CMS Experiment - 2025-2027

Project Leader Mikko Voutilainen

The CMS Experiment project consists (April 2024) of one professor (M. Voutilainen), one Academy Fellow (H. Kirschenmann), one university researcher (S. Laurila, also CERN at 75%), three senior scientists (T. Lampén, K. Lassila-Perini (also Open Data project leader at 70%), S. Lehti (also Tier-2 project at 10%)), six adjoint scientists (J. Heikkilä, M. Kim, M. Kortelainen, L. Martikainen, J. Pekkanen, J. Tuominiemi), two post-docs (Nurfikri Norjoharuddeen, Ravindra Verma), five PhD students (P. Inkaew, M. Myllymäki, N. Toikka, B. Lehtelä, N. Mancilla), and six MSc students (M. Harkki, J. Mäki-Ikola, D. Näsman, R. Öhrnberg, E. Veikkola, A. Stadnitski). The university researcher position was opened with the help of our ERC grant, which also fully supports one post-doc, three PhDs and one MSc, in addition to contributing to the salaries of one professor and a senior scientist. The Research Council of Finland (RCF) supports the Academy Fellow position as well as one post-doc. Our team experienced a major growth spurt in January 2024, with the start of the university researcher, two post-doc and three new PhD positions, funded by the ERC and RCF. L. Martikainen graduated in late 2023 on inclusive jet measurement (now PD in Rome) and K. Kallonen graduated in March 2024 on new physics search and ML applications (now Apple in California).

The team will continue important detector responsibilities in jet corrections (Inkaew, Kirschenmann, Lehti, Myllymäki, Norjoharuddeen, Toikka, Verma, Voutilainen) and prompt calibration loop (Lampén). We also have a strong standing in trigger activities (L1 trigger / Laurila, JetMET HLT trigger / Lehti, EGamma HLT trigger / Verma). The main physics activities in Run 3 (2022-25) are new physics searches (charged Higgs bosons), exploration of electroweak symmetry breaking (vector boson scattering in all-hadronic decay mode and boosted Higgs boson) and precision measurements with jets (top quark mass and jet cross section), with common activities in Deep Learning (DL).

Our focus in the short term is on the completion of precision measurements on the full Run 2 data set of 138 fb^{-1}, as well as on-going calibration of the Run 3 data and publication of the Run 2 Legacy JEC paper. In the longer term, spanning the next project period of 2025-2027, we continue the development of novel precision calibration methods applicable in the high pileup conditions of the HL-LHC. In parallel, we work towards the first measurement of vector boson scattering in the all-hadronic mode with full Run 3 data and continue a new search for doubly-charged Higgs bosons. We are growing further in the direction of studies of electroweak symmetry breaking, towards di-Higgs, and expanding the work on real-time analysis by studying scouting both at L1 and HLT.

Detector operations

Jet energy corrections (JEC) are required by virtually every analysis performed at CMS, as jets are a key physics object in CMS. Our group is contributing a strong institutional commitment to direct analysis through multiple calibration channels (Z + jet, γ + jet, multijet, $t\underline{t}$), with a focus on the development of beyond state-of-the-art methods for the HL-LHC and for our physics analyses. This effort is further supported by the ERC-CoG JEC4HL-LHC (2022-2027) and RCF ForVVard (2023-2027).

Prompt calibration loop (PCL) is responsible for almost real-time, continuous calibration of various subdetectors. Our group participates in the operation and development of PCL, and will in particular capitalise on the synergy with the JEC effort to provide robust and precise calibrations to CMS end users in a timely fashion. We are preparing plans to integrate JEC into PCL for a daily calibration, dubbed JEC4Prompt. This would directly benefit the majority of physics analyses of CMS by making high-quality JEC calibration available already for the promptly reconstructed data, opening the door to publications quickly after data-taking. The first implementation and proof-of-concept of JEC prompt calibration will be carried out in 2024, benefiting from the on-going Run3. In 2025-2027, the calibration channels will be further refined to be fully prepared for the start of HL-LHC.

Triggers are are an essential part of the CMS data analysis chain and are composed of Level-1 trigger (L1T) providing throughput at 100 kHz with coarse trigger objects and High-Level Trigger (HLT) with reconstruction more similar to offline analysis and providing throughput at about 1000 Hz, limited by capacity for data storage and full offline reconstruction. These are complemented by advanced techniques such as scouting (HLT-only analysis) and parking (storing data to tape for later opportunistic offline reconstruction). We have leadership positions in L1T DPG, EGamma HLT, and JetMET HLT trigger groups that enable the Helsinki team to have an impact throughout the entire trigger chain.

Physics analysis

The three main physics efforts in the Helsinki group for the period 2025-2027 are charged Higgs boson searches (Lehti, Mäki-Ikola, Öhrnberg), exploration of electroweak symmetry breaking (Inkaew, Kirschenmann, Laurila, Norjoharuddeen, Toikka) and precision measurements with jets (Lehtelä, Mancilla, Myllymäki, Verma, Veikkola, Voutilainen). As a complementary cross-disciplinary area, we are investigating uses of Deep Learning for jet classification and energy regression (Inkaew, Kirschenmann, Laurila, Norjoharuddeen).

New physics searches effort includes two separate searches of charged Higgs bosons decaying into tau leptons ($H^+ \rightarrow \tau^+\nu$ and $H^{++} \rightarrow \tau^+\tau^+$). Helsinki has a local theory effort in beyond-the-standard-model (BSM) physics and a long experimental tradition of BSM Higgs searches with tau's since the start of the LHC era, which brings the two communities together with the CMS Forward Physics project.

Exploration of electroweak symmetry breaking focuses on two avenues: vector boson scattering for a process that would have violated unitarity in the absence of a Higgs boson, and on boosted Higgs bosons as a steppingstone to probing Higgs trilinear self-coupling through boosted Higgs boson pair production analyses. These are at the very forefront of the CMS physics programme towards the HL-LHC.

Precision measurements with jets effort focuses on two main themes: precise measurement of the top quark mass and measurements of the jet cross sections. Both top quark mass and strong coupling constant α_s (from jets) are key observables due to their direct link to the standard model vacuum metastability, which is the most enduring puzzle that followed from the precise Higgs boson mass measurements. Both measurements depend critically on achieving beyond state-of-the-art precision in JEC, which our group focuses on providing.

Deep learning

As part of the SMARTHEP ITN (Inkaew, Kirschenmann, Voutilainen), an important focus is on improving the jet-tagging capabilities of the scouting dataset. This work is profiting from Laurila's boosted Higgs boson expertise and will adopt and commission state-of-the-art taggers (ParticleNet/ParticleTransformer) to also be fully applicable to the scouting data stream, including retraining the taggers on the reduced event format.

The greatly improved capabilities of the Phase-II L1 trigger enable much more complex algorithms, including the application of jet tagging techniques similar to HLT and offline. Our group is actively engaging in this, profiting from the L1T coordination role and attracting new collaborators from the LUT department of computational engineering.

For the ERC and RFC projects, we will explore the use of ParticleNet and ParticleTransformer for simultaneous flavor tagging and energy regression as part of the JEC workflow to reduce dependence on jet flavor, reducing total uncertainty.

Preparing for HL-LHC exploitation

Phase-II upgrade of the CMS Detector during Long Shutdown 3 in 2026-2028 will provide CMS several new capabilities in Run 4 starting in 2029 that are a step change for electroweak symmetry breaking studies through VBS and VBF modes with jets in the forward region: High Granularity Calorimeter (HGCAL), MIP Timing Detector (MTD) and forward tracker extension. Together these provide unprecedented ability to remove pileup and identify jet types in the forward region, provided CMS reconstruction software can be updated to fully benefit from these upgrades to imaging calorimetry and particle timing.

We plan to expand upon our expertise in jet reconstruction and PF, taking a leading role in the renewal of Particle Flow algorithm for the HL-LHC, also exploring local synergies with *e.g.* Joosep Pata in the Tallinn group working on machine-learning based PF reconstruction (MLPF).

Detailed project plan for 2025-2027

Our international collaboration will proceed both directly at the analysis level (e.g. U. Cyprus for charged Higgs, U. Hamburg and DESY for top quark mass, inclusive jets and VBS) as well as through formal programs such as the EU SMARTHEP ITN and COMETA COST action, which enable us to effectively pursue new avenues in the future. We will continue to apply for additional funding from the Research Council of Finland for our research proposals on H^{++} and JEC4Prompt. The JEC at HL-LHC is funded through ERC-CoG (2022-2027) and the VBS activities through RCF project ForVVard (2023-2027).

While the exploitation of Run 3 data will be the main focus of the next HIP CMS experiment project period in 2025-2027, we are also planning further ahead for HL-LHC exploitation. We can profit significantly from the vastly expanded capabilities of the Level-1 Trigger (L1T), expanded tracking, High-granularity calorimeter (HGCAL), and Minimum ionizing particle Timing Detector (MTD). However, the exploitation needs dedicated effort and we will sketch ideas for development and initiatives after expanding on the concrete medium-term plans for the 2025-2027 period.

Jet corrections

Precise jet corrections are critical for precision jet measurements, in particular those of inclusive jet cross sections and top quark mass covered by HIP. Our JEC effort in 2024-2027 focuses on bringing the precision to 0.1% level with the full Run 2 Legacy data set of 138 fb^{-1} and documenting the results in a Run 2 Legacy JEC paper, as well as providing on-going calibrations for the Run 3 data in order to push improvements to low-level objects and detector simulation through the PdmV group. HIP will also lead the development of new methods to enable maintaining the precision at 0.1% level for Run 3 and the high-pileup environment of HL-LHC. The particular focus areas involve global fit of absolute jet energy corrections with Z + jet, γ + jet, multijet and $t\underline{t}$ ($W \rightarrow q\underline{q'}$) samples, uncertainties and their correlations, data-based jet flavor response corrections (b and gluon jets), and JEC parameterization through PF jet composition and precise models using hadron-level inputs. Our group covers all the main input channels: Z + jet (Lehti), γ + jet (Lehtelä), multijet (Mancilla) and $t\underline{t}$ (Myllymäki, Veikkola), including flavor-specific inputs for each. We have institutional responsibilities in JEC and convene the Physics Data sets and Monte Carlo Validation (PdmV, Voutilainen), JetMET trigger (Lehti) and EGamma trigger (Verma) groups. Our JEC research is supported by ERC-CoG JEC4HL-LHC and RCF ForVVard.

Prompt calibration loop

Calibration of CMS is a key element ensuring reliable and high-quality physics performance. With the automatically running Prompt Calibration Loop (PCL), up-to-the-minute calibration conditions are provided to Prompt reconstruction running almost online, just 48 hours after data-taking. HIP is participating in operation and development of PCL, paving the way to inclusion of daily jet corrections immediately after PCL calibrations, which would allow best possible corrections to be used already in the first reconstruction and provide fast feedback to detector groups. T. Lampén, co-convener of the Alignment, Calibration and DataBase (AlCaDB) group in 2019-21, is serving as CMS PCL Manager in 2021-25.

In 2024, the JEC residual calibration with respect to eta will be implemented with the dijet channel. This will serve as a proof-of-principle for JEC calibration and allows us to familiarize with the tools. Further calibration channels, *e.g.* γ + jet, will be implemented in 2025-2028 prior to the start of HL-LHC, and will include complementary novel techniques such as high-rate readout through so-called AlCaRaw paths.

Trigger

Events that are not triggered cannot be recovered for physics analysis or calibrations later, so stable and efficient triggers strategies are essential for the CMS physics programme. In Run 3, gains in integrated luminosity are modest compared to Run 2 so biggest advances in physics reach can be obtained with novel triggers. At the HL-LHC, huge data rates necessitate refined trigger strategies to optimally exploit the data. Given the opportunity, we are taking on trigger leadership roles on several fronts: S. Laurila as L2 convener of Level-1 trigger, S.Lehti and R. Verma as L3 conveners of JetMET and EGamma triggers, respectively.

The final years of LHC Run 3, 2024–2025, are paramount for the Helsinki group's contributions to the CMS trigger system. Vigilance in the performance monitoring and calibrations of both Level 1 Trigger (L1T) and High-Level Trigger (HLT) is imperative to ensure maximal trigger efficiency, optimizing the Run-3 legacy dataset for physics analyses and offline calibration studies. The late Run-3 period also presents an opportunity to implement and showcase innovative concepts envisioned for the Phase-2 trigger system. These include pioneering data-driven calibration workflows at the trigger level, anomaly detection algorithms integrated into the trigger system, and exploration of data scouting techniques at both HLT and L1T. Active engagement in L1 and HLT activities during this period also accumulates valuable experience within the team, which will be useful in navigating the commissioning period of the high-luminosity era (Run 4) effectively. In addition to successfully finalizing the Run-3 data-taking, during the 2024–2027 period, the Helsinki group will increase its role in the development and refinement of trigger algorithms and selection criteria tailored for the high-luminosity era, taking full advantage of the upgraded "Phase-2" CMS trigger system. Our leadership positions in L1T DPG, EGamma HLT, and JetMET HLT trigger groups enable the Helsinki team to have an impact throughout the entire trigger chain, with the goal of continuous optimization of triggering to effectively capture the physics processes of interest.

Some mid- to long-term plans include implementation of advanced pileup mitigation with PUPPI algorithm to HLT in Run 3, and then to L1T in Run 4 when more advanced tracking capabilities become available. Other critical improvements are bringing b-tagging to L1T for boosted Higgs bosons and online calibrations and flavor tagging to forward jet triggers for VBF and VBS analyses.

New physics searches

The search for singly-charged Higgs bosons ($H^+ \rightarrow \tau^+\nu$) continues in the full mass range beyond 3 TeV with full Run 3 data. The fully hadronic $\tau\nu$ final state is one of the potential discovery channels. The final state is sensitive to Type-2 two-Higgs doublet models, like Minimal Supersymmetric Standard Model, which is a special case of such models. Machine learning will be exploited in estimating the model independent limits on the production rate of charged Higgs bosons. The main contributors from the HIP group are Lehti and Mäki-Ikola.

The new search for doubly-charged Higgs bosons in the $\tau\tau$ final state ($H^{++} \rightarrow \tau^+\tau^+$) will continue by Lehti and Öhrnberg in 2023, in collaboration with the CMS Forward Physics and HIP phenomenology groups. If nature is left-right symmetric, it provides a natural mechanism to generate neutrino masses. In minimal left-right supersymmetric models the supersymmetry can live in a higher scale, explaining why it has not been seen in the LHC data. The LRSUSY model predicts an existence of several Higgs bosons, and it favors doubly charged Higgs bosons always in the lightest part of the particle spectrum. In this model the doubly charged Higgs boson decays to same-sign τ leptons with a high branching fraction.

Exploration of electroweak symmetry breaking

Vector boson scattering (VBS) effort focuses on the all-hadronic decay mode of the two W bosons, which provides unique full access to the W boson kinematics and a handle on the polarisation. This enables the detailed study of the electroweak symmetry breaking for a process that would have violated unitarity in the absence of a Higgs boson. The Run3 analysis will aim for the first measurement of VBS in the all-hadronic channel. This channel has the highest cross-section, but an experimentally challenging signature, which benefits significantly from the strong local jet expertise in the Helsinki group and the complementary activities around boosted Higgs bosons. The analysis benefits from new VBF triggers introduced for Run 3 and the dedicated VBF parking stream, both expanding the phase space of the analysis towards lower energies.

In the absence of evidence of BSM physics from direct searches, the study of vector boson scattering (VBS) has attracted a lot of interest in the theory and experimental communities. It is a powerful probe into the mechanism of electroweak symmetry breaking (EWSB) and highly sensitive to BSM contributions. The HIP group pursues VBS in the all-hadronic final state, which gives full access to the kinematics and a handle on the polarisation. The main contributors from the HIP group are Kirschenmann, Norjoharuddeen and Toikka, funded by RCF project ForVVard and the doctoral pilot by the Finnish government (also ending in autumn 2027). HIP also participates in the COST action network COMETA focused on studying EWSB through multiboson interactions.

VBS analyses in all final states require an excellent understanding of the two tag jets predominantly populating the forward detector region, a focus of improvement in the jet corrections effort. As a further ingredient to the analysis effort, we will apply cutting-edge machine-learning techniques to gain access to the polarisation of wide jets originating from the decay of vector bosons. The Run 3 analysis will aim for the first measurement of VBS in the all-hadronic channel that has the highest cross-section, but experimentally challenging signature, which necessitates focused development of experimental tools throughout Run 3.

With preliminary work already done in summer student projects on polarization tagging, the next steps include a tighter collaboration with the wider ML-based jet tagging community to incorporate polarization tagging into the new unified tagger landscape at CMS. We are expecting a CMS jet substructure publication detailing these new techniques towards the end of Run 3 data-taking in 2026. This new technique and an improved understanding of the forward tag jets will be input to the combined Run2+3 analysis aiming for publication in early 2027, which aligns well with the graduation schedule of Toikka and the coverage of PD Norjoharuddeen through the ForVVard project.

Originally, detailed studies of vector boson scattering and electroweak symmetry breaking were only expected to be feasible on the timescale of HL-LHC and driving physics motivation for HL-LHC. With the work pursued within HIP now, we will be in a top position to also take a leading role beyond the time scale of the next HIP funding period and intend to pursue this research also for HL-LHC.

Boosted Higgs bosons effort contains several analyses exploiting the distinctive experimental fingerprint of highly Lorentz-boosted Higgs bosons: their decay products (e.g. b quark or tau lepton pairs) are so collimated that all decay products are measured as a single jet in the detector. The Helsinki group is involved in the boosted H->bb analysis effort probing the ggF and VBF production modes of the Higgs boson, in the boosted Higgs boson pair production analyses, probing the Higgs trilinear self-coupling, as well as in new physics searches with such boosted Higgs bosons in the final states, developing and applying state-of-the-art machine learning techniques for boosted-jet identification and energy/mass regression. New trigger algorithms introduced for Run 3 and the new "HLT scouting" approach increase the amount of data available for these analyses beyond the luminosity increase.

Precision measurements with jets

Precision measurements with jets lay the foundation for much of the CMS physics programme. HIP will continue to push the precision of the top quark mass and jet cross section measurements beyond state-of-the-art, in conjunction with our strong JEC effort. The jet cross section measurements will be broadened to cover V+jet (Lehtelä) in addition to inclusive jets (Mancilla) to fully capitalize on the synergy with JEC measurements. We will also continue to improve our understanding of flavored (gluon, ud, s, c, b) jet cross sections to obtain deeper understanding of parton distribution functions, final state radiation and jet properties, which are hidden limiting factors in the measurement of the top quark mass and α_s.

The top quark mass (Myllymäki, Veikkola) is aiming at a precision of about 200 MeV, which could rule out absolute stability of the SM vacuum at 3σ confidence level. Our goal is to complete the Run 2 Legacy analysis in 2024-25 with record precision, which requires careful consideration of the experimental uncertainties and their correlations through JEC. The theoretical uncertainty in the interpretation of the top quark mass is being addressed by U. Vienna theorists. The hadronic $W \rightarrow q\underline{q'}$ decay in $t\underline{t}$ lepton + jet events are integrated as part of the JEC global fit to both improve JEC precision and to reduce top quark mass uncertainties. The direction taken after 2025 depends on the final uncertainties and pulls of the unblinded results and would target improved understanding of the main systematics from both theory and experiment.

Inclusive jet cross section (Mancilla) is an important input to global parton distribution function (PDF) fits and α_s measurements, as well as a test of state-of-the-art perturbative QCD predictions at NNLO and NLO+NLL. Our goal is to update the Run 2 Legacy analysis with Legacy JEC in 2024-25 so that the precision will exceed that of any past measurements, and to analyze Run 3 data at higher center-of-mass energy using PUPPI and advanced ML techniques that reduce sensitivity to pileup and jet flavor response. The inclusive jet cross section is integrated as part of the JEC global fit to significantly improve JEC time stability, which makes its continuous measurement throughout Run 3 important.

V+jet cross section (Lehtelä) utilizes the presence of well-reconstructed vector boson (Z or γ) to provide additional constraints to parton distribution and αs fits, and they are a natural extension of precise jet calibration analyses done with Z+jet and γ+jet. Ratios of cross sections provide further constraints on experimental and theoretical uncertainties.

Flavored jet cross sections (Veikkola, Mancilla, Lehtelä, Verma, Voutilainen) are an extension to inclusive jet and V+jet cross sections, with potential for key insights on the systematic uncertainties from both theory and experiment. We will need full jet flavor break-down for the targeted 0.1% JEC precision in the JEC4HL-LHC and will use the opportunity to explore the potential of state-of-the-art unified flavor identification and jet energy regression (ParticleNet / ParticleTransformer) for a simultaneous measurement of exclusive jet flavor cross sections of gluons, ud, s, c and b jets. These measurements are supported by HIP work on quark and gluon discrimination scale factors (Toikka) and on deep learning-based jet flavor identification (Inkaew, Kirschenmann, Laurila). This project is planned as a longer-term exploratory study rather than publications within the next project period of 2025-2027, although spin-off publications are not ruled out, and the topic would be covered within the final report of the JEC4HL-LHC project.

Preparing for HL-LHC exploitation

To fully exploit the HL-LHC's capabilities, CMS undergoes significant upgrades, particularly with the High Granularity Calorimeter (HGCAL) and the MTD (MIP Timing Detector), alongside extended tracking coverage.

Enhanced Detector Capabilities:

HGCAL, a key component of CMS's endcap calorimeter system, offers improved granularity and timing resolution. This upgrade enables precise reconstruction of particle showers, crucial for identifying and characterizing jets in the forward region. The finer segmentation aids in disentangling overlapping showers, enhancing the reconstruction efficiency and energy resolution of jets originating from VBF processes.

MTD provides time-of-flight measurements for MIPs, enhancing the timing capabilities of CMS, using LGADs also studied by HIP. With its unprecedented time resolution, the MTD enables the identification of displaced vertices and the precise determination of interaction times. This information is invaluable for distinguishing prompt signal events from pileup, including for forward VBF/VBS tag jets for which the current detector's pileup suppression is weak.

Tracker extension towards the forward region facilitates the reconstruction of VBF jets originating from quarks produced at large pseudorapidities. The extended tracking coverage complements the capabilities of HGCAL and MTD, enabling comprehensive event reconstruction in the forward region.

Exploitation in reconstruction:

Current CMS reconstruction algorithms are not designed for the imaging calorimetry era of HGCAL and also do not take into account timing information to a large extent. We plan to expand upon our expertise in jet reconstruction and PF, taking a leading role in the renewal of the Particle Flow algorithm for HL-LHC. We also envision to expand our regional collaboration with *e.g.* Joosep Pata in Tallinn, who is one of the authors of machine-learning based PF reconstruction (MLPF).

In 2024, we are already making headway to data-based PF hadron calibration based on new channels and improved models of hadron reconstruction in calorimeters. This, together with fast high-level feedback coming from streamlined jet calibration workflows (*e.g.* JEC4Prompt), should permit robust optimization and validation of advanced ML-based reconstruction techniques and low-level reconstruction for HL-LHC.

Outreach

The CMS outreach activities at HIP consist of participation in regular PR-events in Kumpula, such as Open Days for alumni, high school students and new physics students, as well as organizing our own events. Events that we arrange regularly include hosting of International Physics Masterclass events in Kumpula for high school students, campus tours and lectures for high-school classes going to CERN, and exhibitions in the international Researcher's Night. We plan to expand our portfolio for these events with a new HEPScape room inspired by the successful example in Jyväskylä.

At the CERN end, HIP researchers are actively involved in the outreach activities of CERN and CMS. They include organizing multi-day tours for Finnish high school student and teacher groups and guiding S'Cool Lab cloud chamber and X-ray workshops and CMS experiment visits for both Finnish and international student groups.

The CERN BootCamp, a new innovative study concept for Master students of University of Helsinki and three universities of applied science was introduced in 2018 and repeated annually since then except for the COVID years (2020-2021). It has received funding from ATTRACT, a research and innovation project funded by the European Union. Students from various fields spent five days at CERN IdeaSquare solving demanding societal problems with service design tools, with facilitators and experts from participating universities and HIP, CERN, companies and international organisations in Geneva. We intend to continue organizing this course in 2025-2027.

Physicists and students from all the projects within the CMS programme participate in the outreach activities.

CMS experiment project 2024

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