Summary of Professional Accomplishments

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1. Personal data

Names	**Łukasz Kamil**
Surname	**Graczykowski**

Researcher identification numbers

https://orcid.org/0000-0002-4442-5727
https://www.scopus.com/authid/detail.uri?authorId=45860995900
R https://www.webofscience.com/wos/author/rid/O-7522-2015
https://scholar.google.pl/citations?user=vyEhnTsAAAAJ

2. Diplomas and degrees

2011 – 2015 **Ph.D. in Physical Sciences**
Warsaw University of Technology, Faculty of Physics
Thesis title: "Femtoscopic analysis of hadron-hadron collisions in ultrarelativistic collisions of protons and heavy-ions registered by ALICE at the LHC"
Supervisor: Prof. Adam Kisiel
Date of award: 12.03.2015
Link: https://cds.cern.ch/record/2066992/

2010 – 2011 **Master of Science in Engineering**
Warsaw University of Technology, Faculty of Physics
Thesis title: "Influence of jet-induced global event structures on the pion femtoscopic correlations measured in proton-proton collisions registered by the ALICE experiment"
Specialization: Nuclear physics and technology
Supervisor: Prof. Adam Kisiel
Date of award: 11.02.2011
Studies finished with honors ("summa cum laude"), half-year before expected time.

2006 – 2010 **Bachelor of Science in Engineering**
Warsaw University of Technology, Faculty of Physics
Thesis title: "Characteristics of detectors and collimators for SPECT gamma cameras in nuclear medicine"
Specialization: Computer physics
Supervisor: Dr. Krzysztof Kacperski
Date of award: 12.02.2010
Studies finished with honors ("summa cum laude").

3. Information on employment in research institutes or faculties

15.03.2015 – ·· **Warsaw University of Technology, Faculty of Physics**
Assistant professor (Adiunkt) in the Nuclear Physics Division, in the group of research-teaching staff

1.07.2019 – 30.10.2019 **CERN - European Organization for Nuclear Research**
Corresponding associate (CASS) in the EP-AIP-PAP group

1.07.2015 – 30.10.2015 **CERN - European Organization for Nuclear Research**
Corresponding associate (CASS) in the EP-AIP-PAP group

4. Description of the achievements set out in art. 219 para 1 point 2 of the Act

Cycle of scientific articles related thematically, pursuant to art. 219 para 1. point 2b of the Act

Title: ***ALICE as a laboratory to study strongly interacting systems via particle correlations***

List of publications

H1 **ALICE Collaboration**. "Pion-kaon femtoscopy and the lifetime of the hadronic phase in Pb−Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV". In: *Phys. Lett. B* 813 (2021), p. 136030. DOI: 10.1016/j.physletb.2020.136030.
IF=4.95, MEiN pts=140, WoS citations=2, Scopus citations=3, INSPIRE-HEP citations=9
I was a Paper Committee member of this publication. I contributed to the work by analyzing the data in Spherical Harmonics representation. I was responsible for the calculation of the systematic uncertainty on the extracted radii and asymmetry parameters. I also contributed to writing the internal analysis note and the paper manuscript. I consider my contribution to be of 25%.

H2 **ALICE Collaboration**. "Kaon-proton strong interaction at low relative momentum via femtoscopy in Pb–Pb collisions at the LHC". In: *Phys. Lett. B* 822 (2021), p. 136708. DOI: 10.1016/j.physletb.2021.136708.
IF=4.95, MEiN pts=140, WoS citations=1, Scopus citations=2, INSPIRE-HEP citations=7
I was a Paper Committee member of this publication. I contributed to the work by performing the femtoscopic analysis of experimental data as well as systematic studies (defining the selection criteria and their variations, analyzing the contamination from weak decay particles and particle identification impurities). I also wrote parts of the internal analysis note and the paper manuscript. I consider my contribution to be of 30%.

H3 **ALICE Collaboration**. "Scattering studies with low-energy kaon-proton femtoscopy in proton-proton collisions at the LHC". In: *Phys. Rev. Lett.* 124.9 (2020), p. 092301. DOI: 10.1103/PhysRevLett.124.092301.
IF=9.18, MEiN pts=200, WoS citations=16, Scopus citations=18, INSPIRE-HEP citations=38
I was selected for the role of the Internal Review Committee chair of this publication. I contributed to the work by providing a detailed internal review of the analysis (both the developed software and internal analysis note), the physics message of the results and the paper manuscript itself. I was in charge of collecting requests from other members of the IRC on subsequent cross-checks and validations that were provided to the Paper Committee. The final paper is a result of several iterations between PC and IRC, lasting around 1 year. I consider my contribution to be of 20%.

H4 **ALICE Collaboration**. "Measurement of strange baryon–antibaryon interactions with femtoscopic correlations". In: *Phys. Lett. B* 802 (2020), p. 135223. DOI: 10.1016/j.physletb.2020.135223.
IF=4.95, MEiN pts=140, WoS=5 citations, Scopus citations=12, INSPIRE=HEP citations=20
I was the Paper Committee chair of this publication. I contributed to the work by performing the data analysis, estimating the systematic uncertainties, fitting the data to extract the scattering parameters and calculating the systematic uncertainty of that procedure, writing the internal analysis note and the whole manuscript of the paper, and interacting with the Internal Review Committee, the ALICE Editorial Board, and the Physics Letters B editors. I consider my contribution to be of 60%.

H5 **ALICE Collaboration**. "Insight into particle production mechanisms via angular correlations of identified particles in pp collisions at $\sqrt{s} = 7$ TeV". In: *Eur. Phys. J. C* 77 (2017). [Erratum: Eur.Phys.J.C 79, 998 (2019)], p. 569. DOI: 10.1140/epjc/s10052-017-5129-6.
IF=4.59, MEiN pts=140, WoS citations=25, Scopus citations=31, INSPIRE-HEP citations=46
I was a Paper Committee member of this publication. This experimental paper is a result of a long collaboration with my fellow colleague from WUT Dr. Małgorzata Janik. I contributed to this work in performing data and analysis, Monte Carlo simulations, quality assurance checks, systematic studies, and writing the internal analysis note and the paper manuscript. I consider my contribution to be of 40%.

H6 Małgorzata Anna Janik, **Łukasz Kamil Graczykowski**, and Adam Kisiel. "Influence of quantum conservation laws on particle production in hadron collisions". In: *Nucl. Phys. A* 956 (2016), pp. 886–889. DOI: 10.1016/j.nuclphysa.2016.02.018.
IF=1.56, MEiN pts=100, WoS citations=1, Scopus citations=1, INSPIRE-HEP citations=1
This paper is a write-up of the presentation from Quark Matter 2015. I contributed to the work by performing validation checks of the CALM model and to writing the manuscript. The poster presentation was awarded a "flash talk" at the plenary session, given by Małgorzata Janik. I consider my contribution to be of 15%.

H7 **Łukasz Kamil Graczykowski** and Małgorzata Anna Janik. "Unfolding the effects of final-state interactions and quantum statistics in two-particle angular correlations". In: *Phys. Rev. C* 104 (2021), p. 054909. DOI: 10.1103/PhysRevC.104.054909.
IF=3.19, MEiN pts=140, WoS citations=0, Scopus citations=0, INSPIRE-HEP=2
This work is a result of my long-lasting collaboration with my fellow colleague from WUT, Dr. Małgorzata Janik. I contributed to the work by performing simulations, co-designing the unfolding algorithm, inventing the validation tests, writing the manuscript, and interacting with the editors of the Physical Review C. I consider my contribution to be of 50%.

H8 Tomasz Trzciński, **Łukasz Kamil Graczykowski**, and Michał Glinka. "Using Random Forest Classifier for Particle Identification in the ALICE Experiment". In: *Information Technology, Systems Research, and Computational Physics*. Springer International Publishing, 2020, pp. 3–17. ISBN: 978-3-030-18058-4. DOI: 10.1007/978-3-030-18058-4_1.
IF=N/A, MEiN pts=20, WoS citations=2, Scopus citations=2, INSPIRE-HEP citations=N/A
This is the 1st paper describing our approach to Machine Learning-based Particle Identification in ALICE. I contributed to the work by inventing the idea of using ML PID in the ALICE software. I composed a team of IT and physics specialists at WUT to develop the ML models for this task, and selected the experimental and Monte Carlo data for model training and validation of the results. This paper is a write-up of the talk at the ITSRCP 2019 conference, given by a student Michał Glinka. I consider my contribution to be of 50%.

H9 **Łukasz Kamil Graczykowski** et al. "Using machine learning for particle identification in ALICE". In: *JINST* 17 (2022), p. C07016. DOI: 10.1088/1748-0221/17/07/C07016.
IF=1.12, MEiN pts=70, WoS citations=0, Scopus citations=0, INSPIRE-HEP citations=0
This is the 2nd paper describing our approach to Machine Learning-based Particle Identification in ALICE. It is a write up of my invited talk to the AI4EIC-Workshop at Brookhaven National Laboratory (USA) in 2021. I contributed to the work by inventing the idea of using ML for PID in ALICE. I composed a team of IT and physics specialists at WUT to work on that topic, selected the experimental and Monte Carlo data for model training and validation of the results, and oversaw the writing of the manuscript. I consider my contribution to be of 60%.

H10 Piotr Nowakowski, Przemysław Rokita, and **Łukasz Kamil Graczykowski**. "Distributed simulation and visualization of the ALICE detector magnetic field". In: *Comput. Phys. Commun.* 271 (2022), p. 108206. DOI: 10.1016/j.cpc.2021.108206.
IF=4.71, MEiN pts=140, WoS citations=0, Scopus citations=0, INSPIRE-HEP citations=1
This is a technical publication done in collaboration with WUT computer scientists. I contributed to the work by inventing the idea of visualization of the ALICE magnetic field, proposing validation tests for the final implementation of the GPU algorithm for particle propagation in the event display, interpreting the results, and reviewing the manuscript. I consider my contribution to be of 25%.

H11 **Łukasz Kamil Graczykowski**, Piotr Nowakowski, and Panagiota Foka. "New developments for ALICE MasterClasses and the new Particle Therapy MasterClass". In: *EPJ Web Conf.* 245 (2020), p. 08011. DOI: 10.1051/epjconf/202024508011.
IF=N/A, MEiN pts=N/A, WoS citations=1, Scopus citations=N/A, INSPIRE-HEP citations=5
This paper presents the refreshed ALICE MasterClass software and the new Particle Therapy Masterclass. It is a write-up of my presentation from the CHEP 2019 conference. I contributed to the work by leading the effort of delivering a new ALICE MasterClass tool and making WUT responsible for that project. With Piotr Nowakowski, a computer scientist, we re-designed the implementation of the ALICE IMC tool. I consider my contribution to be of 50%.

Description of the scientific achievement

Łukasz Kamil Graczykowski

1 Introduction

Fundamental interactions govern the behavior of the observed Universe. The Standard Model (SM) of particle physics [1, 2, 3, 4] is a theory describing three out of four of them (excluding gravity), that is electromagnetism, weak and strong forces. SM allows for quantitative predictions of phenomena involving quarks and gluons (jointly referred to as partons) using the mathematical language of quantum field theory [5]. Specifically, Quantum Chromodynamics (QCD) [6] is the name of the gauge field theory describing the strong interaction (SI) [6]. SI is also the major topic of the research undertaken by ALICE (A Large Ion Collider Experiment) [7, 8] at the LHC (Large Hadron Collider) [9] particle accelerator at CERN.

Relativistic heavy-ion collisions at the LHC create Quark-Gluon Plasma (QGP): the hottest and densest fluid ever studied in the laboratory. It is speculated that the early Universe existed in such a state around 10^{-6} seconds after the Big Bang. This is a state of matter where two of the basic features of low-temperature QCD, confinement and chiral symmetry breaking, are no longer present [10, 11, 12]. As the heavy ions collide, an extremely dense region of partons is excited and deposits energy in the overlap region of the collision. Subsequent evolution is described in a series of stages, as shown schematically in Fig. 1. Those stages are the following: (a) an initial state, which can be described by the wave-functions of the incoming projectiles; (b) large momentum transfer interactions of partons from colliding projectiles; (c) smaller momentum transfer interactions generating a pre-equilibrated parton gas; (d) thermodynamic equilibration and hydrodynamic expansion of a QGP; (e) subsequent hadronization (formation of hadrons from quarks and gluons); (f) chemical freeze-out of hadrons (composition of final-state hadrons becomes fixed); (g) kinetic freeze-out (elastics interactions of final-state particles cease); (h) free-streaming of final-state particles to the detector.

The LHC also delivers proton-proton (pp) collisions, where initial state nuclear effects are not relevant, and p–Pb collisions, which have a further complementary role, where cold nuclear matter effects are present. Those collision systems provide a crucial reference to heavy-ion collisions.

My research presented in this habilitation application touches upon several aspects of heavy-ion and pp collisions. The study of the system size and its lifetime for various different particle species, using the technique of femtoscopy, is described in [H1]. The measurements of final-state hadron–hadron interactions utilizing femtoscopy are discussed in [H2, H3, H4]. The process of hadronization is studied using angular correlations in [H5, H6, H7]. In addition to physics related studies, I have contributed to technical aspects of the experiment, improving the particle identifaction algorithms with Machine Learning-based approaches [H8, H9], as well as event visualization [H10]. Last but not least, I am one of the persons responsible in ALICE for outreach activities in the form of the development of a MasterClass software [H11] and organizing almost every year MasterClass sessions locally at WUT.

Finally, I would like to point the reader to the recent comprehensive overview publication of most of the ALICE physics results from the LHC Run 1 and Run 2 [13]. I am one of the main authors of this paper (member of the Paper Committee) – I was selected by the Collaboration to the Steering Group and I was responsible (together with Dr. Francesca Bellini from the University of Bologna) for writing Section 2.1 ("Macroscopic system properties and QGP thermodynamics") of the manuscript. The synopsis of the ALICE experimental results presented in the following sections of my habilitation application is based on that publication.

2 The ALICE experiment

The ALICE detector is situated at the Interaction Point 2 (IP2) of the LHC. It is located about 60 m below the ground level. The apparatus is 16 m high, 16 m wide, 26 m long, and its weight is approximately 10 thousand tons. ALICE was designed, built and is now being operated by a

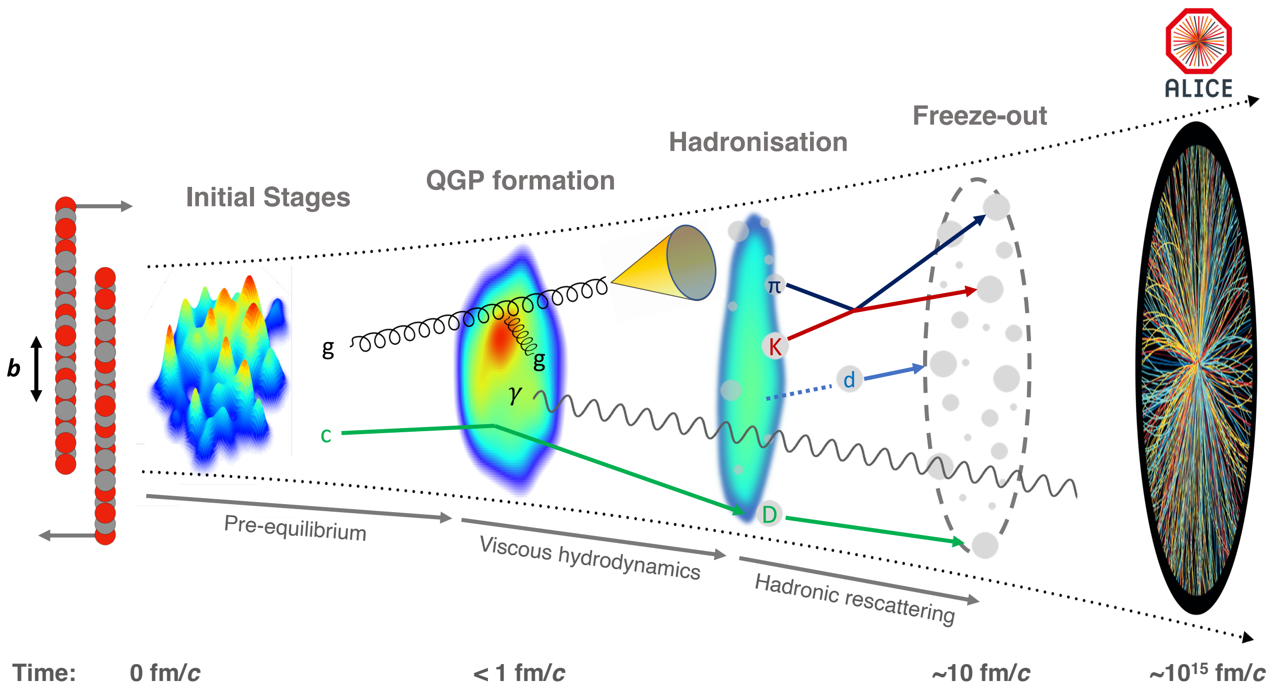

Figure 1: The evolution of a heavy-ion collision at LHC energies. Figure taken from [13].

Collaboration that encompasses over 1,200 scientists and engineers from more than 120 institutes in more than 30 countries around the World.

The layout of the ALICE experiment, with all detector systems as used in the so-called LHC Run 2 data-taking period (2015–2018), is shown in Fig. 2. The so-called "central barrel", which contains most of the tracking detectors, covers full azimuth and the pseudorapidity region $|\eta| < 0.9$. It provides a robust particle identification up to transverse momentum $p_{\mathrm{T}} \sim 20$ GeV/c, together with a very low momentum cut-off ($p_{\mathrm{T}} \sim 0.15$ GeV/c). Figure 3 illustrates, as an example, the PID performance of the TPC which allows excellent separation for various hadrons and light nuclei at low p_{T}. A good separation between protons, kaons and pions is also achieved in the region of the relativistic rise of $\mathrm{d}E/\mathrm{d}x$, up to $p_{\mathrm{T}} \sim 20$ GeV/c. The PID performance of the TPC and TOF systems is shown in Fig. 3.

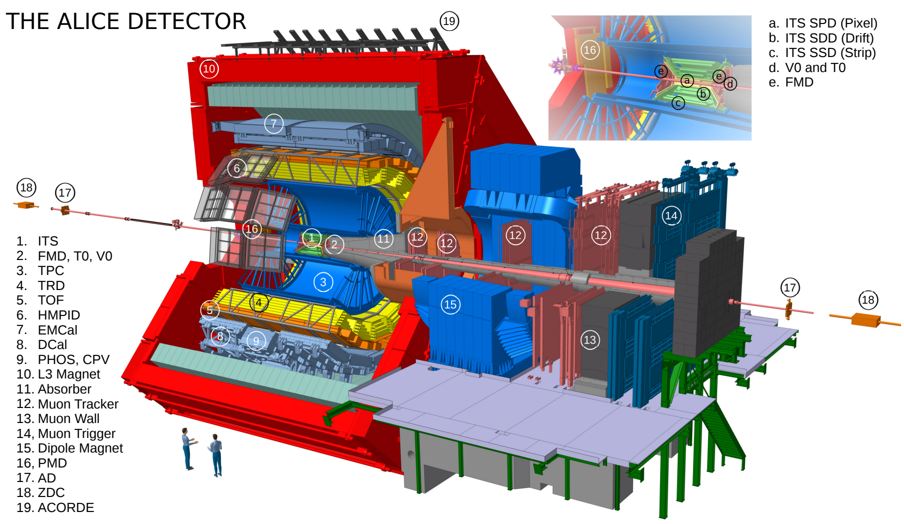

Figure 2: Sketch of the ALICE detector layout during the LHC Run 2. Figure from [13].

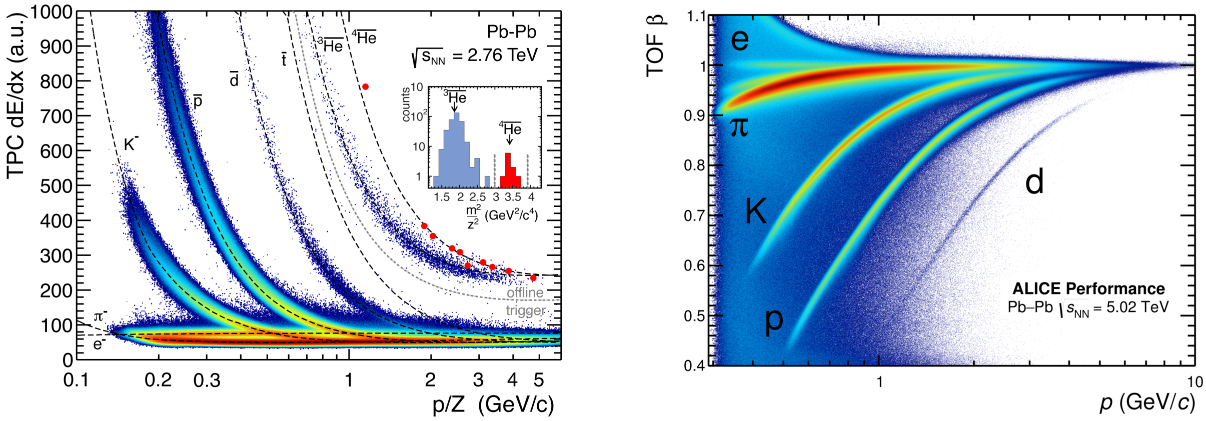

Figure 3: (Left) The dE/dx signal in the ALICE TPC. The expected curves for various particle species are also shown, with the inset panel showing the TOF mass measurement providing additional separation for helium isotopes. (Right) The Time-of-Flight measured in the TOF system. Figures from [13].

3 Role of the hadronic phase in the study of the system size and lifetime with femtoscopy

***This section describes and is based on publication* [H1].**

The size and lifetime of the system created in a collision can be inferred from femtoscopy, which measures particle momentum correlations at kinetic freeze-out. The study of momentum correlations of particles emitted from a common source was historically referred to as "HBT interferometry" in the heavy-ion community, named after the original technique proposed by Hanbury-Brown and Twiss in the 1950s and 1960s to determine the size of laboratory and stellar sources by studying the interference of emitted photons [14, 15].

In the case of two-particle femtoscopy [16, 17, 18], if two particles are emitted from a pp or heavy-ion collision and detected, the two-particle count rate is used to form the momentum correlation function, $C(k^*)$, given by $C(k^*) = \mathcal{N}\frac{A(k^*)}{B(k^*)}$, where $A(k^*)$ is the measured distribution of particle pairs from the same event, i.e. the two-particle count rate, $B(k^*)$ is the reference distribution of pairs created from particles coming from different events (referred to as "mixed events"), $\mathcal{N}$ is the normalisation factor, and k^* is the magnitude of the momentum of each of the particles in their pair rest frame. Note that for identical particle pairs the invariant momentum difference is denoted as $q_{\mathrm{inv}} = 2k^*$. On the theory side, the correlation function has the following form:

$$C(k^*) = \int S(r^*) \left|\Psi(\vec{k}^*, \vec{r}^*)\right|^2 \mathrm{d}^3 r^*, \tag{1}$$

where r^* is the relative distance between the two particles in the pair rest frame and $S(r^*)$ is the souce emission function.

In order to extract the explicit spatial information and implicit time information about the emitting particle source at kinetic freeze-out, the measured two-particle correlation function is, in general, fitted with a formula that includes a quantum statistics term for identical particles, and a parameterisation which incorporates strong final-state interactions between the particles (FSI), for cases where they are important [19, 20]. For example, for uncharged particles:

$$C(k^*) = 1 + \lambda e^{-4k^{*2}R^2} + \lambda\alpha\left[\frac{1}{2}\left|\frac{f(k^*)}{R}\right|^2 + \frac{2\Re f(k^*)}{\sqrt{\pi}R}F_1(2k^*R) - \frac{\Im f(k^*)}{R}F_2(2k^*R) + \Delta C\right], \tag{2}$$

where $f(k^*)$ is the s-wave scattering amplitude, $\alpha = 0.5$ in the case of identical bosons, R is the source radius parameter (assuming a spherical Gaussian source distribution $S(r^*)$), and λ is the correlation strength. The term ΔC is a calculated correction factor that takes into account the deviation of the spherical wave assumption used in the inner region of the short-range potential in the derivation of Eq. 2 [16]. The second term in Eq. 2 describes the quantum statistics if identical bosons are considered, and the third one is the FSI term. In Eq. 2, the R parameter is related to the effective size of the source. In order to improve the description of the particle emitting source, two-particle femtoscopy can be reformulated in three dimensions. The experimental correlation function is then obtained in terms of the components of the pair momentum difference vector: q_{out} (along the direction of the sum of the transverse momenta of the particles), q_{side} (perpendicular to the direction of the sum of the transverse momenta of the particles), and q_{long} (parallel to the beam direction). The correlation function can also be conveniently represented in spherical harmonics (SH) [21, 22]. Moments of the spherical harmonic decomposition of the correlation function are given by:

$$C_l^m(q) = \frac{1}{\sqrt{4\pi}} \int \mathrm{d}\varphi \mathrm{d}(\cos\theta) C(\mathbf{q}) Y_l^{m*}(\theta,\varphi), \tag{3}$$

where θ and φ are the spherical angles, $Y_l^{m*}(\theta,\varphi) = (-1)^m Y_l^{-m}(\theta,\varphi)$ are conjugate spherical harmonic functions ($Y_l^m(\theta,\varphi)$ are the spherical harmonics), l is a natural number, and m is an integer $-l \leq m \leq l$.

The full correlation function $C(\mathbf{q})$ constructed from the spherical harmonic components has therefore the following form:

$$C(\mathbf{q}) = \sqrt{4\pi} \sum_{l,m} C_l^m(q) Y_l^m(\varphi,\theta). \tag{4}$$

Femtoscopy measures the volume of the emitting source, which is in general not equivalent to the total volume occupied by the system at freeze-out. For an expanding source, with strong flow gradients, particles with similar momenta are emitted from a region referred to as the "homogeneity volume", which is smaller than the total volume [23]. The size of the homogeneity region, obtained as the product of the three pion radii R_{out}, R_{side}, and R_{long} was measured at AGS [24], SPS [25, 26, 27], RHIC [28, 29, 30, 31, 32] and LHC [33, 34] energies. The magnitude increases three times from AGS energies to the LHC.

Femtoscopic measurements also allow for the extraction of the system lifetime. The decoupling time of the system is typically approximated with the decoupling time of pions τ_f, since pions are the most abundant species ($\approx 80\%$). According to the implementation of the system evolution in hydrodynamic models, the R_{long} at midrapidity is proportional to the total duration of the longitudinal expansion [35]. The decoupling time τ_f can be obtained from the relation between R_{long} and the transverse mass (m_{T}) that is

$$R^2_{\mathrm{long}}(m_{\mathrm{T}}) = 2\frac{\tau_f^2 T_{\mathrm{kin}}}{m_{\mathrm{T}}} \frac{K_2(m_{\mathrm{T}}/T)}{K_1(m_{\mathrm{T}}/T_{\mathrm{kin}})}, \tag{5}$$

where T_{kin} is the kinetic freeze-out temperature, taken to be 0.12 GeV, and K_1 and K_2 are the integer order modified Bessel functions [35]. The τ_f increases linearly with the cube root of the charged-particle pseudorapidity density. The time measured at AGS is about 4–5 fm/c increasing gradually up to 7–8 fm/c at top RHIC energies, and finally it reaches 10—11 fm/c in central Pb–Pb collisions at $\sqrt{s_{\mathrm{T}}} = 2.76$ TeV [33]. It should be noted that corrections to Eq. 5, due to the transverse expansion and the finite pion chemical potential can increase the decoupling time by up to 25% [36].

The increase in beam energy by a factor of 25 from top RHIC energy to the LHC produces a homogeneity region approximately twice larger in most central collisions. The decoupling time for midrapidity pions lies in the range 10–13 fm/c at the LHC, which is about 40% larger than at RHIC, as shown in Fig. 4. These results indicate that the fireball formed in central Pb–Pb collisions at the LHC lives longer and expands to a larger size at freeze-out compared to lower energies. The quantitative agreement between models based on relativistic hydrodynamics with statistical hadronisation and femtoscopic measurements supports this picture of the evolution of the system created in heavy-ion collisions.

In a hydrodynamical picture, the collective expansion of the fireball reduces the size of the homogeneity region due to the interplay between the collective and thermal velocities of particles. Due to this, each of the femtoscopic radii is expected to decrease with m_{T} following a power-law behavior [17].

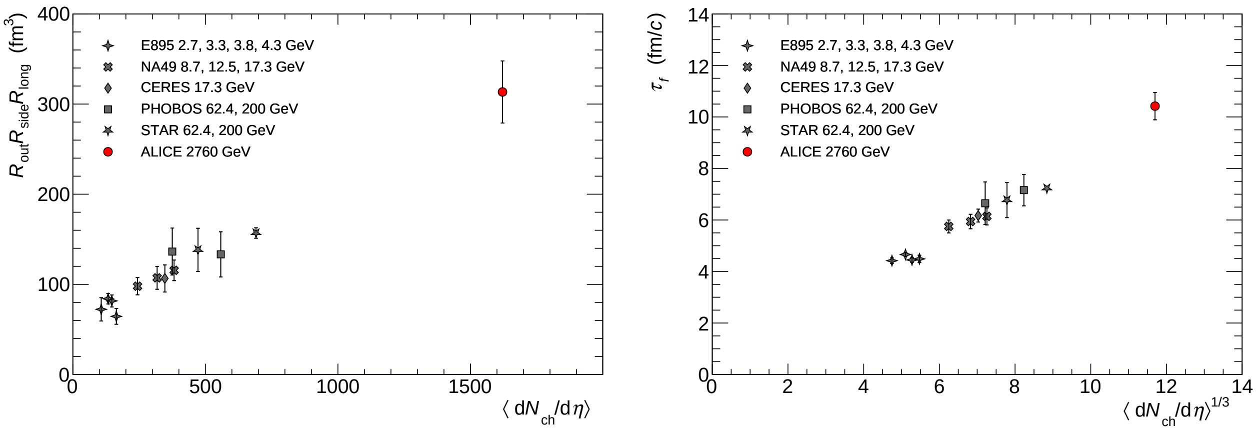

Figure 4: Homogeneity volume (top) and decoupling time τ_f (bottom) measured at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV [33, 34] compared to those obtained for central Au–Au and Pb–Pb collisions at lower energies at the AGS [24], SPS [25, 26, 27], and RHIC [28, 29, 30, 31, 32]. The homogeneity region is determined as the product of the three pion femtoscopic radii at $\langle k_{\mathrm{T}} \rangle = 0.3$ GeVc for 0–5% central events, whereas the decoupling time τ_f is extracted from $R_{\mathrm{long}}(k_{\mathrm{T}})$ according to Eq. 5. Figures from [13].

This is shown in Fig. 5, where the dependence of R_{out}, R_{side} and R_{long} on the pair transverse mass m_{T} is reported on the left, right top and right bottom panels, respectively, for different centralities. ALICE data for identical pion as well as charged and neutral kaon pairs are compared to the calculations [37] from the (3+1)D hydrodynamic model coupled to the THERMINATOR 2 statistical hadronisation code [38] as well as to the two variants (with and without hadronic interactions in the late hadron-gas phase) of the calculation from the HKM model [39] for the 5% most central collisions. A clear deviation between the HKM model calculations without the rescattering phase and the identical kaon data are observed, while the measurements are well reproduced by the full model calculations that includes the effect of the hadronic rescattering in the late stages of the system evolution, thereby showing the importance of the hadronic phase at the LHC.

This behavior can be explained by the fact that the femtoscopic radii are sensitive to production of the production of K*(892) resonance from regeneration, which shifts the emission time of pions and kaons. Since pions from K*(892) decays have a negligible effect on the pion measurements due to the large amount of primary pions in the system, a longer emission time for kaons than for pions is expected. This explains the m_{T}-scaling violation seen in Fig. 5 [42], where the radii of kaons are systematically higher than those of pions in the same centrality class.

The measurement of the emission time of pions and kaons can be found in the pion-kaon fmentoscopic study in the work [H1], to which I contributed significantly. This paper quantifies the difference in the emission time in terms of the pion-kaon emission asymmetry, presented in Fig. 6 for Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV as a function of $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle^{1/3}$. The non-zero emission asymmetry is the consequence of several effects, including the collective expansion of the system, the presence of short-lived resonances decaying into the considered particles, and the radial flow of these resonances. All these features are only qualitatively reproduced by a (3+1) viscous hydrodynamic model [43], coupled to the statistical hadronisation, resonance decay, and propagation code THERMINATOR 2 [44]. In order to reproduce the measured emission asymmetry quantitatively, an emission delay $\Delta\tau$ of 1.0–2.1 fm/c for the kaons has to be specifically included in the model. This $\Delta\tau$ can be interpreted as the delay due to the decay of K*(892) resonances produced by regeneration in the late stages of the hadronic phase.

4 Femtoscopy as a tool to study hadron–hadron interactions

Traditional femtoscopy studies the spatio-temporal characteristics of the source by measuring the correlation function (defined in Eq. 1) directly in experiments and uses particle pairs with well-known

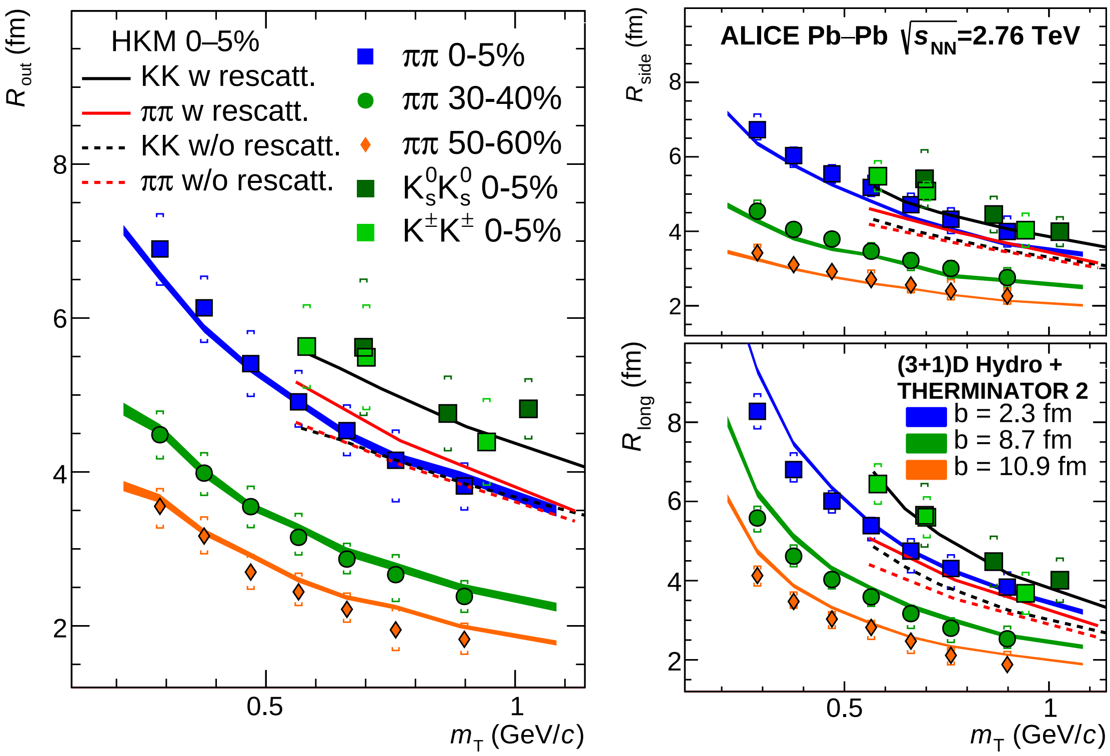

Figure 5: Pair transverse mass dependence of the pion [34] and kaon [40] femtoscopic radii for different event centralities in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. The measured R_{out}, R_{side}, R_{long} are reported in the left, right top and bottom panel, respectively. The experimental data are reported with solid symbols together with statistical and systematic uncertainties. Bands represent theoretical predictions of pion radii by a (3+1)D hydrodynamic model coupled to the THERMINATOR 2 code [37] for the same centralities as in data, selected based on the impact parameter b in the calculation. Lines represent calculations for central collisions by the HKM model with and without rescattering [41]. Figures taken from [13].

interactions. However, taking into account that relativistic collisions of protons and heavy-ions provide an abundant source of many hadron species, in recent years the technique of femtoscopy has been successfully employed in a novel way allowing for the study of the interaction between various hadron species. That specific shift of paradigm comes from the fact that given a known emission function, the interaction term, and hence the two-particle wave-function can be accessed, as indicated in Fig. 7. Both ALICE [45] and STAR [46] collaborations have utilized this approach to establish femtoscopy as a fully-fledged technique to measure hadron–hadron interactions for those pairs where it is poorly known or not known at all, both for matter and antimatter particles. Therefore, femtoscopy can be considered a measurement method of scattering parameters complementary to dedicated scattering experiments.

In this domain I have contributed to the field by being part of the teams performing experimental studies summarized in the papers [H2, H3, H4].

4.1 Kaon–proton interactions: evidence of coupled-channel contributions in small systems and its disappearance in large systems

***This section describes and is based on publications* [H2] *and* [H3].**

Kaon-nucleon interaction is an important ingredient of low-energy QCD. Since perturbation theory is not applicable in this energy regime, experimental data are essential to constrain the currently available effective theories [47]. Moreover, so-called coupled-channel processes are widely present

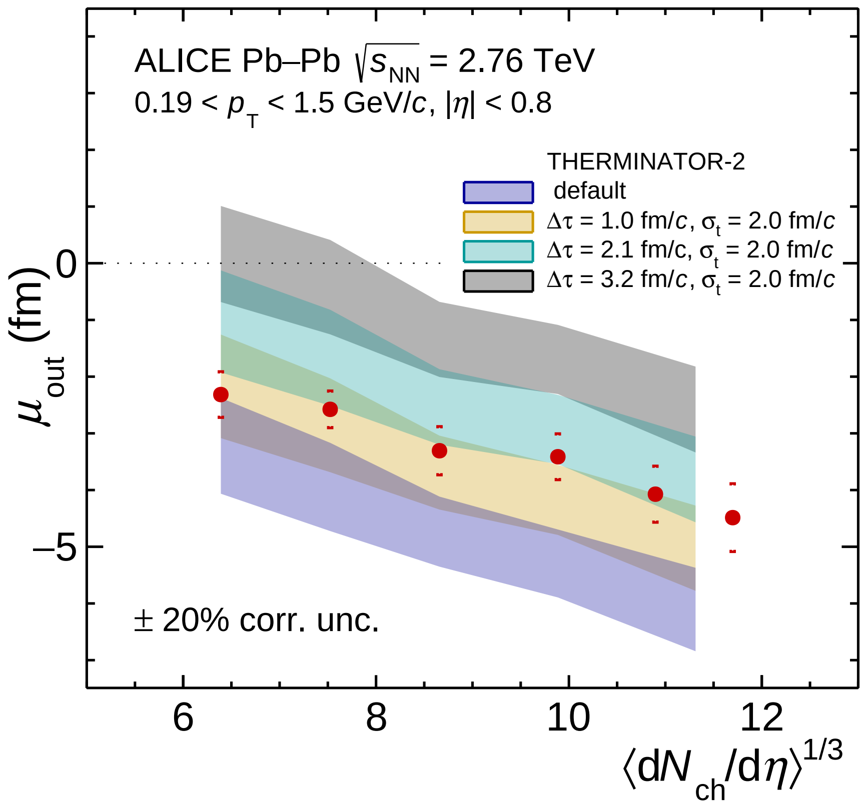

Figure 6: (Left) Pion–kaon emission asymmetry for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV as a function of $\langle dN_{ch}/d\eta \rangle^{1/3}$. The shaded areas show predictions from the THERMINATOR 2 model with default and selected values of additional delay $\Delta\tau$ for kaons [44]. Figure taken from [H1] in the form as reproduced in [13].

in hadron–hadron interactions whenever pairs of particles, relatively close in mass, share the same quantum numbers: baryonic charge, electric charge and strangeness. The coupling translates into on/off-shell processes from one system to the other. The multi-channel dynamics deeply modifies the hadron–hadron interaction and is at the origin of several phenomena, such as bound states and resonances, which crucially depend on the coupling between the inelastic channels. A key example can be found in the $\Lambda(1405)$ resonance, a molecular state arising from the coupling of antikaon-nucleon ($\overline{\mathrm{K}}$–N) to Σ–π [48, 49].

The advantage of the femtoscopic measurement, with respect to scattering experiments for the study of coupled channels, is that the final state is fixed by the measured particle pair, hence the corresponding correlation function represents an inclusive quantity sensitive to all the available initial inelastic channels produced in the collision [50, 51]. The K–p system contains couplings to several inelastic channels below threshold such as π–Λ, π–Σ and, due to the breaking of isospin symmetry, to charge-conjugated $\overline{\mathrm{K}}^0$–n at roughly 4 MeV above threshold.

In the left panel of Fig. 8, a schematic representation of the collision is shown. The correlation of K–p pairs composing the final-state is measured and its decomposition into contributions of different channels contributions is shown for two different source sizes in middle and right panel, respectively. The largest contributions on the correlation function from coupled-channels occur for a small emitting source with Gaussian radius $r_G = 1$ fm as shown in middle panel. The correlation function signal increases as the inelastic contributions are added and the cusp structure, visible when the $\overline{\mathrm{K}}^0$–n channel is explicitly added, indicates the opening of this channel above threshold. The effect of coupled-channels is suppressed when the source size is increased up to 5 fm, as in central heavy-ion collisions (right panel in Fig. 8).

This theoretical scenario and the extreme sensitivity of the correlation function to coupled-channel

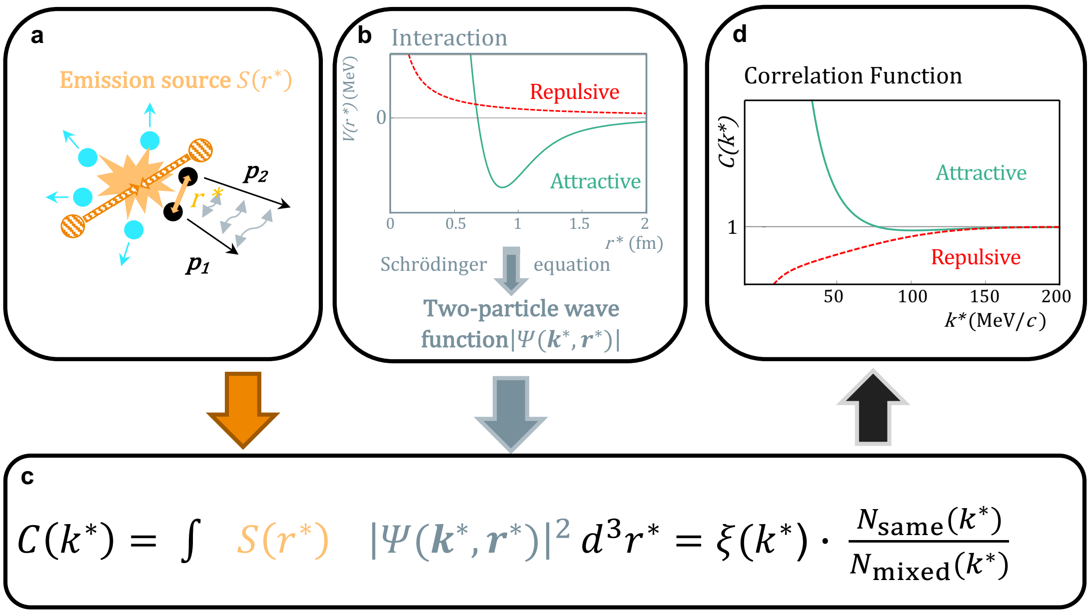

Figure 7: Schematic representation of the correlation femtoscopy method utilized to study hadron-hadron interactions. Figure taken from [45].

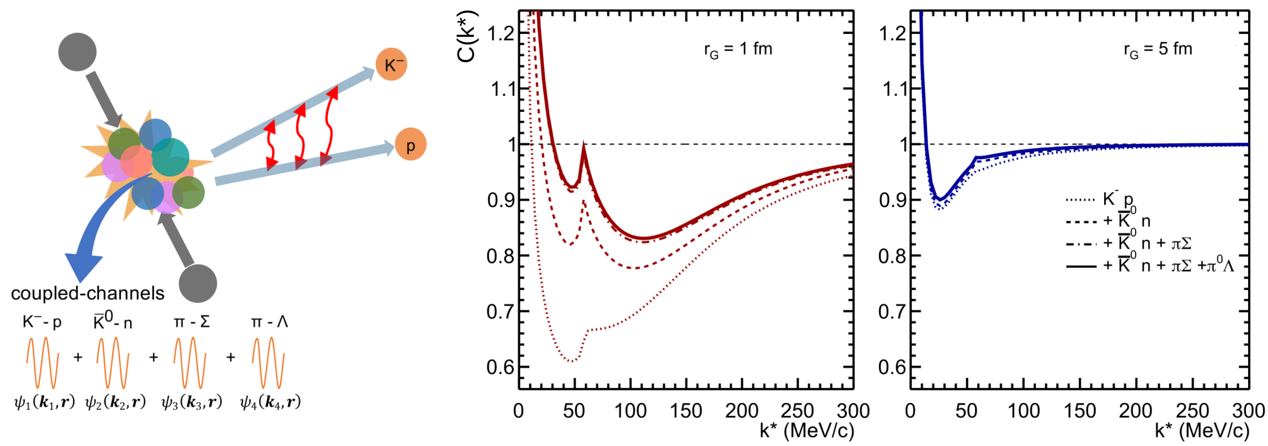

Figure 8: (Left) Sketch of the system configuration in femtoscopic measurements, where only the final K$^-$–p channel is measured. (Middle and right) Theoretical correlation function for K$^-$–p, from the pure elastic term (dotted line) to the full correlation function (solid line) with all coupled-channels ($\overline{\mathrm{K}}^0$–n, π–Σ, π–Λ) included. The results are shown for two different radii, typically achieved in pp collisions (1 fm) and in heavy-ion collisions (5 fm). Figures taken from [13].

dynamics have been confirmed by the measurements of the K$^-$–p correlation function, measured in different colliding systems, shown in Fig. 9. From left to right, the size of the emitting source increases as the correlation function is measured respectively in pp collisions [H2] and Pb–Pb collisions [H3] and the shape of the measured correlation function varies significantly. The cusp signature at $k^* = 58$ MeV/c is not present in large systems. As the source size increases, the enhancement at low momenta due to coupled-channel contributions follows the same trend, becoming less pronounced. In large collision systems such as Pb–Pb, the asymptotic part of the wave function is probed, hence the effects of coupled-channels on the correlation function are noticeably suppressed and a partial direct access to the elastic term can be obtained. This leads to a good agreement between the scattering length f_0 obtained fitting the Pb–Pb data and the values extracted from kaonic atom measurements, in which coupled-channel effects are typically not considered [52]. The small colliding systems on the other hand provide the opportunity to test the coupling strength of different initial channels to the final channel K$^-$–p with unprecedented precision [53].

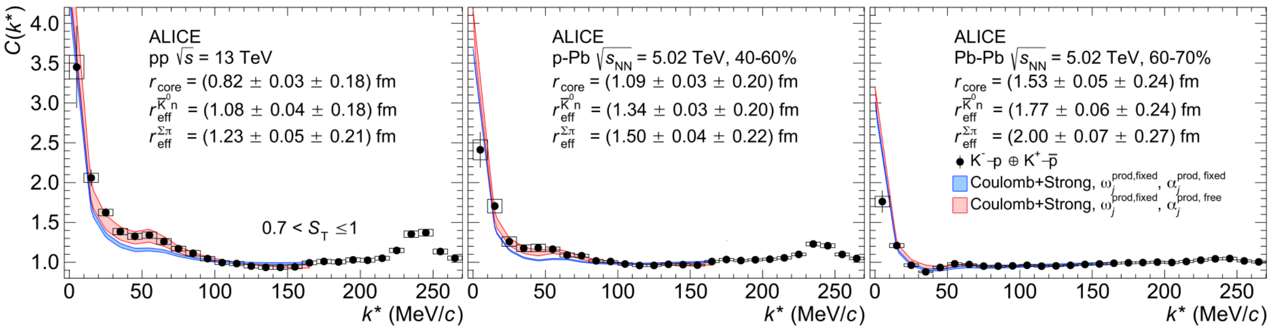

Figure 9: Measured correlation function versus the relative momentum k^* for K$^-$–p ⊕ K$^+$–overlinep pairs in pp collisions at $\sqrt{s} = 13$ TeV (left), in 40–60% centrality interval in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV (middle) and in 60–70% centrality Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV (right). In all the panels, data are compared with the $\chi^{\rm EFT}$-based potential [51] with fixed (blue bands) and free (red bands) coupling weights [53]. Modified versions of figures taken from [H2, H3] as reproduced in [13].

4.2 Baryon–antibaryon interactions: possible existence of bound states

***This section describes and is based on publication* [H4].**

The study of the strong interaction in the baryon–antibaryon sector is very challenging since obtaining beams or targets of antimatter is very difficult. Hence very little is known about the baryon–antibaryon interaction.

From proton–antiproton scattering it is known that the formation of *protonium* (or *antiprotonic hydrogen*) occurs [54, 55], and its 1s and 2p states are of particular interest since there is evidence of a contribution from the strong force. Nevertheless, the nature of protonium, whether it can be considered a nuclear bound state or a result of the Coulomb interaction, remains an open question. Much less is known for baryon–antibaryon pairs with non-zero strangeness, since only few experimental data from scattering experiments exist.

Two particle momentum correlations have been also employed to study the strong interaction in the baryon–antibaryon sector in ultrarelativistic pp and Pb–Pb collisions at the LHC, where the same amount of baryons and antibaryons is produced [56].

Correlation functions for p–$\overline{\rm p}$, p–$\overline{\Lambda}$ ⊕ $\overline{\rm p}$–Λ and Λ–$\overline{\Lambda}$ have been measured in Pb–Pb collisions at energies of $\sqrt{s_{\rm NN}} = 2.76$ TeV and $\sqrt{s_{\rm NN}} = 5.02$ TeV [H4] and also in pp collisions at $\sqrt{s} = 13$ TeV [57]. The analysis in Pb–Pb, to which I significantly contributed, was performed in several centrality intervals; an example for the 10–20% centrality interval can be seen in Fig. 10. A simultaneous fit of all the correlation functions was performed to extract the scattering parameters of the strong interaction. The spin-averaged scattering parameters, i.e. $\Re f_0$ the real and $\Im f_0$ imaginary parts of the spin-averaged scattering length, and d_0 for the real part of the spin-averaged effective range of the interaction for $\overline{\rm p}$–Λ⊕p–$\overline{\Lambda}$ and Λ–$\overline{\Lambda}$ have been obtained and the scattering parameters for baryon–antibaryon pairs, which were not measured directly, were estimated. All of the extracted parameters from the femtoscopic fit are summarized in Fig. 11 and compared with different theoretical models and with measurement performed by other experiments.

The real and imaginary parts of the scattering length, and the effective interaction range extracted from the Pb–Pb fits have similar values for all baryon–antibaryon pairs at low k^*. The significant magnitude of $\Im f_0$ shows that inelastic processes (annihilation) can occur for baryon–antibaryon systems. This finding was verified by the analysis in pp collisions, where an even larger contribution to the inelastic part of the interaction was found for the p–$\overline{\rm p}$ and p–$\overline{\Lambda}$ ⊕ $\overline{\rm p}$–Λ pairs, while the same scattering parameters found in Pb–Pb collisions provided a good description of the Λ–$\overline{\Lambda}$ correlation [57]. The negative values of $\Re f_0$ show either that the interaction between baryons and antibaryons

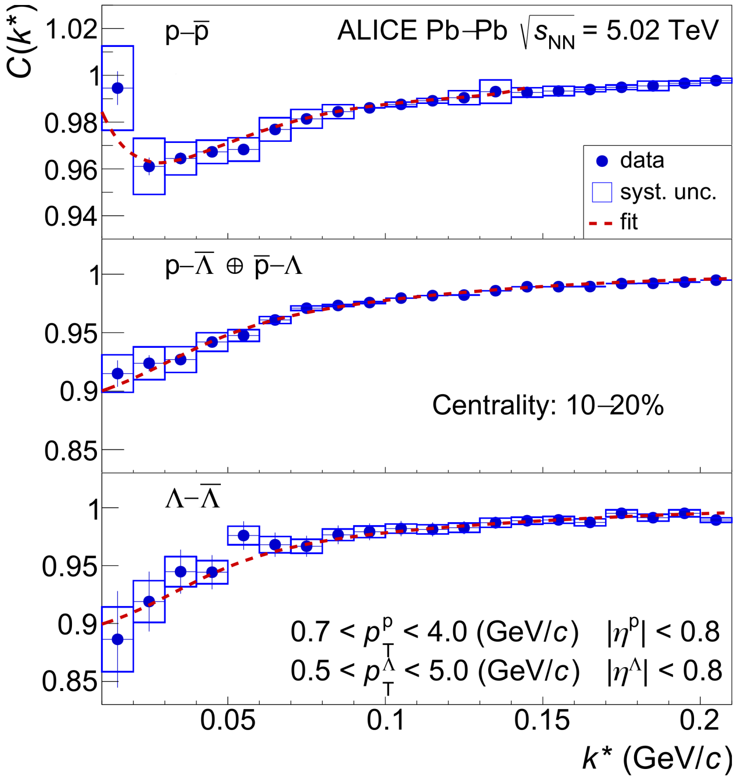

Figure 10: Example of correlation functions (points) of p–p̄, p–$\overline{\Lambda}\oplus\overline{p}$–Λ, and Λ–$\overline{\Lambda}$ pair for the 10–20% centrality class. Dashed lines show a part of the global fit, performed simultaneously to correlation functions of all three pair types in 6 centrality classes. Figure taken from [H4].

is repulsive, or that baryon–antibaryon bound states can be formed. These findings can not exclude the presence of a bound state in the baryon–antibaryon channels but the presence of sizeable inelastic components makes it very difficult to disentangle the two effects.

5 Hadronization mechanism studied via angular correlations of identified hadrons

This section describes and is based on publications **[H5, H6, H7].**

"Hadronization" is a mechanism of QCD. It is intrinsically non-perturbative (cannot be calculated from the first principles of physics) and so far only phenomenological models with parameters constrained from experimental data exist. Studies of this process in elementary collisions date back to the times of R. Feynman and R. Field, who in 1977 proposed a simple mechanism describing the principles of creation of the so-called "jets", collimated streams of particles [65, 66]. They proposed rules on how the particles are created, how the energy is distributed and considered limitations connected to the conservation laws. Elements of the proposed scheme are used even today in the most popular fragmentation models. For instance, one of them is the so-called string fragmentation model, also known as the "Lund model" [67] which is incorporated in the PYTHIA Monte Carlo generator [68]. However, the implementation details of such models have to be constrained from the experimental data.

The baryon production process (quark fragmentation into baryons) has been studied in the measurements of two-baryon rapidity correlations in e^+e^- collisions in the 1980's and early 1990's, at much lower energies and on substantially smaller data samples than available today [69, 70, 71, 72, 73]. Especially the results from work [69] show that pairs of particles with opposite baryon number produce a positive correlation while pairs of particles with the same baryon number (in this case

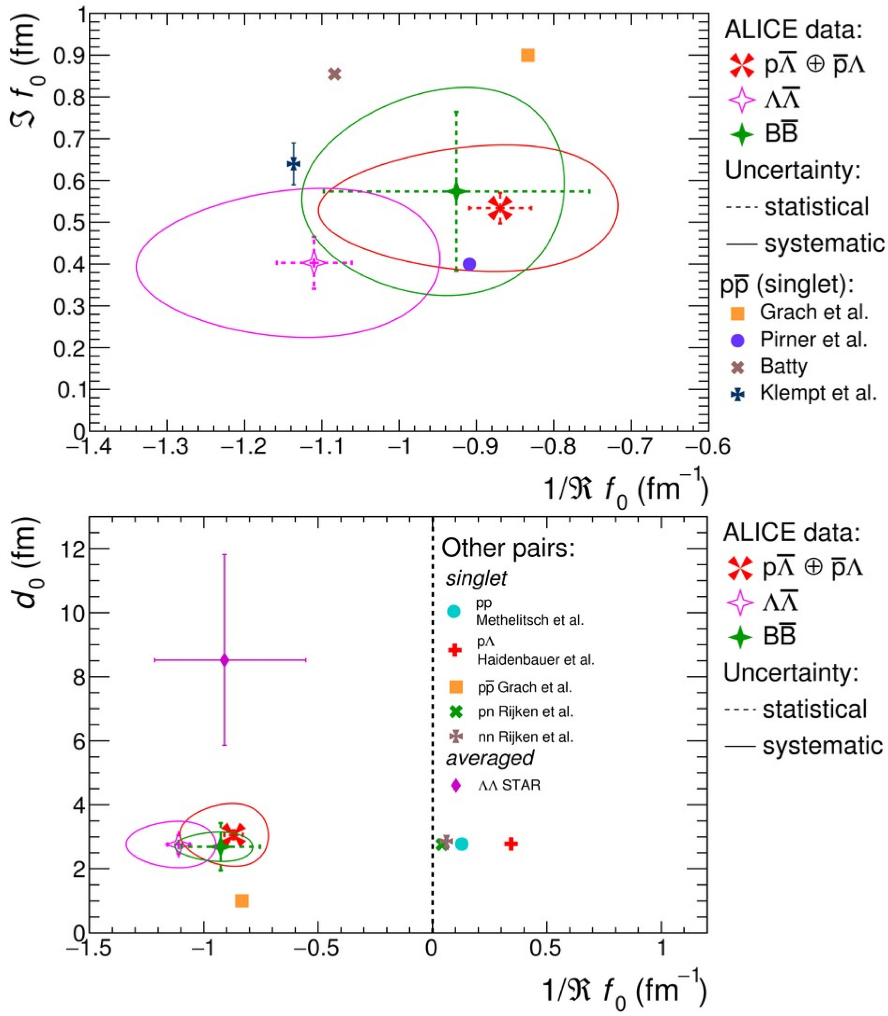

Figure 11: Comparison of extracted spin-averaged scattering parameters $\Im f_0$ and $\Re f_0$ (Top) and d_0 and $\Re f_0$ (Bottom) for p–$\overline{\Lambda}\oplus\overline{\text{p}}$–Λ, Λ–$\overline{\Lambda}$ pairs and effective parameters accounting for the contribution of heavier B–$\overline{\text{B}}$ pairs. Results are compared with different theoretical models [58, 59, 60, 55, 54, 61, 62, 63] and with results obtained by the STAR collaboration [64]. Figures taken from [H4].

antiproton-antiproton, antiproton-antilambda, antilambda-antilambda) produce a significant anticorrelation. These results were compared to the Lund model calculation incorporating local compensation of the baryon number – a mechanism ensuring that the baryon number is conserved not only globally, for the whole colliding system, but also locally for each parton fragmentation. Thus, in order to achieve a positive two-baryon correlation at low rapidity difference, two baryons and two antibaryons, relatively heavy particles, would have to be produced in a single jet. Such a scenario is highly unlikely at $\sqrt{s}$ = 29 GeV. However, this limitation should not be present with collision energies currently achievable in accelerator facilities such as LHC at CERN or RHIC at BNL.

Experimentally, the angular correlation function is defined as the ratio of $A(\Delta\eta, \Delta\varphi)$ divided by $B(\Delta\eta, \Delta\varphi)$, with an additional normalization, similarly to the femtoscopic correlation. An example of such a correlation function, as measured in proton-proton collisions of $\sqrt{s}$ = 7 TeV, is shown in Fig. 12.

Our recent developments in ALICE [75], later followed up by the STAR experiment [74], shed more light on this topic. In ALICE, two-baryon correlations as a function of azimuthal angle difference ($\Delta\varphi$) and pseudorapidity difference ($\Delta\eta$) have been measured in pp collisions at $\sqrt{s}$ = 7 TeV [75]. A similar anticorrelation effect has been observed for proton-proton (antiproton-antiproton), proton-lambda (antiproton-antilambda), as well as lambda-lambda (antilambda-antilambda) pairs, see the results in Fig. 13. The STAR experiment has observed an analogous effect in two-particle correlations as a function of the rapidity difference (Δy) in Au–Au collisions at center-of-mass energies per nucleon

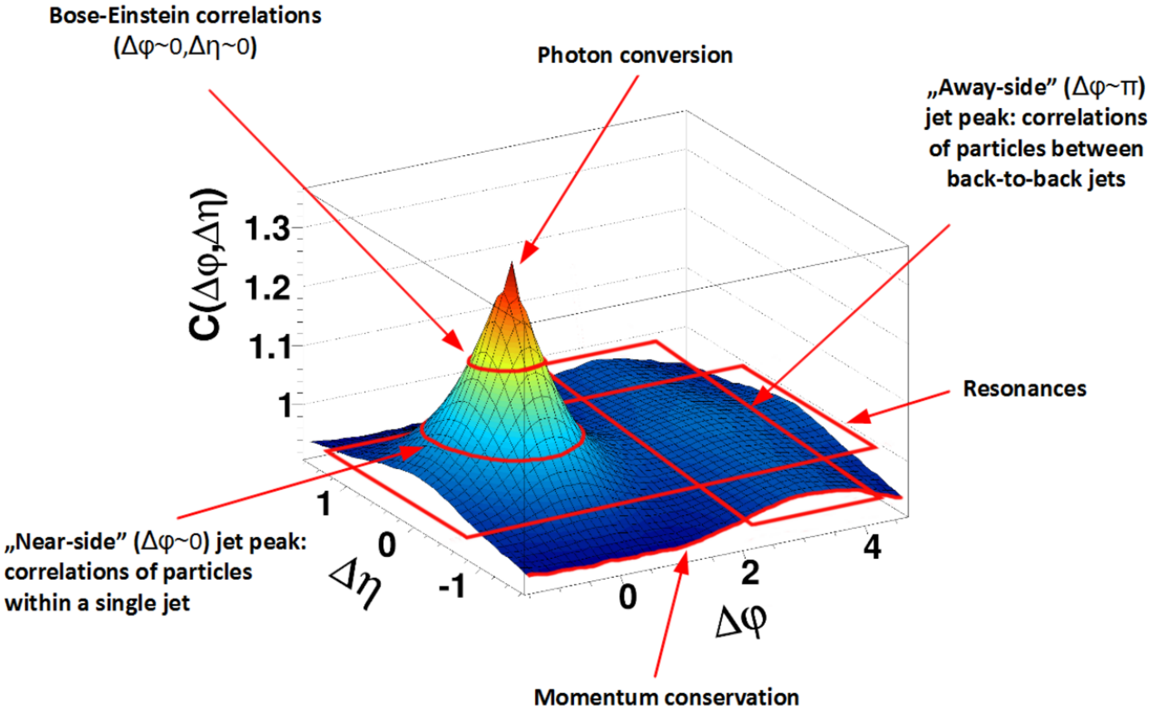

Figure 12: Example $\pi\pi$ two-particle angular correlation function $C(\Delta\eta, \Delta\varphi)$ from pp collisions at $\sqrt{s} = 7$ TeV with marked effects originating from various physical mechanisms. Figure taken from [H7].

pair from $\sqrt{s_{\mathrm{NN}}} = 7.7$ GeV to $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, demonstrating that it is not limited to elementary collisions only [74]. The origin of the anticorrelation effect, which persists at such high collision energies, remains unknown and challenges current hadronisation models.

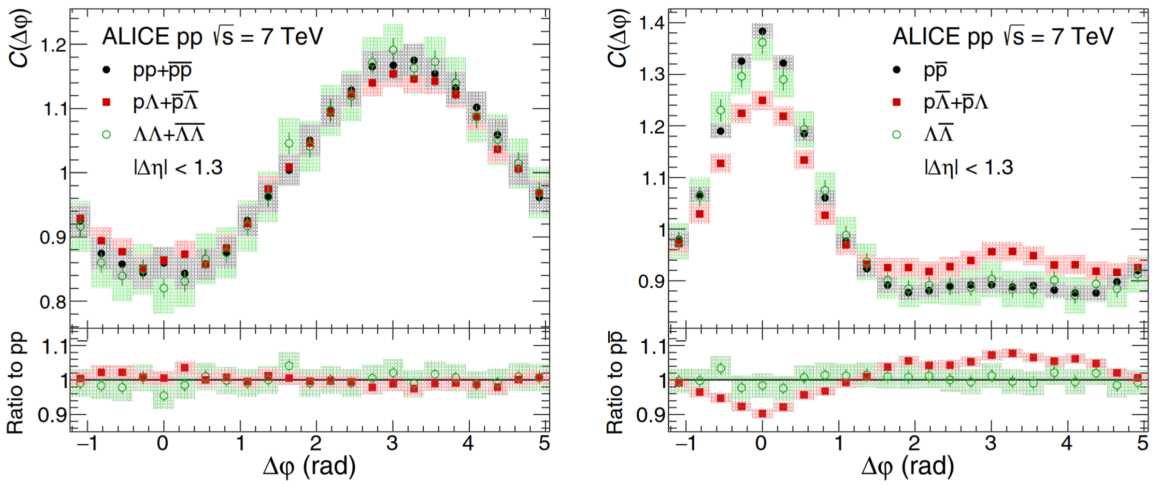

Figure 13: $\Delta\eta$-integrated projections of correlation functions for combined pairs of (left) $\mathrm{pp} \oplus \overline{\mathrm{p}}\overline{\mathrm{p}}$, $\mathrm{p}\Lambda \oplus \overline{\mathrm{p}}\overline{\Lambda}$, $\Lambda\Lambda \oplus \overline{\Lambda}\overline{\Lambda}$, and (right) $\mathrm{p}\overline{\mathrm{p}}$, $\mathrm{p}\overline{\Lambda} \oplus \overline{\mathrm{p}}\Lambda$, $\Lambda\overline{\Lambda}$. Figure taken from [75].

In addition to experimental studies, we have also performed investigations using a simple Monte Carlo simulations [H6]; we showed these studies at the Quark Matter 2015 conference in Kobe (Japan) as a poster, later awarded a flash talk at the plenary session, which was given by my fellow colleague Dr. Małgorzata Janik. Namely, we studied events in which energy and momentum are conserved and no other physics mechanisms are involved. For such a case a toy Monte Carlo model was developed in order to explore the impact of the conservation laws on the correlation functions, which we called "CALM" (ConservAtion Laws Model). CALM allows us to generate collisions where only energy, momentum and locally conserved quantum numbers are conserved in the formation of jets, no other

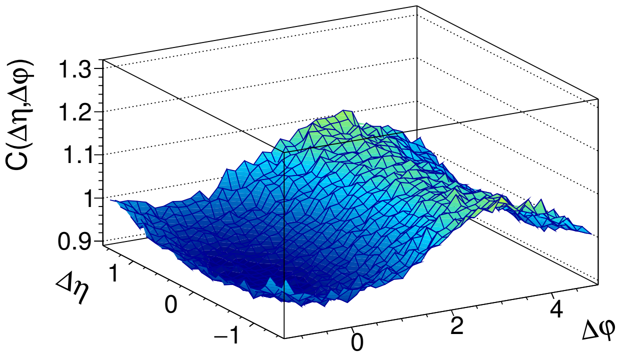

Figure 14: Correlation function of charged particles obtained from CALM model including **only** conservation laws. Figure taken from [H6].

processes are involved. The model also reproduces the usual jet/minijet correlation shape with the near-side peak and the away-side ridge. In Fig. 14 the correlation function presenting neutral pions distributed isotropically in the whole phase-space, with momentum conservation as the only constraint, is shown. Such a simple description reproduces qualitatively structures observed for like-sign protons in ALICE data.

Moreover, in addition to the (mini)jet correlations, the correlation (anticorrelation) arising from the Bose-Einstein (Fermi-Dirac) QS, as well as the effects of the Coulomb and strong final-state interaction (FSI) manifest in the same region of the angular correlation function, that is $(\Delta\eta, \Delta\varphi) \approx (0, 0)$, as demonstrated in Fig. 12. Since the two analyses methods, that is femtoscopyc and angular correlations are sensitive to the same effects (i.e. jets, QS and FSI, but to various degrees), utilizing different observables, they can potentially benefit from each other.

In pp correlations an additional small peak convoluted with the depletion at $(\Delta\varphi, \Delta\eta) = (0, 0)$ is visible in ALICE data [75]. On the other hand, the STAR results also reveal an interesting feature in the analysis of the opposite charge $\mathrm{p\overline{p}}$ pairs, showing yet another depletion around $(\Delta\varphi, \Delta\eta) \approx (0, 0)$, although much narrower with respect to the baryon–baryon case [74]. Both structures, the small peak in pp and a depletion in $\mathrm{p\overline{p}}$ correlations, are postulated to originate from the strong FSI.

Recently, together with Dr. Małgorzata Janik I have proposed and validated with PYTHIA 8 simulations (coupled to Lednický and Lyuboshitz (L-L) formalism for the calculation of the Quantum Statistics (QS) and FSI [19, 76, 77]) a procedure that employs measured femtoscopic correlations to unfold the QS and FSI effects in angular correlations. This work is published in [H7]. It is an iterative process based on random generation of kinematic quantities (p_{T}, η, φ) of two particles from the experimental spectra of transverse momentum, azimuthal angle and pseudorapidity, for two particles to form pairs. Then, pair quantities (q_{inv}, $\Delta\eta$, $\Delta\varphi$) are calculated and from the measured experimental femtoscopic correlation function the weight w is obtained for a given q_{inv}. Then, two histograms are filled (numerator and denominator) for a given $(\Delta\eta, \Delta\varphi)$ bin. The numerator is filled with a weight w, while the denominator with a weight equal to 1. The algorithm can be adopted in a similar way for calculation of the femtoscopic correlation function (q_{inv}) from the angular one $(\Delta\eta, \Delta\varphi)$. The unfolding PYTHIA 8 generated like-sign pion femtoscopic correlation function, with an additional L-L weight related to the QS and FSI, to the $(\Delta\eta, \Delta\varphi)$ space is presented in Fig. 15.

6 Improving ALICE Particle Identification with Machine Learning

***This section describes and is based on publications* [H8] *and* [H9].**

The main task of PID is to provide high-purity samples of particles of a given type required by the analyzer conducting a specific analysis. In the most traditional approach, particles are selected by applying so-called “cuts” to the reconstructed features obtained from the detector response, rejecting

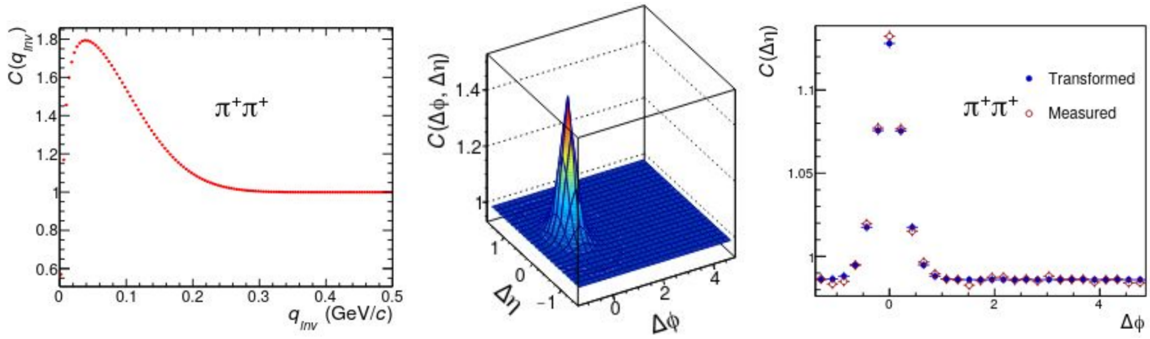

Figure 15: (Left) $\pi^+\pi^+$ femtoscopic correlation function from PYTHIA 8 with QS and FSI weights calculated using the Lednický and Lyuboshitz formalism. (Middle) unfolded $C(\Delta\eta, \Delta\varphi)$ correlation function. (Right) Projection of both original and unfolded $\Delta\varphi$ correlation in mid-$\Delta\eta$ range. Figure prepared using the algorithm proposed in [H7].

the particles not meeting the specified criterion. Such an approach is justified when the separation between various particle species is significantly large. However, when the feature distributions associated with the particle species begin to overlap, the process of combining the information from multiple detectors becomes non-trivial, and the "trial and error" approach based on the intuition and experience of the analyzer becomes not optimal. This leads to lowered PID efficiency and limits the statistical significance of the final data analysis. These shortcomings can be addressed with more advanced classification methods. One particular example is the Bayesian approach, which has proven successful in the ALICE experiment [78]. However, other solutions, i.e., those based on Machine Learning (ML), also have a potentially significant impact. I have proposed investigating ML-based approaches to PID in ALICE and started a cooperation with computer scientists from the IT faculties of WUT on that subject.

For data gathered throughout the LHC Run 2, several attempts to introduce ML-based PID strategies were made. For example, in [H8] we proposed a method based on a Random Forest [79] algorithm and showed the results for kaon selection. This technique is based on the idea of ensemble methods, where a group of weak decision trees is used to produce the final output, which corresponds to the class predicted by most of the individual classifiers. Each tree is trained with only a subset of all available parameters and a subset of available data examples to increase their variance. In [H8], the tree generation method based on the Gini index was used, which is defined as the probability of the wrong classification while using only a given attribute. Proposed experiments indicate that thanks to incorporating additional track-related attributes, the ML-based PID provides much higher efficiency and purity for the selected particles than standard methods. In particular, in [H8] we showed a comparison of purity and efficiency as a function of p_{T} for kaons selected with the traditional method ($n_{\sigma,\mathrm{TCP}} < 2$ for $p_{\mathrm{T}} \leq 0.5$ GeV/c and $\sqrt{n^2_{\sigma,\mathrm{TCP}} + n^2_{\sigma,\mathrm{TOF}}} < 2$ for $p_{\mathrm{T}} > 0.5$ GeV/c, where for a given particle measured in a detector, n_σ is the number of standard deviations from the expected value), and using the Random Forest classifier for PYTHIA 6.4 [68, 80] (Perugia-0 tune [81]) simulated MC pp data at a collision energy of $\sqrt{s} = 7$ TeV, see Fig. 16. In this study on simulated data, the Random Forest classifier outperformed the traditional cut-based selection.

Further extension of the ML PID work is shown in paper [H9], which presents a status of still ongoing activity to deliver a comprehensive PID framework for the LHC Run 3, with a new computing framework and data format (called O^2) being deployed [82]. Based on what we have learned in the preliminary work for LHC Run 2, we propose a novel and more advanced solution based on Domain-Adversarial Training of Neural Networks [83], which also addresses the MC and experimental data misalignment. To improve particle identification performance, in [H9] we propose to implement a classifier based on a multilayered perceptron. We train it with data from corresponding MC simulations. To simplify integration and allow the selection of individual particles independently, we propose to train one model with a binary classification objective for each particle type.

In analysis, PID is used to select particles of desired types in both real experimental data and Monte

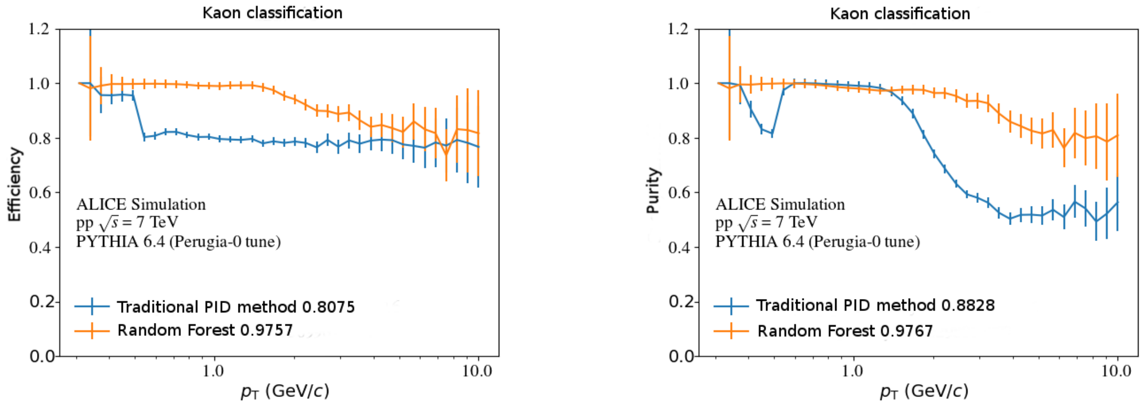

Figure 16: (Left) Comparison of PID efficiency as a function of p_T of the kaon selection between the traditional PID method and the Random Forest classifier. (Right) Comparison of purity as a function of p_T of the kaon selection between the traditional PID method and the Random Forest classifier. Figures taken from [H8].

Carlo simulations. However, recorded signals in physical detectors can differ from those produced in simulations. Therefore, standard PID methods rely on partially automated processes for data domains alignment. For instance, one of ALICE's approaches consists of using the so-called "tune on data". This procedure is based on generating a random detector signal based on a parametrization obtained from data. The resulting distributions of Monte Carlo and experimental data should be equivalent, and only statistical fluctuations are present.

To circumvent the limitations of standard data alignment methods, we propose combining it with particle identification stating it as a known problem of classification with unsupervized domain adaptation. The main idea of this technique is to learn the discrepancies between two data domains, that is, the labeled source domain (in our case simulation data) and the unlabelled target one (in our case experimental data), and translate those to a single hyperspace, where the differences between domains are no longer visible. Classifiers trained on top of features located in combined latent space should have similar performance on both MC simulated and experimental data. Nevertheless, in such a scenario, simulation data is crucial to learn how to distinguish different particles based on aligned representations. The domain-adaptation technique is widely used in natural language processing [84, 85] and computer vision [86, 87]. In the domain of high-energy-physics, its application is limited only to preliminary studies of jet classification [88]. In this work, the authors present that this method can improve the quality of automatic jet tagging on real experimental data.

Our initial experiments with Domain Adversarial Neural Networks (DANN) [83] show that this technique enhances the classification of particles in experimental data. The main idea behind this method is to build a system composed of three neural networks. The goal of the feature mapping network is to map original input into domain invariant features. Those features serve as an input to the standard particle classifier that outputs the particle type. Additionally, the last model, known as domain classifier, enforces domain invariance of extracted features through adversarial training procedure. The training of the model is divided into two steps. First, on top of current features from the feature mapping network, the domain classifier is trained independently to classify domain labels – whether data come from a real or a simulation source. Then, the domain classifier is being frozen so that the particle classifier and the feature mapper can be trained jointly to predict accurate particle types while fouling the domain classifier at the same time. With this approach, the feature mapper's weights are updated with a gradient from the particle classifier and a reversed gradient from the domain classifier. Training a domain-adaptation-based classifier is more complex than the classical neural model. However, the application performance of those two methods is similar and depends on the complexity of the classifier and feature extractor.

Figure 18 presents preliminary results of the proposed DANN model for pion identification in pp data at $\sqrt{s} = 13$ TeV from the LHC Run 2 period. The training dataset was a corresponding MC simulation with PYTHIA 8 Monash tune [89].

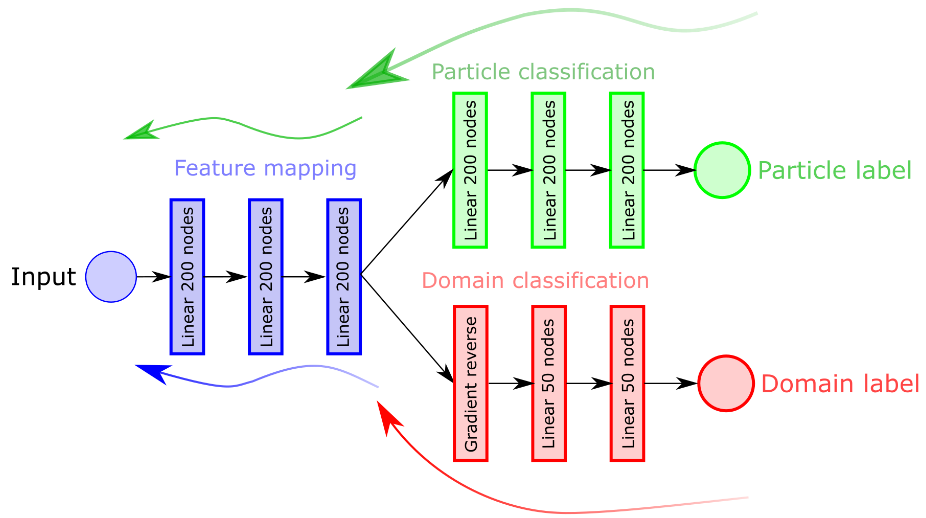

Figure 17: Architecture of DANN composed of three models: feature mapper, particle classifier and domain classifier. Figure from [H9].

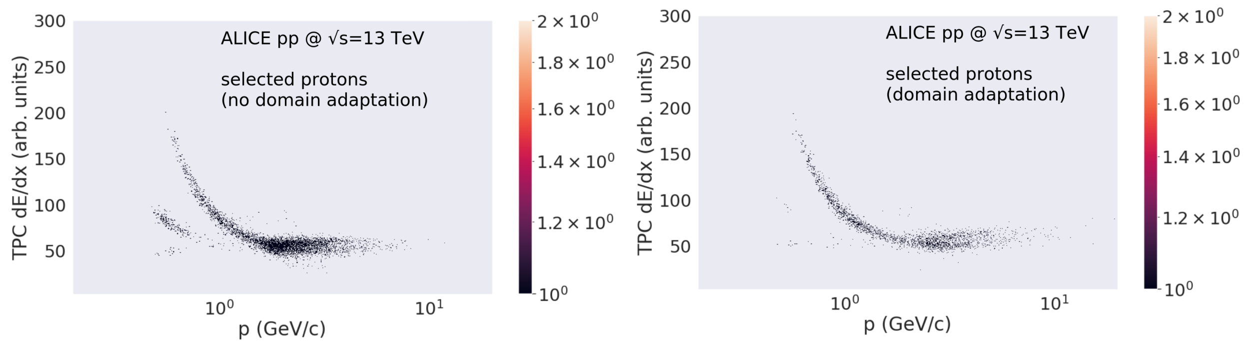

Figure 18: Preliminary result of DANN PID for the TPC detector signal ($\mathrm{d}E/\mathrm{d}x$) as a function of particle momentum for particles identified as protons without domain adaptation (left) and with domain adaptation (right). Figure taken from [H9].

Our preliminary results of classification applied with the proposed model indicate that domain adaptation improves experimental data classification. The enhancement is visible as a reduction of contamination outside the proton band in the energy loss signal of protons classified with DANN in Fig. 17. However, detailed benchmarks will have to be done in the future after the final architecture of the model is achieved in order to support that hypothesis.

Besides developing and improving the neural network models, the new particle identification framework needs to be integrated into the more extensive analysis software. Figure 19 depicts an initial, tentative design of the PID workflow, which will be further tested and updated.

The current developments make use of the ONNX (Open Neural Network Exchange) standard [90], which defines a common file format for storing machine learning models developed in various frameworks such as Tensorflow and PyTorch. Additionally, the ONNX Runtime [91] library enables ONNX models to be used in different programming languages such as Python and C++ with a simple API. ONNX and ONNX Runtime are also tested by other machine learning projects at ALICE, and the solution provided for PID ML will be an example base for the other projects.

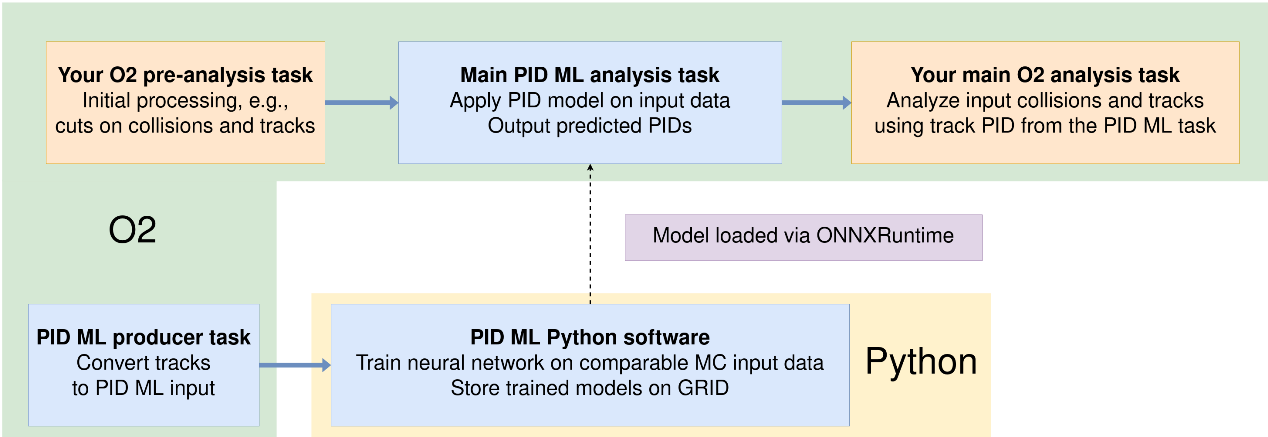

Figure 19: An initial scheme of the particle identification workflow in O^2. Figure taken from [H9].

7 Improving ALICE event visualization with accurate magnetic field model

***This section describes and is based on publication* [H10].**

Event visualization is one of the most important aspects of ALICE operation. While it is not crucial for the detector operation itself, it is widely used for most public communication (i.e. in the CERN press releases) and it is also deployed in the ALICE Control Room and displayed on the central screen, allowing shifters to spot problems in the collected data, not immediately seen by other subsystems. The ALICE Event Display shows the reconstructed tracks of particles, overlayed with the detector geometry.

Full reconstruction of tracks requires precise knowledge, among many other parameters, of the magnetic field generated by the two ALICE electromagnets. Characteristics of them were measured in 2005 by the ALICE Collaboration. The collected data was then used to create a model of the magnetic field. In the ALICE software, that is *AliROOT*, the model is based on the Chebyshev polynomials and is implemented in a way to run efficiently on the CPU. However, the Event Display software, which displays trajectories of particles, does not use this accurate field model, instead implementing the simplest possible – uniform – approximation of only the solenoid field (the dipole field is not taken into account at all).

The main objective of our interdisciplinary study was to create a novel version of the model implementation capable of running on the GPU to create a possibility of using the magnetic field model in real-time, 3D visualizations of particle collisions, and for displaying the field itself. The development of the new model was a task of computer scientists from the Faculty of Electronics and Information Technology of WUT. Six algorithms of magnetic field data access were prepared for our studies:

- Shader Storage Buffer,
- 3D Texture,
- Sparse 3D Texture,
- GLSL (reimplementation of the original algorithm in a GPU shader) with segment cache,
- GLSL without segment cache,
- Constant.

In this document, I will not go into details of the implementation, as they are very technical and specific to the field of computer science. I would like to refer the interested reader to the paper [H10].

My role in the whole project was related to benchmarking the results. The bencharking is shortly described below. We have created two benchmark scenarios:

- *eval*, where we prepare a set of N points inside the detector volume and schedule the $AliROOT$ or GPU implementation with fetching the field vector at each point,
- *fieldline*, where we prepare a set of $N/100$ points inside the detector volume and schedule the $AliROOT$ or the GPU implementation to perform a simulated point drift – they should (1) fetch the field vector at a position, (2) apply it's value to the position, then repeat from (1) 100 times. As the name of the benchmark implies, this operation creates a list of points along a particular field line of the magnetic field.

In both scenarios, the total amount of field value requests is equal to the (tunable) testing parameter N. We have run both benchmarks with the following values of N: 100, 200, 500, 1000, 2000, 5000, 10000, 20000, 50000, 100000, 200000. The number of steps per source point in the *fieldline* benchmark was arbitrarily chosen to be 100.

Three different sources of points were considered for the benchmark scenarios:

(a) randomly, uniformly generated from the whole detector volume,

(b) randomly, uniformly generated from the Solenoid magnet volume only,

(c) generated by track reconstruction software (points along the particle trajectories) from one of the Monte Carlo simulations available in the CERN database.

In both cases we measure the time that the computer spends doing actual computations and the accuracy of the model against the ground truth (the $AliROOT$ model). For the accuracy measurements, we have used the Root Mean Square Error for each individual axis in the laboratory coordinate system used by ALICE. In the *eval* benchmark, the RMSE is calculated on the field vectors. It is expressed in units of kGauss. In the *fieldline* benchmark, the RMSE is calculated on the positions of points in 3D space. It is expressed in centimeters.

As an example result, Tab. 1 presents the Root Mean Square Error measurements for the *eval* benchmark on the maximum amount (200000) of points tested for each scenario.

The worst implementation happens to be the Shader Storage Buffer. This approach in all cases is either worse, or on the same level as the Constant implementation. The texture approach (both standard 3D and Sparse) is in the middle, offering usually an order of magnitude better reflection of the original model than the Constant implementation. Unsurprisingly, the GLSL implementation of the $AliROOT$ performs the best in every category. Its error rate is not zero most likely due to accumulation of floating point errors during the calculation (32-bit operations on GPU vs 64-bit operations on CPU in the original $AliROOT$ algorithm).

Figure 20 presents the total execution time of each scenario, with increasing number of test points N. Here it can be seen that the Constant, Shader Storage Buffer and Texture implementations are very similar to each other in terms of speed and are the fastest. The Sparse Texture implementation is slower then those three, most likely due to not being fully hardware-accelerated. It can be seen that because of the randomly chosen points, the segment cache ends up being a net-negative for the GLSL method, performing slightly worse than the non-cache version. These versions managed to outperform the CPU implementation by the 1000 (cache) and 500 (no cache) requested points mark.

Similar benchmarks have also been performed for the *fieldline* method. Test results show that, if enough work is scheduled for the GPU, the proposed techniques can be used to evaluate the field significantly faster than the $AliROOT$ algorithm. Their performance is also sufficient for usage in a real-time rendering application, with the frame time margin large enough for other operations, such as processing of the field data. All implemented methods (except for the naive approach with the Shader Storage Buffer) offer 100 times or more better accuracy than the uniform model (currently used in 3D applications). Finally, the ALICE magnetic field itself visualized by the code developed for that project can be seen in Fig. 21).

Algorithm	RMSE (x)	RMSE (y)	RMSE (z)
Random points (detector volume)			
Shader Storage	8.80e-01	1.83e-01	2.82e+00
3D Texture	1.41e-01	4.24e-02	2.77e-01
Sparse 3D Texture	1.41e-01	4.24e-02	2.77e-01
GLSL (nocache)	3.67e-08	2.35e-08	5.38e-08
GLSL (cache)	3.67e-08	2.35e-08	5.38e-08
Random points (Solenoid volume)			
Shader Storage	1.16e-01	1.16e-01	4.91e+00
3D Texture	3.92e-03	3.97e-03	6.19e-03
Sparse 3D Texture	3.92e-03	3.97e-03	6.19e-03
GLSL (nocache)	9.71e-05	7.48e-05	8.19e-05
GLSL (cache)	9.71e-05	7.49e-05	8.21e-05
Constant	1.16e-01	1.16e-01	2.38e-01
Points from tracks			
Shader Storage	4.50e-02	4.56e-02	4.90e+00
3D Texture	1.85e-03	1.91e-03	3.56e-03
Sparse 3D Texture	1.85e-03	1.91e-03	3.56e-03
GLSL (nocache)	1.10e-08	1.06e-08	6.32e-08
GLSL (cache)	1.10e-08	1.06e-08	6.32e-08
Constant	4.50e-02	4.56e-02	1.87e-01

Table 1: RMSE values for experiments with maximum tested (200000) amount of points. Values are expressed in kGauss. Table taken from [H10].

8 Improving the ALICE MasterClass software

***This section describes and is based on publication* [H11].**

The last part of my work is related to educational activities and science popularization. I strongly believe that no research should be done without a proper presentation of it to the general public, explaining the need for such studies and even enrolling schoolchildren in taking some part in that endeavor. In the end, it is the society who also funds our research and it is our responsibility to communicate properly what we are doing. Our work related to refactoring the ALICE MasterClass software has was shown by me at the CHEP 2019 conference in Adelaide (Australia), and is discussed in [H11].

The International Particle Physics Outreach Group (IPPOG) [92] is a collaboration of particle physicists and engineers, science educators and communication specialists from all over the world, with the aim of communicating the fundamental particle physics research to general public. The "International MasterClasses – Hands-On Particle Physics" (IMC) [93] is the leading activity of IPPOG, which aims at providing high school students with access to particle physics data with dedicated packages of analysis software and instructions. Every year in the period from February to April, students are invited to one of the participating universities or research laboratories to attend particle physics lectures and perform measurements using real data from the Large Hadron Collider (LHC) [9] experiments. All four LHC experiments (ATLAS, CMS, LHCb, and ALICE) participate in the IMC providing various measurements on different aspects of particle physics. All MC measurements use especially prefiltered samples of real collision data, recorded by the respective experiment. In most cases, they are built on visualization tools that are part of the experiment's software framework. Hence, students have the possibility to work on real data as scientists do. Thousands of students from across the globe attend the event annually.

The ALICE software is based on the CERN's ROOT framework which is used for the experiment's

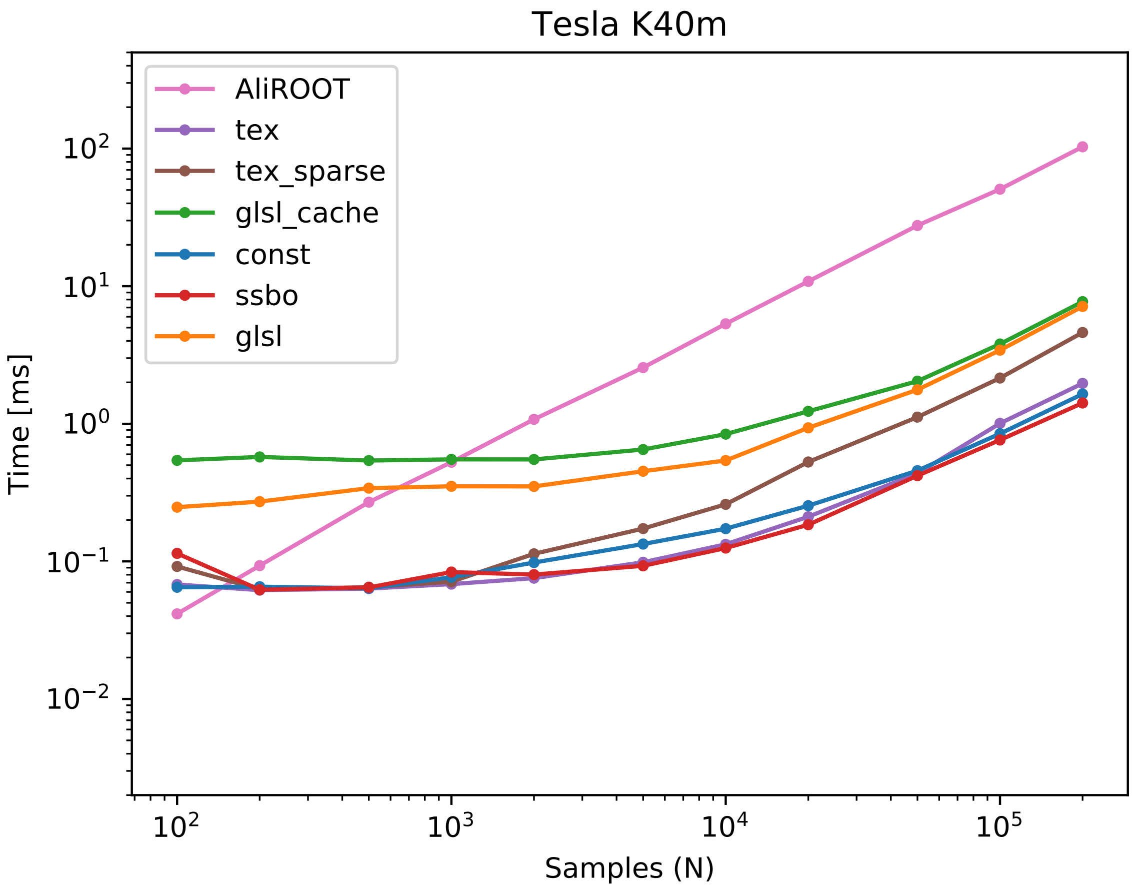

Figure 20: Execution time (in milliseconds) of all implementations for the *eval* benchmark against the execution time of *AliROOT* algorithm, for each sample size. Figure taken from [H10].

data processing and analysis. Consequently, the ALICE MasterClasses are also based on ROOT to fulfil the requirement of the MC to be as close as possible to the experimental reality. The advantage is that school-children are thrilled to know that they use the very same tools as the ALICE scientists. The downside is that the installation of the ROOT framework is required which makes the preparation process cumbersome. Historically, the MasterClass on strangeness was developed first [94] and then adapted for the nuclear modification factor [95]. Those fully developed and documented MC measurements are included in the IMC schedule. The third MC on the J/Psi measurement was also developed with starting point the existing MC software and is currently being finalized. Despite their common origin they soon diverged as different groups and individuals implemented additional functionality or corrections in the individual computer codes with no tracking of different versions. In order to facilitate maintenance and coherency, a concerted effort started as a CERN summer student project in 2018, followed by an educational grant of the Warsaw University of Technology, with the aim to unify the existing MC code integrating it in a single framework, taking advantage at the same time of the enhanced functionality of ROOT 6. The new framework, where all three ALICE MC are integrated, is now used in the IMC 2020 schedule.

Figure 22 represents the new design of the ALICE MasterClass framework at the functional level. The aim was to identify common elements such as the Event Display and reading of experimental data files.

The new framework is distributed and installed as compiled binary standalone application which presents advantages compared to the previous script-based and interpreted form of the project in terms of size and performance. To create the package for Linux systems a *AppImage* framework was used, which bundles the whole application (executable, ROOT framework and experimental data) into

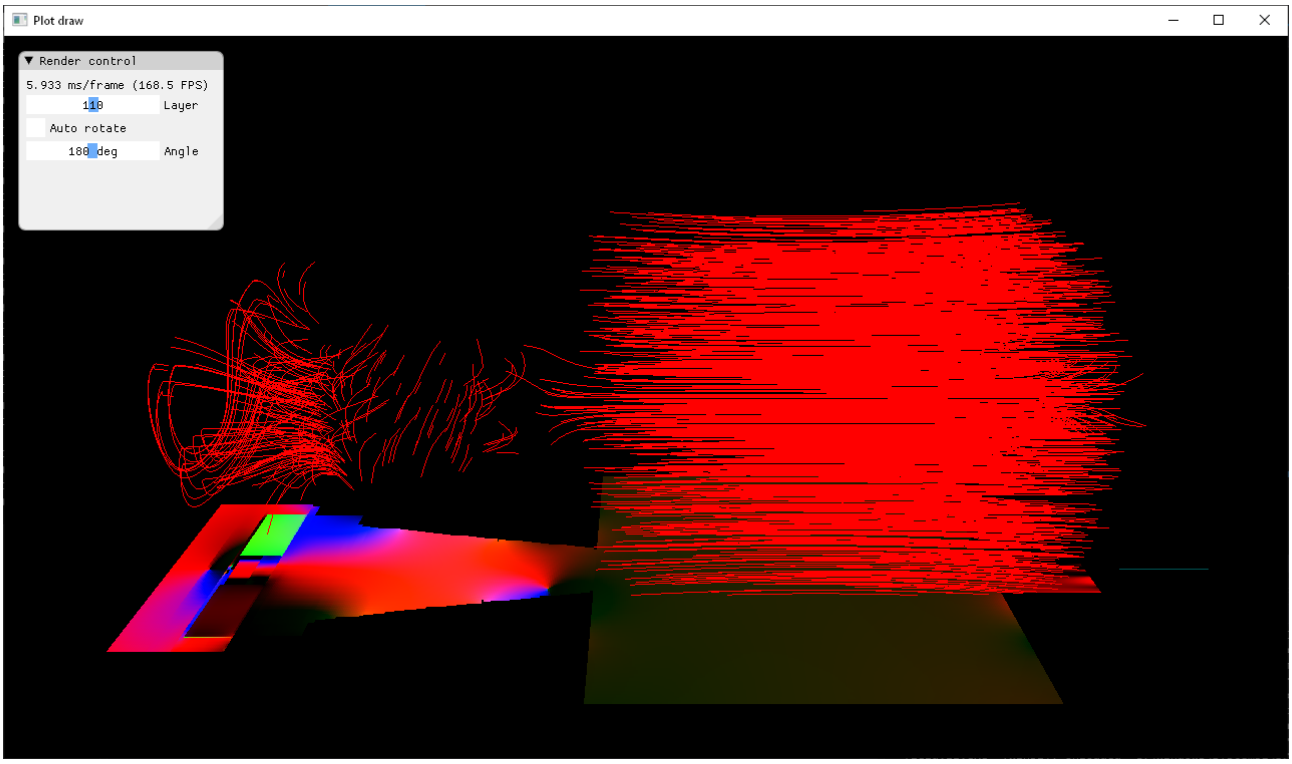

Figure 21: An example of usage of the magnetic field data for visualisation. Figure taken from [H10].

a single file, which can be executed via a double-click gesture like any other program. For Mac OSX a standard *pkg* installer was created which places the MC among other programs in the *Applications* directory. For Windows a standard *.msi* installer was created which can be used to place the MC app in *Program Files* directory with Desktop and Start Menu shortcuts. Figure 23 shows the event display of the strangeness MC in the new framework.

Later on, during the COVID-19 pandemic, we moved the whole functionality of the desktop framework to the web, so finally, no installation at local machines is necessary. The new ALICE MasterClass suite of applications can be downloaded from the official ALICE MC website [96].

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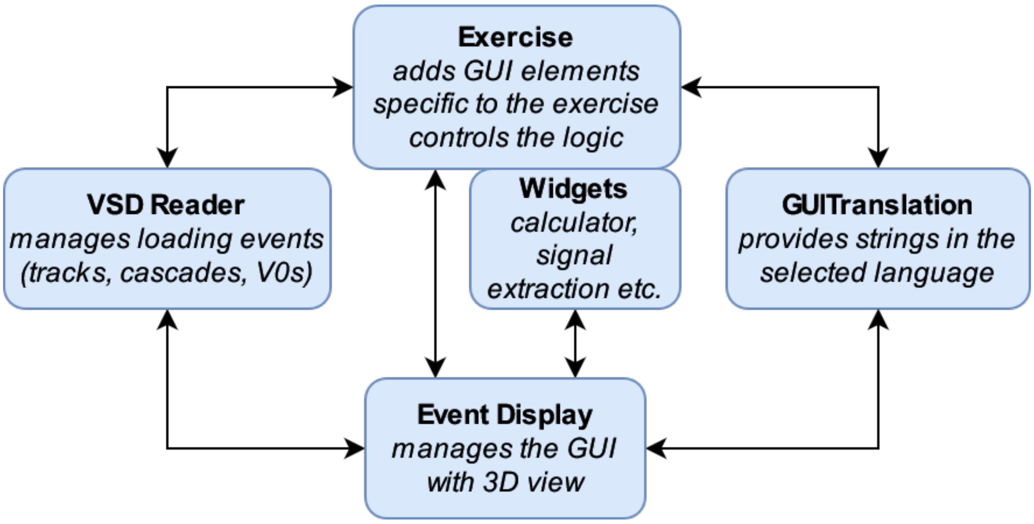

Figure 22: Structural diagram of the new ALICE MasterClass framework integrating the three existing measurements. Figure taken from [H11].

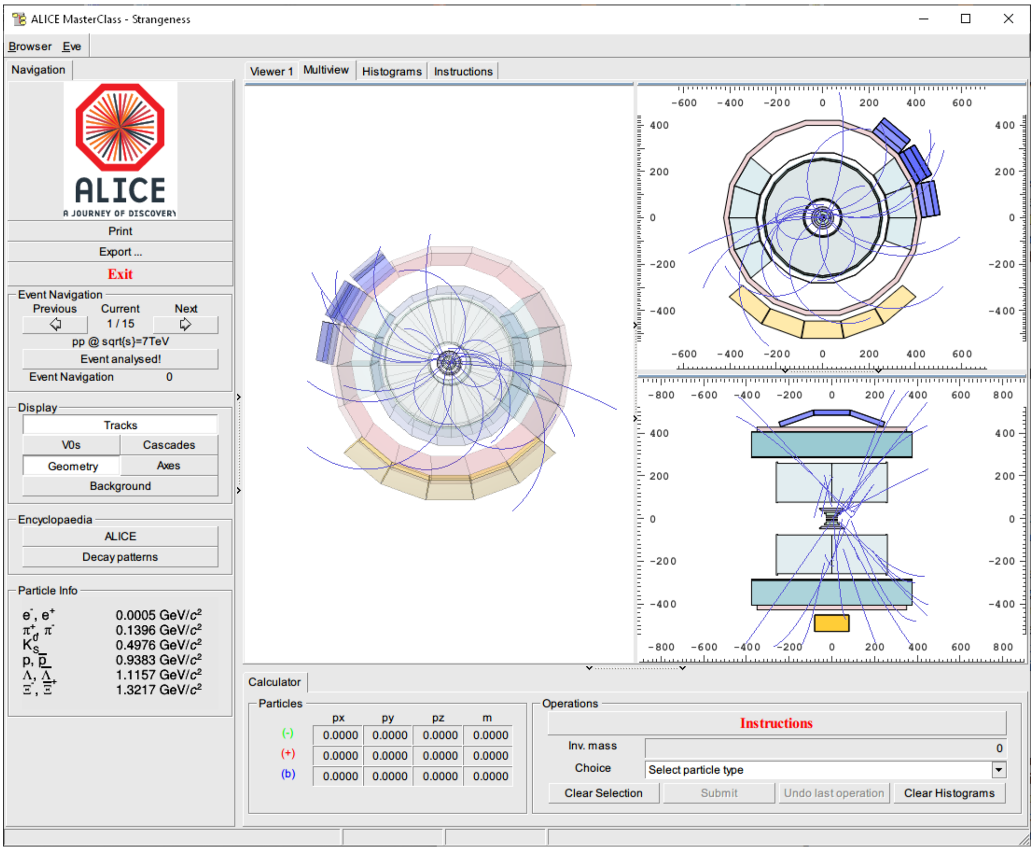

Figure 23: Main window of the ALICE MasterClass (production of strange particles measurement) showing the 3D visualisation of the ALICE detector with reconstructed particle tracks from pp collisions at $\sqrt{s} = 7$ TeV. Figure taken from [H11].

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5. Significant scientific activity

General description

Since 2009, starting as a 3rd year undergraduate student, until today I am a member of the ALICE (A Large Ion Collider Experiment) experiment on the Large Hadron Collider (LHC – Large Hadron Collider, https://alice-collaboration.web.cern.ch) at CERN – the European Organization for Nuclear Research in Geneva. In the period 2009-2022, I spent a total of 37 months at CERN with funding from various sources (NCN grants, EU scholarships, via CERN programmes and from the ALICE Collaboration funds). My experimental work focused on particle correlations with two experimental techniques – femtoscopy and angular correlations of identified particles. I am one of the main developers of the AliFemto package in the AliRoot/AliPhysics software (https://github.com/alisw/AliPhysics/) and FemtoWorld in the new O^2/O^2Physics software of ALICE (https://github.com/AliceO2Group/O2Physics). I am also, in coordination with Dr. Despina Hatzifotiadou (ALICE Outreach Coordinator), together with my fellow colleague from WUT Dr. Małgorzata Janik, responsible for the maintenance and development of the ALICE MasterClass package (https://alice-web-masterclass.app.cern.ch/). I have also indirectly contributed to the new data acquisition system of ALICE part of the O^2 framework, by supervising (as auxiliary supervisor – "promotor pomocniczy" in Polish) a computer science Ph.D. student from the Faculty of Electrical Engineering of WUT (Monika Jakubowska) on prototyping a new data monitoring scheme for ALICE.

Within the ALICE Collaboration, I have served the role of a coordinator of two Physics Analysis Groups (Femtoscopy and Correlations) within the scope of the Physics Working Group – Correlations and Fluctuations. Ccurrently, I am the Team Leader of the WUT group in ALICE and a member of the ALICE Collaboration Board.

My research experience in ALICE allowed me to gain experience in working in an international environment of scientific collaboration with thousands of people from all over the world. In terms of research, I have gained a deep understanding of the strong and Coulomb interactions between matter and antimatter and allowed to join, together with my fellow colleagues from WUT, the AEgIS experimental collaboration (https://aegis.web.cern.ch/) at Antiproton Decelerator facility in 2021. Within the scope of AEgIS, together with Dr. Małgorzata Janik, I have developed a new online monitoring tool for scintillator counters (https://gitlab.cern.ch/aegis-online/AEgIS-Online).

Finally, I have been awarded several research grants and scholarships, which allowed me for continues travels to CERN up to 4 months every year since 2009. Moreover, those projects allowed me to attract and hire two foreign Ph.D. students at WUT within our ALICE group, enhancing the internationalization of the university (Daniela Ruggiano – a graduate of the University of Naples (Italy), and Shirajum Monira – a graduate of the University of Helsinki (Finland)).

Research project coordination

Projects in which I act as a Project Leader and that have been prepared and sent by me to the funding agency

After Ph.D.

Institution	*Project details*
NCN SONATA	*Do the mass and flavor matter? Experimental studies towards a better understanding of the hadron production mechanism using angular correlations in the ALICE experiment at the LHC* reg. no. 2021/43/D/ST2/02214 period: 24.06.2022 - 23.06.2025 funding: 840 400 PLN
CERN & MEiN	*ML4ALICE: Development of machine learning algorithms for the new ALICE experiment software in LHC Run 3* CERN-WUT agreement no. KE 5319/EP MEiN-WUT agreement no. 5236/CERN/2022/0 period: 1.01.2022 - 31.12.2025 funding: 2 228 667 PLN

5. Significant scientific activity (continued)

Institution	Project details
WUT IDUB	*WUT@ALICE: Study of fundamental properties of strongly interacting matter with particle correlations and machine learning in ALICE at LHC* call no. IDUB-POB-FWEiTE-1 period: 1.07.2020 - 30.09.2022 funding: 301 875 PLN

Before Ph.D.

Institution	***Project details***
NCN PRELUDIUM	*Angular correlations in proton-proton collision in the ALICE experiment at the Large Hadron Collider at CERN* reg. no. 2012/05/N/ST2/02757 period: 18.03.2013 - 17.03.2015 funding: 96 890 PLN

Projects in consortium in which I act as a local Project Coordinator at WUT

After Ph.D.

Institution	***Project details***
MEiN	*The ALICE experiment the Large Hadron Collider at CERN* project conducted by the ALICE-PL consortium (leader: IFJ PAN) agreement no. 2022/WK/01 period: 1.01.2022 - 31.12.2026 funding for WUT: 2 085 132.35 PLN

Research project participation

Projects funded from external sources in which I act as an Investigator in one or several research tasks

After Ph.D.

Institution	***Project details***
NCN HARMONIA	*Research of fundamental properties of nuclear matter in the ALICE experiment at the Large Hadron Collider LHC at CERN* reg. no. 2016/22/M/ST2/00176 project conducted by the ALICE-PL consortium (leader: IFJ PAN) project leader: Prof. Marek Kowalski (IFJ PAN) period: 10.05.2017 - 9.05.2022 funding: 1 481 823 PLN
NCN OPUS	*Probing baryon and antibaryon interactions in relativistic ion collisions in STAR at RHIC and ALICE at LHC* reg. no. 2016/22/M/ST2/00176 project leader: Prof. Adam Kisiel period: 29.06.2018 - 28.06.2022 funding: 1 068 800 PLN
NCN SONATA	*Study of particle production mechanisms via angular correlations in the ALICE experiment at the LHC* reg. no. 2015/19/D/ST2/01600 project leader: Dr. Małgorzata Janik period: 9.06.2016 - 8.12.2019 funding: 283 400 PLN

5. Significant scientific activity (continued)

MNiSW	*The ALICE experiment at the Large Hadron Collider at CERN* decision no. DIR/WK/2016/17 project conducted by the ALICE-PL consortium (leader: IFJ PAN) project leader: Prof. Marek Kowalski (IFJ PAN) period: 1.01.2016 - 31.12.2021 funding: 7 466 118 PLN
NCN OPUS	*Study of two-particle interactions for non-identical hadrons in ALICE at LHC and STAR at RHIC* reg. no. 2014/13/B/ST2/04054 project leader: Prof. Adam Kisiel period: 23.02.2015 - 22.07.2018 funding: 668 610 PLN

Before Ph.D.

Institution	***Project details***
NCN OPUS	*Study of two-particle interactions for non-identical hadrons in ALICE at LHC and STAR at RHIC* reg. no. 2011/01/B/ST2/03483 project leader: Prof. Jan Pluta period: 27.12.2011 - 26.02.2015 funding: 407 600 PLN

Scientific stays abroad

After Ph.D.

2015 – ··	Visiting Scientist at CERN (Associated Member of the Personnel – with the status of CERN User and in periods of Corresponding Associate) for 2-4 months every year with funding from various sources, including CERN CASS program and NCN projects (total time spent at CERN after Ph.D.: 20 months)

Before Ph.D.

2009 – 2015	Visiting Student at CERN for 2-4 months every year with funding from various sources, including CERN subsistence from the ALICE Collaboration, NCN grants and scholarships from the EU funds (total time spent at CERN before Ph.D.: 17 months)

Reviewer in scientific journals

After Ph.D.

I have been selected to review scientific publications in the following journals:

1 Physical Review Letters

2 Physical Review C

3 Reviews in Physics

4 Acta Physica Polonica B

5. Significant scientific activity (continued)

Presentations at international conferences

Invited presentations

After Ph.D.

1 **Ł. Graczykowski**, “Advances in realtivistic heavy-ion collisions”, 5th Symposium of the Division for Physics of Fundamental Interactions of the Polish Physical Society, University of Silesia, Katowice, Poland, 21.10.2022

2 **Ł. Graczykowski**, K. Deja, M. Kabus, M. Jakubowska (for the ALICE Collaboration), “Using Machine Learning for Particle Identification in ALICE”, AI4EIC-Exp Workshop (online), Brookhaven National Laboratory, USA, 8.09.2021

3 **Ł. Graczykowski** (for the ALICE Collaboration), ”Probing space-time evolution at the femtometer scale in pp and Pb-Pb collisions with ALICE”, CERN-LHC Seminar, CERN, Geneva, Switzerland, 5.03.2019
Recording: https://cds.cern.ch/record/2665668

4 **Ł. Graczykowski** (for the ALICE Collaboration), “Femtoscopy in heavy ions”, Exploring the Perfect Liquid (MIAPP Topical Workshop), Munich, Germany, 6-8.09.2018

5 T. Trzciński, **Ł. Graczykowski**, M. Glinka (for the ALICE Collaboration), “Using Machine Learning methods for improving data quality in the ALICE experiment”, XIIIth Quark Confinement and the Hadron Spectrum (CONF13) - invited to the session ”Statistical Methods for Physics Analysis in the XXI Century”, Maynooth, Ireland, 31.07-6.08.2018

6 **Ł. Graczykowski** (for the ALICE Collaboration), “What can we learn from femtoscopic and angular correlations of identified particles in ALICE?”, XLVII International Symposium on Multiparticle Dynamics (ISMD 2017), Tlaxcala, Mexico, 11-15.05.2017

7 **Ł. Graczykowski** (for the ALICE Collaboration), “What can we learn from femtoscopy studies in ALICE?”, ISTROS 2017, Častá-Papiernička, Slovakia, 14-19.05.2017

8 **Ł. Graczykowski** (for the ALICE Collaboration), “Soft QGP probes with ALICE”, XXII Cracow EPIPHANY Conference, Kraków, Poland, 7-9.01.2016

9 **Ł. Graczykowski** (for the ALICE Collaboration), “Two-pion femtoscopy in p-Pb collisions in ALICE”, HEP Seminar “Białasówka”, 13.06.2015, Kraków, Poland

Contributed presentations

After Ph.D.

1 **Ł. Graczykowski**, M. Janik, “Unfolding the effects of FSI and QS in two-particle angular correlations”, Quark Matter 2022, Kraków, Poland, 4-10.04.2022 (poster)

2 P. Nowakowski, **Ł. Graczykowski**, “Propagation of tracks using accurate model of ALICE detector magnet system for event visualisation”, Quark Matter 2022, Kraków, Poland, 4-10.04.2022 (poster)

3 **Ł. Graczykowski** (for the ALICE Collaboration), “Studying the kaon-proton strong interactions with ALICE at the LHC”, 19th International Conference on Hadron Spectroscopy and Structure (HADRON 2021), 23-31.07.2021, Mexico City, Mexico (online conference)

4 **Ł. Graczykowski**, P. Nowakowski, P. Foka (for the IPPOG Collaboration), “New developments for ALICE MasterClassesand the new Particle Therapy MasterClassand the new Particle Therapy MasterClass”, 24th International Conference on Computing in High Energy and Nuclear Physics (CHEP 2019), 4-8.11.2019, Adelaide, Australia

5. Significant scientific activity (continued)

5 **Ł. Graczykowski** (for the ALICE Collaboration), "Measurement of the strong interaction between matter and antimatter in heavy-ion collisions with ALICE", XIV Workshop on Particle Correlations and Femtoscopy (WPCF 2019), Dubna, Russia, 3-7.06.2019

6 **Ł. Graczykowski** (for the ALICE Collaboration), "What can we learn from femtoscopic and angular correlations of identified particles in ALICE?", XIII Polish Workshop on Relativistic Heavy-Ion Collisions, Wrocław, Poland, 6-7.01.2018

7 **Ł. Graczykowski** (for the ALICE Collaboration), "Using machine learning for data quality assurance, particle identification, and fast simulations in ALICE", Quark Matter 2018, Venice, Italy, 13-19.05.2018 (poster)

8 **Ł. Graczykowski** (for the ALICE Collaboration), "Studies of final state interactions via femtoscopy in ALICE", 16th International Conference on Strangeness in Quark Matter (SQM 2016), 27.06-1.07 2016, Berkeley (CA), USA

9 M. Janik, **Ł. Graczykowski**, A. Kisiel, "Influence of quantum conservation laws on particle production in hadron collisions", XXV International Conference on Ultrarelativistic Nucleus-Nucleus Collisions (Quark Matter 2015), Kobe, Japan, 27.09-3.10.2015 (poster)
$\rightarrow$ The poster was awarded a "flash talk", which was presented at a plenary session by my fellow colleague from WUT Dr. Małgorzata Janik.

10 **Ł. Graczykowski** (for the ALICE Collaboration), "Pion femtoscopy measurements in small systems with ALICE at the LHC", 3rd International Conference on New Frontiers in Physics, Kolymbari, Crete, Greece, 28.08-6.07.2015

Before Ph.D.

1 **Ł. Graczykowski** (for the ALICE Collaboration), "Three-dimensional pion femtoscopy measurements in p–Pb collisions in ALICE", X Workshop on Particle Correlations and Femtoscopy (WPCF 2014), Gyöngyös, Hungary, 25-29.08.2014

2 **Ł. Graczykowski** (for the ALICE Collaboration), "Pion femtoscopy measurements in small systems with ALICE at the LHC", Quark Matter 2014, Darmstadt, Germany, 19-24.05.2014 (poster)

3 **Ł. Graczykowski** (for the ALICE Collaboration), "Angular correlations measured in pp collisions at the LHC by the ALICE experiment", IX Workshop on Particle Correlations and Femtoscopy (WPCF 2013), Acireale, Italy, 5-8.11.2013

4 **Ł. Graczykowski** (for the ALICE Collaboration), "Angular correlations measured in pp collisions by ALICE at the LHC", 1st International Conference on the Initial Stages in High-Energy Nuclear Collisions (IS 2013), Isla de la Toja, Spain, 8-14.09.2013

5 **Ł. Graczykowski** (for the ALICE Collaboration), "Pion femtoscopy measurements in ALICE at the LHC", 2nd International Conference on New Frontiers in Physics (ICNFP 2013), Kolymbari, Crete, Greece, 28.08-5.09.2013

6 **Ł. Graczykowski** (for the ALICE Collaboration), "ALICE: the heavy-ion experiment at the CERN/LHC", XXXI-th IEEE-SPIE Joint Symposium on Photonics, Web Engineering, Electronics for Astronomy and High Energy Physics Experiments, Wilga, Poland, 27.05.2013

7 **Ł. Graczykowski** (for the ALICE Collaboration), "Proton-lambda and lambda-lambda femtoscopy in Pb-Pb collisions in ALICE", XIV GDRE Heavy Ion Workshop, Dubna, Russia, 12.12-14.12.2012

8 **Ł. Graczykowski** (for the ALICE Collaboration), "Baryon femtoscopy in collisions of lead ions with the ALICE", VIII Workshop on Particle Correlations and Femtoscopy (WPCF 2012), Frankfurt am Main, Germany, 10-14.09.2012

5. Significant scientific activity (continued)

9 **Ł. Graczykowski** (for the ALICE Collaboration), "Baryon femtoscopy in collisions of lead ions with the ALICE", XIII GDRE Heavy Ion Workshop, Nantes, France, 8-14.07.2012

10 **Ł. Graczykowski** (for the ALICE Collaboration), "Femtoscopy of pp collisions at the LHC with the ALICE experiment", VIII Polish Workshop on Relativistic Heavy-Ion Collisions, Hucisko, Poland, 17-18.12.2011

11 **Ł. Graczykowski** (for the ALICE Collaboration), "Femtoscopy of pp collisions at the LHC with the ALICE experiment", 11. Zimanyi Winter School on Heavy Ion Physics, Budapest, Hungary, 28.11-2.12.2011

12 **Ł. Graczykowski** (for the ALICE Collaboration), "Femtoscopy of pp collisions at the LHC with the ALICE experiment", VII Workshop on Particle Correlations and Femtoscopy (WPCF 2011), Tokyo, Japan, 20-24.09.2011

Membership in ALICE Paper Committees (PC) and Internal Review Committees (IRC)

During the paper preparation process, the ALICE Collaboration nominates two small groups (3-5 people in most cases), the *Paper Committee (PC)* which is responsible for the preparation of the manuscript and the analysis itself, and the *Internal Review Committee (IRC)* which task is to perform a detailed review of the analysis and the paper. The IRC can disagree with a particular statement in the paper or a result, it can also propose new studies and ask for additional verification. The final version of the manuscript is always a result of long discussions between PC and IRC, which can last over a year. Each physics paper has its own PC and IRC.

***Paper Committee*: 7**

1 Phys. Rev. C 91 (2015) 034906

2 Eur. Phys. J. C77 (2017) 569, Eur. Phys. J. C 79 (2019) 12, 998 (erratum)

3 Phys. Rev. C 99 (2019) 024001

4 Phys. Lett. B 802 (2020) 135223

5 Phys. Lett. B 813 (2021) 136030

6 Phys. Lett. B 822 (2021) 136708

7 https://arxiv.org/abs/2211.04384 (submitted to Eur. Phys. J. C)

***Internal Review Committee*: 5**

1 Phys. Lett. B 790 (2019) 22

2 Phys. Rev. Lett. 124 (2020) 092301

3 Phys. Lett. B 811 (2020) 135849

4 Phys. Rev. Lett. 127 (2021) 172301

5 Phys. Lett. B 833 (2022) 137272

6. Significant teaching, organizational and popularization activity

Student supervision

Ph.D. students

After Ph.D.

Name ***Thesis details***

6. Significant teaching, organizational and popularization activity (continued)

M. Kabus	Warsaw University of Technology, Faculty of Physics ***Thesis title***: *Two-particle correlations of strange and heavy flavor hadrons in the ALICE experiment at the LHC* ***Scientific discipline***: Physical Sciences ***Role***: auxiliary supervisor (Polish: "promotor pomocniczy") ***Main supervisor***: Prof. Daniel Kikoła ***Thesis ongoing***
M. Jakubowska	Warsaw University of Technology, Faculty of Electrical Engineering ***Thesis title***: *Investigation and Prototyping of a New Data Monitoring Scheme for the ALICE Experiment (CERN)* ***Scientific discipline***: Information Technology and Telecommunication ***Role***: auxiliary supervisor (Polish: "promotor pomocniczy") ***Main supervisor***: Prof. Lech Grzesiak, Dean of the Faculty of Electrical Engineering ***Date of award***: 29.09.2020 ***Link***: http://cds.cern.ch/record/2729632/

B.Sc. and M.Sc. students

After Ph.D.

Name	***Thesis details***
Ł. Sawicki	Warsaw University of Technology, Faculty of Physics ***Thesis title***: *Integration of Particle Identification machine-learning based models with the* O^2 *system of the ALICE experiment* ***Diploma level***: B.Sc. ***Defense date***: 9.02.2022
J. Zieliński	Warsaw University of Technology, Faculty of Physics ***Thesis title***: *Collective flow in femtoscopic measurements* ***Diploma level***: M.Sc. ***Defense date***: 24.01.2022
M. Kabus	Warsaw University of Technology, Faculty of Mathematics and Computer Science ***Thesis title***: *Calibration of the distortion fluctuations of the electric field in the ALICE Time Projection Chamber with deep neural networks* ***Diploma level***: M.Sc. ***Defense date***: 21.06.2021
E. Łobejko	Warsaw University of Technology, Faculty of Physics ***Thesis title***: *Angular correlations of baryons in proton-proton collisions at* $\sqrt{s} = 13$ *TeV with the ALICE experiment* ***Diploma level***: M.Sc. ***Defense date***: 9.03.2020
J. Zieliński	Warsaw University of Technology, Faculty of Physics ***Thesis title***: *Feasibility studies of baryon correlations in the MPD experiment at the NICA complex* ***Diploma level***: B.Sc. ***Defense date***: 6.02.2020
M. Kabus	Warsaw University of Technology, Faculty of Mathematics and Computer Science ***Thesis title***: *Preparation of the collision visualisation system for the 3rd phase of the ALICE experiment (CERN)* ***Diploma level***: B.Sc. ***Defense date***: 5.02.2020

6. Significant teaching, organizational and popularization activity (continued)

P. Spinalski	Warsaw University of Technology, Faculty of Physics ***Thesis title***: *Femtoscopy of π mesons in proton-proton collisions at $\sqrt{s}$=13 TeV with the ALICE experiment* ***Diploma level***: B.Sc. ***Defense date***: 15.09.2019
E. Łobejko	Warsaw University of Technology, Faculty of Physics ***Thesis title***: *Determination of systematic effects in the measurement of femtoscopic correlation functions of non-identical particle pairs in the ALICE experiment* ***Diploma level***: B.Sc. ***Defense date***: 14.08.2018
M. Lewandowski	Warsaw University of Technology, Faculty of Physics ***Thesis title***: *Theoretical predictions for non-identical correlations in heavy-ion collisions at LHC* ***Diploma level***: B.Sc. ***Defense date***: 11.04.2017
P. Karczmarczyk	Warsaw University of Technology, Faculty of Physics ***Thesis title***: *Analysis of emission asymmetry based on non-identical particle femtoscopy in heavy-ion collisions at LHC energies* ***Diploma level***: M.Sc. ***Defense date***: 19.09.2016

Before Ph.D.

P. Karczmarczyk	Warsaw University of Technology, Faculty of Physics ***Thesis title***: *Numerical analysis of background effects in femtoscopic correlations of identical pions in the ALICE experiment* ***Diploma level***: B.Sc. ***Defense date***: 27.02.2015
A. Zaborowska	Warsaw University of Technology, Faculty of Physics ***Thesis title***: *Optimisation of fitting methods for the analysis of angular correlations of "identified" particles in the ALICE experiment* ***Diploma level***: B.Sc. ***Defense date***: 6.02.2013

CERN Summer Students

After Ph.D.

Name	***Project details***
Amara McCune	Stanford University ***Period***: June-August 2017 ***Project topic***: simulations studies of angular correlations of pions, kaons, and protons using various versions (tunes) of PYTHIA Monte Carlo event generator ***Link to report***: https://cds.cern.ch/record/2278416/
Pavle Vulanovic	New York University Abu Dhabi ***Period***: June-August 2020 (online) ***Project topic***: first developments of the online version of the ALICE MasterClass for measurements of femtoscopic correlations ***Link to report***: https://cds.cern.ch/record/2779552

6. Significant teaching, organizational and popularization activity (continued)

Courses and lectures for students

After Ph.D.

Period	*Course*
2019 – ··	Computer networks (http://www.if.pw.edu.pl/~lgraczyk/wiki/index.php/Sieci_komputerowe_2021/2022_lato) – course coordinator, delivering lectures (8h) and responsible for laboratories (22h) at the 3rd year of studies
	Computer-aided data analysis (http://www.if.pw.edu.pl/~lgraczyk/wiki/index.php/KADD_2021/2022) – course coordinator, delivering lectures (15h) and responsible for laboratories (30h) at the 3rd year of studies
2011 – ··	Programming languages – teaching laboratories on basic concepts of C++ (30h) at the 2nd year of studies; I started teaching that lab right after enrolling as a Ph.D. student

Before Ph.D.

2015	Basics of programming – teaching laboratories on basic concepts of C (30h) at the 1st year of studies
2014	Object-oriented programming – teaching laboratories on basic concepts of Java (45h) at the 3rd year of studies
2012	Physics laboratory 2 – teaching laboratories on radiation measurements with scintillator and solid state detectors, at the 3rd year of studies

Membership and functions, organizational experience

After Ph.D.

Period	*Organization, role, ...*
2020 – ··	Member of the AEgIS Collaboration via WUT
2020 – 2022	Coordinator of the Correlations Physics Analysis Group* (Correlations PAG) within the ALICE Collaboration
2019 – ··	Team Leader of the WUT group in ALICE, member of the ALICE Collaboration Board
	Task Coordinator of the ALICE MasterClass development within the MatPhysChemWUT (https://mfch.mini.pw.edu.pl/) project financed from the European Union structural funds within the Knowledge Education Development Programme. WUT is responsible for the maintenance and development of the ALICE MasterClass software and I am supervising a computer scientist (Piotr Nowakowski), who is the main developer. Web application: https://alice-web-masterclass.app.cern.ch
2018 – ··	Coordinator of WUT computer scientists (from Faculties of Electronics and Information Technology and Electrical Engineering) within ALICE – machine learning and event visualization
2016 – ··	Elected member of the Faculty Council of the Faculty of Physics and of the Scientific Council for Physical Sciences at WUT
2015 – 2018	Coordinator of the Femtoscopy Physics Analysis Group* (Femto PAG) within the ALICE Collaboration

Before Ph.D.

2013	Head of the Doctoral Students' Association at the Faculty of Physics at WUT

6. Significant teaching, organizational and popularization activity (continued)

*In the ALICE Collaboration structure, PAGs (Physics Analysis Groups) are formed within the Physics Working Groups (PWGs) and group scientists working on a given topic (usually around 30-40 people are active members of a given PAG). Every single analysis starts within the PAG before progressing to official Preliminary results or a publication, upon acceptance by the PAG. Each PAG has a weekly meeting, organized by two conveners, during which analyses conducted by PAG members are shown and discussed. PAGs are formed by the Physics Coordination and the PAG convenership is a position for which one is appointed by the Collaboration (usually there is an internal competition for this position). Being a PAG coordinator shows the broad expertise of a person in a given field and confidence in managing a diverse group of fellow ALICE members in terms of progressing their research projects. A PAG coordinator has to oversee all analyses within a given PAG and ensure a high quality of the results aiming for approvals, run the weekly PAG meetings, attend the PAG Coordination meeting within a given PWG, plan potential approval of the results from the PAG, and review plots and figures that are to be approved as Preliminary from his/her PAG. More on the ALICE organizational structure is available here: https://alice-collaboration.web.cern.ch/organization/phb/index.html

Scientific conference organization

After Ph.D.

Name	*Role, conference info...*
2016, 2017, 2019	Member of the Local Organizing Committee of the NICA Days workshop series, Warsaw Poland https://indico.cern.ch/event/802303/ (NICA Days 2019) https://indico.cern.ch/event/638553/ (NICA Days 2017) https://indico.cern.ch/event/472093/ (NICA Days 2016)
2016	Member of the Local Organizing Committee of the XIIth Quark Confinement and the Hadron Spectrum, Thessaloniki, Greece, 28.08-4.09.2016 https://indico.cern.ch/event/353906/
2015	Member of the Local Organizing Committee of the XI Workshop on Particle Correlations and Femtoscopy, Warsaw, Poland, 3-7.11.2015 https://indico.cern.ch/event/387606/

Before Ph.D.

Name	*Role, conference info...*
2015	Member of the Organizing Committee of the XI Polish Workshop on Relativistic Heavy-Ion Collisions, Warsaw, Poland, 17-18.012015 https://indico.cern.ch/event/348749/
2013	Member of the Local Organizing Committee of the 3rd International Conference on New Frontiers in Physics (INCFP 2013), Kolymbari, Crete, Greece, 28.08-5.09.2013 https://indico.cern.ch/event/198153/

International MasterClasses - Hands-On Particle Physics

Together with my fellow colleague from WUT, Dr. Małgorzata Janik, we regularly organize ALICE MasterClass sessions at WUT. Agendas of the events organized by me at WUT are available here:

2021	https://indico.cern.ch/event/1036641/ (online)
2020	https://indico.cern.ch/event/863759/ (online)
2019	https://indico.cern.ch/event/790280/
2017	https://indico.cern.ch/event/608845/
2016	https://indico.cern.ch/event/491272/
2015	https://indico.cern.ch/event/358553/

6. Significant teaching, organizational and popularization activity (continued)

Moreover, in the years 2019-2021 I also held the role of the Task Coordinator of the ALICE MasterClasses development within the MatPhysChemWUT project financed from the European Union structural funds within the Knowledge Education Development Operational Programme (https://mfch.mini.pw.edu.pl/node/594). WUT is responsible for the development and maintenance of the ALICE MasterClass software, and I was supervising a computer scientist (Piotr Nowakowski, M.Sc.), who is the main developer of the ALICE MasterClass framework. The current (web) version of the application is accessible here: https://alice-web-masterclass.app.cern.ch.

Invited science popularization lectures and other outreach activities

After Ph.D.

2021	Coordination of WUT activities within the event "30 years PL@CERN" (https://pl30cern.ifj.edu.pl/)
2019	Lecture on research conducted at CERN for I High School in Gorzów Wlkp.
2016	Lecture on research conducted at CERN for dla XIII High School in Szczecin
	Lecture on research conducted at CERN for WUT University of the Third Age

Before Ph.D.

2014	Lecture on research conducted at CERN at the Science Festival within the project Masovian Talent and Career Centers in Ostrołęka
2013	Lecture on research conducted at CERN for XIV High School in Warsaw
	Lecture on research conducted at CERN for V High School in Warsaw

7. Other important information

Awards and scholarships

After Ph.D.

2022	WUT Rector prize for scientific achievements - group award, 1st grade (leader of the group)
2021	WUT Best Paper prize from the IDUB programme for papers published in 2020, for participation (as the IRC Chair) in the preparation of the ALICE paper "Scattering studies with low-energy kaon-proton femtoscopy in proton-proton collisions at the LHC", Phys. Rev. Lett. 124, 092301 (2020)
	WUT Faculty of Physics Best Paper prize for papers published in 2020, from the Faculty of Physics of the Warsaw University of Technology for participation (as Paper Committee Chair) in the preparation of the ALICE paper "Measurement of strange baryon–antibaryon interactions with femtoscopic correlations", Phys. Lett. B 802 (2020) 135223

Before Ph.D.

2014	Awarded scholarship for best Ph.D. students originating from the Lubuskie Region of Poland, Marshal Office of the Lubuskie Region
2012	Awarded scholarships (a stationary one and a travel one) for best Ph.D. students at the Warsaw University of Technology from the Center for Advanced Studies