

# Review of the PhD Thesis by Aram Hayrapetyan “Search for Long-Lived Particles Beyond the Standard Model with the CMS Experiment at the LHC and Development of High-Precision Timing and Spatial Semiconductor Detectors”

Many well-motivated theories (supersymmetry, hidden valleys, dark matter models, etc.) predict long-lived particles (LLPs) that decay far from the interaction point. Detecting such particles is challenging because standard reconstruction algorithms are optimized for promptly decaying particles. The author performs a dedicated search for LLPs decaying inside the muon system of the CMS detector using a specially collected “B-parking” dataset. This extends the sensitivity to previously unexplored regions of LLP parameter space (masses 0.3–3 GeV, proper decay lengths up to 10 m). The obtained upper limits on the branching fraction are a factor of ten better than previous results, demonstrating the value of the analysis strategy.

Second part of the presented work is the development of precision timing and spatial semiconductor detectors for the High-Luminosity LHC (HL-LHC) and future colliders. The HL-LHC will have an average pile-up of up to 200 events per bunch crossing. To disentangle vertices, a timing resolution of 30–50 ps is required. The thesis presents systematic studies of AC-LGAD sensors (strip and pixel geometries) and tests of the Endcap Timing Layer (ETL) modules with the ETROC readout chip. These studies are directly feeding into the CMS Phase-2 upgrade and are also relevant for other future facilities (FCC, EIC, muon collider). The achieved timing resolutions and the demonstration of near 100% efficiency are important steps towards 4D tracking.

Thus, both parts of the work are highly timely and important for the experimental particle physics community.

The thesis is organized into four chapters, an Introduction, and Conclusion. A separate section describes the personal contribution.

The **Introduction** introduces the key issues. **Chapter 1** provides a concise but comprehensive description of the LHC, the CMS detector, its subsystems, and the planned upgrades for the HL-LHC. This sets the context for the original research. **Chapter 2** describes the search for LLPs using the CMS muon system and contains corresponding description of experimental data, methods, systematic studies (trigger, pile-up, muon ID, cluster timing, veto efficiencies, cluster size correction), and contains the result: upper limits on the branching fraction as a function of LLP mass and proper decay length. **Chapter 3** presents the development and testing of a Constant Fraction Discriminator ASIC (FCFD) at Fermilab while **Chapter 4** covers principles of operation of LGAD, DC-LGAD, and AC-LGAD sensors, beam tests results for AC-LGAD strip and pixel sensors, testing of ETL module prototypes (version 0 and version 1) with lasers, electron beams (DESY, 6 GeV), and proton beams (CERN SPS, 120 GeV). The thesis ends with a **Conclusion** summarizing the main results.

The thesis presents two complete, independent, and high-quality research projects – a collider data analysis and a detector R&D campaign – both of which have led to published or publishable results. The LLP search uses a novel data set and a sophisticated background estimation strategy, resulting in world-leading limits for the considered model. The detector studies are thorough: many sensor variants (thickness, pitch, electrode shape, manufacturer) were systematically compared, and multiple test beam campaigns (FNAL, DESY, CERN) were carried out with consistent methodology. The obtained timing resolutions meet or approach the requirements for the HL-LHC MTD/ETL,

and the efficiency maps demonstrate excellent performance. The author contributed to all stages: simulation, data analysis, test beam setup, data acquisition, offline reconstruction, and interpretation. This demonstrates a wide range of experimental skills. The obtained results are convincing and relevant. They have been presented in a sufficient number of publications in reputable scientific journals and have been validated at high-level international conferences.

The presented Thesis is not without minor shortcomings:

- 1) In Eq. (3) the  $\theta$  angle is not introduced. What's the point of showing it separately instead of hiding it inside parameter  $\epsilon$ ?
- 2) In the Section 2.4 the author mentions the use of PYTHIA and EVTGEN generators, but says nothing about the settings used. Is this a standard set of parameters optimized for the CMS energy, or some other one?
- 3) The difference between asymmetric errors is so small that such a notation as  $58760^{+1263}_{-1261}$  becomes meaningless.
- 4) A  $y_x$  variable in Eqs. 19-20 is misleading. What does it mean exactly?
- 5) At p. 87 the author said "It was possible to reach 20, 24 and 35 ps timing resolution respectively for 20, 30 and 50  $\mu\text{m}$  thick sensors." It would be reasonable here to indicate what the best achievable resolution is when further reducing the sensor thickness, since the resolution cannot be improved indefinitely due to the drop in signal amplitude as the thickness decreases.

and some amount of misprints:

- 6) Line 3 at p. 52: obviously, neutral pions should be in the decay formula in the brackets.
- 7) Line 1 at p 17: "LHC began operation at 2010 with 7 GeV..." Obviously, 7 TeV.
- 8) ...

But these issues do not undermine the scientific validity of the results. They are typical of a thesis draft and can be corrected during final editing.

**Overall assessment:**

The dissertation contains original, high-quality research that makes significant contributions both to the search for new physics at the LHC and to the development of precision timing detectors for future colliders. The work meets and exceeds the standards for a PhD in experimental particle physics. The author of the Thesis, Aram Hayrapetyan, deserving of the PhD degree.

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