2023

The role of the underlying event in the heavy-flavor baryon enhancement. — Perturbative quantum chromodynamics (pQCD) calculations have been successful in describing the production of heavy-flavor mesons at several energies at the LHC. These descriptions usually rely on the factorization approach, in which the production cross sections of heavy-flavor hadrons in hadronic collisions are calculated as a convolution of the parton density functions (PDFs) of the colliding hadrons, the cross section of the hard-scattering process and the heavy-quark fragmentation function. Recent experiments from the LHC, however, show a relative enhancement of charmed baryons compared to expectations using the factorization approach with universal fragmentation. We investigated the production of charmed baryons with different isospin and strangeness content, compared to both charmed D^0 mesons and to the Λ_c^+ baryon in proton–proton collisions at LHC energies (Figure 1). We used the PYTHIA 8 Monte Carlo event generator with color reconnection beyond leading-color approximation and proposed methods based on event-activity classifiers to probe the source of the charmed-baryon enhancement. We conclude that in the considered model class, the isospin of the charmed-baryon state has a strong impact on the enhancement pattern. Using the observables we propose, upcoming high-precision experimental data will be able to differentiate between mechanisms of strangeness and charm enhancement [1].

Heavy-flavor azimuthal correlations in the ALICE experiment and in simulations. — In high-energy hadronic collisions, heavy quarks (charm and beauty) are mainly produced in hard parton scattering processes. Two-particle angular correlations originating from heavy-flavor particles allow for the characterization of parton shower and fragmentation. We contributed to the measurement of heavy-flavor electron-hadron azimuthal correlation distributions between heavy-flavor decay electrons and associated charged particles, by the ALICE experiment at the LHC, in pp and p–Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV. The correlation structures are fitted with a constant and two von Mises functions to obtain the baseline and the near- and away-side peaks, respectively. The evolution of the near- and away-side peaks of the correlation functions in pp and p–Pb collisions is found to be similar in all the considered kinematic ranges. This suggests that the modification of the fragmentation and hadronization of heavy quarks due to cold-nuclear-matter effects is indistinguishable within the current precision of the measurements [2].
In high-energy collisions of small systems, by high-enough final-state multiplicities, a collective behavior is present that is similar to the flow patterns observed in heavy-ion collisions. Recent studies connect this collectivity to semi-soft vacuum-QCD processes. In a recent work we explored QCD production mechanisms using angular correlations of heavy flavor using simulated proton-proton collisions at $\sqrt{s}$=13 TeV with the PYTHIA8 Monte Carlo event generator. We demonstrate that the event shape is strongly connected to the production mechanisms. Flattenicity (ρ), a novel event descriptor, can be used to separate events containing the final-state radiation from the rest of the events [3], as shown in Figure 2.
We have also carried out an ALICE measurement of D-meson production in function of the transverse event-activity classifier R_T. This work will become part of a later ALICE publication.

Multi-parton interactions in pp collisions using charged-particle flattenicity. — Despite the large amount of soft-QCD results on collectivity in pp and p–Pb collisions (small-collision systems), the origin of these phenomena is not yet fully understood. Amongst various theoretical approaches, the PYHTIA 8 model can reproduce many of the experimental results by the modeling of a non-perturbative final-state effect, color reconnection (CR), and multi-parton interactions (MPI). MPI allow the simultaneous occurrence of several incoherent binary semi-hard partonic interactions in a single pp collision, which produce multi-minijets topologies. When the event classification is performed in charged-particle multiplicity measured at large pseudorapidities, the multiplicity based on PYTHIA is strongly correlated with the MPI activity.
We explored a novel event classifier, flattenicity, that quantifies the shape of the event using experimental information from both azimuthal and forward/backward pseudorapidity directions [4].
For the first time, the ALICE experiment at the LHC studied the transverse momentum (p_T) spectra of primary charged pions, kaons, (anti)protons and unidentified hadrons as a function of flattenicity and double-differentially as a function of flattenicity and charged-particle multiplicity in pp collisions at $\sqrt{s}$=13 TeV. The preliminary data suggest that, for multi-minijet events, the ratio of event-class dependent pT spectra to that of MB (Q_{pp}) develops a pronounced peak with increasing multiplicity that is mass dependent. Results are qualitatively described by the PYTHIA model based on color strings and indicate that flattenicity-selected events show reduced sensitivity to multijets [5].

Novel reconstruction methods for forward protons. — The TOTEM Roman pot detectors are used to reconstruct the transverse momentum of scattered protons and to estimate the transverse location of the primary interaction. We have developed advanced methods for local track reconstruction, for the measurement of strip-level detection efficiencies, cross-checks of beam optics, and steps of detector alignment, along with their application in the selection of signal collision events. The local track reconstruction is performed by exploiting hit cluster information through finding a common polygonal area in the intercept-slope plane. The tool is applied in the relative alignment of detector layers with μm precision. A tag-and-probe method is used to extract strip-level detection efficiencies. The proton reconstruction corrections are calculated using a simulation. The absolute alignment of the Roman pot system is performed through several measured quantities. The necessary run-by-run adjustments are in the range ±50 μm in horizontal, and ±0.5 mm in vertical directions. The goal was to provide a solid ground for physics analyses based on the high-β^* data taking period at the LHC.

Jet substructure and fragmentation studies with ALICE and CMS. — The Koba-Nielsen-Olesen (KNO) scaling hypothesis is an influential contribution to the analysis of event multiplicities in high-energy particle collisions, according to which the event-multiplicity distributions can be all collapsed onto a universal scaling curve. Recent phenomenological studies suggest that a similar scaling may hold within single jets, if we consider the jet multiplicity as a function of the jet transverse momentum. We have been working on the first measurement of this scaling for single jets in proton-proton collisions at $\sqrt{s}$=13 TeV with ALICE, which can help further our understanding of jet fragmentation properties.
We continued to analyze the intrinsic structure of the jets recorded by the CMS. By studying a large sample of data obtained by various triggers from 2017, we were able to obtain information on the extreme corners of the phase space. The promising preliminary studies include the corresponding systematic uncertainties and the results are compared to various model predictions.

Detection of forward neutrons and high-precision luminosity measurements at CMS. — Continuing the analysis we began last year, we obtained gain factors for the channels of the ZDC. We also participated in the heavy ion data taking at CERN, where the ZDC was also used as a trigger measuring the one-neutron peak. For the ZDC trigger we also carried out validation during the whole data-taking period.
Based on the ideas depicted last year, we worked on obtaining the XY factorization bias for the proton-proton data from 2022. We carried out 1D fits and obtained an additional orbit drift correction, with which 2D fits can be carried out more precisely. We then fitted the data points in 2D (pairing different types of measured data) with various shapes (fitting models). We did simulations in order to obtain the corrections on the visible cross-section. We also examined multiple parameter-dependences of these obtained values. After choosing the stable models and checking that all luminometers can be trusted, we could obtain the final correction value with its RMS. We also determined the corresponding systematic uncertainty.
The Beam Position Monitors (BPMs), located near the CMS detector and in the adjacent arc of the LHC, measure the positions of the circulating beams. To obtain an accurate calibration, the measurements have to be corrected for the time-dependent movement of the beams and the residual component of the orbit drift. We joined the efforts of the CMS BRIL (Beam Radiation, Instrumentation and Luminosity) team to calculate these corrections for the latest van der Meer calibration fill recorded in 2023.

Application of the Tsallis-thermometer for charm hadrons from RHIC to LHC energies. — We analyzed the transverse momentum distributions of the identified D^0, D^+ and D^{*+} mesons within a non-extensive statistical framework. The studied D meson data comes from pp, p-Pb and A-A collisions from ALICE and STAR experiments, covering the center-of-mass energy range between 200 GeV and 7 TeV. We investigate the behavior of heavy-flavored D mesons with the so-called Tsallis-thermometer and compare it to the light-flavored hadrons. In our preliminary results we show that mass hierarchy and strong multiplicity dependence are more distinct for D mesons compared to the light-flavor particles. Moreover, the common equilibrium values of Tsallis parameters for D mesons correspond to the higher temperatures and degrees of freedom, which may point that D mesons are coming from the earlier stages of a collision.

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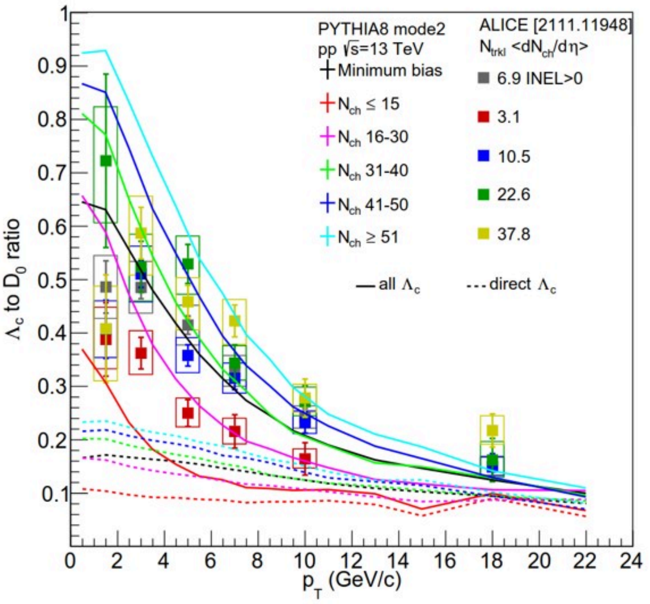

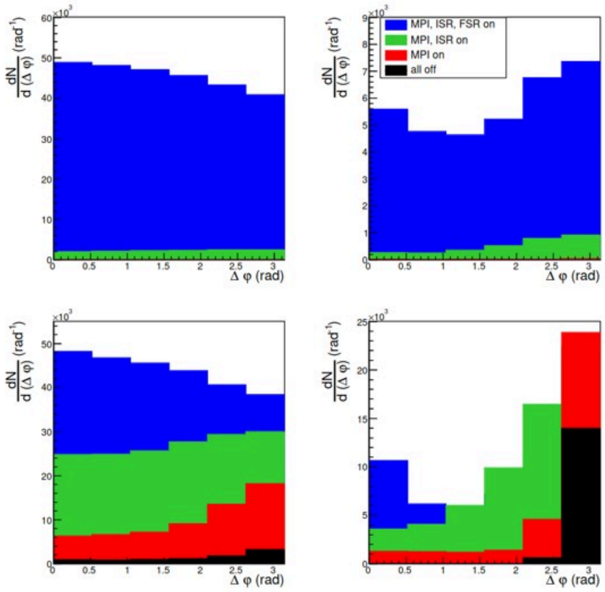

Figure 1. Λ_c^+/D^0 ratio from PYTHIA 8 simulations with enhanced color reconnection as a function of p_T, for minimum bias events as well as for different mid-rapidity charged-hadron multiplicity (N_{ch}), compared to data from ALICE data. The contribution of direct Λc+ production is shown as dashed lines. Figure 2. The azimuthal correlation of charm–anticharm pairs, where $p_T < 4$ GeV/c and $p_T > 4$ GeV/c (left and right columns respectively), and the top row shows the low ρ range, and the bottom row represent high ρ. Different parton-level process settings are presented with different colors.

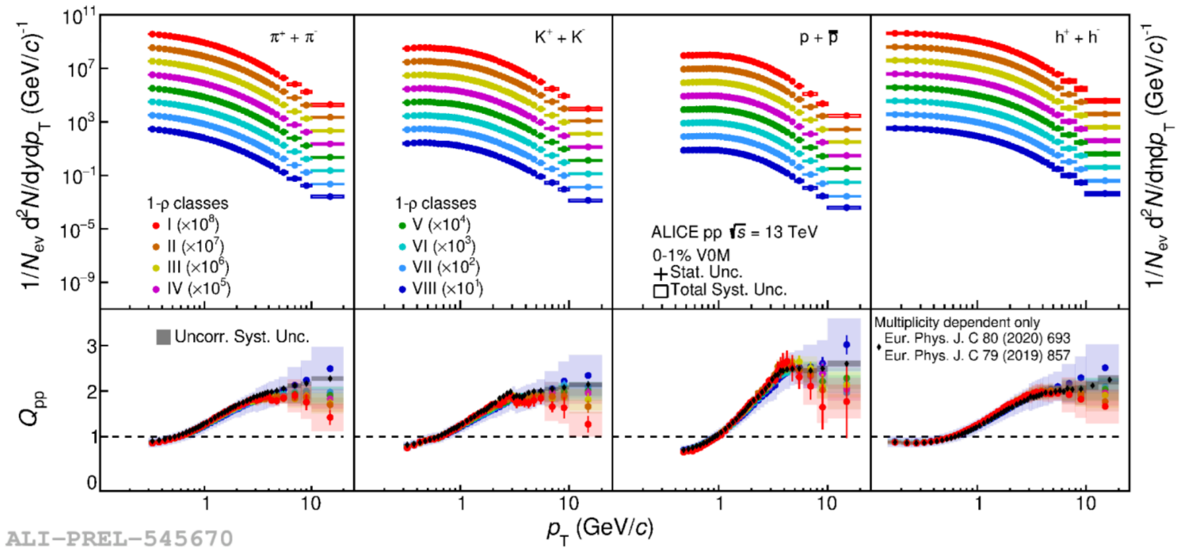

Figure 3: Transverse momentum (p_T) spectra of charged pions, kaons, (anti)protons and unidentified hadrons for different flattenicity event classes (top figure), and for high-multiplicity events (0-1% V0M) in the same flattenicity event classes (bottom figure). Bottom panels in each figure show the event-class dependent pT spectra to that of MB for the corresponding event classes.

2022

Heavy-flavor jets with the ALICE experiment. — The production of heavy-flavor jets in proton-proton collisions serves as a fundamental test of perturbative QCD, while p-Pb (Pb-Pb) measurements provide information about the effects of the cold (hot) nuclear matter. Our group plays a key role in several experimental measurements within the ALICE Heavy Flavor Jets and Correlations physics analysis groups. The final results on the production cross-section and b-jet fractions in $\sqrt{s}$=5.02 TeV in pp and p-Pb collisions, as well as the nuclear modification factor in p-Pb collisions, have been published [1]. With the excellent particle tracking capabilities of the ALICE detector, these results extend to unprecedentedly low momenta (p_T>10 GeV/c) and pave the way to the understanding of flavor-dependent jet fragmentation as well as nuclear modification.

Heavy-flavor correlations in the experiment and in phenomenology. — Correlation measurements of D mesons with charged hadrons reveal the heavy-flavor jet structure at intermediate momenta. We are one of the main contributors to the D-h correlation measurements in pp collisions at $\sqrt{s}$=13 TeV by the ALICE experiment, recently published [2]. Our group is responsible for the ALICE analysis of D-meson production in function of the transverse event-activity classifier RT. In a recent paper, we further explore experimental possibilities of similar heavy-flavor measurements with hadron as well as jet triggers (Fig. 1) [3]. Furthermore, our group participates in the peak shape analysis of heavy-flavor electron to hadron correlations in $\sqrt{s}$=5 TeV pp and p-Pb collisions. This work will become part of a later ALICE publication.

Unveiling the effects of soft multipaton interactions using novel event classifiers. — Nowadays, event classifiers as well as event shape variables have been considered as efficient tools to study the characteristics of high-energy proton-proton collision events at the LHC. For example, the event selection based on the charged-particle multiplicities at forward pseudorapidities helped to discover the strangeness enhancement in high-multiplicity proton-proton collisions at the ALICE experiment. However, it turned out that the obtained results suffer from significant selection bias due to presence of mutl-jet events. This makes it difficult to interpret the results from e.g. jet-quenching searches in small collision systems. To overcome the unwanted bias a novel event classifier is introduced which considers a self-normalized quantity using charged-particle multiplicities in a broad phase space region measurable experimentally. In Monte Carlo models we explore the sensitivity of this classifier to the “hardness” of the event and its sensitivity to soft multi-parton interactions [4]. The results from such phenomenological studies are being verified in the ALICE experiment using data from the Run 2 data taking period of the LHC. Good understanding of the effects is essential to plan long-term measurements in the Run 3 period and beyond.

Scaling properties of light and heavy-flavor jets. — In an earlier work we showed that Koba–Nielsen–Olesen (KNO)-like scaling is fulfilled inside the jets, which indicates that KNO scaling is violated by complex vacuum quantum chromodynamics (QCD) processes outside the jet development, such as single and double parton scattering or softer multiple parton interactions. In a subsequent publication we investigated the scaling properties of heavy-flavor jets using Monte-Carlo simulations. We found that while jets from leading-order flavor-creation processes exhibit flavor-dependent patterns, heavy-flavor jets from production in parton showers follow inclusive-jet patterns. This suggests that KNO-like scaling is driven by initial hard parton production and not by processes in the later stages of the reaction [5].

Interpreting the charm-baryon enhancement. — The enhancement of charmed baryons, observed in pp collisions at the LHC, questions the validity of the factorization approach in heavy-flavor production. Based on the comparative use of several event-activity classifiers in simulations with color-reconnection beyond leading color approximation, we proposed methods to identify the source of the observed enhancement. We also conclude that in the scenario under investigation the excess charmed Λ_c^+-baryon production is primarily linked to the underlying event activity and not to the production of jets (Fig. 2) [6]. More recently we investigated the production of charmed baryons with different isospin and strangeness content, and proposed methods based on event-activity classifiers to probe the source of the charm baryon enhancement. We conclude that in the considered model class, the isospin of the charmed baryon state has a strong impact on the enhancement pattern. Using the observables we propose in our manuscript in preparation, upcoming high-precision experimental data will be able to differentiate between mechanisms of strangeness and charm enhancement.

Image reconstruction for proton CT. — Proton CT can be used to measure the energy loss of individual protons and reconstruct the relative stopping power (RSP) distribution of the patient. We developed a novel algorithm for the image reconstruction as we first time applied the Richardson–Lucy iteration cycle for pCT with a simplified probability density based interaction calculation. We also investigated the energy dependence of the RSP which represents a theoretical limitation for the accuracy of the pCT imaging. We concluded that this dependence does not limit the applicability of pCT systems, but the measurement accuracy of the state of the art prototypes are close to this theoretical limit.
ALICE 3: cooling system development for the inner tracking system. — One of the main motivations behind the inner tracking system (ITS) development is to minimize the material budget of this detector with a drastic cut on the support and cooling structure. The sensitive detector will be a self-supporting blended, large silicon layer. The minimal material budget cooling system is forced airflow. The high power consumption parts of the detector layer require more effective cooling. In a novel concept, the carbon foam rings of the support structure will be used as heat exchangers. The main contribution of our group is the characterization of this material, which is challenging because of the non-Fourier thermal behavior of the foam. We are further involved in the numerical simulations and test measurements of the prototype detector.

Estimating the elliptic flow using machine learning techniques. — In this work, carried out jointly with the Heavy-Ion workgroup, we explore the prospects of using deep learning techniques to estimate elliptic flow (v_2) in heavy-ion collisions at the RHIC and LHC energies. A novel method is developed to process the input observables from particle kinematic information. Predictions from the proposed deep neural network (DNN) are compared to both simulation and experiment. It seems to preserve the centrality and energy dependence of v2 for LHC and RHIC energies. The DNN model is also quite successful in predicting the pT dependence of v_2, and keeps the robustness and prediction accuracy when subjected to noise [7].

Jet substructure. — We continued working on the analysis on the intrinsic structure of jets recorded by the CMS. Studying a large data sample from 2017, we were able to acquire information on the extreme corners of the phase space. The promising preliminary studies show which model is favored by the recorded data, although a detailed supervision of the results is needed to get to the final conclusion.

Pomeron physics. — We have finished the study of central exclusive production of charged hadron pairs in pp collisions at a center-of-mass energy of 13 TeV, using joint CMS and TOTEM data. The differential cross sections as functions of the polar scattering angle between the outgoing protons and of several squared four-momenta are measured in a wide region of scattered proton transverse momenta. A rich structure of interactions related to double pomeron exchange emerges, and the dynamics of the nonresonant continuum is determined. Based on an extensive model tuning effort, various physical quantities related to pomeron cross sections, pomeron-proton and pomeron-hadron form factors, trajectory slopes and intercepts, as well as coefficients of the supposed diffractive eigenstates of the proton are determined.

Detection of forward neutrons. — Studying forward neutrons at LHC energies can help in the understanding of cosmic rays through the tuning of models. Analyzing data from the Zero Degree Calorimeter of CMS for different collision geometries (p+p, p+Pb, Pb+p), we studied the time-dependent signals of various detector layers. We developed a technique to properly handle overflows using previously determined fits. After this first treatment the few-neutron peaks are clearly visible.

High-precision luminosity measurements. — The Beam Position Monitors (BPMs) placed close to the CMS detector measure the positions of the circulating beams. The exact location is crucial for the calibration of the luminosity during special Van der Meer (VdM) scans. In order to synchronize the measured data between the different BPMs, we need to determine the exact length-scale for each detector. We joined the efforts of the CMS BRIL (Beam Radiation, Instrumentation and Luminosity) team to study the results of the BPMs recorded in 2018. The shape of the incoming bunches in x direction differs from that in the y direction. The task of xy correlation analyses is to measure the non-factorizability of the directions, and to correct for this effect. Besides code refactoring, we started to work on the recent (2022) data.

2021

High-momentum hadron production in the ALICE experiment. — Light-flavor particle spectra are the benchmark test for perturbative QCD calculations beyond leading order, as well as for fragmentation models (Fig. 1). They also provide the baseline for potential nuclear modification in larger collision systems as well as small systems with high final-state multiplicities. The production of light-flavor mesons and baryons was measured in inelastic proton-proton (pp) collisions at a center-of-mass energy of $\sqrt{s}$=7 TeV and $\sqrt{s}$=13 TeV at midrapidity as a function of transverse momentum, using the ALICE detector at the CERN LHC. A hardening of the spectra at high p_T with increasing collision energy was observed. Our group played a leading role in these measurements [1]. This work is being continued with differential data analysis in ALICE pp and pPb collisions, by characterizing the underlying event region as a function of the transverse event activity classifier.

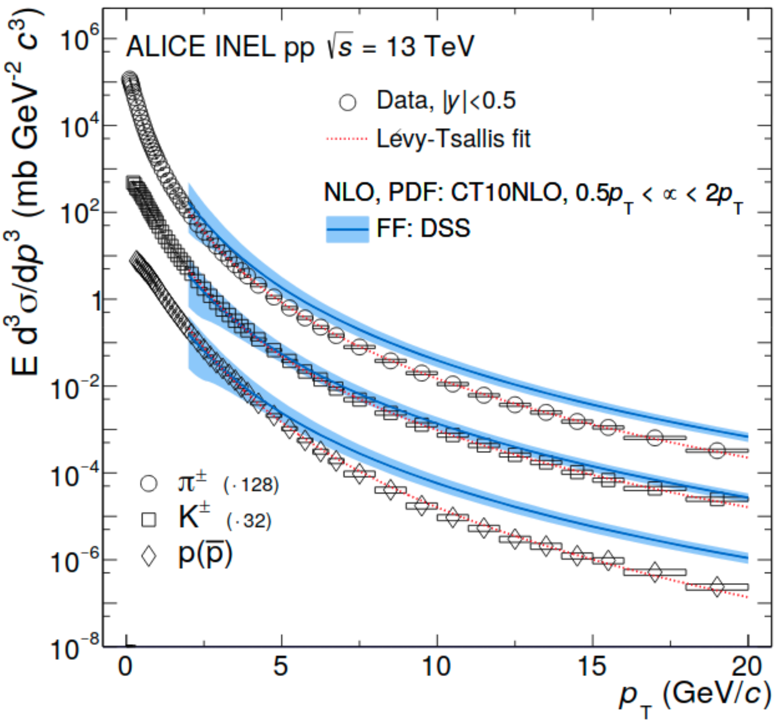

Figure 1. *Invariant differential cross sections for $\pi^{\pm}$, $K^{\pm}$, and p(anti-p) production in pp collisions at $\sqrt{s}$=13 TeV with the ALICE experiment, compared to pQCD model calculations and a phenomenological fit.*

Central exclusive production with the CMS experiment. — We published a paper on the central exclusive and semi-exclusive production of $\pi^{+}\pi^{-}$ pairs measured with the CMS detector in pp collisions at center-of-mass energies of $\sqrt{s}$=5.02 and 13 TeV [2]. The theoretical description of these nonperturbative processes, which have not yet been measured in detail at the LHC, poses a significant challenge to models. The two pions are measured and identified in the CMS silicon tracker based on specific energy loss, whereas the absence of other particles is ensured by calorimeter information. The total and differential cross sections of exclusive and semi-exclusive central $\pi^{+}\pi^{-}$ production are measured as functions of invariant mass, transverse momentum, and rapidity of the $\pi^{+}\pi^{-}$ system in the fiducial region defined as transverse momentum $p_{T,\pi} > 0.2$ GeV and pseudorapidity $|\eta_{\pi}|<2.4$ (Fig. 2). The production cross sections for the four resonant channels $f_0(500)$, $\rho^0(770)$, $f_0(980)$, and $f_2(1270)$ are extracted using a simple model. These results represent the first measurement of this process at the LHC collision energies of 5.02 and 13 TeV [3].

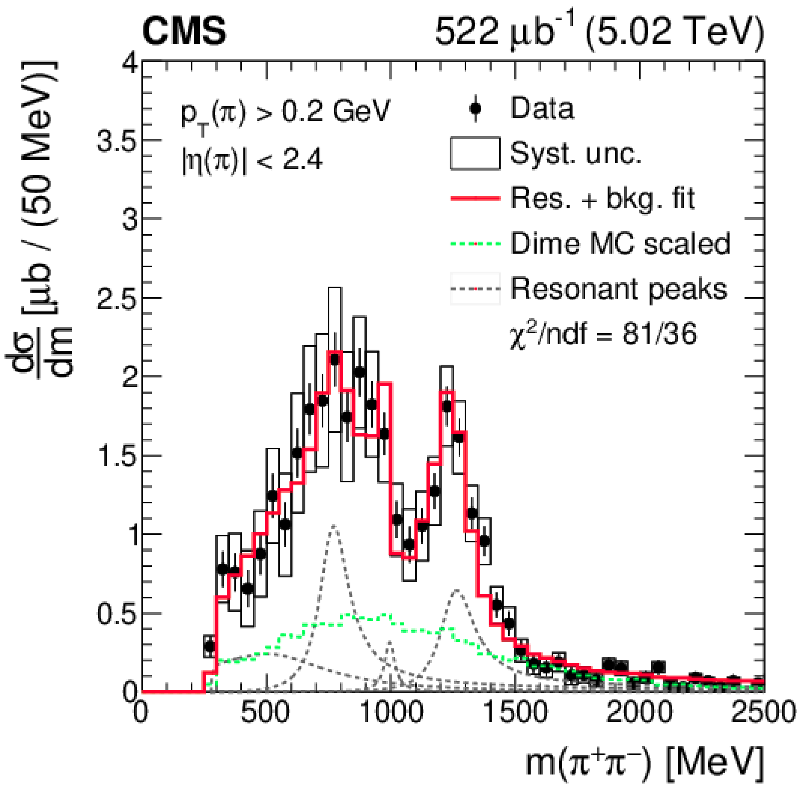

Figure 2. *Central exclusive $\pi^+\pi^-$ production cross sections with the CMS experiment in pp collisions at $\sqrt{s}$=5.02 TeV, and a model fit that accounts for resonances as well as the continuum.*

We have completed the analysis of a large amount of high-quality pp collision data taken in 2018, at $\sqrt{s}$=13 TeV centre-of-mass energy. Our aim was to study and understand exclusive production, trying to uncover the spin-structure of the pomeron. Events are selected by requiring scattered protons detected in the very forward roman pot detectors, exactly two centrally produced oppositely charged particles identified in the silicon tracker, and a momentum balance of the four particles. A fully differential, detailed partial wave (spin-parity) analysis of the angular distributions of the decay daughters reveals several f_0 and f_2 resonances. Their helicity amplitudes as functions of invariants are precisely measured and compared to vector- and tensor-pomeron models. We have measured the effective meson-pomeron form factors, an essential input for theoretical models. The mass pole and couplings of the $f_0(980)$ are measured, along with branching ratios of scalar and tensor resonances. The analysis of the four-hadron final state is promising, where we collaborate with other groups with the final goal to elucidate the case for some potential glueball candidates near 2 GeV mass. We are in the process of writing an initial paper on the nonresonant continuum and preparing another on resonance production.

Beauty-jet production in small systems with the ALICE experiment. — The production of heavy-flavor jets in proton-proton collisions serves as a fundamental test of perturbative QCD, while p-Pb (Pb-Pb) measurements provide information about the effects of the cold (and hot) nuclear matter. Our group plays a key role in several experimental measurements within the ALICE Heavy Flavor Jets and Correlations physics analysis group [4]. One such analysis is the measurement of the b-jet production at $\sqrt{s}$=5 TeV in pp and p-Pb collisions. Preliminary results on the production spectra in both systems, as well as the nuclear modification factor in p-Pb collisions, have already been made public [5]. With the excellent particle tracking capabilities of ALICE detector, these results extend to unprecedentedly low momenta (10 GeV/*c*) and pave the way to the understanding of flavor-dependent jet fragmentation as well as nuclear modification. Finalization of the results is currently underway.

Correlation of D mesons with charged hadrons. — Correlation measurements of D mesons with charged hadrons reveal the heavy-flavor jet structure at intermediate momenta. Simulations on D-h correlations in pp collisions at $\sqrt{s}$=5 TeV, aimed at the detailed understanding of partonic and hadronic contributions to heavy-flavor jet production were evaluated [5]. Our group is also a main contributor to the D-h correlation measurements in pp collisions at $\sqrt{s}$=13 TeV by the ALICE experiment [6], and to the preparation of the corresponding publication. Furthermore, we participate in the peak shape analysis of heavy-flavor electron to hadron correlations in $\sqrt{s}$=5 TeV pp and p-Pb collisions. This work will become part of a later ALICE publication.

Investigating the underlying event with identified leading processes. — The event-activity differential investigation of particle production reveals the connection between the leading process and the underlying event. It allows for the study of semi-soft vacuum-QCD effects potentially responsible for collectivity in events with higher activity, such as multiple-parton interactions (MPI). Flavor-dependent studies of these mechanisms can help separate color-charge and mass effects in jet production and fragmentation [7]. We conduct an ALICE measurement of the transverse event-activity dependent D^0 meson production.

We investigate the connection of flavor-dependent hard hadroproduction to the underlying event in a phenomenological study together with the colleagues at UNAM, using Monte Carlo simulations. A characteristic enhancement of MPI was found at intermediate momenta, that could be identified as gluon-initiated triggers. We also demonstrated that beauty triggers can be used as proxies for quark-initiated processes [8]. We used simulations to interpret heavy-flavor production in the jet and the underlying event region in case of unidentified as well as identified jet triggers, and proposed a method that establishes the connection of higher-order heavy-flavor production to MPI activity [9].

Scaling properties of jet structures. — A. Gémes contributed to the research of the group during his summer practice, with advisor R. Vértesi and external expert G. G. Barnaföldi. We studied the structure of jets in proton-proton collisions at LHC energies using Monte Carlo simulations. We demonstrate that the radial jet profiles exhibit scaling properties with charged-hadron event multiplicity over a broad transverse-momentum range (Fig. 3). We also provided parametrizations of the jet profiles based on different statistically-motivated analytical distributions. Based on this we proposed that the scaling behavior stems from fundamental statistical properties of jet fragmentation [10]. We also observed that the charged-hadron multiplicity distributions scale with jet momentum. This suggests that the Koba–Nielsen–Olesen (KNO) scaling holds within a jet. The in-jet scaling is fulfilled without MPI, but breaks down in case MPI is present without color reconnection. Our findings imply that KNO scaling is violated by parton shower or multiple-parton interactions in higher-energy collisions [11]. We also contributed to the jet structure studies in ALICE data jointly with the ALICE CCNU group.

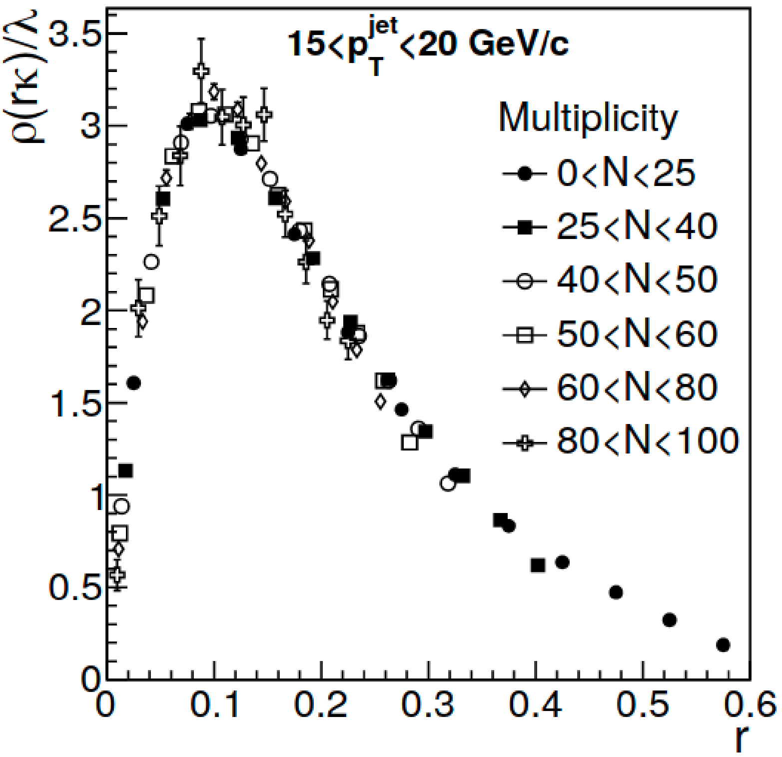

Figure 3. *Jet-momentum profiles after background subtraction, in different event-multiplicity classes in simulated pp collisions at √s=7 TeV, after the application of the scaling function.*

Jet substructure measurements with the CMS experiment. — The internal substructure of jets reveals the mechanisms of the parton fragmentation processes. We have compared different model predictions to proton-proton collision data recorded by the CMS experiment. We investigated clusters with high rapidity along the jet axis, and found that the basic properties of these clusters are sensitive to the applied fragmentation models.

Sudden increase in the degrees of freedom in dense QCD matter. — One of the main challenges in high energy heavy-ion collisions is to simultaneously determine the temperature and the energy density of the matter produced in a collision, and hence the number of thermodynamic degrees of freedom (DOF). We presented the extraction of the temperature by analyzing the charged particle transverse momentum spectra in lead-lead and proton-proton collisions at LHC energies from the ALICE Collaboration using the Color String Percolation Model (CSPM). From the measured energy density (ε) and the temperature (T) the dimensionless quantity ε/T^4 is obtained to get the degrees of freedom (DOF), $\varepsilon/T^4 = DOF^2/30$. We observe for the first time a two-step behavior in the increase of DOF, characteristic of deconfinement, above the hadronization temperature, at a temperature ~210 MeV for both Pb-Pb and pp collisions, and a sudden increase of the DOF to the ideal gas value of ~47 corresponding to three quark flavors in the case of Pb-Pb collisions [12].

Study the quark-gluon plasma using correlations of identified light hadrons. — The interaction of intermediate-momentum particles with the hot and dense, strongly interacting matter created in nucleus-nucleus collisions is possible using correlations of light-flavor hadrons. We have analyzed Pb-Pb collisions at √sNN=5.02 TeV data taken by the ALICE collaboration in 2018. The unidentified angular correlation results shows a similar broadening of the jet peak towards central collisions at low transverse momentum in Pb-Pb collisions at √sNN=5.02 TeV to that already observed at √sNN=2.76 TeV. The identified angular correlation results exhibit a clear particle species dependence. In addition, we are working on the analysis of different Monte Carlo simulations to determine the origin of the observed phenomena [13].

Medical applications of high energy detector technologies. — We participate in the Bergen pCT collaboration, formed for the development of a sampling calorimeter to be used for imaging in cancer therapy. Irradiation of cancer tumors using well-focused hadron (most commonly proton) beams can be a very effective treatment as the patient receives less unnecessary dose, thus allowing for a deposit of high destructive dose close to the critical organs. The ALPIDE calorimeter (Fig. 4) is based on the silicon pixel detector developed for the upgrade of the Inner Tracking System of ALICE. We have estimated the performance of the detector design using Monte Carlo simulations [14]. The ALPIDE detectors are already being produced and tested, and the group is currently working on the last refinements of the electronics and mechanics. In parallel, we are in the development of a data and image reconstruction algorithm partially based on machine learning techniques [15]. We expect the first real test results in the near future.

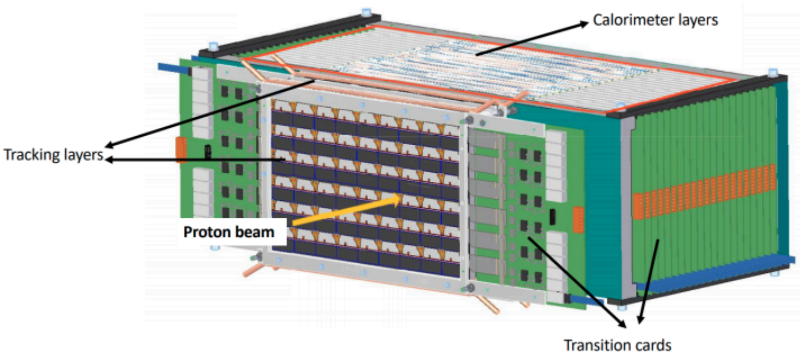

Figure 4. *Visualization of the Bergen pCT detector without the support structure.*

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Our research group aims to gain a better understanding of the strong interaction, one of Nature's fundamental forces, under extreme conditions. We participate in several complementary experiments (mainly ALICE and CMS), where we play leading roles in heavy-flavor and correlation measurements in high-energy nuclear reactions as well as in the exploration of gluon states in proton-proton collisions. We continue to play an active role in phenomenological and methodological studies such as the analysis of collective phenomena in small colliding systems and the development of novel particle tracking and identification algorithms. We apply our expertise in the field of detectors in developing a new proton-CT method for medical diagnosis and treatment.

Angular-correlation measurements. — We have analyzed the Pb-Pb and p-Pb data taken by the ALICE collaboration in 2015 and 2018. New results from this analysis showed a similar broadening of the jet peak towards central collisions at low transverse momentum in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV as what was seen previously at $\sqrt{s_{NN}}$= 2.76 TeV. [1] In addition, identified two-particle angular correlations in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV showed that both the broadening of the jet peak and the depletion yield depend on particle species dependence. Different Monte Carlo event generators (PYTHIA8/Angantyr, AMPT, JetScape) were used to determine the origin of the observed phenomena (Fig. 1 left). The trends observed for both identified and unidentified particles are reproduced by AMPT, hinting that microscopic processes alone are not sufficient to understand the observed jet broadening [2].

Heavy-flavour jets and correlations. — Since heavy (charm and bottom) quarks are mostly created in the initial hard scatterings and their numbers are largely unchanged throughout the reaction, they serve as ideal probes to test the properties of the strongly interacting medium produced in such collisions. Jets containing heavy flavour hadrons probe the influence of mass and color-charge effects on fragmentation, as well as provide insight to gluon-splitting processes. The ALICE detector has the unique capability of measuring beauty-jets down to relatively low momenta. Our group plays a leading role in ALICE heavy-flavour jet and correlation measurements. Preliminary results of beauty-jet cross sections and nuclear modification factors in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (Fig. 2 left) indicate that the nuclear modification of beauty jets by cold nuclear matter effects are weak [3].

We also analyzed azimuthal-correlation distributions of D mesons and light hadrons (D-h) in pp collisions at √s = 5.02 TeV in simulations with the PYTHIA 8 event generator. The results provide a better understanding on the role of partonic and hadronic effects in the developing correlation patterns, thus help us interpret charm production, understand their fragmentation, hadronization, and may also aid the identification of heavy particles [4]. In addition, we are working on ALICE analyses and simulations aimed at the understanding of the multiplicity-dependence of D-h correlations and their relations to the underlying event (Fig. 1 right).

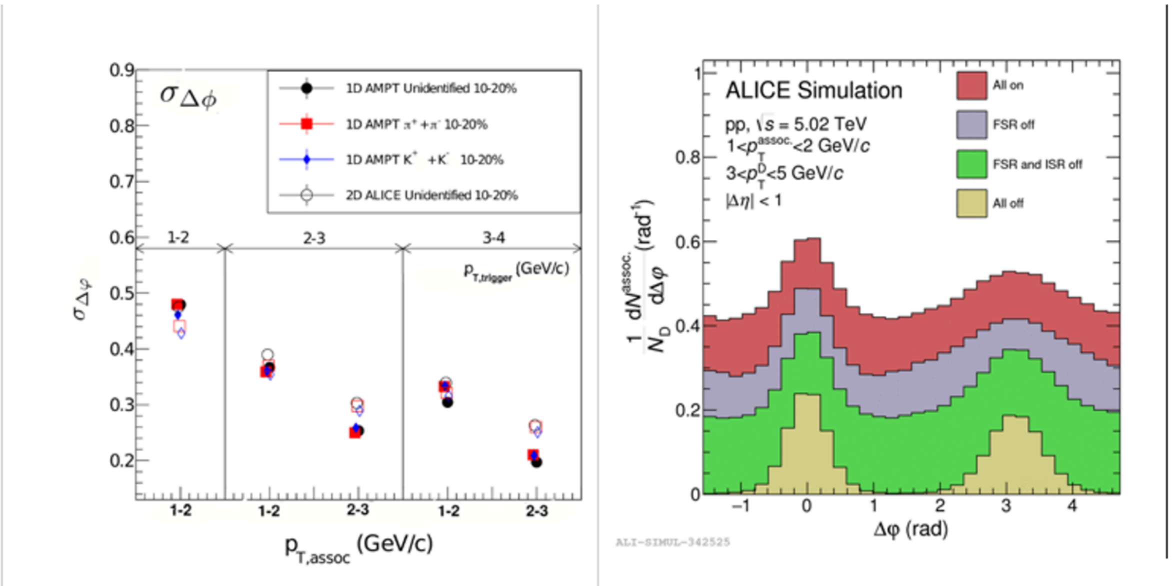

Figure 1. Left: Comparison of the correlation peak variances in the azimuthal direction from AMPT to those from ALICE data in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. Right: Different parton level contributions to the D-h correlation peak in the ALICE detector, computed using PYTHIA8 simulations.

Study of small collision systems with identifed particles. — The transverse-momentum spectra of light-flavour hadrons in pp collisions measured over a broad p_T range provide important input for the study of particle production mechanisms in the soft and hard scattering regime of QCD. We play a leading role within ALICE in the measurement and publication of light-flavour identified hadron spectra measured at mid-rapidity in inelastic pp collisions at 13 TeV. These measurements complement the existing ones at lower collision energies, allowing particle production to be studied over a wide range of √s. Furthermore, we investigated the multiplicity and spherocity dependencies of the average transverse momenta and integrated yields as a function of charged-particle multiplicity [5]. Recently we started to investigate the multiple-parton interactions with identified particles in pp collisions by studying the underlying event as a function of multiplicity. Also, by going to extremely high multiplicities with a designated trigger in the LHC Run-2 data taking period we aim to understand the strangeness enhancement observed in small systems, and consequently get better insight into collective-like phenomena.

Physics with pomerons. — Within the CMS Collaboration, we have started a comprehensive study of double pomeron exchange, central exclusive production of charged hadron pairs in pp collisions at a center-of-mass energy of 13 TeV. Events are selected by requiring both scattered protons detected in the roman pots, exactly two oppositely charged identified particles in the silicon tracker, and the momentum balance of these four particles. The interplay of resonant and nonresonant continuum processes is studied through multi-dimensional measurements using scattering angles and squared four-momentum transfers of the incoming protons, together with the invariant mass and decay angles of the centrally produced system. A rich structure of interactions related to double pomeron exchange emerges. The dynamics of various f_0 and f_2 resonances and the nonresonant continuum is used to test models on spin content, vector or tensor nature, of the pomeron.

Jet structures. — The discovery of collective-like behavior in high-multiplicity pp and p-A collisions was a major surprise in early LHC results. While the presence of the Quark-Gluon Plasma is needed to explain such collective behavior is still an open question, relatively soft vacuum-QCD effects such as multiple-parton interactions or the rearrangement of the color structure may also provide a viable explanation. Although the properties of jets are well described by different Monte Carlo event generators, discrepancies have been found in various corners of the phase space. Using the PYTHIA8 and HIJING++ Monte-Carlo event generators, we gave predictions for multiplicity-dependent jet structures. We demonstrated that vacuum QCD effects can modify the jet structure as well as two-particle angular correlation patterns in high-multiplicity events [6]. In Fig. 2 (right) we show predictions for the flavour-dependence of jet shape modification at various multiplicities [7]. Besides that, we investigated the effect of quark fragmentation on the final state of high energy proton-proton collisions using jet substructure observables. We have used several Monte Carlo event generators with different color reconnection algorithms, and compared the predictions with CMS data. According to the ongoing analysis results, the charge distribution of jets with rapidity gap is sensitive to the applied color reconnection algorithm.

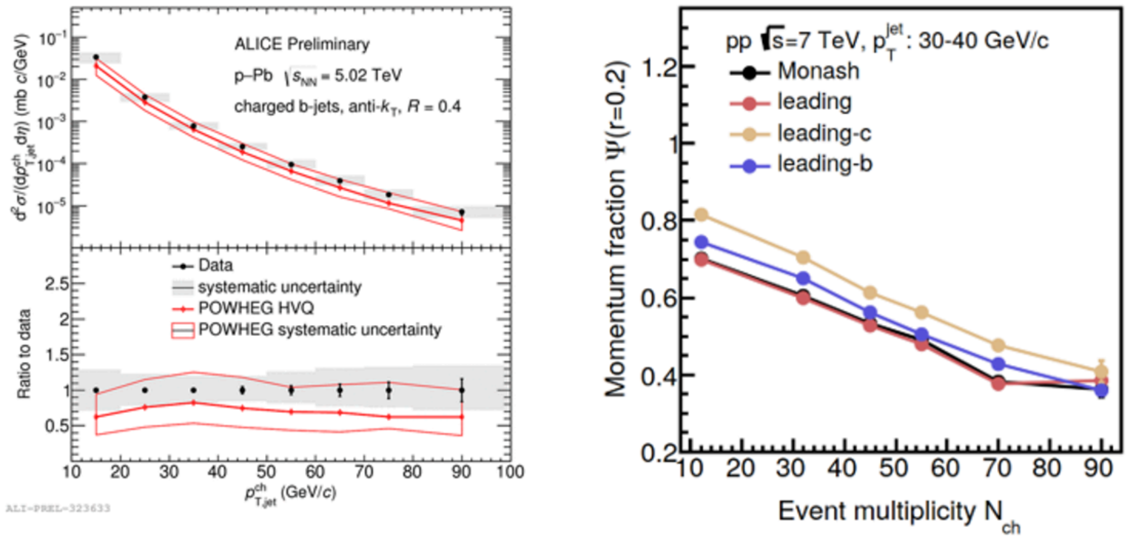

Figure 2. Left: Cross section of beauty jets in p-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV in the ALICE experiment, compared to a theory calculation. Right: Comparison of light- and heavy-flavour jet structures for different final-state multiplicites in simulations with PYTHIA8.

Novel reconstruction methods. — We have published a paper on a novel combination of data analysis techniques for the reconstruction of all tracks of primary charged particles, as well as daughters of displaced vertices, created in high energy collisions. [8] Instead of performing a classical trajectory building or an image transformation, efficient use of both local and global information is undertaken while keeping competing choices open. The measured hits of adjacent tracking layers are clustered first with the help of a mutual nearest neighbor search in the angular distance. The resulted chains of connected hits are used as initial clusters and as input for cluster analysis algorithms, such as the robust k-medians clustering. The clustering is complemented with elements from a more sophisticated Metropolis-Hastings MCMC algorithm, with the possibility of adding new track hypotheses or removing unnecessary ones. Simplified but realistic models of today's silicon trackers are employed to test and study the performance of the proposed method as a function of the particle multiplicity in the collision event (Fig. 3).

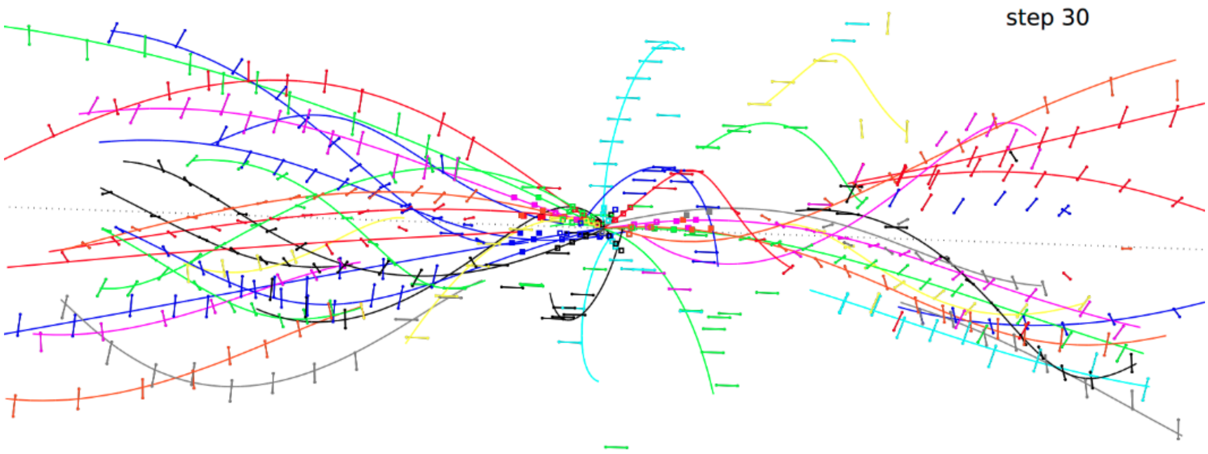

Figure 3. Hits (points and line segments) and reconstructed trajectories (colored curves), of a simulated proton-proton collision event.

Medical applications of high energy detector technologies. — We participate in the development of a sampling calorimeter to be used for imaging in cancer therapy [9,10]. Irradiation of cancer tumors using well-focused hadron (most commonly proton) beams can be a very effective treatment as the patient receives less unnecessary dose, thus allowing for a deposit of high destructive dose close to the critical organs. The ALPIDE calorimeter is based on the silicon pixel detector developed for the upgrade of the Inner Tracking System of ALICE. We have analyzed the data of a test beam measurement (Fig. 4 left). We determined the energy dependence of the cluster size of this pixel detector between 50 and 220 MeV/μ for alpha and proton particles (Fig. 4 right) [11]. We also measured the efficiency of the tracking algorithm on previous energy, which was higher than 99% in case of alpha particles. Furthermore, we participate in the mechanical design of the calorimeter. We have calculated the temperature distribution inside the calorimeter to find the optimal cooling system concept for the detector.

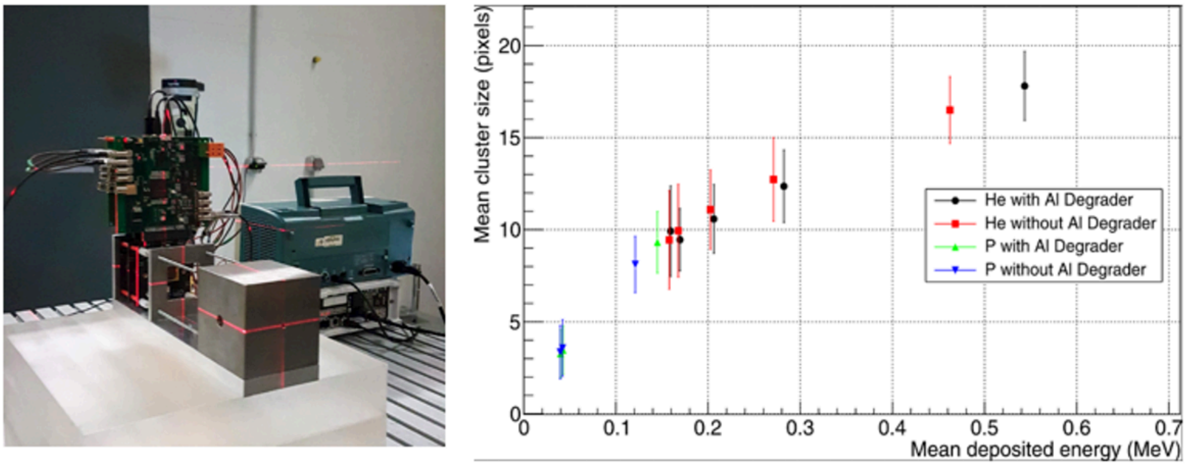

Figure 4. Left: Test beam setup for the characterization of detectors to be used as sampling calorimeter for the pCT medical application. Right: Energy dependence of the cluster size of the ALPIDE pixel detector.

2018

The aim of our research group is to better understand the strong interaction through collisions of nucleons and nuclei by performing basic and advanced measurements (cross sections, particle spectra and correlations), and by testing various theoretical ideas (quark-gluon plasma, gluon saturation, critical endpoint of the phase diagram). We participate in several complementary experiments (mainly ALICE and CMS), both in data-taking and physics analysis.

Quantum correlations. — We have finally published a paper on short-range two-particle correlation functions of identified hadrons in pp, p-Pb, and peripheral Pb-Pb collisions at LHC energies. The extracted radii of the particle emitting source (via Bose-Einstein correlations) are in the range 1-5 fm, reaching highest values for very high multiplicity p-Pb and Pb-Pb collisions (Fig 1, left). The dependence of the radii on the multiplicity and pair transverse momentum factorizes and appears to be less sensitive to the type of the collision system and center-of-mass energy. The observed similarities may point to a common critical hadron density reached in the collisions.

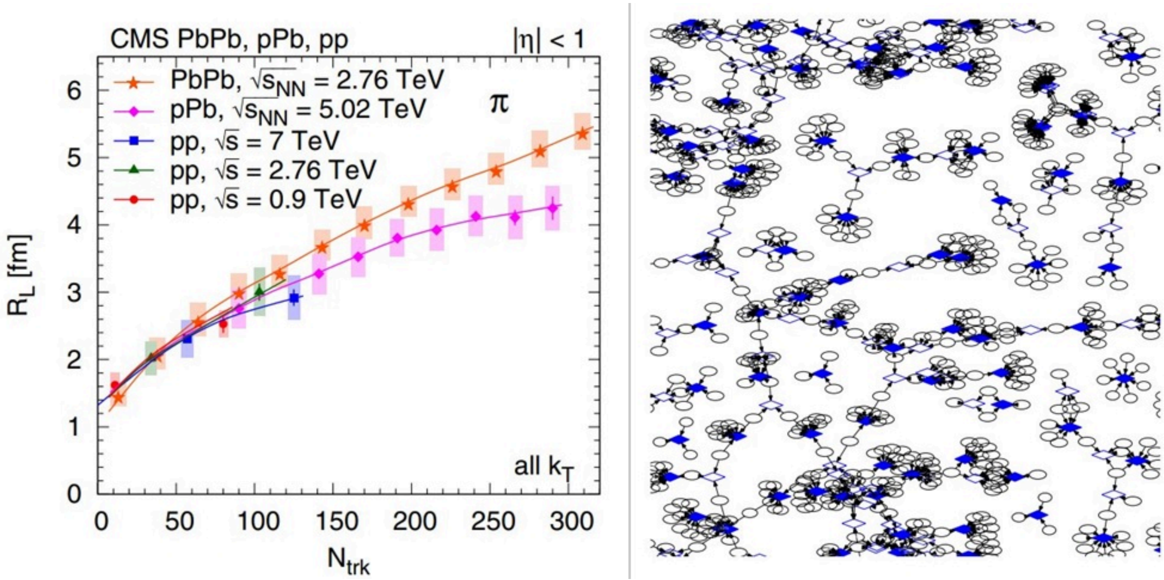

Figure 1. *Left: Track-multiplicity dependence of the two-dimensional pion radius parameters obtained from fits for all collision systems studied. Lines are drawn to guide the eye.. Right: A small fraction of the bipartite graph of hits (ellipses) and track candidates (diamonds) for an event with multiple (40) pp collisions. Directed arrows, graph edges, show potential hit-to-track candidate assignments.*

Novel reconstruction methods. — We have published a paper on a novel combination of established data analysis techniques for the reconstruction of all tracks of primary charged particles created in high energy collisions. Suitable track candidates are selected by transforming measured hits to a binned track parameter space. Subsequently, their number is further narrowed down by a Kalman filter-based technique. Track candidates and their corresponding hits form a highly connected network, a bipartite graph, where one allows for multiple assignments of hits to track candidates (Fig 1, right). The graph is cut into very many mini-graphs by removing a few of its components. Finally, the hits are distributed among the track candidates by exploring a deterministic decision tree. Simplified models of LHC silicon trackers are employed to study the performance of the proposed method in the case of single or many simultaneous proton-proton collisions, and for single heavy-ion collisions.

In addition, we have developed another track reconstruction method which uses of both local and global information while keeping competing choices open. The measured hits of adjacent tracking layers are clustered first with help of a mutual nearest neighbor search in angular distance. The resulted chains of connected hits are used as initial clusters for the robust *k*-medians clustering. This latter proceeds by alternating between the hit-to-track assignment and the track-fit update steps, until convergence. The calculation of the hit-to-track distance and that of the track-fit $\chi2$ is performed through the global covariance of the measured hits. The clustering is complemented with elements from a more sophisticated Metropolis-Hastings MCMC algorithm, with the possibility of adding new track hypotheses or removing unnecessary ones.

Angular-correlation measurements. — We have analyzed the Pb-Pb data taken by the ALICE collaboration in 2015, and we have shown new preliminary results from it at The 27th International Conference On Ultrarelativistic Nucleus-Nucleus Collisions (QM 2018) on unidentified two-particle angular correlations in Pb-Pb and pp collisions. The presented new results exhibit a similar broadening of the jet peak towards central collisions at low transverse momentum in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV as was seen previously at $\sqrt{s_{NN}}$ = 2.76 TeV. The results were accepted for publication in Nuclear Physics A. In addition, we are working on the analysis of different Monte Carlo simulations to determine the origin of the observed phenomena. We are analyzing both unidentified and identified two-particle correlations, and the results were presented on a poster at the International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions in 2018.

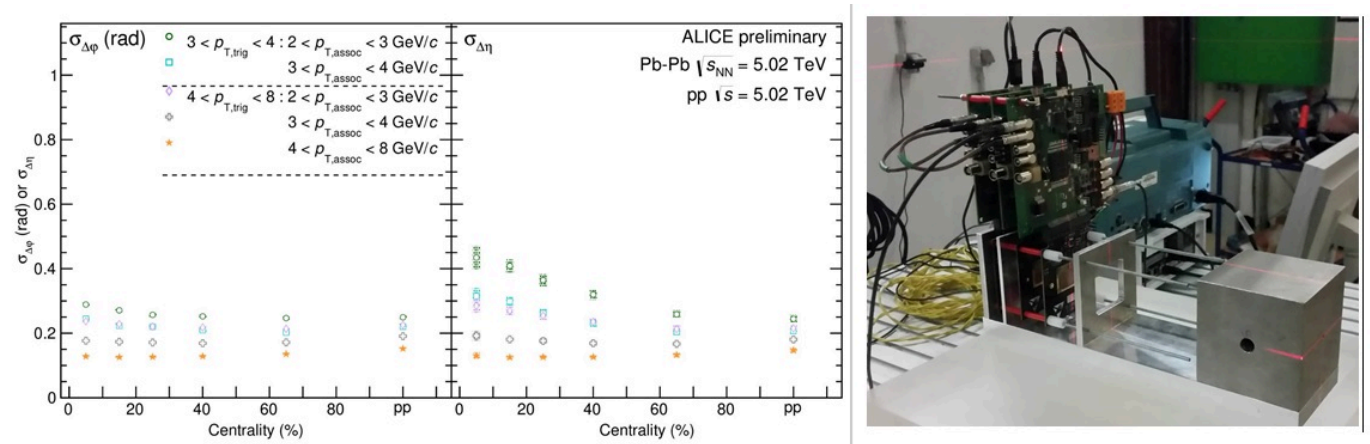

Figure 2. *Left: Width of the jet peak from two-particle angular correlations in Pb-Pb collisions at √sNN = 5.02 TeV as a function of centrality. The rightmost points show results from pp collisions at the same energy for comparison. Right: Test beam setup used for the characterization of detectors to be used as a sampling calorimeter for the medical application.*

Medical applications of high energy detector technologies. — We have joined the development of a sampling calorimeter to be used for imaging in cancer therapy. Cancer tumors can be killed by irradiating them by photons or hadrons. In the case of the treatment by hadrons, the energy deposition and therefore the destructive effect can be focused into the tumor with changing the energy of the hadron beam. In the case of photons, however, most of the energy is deposited at the entrance of the beam. This means that in the treatment with hadrons, the patient receives less unnecessary dose and the treatment can be applied closer to critical organs. However, to reach the full potential of such a treatment the imaging of the patient has to be done by hadrons (mostly commonly protons) as well. We are developing a calorimeter based on the silicon detector developed for the upgrade of the Inner Tracking System of ALICE for such imaging purposes. Our group is taking part in the analysis of the test beam data that will determine whether the chosen detector is suitable for this lower energy regime compared to its original purpose at the LHC.

Production of (un)identified particles in pp collisions. — The transverse momentum (p_T) spectra of light-flavor hadrons in pp collisions measured over a broad p_T range provide important input for the study of particle production mechanisms in the soft and hard scattering regime of QCD. We have measured the inclusive, as well as multiplicity-dependent, charged particle transverse momentum distributions for pp collisions at different center-of-mass energies at the ALICE experiment. For pp collisions at √s = 13 TeV and for a fixed multiplicity interval, the parameters obtained from the blast wave analysis of momentum spectra are used to characterize the evolution of the spectral shapes for different event topologies. The multiplicity and spherocity dependencies of the average transverse momenta and integrated yields as a function of charged-particle multiplicity are investigated. The average p_T is larger (smaller) in “jetty” (isotropic) events hinting at different dynamics of particle production. The evolution of the proton-to-pion and kaon-to-pion particle ratios as a function of p_T suggest that the collective-like behavior can be controlled by transverse spherocity. The hadron yields scale with charged-particle multiplicity across different √s and colliding systems which indicates that hadrochemistry is dominantly driven by multiplicity. The QCD-inspired models describe several aspects of data. These results were presented at The 27th International Conference On Ultrarelativistic Nucleus-Nucleus Collisions (QM 2018).

Heavy-flavour production. — Heavy-flavour (beauty and charm) quarks are produced almost exclusively in initial hard processes, and their yields remain largely unchanged throughout a heavy-ion reaction. Nevertheless, they interact with the nuclear matter in all the stages of its evolution. Thus, heavy quarks serve as ideal self-generated penetrating probes of the strongly interacting QGP. Jets containing heavy flavour hadrons probe the influence of mass and color-charge effects on fragmentation, as well as provide insight to gluon splitting processes. The ALICE detector has the unique capability of measuring beauty-jets down to relatively low momenta. Our group plays a leading role in ALICE beauty-jet measurement in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV.

Jet structures. — Collective behavior of high multiplicity events in small systems have also been observed in the heavy-flavour sector. Recent analyses of pp and p-Pb collisions show a universal enhancement of heavy-flavour particles that is usually attributed to multiple parton interactions and higher gluon radiation associated with short distance production processes. We have carried out extensive studies using the PYTHIA8 as well as the HIJING++ Monte-Carlo event generators. We have given predictions for multiplicity-dependent jet structures, and proposed a way to validate the presence and extent of effects such as multiple-parton interactions or color reconnection. We have demonstrated that vacuum QCD effects can modify the jet structure, as well as two-particle angular correlation pictures, in high-multiplicity events. We also gave predictions to flavour-dependence of jet shape modification vs. momentum and multiplicity. We have also introduced a definition of a characteristic jet size measure that is independent of multiplicity. We started the experimental analysis of jet shapes in ALICE Run-2 data in cooperation with the CCNU ALICE group in order to verify or exclude the presence of jet-modification by vacuum-QCD effects.

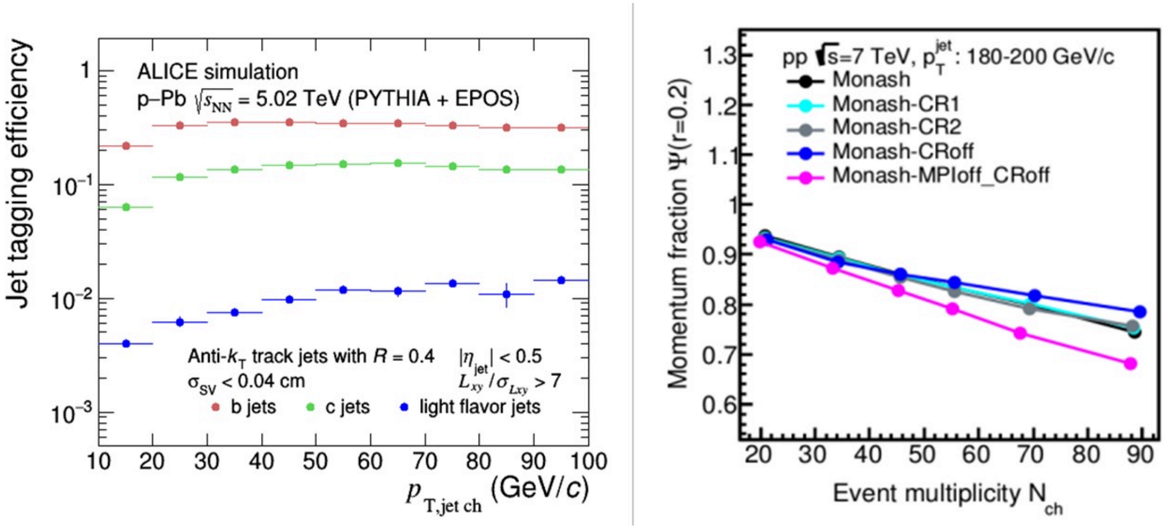

Figure 3. *Left: Tagging efficiencies of beauty, charm and light flavour jets in p-Pb collisions at $\sqrt{s_{NN}}$ =5.02 TeV in the ALICE experiment. Right: Modification of the jet structures by multiple-parton interactions and different color reconnection schemes in simulations with PYTHIA8.*

2017

The aim of our research group is to better understand the strong interaction through collisions of nucleons and nuclei by performing basic and advanced measurements (cross sections, particle spectra and correlations), and by testing various theoretical ideas (quark-gluon plasma, gluon saturation, critical endpoint of the phase diagram). We participate in several complementary experiments (mainly ALICE and CMS), both in data-taking and physics analysis.

With the help of ultra-relativistic heavy-ion collisions, the properties of strongly-interacting hadronic matter can be studied under extreme conditions of temperature and energy density. Characteristics of this phase of matter are important for a better understanding of the strong interaction as well as to address cosmological questions of the early Universe. Recently the study of particle production in high-multiplicity events in small collision systems at the LHC has revealed unexpected new collective-like phenomena. In particular, for high-multiplicity pp and p-Pb collisions, radial flow signals, long-range angular correlations, and strangeness enhancement have been reported. Our activities this year focused on the above-listed topics.

Spectra of identified hadrons. — We have measured the transverse momentum spectra of identified charged hadrons (pions, kaons, and protons) in proton-proton collisions at √s = 13 TeV. The pT spectra and integrated yields are compared to lower center-of-mass energy pp results and to Monte Carlo simulations. The average pT increases with particle mass and the charged-particle multiplicity of the event (Fig. 1, left). A comparison with lower energy data shows only a moderate dependence of the average pT on the center-of-mass energy. The PYTHIA8 CUETP8M1 event generator reproduces most features of the measured distributions, but EPOS LHC also gives a satisfactory description of several aspects. Particle production is strongly correlated with event multiplicity in all collision types, rather than with the center-of-mass energy or collision system. The data supports the assumption that the characteristics of particle production are constrained by the amount of initial parton energy that is available in any given collision.

Sources of radial flow patterns. — We have proposed a tool to reveal the origin of the collective-like phenomena observed in proton-proton collisions. We exploit the fundamental difference between the underlying mechanisms, color reconnection, and hydrodynamics, which produce radial flow patterns in PYTHIA8 and EPOS3 Monte Carlo event generators, respectively. The strength of the coupling between the soft and hard components, by construction, is larger in PYTHIA8 than in EPOS3. We studied the transverse momentum (pT) distributions of charged pions, kaons and (anti) protons in inelastic pp collisions at $\sqrt{s}$ = 7 TeV produced at mid-rapidity. Specific selections are made on an event-by-event basis as a function of the charged particle multiplicity and the transverse momentum of the leading jet reconstructed using the FastJet algorithm at mid-pseudorapidity. From our studies, quantitative and qualitative differences between PYTHIA8 and EPOS3 are found in the pT spectra when (for a given multiplicity class) the leading jet pT is increased. In addition, we showed that for low-multiplicity events the presence of jets can produce radial flow-like behavior, shown in Fig. 1 (right). The observed differences between the two event classes (low and high multiplicities) similar to those seen in the hadrochemistry measured in the jet and bulk regions in pp and Pb-Pb collisions by the ALICE collaboration. Motivated by our findings, we proposed to perform a similar analysis using experimental data from RHIC and the LHC.

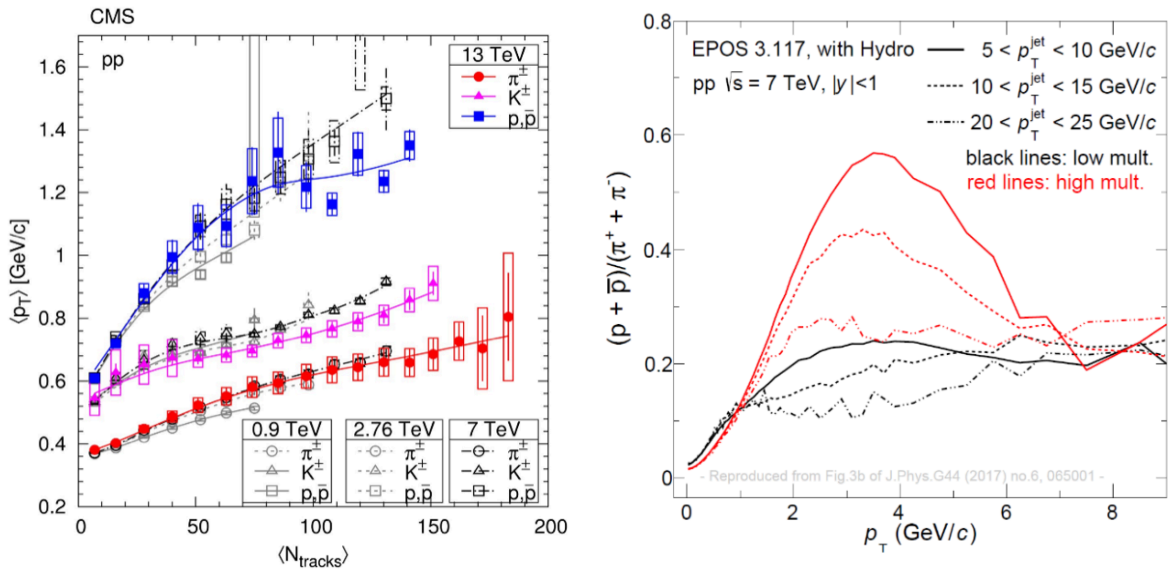

Figure 1. *Left: Average transverse momentum of identified charged hadrons (pions, kaons, and protons) at mid-rapidity as a function of the corrected track multiplicity in the range |η|<2.4, for pp collisions at √s =13 TeV (filled symbols) and at lower energies (open symbols). Lines are drawn to guide the eye. Right: Proton-to-pion particle ratio as a function of pT for low (black lines) and high (red lines) multiplicity event classes, and for different leading jet pT intervals simulated by the EPOS3 Monte Carlo event generator.*

Angular correlations. — Previous studies have shown that several mechanisms can play a role in producing collective-like behavior. It has been demonstrated that multi-parton interactions and color reconnection as implemented in PYTHIA MC event generator produce radial flow patterns via boosted color strings. Also, azimuthal correlations have been studied in A Multi-Phase Transport model (AMPT), where the ridge structure can be generated assuming incoherent elastic scattering of partons and the string melting mechanism. Besides, phenomenological studies (as described above) show that it is possible to find a subclass of low-multiplicity events where radial flow patterns arise, despite the fact that at very low multiplicity hydrodynamics cannot be applied and color reconnection effects are small.

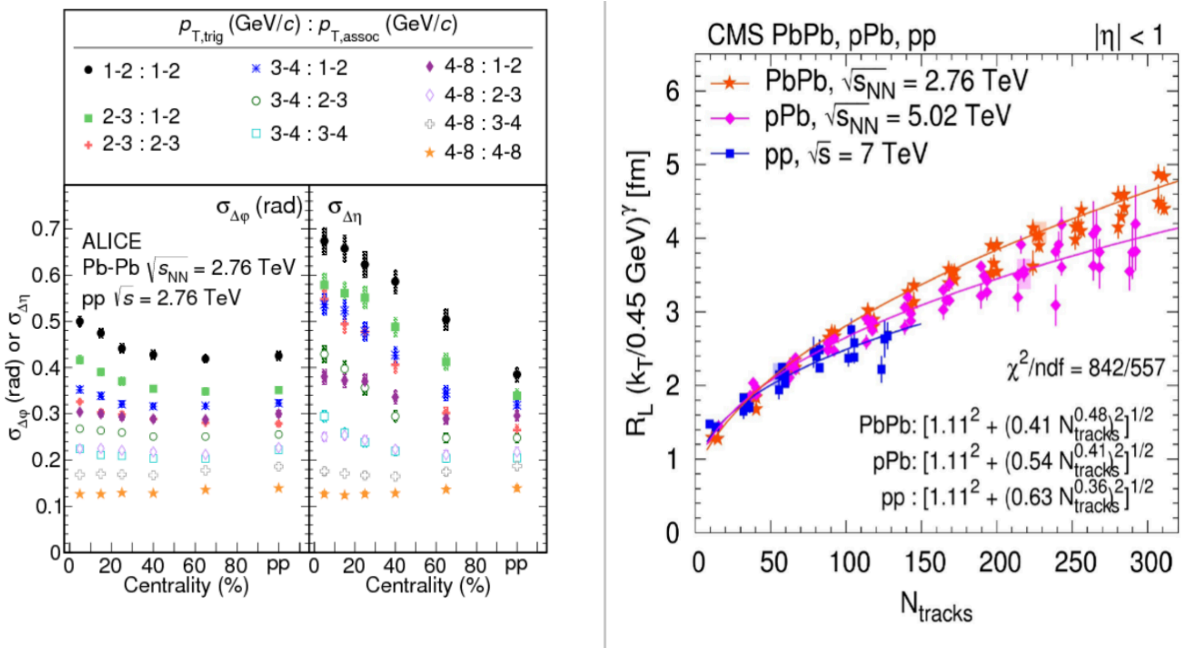

Figure 2. *Left: Width of the jet peak in the Δϕ and Δη directions from Pb-Pb and pp (rightmost points) collisions at √sNN = 2.76 TeV. Right: Cauchy-type radius parameters for pions from Bose-Einstein correlation analyses of various collision systems and center-of-mass energies as a function of the corrected track multiplicity in the range Iηl<2.4, scaled to kT = 0.45 GeV/c with help of a specific parametrization.*

We have measured the two-particle angular correlations of charged particles in Pb-Pb collisions at √sNN = 2.76 TeV. The azimuthal angle (Δϕ) and pseudorapidity (Δη) difference of a trigger particle with high pT and an associated particle with lower pT are evaluated. In the distribution of these angles, jets manifest themselves as a peak around (Δϕ, Δη) = (0, 0) and as an elongated structure in (Δη) at Δϕ = π. Studying the centrality and pT dependence of the shape of the jet peak and comparing it to the shape in proton-proton collisions can provide insight on the interaction of jets with the quark-gluon plasma (QGP). The jet peak is found to broaden at low pT in Pb-Pb collisions towards central collisions (Fig. 2, left). It is also found to become asymmetric (broader in Δη than in Δϕ). An unexpected depletion around (Δϕ, Δη) = (0, 0) also develops at low pT. The comparison of the modification of the jet peak with the AMPT model shows that both effects are accompanied by large radial and longitudinal flow, suggesting that they arise as a consequence of the interaction of the jets with the flowing QGP.

Quantum correlations. — We have measured short-range two-particle correlation functions of identified hadrons in pp, p-Pb, and peripheral Pb-Pb collisions. The extracted radii of the particle emitting source (via Bose-Einstein correlations) are in the range 1-5 fm, reaching highest values for very high multiplicity p-Pb and Pb-Pb collisions. The pp and p-Pb source is elongated in the beam direction, while in the peripheral Pb-Pb case the source is symmetric. The dependence of the radii on the multiplicity and kT factorizes and appears to be less sensitive to the type of the collision system and center-of-mass energy (Fig. 2, right). The observed similarities may point to a common critical hadron density reached in the collisions.

Heavy flavour production. — Heavy-flavour (beauty and charm) quarks are produced almost exclusively in initial hard processes, and their yields remain largely unchanged throughout a heavy-ion reaction. Nevertheless, they interact with the nuclear matter in all the stages of its evolution. Thus, heavy quarks serve as ideal self-generated penetrating probes of the strongly interacting QGP. Jets containing heavy flavour hadrons are also sensitive to flavour-dependent fragmentation and gluon splitting. Recent heavy-flavour jet measurements by the ALICE experiment, with contributions from our group, provide strong constraints on theoretical models of heavy-flavour production and fragmentation.

Jet structure. — Non-trivial behavior of high multiplicity events in small systems have also been observed in the heavy-flavour sector. Recent analyses of pp and p-Pb collisions show a universal enhancement of heavy-flavour particles that is usually attributed to multiple parton interactions and higher gluon radiation associated with short distance production processes. We have carried out extensive studies using MC event generators. We have given predictions for multiplicity-dependent jet structures, and proposed a way to validate the presence and extent of effects such as multiple-parton interactions or color reconnection, based on the detection of non-trivial jet shape modification in high multiplicity events. We proposed a way to use the multiplicity-dependent jet structures to experimentally differentiate between equally well-performing simulation tunes. We have also introduced a definition of a characteristic jet size measure that is independent of multiplicity. These studies can serve as a baseline for jet structure analyses in heavy-ion collisions as well as flavour-dependent studies.

New method for tracking of charged particles at high multiplicities. — We have developed a novel combination of established data analysis techniques for reconstructing charged particles in very high multiplicity collisions. It uses all information available while keeping competing choices open as long as possible. Suitable track candidates are selected by transforming measured hits to a track parameter space with help of templates. The highly connected network of track candidates and their corresponding hits is cut into very many subgraphs by removing a few of its vulnerable components, edges, and nodes. Finally, the hits distributed among the candidates by exploring a deterministic decision tree. A depth-limited search is performed maximizing the number of hits on tracks, and also the sum of track-fit quality measures.