R-F. 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.

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.

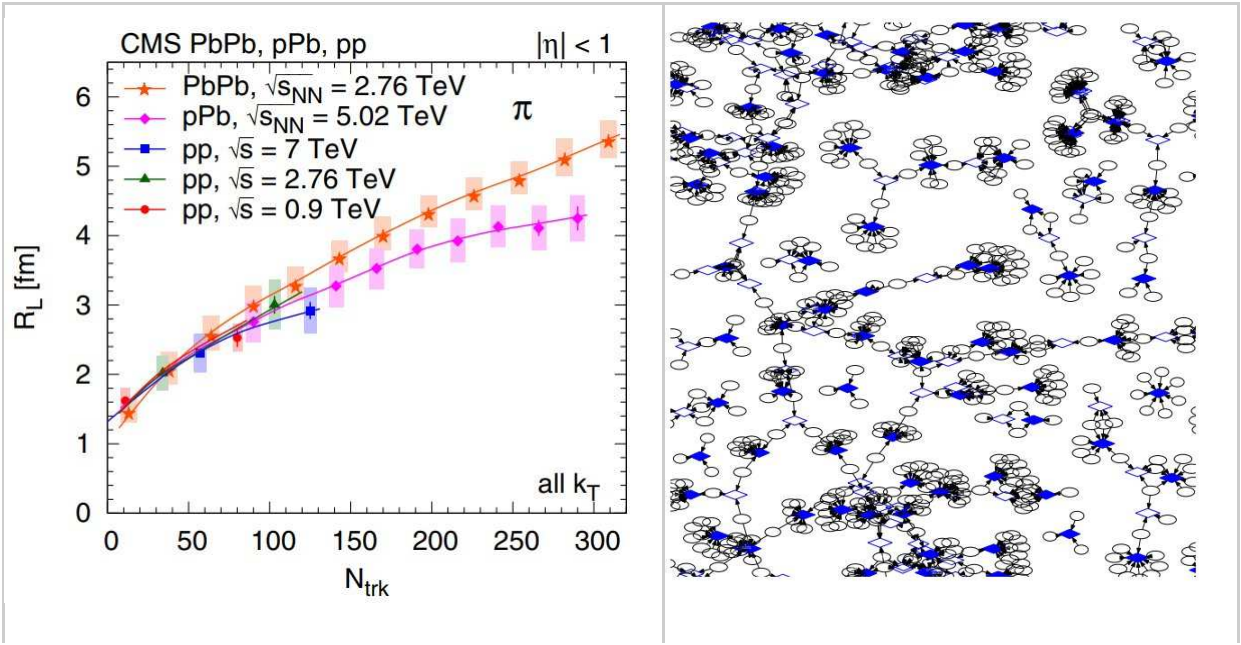

Figure 1. *Left: Track-multiplicity dependence of the two-dimensional pion radius parameters obtained from fits for all collision systems studied. Lines are drawn to guide the eye.. Right: A small fraction of the bipartite graph of hits (ellipses) and track candidates (diamonds) for an event with multiple (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 χ2 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 (Fig 2, left). 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.

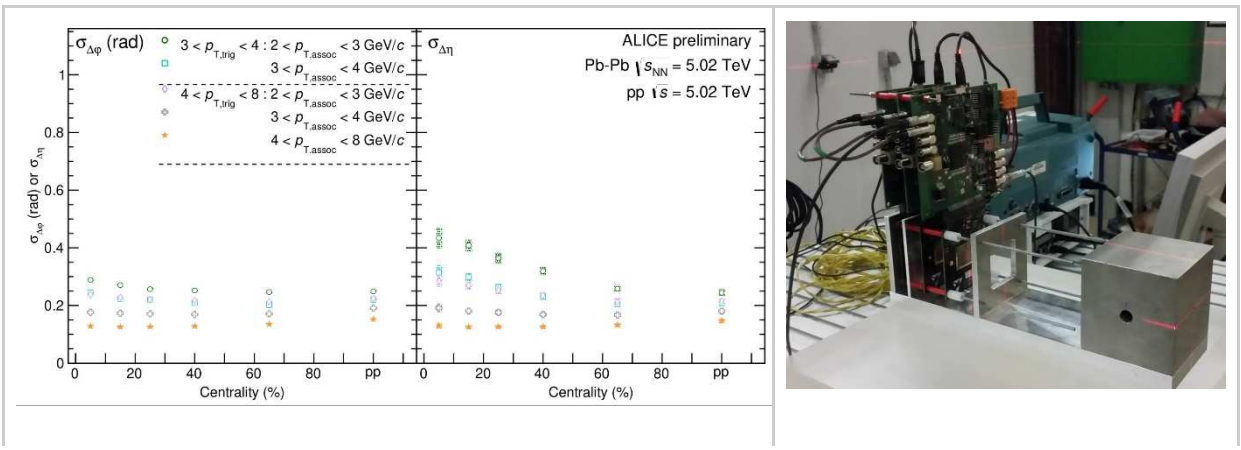

Figure 2. *Left: Width of the jet peak from two-particle angular correlations in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV as a function of centrality. The rightmost points show results from pp collisions at the same energy for comparison. Right: Test beam setup used for the characterization of 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(Fig 2, right).

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 Quantum Chromodynamics (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 (Fig 3, left).

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 (Fig 3, right). 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.

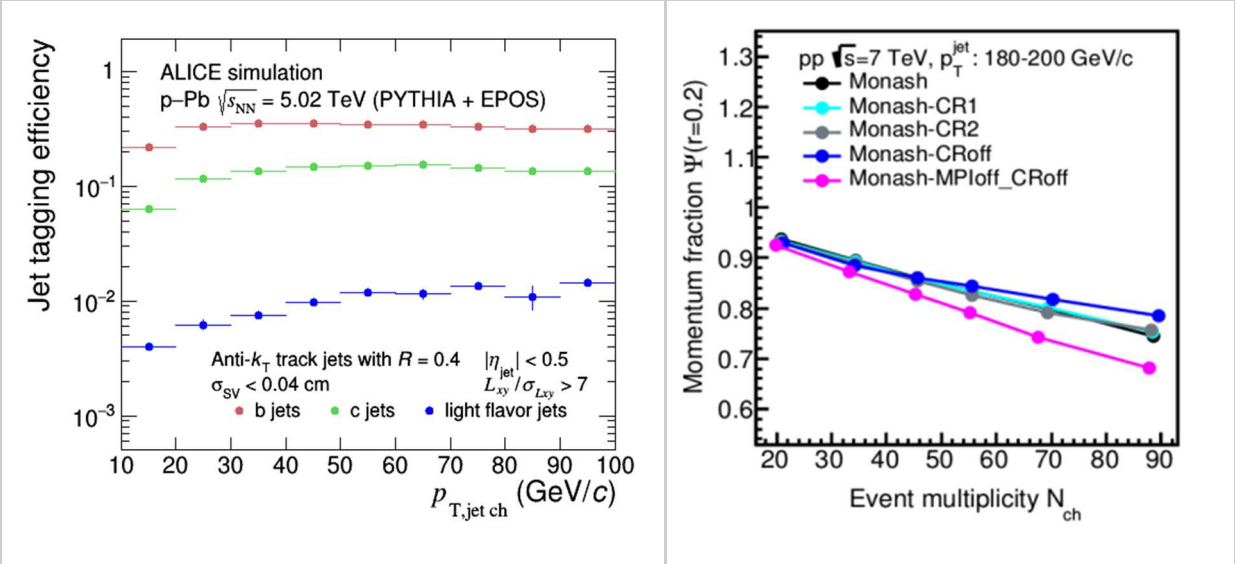

Figure 3. *Left: Tagging efficiencies of beauty, charm and light flavour jets in p-Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV in the ALICE experiment. Right: Modification of the jet structures by multiple-parton interactions and different color reconnection schemes in simulations with PYTHIA8.*

Grants

NKFIH K 128786: Consortional assoc.: Novel tests of the strong interaction with the CERN CMS experiment (F Siklér, 2018-2022)

NKFIH K 120660: Investigation of the identified hadron production in the heavy-ion collisions at the high-luminosity LHC by the ALICE experiment (GG Barnaföldi, 2016-2020)

International cooperation

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

Publications

Articles

1. Münzer R et al. incl. Fodor Z, Kecskeméti J, Seres Z [70 authors]: Determination of N* amplitudes from associated strangeness production in p+p collisions. ***PHYS LETT B*** **785**: 574-580 (2018)
2. Siklér F: A combination of analysis techniques for efficient track reconstruction of high multiplicity events in silicon detectors. ***EUR PHYS J A*** **54**:6 113/1-11 (2018)

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. Wigner authors in the Collaboration are: Bencze G, Hajdú C, Horváth D, Hunyadi Á, Siklér F, Vámi TÁ, Veszprémi V, Vesztergombi G, Zsigmond AJ.

1. Sirunyan AM et al. (CMS Collaboration) [2289 authors]: Elliptic flow of charm and strange hadrons in high-multiplicity *p*+Pb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV. ***PHYS REV LETT*** **121**:8 082301/1-18 (2018)
2. Sirunyan AM et al. (CMS Collaboration) [2300 authors]: Observation of the χ_{b1}(3P) and χ_{b2}(3P) and measurement of their masses. ***PHYS REV LETT*** **121**:9 092002/1-17 (2018)
3. Sirunyan AM et al. (CMS Collaboration) [2228 authors]: Constraining gluon distributions in nuclei using dijets in proton-proton and proton-lead collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. ***PHYS REV LETT*** **121**:6 62002/1-18 (2018)
4. Sirunyan AM et al. (CMS Collaboration) [2239 authors]: Measurement of prompt D^0 meson azimuthal anisotropy in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. ***PHYS REV LETT*** **120**:20 202301-1-17 (2018)
5. Sirunyan AM et al. (CMS Collaboration) [2259 authors]: Search for the X (5568) State Decaying into $B_s^0\pi^{\pm}$ Bs0 π± in proton-proton collisions at $\sqrt{s}$ = 8 TeV. ***PHYS REV LETT*** **120**:20 202005/1-17 (2018)
6. Sirunyan AM et al. (CMS Collaboration) [2290 authors]: Search for heavy neutral leptons in events with three charged leptons in proton-proton collisions at $\sqrt{s}$ = 13 TeV. ***PHYS REV LETT*** **120**:22 221801/1-20 (2018)
7. Sirunyan AM et al. (CMS Collaboration) [2301 authors]: Search for narrow resonances in the *b*-tagged dijet mass spectrum in proton-proton collisions at $\sqrt{s}$ = 8 TeV. ***PHYS REV LETT*** **120**:20 201801/1-19 (2018)
8. Sirunyan AM et al. (CMS Collaboration) [2229 authors]: Suppression of excited Υ states relative to the ground state in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. ***PHYS REV LETT*** **120**:14 142301/1-17 (2018)
9. Sirunyan AM et al. (CMS Collaboration) [2258 authors]: Measurement of the splitting function in *pp* and Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. ***PHYS REV LETT*** **120**:14 142302/1-17 (2018)
10. Sirunyan AM et al. (CMS Collaboration) [2301 authors]: Observation of $t\bar{t}H$ production. ***PHYS REV LETT*** **120**:23 231801/1-17 (2018)
11. Sirunyan AM et al. (CMS Collaboration) [2290 authors]: Search for physics beyond the standard model in events with high-momentum Higgs bosons and missing transverse momentum in proton-proton collisions at 13 TeV. ***PHYS REV LETT*** **120**:24 241801/1-17 (2018)
12. Sirunyan AM et al. (CMS Collaboration) [2228 authors]: Observation of correlated azimuthal anisotropy Fourier harmonics in *pp* and *p* + Pb collisions at the LHC. ***PHYS REV LETT*** **120**:9 092301/1-17 (2018)
13. Sirunyan AM et al. (CMS Collaboration) [2265 authors]: Observation of electroweak production of same-sign W boson pairs in the two jet and two same-sign lepton final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV. ***PHYS REV LETT*** **120**:8 081801/1-17 (2018)

14. Sirunyan AM et al. (CMS Collaboration) [2263 authors]: Inclusive search for a highly boosted Higgs boson decaying to a bottom quark-antiquark pair. ***PHYS REV LETT* 120**:7 071802/1-18 (2018)
15. Sirunyan AM et al. (CMS Collaboration) [2283 authors]: Observation of medium-induced modifications of jet fragmentation in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV using isolated photon-tagged jets. ***PHYS REV LETT* 121**:24 242301/1-18 (2018)
16. Sirunyan AM et al. (CMS Collaboration) [2303 authors]: Search for leptoquarks coupled to third-generation quarks in proton-proton collisions at $\sqrt{s}$ = 13 TeV. ***PHYS REV LETT* 121**:24 241802/1-19 (2018)
17. Sirunyan AM et al. (CMS Collaboration) [2285 authors]: Observation of Higgs boson decay to bottom quarks. ***PHYS REV LETT* 121**:12 121801/1-20 (2018)
18. Sirunyan AM et al. (CMS Collaboration) [2305 authors]: Evidence for the associated production of a single top quark and a photon in proton-proton collisions at $\sqrt{s}$ = 13 TeV. ***PHYS REV LETT* 121**:22 221802/1-18 (2018)
19. Sirunyan AM et al. (CMS Collaboration) [2291 authors]: Search for vector-like T and B quark pairs in final states with leptons at $\sqrt{s}$ = 13 TeV. ***J HIGH ENERGY PHYS* 2018**:8 177/1-51 (2018)
20. Sirunyan AM et al. (CMS Collaboration) [2305 authors]: Search for additional neutral MSSM Higgs bosons in the tau tau final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV. ***J HIGH ENERGY PHYS* 2018**:9 007/1-60 (2018)
21. Sirunyan AM et al. (CMS Collaboration) [2304 authors]: Search for resonant pair production of Higgs bosons decaying to bottom quark-antiquark pairs in proton-proton collisions at 13 TeV. ***J HIGH ENERGY PHYS* 2018**:8 152/1-38 (2018)
22. Sirunyan AM et al. (CMS Collaboration) [2290 authors]: Search for disappearing tracks as a signature of new long-lived particles in proton-proton collisions at $\sqrt{s}$ = 13 TeV. ***J HIGH ENERGY PHYS* 2018**:8 016/1-40 (2018)
23. Sirunyan AM et al. (CMS Collaboration) [2258 authors]: Measurement of the cross section for top quark pair production in association with a W or Z boson in proton-proton collisions at $\sqrt{s}$ = 13 TeV. ***J HIGH ENERGY PHYS* 2018**:8 011/1-50 (2018)
24. Sirunyan AM et al. (CMS and TOTEM Collaborations) [2382 authors]: Observation of proton-tagged, central (semi)exclusive production of high-mass lepton pairs in pp collisions at 13 TeV with the CMS-TOTEM precision proton spectrometer. ***J HIGH ENERGY PHYS* 2018**:7 153/1-45 (2018)
25. Sirunyan, AM et al. (CMS Collaboration) [2282 authors]: Measurement of the inelastic proton-proton cross section at $\sqrt{s}$ = 13 TeV. ***J HIGH ENERGY PHYS* 2018**:7 161/1-33 (2018)

See also: R-B: ALICE Collaboration (Varga-Kőfaragó M), R-D PHENIX Collaboration 13