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Director of Laboratory

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REPORT ON THEME IN RESEARCH AREA
WITHIN THE TOPICAL PLAN FOR JINR RESEARCH

1. General information on the Theme

1.1. Theme code
02-0-1083-2009/2023

1.2. Laboratory
LHEP

1.3. Scientific field
Elementary particle physics and relativistic nuclear physics

1.4. The name of the Theme
CMS. Compact muon solenoid on LHC

1.5. Theme Leader
V. Yu. Karjavin

1.6. Projects in the Theme
CMS. Compact muon solenoid on LHC, 2020-2023.
Leader: V. Yu. Karjavin

Upgrade of the CMS Detector, 2022-2023.
Leader: V. Yu. Karjavin

2. Scientific report on the implementation of the Theme
2.1. Annotation

The Compact Muon Solenoid (CMS) is a general-purpose detector at the Large Hadron Collider (LHC). It is designed to study pp interactions at the Large Hadron Collider (LHC) aimed at comprehensive research in the field of elementary particle physics to study the fundamental laws of nature. The prime goals of CMS are to explore physics at the TeV scale and to confirm the mechanism of electroweak symmetry breaking through the studies of the Higgs particles discovered in 2012 and search for extra Higgs bosons beyond the Standard Model (BSM), or otherwise, search for supersymmetric partners the SM particles, search for extra dimensions at TeV-energy scale. Other important problem which can be cleared with LHC is looking for ways to unify of fundamental interactions, for example via extended gauge models. Also, the CMS physics program is included the tests of Standard Model (SM) itself in the new energy region, studies of EWK and QCD processes, search for quark-gluon plasma etc.

JINR participates in the CMS project as part of the cooperation between scientific centers of Russia and the JINR Member States Collaboration (Russia and Dubna Member States CMS Collaboration, RDMS), starting from the development of the concept of the experiment in 1992. JINR physicists made a key contribution to the construction of the CMS facility, are actively involved in obtaining experimental information, data processing and analyses.

The priority tasks of the JINR Group's physics program include searches for candidates for dark matter particles, tests of predictions of TeV-energy scenarios of gravity, extended Higgs and extended gauge models. JINR physicists also take an active part in study of lepton pair production in the Drell-Yang process to test the SM and in measuring the multiplicity of particles in jets to clarify the mechanisms of parton hadronization.

The main effort of JINR was focused on the construction of detectors of the Endcap of the CMS experimental setup with full responsibility of RDMS for the design, construction, commissioning, and operation of the endcap hadron calorimeter (HCAL) and the forward muon station (ME1/1). This responsibility was maintained both during the first (2010−2012) and second stages of LHC operation (2016−2018), as well as during long LHC shutdowns in 2013−2015 (LS1) and 2018−2022 (LS2), during which the CMS detector was upgraded to ensure effective operation at high luminosity of more than 10^{34} cm^{-2}s^{-1} in pp−collisions at the nominal LHC energy $\sqrt{s}$ =14 TeV. Starting from 2027 the LHC will be running at luminosity of $\mathscr{L} = 7.5\times10^{34}$ cm^{-2}s^{-1} (High Luminosity LHC, HL−LHC) that will allow increasing statistics by more than one order of magnitude ($\mathscr{L}_{int}$ ~ 3000 fb^{-1}). From 2025 to 2027, a long stop (LS3) is planned for the modernization of the LHC. The main task of upgrading the CMS installation during this period is to ensure the efficient operation of all systems in conditions in the HL–LHC mode.

In 2020−2023, JINR physicists participated in the processing and analysis of Run 1 and Run 2 data, were responsible for the maintenance and operation of detector systems in accordance with M&O category B. In accordance with the memoranda of understanding between CERN and JINR, the main areas of work under the CMS facility upgrade program were: upgrade of the muon system (CMS Muon system) and the hadron calorimeter (HCAL), and the construction of a high granularity calorimeter (HGCal).

In total, during the reporting period, JINR physicists contributed to the preparation 22 journal publications (five of them are articles of CMS collaboration), 5 notes of the CMS collaboration, 5 reviews in monographs and 2 patents. The complete list of publications of the CMS collaboration for 2020−2023, which includes JINR representatives, includes more than 250 scientific papers. The results of the work were also presented in 68 reports at conferences and workshops. Two habilitation and two master's theses were defended on the subject of the works. The main results are included in the regular reviews of particle physics by Particle Data Group, the results of the study were awarded the JINR Encouraging Prize for 2021, the first prize of the JINR VBLHEP for 2021, the second prize of the JINR VBLHEP for 2020.

2.2. A detailed scientific report

2.2.1. A description of the work carried out and the results obtained for all projects and activities of the theme.

In 2020–2023 JINR participation in the CMS Physics Program was focused on the processing and analysis of Run 1 and Run 2 data collected in proton-proton collisions at energies of 8 and 13 TeV in the c.m. with total integrated luminosity up to 160 fb^{-1}. It also included the development of algorithms for the reconstruction of high-energy muons, the development of algorithms for the restoration and correction of jets. At the same time, Run 3 data taking, processing and analysis were being prepared, Run 3 was successfully started in mid-2022. The works were carried out in the following areas:

- search for new physics with two leptons in the final state and testing the scenarios beyond the SM (gravity at the TeV scale, extended gauge models, scenarios with dark matter candidates, processes with lepton flavor violation, etc.);
- search for new physics with two leptons/two b-quarks and a missing transverse energy in the final

state and testing the scenarios beyond the SM (search for the extended Higgs sector and dark matter candidates);

- study of the properties of the Higgs boson and the search for new scalar bosons beyond the SM in the channels of decay into leptons and pairs of b-quarkss
- study of muon pair production in the Drell–Yan process to test the SM predictions at the new energy range, measure the weak mixing angle, and probes of quark and gluon distribution functionss
- study of the QCD jets and refinement of fragmentation functions.

In total, JINR physicists are responsible for 9 physics analyses, including software development, simulation, software development.

Search for new physics with dimuons

One of the priorities of modern particle physics is the search for violations of the SM predictions. Such violations in a channel with a pair of leptons can serve as a sign of new physics, for example, production of new neutral gauge bosons Z′ from models of the Grand Unification (GUT), Kaluza-Klein (KK) graviton states in scenarios of multidimensional gravity with a reduced fundamental scale, or candidates for dark matter (DM) particles. In addition, this channel is sensitive to the existence of new light Higgs states predicted in models with a non-minimal construction of the Higgs sector with two doublets and one singlet of Higgs fields, 2HDM+S (in particular, in the non-minimal supersymmetric NMSSM model, as a particular case of 2HDM+S) and in other more extended versions [1-2].

If no evidence for BSM physics is observed at $\sqrt{s}$ =13 TeV. Upper limits are set at 95% confidence level on the ratio of the product of the production cross section and the branching fraction in a dilepton channel of a new spin-1 and spin-2 resonances. A notable feature is that the limits have been calculated in a model-independent way in the narrow width approximation to enable straightforward reinterpretation in any model predicting a resonance structure. The example of observed and expected upper limits is given at the Fig. 1 [3].

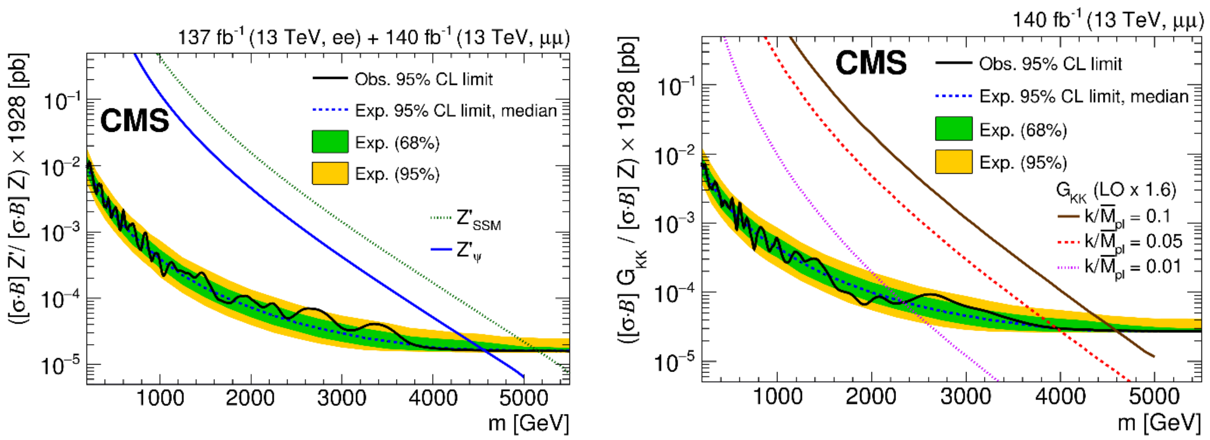

Fig. 1. The upper model-independent limits at 95% CL on the product of the production cross section and the branching fraction for a spin-1 (left) and spin-2 (right) resonances, relative to the product of the production cross section and the branching fraction of a Z boson, multiplied by the theoretical value of 1928 pb [3]. The shaded bands correspond to the 68% and 95% CL for the expected limits. Simulated predictions for the spin-1 Z′SSM and Z′ψ resonances as well as for the spin-2 resonances for coupling parameters k/MPl of 0.01, 0.05, and 0.10, respectively, are shown for comparison.

Comparison of the observed upper limits with theoretical predictions made it possible to establish [1] fundamentally new experimental limits on the masses of heavy resonances predicted by these models and a number of other model parameters. In a channel with a pair of muons, the existence of new neutral gauge bosons is excluded at $\sqrt{s}$ =13 TeV (Fig. 1, left) in the region of masses less than 4.89 TeV/c^2 for the SSM model and 4.29 TeV/c^2 for the ψ model (one of the TBO scenarios). Combining data in the muon and electron pair production channel expands these limits to 5.15 TeV/c^2 and 4.56 TeV/c^2, respectively. Depending on the value of the ratio of the curvature of the multidimensional anti-de Sitter space κ and the fundamental Planck mass (0.01–0.1) of the RS1 scenario, the restrictions on the mass of the graviton KK state were 2.34–4.59 TeV/c^2 in the μ+μ− channel, with the combined (μ+μ− and e+e-), the limit reaches 2.47–4.78 TeV/c^2 (Fig. 1, right). These limitations significantly improve previous measurements in the dilepton channel both at $\sqrt{s}$ = 7 and 8 TeV and at 13 TeV on an incomplete amount of data.

The limits are interpreted in the context of two types of models resulting in resonances at high dilepton masses: Z′ particles of U′(1) gauge group models and spin-2 gravitons in Randall–Sundrum model of extra dimensions. We consider sequential SM (SSM) and superstring-inspired and GUT models that predict spin-1 resonances [3]. In general, the observed limit on narrow spin-1 and spin-2 resonances presented in Fig. 2 can be translated into limits on generalized couplings in several classes of new physics models.

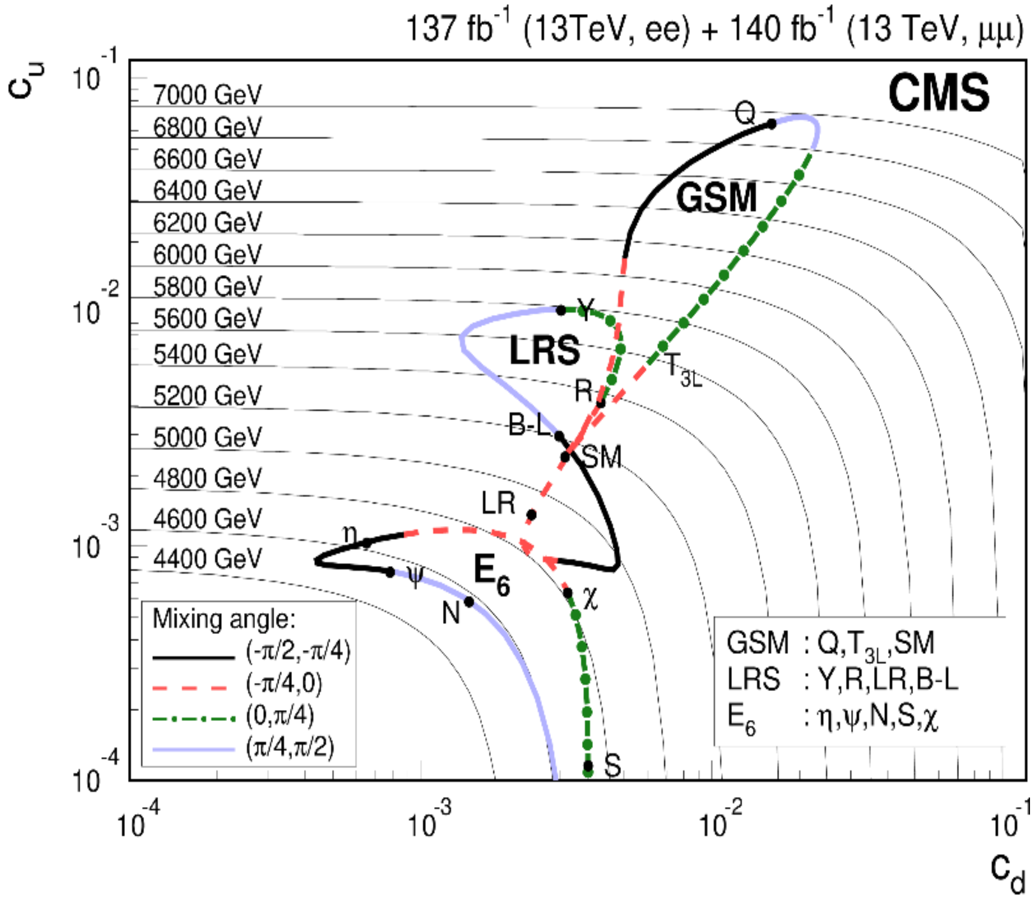

Fig. 2. Lower limits in the (c_u,c_d) plane obtained by recasting the combined limit at 95% CL on the Z' boson cross section [3]. For a given Z' boson mass, the cross section limit results in a solid thin black line. These lines are labeled with the relevant Z' boson masses. The thick curve segments represent the GSM, LRS, and E_6 model classes of extended gauge segments.

By generalizing the results obtained with Run 1 and Run 2 data, projections (Fig. 3) were estimated for the mass limits of the new heavy boson Z′ of the extended gauge sector of the SM, which can be achieved when the LHC operates in the high luminosity mode (1000–3000 fb-1). For the SSM model, the kinematic limit is predicted in the region of about 7 TeV at energy $\sqrt{s}$ = 13 TeV, which corresponds to 7–8 TeV at $\sqrt{s}$ = 14 TeV.

In 2022−2023, Run 3 data collection at the LHC collider has started at energy of $\sqrt{s}$ =13.6 TeV. The available statistics on dimuon events with an integral luminosity of 37 fb^{-1} has been processed and various distributions have been studied.

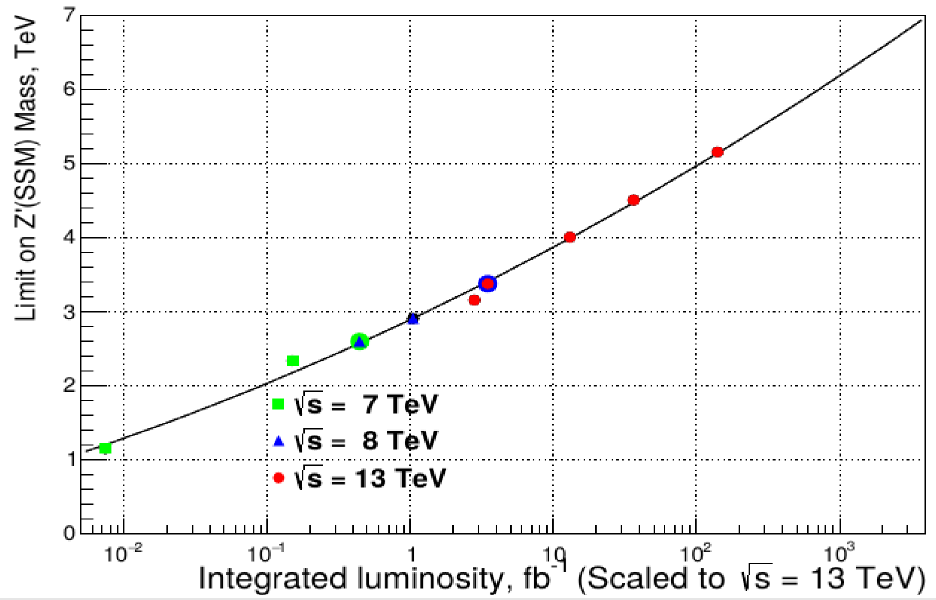

Fig. 3. The CMS mass limits observed at $\sqrt{s}$ = 7, 8, and 13 TeV for the hypothetical gauge boson Z′ in the SSM model as a function of the integrated luminosity scaled to 13 TeV.

The possibility for search for heavy resonances in the dilepton channel at the high-luminosity LHC (HL–LHC) was studied. It is shown that the expected mass limit for the extended gauge boson is 6.85 TeV for the reference model (SSM). The 5σ cross section limits (including branching to the muon pair) range from 9.0×10^{-5} pb for a resonance mass of 1 TeV to 1.8×10^{-6} pb at 7 TeV. In this case, at the HL-LHC there could be detected bosons Z_{SSM} and Z_{ψ} with masses up to 6.27 TeV and 5.72 TeV, respectively.

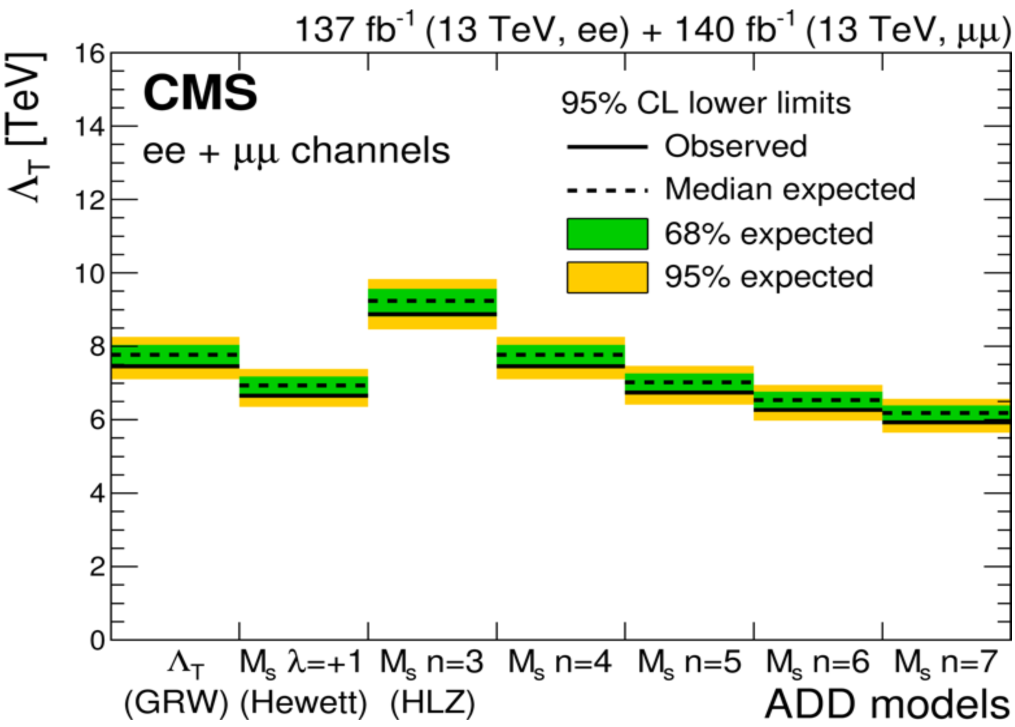

Fig. 4. Exclusion limits at 95% CL on the ultraviolet cutoff for the combination of dielectron and dimuon channels in the GRW (first bin), Hewett (second bin), and HLZ conventions (third to seventh bin) for the ADD model [34].

Upper limits are set on the cross section of non-resonant production of muon pairs with virtual exchange of KK-states of the graviton, and most stringent experimental constraints on the fundamental scale of multidimensional gravity Λ_T and M_S are obtained in an alternative description, depending on the number of extra dimensions n in the ADD model (Fig. 4) [3]. Similar to the case of searching for a resonant signal, the limits are set both independently in the $\mu^+\mu^-$ and e^+e^- channels, and in the combined dilepton channel.

Based on the Run 2 LHC data, the limitations on the value of M_S for the number n = 3–7 at the 95% confidence level were 5.8–8.6 TeV, and on the value of Λ_T of 7.2 TeV [1]. The combined analysis of the muon and electron channels established stronger limits: $M_S \geq 5.9$–8.9 TeV and $\Lambda_T \geq 7.5$ TeV. The scale of contact interactions was limited to $\Lambda > 23.9$–35.8 TeV, depending on the model under consideration.

Lepton flavor universality (LFU) is tested at the TeV scale for the first time by comparing the dimuon and dielectron mass spectra [34]. One of the rules of the standard model is that bosons such as the Z boson will decay equally into muons and electrons. But if the standard model is incomplete, the data could show a preference for one type of lepton over the other. We searched for this at high masses for the first time! Unfortunately, we didn’t see strong evidence of any preference (although there were some small deviations due to an excess of electron events, which we should keep an eye on in the future). Figure 5 shows the ratio we observed.

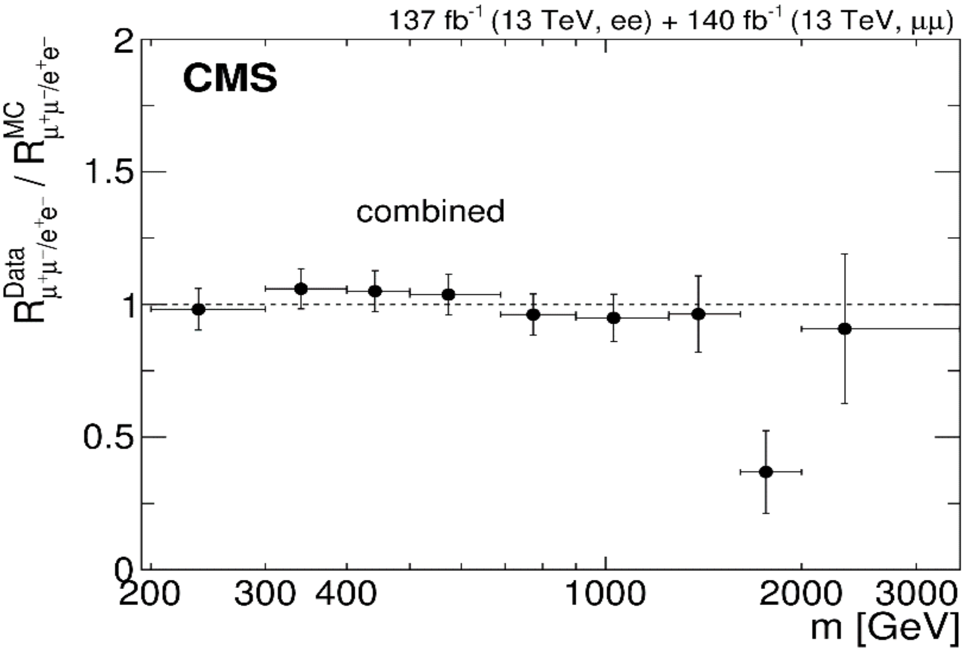

Fig. 5. The ratio of the decay probabilities of the Z-boson шт the electron and muon channels, obtained in the CMS experiment; for comparison, also shown the SM prediction (dashed line) [3].

The possibility for tests of the universality of the lepton flavor search in the dilepton channel at the high-luminosity LHC (HL–LHC) was studied. It was demonstrated that it can be performed with an accuracy of 5 times better than the current one, therefore a significant improvement in the sensitivity of the search for new physics is expected.

Searches for dark matter candidates and new higgs states

In a channel with a pair of oppositely charged leptons, an experimental search was made for the carrier of interaction between the SM fields and the dark matter sector [1, 3]. In the absence of a significant excess of the signal over the expected SM background, within the framework of a simplified Dark Matter (DM) model (one Dirac DM particle and one mediator between SM and dark matter sector), upper limits (95% C.L.) on the masses of the DM particles and both axial-vector and vector mediators are established. (Fig. 6). Assuming a vector mediator with a suppressed coupling constant with leptons ($g_q = 0.1$, $g_l = 0.01$), the limit on the mass of the mediator m_{med} is 1.92 TeV/c^2 at large masses of a candidate for the DM particle. In the case of equal coupling constants of the axial vector carrier with leptons and quarks ($g_q = 0.1 = g_l = 0.1$), the limit on m_{Med} is much higher and reach 4.64 TeV/c^2. In the region of low masses of DM particles ($m_{DM} = 0$), the mass limits for mediators are 1.04 and 3.41 TeV/c^2, respectively.

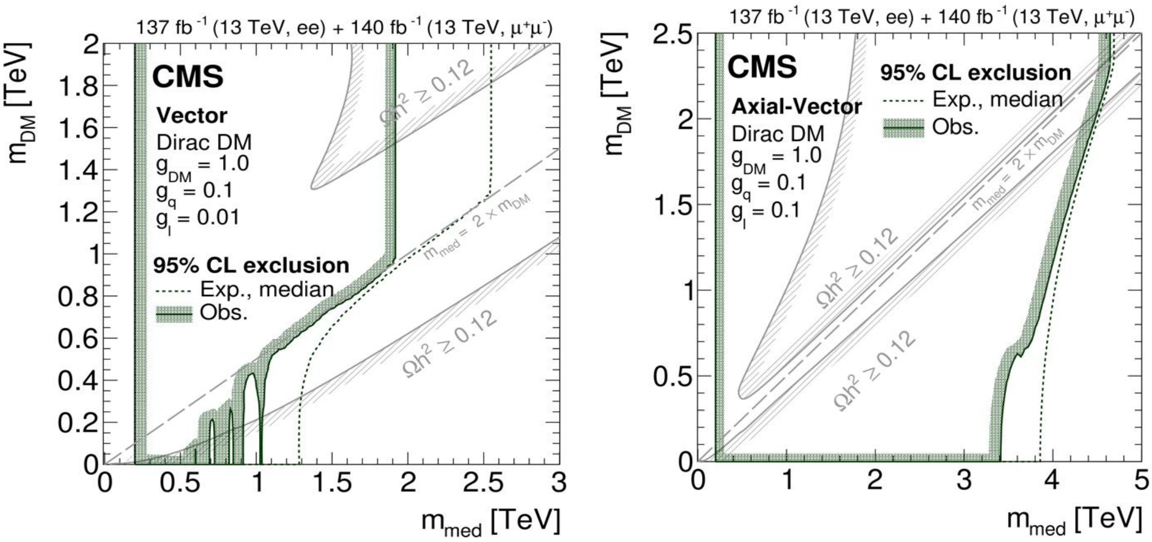

Fig. 6. Summary of upper limits at 95% CL on the masses of the DM particle, which is assumed to be a Dirac fermion, and its associated mediator, in a simplified model of DM production via a (left) vector or (right) axial-vector mediator [3]. The curves with the hatching represent the excluded regions. The solid gray curves, marked as "$\Omega h^2 \geq 0.12$", correspond to parameter regions that reproduce the observed DM relic density in the universe, with the hatched area indicating the region where the DM relic abundance exceeds the observed value.

Search for new Higgs states

A search for light pseudoscalar states is performed in proton-proton collisions having final states with pairs of muons and two b-quarks. An analysis of a part of the Run 2 data (L_{int} = 35.9 fb^{-1}) did not confirm the results of the Run 1 analysis on the observation of a peak in the spectrum of muon pairs in the region of 28 GeV/c^2 with a local statistical significance of up to 4.2σ. For the final conclusion, it is necessary to analyze full Run 2 statistics [8]. With no evidence for a signal, the observed 95% confidence level upper limit on the product of the inclusive signal cross section and the branching fraction, relative to the SM Higg boson production cross section σ_h = 5–36 fb^{-1}. The branching fraction is limited by (1–6) $\times 10^{-4}$.

The complete analysis of the 2017 data set was carried out and the events were compared with the result of processing by the SINP MSU group, the analysis note AN-21-089 was supplemented with new sections describing the selection of muons, the use of the dimuon vertex fit and the filter for bad global muons.

Search for lepton flavor violation

A generalized analysis of the results and prospects of the searches for signals from multidimensional low-energy gravity was performed under conditions of limited LHC energy (14 TeV) [9]. It is demonstrated that the LHC has reached the threshold of its capabilities in observing the possible signals of semiclassical multidimensional black holes (RS- and ADD-type). Further data collection during the Run 3 LHC and HL-LHC will not change much in this situation, and the next interesting window of opportunity will open only in the FCC era if this project is approved in the future.

However, there is and still remains a window of opportunity for so-called "quantum" black holes, i.e., states with low entropy (mass) that can be produced near the threshold of multidimensional gravity. Their distinctive experimental signature is the decay into a two-particle state with flavor violation (eμ/eτ/μτ). The mass limits for quantum black holes range from 3.6 to 5.6 TeV/c^2, depending on the model and the number of extra dimensions n.

Tests of Standard Model with dilepton and jet production

The differential cross section dσ/dm of the Drell–Yan process is measured in the range of invariant masses of a pair of leptons from 15 to 3000 GeV/c^2 at the proton interaction energy $\sqrt{s}$ = 13 TeV. The values of the measured cross sections are in good agreement with the SM predictions (NNLO QCD and NLO ES) in the entire range of invariant masses. These results were confirmed by independent measurements in the electron pair channel and in the muon pair channel, which also coincide. To analyze the statistics on the Monte Carlo data, we continued to study the background induced by photons in the events of muon pair production. The background value was estimated, and the accuracy of cross section calculations was studied depending on the statistics used.

The differential cross section dσ/dm in the dilepton mass range 15 to 3000 GeV is measured with proton-proton collision data at a centre-of-mass energy of 13 TeV. The measurements are in good agreement with the NNLO QCA and NLO EW theoretical calculations. These results were obtained independently both in the dielectrons and dimuon channels, and in their combinations.

The forward-backward asymmetry of pairs of oppositely charged leptons (dimuons and dielectrons) produced by the Drell-Yan process was measured as a function of lepton pair mass [6]. In addition, the analysis is continued to measure the angular coefficients in the different intervals of the mass, rapidity and transverse momentum of the lepton pair. The full statistics of RUN2 is used. For the first time, preliminary results were obtained both for the Z^0 region and beyond it [7].

One-loop electroweak and QCD radiative corrections are calculated in the Drell–Yan process at ultrahigh energies and invariant masses of a lepton pair. A detailed numerical analysis of the effects of radiative corrections to the observed cross sections and forward-backward asymmetry was carried out for the CMS experiment in the RUN3/HL–LHC mode [8−15].

A new technique is developed for calculating the contribution of two-boson exchange diagrams with one and two complex masses to the cross section of the four-fermion process. The method was applied to take into account the radiative corrections to the differential (with respect to the invariant mass) and doubly differential (with respect to the invariant mass and velocity of the pair) cross sections, as well as the forward-backward asymmetry of the Drell–Yan process in the CMS experiment in the Run 3/HL–LHC mode [8 −15].

One-loop electroweak radiative corrections to the process of dilepton production in the photon fusion channel are estimated for the LHC experimental program for studying the Drell–Yan process. A detailed numerical analysis of the effects of electroweak radiative corrections to observables (cross sections and forward-backward asymmetries) in a wide kinematic region was performed for the CMS LHC experiment in the Run 3/HL-LHC mode [8−15].

The multiplicity of charged particles in jets was measured [16–20]. A method has been developed for measuring the fraction of gluon jets in a sample of jets, which uses Monte Carlo (MC) quark-gluon (q/g) templates - the MC distribution of q/g jets over the likelihood discriminator. The fraction of g jets was measured in the semileptonic ttbar channel, in the channel with two jets (“dijet”), and in the channel of inclusive jets (Fig. 7). The results of measurements of the gluon fraction show a strong suppression of g-jets relative to theoretical and model predictions. Based on the measured fraction of g-jets, a data-motivated correction of the MC q/g-patterns is proposed.

A technique has been developed for measuring the characteristics of q/g jets, which is based on measuring the fraction of g jets in a sample of jets. This technique was applied to measure the average multiplicity of charged particles in q/g jets for the data of CMS periods Run 1 and Run 2 in the dijet channel. Figure 8 shows the average multiplicity of charged particles in q/g jets. The unstable behavior in the transverse momentum region of 300 GeV is due to the small difference in gluon fractions between the dijet–1 and dijet–3 samples. A generalization of the method for measuring the gluon fraction in samples of hadron jets was proposed. It is shown that together with the measurement of the fractions of quark and gluon jets, it is possible to measure the fraction of jets with an unidentified flavor.

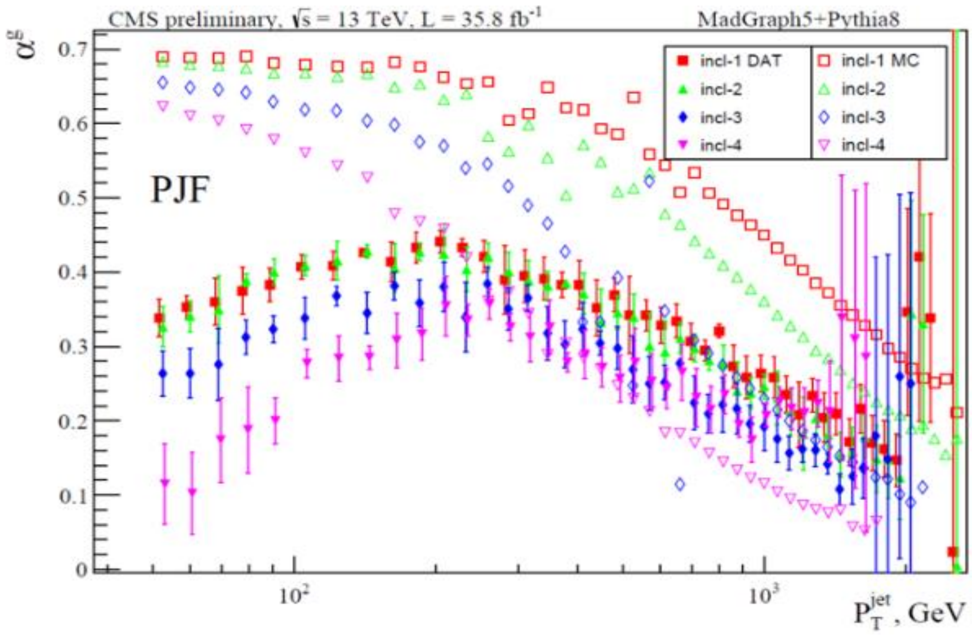

Fig. 7. Measured g-fractions in inclusive jets. The results are presented both for Monte Carlo (empty markers) and for the CMS RUN2 data (2016) (solid markers) in the four jet rapidity intervals. Four kinematic jet velocity ranges are considered: [0, 0.5] (“incl-1”), [0.5,1] (“incl-2”), [1, 1.5] (“incl-3”), [1.5, 2] ("incl-4").

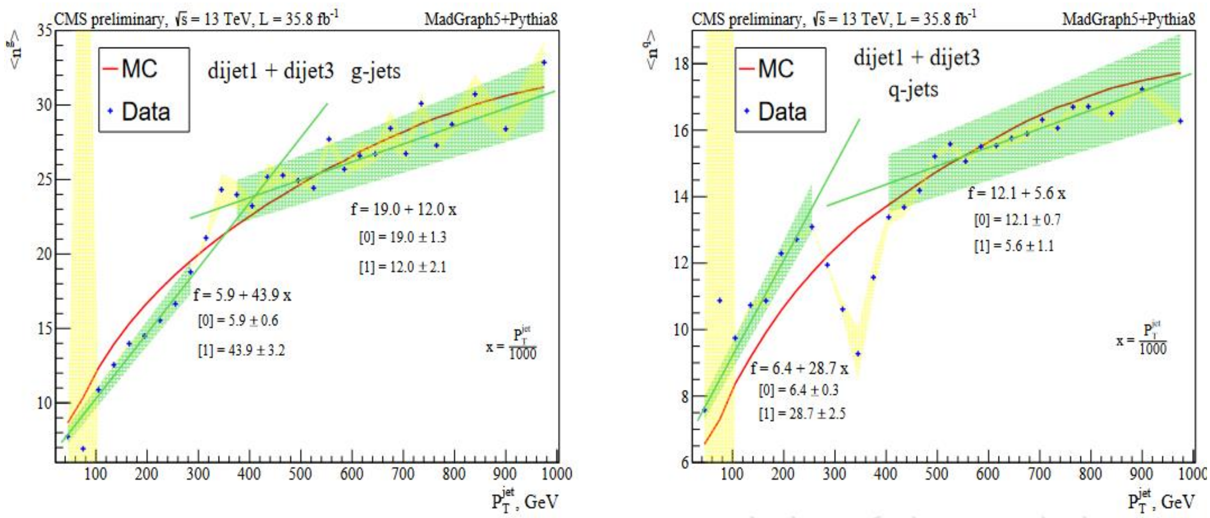

Fig. 8. Mean CPM in g-jets (left) and in q-jets (right) obtained by measured g-fractions in two jet samples of the “dijet” channel with RUN 2 data.

Reconstruction of physics objects

Reconstruction of muons and muon pairs

A detailed study of the characteristics of high momentum muons has been performed with the Run2 data. These muons could provide a direct access to new physical regimes beyond the standard model. Since physics and reconstruction of these muons differ from their lower momentum counterparts, special studies of the efficiency and momentum resolution of high momentum muons obtained in the CMS have been presented for the first time.

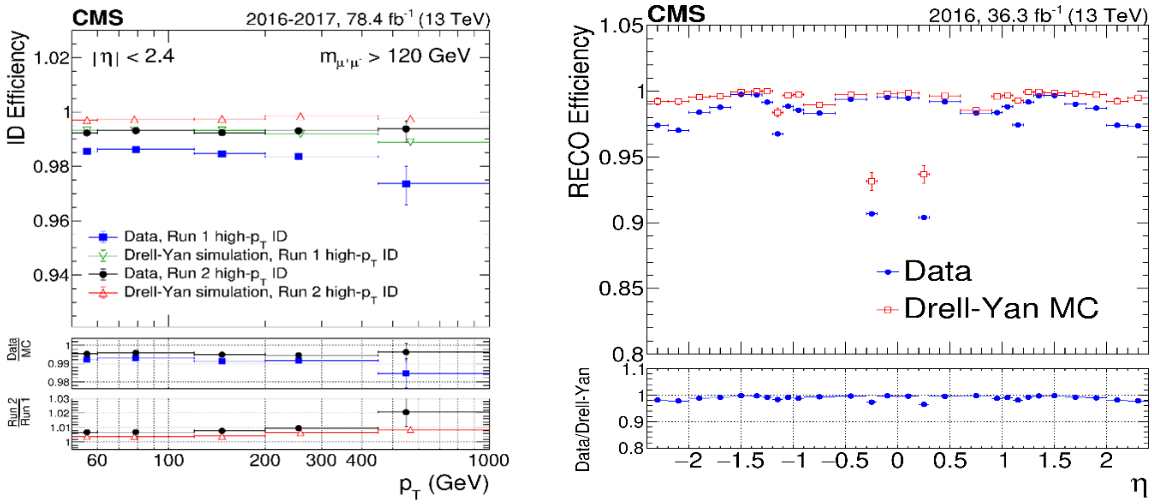

Fig. 9. The muon identification (left) and reconstruction (right) efficiency as a function of the muon transverse momentum p_T [25]. The events with dimuon invariant mass greater than 120 GeV. The RUN1/RUN2 data and Monte Carlo data are presented.

The high efficiencies of identification and reconstruction (Fig. 9) of muons, high accuracy of reconstruction, and low error in incorrect determination of the charge sign (Fig. 10) have been achieved. The momentum dependence of the muon momentum resolution was studied using two muon tracks formed by cosmic muons. The data and the Monte Carlo are in good agreements for the Drell–Yan process.

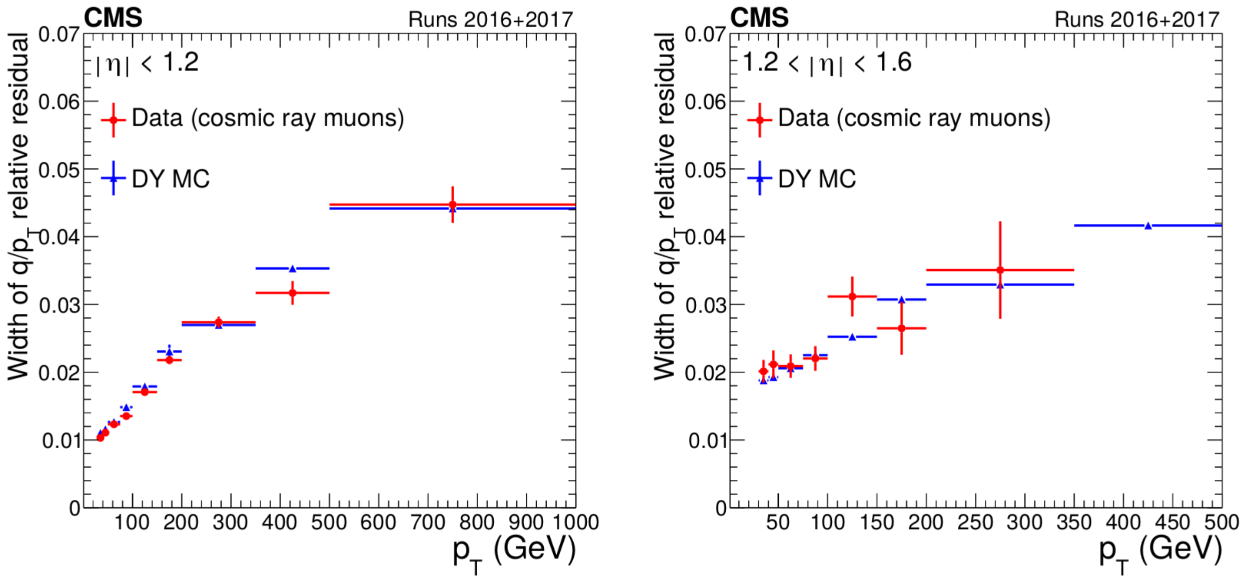

Fig. 10. The width of the Gaussian distribution of the momentum resolution as a function of the transverse momentum of cosmic muons in the 2016–2017 data [L1]. Three different datasets were used, obtained both in the proton-proton collisions and in the runs of the cosmic muon dataset. A comparison is made with the results of Monte Carlo simulations using Drell–Yan processes, and a good agreement is observed.

Development of CSC track-segment reconstruction algorithm

With the start of the HL–LHC, a significant increase of background is expected for the coordinate detectors of the CMS Endcap. This will distort the signals from the CSC strips and ultimately degrade the spatial resolution. To improve the accuracy of the spatial coordinate reconstruction in the CSC, a new algorithm was developed using "wavelet analysis". The algorithm is capable to separate up to 4 overlapping signals on strips with high accuracy (Fig. 11). As one can see from the figure one of the signal coordinates (with the lowest amplitude!) coincides with the initial muon coordinate.

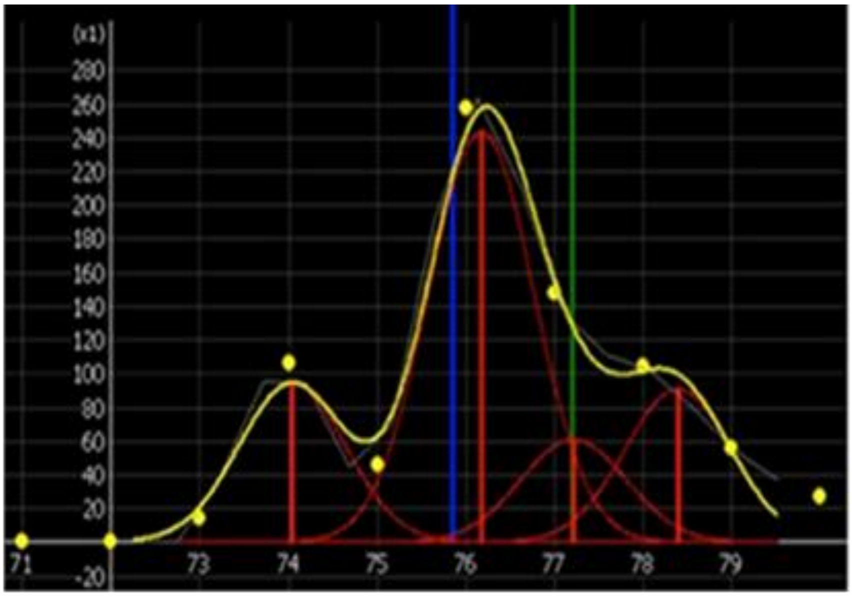

Fig. 11. An example of the reconstruction of four overlapping signals on a single CSC layer (ADC value vs strip number). The green line is the MC simulated (true) coordinate of the muon; yellow – the noise-smeared signal distribution; blue – coordinate restored by the standard algorithm; red – 4 overlapping cathode signals recognized by the proposed algorithm.

For the same purpose, a faster algorithm for separating two overlapping signals was developed. It showed the same accuracy as the algorithm using "wavelet analysis", but at the same time, the speed of finding the coordinates turned out to be an order of magnitude faster. As seen in Fig. 12, track-segments that contained hits recovered from overlapping signals became longer, and their χ^2 decreased when using the proposed approach, which should lead to a more accurate reconstruction of the global muon trajectory.

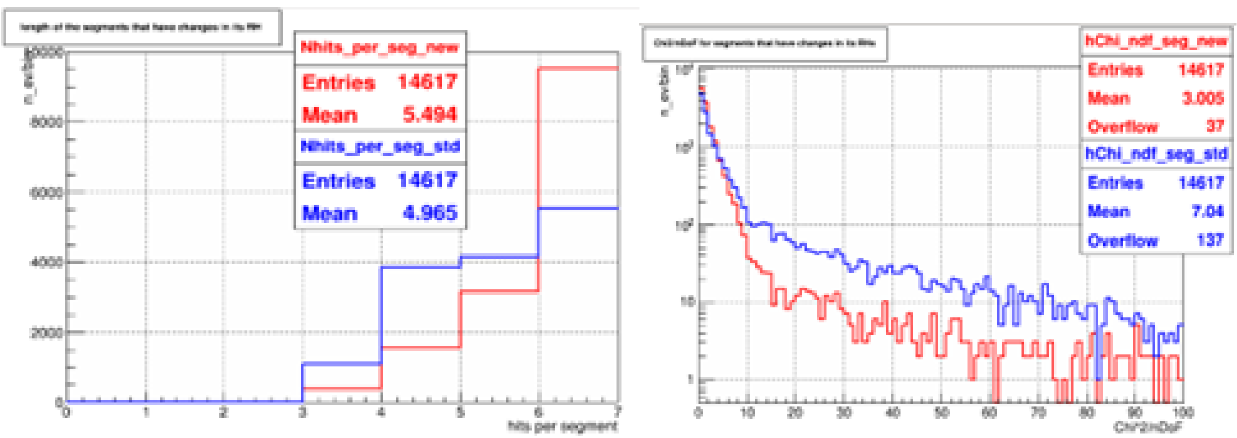

Fig 12. Track-segment length in hits (left), standard deviation of hits from the track segment χ^2/NDF (right) for modified muon track segments. Blue - standard; red - proposed approach.

For ME1/1 CSC, which has a different design from the other chambers, the algorithm for hit and track-segment reconstruction was adjusted. The use of new algorithms led to a more accurate reconstruction procedure in the CMS muon system and in the ME1/1 CSCs in particular (Fig. 13). The author's code has been implemented into the official CMS software and will be used by default starting with the LHC Run3 data taking.

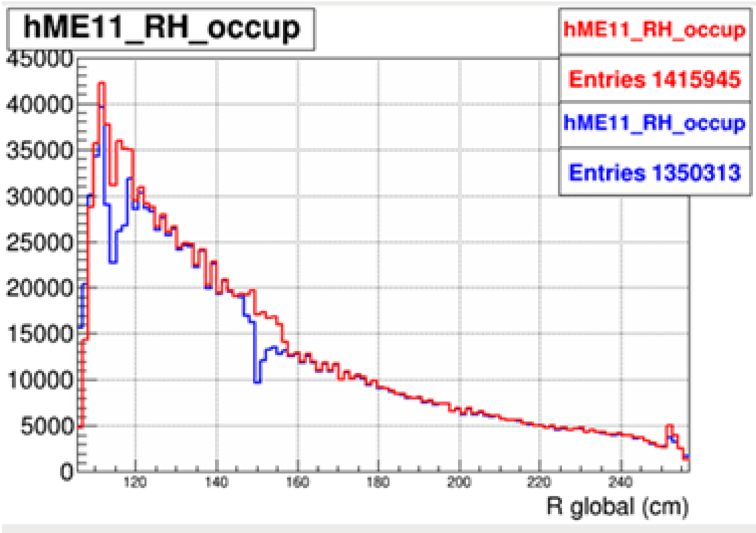

Fig. 13. Distribution of hits in ME1/1 CSC vs radial coordinate R. The new algorithm (red) eliminates the inefficiency of hit reconstruction in the R=115cm and R=150cm zones, which is typical for the standard algorithm (blue).

Development of Muon DQM Software

The JINR CMS group contributed to Muon POG Data Quality Monitoring activities. Our group is involved both in CMS software release validation and in Data Certification (DC) software development. We are developing software to automate DC and employ machine learning (ML) algorithms.

Upgrade of the CMS Detector

Starting 2010, JINR takes part in the upgrade of the CMS experiment to be developed in two stages, the purpose of which is:

– The Phase 1 of the CMS upgrade is to ensure the setup efficient operation at LHC high luminosity –2×10^{34} $cm^{-2}s^{-1}$ and up to center-of-mass energy 14 TeV. These works were completed during the two long technical stops in 2013–2015 (LS1) and 2019–2022 (LS2).
– The Phase 2 is scheduled for 2027–2038, 2027 LHC will begin operation with high luminosities reaching 5×10^{34} $cm^{-2}s^{-1}$ (High Luminosity LHC, HL–LHC), that will allow to increase statistics by more than one order of magnitude (Lint ~3000 fb−1). During the LS3 in 2025–2027 the major LHC upgrade to HL–LHC is planned. The related CMS upgrade will ensure effective operation of the detector to provide the efficient operation at the high HL−LHC.

In 2020-2022 the JINR group took an active part in the completion of the Phase 1 upgrade of the HCAL hadron calorimeter, and the modernization of the CMS muon system and preparations for construction of the high-granularity calorimeter (HGCal) within the Phase 2 program. All work is carried out within the framework of the obligations assumed in accordance with the Memorandum of Understanding for Collaboration in the Construction of the CMS Detector between CERN and JINR, relevant Addenda and Memorandum of Understanding on participation of JINR in the CMS Phase-2 HGCal Project.

Upgrade of the ME1/1 Cathode Strip Chambers

The main task of ME CSC modernization during LS2 period is upgrade of CSC electronics of the inner rings of CMS Muon Endcap stations MEx/1. The 120 new Low Voltage Distribution boards (LVDB-5) and the test stand for LVDB5(7) boards have been designed and constructed by JINR physicists.

Totally 180 chambers were dismounted from the CMS, moved to the surface laboratory, refurbished with the new electronics, tested, and finally reinstalled in the experimental cavern. In addition, for 72 ME1/1 CSCs the on-chamber cooling systems have been replaced. Tests of the assembled chambers were done with cosmic rays.

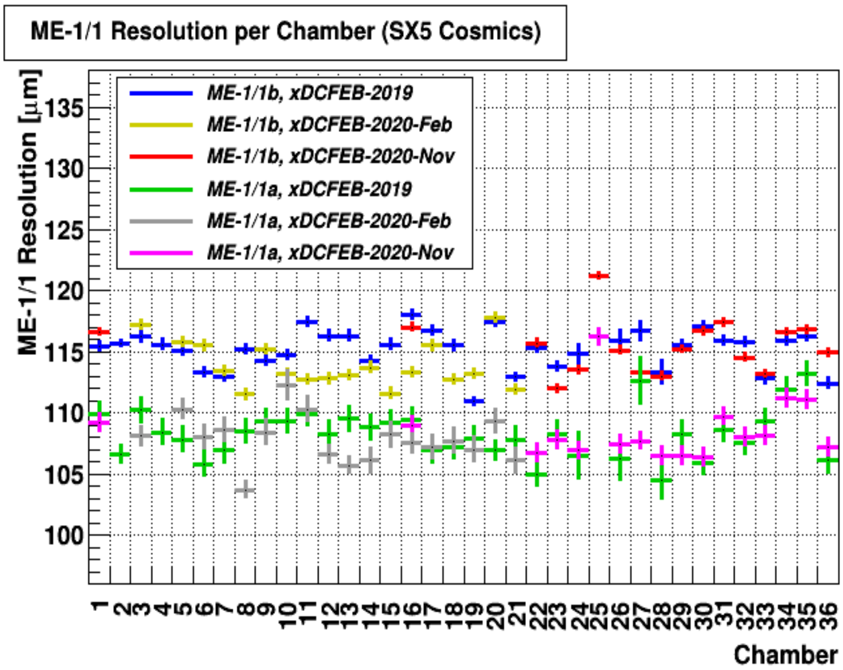

Fig. 14. Spatial resolution of the refurbished ME1/1 CSCs with cosmics.

Totally 180 chambers were dismounted from the CMS, moved to the surface laboratory, refurbished with the new electronics, tested, and finally reinstalled in the experimental cavern. In addition, for 72 ME1/1 CSCs the on-chamber cooling systems have been replaced. Tests of the assembled chambers were done with cosmic rays. The ME1/1 chambers test results are shown in Fig. 14, which presents the spatial resolution of the chambers. The results obtained in 2020 are in good agreement with the 2019 ones.

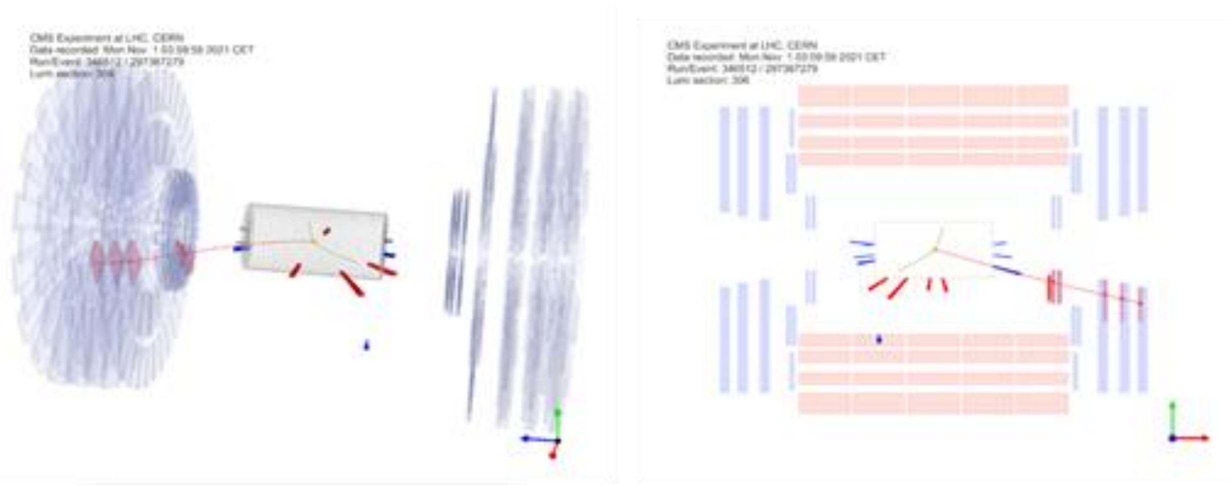

Fig. 15. Event display of the CMS pp-collision with a global muon registered in the Endcap muon stations.

In 2021 Endcap CMS muon stations started operation in the CRAFT test and first LHC pp-collisions runs. Fig. 15 shows two projections of the CMS IP event where collision muon is registered by 4 Endcap muon stations including ME1/1 and newly installed GE1/1 station.

CSC in the CMS data taking with p-p collisions in Run3, 2022

Figure 16 shows the spatial resolution of the CMS Endcap muon stations during the 2018 and 2022 data taking periods at pp interactions. The statistical errors are negligible. Systematic errors do not exceed 1−2%. At the end of the data set in 2018, the operating voltage was lowered for most stations to reduce the effect of radiation ageing of the chambers (2018D"').

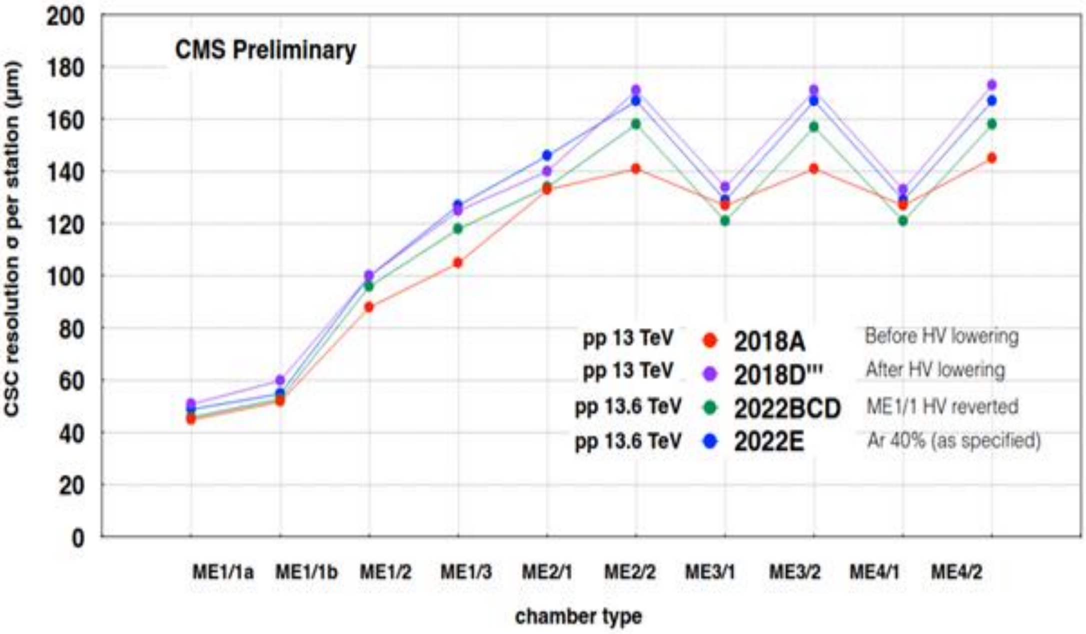

Figure 16: Spatial resolution of CMS Endcap muon stations.

During the initial data set period, 2022BCD, the CMS gas system was operated at a higher argon content in the mixture (~41% vs. 40% nominal), resulting in improved spatial resolution for all stations. It must be concluded that the data from 2022E and 2018D" are in good agreement. Figure 17 shows the Z→μμ decay event recorded by four CMS end muon stations.

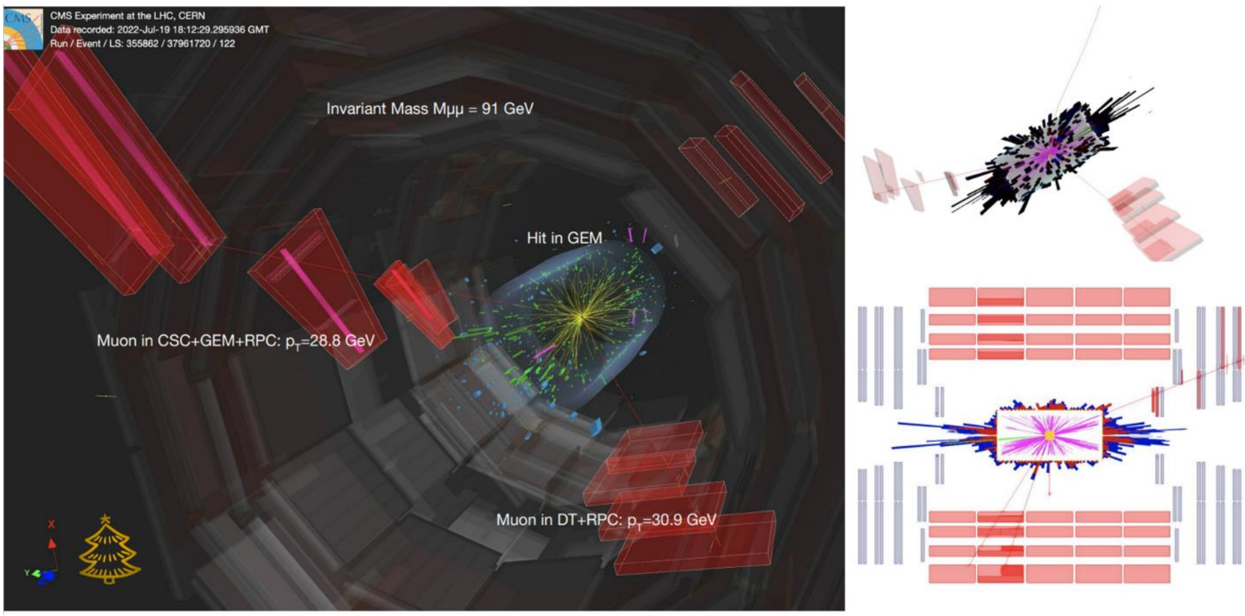

Figure 17. Z→μμ decay event recorded by the four stations of the CMS Endcap muon system.

The design of integration of the ME1/1 cables and services was done in the framework of the JINR commitments to the Phase 2 of CMS upgrade. A conceptual design of the ME1/1 patch panel (ME1/1 PP) modification was made to release space for the laying cables and services of the new HGCal calorimeter. A full-scale prototype of the ME1/1 PP has been constructed. ME1/1 PP is a complex device that includes 2 active interface boards (PPIB) for communication with electronics in the peripheral crates (Figure 18). The production drawings are being developed by JINR group for the manufacture of 36 ME1/1 PP, which will be installed on the YE1 disks in the LS3 period.

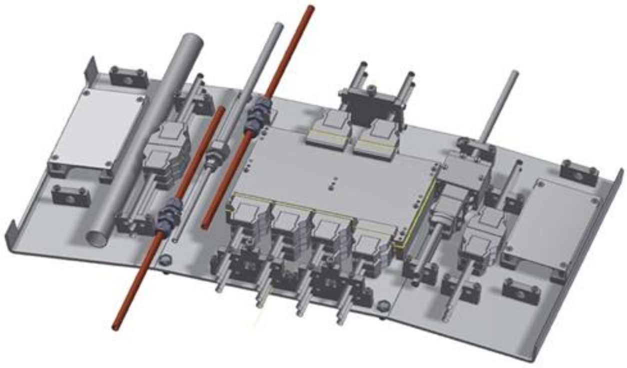

Figure 18. The ME1/1 patchpanel (left – 3D model, right – prototype).

Studies of the CSC at the GIF++

The JINR team participated in CSC tests at the GIF++ facility at CERN. The tests were carried out on H4 SPS muon beam with a GIF++ Cs137 gamma-ray source with an activity of 12 TBq using absorption factors from 4.6 to 100. The study was done with full-scale CSCs. CSC operation with gas mixtures with different CF4 contents, ageing effects and chamber performance with high background were studied.

The results show that the spatial resolution of the full-scale CSC ME1/1 is stable up to an accumulated charge of 706 mC per centimeter of anode wire length (Figure 19). The value of this charge is 3 times higher than expected during the lifetime of HL–LHC.

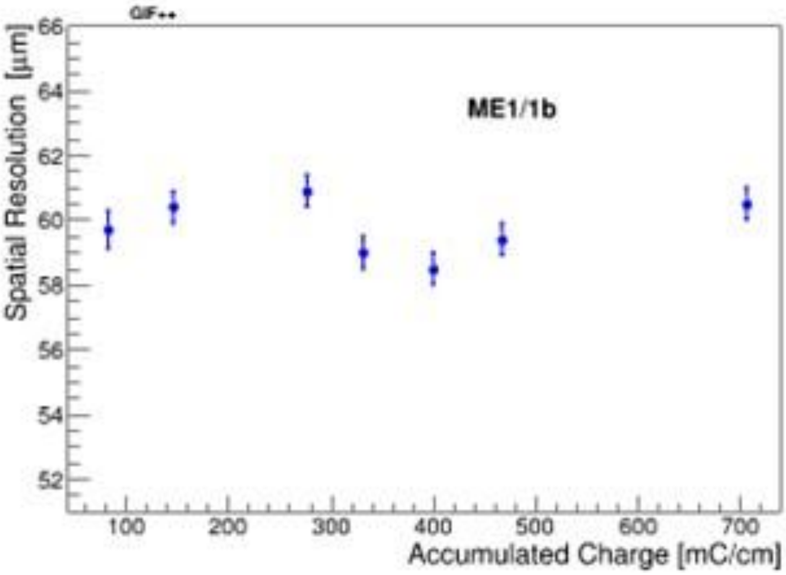

Figure 19: Spatial resolution of ME1/1 CSC as a function of accumulated charge.

JINR physicists are participating in experiments to study the characteristics of CSC and the effects of aging detectors when working with new gas mixtures, which are planned to be carried out both with laboratory radioactive sources and at the GIF++ facility. The CF_4 gas currently used in the CSC gas mixture is a member of the fluorocarbon class of greenhouse gases with a very high global warming potential of 7390. In the near future the use of such gases will be drastically restricted. Therefore, in addition to the CSC tests carried out at the GIF++ facility using reduced content of CF_4 in the mixture, it was decided to start investigations of new gas mixtures excluding greenhouse gases in their composition. The JINR staff took part in the design and construction of a new gas mixer to study the operation of chambers with eco-friendly gas mixtures (Figure 20). Also, for these works, a group of JINR staff members designed and manufactured at CERN six two-layer mini-cameras (mini-CSC) with a small sensitive area of 30x30 cm2. They will be used to study the effects of ageing and to investigate the operation of CSCs with new gas mixtures.

Fig. 20 Gas mixer for mini-CSC (left). Mini-CSC panel production (right).

Upgrade of the Hadron Calorimeter during LS2 shutdown

During the long-term technical shutdown of LS2 2019–2022 (Long Stop 2), the JINR team carried out a cycle of works aimed at modernization of CMS Hadron Calorimeter readout electronics systems and commissioning of the modernized systems. The modernization of the readout electronics system of the Hadron Barrel Calorimeter included both the replacement of the multichannel hybrid PD (HPD) with a new silicon photomultiplier (SiPM) and the replacement of all elements of the corresponding system.

JINR group has created a test-stand for long-term burn-in tests of readout electronics components using SiPMs for HB Calorimeter. Testing of the readout modules for Hadron Barrel Calorimeter was based on the analysis of single-two-photoelectron charge spectra and on spectrum analysis for the impulses of calibrated light emitting diodes.

Following preparatory work in 2018-2019, the new readout electronics system was installed on CMS detector. Specifically, 144 readout modules were replaced, 4 for each 10-degree sector of two Hadron Barrel Calorimeters, new SiPM bias voltage supply system was installed, 36 calibration modules and 72 clock and control modules, two modules for each sector of the HB Calorimeter, respectively.

During the Hadron Barrel Calorimeters commissioning work, the amplitude and pedestal characteristics of newly installed electronics system were studied. The electronics channels were pre-calibrated based on the measurement of light output level from HB Calorimeter scintillators using the high-intensity radioactive source Co^{60}.

Hadron Forward readout system has been transferred from single mode to multi mode readout. All LV power supplies for Hadron Forward calorimeters and its related infrastructure (power, control, and safety systems) were moved to an area with reduced background radiation (up to 5 Sv by 2026), also a project of the improvement of HCAL racks air cooling system was developed and implemented.

During the first year of the Run 3 data taking (2022), JINR team provided a full methodological and technical support for a high efficiency operation of Hadron Calorimeters, including Barrel, Endcap, Outer and Forward calorimeters. After LHC started its operation, the amplitude and timing signals of the upgraded HB readout electronics were aligned by using data from proton-proton collisions. During RUN3 a weekly certification of proton-proton collision data for HCAL components has been performed. So far, 37.6 fb-1 have been selected to satisfy the conditions of the physical program, with losses in hadron calorimetry not exceeding 3.6% of the collected data. During the 2022 data taking, a number of outages were detected in several clock and control modules in HE and HB: 5 modules out of 108 showed unstable operation on the primary communication line and have been switched to their secondary communication line. The faulty modules were replaced during the year-end technical stop in 2022–2023. In the process of newly installed modules commissioning, both communication lines of all 108 clock and control modules installed on the detector were checked. The 8 secondary communication lines (not used in detector operation since installation in 2019) for the corresponding eight modules were found to be out of service. These modules were also replaced. The reasons for the failures of the extracted modules are being investigated.

Installation of modified low-voltage power supplies for CMS HCAL is finished. Work was carried out on the installation of voltage-spike protection circuits for the low-voltage power supplies. As a part of the program of readout box replacement scheduled for the LS3 in 2026–2028, there is the work continuation on measuring readout box temperatures under different loads and different water-cooling flows, as well as in different modifications of the readout box mechanics and cooling elements. The new cooling circuits design as well as a program of the HB readout box replacement are under development. This replacement can only be done during the long technical stop LS3. Also, given the full-scale, including mechanical works, modernization of CMS detectors and the replacement of relevant equipment during LS3, it was decided to dismantle all the readout modules from Hadron Barrel Calorimeters. In addition to moving readout modules to a safe place (to a special lab) for the duration of LS3, there is an opportunity to upgrade the barrel calorimeter frontend electronics for operation in hard radiation background and increased luminosity conditions. This project, as well as the project of intermediate modernization of the Hadron Calorimeter within LS3, is under development.

Construction of the high granularity calorimeter

The created calorimeter with high granularity (HGCal) is the result of a deep modernization of the endcap of the hadron calorimeter (HCAL) of the CMS spectrometer. This will significantly increase the spatial and temporal resolution of the detector at the next period of the accelerator operation in high-luminosity conditions. The main requirements for the HGCAL are summarized in the HGCal CMS project and the JINR project “Upgrade of the CMS Detector”.

The HGCAL calorimeter consists of continuity layers of the absorber, the gaps between which are placed cassettes with active elements of the detector. The HGCAL is structurally divided into electromagnetic (CE-E) and hadron parts (CE-H).

The longitudinal structure (along the beam direction) includes 47 layers (Fig. 21). The first 26 layers form the electromagnetic section of the calorimeter (CE-E). The next 21 layers form the hadron section (CE-H): the first 7 layers of the inner part of the CE-H are similar to the layers of CE-E, and the last 14 include both silicon modules and scintillator cells with light registration using SiPM. The use of two technologies for active element, one’s based on semiconductors (silicon sensors in CE-H and the inner part of CE-H), and the other is scintillators (in CE-H); optimizes the cost of HGCAL and support the required characteristics. The whole calorimeter sits in a thermally shielded volume that will be cooled by a two-phase CO2 system and maintained at –30°C.

The obligations for the construction of high granularity endcap calorimeters HGCal of CMS include HGCal cooling plates production, − manufacturing of the cassette testing facility, silicon sensors and SiPM purchases, testing of cassettes, assembly and commissioning of HGCal.

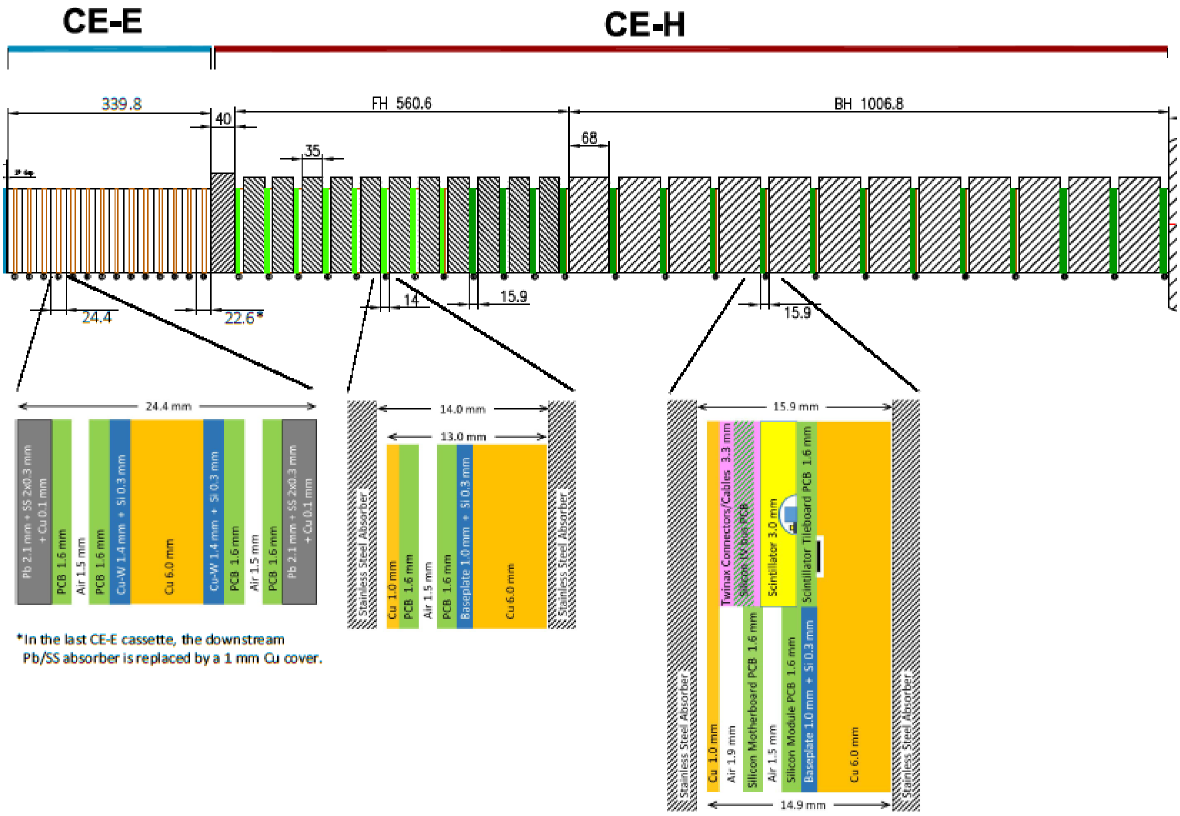

Fig. 21. Longitudinal structure of the HGCAL with cross-sections of the three types of cassettes: CE-E cassettes, CE-H silicon sensor cassettes, and CE-H mixed silicon/scintillator cassettes.

Construction of the experimental complex for the HGCal cassettes tests

The condition and characteristics of the assembled CE-E and CE-H cassettes must be checked in the cooled state up to –30°C. The cassettes prepared for testing are planned to be placed in a heat-insulated room between two scintillation planes that detect cosmic particles passing through the entire set of detectors. In the assembly area, you need to place two such rooms. The number of rooms is determined by a 14-day testing period in a cooled state up to-30OC. It is planned to use the room alternately to carry out "cold" tests of the detectors in one room and in parallel to carry out service work on the extraction of the studied cassettes and preparation for testing a new batch of cassettes in another room. This mode will ensure a continuous production and testing process.

The cooling of the cassettes is planned to be carried out according to the working scheme using perfluorohexane C_6F_4 as a coolant instead of CO_2. The appearance and location of the cooling rooms are shown in Figure 22.

In the framework of the JINR responsibilities the design and construction of 2 dual use (CE-E and CE-H) multi-cassette cold-rooms for the HGCaL test facility was completed. Cold rooms will be delivered and assembled at CERN in 2023 fall.

The test system shown in Figure 23 consists of a low-temperature chamber, a rack for placing several cassettes of various types inside the chamber, and trigger scintillation plates located above and below the chamber. The illustration on the left shows the placement of the cassette inside the rack.

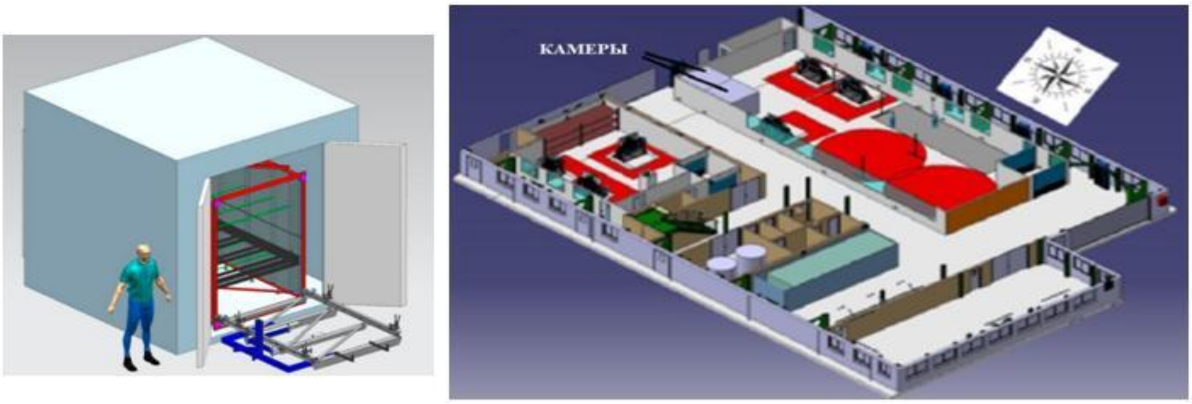

Fig. 22. Schematic view of the cooling chamber and loading platform and location of the cold storage rooms in the HGCAL assembly area in the SXA5 building.

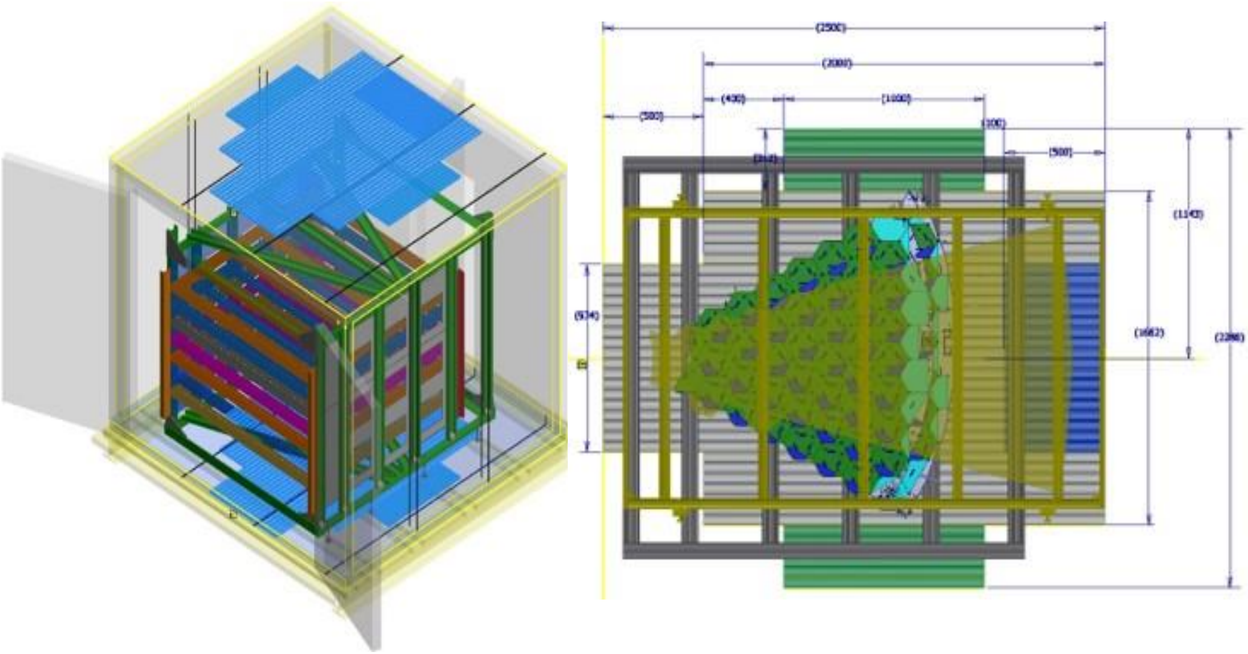

Fig. 23. Testing system for HGCal cassettes type CE-E and CE-H.

Simulation of the HGCaL cassettes test setup with cosmic muons in a cold room

The performance and characteristics of the assembled CE-E and CE-H cassettes must be checked in a cooled state down to -30 C. The cassettes prepared for testing are planned to be placed in a heat-insulated chamber between two scintillation planes that detect cosmic particles passing through the entire set of detectors. Cassettes are formed by hexagonal Si sensors (8-inch side size wafers) which in turn are subdivided into 432 hexagonal cells with 0.52 cm^2 size. The original plan was to place the trigger planes as close to the cassettes as possible, i.e., inside the cold chamber. On a later stage the possibility of placing trigger planes outside the chamber and the necessary changes in the geometry of trigger planes for this option were also evaluated.

Test stand geometry was implemented in a standalone simulation code based on GEANT4 package which includes Cold room, trigger planes and cassette racks description. Drawings of the cassette are presented on Figure 24.

Realistic cosmic muon momenta and polar angle distributions were modelled using Reyna parametrization function [1] using for normalization the CMS adopted value for 100 GeV vertical muons. The integral of muon flux over all momenta and angles with such function gives out 0.986 or roughly 1/cm^2 /min. Number of muons passing through the trigger planes (70000 cm^2 approx.) for 2 weeks is 1.4*10^9. We estimated muon flux for all cells of the cassettes using different trigger planes geometries, see Figure 25, upper row.

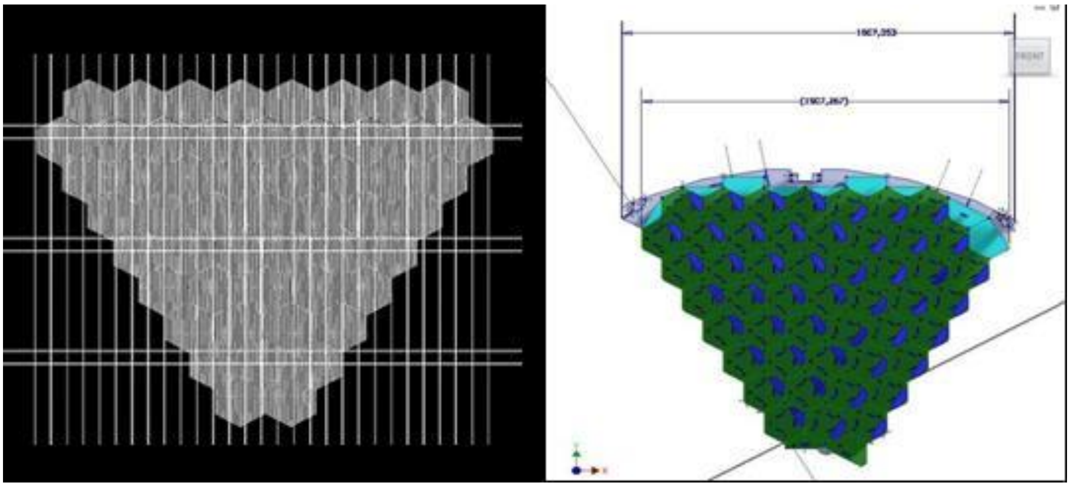

Fig.24 GEANT4 simplified model of the cassette (left) and realistic cassette drawing (right).

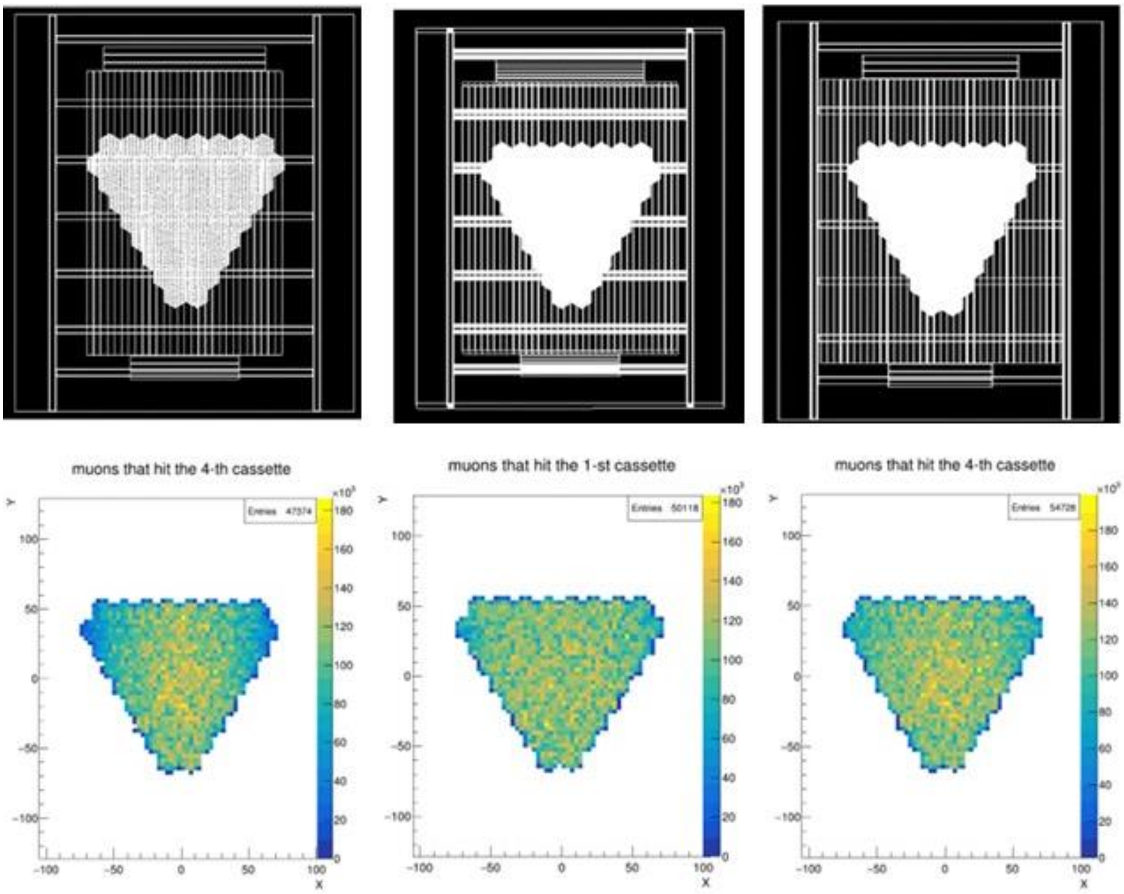

Fig.25 Trigger planes geometry (upper row) and 2d muon distributions (lower row) for various trigger plane widths, 150 cm (left plots), 180 cm (central plots) and 190 cm (right plots).

The widths of the trigger planes are: 150, 180, or 190 cm. 2d distributions of muons crossing both trigger planes and upmost cassette cells are shown on Figure 25, lower row. One can see lower statistics at the far most regions of the cassette, which are close the edges of the trigger planes.

Cells occupancies distribution for the widest cassette row for different trigger planes geometries, are shown on Figure 26, upper row. One can see lower occupancies on the far most edges of the cassette.

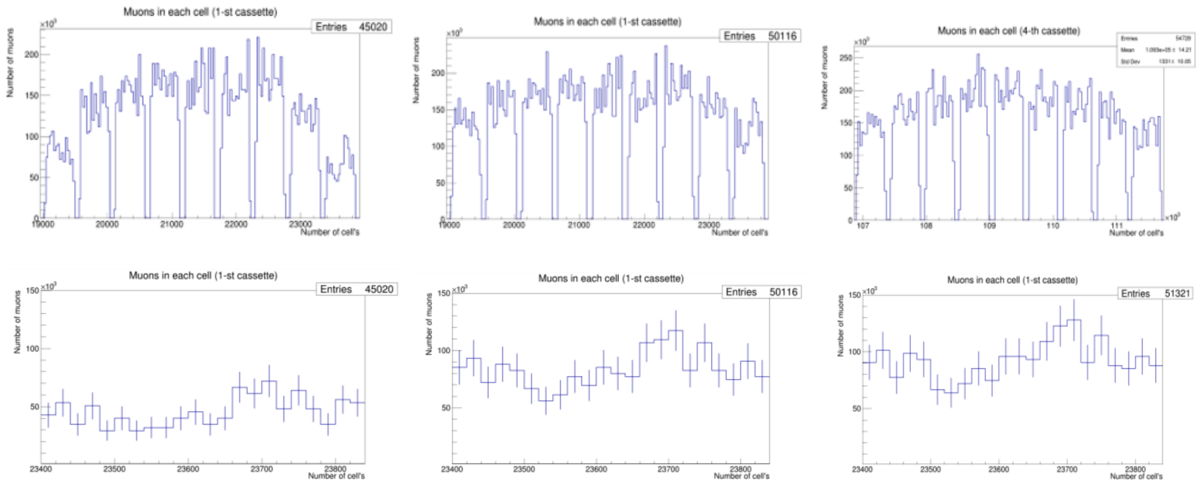

Fig.26 Cell occupancies for the widest cassette row (upper figure row) and zoomed distributions (lower row) for the worst regions, for trigger planes sizes of 150 cm (left plots), 180 cm (central plots) and 190 cm (right plots).

After proper normalization, the lowest statistics for two weeks of data accumulation are 2350 muons per cell with a trigger plane width of 150 cm, 4250 muons with a width of 180 cm, and 4700 muons with a width of 190 cm. If at least 8 active layers (out of 12) fired from a single muon, the corresponding statistics will be equal to 2000 muons per cell for a trigger plane width of 150 cm, 3300 muons for a width of 180 cm, and 3570 muons for a width of 190 cm. Our conclusion is that the width of the trigger plane should be chosen in the range of 180-190 cm in case of placing the trigger planes inside the room.

In order to facilitate access to the trigger planes, as well as to eliminate the negative effects of multiple cooling and heating cycles affecting the optical fibers used for signal collection from the trigger plane scintillators, the possibility of locating the trigger planes outside the cold room was also considered.

Preliminary modeling showed that if the trigger planes are placed outside the cold room, due to the greater distance between the trigger planes, the number of muons per cell will noticeably decrease and a significant change in the geometry of the trigger planes is necessary, also taking into account the limited amount of material available for the manufacture of scintillators (90 bars 200x5 cm on two planes). As a result, modified geometry of the trigger planes was proposed, shown in Figure 27.

As a result of the simulation, it was estimated that after proper normalization, the lowest statistics for two weeks of data accumulation is on the order of 1800-2000 muons per cell for the geometry presented in Figure 27. According to HGCAL TDR [3] the energy calibration should provide intercalibration precision of 3%. Initial S/N requirement for MIP for different sensor active thickness is 11 (300 μm), 6 (200 μm) and 4.5 (120 μm). Here values N and S correspond to the standard deviation of the noise amplitude (pedestal σ) and MPV for MIP signal (S) measured by an individual cell in ADC channels correspondingly. The results of the test measurements show that the signal statistics of about 1000 events should be sufficient to measure the MIP MPV with the desired accuracy. Thus, the proposed geometry of trigger planes located outside the cold room allows us to collect the necessary statistics.

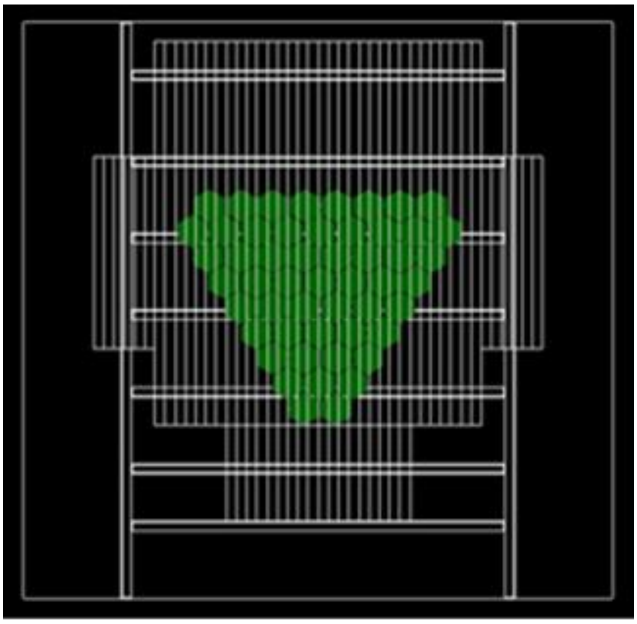

Fig.27 Simplified model of the trigger plane and GEANT4 cassette (right).

Cooling Plates for the High Granularity Calorimeter

The cassettes of the hadronic compartment of the calorimeter differ in type of active elements: CE-H (Si) cassettes with silicon sensors assembled into 6-inch hexagonal modules and CE-H (mixed) cassettes with a mixed set of active elements (silicon modules at the inner side and scintillator modules at the outer side). The total number of layers of the hadronic compartment of the calorimeter is 21 according to "Scenario 13" (Fig. 28).

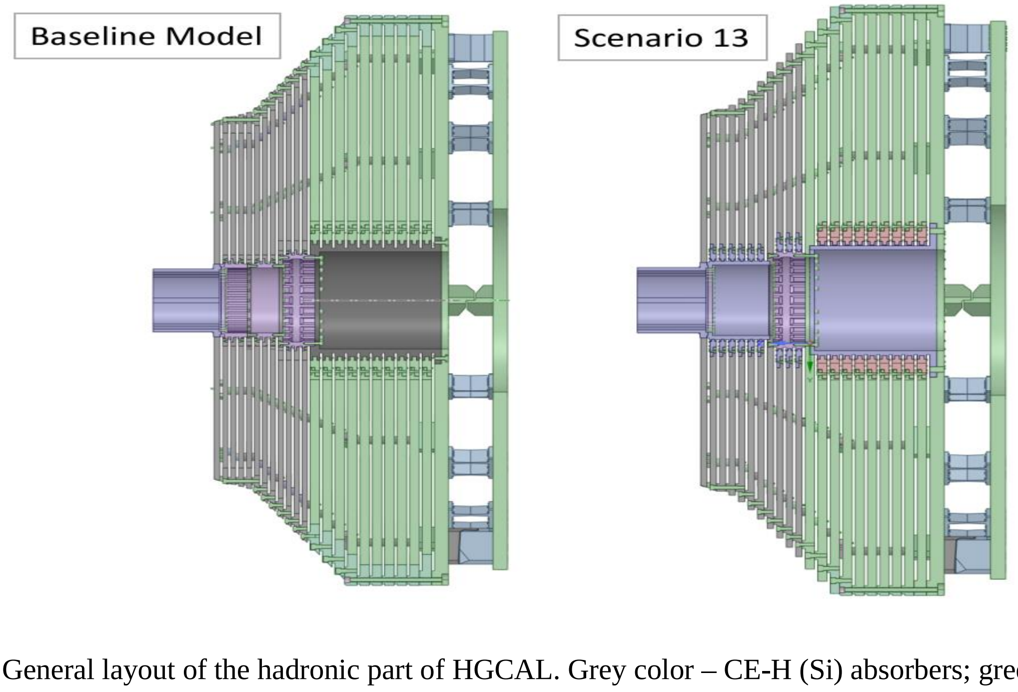

Fig. 28. General layout of the hadronic part of HGCAL. Grey color – CE-H (Si) absorbers; green – CE-H (mixed) absorbers; white gaps are used for cassettes mounting. "Scenario 13" – the latest calorimeter layout project with reduced number of layers.

The cassettes are based on the copper plates as a mechanical support for the silicon and/or scintillator modules and electronics. The cooling plates are made of high-purity oxygen-free copper sheets of 6.3 mm thickness with a set of mounting holes and a groove with a cooling circuit tube mounted (soldered) and provide efficient heat removal from the active elements of the cassette. The plate is designed to keep the temperature deviations on the surface within the limits of 1–2°C by regulating the coolant flow rate along the cooling circuit. Each calorimeter layer is divided into 12 segments, which make up identical 60-degree sections of 30-degree plates in pairs.

This project is aimed to produce the full set of the copper cooling plates for the hadronic part of HGCal (Fig. 29). The plates must be machined, tested, and delivered to CERN. Total number of plates – 546 including 5 to 10% spare items.

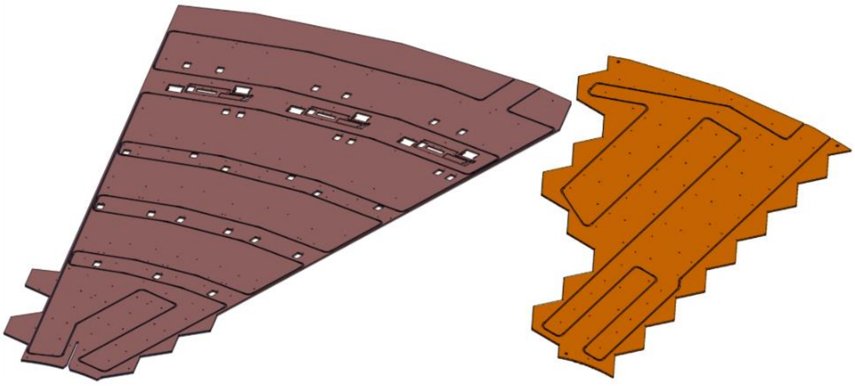

Fig. 29 Isometric view of CE-H cooling plates (layers L49-D and L29-B).

A total of eight different cooling plate prototypes were manufactured to work out the production technology (Fig. 30).

The effects of milling and tube soldering on the copper sheet flatness were studied. The various tube plating technologies (electroplating and spraying) and various Ni/Cu layer thickness were also tested to ensure the efficient tube bending and soldering procedures. The various tube bending algorithms were checked out.

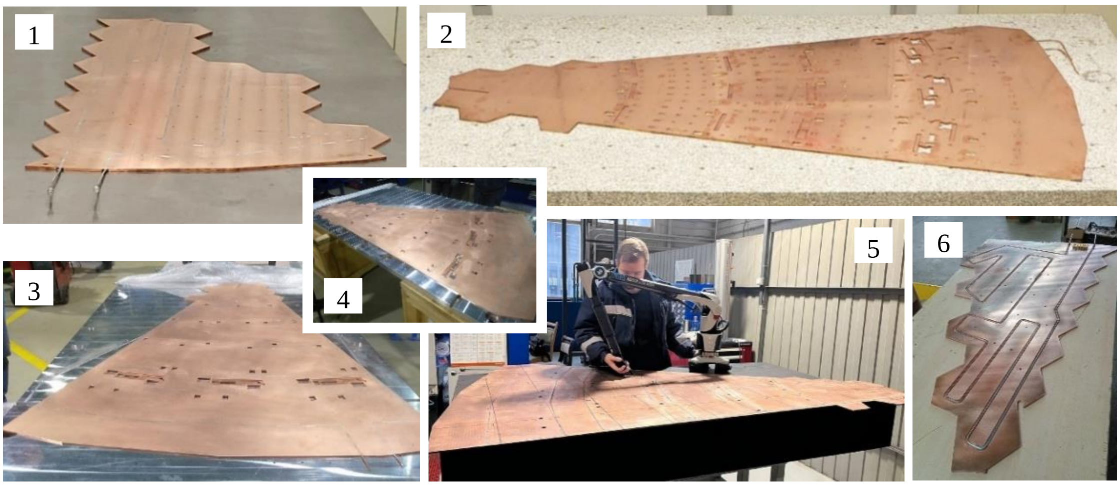

Fig. 30. HGCal CE-H cooling plate prototypes manufactured: 1 – small L29-B (late 2020), 2 – large L49-D (early 2021), 3–4 large pair L49-D и L49-D-inversed (late 2021), 5 – automatic soldered large L49-D (late 2022), 6 – press fitted small prototype L29-B (late 2022).

Also, various tube mounting technologies were tested: both manual and automatic soldering using a preheating table as well as the cold press fit and glue techniques. Several methods were developed to hold the tube at the bottom of the groove during the soldering process. The copper sheet of various hardness, thickness and rolling methods were tested. The various tube and groove tinning techniques were also worked out.

A number of feedback documents were provided to the HGCal collaboration summarizing the remarks and proposals from manufacturers on the technical specification and drawings of the cooling plates. The proposals were aimed to solve a few problems appeared due to poor documentation provided by collaboration: 1) the excessive strict tolerances for long-distance elements which are not really required for the experiment; 2) the discrepancy between documentation requirements and machining standards for both milling and copper sheet production.

The two enterprises with experience in mass production of accelerator and detector mechanics for CERN and JINR were involved into the project in 2020–2022: «Artmash» (Minsk) and «StroyTechProgress» (Minsk). One of vendors has proved to be ready for mass production of the CE-H cooling plates at the 0.2/200 mm flatness tolerance.

A series of prototype tests at CERN is planned for 2023. The task is to measure the efficiency of press-fit tube binding compared to automatic soldering. The purpose is to prove that one may avoid the hot soldering process to maintain the flatness of the copper sheet during processing. The mass production has to be started in 2024.

Development of software for distributed computation, data processing and analysis based on GRID-technology.

The JINR grid infrastructure for the CMS experiment is represented by the Tier1 and Tier2 centers. They are used for processing and storing data from the experiment, ensuring 100% availability and reliability of services.

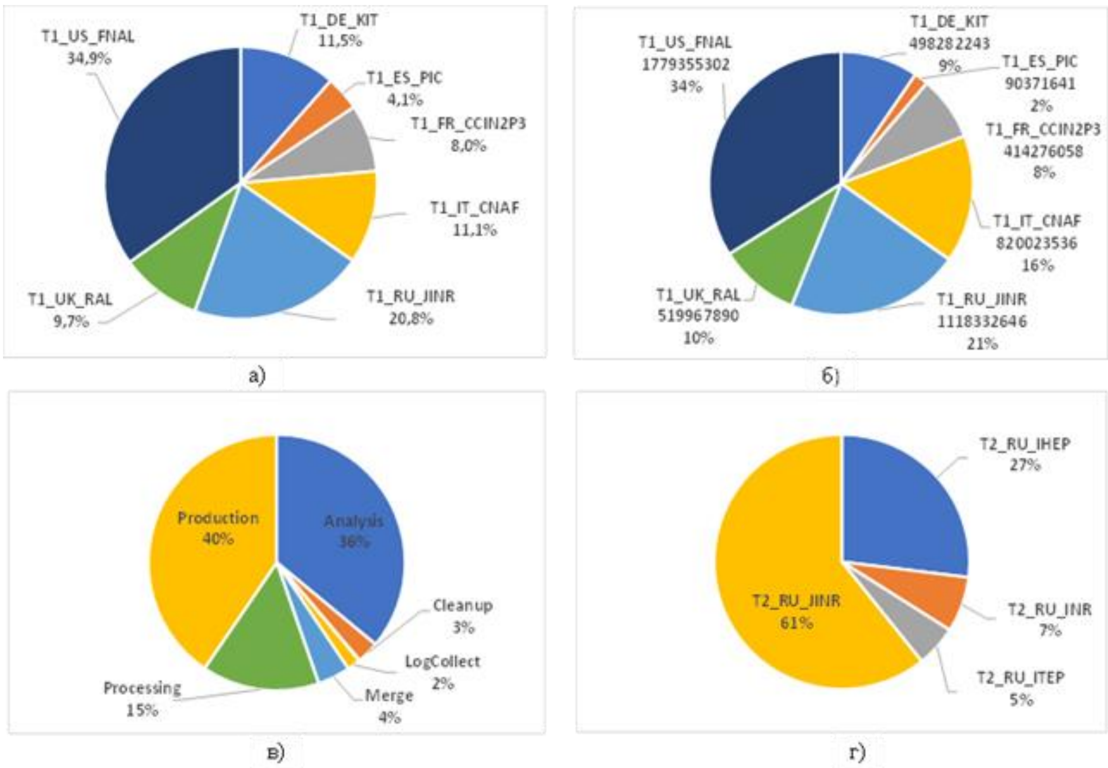

Fig. 31. Contribution of the world Tier1 centers to CMS experimental data processing in 2020-2023: a) distribution by the number of finished jobs; b) number of processed events; c) Statistics on the use of the JINR Tier1 center by the CMS experiment by different types of data stream processing in the jobs. d) Ratio of successfully processed jobs by Russian T2 sites

The Tier1 data processing system was increased to 18 656 cores, providing a overall performance of 1497365,628 kHS06. In terms of performance, Tier1 (T1_RU_JINR) is ranked second among all the Tier1 world centers for the CMS experiment (Fig. 31a). In 2020-2023 time period, more than 1.1 billion events were processed, which accounts for 21.3 % of the total number of processed events (Fig. 31b) and 20.8% of the total successfully finished jobs of all Tier1 centers for the CMS experiment.

Figure 31 (c) shows the number of jobs processed at the JINR CMS Tier1 center in 2020-2023 time period by different types of data stream processing (reconstruction, modeling, reprocessing, analysis, etc.).

The computing resources of the Tier2 center were expanded to 4416 cores, which provided an overall performance of 184190,115 kHS06 and gave the possibility to successfully process 6919141 jobs during 2020-2023, that represents 61% of the jobs processed by all Russian T2 sites in this time period (fig. 31d).

Participation in data taking shifts, maintenance and operation of the experimental complex

In accordance with the Memorandum of Agreement (MoA), each institute participating in the collaboration must perform a certain amount of maintenance and operation works of the experimental complex, including participation in computing (Experimental Physics Responsibilities, EPR). The amount of work is determined based on the total number of authors of the Institute and is expressed in months (EPR-months) spent on the execution of the work, in terms of the full time equivalent (FTE) (~4 FTE-months[1] per author). The EPR works also include obligations to participate in central shifts, calculation of participation in Central Shift Points (SCP)[2]. In 2020-2022, all JINR obligations were fully fulfilled (see Table 1).

Table 1. Fulfillment of JINR obligations for the maintenance and operation of the experimental CMS complex (including computing) in 2020-2023 (in EPR months).

EPR-months	2020	2021	2022	2023
Pledged work	88.61	91.85	81.32	84
Done work	98.95	105.00	83.5	
Central shifts (EPR/CSP)	1.78/38.69	0.23/5	2.86/62.17	
Done to pledged work ratio	1.14	1.15	1.06	

2.2.2. Key publications (list of bibliographic references).

1. A.M. Sirunyan et al. (CMS Collab.), "Search for resonant and nonresonant new phenomena in high-mass dilepton final states at 13 TeV ", JHEP 07, 208 (2021).
2. CMS Collaboration, "Sensitivity projections for a search for new phenomena at high dilepton mass for the LHC Run 3 and the HL-LHC", CMS-PAS-FTR-21-005, Mar. 2022.
3. M. Savina, "DM interpretations of heavy resonances and BSM-Higgs searches in ATLAS and CMS", The Eighth Annual Conference on Large Hadron Collider Physics-LHCP2020, 25-30 May, 2020, PoS(LHCP2020) 176; CMS CR-2020/229, Geneva, 2020.
4. D. Barducci et al., "Search for a mu+mu-+b-jet event excess at the dimuon mass of 28 GeV in pp collisions at $\sqrt{s} = 13$ TeV using full Run II dataset", Analysis Note AN-21-089, CERN, 2021, version of Mar. 2023
5. M. V. Savina and D. Seitova, “Program of Searches with the CMS Detector for Signals from Multidimensional Low-Energy Gravity at the Large Hadron Collider”, Phys. At. Nucl. 84 №2 (2021) 190–196 (Yad. Fiz. 84 №2 (2021) 149–155).

[1] In the CMS collaboration, the amount of work within Experimental Physics Responsibilities is expressed in EPR-months (1 EPR-month = 1 FTE-month)

[2] 1 EPR-month= CSP * 0.046

6. A.M. Sirunyan et al. (CMS Collab.), "Measurement of the Drell-Yan forward-backward asymmetry at high dilepton masses in proton-proton collisions at 13 TeV", CMS-PAS-SMP-21-002, arXiv:2202.12327, submitted to JHEP.
7. I. Gorbunov and V. Shalaev, "The Drell-Yan Angular Coefficients Measurement at 13 TeV", CMS-AN-2020-220.
8. V.A. Zykunov, "Perturabtive calculations in High Energy Physics", Skorina GSU, Gomel, 2020) 277 P., ISBN 978-985-577-625-4.
9. M.P. Buhayeuskaya and V.A.Zykunov, "NLO Radiative Corrections to the Drell–Yan Process at the LHC Run3", J.Phys.: Conf. Series. 1435, 012029 (2020).
10. V.A. Zykunov, "Effects of radiative corrections in the Drell–Yan process at ultra-high invariant mass of dilepton", Phys. At. Nucl. 84 № 4. (2021) 492– 512.
11. V.A. Zykunov, "Calculation of two-boson exchange with complex masses", Phys. At. Nucl. 84 №6 (2021) 867– 885.
12. V.A. Zykunov, "Influence of electroweak corrections on Z-resonance shape in neutrino production process", Phys. At. Nucl. 84 № 6 (2021) 856– 866.
13. V.A. Zykunov, "Two-boson exchange in polarized process with charged current", Phys. At. Nucl. 84, 192 (2022).
14. V.A. Zykunov, "Effects of electromagnetic radiative corrections in lepton pair production via photon-photon fusion at LHC", Phys. At. Nucl. 84, 500 (2022).
15. V.A. Zykunov, "Electroweak corrections to dilepton pair production via photon fusion at LHC", Phys. At. Nucl. 84, 9 (2023).
16. S. Shulha, D. Budkouski, "Methodology for measuring gluon jet fraction and characteristics of quark and gluon jets for hadron-hadron collisions", Phys. Part. Nucl. Lett. 18 № 2 (2021) 239-243, arXiv:2008.02054.
17. S. Shulha, D. Budkouski, "Measurement of mean charged-particle multiplicities in gluon and quark jets produced in pp-collisions at 8 TeV and 13 TeV with the CMS detector", CMS AN-2021/024; January 2021.
18. S. Shulha, D. Budkouski, "Measurement of gluon jet fraction and data-driven correction of quark and gluon jets likelihood discriminator distributions for jets selected in pp-collisions at 8 TeV and 13 TeV with the CMS detector", CMS AN-2020/143; August 2020.
19. S. Shulha, D. Budkouski, "On the measurement of the fractions of quark and gluon jets in hadron-hadron collisions", In Conference Proceedings "The Physics of the Dimuons at the LHC", June 23-24, 2022; PEPAN, 2023 (in print)
20. S. Shulha, D. Budkouski, "Simulation of measurements of the fractions of quark, gluon, and unidentified jets in jet sample for the LHC", In Conference Proceedings "The XXVI International Scientific Conference of Young Scientists and Specialists (AYSS-2022)", October 24-28, 2022; PEPAN Lett., 2023 (in print)
21. A.M. Sirunyan et al. (CMS Collab.), "Performance of the reconstruction and identification of high-momentum muons in proton-proton collisions at 13 TeV", JINST 15 (2020) P02027.
22. V.V. Palichik, N.N. Voytishin, "Moun Trajectory Reconstruction in the Cathode-Strip chambers of the CMS experiment", to be published in PEPAN.
23. M.V. Savina and S.V. Shmatov, "In Search for New Physics", in Essays on Modern Particle Physics. Eds. V.A. Matveev and I.A. Golutvin – Dubna: JINR, 2020 – p. 133–215, ISBN 978-5-9530-0506-7.
24. A.V. Zarubin, A.V. Lanyov, M.V. Savina, and S.V. Shmatov, "Physics with Heavy Dimuons", in Essays on Modern Particle Physics. Eds. V.A. Matveev and I.A. Golutvin – Dubna: JINR, 2020 – p. 290–317, ISBN 978-5-9530-0506-7.

25. I. A. Zhizhin, A. V. Lanyov, and S. V. Shmatov, “Search for Heavy Neutral Gauge Bosons in the Dilepton Channel in the CMS Experiment at the LHC”, Phys. At. Nucl. 84 № 10 (2021) 1–5.
26. I. A. Zhizhin, A. V. Lanyov, and S. V. Shmatov, “Searches for New Physics in the Dilepton Channel with the CMS Detector at the Large Hadron Collider”, Phys. At. Nucl. 84 №2 (2021) 184–189 (Yad. Fiz. 84 №2 (2021) 143–148).
27. A. V. Lanyov, S. V. Shmatov, I. A. Zhizhin, "Search for a High-Mass Dark Matter Mediator Decaying to Dilepton Final State in the CMS Experiment at the LHC", AIP Conference Proceedings, 2377 (2021) 030009.
28. I.A. Golutvin, S.V. Shmatov, "Plans and Prospects of the LHC Physics ", in Essays on Modern Particle Physics. Eds. V.A. Matveev and I.A. Golutvin – Dubna: JINR, 2020 - p. 99-111, ISBN 978-5-9530-0506-7.
29. I. Gorbunov, “Electroweak precision measurements in CMS”, CR-2020/148, Accepted by PoS.
30. I. Gorbunov, “Drell-Yan Measurements with the CMS experiment”, CR-2020/241, Accepted by PoS.
31. I.N. Grobunov and O.V. Teryaev, "Polarization Effects and Angular Distributions in Drell-Yan Process with the CMS", in Essays on Modern Particle Physics. Eds. V.A. Matveev and I.A. Golutvin – Dubna: JINR, 2020 – p.318–334, ISBN 978-5-9530-0506-7.
32. V.V. Shalaev, S.V. Shmatov, “Electroweak Physics with the CMS experiment at the LHC”, Phys. At. Nucl. 84 №1 (2021) 37–41 (Yad. Fiz. 84 №1 (2021) 20-25).

2.2.3. A complete list of publications on the theme.

The full list of publications on the theme for 2020-2023 includes in addition more than 250 articles of the CMS collaboration
https://cms-results.web.cern.ch/cms-results/public-results/publications/CMS/publi.pdf

2.2.4. List of papers presented at international conferences and meetings (electronic annex).

2.2.5. Patent activity.

1. S.V. Afanasiev, A.O. Golunov, N.V. Gorbunov, Yu.V. Ershov, “A method for positioning scintillation cells in segmented detectors and a device for its implementation”, Patent № 2776102.
2. S.V. Afanasiev et. al., “Scintillation detector”, Patent № 2748153.

2.3. Results of related activities

2.3.1. Scientific and educational activities.

The staff of the theme give regular lectures at the University of Dubna and the UNC JINR, are invited lecturers at schools on high energy physics.

1. S.V. Shmatov, “Experimental methods of elementary particle physics”, a regular course of lectures for masters of the 1st year of study. Dubna International University, UNC JINR.
2. M.V. Savina, “ Physics beyond the standard model”, a regular course of lectures for graduate students of the 2nd year of study. Dubna International University, UNC JINR.
3. M.V. Savina, “ Quantum Mechanics”, a regular course of lectures for undergraduate students. Dubna International University, UNC JINR.

4. S.V. Shmatov, “Physics at Energy Frontier”, course of lectures на Moscow International School of Physics, 24 July 2022 to 2 August 2022.

List of theses and dissertations defended.

1. S. V. Shmatov, “Investigation of the processes of dimuon generation in the CMS experiment at the Large Hadron Collider”, Dissertation for the habilitation degree of Doctor of Physical and Mathematical Sciences. Defended in the P.N. Lebedev Physical Institute of the Russian Academy of Sciences DC.002.023.04. The date of awarding the degree is March 5, 2020.
2. V.Yu. Karjavine,”Creation of an experimental complex of the front muon station of the Compact Muon Solenoid (CMS) installation ”, Dissertation for the habilitation degree of Doctor of Technical Sciences. Defense in the JINR DC.03.01.2022.P. Date of degree award – April 30, 2021.
3. K.V. Slizhevsky, "Search for a Dark Matter candidate particles in dilepton final state with missing energy”. Dissertation for a master's degree. The defense took place at Dubna University on June 22, 2022.
4. D.V. Budkouski, “Measurement of characteristics of gluon and quark jets produced in pp-collisions at 13 TeV with the CMS detector”, Dissertation for a master's degree. The defense took place at Dubna University on June 22, 2022.

2.3.2. JINR grants (scholarships) received.

1. I. Zhizhin, V. I. Veksler Scholarship for young scientists and specialists of the JINR VBLHEP for 2020. For the cycle of works “Searches for New Physics in the Dilepton Channel with the CMS Detector at the LHC”.
2. V. Shalaev, S. Shmatov, RFBR Grant: № 20-32-90212. Competition for the best projects of fundamental scientific research carried out by young scientists studying in graduate school ("Graduate students"), 2020.

2.3.3. Awards and prizes.

1. JINR Incentive Award for Research and Experimental work for 2021. For a cycle of works “Test of the Standard Model and search for new physics in the Dimuon Final State with the CMS experiment at the Large Hadron Collider”, I. Golutvin, A. Zarubin, V. Zykunov, V. Karjavin, V. Korenkov, A. Lanyov, V. Matveev, V. Palchik, M. Savina, S. Shmatov.
2. The first prize of the JINR VBLHEP in the topic of "Experimental and theoretical physics of particles and nuclei, development of a physical program and modeling of processes for the NICA complex" for 2021. For the cycle of works "Search for new physics in the channel with pairs of high-energy leptons in the CMS experiment at LHC”. I. Zhizhin ,V. Zykunov, A. Lanyov, V. Matveev, M. Savina, V. Shalaev ,S. Shmatov.
3. The second prize of the JINR VBLHEP in the topic of "Experimental and theoretical physics of particles and nuclei, development of a physical program and modeling of processes for the NICA complex" for 2020. For the cycle of works "Search for violations of the lepton universality of interactions and dark matter in a channel with a pair of leptons in the CMS experiment at LHC” (I. Golutvin, M. Gavrilenko, I. Zhizhin, A. Zarubin, A. Lanyov, M. Savina, V. Shalaev, S. Shmatov)

2.3.4. Other results (expert, scientific-organizational, scientific-propaganda activities).

The staff of the theme are reviewers of PEPAN journal, PEPAN Letters, Journal of High Energy Physics, they conduct scientific and popularization activities (for example, the podcast “Cat Scientist” Radio SPUTNIK).

3. International scientific and technical cooperation

The countries, institutions and organizations actually involved.

Organization	Country	City	Participants	Type of agreement
Foundation ANSL	Armenia	Yerevan	Tumasyan A. + 6	
HEPHY	Austria	Vienna	Wulz C.-E. + 57	
GSU	Belarus	Gomel	Maksimenko N. Andreev V. + 4	Visits
INP BSU	Belarus	Minsk	Makarenko V. + 22	
UAntwerp	Belgium	Antwerp	Van Mechelen P. + 15	
ULB	Belgium	Brussels	Vanlaer P. + 31	
VUB	Belgium	Brussels	D'Hondt J. + 11	
Ugent	Belgium	Ghent	Tytgat M. + 21	
KU Leuven	Belgium	Leuven	Leroux P. +4	
UCL	Belgium	Louvain-la-Neuve	Delaere Ch. + 26	
UMONS	Belgium	Mons	Daubie E.	
CBPF	Brazil	Rio de Janeiro, RJ	Alves G. + 8	
UERJ	Brazil	Rio de Janeiro, RJ	Mundim L. + 39	
Unesp	Brazil	Sao Paulo, SP	Novaes S. + 23	
INRNE BAS	Bulgaria	Sofia	Sultanov G. + 17	
SU	Bulgaria	Sofia	Litov L. + 10	
CERN	CERN	Geneva	Camporesi T + 302	Agreement
"Tsinghua"	China	Beijing	Hu Zh. + 6	
IHEP CAS	China	Beijing	Chen M. + 54	
PKU	China	Beijing	Mao Y. + 30	
ZJU	China	Hangzhou	Hao M. + 9	
Univ.	Croatia	Split	Sculac T. + 6	
FESB	Croatia	Split	Lelas D. + 14 Puljak I. + 12	
RBI	Croatia	Zagreb	Brigljevic V. + 10	

UCY	Cyprus	Nicosia	Razis P. + 13	
CU	Czech Republic	Prague	Finger M. + 7	
HIP	Finland	Helsinki	Voutilainen M. + 41	
UH	Finland	Helsinki	Voutilainen M. + 4	
LUT	Finland	Lappeenranta	Tuuva T. + 4	
UL	France	Lyon	Gascon S. + 51	
IN2P3	France	Paris	Beaudette F. + 55	
IRFU	France	Saclay	Besancon M. + 30	
IPHC	France	Strasbourg	Bloch D. + 40	
GTU	Georgia	Tbilisi	Tsamalaidze Z. + 11	
HEPI-TSU	Georgia	Tbilisi	Tsamalaidze Z. + 1	
RWTH	Germany	Aachen	Stahl A. + 10 Feld L. +15 Hebbeker T. +79	
DESY	Germany	Hamburg	Gallo E. + 110	
Univ.	Germany	Hamburg	Schleper P. + 76	
KIT	Germany	Karlsruhe	Müller T. + 90	
INP NCSR "Demokritos"	Greece	Athens	Loukas D. + 10	
NTU	Greece	Athens	Tsipolitis G. + 8	
UoA	Greece	Athens	Sphikas P. + 26	
UI	Greece	Ioannina	Foudas C. + 14	
Wigner RCP	Hungary	Budapest	Sikler F. + 8	
Atomki	Hungary	Debrecen	Molnar J. + 6	
UD	Hungary	Debrecen	Ujvari B. + 2	
PU	India	Chandigarh	Bhatnagar V. + 19	
NISER	India	Jatani	Swain S. + 24	
SINP	India	Kolkata	Sarkar S. + 31	
BARC	India	Mumbai	Pant L.	
TIFR	India	Mumbai	Dugad S. + 14	
TIFR	India	Mumbai	Mazumdar K + 19	

IPM	Iran	Tehran	Mohammadi M. + 6	
UCD	Ireland	Dublin	Grunewald M. + 1	
INFN	Italy	Bari	Pugliese G. + 54	
INFN	Italy	Bologna	Fabbri F. + 44	
INFN LNS	Italy	Catania	Tricomi A. + 8	
INFN	Italy	Florence	Paoletti S. + 31	
INFN LNF	Italy	Frascati	Piccolo D. + 8	
INFN	Italy	Genoa	Ferro F. + 10	
INFN	Italy	Milan	Ghezzi A. + 41	
INFN	Italy	Naples	Fabozzi F. + 20	
INFN	Italy	Padua	Rossin R. + 81	
INFN	Italy	Pavia	Braghieri A. + 19	
INFN	Italy	Perugia	Moscatelli F. + 37	
INFN	Italy	Pisa	Venturi A. + 58	
INFN	Italy	Rome	Paramatti R. + 29	
INFN	Italy	Trieste	Della Ricca G. + 7	
INFN	Italy	Turin	Solano A. + 77	
Cinvestav	Mexico	Mexico City	Castilla-Valdez H. + 10	
BUAP	Mexico	Puebla	Salazar-Ibarguen H. A. + 8	
Univ.	Montenegro	Podgorica	Raicevic N. + 4	
TU/e	Netherlands	Eindhoven	Aerts A. + 2	
Univ.	New Zealand	Auckland	Krofcheck D. + 2	
UC	New Zealand	Christchurch	Butler P. + 4	
QAU	Pakistan	Islamabad	Hoorani H. + 26	
AGH	Poland	Krakow	Malawski M. + 10	
AGH-UST	Poland	Krakow	Idzik M. + 3	
NCBJ	Poland	Otwock (Swierk)	Gorski M. + 8	
UW	Poland	Warsaw	Krolikowski J. + 17	
KIST	Republic of Korea	Daejeon	Ryu G. + 4	

CNU	Republic of Korea	Kwangju	Moon-Dong H. + 5	
KU	Republic of Korea	Seoul	Choi S. + 18	
SJU	Republic of Korea	Seoul	Kim H. + 4	
SKKU	Republic of Korea	Seoul	Choi Y. + 9	
SNU	Republic of Korea	Seoul	Yang U. + 23	
Yonsei Univ.	Republic of Korea	Seoul	Yoo H.-D. + 4	
MIPT	Russia	Dolgoprudny	Aushev T. + 7	
NRC KI PNPI	Russia	Gatchina	Vorobyov A. + 19	
ITEP	Russia	Moscow	Gavrilov V. + 22	
LPI RAS	Russia	Moscow	Dremin I. + 9	
NIKIET	Russia	Moscow	Orlov A. + 17	
NNRU "MEPhI"	Russia	Moscow	Danilov M. + 18	
SINP MSU	Russia	Moscow	Boos E. + 37	
INR RAS	Russia	Moscow, Troitsk	Gninenko + 29	
NSU	Russia	Novosibirsk	Skovpen Y. + 8	
IHEP	Russia	Protvino	Tyurin N., Kachanov V. + 23	
TSU	Russia	Tomsk	Ivanchenko V. + 5	
TPU	Russia	Tomsk	Babaev A. + 4	
INS "VINCA"	Serbia	Belgrade	Adzic P. + 9	
CIEMAT	Spain	Madrid	Alcaraz Maestre J. + 46	
UAM	Spain	Madrid	De Troconiz J. + 1	
UO	Spain	Oviedo	Cuevas J. + 12	
IFCA	Spain	Santander	Martinez Rivero C. + 40	
PSI	Switzerland	Villigen	Caminada L. + 23	
ETH	Switzerland	Zurich	Wallny R. + 80	
UZH	Switzerland	Zurich	Kilminster B. + 31	
NTU	Taiwan	Taipei	Hou G. + 37	
NCU	Taiwan	Taoyuan City	Kuo C.-M + 26	
CU	Turkey	Adana	Dumanoglu I. + 35	

METU	Turkey	Ankara	Zeyrek M. + 25	
BU	Turkey	Istanbul	Gulmez E. + 23	
YTU	Turkey	Istanbul	Cankocak K. + 11	
Univ.	United Kingdom	Bristol	Goldstein J +24	
RAL	United Kingdom	Didcot	Shepherd-Themistocleous C. + 49	
Imperial College	United Kingdom	London	Tapper A. + 71	
JHU	USA	Baltimore, MD	Swartz M. + 25	
Fermilab	USA	Batavia, IL	Canepa A. + 230	
BU	USA	Boston, MA	Rohlf J. + 58	
NU	USA	Boston, MA	Barberis E. + 25	
CU	USA	Boulder, CO	Cumalat J. + 22	
UB	USA	Buffalo, NY	Kharchilava A. +16	
MIT	USA	Cambridge, MA	Paus C. + 44	
UVa	USA	Charlottesville, VA	Hirosky R. + 20	
UIC	USA	Chicago, IL	Gerber C. + 32	
UMD	USA	College Park, MD	Skuja A. + 46	
Texas A&M	USA	College Station, TX	Safonov A. +27	
OSU	USA	Columbus, OH	Hill C. + 9	
UCDavis	USA	Davis, CA	Conway J. + 35	
WSU	USA	Detroit, MI	Karchin P. + 2	
NU	USA	Evanston, IL	Velasco M. + 15	
UF	USA	Gainesville, FL	Mitselmakher G. + 29	
Rice Univ.	USA	Houston, TX	Padley B. + 33	
UIowa	USA	Iowa City, IA	Onel Y. + 44	
Cornell Univ.	USA	Ithaca, NY	Ryd A. + 47	
UTK	USA	Knoxville, TN	Spainer S. + 19	
KU	USA	Lawrence, KS	Bean A. + 37	
UNL	USA	Lincoln, NE	Bloom K. + 28	
LLNL	USA	Livermore, CA	Wright D. + 2	

UCLA	USA	Los Angeles, CA	Hauser J. + 21	
TTU	USA	Lubbock, TX	Akchurin N. + 19	
UW-Madison	USA	Madison, WI	Dasu S. + 53	
KSU	USA	Manhattan, KS	Maravin Y. + 15	
U of M	USA	Minneapolis, MN	Rusack R. + 24	
VU	USA	Nashville, TN	Johns W. + 48	
RU	USA	New York, NY	Goulianos K + 2	
ND	USA	Notre Dame, IN	Jessop C. + 46	
UM	USA	Oxford, MS	Cremaldi L. + 5	
Caltech	USA	Pasadena, CA	Newman H. + 38	
CMU	USA	Pittsburgh, PA	Paulini M. + 17	
PU	USA	Princeton, NJ	Olsen J. + 44	
Brown	USA	Providence, RI	Heintz U. + 42	
UCR	USA	Riverside, CA	Hanson G. + 9	
UR	USA	Rochester, NY	Demina R. + 18	
UCSD	USA	San Diego, CA	Branson J. + 40	
UCSB	USA	Santa Barbara, CA	Incandela J. + 32	
FSU	USA	Tallahassee, FL	Prosper H. + 35	
UA	USA	Tuscaloosa, AL	Rumerio P. + 13	
Purdue Univ.	USA	West Lafayette, IN	Neumeister N. + 41	
INP AS RUz	Uzbekistan	Tashkent	Yuldashev B. + 5	

4. Plan/actual analysis of resources used: human (including associated personnel), financial, IT, infrastructure

4.1. Human resources (actual at the time of reporting)

№№ п/а	Категория работника	Core staff FTE amount	Associated personnel FTE amount
1.	Scientific staff	17	
2.	Engineers	4.4	
3.	Professionals	2	
	Total:	**23.4**	

4.2. Actual estimated cost of the Theme

№№ п/а	Name of work	Full cost	Expenditure for the year, prior to the reporting period (Thousands of United States dollars)
1.	International cooperation (IC)	1313	215.6
2.	Materials	2610	537.58
3.	Equipment and third-party services		
4.	Commissioning work		
5.	Services of research organizations		
6.	Acquisition of software		
7.	Design/construction		
8.	Service costs *(planned in case of direct project affiliation)*		
TOTAL:		**3923**	**753.18**

4.3. Other resources

Theme leader

_____________/______ ____________/

“_____“___________________202_г.

Project leader (project code)

_____________/______ ____________/

“_____“___________________202_г.

Laboratory Economist

_____________/______ ____________/

“_____“___________________202_ г.

Annex

List of papers presented at international conferences and meetings for 2020−2023.

1. S. V. Shmatov, "Searches for New Physics with the CMS Experiment at the LHC", International Conference on Quantum Field Theory, High-Energy Physics, and Cosmology, Joint Institute for Nuclear Research, Dubna, Russia, July18−21, 2022 г., Dubna.
2. M. V. Savina, "Dark Matter Search at the LHC", International Conference on Quantum Field Theory, High-Energy Physics, and Cosmology, Joint Institute for Nuclear Research, Dubna, Russia, July 18−21, 2022 г, Dubna.
3. M. Savina, S. Shmatov, К. Slizhevskiy, "Search for dark matter produced in association with a leptonically decaying Z boson with the CMS Experiment at the LHC", 6th International Conference on Particle Physics and Astrophysics, 29 Nov − 2 Dec 2022, National Research Nuclear University MEPhI, Moscow.
4. V. Shalaev, S. Shmatov, "Searches for Long-Lived Particles in CMS experiment", LXXII International conference "Nucleus−2022: Fundamental problems and applications", Lomonosov Moscow State University, Moscow, Russia, 11−16 July, 2022.
5. I. A. Zhizhin, A. V. Lanyov, S. V. Shmatov, «Searches for new physics in the dilepton channel with the CMS detector at the LHC», LXXII International conference "Nucleus−2022: Fundamental problems and applications", Lomonosov Moscow State University, Moscow, Russia, 11−16 July, 2022,
6. S.V. Shmatov, "Physics at Energy Frontier", Moscow International School of Physics, 24 July 2022 to 2 August 2022, Dubna.
7. A.V. Zarubin, "CMS Experiment at the LHC", The Workshop "The Physics of the Dimuons at the LHC" (DIMUONS2022), June 23-24, 2022, Dubna.
8. S.V. Shmatov, "Dimuons. The Beginning and Legacy", The Workshop "The Physics of the Dimuons at the LHC" (DIMUONS2022), June 23-24, 2022, Dubna.
9. V. Perelygin, "CMS Muon System", The Workshop "The Physics of the Dimuons at the LHC" (DIMUONS2022), June 23-24, 2022, Dubna.
10. P. Bunin, "CMS HCAL System", The Workshop "The Physics of the Dimuons at the LHC" (DIMUONS2022), June 23-24, 2022, Dubna.
11. V. Palchik, "Reconstruction of High-energy Muons", The Workshop "The Physics of the Dimuons at the LHC" (DIMUONS2022), June 23-24, 2022, Dubna.
12. A. Lanyov, «Physics with Dimuons in the CMS Experiment at the LHC», The Workshop "The Physics of the Dimuons at the LHC" (DIMUONS2022), June 23-24, 2022, Dubna.
13. M. Savina, "Searches for Dark Matter at the LHC", The Workshop "The Physics of the Dimuons at the LHC" (DIMUONS2022), June 23-24, 2022, Dubna.
14. A. Hayrapetyan, M. Savina, S. Shmatov, A. Tumasyan, "Searches for Dark Matter with the CMS Detector in bb/Z + MET channels", The Workshop "The Physics of the Dimuons at the LHC" (DIMUONS2022), June 23-24, 2022, Dubna.
15. O. Teryaev, "Dilepton Angular Distributions in Standard Model and Beyond", The Workshop "The Physics of the Dimuons at the LHC" (DIMUONS2022), June 23-24, 2022, Dubna.
16. V. Zykunov, "Radiative corrections to dilepton production at Run3/HL LHC", The Workshop "The Physics of the Dimuons at the LHC" (DIMUONS2022), June 23-24, 2022, Dubna.

17. I. Gorbunov, “Drell-Yan Radiative Corrections”, The Workshop “The Physics of the Dimuons at the LHC” (DIMUONS2022), June 23-24, 2022, Dubna.
18. V.Shalaev, S. Shmatov, I. Gorbunov, “Drell-Yan angular coefficients measurements with the CMS experiment at the LHC”, The Workshop “The Physics of the Dimuons at the LHC” (DIMUONS2022), June 23-24, 2022, Dubna.
19. V. Korenkov, “Computing @ LHC and NICA”, The Workshop “The Physics of the Dimuons at the LHC” (DIMUONS2022), June 23-24, 2022, Dubna.
20. A. Tumasyan, “Studies of the Standard Model Higgs Boson produced through vector boson fusion and decaying to bbar”, The Workshop “The Physics of the Dimuons at the LHC” (DIMUONS2022), June 23-24, 2022, Dubna.
21. N. Voytishin, “Development of Algorithms for CSC Track-Segment Reconstruction”, The Workshop “The Physics of the Dimuons at the LHC” (DIMUONS2022), June 23-24, 2022, Dubna.
22. A. Kamenev, “CMS Muon System Alignment”, The Workshop “The Physics of the Dimuons at the LHC” (DIMUONS2022), June 23-24, 2022, Dubna.
23. I. Gorbunov, “Anomaly detection with ML for Muon DQM Development of Machine”, The Workshop “The Physics of the Dimuons at the LHC” (DIMUONS2022), June 23-24, 2022, Dubna.
24. A. Lanyov, S. Shmatov, I. Zhizhin, “Optimization of Dimuon Selection and Photon Induced Background”, The Workshop “The Physics of the Dimuons at the LHC” (DIMUONS2022), June 23-24, 2022, Dubna.
25. S. Shulha, “Measurement of Fractions and Characteristics of Quark and Gluon Jets with the CMS”, The Workshop “The Physics of the Dimuons at the LHC” (DIMUONS2022), June 23-24, 2022, Dubna.
26. D. Budkouski, “Measurement of Gluon Jet Fractions in Inclusive Jet Data The Workshop “The Physics of the Dimuons at the LHC” (DIMUONS2022), June 23-24, 2022, Dubna.
27. M. Savina, S. Shmatov, K. Slizhevskiy, “Search for dark matter produced in association with a leptonically decaying Z boson with the CMS Experiment at the LHC”, XXVI International Conference of Young Scientists and Specialists (AYSS-2022), JINR, Dubna, 24-28 October, 2022.
28. S. Shulha, D. Budkouski, “Measurement of gluon jet fraction in the inclusive jets channel”, XXVI International Conference of Young Scientists and Specialists (AYSS-2022), JINR, Dubna, 24-28 October, 2022.
29. I. Zhizhin, Summer Scientific School "Super c-tau Factory", National Center of Physics and Mathematics and a branch of Lomonosov Moscow State University in Sarov, Nizhny Novgorod region, Sarov, Russia, 2022.
30. I. Zhizhin, «Searches for new heavy resonances in the dilepton channel», poster presented at 56th meeting of the PAC for Particle Physics, JINR, Dubna, Russia, 24.01.2022.
31. I. Zhizhin, «Search for new physics in the dilepton channel with the CMS at the LHC», poster presented at 2022 European school of high-energy physics, 05.12.2022.
32. V. Shalaev, S. Shmatov, I. Gorbunov, “Drell-Yan angular coefficients measurements with the CMS experiment at the LHC”, Seminar of VBLHEP, 25 November 2022, VBLHEP JINR, Dubna, Russia.
33. V.Shalaev, S. Shmatov, I. Gorbunov, “Study of Z-boson polarization effects at the CMS experiment at the LHC”, 5-12 June 2022, Alushta, Russia.
34. V.Shalaev, S. Shmatov, I. Gorbunov, “Drell-Yan angular coefficients measurements with the CMS experiment at the LHC”, 56th meeting of the Programme Advisory Committee for Particle Physics of JINR, 24 January 2022, Dubna, Russia.

35. D. Budkouski, J. Strologas, O. Atakisi, S. Shulha, “Double-Differential gluon jet fractions measurement in UL-2016 inclusive jet data”, 7th Yearly SMP-HAD Workshop, 2022.
36. S. Shulha, D. Budkouski, “Jet flavour discrimination and measurement of quark and gluon jet fractions”, 6th International Conference on Particle Physics and Astrophysics (ICPPA2022), November, 29 November − 2 December, 2022.
37. D. Budkouski, S. Shulha, “Measurement of gluon jet fraction and characteristics of quark and gluon jets produced in pp collisions at the CMS detector”, 56th meeting of the PAC for Particle Physics, JINR, Dubna, Russia, 2022.
38. V.A. Zykunov, “Electroweak radiative corrections to dilepton production via photon fusion at LHC”, VII International Conference “Models in Quantum Field Theory” (MQFT–2022), Saint Petersburg, Russia, October 10–14, 2022.
39. S. Shmatov (on behalf of the CMS Collaboration), “Highlights from the CMS Experiment”, The 20th Lomonosov Conference on Elementary Particle Physics, MSU, JINR, INR RAS, Bruno Pontecorvo Neutrino and Astrophysics Laboratory, 19-25 August 2021, Moscow, Russia.
40. S. Shmatov (on behalf of the CMS Collaboration), “CMS Overview”, LXXI International Conference "NUCLEUS – 2021. Nuclear physics and elementary particle physics. Nuclear physics technologies", 20-25 September, St. Petersburg, Russia
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42. A. Lanyov (on behalf of the CMS Collaboration), “Electroweak measurements at CMS”, The 20th Lomonosov Conference on Elementary Particle Physics, MSU, JINR, 19-25 August 2021, Moscow, Russia.
43. I. Gorbunov (on behalf of the ATLAS, CMS and LHCb Collaborations), “EWK Precision Measurements”, LHCP2021: 9th Edition of the Large Hadron Collider Physics Conference, 7-12 Jun 2021, Paris
44. V.V. Shalaev (on behalf of the CMS Collaboration), “CMS Standard Model Results”, LXXI International conference "NUCLEUS – 2021. Nuclear physics and elementary particle physics. Nuclear physics technologies", 20-25 September, St. Petersburg, Russia
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47. V. Shalaev, S. Shmatov (on behalf of the CMS Collaboration), “Search for New Physics in Leptonic Decays with the CMS Experiment at the LHC”, 6th Summer School on Intelligent signal processing for FrontiEr Research and Industry (INFIERI-2021), Madrid, Spain. 23 August – 5 September 2021.
48. S.V. Shmatov, “Searches for new physics with the CMS at the LHC”, Seminar “Theory of Fundamental Interactions”, BLTP JINR, Dubna, 11 February 2021.
49. V.A. Zykunov, “Effects of radiative corrections in the Drell–Yan process at ultra-high invariant mass of dilepton” на XXVIII International Seminar in memory of Prof. V.I. Kuvshinov, NPCS-2021, Minsk, May 18–21, 2021

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51. P. Bunin (on behalf of the CMS Collaboration), “CMS detector upgrade”, LXXI International conference "NUCLEUS – 2021. Nuclear physics and elementary particle physics. Nuclear physics technologies", St. Petersburg, Russia. 20-25 September 2021.
52. I. Gorbunov, “Machine Learning for Data Quality Monitoring at CMS Experiment”, 9th International Conference "Distributed Computing and Grid Technologies in Science and Education" (GRID`2021), JINR, Dubna, Russia.
53. M. Savina, “DM interpretations of heavy resonances and BSM-Higgs searches in ATLAS and CMS”, The Eighth Annual Conference on Large Hadron Collider Physics (LHCP2020), 25-30 May, 2020, Paris, France (on-line).
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55. I. Gorbunov, “Drell-Yan Measurements with the CMS experiment”, 40th International Conference on High Energy Physics (ICHEP), The C11 commission of the International Union of Pure and Applied Physics (IUPAP), Prague, Czech Republic, 2020 (on-line).
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