The Standard Model and beyond:
Searching for New Physics with the CERN LHC CMS experiment
Final report (grant no. K 124845 / 124850)

Our research program had two main pillars: tests of the Standard Model (SM) electroweak (EW) sector and searches for new exotic phenomena; and the operation, calibration, performance measurements and upgrade of the CMS Tracker and Beam Radiation Instrumentation and Luminosity (BRIL) systems in the CMS Experiment at the CERN LHC.

The measurements were conducted first using a **partial Run 2 data set,** corresponding to 35.9 fb^{-1} integrated luminosity, collected in 2016 at $\sqrt{s}$ = 13 TeV in pp collisions. It was typically combined with Run 1 results at 8 TeV based on 19.7 fb^{-1} to reach an observation of rare processes at 5 standard deviations (s.d.). The **full Run 2 data set** collected up to 2018, corresponding to 137 fb^{-1} were analysed to improve the sensitivity.

Standard Model measurements

Electroweak diboson production and scattering

An essential part of the research program was the study of EW diboson production, a sensitive probe of **EW symmetry breaking** (EWSB) as well as possible **New Physics**. We performed precise measurements of diboson final states accompanied or not by hadronic jets, compared them to **state-of-the-art higher-order perturbative calculations**, and derived **constraints on anomalous quartic and triple gauge couplings** (aQGCs and aTGCs) that could arise in extended (such as supersymmetric or general two-Higgs-doublet) models with new heavy states.

We published several papers on cross-section measurements of **electroweak diboson production in association with a forward jet pair** with large rapidity separation (VV'jj, V=W, Z, V'=W, Z, γ), where the weak vector bosons decay leptonically resulting in electron(s) and / or muon(s) in the final state. While **vector boson scattering** (VBS) cross-section can not be extracted directly, strongly VBS-enriched event samples were used to test NLO pQCD predictions. The **total** and the **EW VV'jj production cross-sections** were measured. The results were also interpreted in an **effective field theory** (EFT) containing a collection of linearly independent higher dimensional operators $O_{X,i}$. Constraints were derived on the coefficients (also referred to as **anomalous couplings**) $f_{X,i}/\Lambda^4$ corresponding to the $O_{X,i}$ operators and normalized by the cut-off scale Λ. Here, 8 operators $O_{M,i}$ are built from the SM SU(2) and U(1) field strengths, and the covariant derivative of the Higgs doublet, while 10 operators $O_{T,i}$ contain only field strengths.

Studying events with **two pairs of oppositely charged same flavour leptons** brought an evidence of 4.0 s.d. for EW **ZZjj production** using the full Run 2 data set [PLB 812 (2021)135992]. The cross-section in a VBS-enriched region was found to be $\sigma_{EW,fid}$(ZZjj) = 0.09 +0.04–0.03 (stat) ±0.02 (syst) fb, in excellent agreement with the NLO QCD prediction. The 4-lepton invariant mass distribution was used to probe new physics searching for evidence of charged ($O_{T,0-2}$) and neutral current ($O_{T,8-9}$) dim-8 operators, corresponding to couplings of the transverse degrees of freedom in the SM EFT extension. Stringent constraints were placed on the corresponding aQGCs. Of these, the limits on $f_{T,8-9}/\Lambda^4$ were the most stringent to date. Moreover, a measurement of the **differential cross sections** as a function of various jet variables for **ZZ pair production in association with jets** at $\sqrt{s}$ = 8 and 13 TeV, considering $Z\to e^+e^-$, $\mu^+\mu^-$ decays, showed a good agreement with theoretical predictions when next-to-leading order (NLO) matrix-element calculations in perturbative quantum chromodynamics (pQCD) were used together with the PYTHIA parton shower simulation [PLB 789 (2019) 19].

EW **Zγjj production** was observed with a significance well above 5 s.d. with a signal strength – defined as the measured cross-section normalized to the SM prediction – of 1.20+0.18–0.17 [JHEP 06 (2020) 076, PRD 104 (2021) 072001]. The full data set allowed the measurement of differential cross sections for EW and EW+QCD processes for several observables, which manifest agreement with SM predictions. The result improved the limits on $F_{T,9}/\Lambda^4$.

EW **Wγjj production** was discovered with significance of 6.0 s.d. and a signal strength of 0.88+0.19–0.18 [PLB 811 (2020) 135988, arXiv:2212.12592 [hep-ex]]. The cross-section measurement in a fiducial region covering 3.4% of the total phase space is dominated by systematic uncertainty but still has a sizeable statistical component: $\sigma_{EW,fid}$ = 23.5 ± 2.8 (stat) +1.9−1.7 (theo) +3.5−3.4 (syst) fb = 23.5 +4.9−4.7 fb. Constraints placed on anomalous quartic gauge couplings were the most stringent limits to date on $f_{M,2-5}/\Lambda^4$ and $f_{T,6-7}/\Lambda^4$.

As most of the measurements have significant statistical uncertainties, the **combination** of the results of the ATLAS and CMS experiments can bring significant improvements. In the LHC Electroweak Working Group, we performed RIVET-based Monte Carlo simulation studies for **$W^\pm W^\pm$jj production** comparing the generated samples of the collaborations [CERN-CMS-DP-2020-043]. We also conducted generator-based VBS studies to explore the sensitivity to **W polarization states** and measure the cross-section of **longitudinal $W^\pm W^\pm$ scattering** to get complementary information on EWSB to direct measurements of the Higgs boson couplings to gauge bosons. In a pioneering analysis, the cross section of EW $W^\pm W^\pm$jj production was measured for final states where at least one of the W bosons is longitudinally polarized to be 1.40+0.60−0.57 fb, in good agreement with the prediction [PLB 812 (2021)136018]. While the analysis demonstrated the possibility to study polarized WW scattering at the LHC, it only reached a significance of 2.3 s.d. (3.1 s.d. expected) due to statistics limitations. The first observation of the EW production of **opposite-sign WW bosons in association with two jets** reached a significance of 5.6 s.d. utilizing a deep neural network to suppress the challenging irreducible contribution of top quark pairs and of the QCD-induced production of W boson pairs. The fiducial cross section is measured to be 10.2±2.0 fb, consistent with the SM [arXiv:2205.05711 [hep-ex]]. The analysis to interpret the results in SM EFT is ongoing. Finally, the first evidence of VBS in the **$\ell\nu$qq channel** – using a multivariate machine learning method – was achieved in the search for **EW WW and WZ production** with 4.4 s.d. significance (5.1 s.d. expected), with a signal strength of 0.85 ± 0.12 (stat) +0.19−0.17 (syst) [PLB 834 (2022) 137438].

VV'jj final states can be produced through processes containing a quartic or two triple EW gauge couplings. **Diboson pairs with no accompanying jets** get contributions through single EW TGCs. The high tail of the photon transverse momentum (p_T) distribution in the **Wγ final state** was used to measure in a dim-6 EFT the four aTGC couplings that affect this process. The most stringent limit to date on the coefficient of O_{WWW}, the lowest dimension CP-even operator that directly alters the WWγ TGC, was derived. The measured cross section 15.58 ± 0.05 (stat) ± 0.73 (syst) ± 0.15 (theo) pb agrees well with the MADGRAPH5 aMC@NLO prediction, but is significantly lower than that of POWHEG NLO [PRL 126 (2021) 252002]. A 2-dimensional analysis using also the azimuthal angle of the charged lepton enhances the sensitivity to the interference between the SM and the O_{WWW} operators, thus reduces the dependence on missing higher-order contributions. Differential cross sections for several observables were compared to predictions computed at NLO and next-to-NLO (NNLO) in pQCD. The suppression of the cross section, due to interference between Wγ production diagrams, for small rapidity differences between the charged lepton and the photon (called radiation amplitude zero effect) is stronger in data and prefers the NNLO description [PRD 105 (2022) 052003].

During the grant period, we contributed to a number of EW results on gauge couplings and vector boson scattering, leading to the **observation of these rare processes** in several final states but to **no sign of non-zero aTGCs or aQGCs yet**. A. Mehta **co-leads the Vector Boson Pair Production Subgroup (SMP-VV) of the CMS Standard Model Physics Analysis Group** (SMP PAG). A **BSc thesis** (2018) and an advanced computer modeling laboratory project (2021) were successfully completed on related research. We gave several presentations representing CMS at international conferences. We were chosen to organize the 3rd Annual Meeting of the COST VBScan Action in 2020 at ELTE. Due to the COVID-19 pandemic the event was merged to the virtual "Winter 2021 topical meeting on VBS" that we co-organized. The work continues: the current data taking period (Run 3) will double, and then the HL-LHC will increase by an order of magnitude the available statistics, thus this area – that is still to a large extent limited by the low event rates – will remain in the limelight of research and could lead to new insights on the fundamental description of nature.

Other SM results

We have contributed to the rich CMS Standard Model measurement program through various responsibilities and leadership positions within the collaboration. We are also responsible for the Standard Model physics validation of new CMS software releases. We gave three subsequent **trigger conveners of the CMS Standard Model Physics Analysis Group** (G. Pásztor, G. Veres, O. Surányi), as well as the **convener of the CMS Electron – Photon Physics Object Group** (G. Pásztor, until 2018). They were responsible for the real-time event selection (= trigger) algorithm and strategy development, including special data taking aimed at precision measurements of the W and Z bosons at low instantaneous luminosity targeting critical goals like the determination of the W boson mass. As another example, many physics results on W, Z, Higgs bosons and top quarks rely on electron or photon triggers that were optimized, their efficiencies measured with our leadership. The performance of the CMS electron and photon reconstruction in Run 2, both real-time (online) and at high-precision (offline), as well as the main trigger algorithms were summarized in [JINST 16 (2021) P05014].

The internal review process of results within the collaboration before submission to a refereed journal has various stages: internal review and pre-approval within the Physics Analysis Group, scrutiny by the Analysis Review Committee, approval on a plenary meeting, collaboration-wide circulation including a compulsory review by a number of institutions, review by members of the publication committee, final reading, and sign-off by the publication officer. H. Dezső, as a member of the **CMS Publication Committee's Board for Standard Model Physics and Detector Performance**, contributed to 63 articles. We also performed **institutional review**s of 10 publications in the field of SM physics, including measurements of Higgs and Z boson, top quark, jet and hadron resonance properties.

These contributions were also recognised in the form of various conference presentations offered to our team members. We organized the FFK-2019 International Conference on Precision Physics and Fundamental Physical Constants in Tihany.

Luminosity measurement

The precise determination of **integrated luminosity, a measure of the data volume**, is essential for all cross section measurements in and beyond the SM. Its accuracy is critical as (one of) the **dominant source**(s) **of uncertainty** for leptonic final states from the production of EW bosons and top quarks**.**

The absolute calibration of luminosity requires **transverse beam separation**, so called **van der Meer (vdM) scans** in special beam and data taking (including trigger) conditions. We co-led in 2018 and 2022 the optimisation of the vdM data taking strategy, and the monitoring of the data taking and trigger performance, as well as the preliminary analysis that allowed in 2022 to release the very first 13.6 TeV results on top quark pair production just a month after the vdM campaign [CMS-PAS-TOP-22-012].

A major achievement was the development of two new methods to determine with an improved uncertainty the correction and its time dependence due to the assumption that the **beam particle density functions** are factorizable in the transverse coordinates. The most accurate method performs beam tomography using the reconstructed parameters of the **luminous region** (beam spot) from the primary interaction vertices, while the method applicable also in heavy ion collisions is based on a 2-dimensional fit directly on the sampled beam overlap shape in dedicated **offset and diagonal separation scans**. We also studied the effect of **orbit drifts** both in the **length scale calibration** and in the **van der Meer scan analysis** for the absolute luminosity calibration. In collaboration with LHC colleagues, we completed the systematics bias estimation due the uncertainty on the betatron tune affecting the **electromagnetic (EM) interactions** between the charged particle bunches, and evaluated the **optical distortion of the beam shape** due to the EM force, an effect that also affects the factorisation bias measurement.

We **improved major systematic uncertainties** and led the review of the first published CMS precision luminosity measurement achieving an uncertainty as low as 1.2% for the 2016 pp data [EPJC 81 (2021) 800], as well as several preliminary luminosity calibration results for pp [CMS-PAS-LUM-17-004, CMS-PAS-LUM-18-002], p-Pb [CMS-PAS-LUM-17-002] and PbPb data [CMS-PAS-LUM-18-001].

We contributed in **leading roles in this area.** G. Pásztor was the **convener of the CMS Luminosity Physics Object Group (LUM POG)** (2018-2020), and also acts as **trigger contact** for physics and special data taking fills. A. Rádl (PhD student) is the **contact to the Alignment and Calibration Working Group** that coordinates the design, implementation and operation of the calibration infrastructure in CMS, which is particularly important for the luminosity measurement via Pixel Cluster Counting. P. Major (PhD candidate) is the **contact person and paper editor** for the final Run 2 calibration, coordinating the work of about 40 contributors, and was announced as the recipient of the **2022 CMS Award** for his achievements on precision luminosity measurements. We organized the **CMS BRIL and Luminosity Workshop at Eötvös University** with about 30 participants in late 2017. We gave numerous presentations, frequently being the first to show the results publicly. **An MSc thesis** (2019) was successfully completed on the linearity of the pixel cluster and vertex counting methods.

Beyond the Standard Model

Search for supersymmetry

While the SM describes our observations at collider experiments well, it clearly can not offer a candidate for dark matter and dark energy, or mechanisms to explain the small but non-zero neutrino masses, the stabilization of the weak boson masses at the EW scale and more. This is why the most important goal of the LHC physics program is to study **exotic phenomena** to aid the development of the fundamental theoretical description of the microworld at high energies. We primarily contributed to **supersymmetric (SUSY) partner particle searches** in CMS using simplified models, where the lightest supersymmetric particle (LSP) is stable, neutral and weakly interacting, thus an ideal **dark matter candidate**.

Searches for the pair production of **scalar top quarks** in **supergravity (SuGra) inspired R-parity conserving models** are particularly attractive as in a large region of the SUSY phase space they are expected to be light, and thus could be produced at the LHC. The **inclusive search** for SUSY in **0-lepton and 1-lepton (e, μ) final states** using **razor kinematic variables** – that are sensitive to large mass differences between the parent particle and the invisible LSP in the decay chain – also reconstructs **boosted** high-p_T hadronically decaying **W boson** and **top quark** candidates, and requires large jet multiplicity, large transverse energy and large missing transverse momentum (p_T^{miss}). By binning the observed events in multiple variables, it is sensitive for a broad range of SUSY signatures. In the absence of significant excess over the SM background, the results were presented as constraints on **scalar top quark pair** ($\hat{t}_1 \hat{\bar{t}}_1 \rightarrow t\hat{\chi}_1^0 \bar{t}\hat{\chi}_1^0$) and **gluino pair** ($\widehat{gg} \rightarrow t\bar{t}\hat{\chi}_1^0 t\bar{t}\hat{\chi}_1^0$, $\widehat{gg} \rightarrow t\bar{c}\hat{\chi}_1^0 \bar{c}t\hat{\chi}_1^0$) production, turning the cross-section upper limits at the 95% CL to lower limits on the scalar top quark and gluino masses: 1.14 TeV and 2 TeV, respectively, for a wide range of neutralino LSP masses [JHEP 03 (2019) 031]. The analysis of the full Run 2 data set using the fully re-reconstructed data with the most precise detector calibration is still ongoing. We improved the sensitivity by incorporating the latest deep learning techniques and by introducing additional boosted objects into the event categorization, such that it now includes hadronically decaying W and Z bosons, Higgs bosons decaying to a b quark pair and top quarks decaying both hadronically and leptonically. For the latter, we developed a new, highly efficient tagging method.

A dedicated search for the **fully hadronic decay of scalar top quark pairs** revealed no signs of new physics, even though it extended the reach towards soft decay products. The analysis has benefited from novel **deep neural network based tagging** algorithms for top quarks and W bosons both at low and high p_T. Limits on the scalar top quark production cross section were obtained for various production and decay modes, and lower limits derived on the SUSY particle masses: as high as 1.31 TeV on the scalar top mass for direct production models, and 2.26 TeV on the gluino mass for gluino-mediated production models [PRD 104 (2021) 052001]. The identification of low-p_T (soft) b-jets based on **secondary vertex tagging** allowed us to cover regions where the masses of the scalar top and the LSP are close, providing exclusions down to 10 GeV mass difference (Δm).

The search for **leptonically decaying scalar top quarks** in final states with **two oppositely charged leptons**, jets identified as originating from b quarks, and large p_T^{miss} did not show either a significant excess over the expected SM background. Limits were set on the masses of the pair produced lightest scalar top quark and the neutralino LSP reaching lower bounds as high as 850 GeV – 1.4 TeV and 420 GeV – 900 GeV, respectively. The exact values depended on the model assumptions, in particular on the nature of the intermediate particles through which the cascade decay proceeded [EPJC 81 (2021) 3]. Models with a **compressed mass spectrum** (having a small Δm between the LSP and the SUSY partner particle produced in the hard interaction) are particularly challenging as the visible decay products are soft. Moreover, the scalar top quarks can have a **significant lifetime** leading to **soft and displaced leptons**. The key experimental challenge to tackle such models is the efficient reconstruction and identification of low-p_T leptons with large impact parameters, and the implementation of the **soft b-tagging** algorithm developed originally for the hadronic analysis. The measurement requiring a soft lepton with or without a soft b-jet, large p_T^{miss} and a high-p_T initial state radiation hadronic jet – to boost the produced scalar top quark pair system – is ongoing to target the very low Δm region.

EW gauginos are frequently also expected to have masses accessible at the LHC, and the current constraints on their masses are typically lower than those on colored particles. A dedicated analysis of models with a **compressed mass spectrum** with Δm = 1 to 54 GeV between the light gaugino(s) and the neutralino LSP was performed in the **vector boson fusion (VBF) topology** requiring two well-separated jets that appear in opposite hemispheres, with large invariant dijet mass considering **0-lepton and 1-lepton (e, μ, τ) final states** in the 2016 data set. As the observed dijet mass and lepton – missing momentum transverse mass distributions did not reveal evidence for new physics, the search for **non-colored gaugino pair** (chargino - chargino or mass degenerate chargino - 2nd lightest neutralino) production succeeded to set the world's most stringent limits to date for charginos and neutralinos decaying to leptons for Δm = 1-3 GeV and Δm = 25-50 GeV, and thus demonstrated that the VBF topology is a powerful tool for such analyses. The observed lower limit on the 2^{nd} lightest EW gaugino, assuming it decays with 100% probability to a lepton, a neutralino and the LSP, ranges between 112 GeV for Δm = 1 GeV, and 175 GeV or 225 GeV for Δm = 30 GeV depending on the assumed intermediated particle, a virtual SM EW vector boson or a light scalar lepton [JHEP 08 (2019) 150].

Another interesting possibility is to consider models where SUSY breaking is communicated from the hidden sector to the visible sector by gauge interactions, often called **General Gauge Mediation** (GGM) or **Gauge Mediated SUSY Breaking** (GMSB). In such models the LSP is a light gravitino and the 2nd lightest particle is often a neutralino. The search for final states with **two oppositely charged same-flavor leptons and significant p_T^{miss}** targets (among others) such models: either considering the weak production of gaugino ($\hat{\chi} = \hat{\chi}_i^0, \hat{\chi}_i^+$) pairs ($\widehat{\chi\chi} \rightarrow \hat{\chi}_1^0\hat{\chi}_1^0 (+ X_{soft}) \rightarrow V\hat{G}V'\hat{G}$) resulting in two EW neutral bosons (V = H, Z) and p_T^{miss}, or the strong production of gluino pairs ($\widehat{gg} \rightarrow q\bar{q}\hat{\chi}_1^0 q\bar{q}\hat{\chi}_1^0 \rightarrow q\bar{q}V\hat{G}q\bar{q}V'\hat{G}$) decaying to hadronic jets, two electroweak bosons and p_T^{miss}. The observed yields were consistent with those expected from SM backgrounds in all search regions, defined to be sensitive to a wide range of signatures. In particular, neutralino masses up to 800 GeV and gluino masses up to 1.87 TeV are excluded [JHEP 04 (2021) 123]. In models where the neutralino has a significant bino component, the decay into a photon and the gravitino LSP is allowed. The search for a **high-p_T photon and large p_T^{miss}** in the 2016 data set placed a 1.86 TeV limit on the gluino mass [JHEP 1906 (2019) 143]. A dedicated study of gaugino pair and gluino pair production in the **high-p_T photon + Higgs boson + large p_T^{miss}** final state in the full Run 2 data set is progressing toward completion using the final, most precise re-reconstructed samples. With the strategy to fully reconstruct the Higgs boson decay into a pair of b jets either with two resolved jets or a wide jet with substructure, the sensitivity of the search with respect to previous results is expected to be improved.

While no evidence for new physics were found, we have **constrained a number of supersymmetric models**, in particular with respect to the production of **scalar top quarks**, the possibility of a **compressed mass spectrum**, and extensions with **gauge mediation**. We gave a large number of presentations on these results representing the CMS collaboration on international conferences. **A PhD** (2019), **4 MSc** (2019, 2x2021, 2022), **7 BSc** (3x2019, 2020, 2x2021, 2022) and **2 TDK** (2018, 2020) **theses** have also been successfully completed on research related to the above topics.

Other searches

Light-by-light (LbL) γ γ → γ γ scattering, proceeding via a charged-fermion-box diagram in the SM, is particularly sensitive to new physics (magnetic monopoles, vector-like fermions, dark sector particles, axion-like particles, gravitons). We studied LbL scattering in **ultraperipheral PbPb collisions** at 5.02 TeV per nucleon pair energy with an integrated luminosity of 390 μb^{-1}. A 3.7 s.d. evidence was established, with the cross section of 120 ± 46 (stat) ± 28 (syst) ± 12 (theo) nb being consistent with the SM prediction [PLB 797 (2019) 154]. The diphoton mass distribution was used to search for the production of **pseudoscalar axion-like particles** (ALPs) in an s-channel process in the mass range of 5–90 GeV. For ALPs coupling to the electromagnetic (electroweak) current, the exclusion limits were the best to date over the mass range 5–50 GeV (5–10 GeV). The analysis of the 2018 data is in progress, with **an MSc** (2020) **and a TDK** (2019) **thesis** successfully completed.

The search for **heavy bosons decaying to Z(*νν*)V(qq)**, where V is a W or a Z boson identified via **jet substructure techniques,** has shown no discrepancy with respect to the SM. The results were interpreted in terms of **radion, W' boson, and graviton models**, under the assumption that these bosons were produced via gluon-gluon fusion, Drell-Yan, or weak vector boson fusion process: the observed lower limits on the masses of the heavy boson ranges from 1.2 to 4.0 TeV [PRD 106 (2022) 012004]. We also acted as institutional reviewers for a charged Higgs boson, a heavy Majorana neutrino, and two exotic heavy resonance analyses.

Detector operation, performance, and upgrade

CMS operations

We contributed to the detector operations by taking shifts in the CMS Control Room, in particular BRIL and Trigger desk shifts, central Shift Leader and Data Quality Monitoring shifts, as well as BRIL and High-Level Trigger Detector On-Call (DOC) expert shifts, and remote Tracker Data Quality shift (also during data reprocessing). We are responsible for the validation of the electron and photon reconstruction in new CMS software releases. An article describing the CMS detector configuration to be used in Run 3 is in preparation, including our contribution for the pixel detector and the BRIL systems.

We were responsible for the **online reconstruction of the luminous beam interaction region** (beam spot) during 2017-2018 data taking. We developed a new algorithm to measure the beam spot position using particle tracks identified by the high level trigger algorithm. The measurement became more stable and precise, increasing reconstruction data quality, especially important for tracking and vertexing. The pp algorithm was adjusted so that it could be used successfully in the heavy-ion data taking as well.

Pixel detector operation and calibration

We participated in the **data taking** with the Silicon Tracker Detector and its **data quality assurance**. Our group maintains the **reconstruction database** that includes information on bad detector modules, gain calibrations, simulated inefficiency, and radiation damage.

A article was published on the Data Acquisition (DAQ) and Control system of the Phase-1 Pixel Detector, the innermost tracking system of CMS [JINST 14 (2019) P10017], including our work on the construction and verification of the **read-out electronics**, the load-balancing technique applied for optimization for high occupancy environment, the beam test of the Phase-1 prototype modules, the measurements of bad detector components and efficiency loss. It was followed by publication on the design and construction of the detector [JINST 16 (2021) P02027], covering our contribution to the design and production of the control, programming, and read-out electronics, the **timing adjustment** and **optimization of the read-out chip settings** for the LHC collisions, the **reconstruction** of the hit measurements, the periodic monitoring of the **detector performance**, and the detector **simulation**.

We recomputed all **calibration parameters** for the Pixel Detector for 2016-2018. We contributed to the assessment and bookkeeping of **dead areas**, and implemented a statistically accurate simulation of their time evolution, improving charged particle tracking and the assessment of its systematic uncertainties. We improved the efficiency loss simulation of functional modules so that it more closely reproduces the efficiency of tracking, b-tagging, and lepton reconstruction seen in data, reducing the systematic uncertainty for physics analyses. We measured the **pixel cluster properties** and developed an updated **hit efficiency** measurement using muon candidates only. The results on the **alignment and calibration** and the study of its **radiation damage** effects was published [NIM A1037 (2022) 166795]. We improved the pixel cluster parameterization algorithm using partially damaged hit pixel information obtained with heavily irradiated sensors and diminished charge collection efficiency.

We co-lead the complex **refurbishment of the pixel detector** and its reinsertion into CMS for Run 3. From the components designed and produced at Wigner RCP, two digital opto-hybrid (DOH) motherboards – that were exchanged with spare boards – have been repaired. We co-led the **commissioning** of the detector which included the calibration of the newly installed Layer 1 in the barrel. We reestablished the time and spatial alignment with cosmic ray measurements and then LHC collisions. We studied the performance of the detector to verify the efficiency and resolution of each layer. We updated the **beam spot monitoring** system and observed an unexpected large (1.2 mm) misalignment in the horizontal direction that would lead to a considerable reduction of the detector lifetime due to asymmetric radiation damage. The realignment of the magnet system by the LHC operation team and the verification of its result was completed recently.

We have important leadership roles in this area: J. Karancsi and T. Vámi were consecutive **conveners of CMS Pixel Calibration, Reconstruction, and Simulation Group**. T. Vámi became the **coordinator of the Alignment, Calibration and Database Group** in 2021. V. Veszprémi was **Detector Performance Group convener** until 2018, since then he has been serving as **Deputy Project Manager.** He participated in the organization of CMS Tracker Weeks about four times a year. We represented the project on major reviews and presented our work at various conferences.

Tracker Phase-2 upgrade

We set up a **read-out system for the RD53 ASIC of the Phase-2 Inner Tracker** (pixel) detector to develop the FPGA firmware application for programming and reading out the chip.

We contributed to the **CHROMIE high-rate test-beam telescope** to be used for testing silicon sensors at high data rate. We completed the design and construction of the read-out electronics, the offline reconstruction of the telescope data. The first telescope was installed at the CERN SPS test beam facility. A copy of the telescope called CHROMini was also developed where the hit rate limit was raised from 200 MHz/cm^2 to around 600 MHz/cm^2 for a beam facility at IPHC, Strasbourg, France.

We developed a **uTCA-based clock and trigger distribution system** along with a firmware targeting primarily the CHROMIE telescope, but also to be used as a DAQ system to read out a large number of prototype modules and check scalability. It is now possible to inject external clock and trigger signals to the DAQ of the modules according to the bunch structure of the test beam, as well as to the external electronics that monitors the beam presence. First tests of the module prototype were completed. We extended the firmware functionalities with a read back of the module status to allow the modules to send back-pressure signals in **high rate data-taking**. We started to integrate the software interface for this card into the CMS DAQ framework which will be used in the following test beam measurements.

We participated in the development of the **simulation for the Phase 2 Inner Tracker** and reviewed the new **FPGA-based tracking** for the CMS Level-1 trigger using the tracklet algorithm.

We set up a clean room with temperature and humidity control at Wigner RCP for the **visual inspection of roughly 20'000 Phase-2 Outer Tracker front-end hybrid printed circuit boards** during module production using a novel, automated image processing technique. We participated in the inspection of several prototyping cycles of the hybrids at CERN. Plans for the logistics to be followed during production were set, and an "inspection manual" was prepared to aid the training of team members. We improved the image processing software for the optical scanner, and designed special holders for each type of hybrids. The status and planning of the hybrid component production was presented in a successful Engineering Design Review in Oct 2022 at CERN.

Many items for the Phase 2 **Tracker construction projec**t were finalized and published [JINST 15 (2020) P03014, JINST 16 (2021) P12014, JINST 17 (2022) P06039], allowing to move to the production phase, as is the case for the silicon sensors [JINST 15 (2020) P04017, JINST (2021) 16 P11028].

Beam Radiation Instrumentation and Luminosity (BRIL) system operation

The BRIL project is responsible for the construction, operation and calibration of **14 technical systems** that provide **online luminosity measurement, beam-induced background, beam timing, beam loss monitoring** (with abort functionality to protect the Silicon Tracker), and **neutron and mixed field radiation monitoring**.

We worked on **detector data quality monitoring** for the **Pixel Luminosity Telescope (PLT)**, a standalone luminometer. We developed a new monitoring and warning system based on **signal shape analysis** to foresee efficiency loss due to radiation damage and allow its compensation by adjusting the operational condition (the high voltage settings). We applied an **unsupervised machine learning algorithm** (k-means) to find hardware or configuration problems based on the **occupancy maps** of the silicon pixel sensors that form the three layers of the telescope, and provided a fast implementation to the BRIL software framework for real-time application. The paper on the operation and performance of PLT in Run 2 was accepted by EPJC [arXiv:2206.08870 (physics.ins-det)].

G. Pásztor was the **BRIL Deputy Project Manager** from Sep 2021, then became the **BRIL Project Manager** in March 2022. She co-led the system commissioning and then the data taking of the BRIL systems that underwent several upgrades: the PLT and the BCM (Beam Condition Monitor) have been rebuilt with improved design during Long Shutdown 2 (LS2) between 2019-2021. She also organized several BRIL performance reviews and workshops. **Two BSc theses** (2021, 2023) were successfully defended on PLT data quality monitoring.

BRIL Phase-2 upgrade

ELTE is a main contributor to the Phase-2 upgrade of the BRIL system in preparation for High-Luminosity LHC (HL-LHC). We worked on the **global upgrade strategy for luminometry**, on **project coordination**, and on the R&D for the new **Tracker Endcap Pixel Detector (TEPX)** to adapt it as one of the main high-precision online bunch-by-bunch luminometers. We performed GEANT4 **simulations** to study the effect of the cooling pipe material on coincidence reconstruction performance in overlapping regions of the pixel modules. We created a standalone simulation to study out-of-time contributions to the pixel cluster counts, a main source of uncertainty at high pile up conditions. We set up an RD53 **pixel detector readout electronics test system** at ELTE to develop and validate luminometry specific functions.

The project completed a major milestone, the publication and approval of the **Technical Design Report** [CERN-LHCC-2021-008] by the LHC Committee (LHCC) and now prepares the detailed Engineering Design to be presented in 2024. Major progress has been achieved on the mechanical and electronics design of the standalone luminometer and beam background monitor, the **Fast Beam Condition Monitor (FBCM)** that is based on silicon pad sensors and a continuous readout with ~ns time resolution.

G. Pásztor had various leadership roles, starting as chapter editor of Luminosity Strategy for the **Conceptual Design Report** in 2020 [CMS-NOTE-2019-008]. She became **BRIL Upgrade Coordinator** (2020-2021) and served as the **editor and chapter editor** of the **Technical Design Report**. She kept her leading role in the upgrade project ever since as (Deputy) Project Manager. She organized major reviews of the project, represented it during the LHCC approval and scrutiny process, and at major conferences. **A BSc** (2021) and **a TDK** (2021) **thesis**, and an MSc-level advanced computer modeling laboratory project (2020) were completed.

Other activities and final comments

Our group produced a wealth of **outreach presentations and articles** (8 in Fizikai Szemle) in the Hungarian media. Both of our institutes host annual **International Particle Physics Masterclass** events for high-school students and their teachers. We organized **two large (half-day) outreach events**: "Particle Physics without Borders: Hungary – a member state of CERN for 25 years" (Nov 2018) and "The Higgs boson turned 10 years old – What does the teenage particle tell us about the microworld?" (Nov 2022). We participate in the **annual Hungarian Teachers Programme at CERN**.

The ELTE group organized the **2018 CMS Physics and Upgrade week in Budapest** for ~300 participants.

The main investigators are present at the highest level of CMS management, the **CMS Management Board**, G. Pásztor as BRIL Project Manager and as the elected representative of 11 European "OCMS" (Other CERN Member State) countries, and V. Veszprémi as Tracker Deputy Project Manager. G. Pásztor represented the collaboration at the Open LHCC Session in June 2022, a presentation that requires an intimate knowledge of the whole experiment from detector operations to upgrade and all fields of LHC physics research. We have given a **large number of presentations** in international conferences representing the collaboration, of which 29 conference proceedings publications were born. The total number of successful theses defended in the areas covered by this grant is **1 PhD, 6 MSc, 11 BSc and 4 TDK.**

The CMS Collaboration published **401 articles where NKFIH is acknowledged** to date, of which 365 contains the contract number as certain letter-style publications can not list all funding agency contract numbers due to length constraints from the publisher. In the publication list only those are given where we had personal contributions to the work. Certain documents without acknowledgements are also listed if they contain preliminary results or prove personal contributions to the large CMS collaboration.

Due to the **Russian aggression in Ukraine**, since February 2022 all CMS papers were submitted without an author list and acknowledgements to the refereed journals. After a long debate on the authorship of the results and the inclusion of institutes and funding agencies connected to the aggressor states, the LHC collaborations have recently reached an agreement, which is now under implementation. The large number of publications currently waiting in the "accepted" status after the peer review at the journal are **expected to start to appear in print around May 2023**. They will contain the full affiliation of all authors participating in this project and a proper acknowledgement of the relevant funding agencies, in particular this NKFIH research grant.