R-H. Hadron physics

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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 p_T spectra and integrated yields are compared to lower center-of-mass energy pp results and to Monte Carlo simulations. The average p_T 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 p_T 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 (p_T) distributions of charged pions, kaons and (anti) protons in inelastic pp collisions at *√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 p_T spectra when (for a given multiplicity class) the leading jet p_T 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.

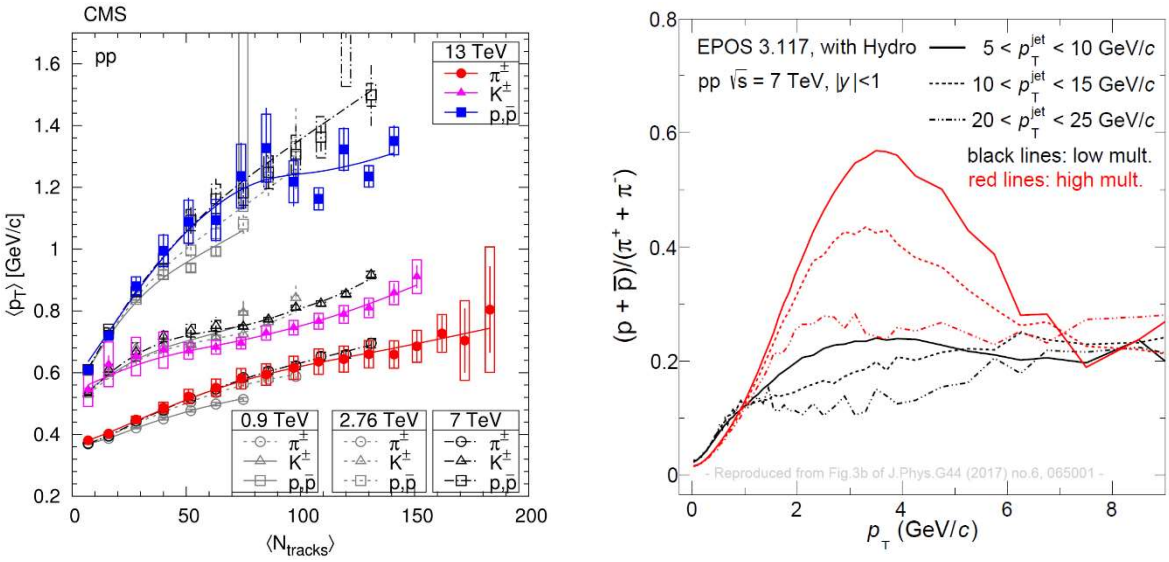

Figure 1. *Left: Average transverse momentum of identified charged hadrons (pions, kaons, and protons) at mid-rapidity as a function of the corrected track multiplicity in the range $|\eta|<2.4$, for pp collisions at $\sqrt{s}$ =13 TeV (filled symbols) and at lower energies (open symbols). Lines are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

We have measured the two-particle angular correlations of charged particles in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. The azimuthal angle ($\Delta\varphi$) and pseudorapidity ($\Delta\eta$) difference of a trigger particle with high p_T and an associated particle with lower p_T are evaluated. In the distribution of these angles, jets manifest themselves as a peak around ($\Delta\varphi$, $\Delta\eta$) = (0, 0) and as an elongated structure in ($\Delta\eta$) at $\Delta\varphi = \pi$. Studying the centrality and p_T 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 p_T in Pb-Pb collisions towards central collisions (Fig. 2, left). It is also found to become asymmetric (broader in $\Delta\eta$ than in $\Delta\varphi$). An unexpected depletion around ($\Delta\varphi$, $\Delta\eta$) = (0, 0) also develops at low p_T. 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 k_T 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.

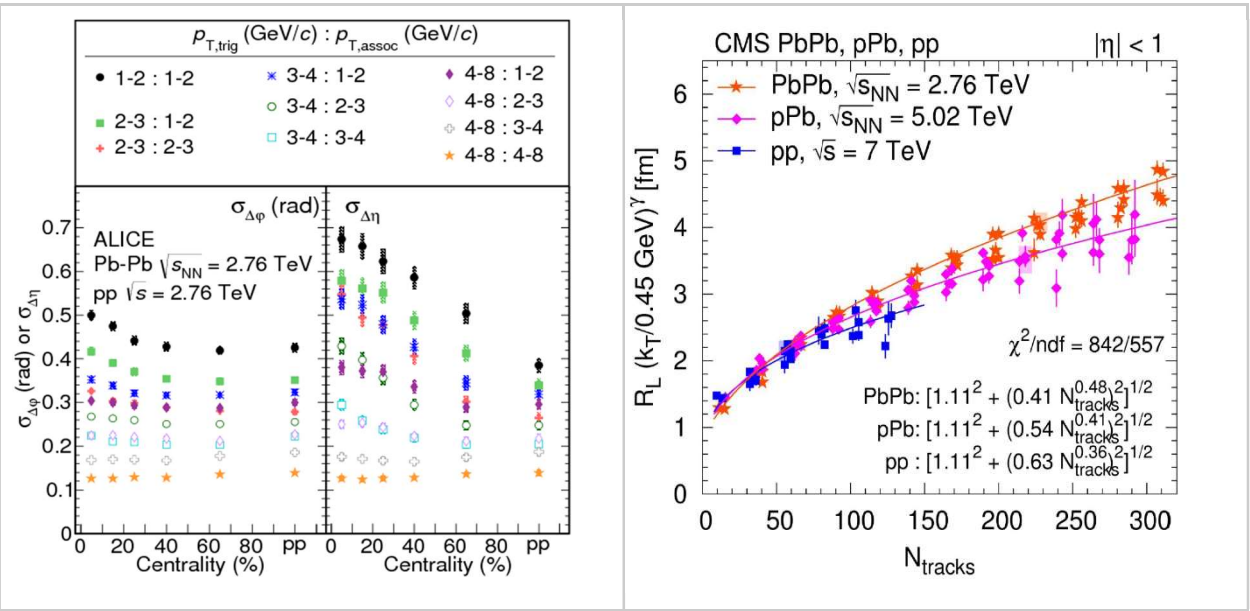

Figure 2. *Left: Width of the jet peak in the $\Delta\varphi$ and $\Delta\eta$ directions from Pb-Pb and pp (rightmost points) collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. Right: Cauchy-type radius parameters for pions from Bose-Einstein correlation analyses of various collision systems and center-of-mass energies as a function of the corrected track multiplicity in the range $|\eta|<2.4$, scaled to k_T = 0.45 GeV/c with help of a specific parametrization.*

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.

Grants

NKFI K 109703: Consortional main: Hungary in the CMS experiment of the Large Hadron Collider (F. Siklér, 2013-2017)

Swiss National Science Foundation, SCOPES 152601: Preparation for and exploitation of the CMS data taking at the next LHC run (G. Dissertori ETHZ, 2014-2017)

International cooperation

ALICE, CMS, FOPI, NA49, and NA61 (CERN), PHENIX and STAR (RHIC)

Publications

Articles

1. Adam W et al. incl. Siklér F, Veszprémi V [674 authors]: P-Type Silicon Strip Sensors for the new CMS Tracker at HL-LHC. JOURNAL OF INSTRUMENTATION 12:(6) Paper P06018. 26 p. (2017)

2. Aduszkiewicz A et al. incl. Fodor Z, László A, Márton K, Vesztergombi G [154 authors]: Two-particle correlations in azimuthal angle and pseudorapidity in inelastic p + p interactions at the CERN Super Proton Synchrotron. ***EUR PHYS J C* 77**:(2) 59/1-15 p. (2017)
3. Siklér F: Combination of various data analysis techniques for efficient track reconstruction in very high multiplicity events. ***EPJ WEB CONF* 150**: 00011/1-13 (2017) (CTD/WIT 2017 - Connecting The Dots/Intelligent Trackers, Orsay, France, 06-09 March 2017)
4. Siklér F: Femtoscopy with identified hadrons in pp, pPb, and PbPb collisions in CMS. ***UNIVERSE* 3**:(4) 76/1-10 (2017)
5. Abbaneo D et al. incl. Bencze G, Endrőczi G [151 authors]: Overview of large area triple-GEM detectors for the CMS forward muon upgrade. ***NUCL INSTRUM METH A* 845**: 298-303 (2017)
6. Abbaneo D et al. incl. Bencze G, Endrőczi G [153 authors]: R&D on a new type of micropattern gaseous detector: The Fast Timing Micropattern detector. ***NUCL INSTRUM METH A* 845**: 313-317 (2017)
7. Ahmed W et al. incl. Bencze G, Endrőczi G [155 authors]: The Triple GEM Detector Control System for CMS forward muon spectrometer upgrade. ***J INSTRUM* 12**: P02003/1-14 (2017)
8. Ortiz A, Bencédi G, Bello H: Revealing the source of the radial flow patterns in proton-proton collisions using hard probes. ***J PHYS G NUCL PARTIC* 44**:(6) 065001/1-14 (2017)
9. Zsigmond AJ: Z bozonok jelentősége nehézion-ütközésekben (Significance of bosons in heavy ion collisions, in Hungarian). ***FIZIKAI SZEMLE* 67**:(7-8) 251-254 (2017)

Book chapter

10. Vértesi R: Production of quarkonia at RHIC. In: *Gribov-85 Memorial Volume: Exploring Quantum Field Theory: Proceedings of the Memorial Workshop Devoted to the 85th Birthday of VN Gribov (Budapest, Hungary, 17-20 June 2015).Eds::* Dokshitzer Y, Lévai P, Nyíri J, Singapore: World Scientific Publishing, 2017 pp. 355-363

See also: R-I.1

CMS Collaboration

Due to the vast number of publications of the large collaborations in which the research group participated in 2015, here we list only a short selection of appearences in journals with the highest impact factor.

1.

NA49 Collaboration

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NA61 Collaboration

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FOPI Collaboration

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