“Development of a software and algorithmic complex for the reconstruction, identification and selection of high-energy muons in the CMS experiment at the LHC”

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The series of scientific papers is based on the results of research carried out at the Joint Institute for Nuclear Research (JINR, Dubna) and the European Organization for Nuclear Research (CERN, Geneva) within the theme “CMS. Compact Muon Solenoid at the LHC, 02-0-1083-2009/2023”.

The series of works embraces the results of the development of mathematical methods and algorithms for the identification and reconstruction of high-energy muons, their selection in real time and of the creation of appropriate software complexes for the preparation, implementation and development of the physics research program in the channel with a muon pair on the multi-purpose detector complex, Compact Muon Solenoid (CMS), at the Large Hadron Collider (LHC).

A systematic study of the processes of production of high-energy muon pairs in the CMS experiment was initiated by JINR physicists in 2002 to test the predictions of the Standard Model in a new energy region and search for signals of new physics based on possible deviations from its predictions. This direction of the physics program of the CMS experiment has become one of the priorities for RDMS (Russia and Dubna Member States, a CMS collaboration of Russian institutes and JINR) specialists from JINR.

The distinctive features of high-energy muons (from several hundreds of GeV to several TeV) that complicate their reconstruction and selection are the high multiplicity of secondary particles, low track curvature, the high sensitivity of the reconstruction accuracy to the spatial imbalance of detector systems, etc. In addition, the precision (with an accuracy of several %) measurements of the momentum of elementary particles are hindered due to the increasingly complex configuration of experimental facilities, the growth of energy and intensity of accelerated beams, which leads to an increase in the data flow (up to tens of MHz from the interaction point), the temporary superposition of events (up to dozens of interactions per event), a rise in the multiplicity of produced particles in one event (up to several hundreds per event) and, as a consequence, to “noisy” particle trajectories and a high level of load in detectors. Previously, such signals were not observed in accelerator experiments, which entails the need to develop the corresponding mathematical apparatus, as well as algorithms and methods based on it, and adapt them to such experimental conditions.

Main results obtained within the presented series of works:

1. Development of algorithms for the reconstruction of high-energy muons

The software-algorithmic architecture was designed using the concept of regional reconstruction and the ability to work in distributed data processing systems. The elaborated local and global reconstruction algorithms are based on iterative methods for reconstructing particle trajectories using recursive filters and the Bayesian approach to estimate the uncertainty of the state vector (Kalman filter). Taking into account the peculiarities of high-energy muons, the following algorithms and methods were developed, implemented and studied using Monte Carlo and experimental data [2–7, 8–13]:

- Algorithm for separating overlapping signals in the cathode-strip chambers (CSC) of the CMS experiment, which enhances the accuracy of measuring the azimuthal coordinate of muons on a single layer of the detector.
- Procedure for reconstructing hits in the Dubna ME1/1 muon stations of the CMS experiment, modified taking into account the specific geometry, which makes it possible to reconstruct hits and track segments with high efficiency in the zone of maximum load of the detector systems of the experiment.
- Algorithm for reconstructing individual track sections (track segments) in various detectors of the muon system (drift chambers, cathode strip chambers, resistive plate chambers) or the strip and pixel detectors of the tracker system.
- Local track reconstruction algorithm that stitches together track segments within one system (muon or tracker).
- Global reconstruction algorithms that combine local tracks into one common track and use various combinations of local tracks: local tracks found in all detector subsystems, reconstruction based on the use of i) only hits in the tracker, ii) all hits in the tracker and hits in only one muon station closest to the interaction point, iii) muon hits from several "clean" stations, i.e., stations least affected by secondary interactions.
- Algorithms based on a combination of different approaches, the so-called "cocktails" of algorithms: i) combining collections of muon tracks of different algorithms, ii) a combination based on the comparison of the quality of fits of algorithms, iii) combinations including all possible algorithms.
- Method for determining the transverse momentum of muons based on the approach of equidistant hits of a muon trajectory curved in a magnetic field.
- Method for measuring the efficiency of muon reconstruction from experimental data using the "tag and probe muon" method.
- Method for correcting the muon momentum based on the calculation of independent corrections to the momenta of positively and negatively charged muons, according to data on the production of the Z^0 boson.
- Sequential data correction method to take into account the influence of systematic effects on the reconstruction accuracy (finite resolution and final state radiation, FSR).

All algorithms were tuned, optimized and further developed using Monte Carlo data, atmospheric muons and experimental data obtained at the interaction energy of proton beams in the center of mass system $\sqrt{s}$ = 7 and 8 TeV (first stage of the LHC operation, RUN1) and $\sqrt{s}$ = 13 TeV (second stage of the LHC operation, RUN2). The corresponding software enables to select one or another algorithm either manually or automatically, depending on the quality of the algorithms under certain experimental conditions.

The developed algorithms make it possible to carry out offline muon reconstruction with an efficiency of no less than 98% and an accuracy of no worse than 5-7% in the range of muon momentum values up to 2,000-3,000 GeV/c. For less hard muons, the accuracy is much better (1-2% in the momentum range up to 300 GeV/c). In this case, the probability of erroneous identification of the sign of the muon charge is a fraction of a percent in the central part of the CMS facility ($|\eta| < 1.4$), and in the end parts, the value of this error does not exceed 6% in all considered ranges of p_T and η (up to $|\eta| = 2.4$).

2. Development of methods for identifying and selecting muons and muon pairs

To analyze events with muons, in addition to accurate algorithms for their reconstruction, it is necessary to have a highly efficient procedure for their identification and selection, including in real time (in the trigger system). The members of the team of authors performed the following work [1, 5, 13–15]:

- Development of a muon identification method based on the extrapolation of the reconstructed tracker track to the most probable regions of the presence of a muon signal in external detector systems (electromagnetic calorimeter, hadronic calorimeter, external hadronic calorimeter, muon system) and on the assessment of combined compatibility using various agreement criteria.
- Development of a method for combining two main logical solutions of the first-level trigger: a trigger for single muons and a trigger for a muon pair, optimization of kinematic thresholds for the efficient selection of muon pairs.
- Modernization of the algorithm for reconstructing muons and muon pairs in real time, used in the second-level trigger. As a result, the algorithm made it possible to reevaluate the muon trajectory parameters obtained by the first-level algorithm, as well as to filter events in accordance with optimized selection criteria.
- Development of a method for applying criteria for the spatial isolation of a high-energy muon track when selecting events by high-level trigger systems. The method enabled to suppress the background from QCD processes without significantly reducing the selection efficiency of the useful signal.

The developed algorithms allow selecting muons with high efficiency (not lower than 97% with the first-level trigger and ~100% with the high-level trigger for the number of vertices up to 60 in one event) throughout the entire acceptance of the muon system of the CMS facility ($|\eta| \leq 2.4$) and muon transverse momentum p_T values over 1000 GeV/c.

3. Implementation of the methods and algorithms into software complexes

All developed muon reconstruction algorithms and software implementations of methods for their identification and selection were included in the official software (CMSSW) of the CMS experiment in the form of a single software-algorithmic complex.

The software-algorithmic complex was adapted for both working on local computing resources and using it in grid-oriented systems of the WLCG (Worldwide LHC Computing Grid) project, which provide geographically distributed data processing. The corresponding optimization and configuration were performed using the Tier2 and Tier1 grid sites of the JINR Multifunctional Information and Computing Complex.

The created software-algorithmic complex was used as the main tool for data processing and analysis during all three stages of the LHC operation. With its help, with the active participation of JINR physicists, the discovery and further research of the properties of the Higgs boson (in the decay channel into four leptons) were carried out, a series of search experiments to detect signals from new physics (dark matter, additional Higgs states, additional dimensions in low-energy gravity models, extended calibration models, etc.) were conducted, and the precision measurements of the characteristics of the Drell-Yan process (cross sections, angular distributions, spatial asymmetries) to test the predictions of the Standard Model were performed.

The uniqueness and novelty of the presented developments are driven not only by the above-described features of the operating conditions of the algorithms, but also by the possibility of scaling them for the conditions of conducting different experiments. Most algorithms can be adapted for the reconstruction of charged particles under experimental conditions at the NICA accelerator complex. Currently, this work is already underway, in particular, the adapted algorithms are included in the software complex of the BM@N experiment for reconstructing the trajectories of charged particles in the drift chamber system and used to implement the experiment's research program. In addition, the developed methods can also be useful for elementary-particle physics experiments using cosmic rays, for the development of nuclear physics technologies, life sciences, radiobiology and biophysics, etc.

The results of the series of works were included in three doctoral, three candidate and one PhD theses.

The presented series of works includes 15 publications:

1. A.M. Sirunyan et al. (CMS Collab.). "Performance of the CMS muon trigger system in proton-proton collisions at 13 TeV", JINST 16 (2021) P07001.
2. 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.
3. N.Voytishin. "Hit Reconstruction Improvements in the Cathode Strip Chambers of the CMS Experiment", CEUR Workshop Proceedings 2507, 120–124, (2019).
4. A.M. Sirunyan et al. (CMS Collab.). "Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at 13 TeV", JINST 13 (2018) P06015.
5. A.M. Sirunyan et al. (CMS Collab.). "The Phase-2 Upgrade of the CMS Muon Detectors", CMS-TDR-016, CERN-LHCC-2017-012, CERN, Geneva; ISBN 978-92-9083-457-1, 365 p.
6. V. Palichik, N. Voytishin. "New CSC segment builder algorithm with Monte-Carlo TeV muons in CMS experiment", Phys. Part. Nuclei 48 №5, 786–788, (2017).
7. I. Golutvin, V. Karjavin, V. Palichik, N. Voytishin and A. Zarubin. "A New Segment Building Algorithm for the Cathode Strip Chambers in the CMS Experiment", EPJ Web of Conferences 108, 02023, (2016).
8. A. Dolbilov, V. Korenkov, V. Mitsyn, V. Palichik, S. Shmatov, T. Strizh, E. Tikhonenko, V. Trofimov, N. Voytishin. "Grid technologies for large-scale projects", U.T.PRESS, 978-606-737-039-3, (2015).
9. S. Chatrchyan (CMS Collab.). "The performance of the CMS muon detector in proton-proton collisions at 7 TeV at the LHC", JINST 8 (2013) P11002.
10. S. Chatrchyan (CMS Collab.). "Performance of CMS muon reconstruction in pp collision events at 7 TeV", JINST 7 (2012) P10002.
11. V. Khachatryan (CMS Collab.). "Measurement of the charge ratio of atmospheric muons with the CMS detector", PLB 692 (2010) 83-104.
12. S. Chatrchyan, V. Khachatryan, A. M. Sirunyan et al. (CMS Collab.). "Performance of CMS Muon Reconstruction in Cosmic–Ray Events", JINST 5, T03022 (2010).
13. G. Bayatian et al. (CMS Collab.). "CMS Physics Technical Design Report Vol.I: Detector performance and software", CERN-LHCC-2006-001; CMS-TDR-008-1, CERN, Geneva, 2006; ISBN 978-92-9083-268-3, 521 p., pp. 332–364.
14. G. Bayatian et al. (CMS Collab.). "CMS Technical Design Report: The Trigger and Data Acquisition project, Vol.II, Data Acquisition and High-Level Trigger", CMS-TDR-006-2, CERN/LHCC-2002-026, CERN, Geneva, 2002; ISBN 92-9083-111-4, 4681 p.
15. G. Bayatian et al. (CMS Collab.). "CMS Technical Design Report: The Trigger and Data Acquisition project, Vol.I, The Level-1 Trigger", CMS-TDR-006-1, CERN/LHCC-2000–38, CERN-LHCC-2000-038, CERN, Geneva, 2000; ISBN 92-9083-110-2, 599 p.