endeavors demonstrated the LHC's unparalleled ability to push the boundaries of our knowledge, both through direct searches and precision measurements.

As the LHC entered its precision era, significant improvements in detector technology and novel computational algorithms, including advances in Deep Learning, have enabled unprecedented levels of precision in data analysis. With the advent of new data-taking strategies, such as scouting and parking, the experiments could maximize their reach and overcome challenges related to the immense data volumes. The combination of these innovations has allowed LHC experiments to surpass the precision of previous machines like LEP and Tevatron on many fronts, setting the stage for even more refined tests of the SM.

Looking toward the future, the upcoming HL-LHC will further enhance precision through new detector capabilities, allowing the experiments to continue to explore fundamental questions such as the Higgs potential and vacuum stability. With the HL-LHC, the ATLAS and CMS detectors will be equipped with new capabilities, enabling them to remain the leader in high-energy physics experiments for the foreseeable future, maintaining an unchallenged position until the next major collider. The legacy of the LHC, both in terms of its direct contributions to understanding particle physics and its critical role in shaping future collider experiments, will leave an enduring mark on the field.

Acknowledgments

I would like to thank the organizers of the "Rise of Particle Physics" workshop for the opportunity to speak at such an engaging event. It was an honor to share the stage with some of the pioneers of the SM, whose remarkable contributions to particle physics I studied in the very same place where this workshop was held.

Conflicts of Interest

The author declares no conflict of interest.

References

1. ATLAS Collaboration. Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC. *Phys. Lett. B* **2012**, *716*, 1–29.
2. CMS Collaboration. Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC. *Phys. Lett. B* **2012**, *716*, 30–61.
3. Gianotti, F. Talk at ICHEP 2022, Bologna, Italy. Available online: https://agenda.infn.it/event/28874/contributions/171915/attachments/95072/130540/ICHEP-Higgs-2022-Fabiola.pdf (accessed on 30 March 2025).
4. CMS Collaboration. Enriching the physics program of the CMS experiment via data scouting and data parking. *Phys. Rep.* **2025**, *1115*, 678–772.
5. Aaij, R.; Benson, S.; Cian, M.D.; et al. A comprehensive real-time analysis model at the LHCb experiment. *J. Instrum.* **2019**, *14*, P04006.
6. Boveia, A.; ATLAS Collaboration. Trigger Level Analysis Technique in ATLAS for Run 2 and Beyond. 2019. Available online: https://cds.cern.ch/record/2703715 (accessed on 20 November 2024).
7. CMS Collaboration. *Performance of Heavy-Flavour Jet Identification in Boosted Topologies in Proton-Proton Collisions at* $\sqrt{s} = 13$ *TeV*; CMS-PAS-BTV-22-001; CERN: Geneva, Switzerland, 2023.
8. ATLAS Collaboration; CERN. ATL-PHYS-PUB-2023-021. 2023. Available online: https://cds.cern.ch/record/2866601 (accessed on 20 November 2024).
9. CMS Collaboration. Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV. *J. Instrum.* **2018**, *13*, P05011.
10. ATLAS Collaboration. ATLAS flavour-tagging algorithms for the LHC Run 2 *pp* collision dataset. *Eur. Phys. J. C* **2023**, *83*, 681.
11. CMS Collaboration. Identification of hadronic tau lepton decays using a deep neural network. *J. Instrum.* **2022**, *17*, P07023.
12. ATLAS Collaboration. *Identification of Hadronic Tau Lepton Decays Using Neural Networks in the ATLAS Experiment*; ATL-PHYS-PUB-2019-033; CERN: Geneva, Switzerland, 2019.
13. CMS Collaboration. A portrait of the Higgs boson by the CMS experiment ten years after the discovery. *Nature* **2022**, *607*, 60–68.
14. ATLAS Collaboration. A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery. *Nature* **2022**, *607*, 52–59.
15. ATLAS; CMS Collaborations; CERN. CMS-PAS-FTR-22-001. 2022. Available online: https://cds.cern.ch/record/2806962 (accessed on 20 November 2024).

16. CMS Collaboration. Measurement of the W boson decay branching fraction ratio $\mathcal{B}(\mathrm{W} \to cq)/\mathcal{B}(\mathrm{W} \to \mathrm{q}\bar{\mathrm{q}}')$ in proton-proton collisions at $\sqrt{s}$ = 13 TeV. *arXiv* **2024**, arXiv:2412.16296.
17. CMS Collaboration. Measurement of the Drell-Yan forward-backward asymmetry and of the effective leptonic weak mixing angle in proton-proton collisions at $\sqrt{s}$ = 13 TeV. *arXiv* **2024**, arXiv:2408.07622.
18. LHCb Collaboration. Measurement of the effective leptonic weak mixing angle. *J. High Energy Phys.* **2024**, *12*, 026.
19. ATLAS Collaboration. Measurement of the W-boson mass and width with the ATLAS detector using proton–proton collisions at $\sqrt{s}$ = 7 TeV. *Eur. Phys. J. C* **2024**, *84*, 1309.
20. CMS Collaboration. High-precision measurement of the W boson mass with the CMS experiment at the LHC. *arXiv* **2024**, arXiv:2412.13872.
21. CMS Collaboration. Review of top quark mass measurements in CMS. *Phys. Rep.* **2025**, *1115*, 116–218.
22. ATLAS; CMS Collaborations. Combination of inclusive top-quark pair production cross-section measurements using ATLAS and CMS data at $\sqrt{s}$ = 7 and 8 TeV. *J. High Energy Phys.* **2023**, *7*, 213.
23. ATLAS Collaboration. Combined Measurement of the Higgs Boson Mass from the and Decay Channels with the ATLAS Detector Using , 8, and 13 TeV Collision Data. *Phys. Rev. Lett.* **2023**, *131*, 251802.
24. CMS Collaboration. Measurement of the Higgs boson mass and width using the four-lepton final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV. *arXiv* **2024**, arXiv:2409.13663.
25. Espinosa, J.R.; Giudice, G.F.; Morgante, E.; et al. The cosmological Higgstory of the vacuum instability. *J. High Energy Phys.* **2015**, *9*, 174.
26. Hiller, G.; Höhne, T.; Litim, D.F.; et al. Vacuum stability in the Standard Model and beyond. *Phys. Rev. D* **2024**, *110*, 115017.
27. CMS Collaboration. Determination of the strong coupling and its running from measurements of inclusive jet production. *arXiv* **2024**, arXiv:2412.16665.
28. ATLAS Collaboration. A precise determination of the strong-coupling constant from the recoil of Z bosons with the ATLAS experiment at $\sqrt{s}$ = 8 TeV. *arXiv* **2023**, arXiv:2309.12986.
29. LHCb Collaboration. Simultaneous determination of CKM angle γ and charm mixing parameters. *J. High Energy Phys.* **2021**, *12*, 141,
30. UTfit Collaboration. New UTfit analysis of the unitarity triangle in the Cabibbo–Kobayashi–Maskawa scheme. *Rend. Lincei. Sci. Fis. Nat.* **2023**, *34*, 37–57.
31. CMS Collaboration. Evidence for CP violation and measurement of CP-violating parameters in $\mathrm{B_s^0} \to \mathrm{J}/\psi, \phi(1020)$ decays in pp collisions at $\sqrt{s}$ = 13 TeV. *arXiv* **2024**, arXiv:2412.19952.
32. Cranmer, K.; Yavin, I. RECAST—extending the impact of existing analyses. *J. High Energy Phys.* **2011**, *4*, 38.
33. ATLAS; CMS Collaborations. Highlights of the HL-LHC physics projections by ATLAS and CMS. *arXiv* **2025**, arXiv:2504.00672.
34. ATLAS; Belle II; CMS; et al. Projections for Key Measurements in Heavy Flavour Physics. *arXiv* **2025**, arXiv:2503.24346.