

## R-G. “Lendület” innovative gaseous detector development



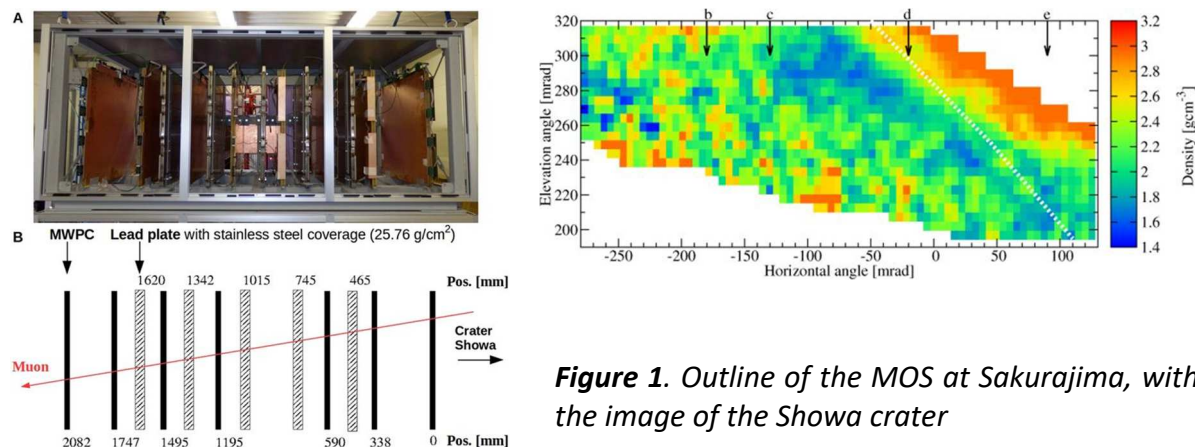
“Momentum” Research Team

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The concluded “Momentum” grant support from the HAS has been converted to a permanent funding starting from this year. The group has concluded commitment to the CERN ALICE TPC Upgrade experiment, as well as completed two deliverables for the H2020 grants BrightnESS and AIDA2020, respectively. An interesting test of General Relativity has been formulated. Using detectors developed by the group, an active volcano imaging has been performed, in collaboration with Tokyo University and the NEC company.

**Contributions to CERN ALICE TPC Upgrade Collaboration.** — The activities of the group in the TPC Upgrade Collaboration has been concluded, with about 400 large size GEM foils processed in Budapest. The Advanced Quality Assurance testing site which was established, is the second step of the TPC construction after production (at CERN), and the foils were forwarded to Germany and the USA.

**Imaging with cosmic muons.** — The application of cosmic muons for large-scale imaging has been a research direction in the group in the previous years. An important application for cosmic muons detectors, developed in the last years by the group, is imaging the interior of volcanos. This direction was pursued by Japanese and various European groups. Gaseous tracking detectors, and in our case, a specific type of a Multi-Wire-Proportional-Chamber (MWPC) developed by our group, are highly competitive with the traditional scintillators in terms of cost, weight and power consumption. The detector system has been installed by the Sakurajima volcano in Japan (southern island, see Fig 1), to demonstrate the true applicability and sufficiently low level of background, and to gain experience for the future developments. Presently 4 square meter sensitive area is installed, the largest of its kind in the world, with the results published in Scientific Reports. The japanese NEC company has licensed the

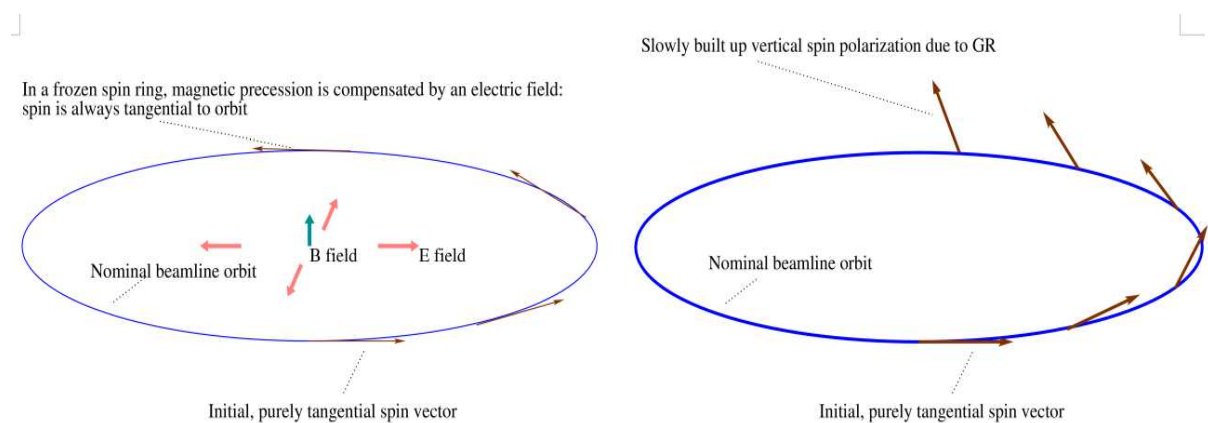


**Figure 1.** Outline of the MOS at Sakurajima, with the image of the Showa crater

muography observation system (MOS) for research purposes, and continued its licensing rights and funding also this year.

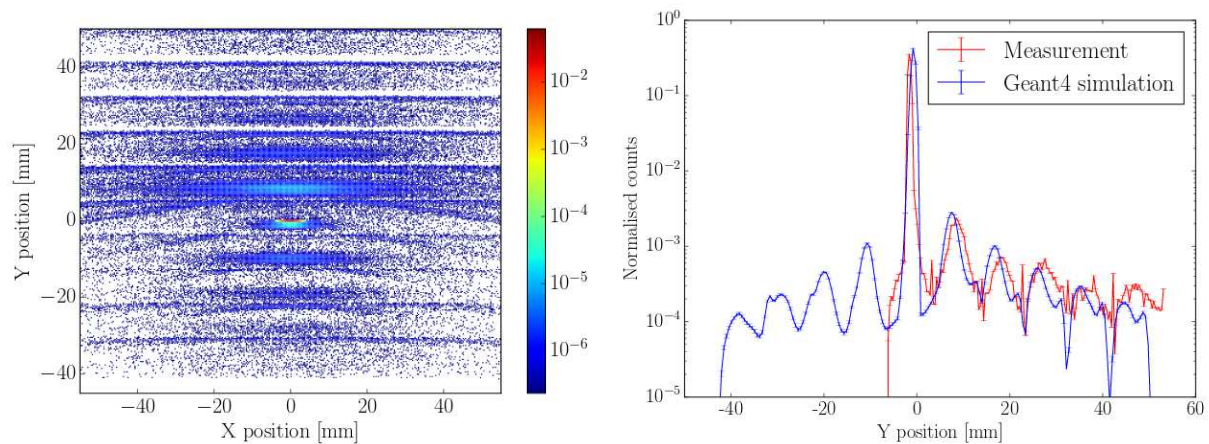
**General Relativity effects in storage ring.** — A mechanism was proposed in order to perform a General Relativity (GR) experiment using spin-polarized particle beams. The principle of the experiment is the following.

The magnetic moment anomaly, also called  $g-2$ , of particles are measured in magnetic storage rings: in a homogeneous magnetic field, the particle spin precesses in the orbital plane at a rate, which is proportional to the magnetic moment anomaly. The electric dipole moment (EDM) of particles are measured in combined magnetic and electric storage rings in which the magnetic spin precession is compensated by a suitably chosen electric field, and such settings are therefore called frozen spin storage rings (Fig.2, left panel). If an EDM of a particle existed, it would torque the spin out of the orbital plane in a frozen spin ring setting. In our paper it was shown that due to General Relativity, Earth's gravitational field also would torque the particle spin out of the orbital plane, similar to an EDM effect (Fig.2, right panel). Therefore, it was proposed to consider the optimization of EDM rings in such a way that the pertinent GR effect can also be detected. This would provide an unusual test of GR in laboratory circumstances: for microscopic particles, at relativistic speeds, along non-geodesic (forced) trajectories, and the tensorial nature of GR would be at test, not merely the gravitational drag.



**Figure 2.** .Frozen spin muon experiment, and precession effect due to General Relativity effect

**Investigation of neutron scattering.** — In order to quantify the neutron scattering in the ESS Multi-Blade detector, highly detailed simulations were performed and compared to measurements, shown in Fig.3. This study has revealed that the scattering (causing background and degradation of image contrast) is extremely small, matching the ESS requirements.



**Figure 3.** Scattered neutron position for the Multi Blade detector (in the plane vertical to the beam, left panel), and comparison of the simulations to actual measurement (right panel)

## Grants

ADIA-2020 (Advanced European Infrastructures for Detectors at Accelerators), H2020 support (D. Varga, 2015-2018)

BrightnESS (Research Infrastructure for ESS), H2020 support (D. Varga, 2015 - 2018)

NKFIH-FK 123959, (A. László, 2017-2020)

Japanese-Hungarian Tét, Serbian-Hungarian Tét, (2017-2019)

## International cooperation

CERN NA61 Collaboration (A. László), CERN RD51 Collaboration (D. Varga), CERN ALICE TPC Upgrade Collaboration (D. Varga, G. Hamar, Á. Gera)

Earthquake Research Institute, Tokyo Uni., Muography for Volcano Monitoring (L. Oláh, G. Hamar, Á. Gera, G. Nyitrai, D. Varga)

University of Novi Sad (Serbia), Novel Imaging Methods (G. Hamar, D. Varga)

## Publications

### Articles

1. Galgóczi G, Kanaki K, Piscitelli F, Kittelmann T, Varga D, Hall-Wilton R: Investigation of neutron scattering in the Multi-Blade detector with Geant4 simulations. *J INSTRUM* **13**: P12031/1-17 (2018)
2. László A, Zimborás Z: Quantification of GR effects in muon g-2, EDM and other spin precession experiments. *CLASSICAL QUANT GRAV* **35**:17 175003/1-29 (2018)
3. Mauri G, Messi F, Anastasopoulos M, Arnold T, Glavic A, Høglund C, Ilves T, Higuera IL, Pázmándi P, Raspino D, Robinson L, Schmidt S, Svensson P, Varga D, Hall-Wilton R, Piscitelli F: Neutron reflectometry with the Multi-Blade B-10-based detector. *P ROY SOC A-MATH PHY* **474**:2216 20180266/1-16 (2018)
4. Oláh L, Tanaka HKM, Ohminato T, Varga D: High-definition and low-noise muography of the Sakurajima volcano with gaseous tracking detectors. *SCI REP-UK* **8**:1 3207/1-13 (2018)

5. Oláh L, Tanaka HKM, Hamar G, Varga D: Investigation of the limits of high-definition muography for observation of Mt Sakurajima. *PHILOS T ROY SOC A* **377**:2137 20180135/1-14 (2018)
6. Piscitelli F, Mauri G, Messi F, Anastasopoulos M, Arnold T, Glavic A, Hoglund C, Ilves T Higuera IL, Pázmándi P, Raspino D, Robinson L, Schmidt S, Svensson P, Varga D, Hall-Wilton R: Characterization of the Multi-Blade 10B-based detector at the CRISP reflectometer at ISIS for neutron reflectometry at ESS. *J INSTRUM* **13**: P05009/1-27 (2018)

#### **Conference proceedings**

7. Abbaneo D et al. incl. Bencze G, Endrőczi G [158 authors]: A novel application of Fiber Bragg Grating (FBG) sensors in MPGD. In: *4<sup>th</sup> International Conference on Micro Pattern Gaseous Detectors (MPGD 2015), Trieste, Italy, October 12-15, 2015*. Eds: Dalla Torre S, Gobbo B, Levorato S, Ropelewski L Tassarotto F, *EPJ WEB CONF* **174**: 03002/1-4 (2018)
8. Abbaneo D et al. incl. Bencze G, Endrőczi G [150 authors]: Quality control for the first large areas of triple-GEM chambers for the CMS endcaps. In: *4<sup>th</sup> International Conference on Micro Pattern Gaseous Detectors (MPGD 2015), Trieste, Italy, October 12-15, 2015*. Eds: Dalla Torre S, Gobbo B, Levorato S, Ropelewski L Tassarotto F, *EPJ WEB CONF* **174**: 03003/1-4 (2018)
9. Hamar G, Torre SD, Dasgupta SS, Levorato S, Tassarotto F, Varga D: Investigation of the microstructure of Thick-GEMs with single photo electrons. In: *4<sup>th</sup> International Conference on Micro Pattern Gaseous Detectors (MPGD 2015), Trieste, Italy, October 12-15, 2015*. Eds: Dalla Torre S, Gobbo B, Levorato S, Ropelewski L Tassarotto F, *EPJ WEB CONF* **174**: 03006/1-3 (2018)
10. László A: Possible alternative mechanism to SUSY: Conservative extensions of the Poincaré group. In: *Quantum Theory and Symmetries with Lie Theory and Its Applications in Physics Volume 2*. Ed: Dobrev V, Springer Proceedings in Mathematics & Statistics, vol 255. Springer, Singapore, pp.353-362
11. Messi F, Piscitelli F, Mauri G, Anastasopoulos, M. ; Fissum, K. ; Hall-Wilton, R. ; Hoglund, C. ; Kanari, K. ; Karnickis, E. ; Khaplanov, A. Pázmándi P, Perrey H, Robinson L, Scherzinger J, Varga D: Gamma- and fast neutron- sensitivity of 10B- based neutron detectors at ESS. In: *Proc. 2017 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC 2017), Atlanta, United States, 21 Oct. 2017-28 Oct. 2017*. (2018) 8533095 2p

**See also: R-B ALICE Collaboration (Boldizsár L, Hamar G, Oláh L, Varga D)**

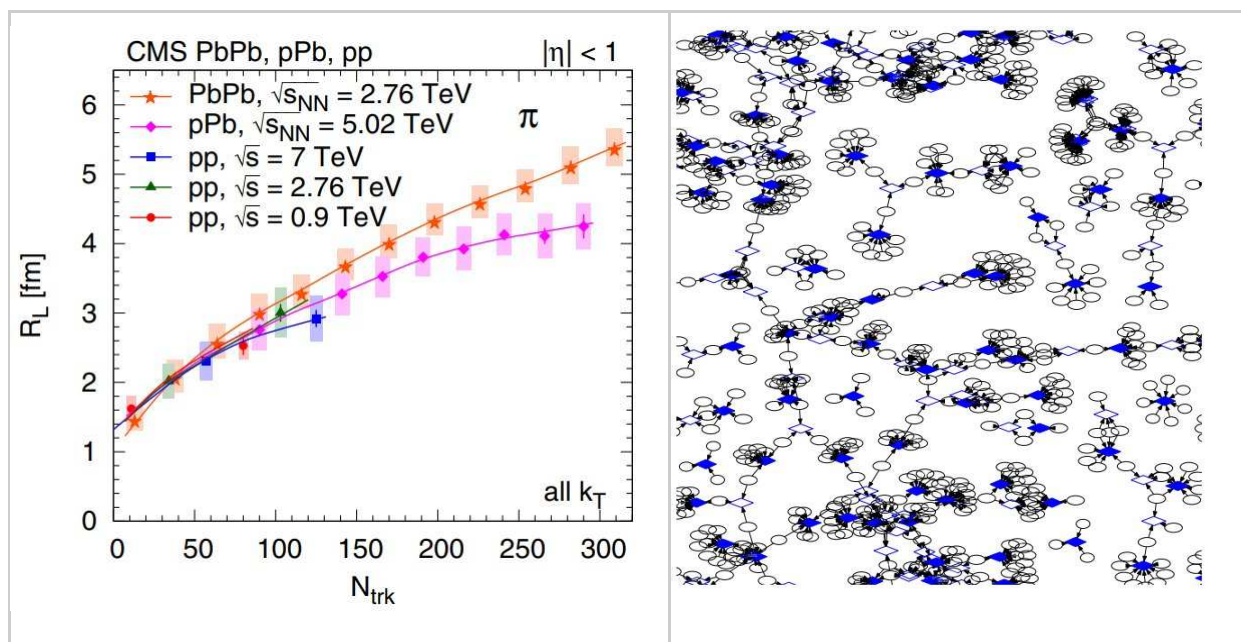
## R-F. Hadron physics

**Ferenc Siklér**, Gyula Bencédi, Zoltán Fodor<sup>A</sup>, Endre Futó<sup>A</sup>, Sándor Hegyi, Gábor Jancsó<sup>A</sup>, József Kecskeméti<sup>A</sup>, Gabriella Pálfa<sup>E</sup>, Zoltán Seres<sup>A</sup>, Mónika Varga-Kófaragó, Róbert Vértesi



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.



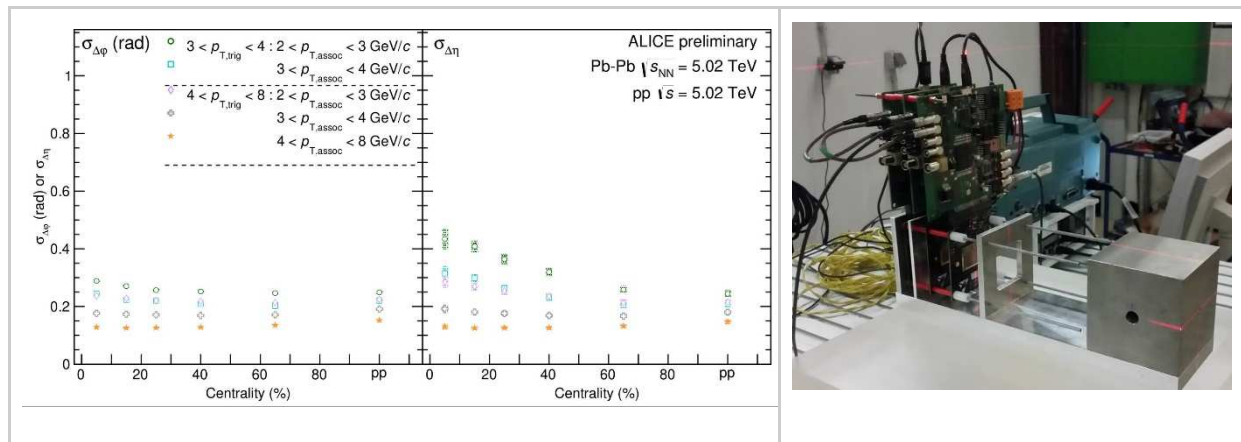
**Figure 1.** Left: Track-multiplicity dependence of the two-dimensional pion radius parameters obtained from fits for all collision systems studied. Lines are drawn to guide the eye.. Right: A small fraction of the bipartite graph of hits (ellipses) and track candidates (diamonds) for an event with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

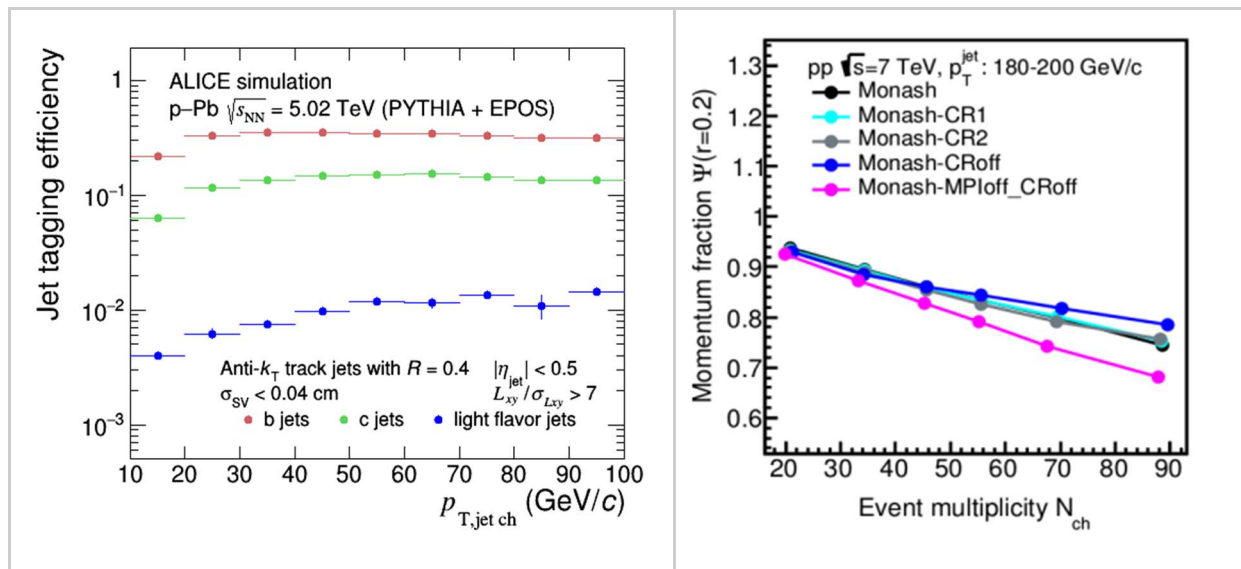
**Medical applications of high-energy detector technologies.** — We have joined the development of a sampling calorimeter to be used for imaging in cancer therapy. Cancer tumors can be killed by irradiating them by photons or hadrons. In the case of the treatment by hadrons, the energy deposition and 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  $\sqrt{s} = 13$  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 sphericity 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 sphericity. The hadron yields scale with charged-particle multiplicity across different  $\sqrt{s}$  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 27<sup>th</sup> 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 appearances 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  $\chi_{b1}(3P)$  and  $\chi_{b2}(3P)$  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  $B_s^0 \pi^\pm$   $B_s^0 \pi^\pm$  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  $\Upsilon$  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  $t\bar{t}\bar{H}$  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**

## R-H. Standard model and new physics

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**Physics analyses and theoretical work.** — The group has contributed to bringing an inclusive search for supersymmetry with boosted objects to publication stage using proton-proton collision data that corresponded to an integrated luminosity of  $35.9 \text{ fb}^{-1}$ , taken prior to 2017. Exclusion limits on the gluino mass were extended to 2 TeV, while on the stop quark mass to 1.14 TeV. Profiting from the opportunity that the LHC has gone into a more than two-year long shutdown, we have started to reprocess the data we took with the new pixel detector in the last two years using improved calibration and detector description models for further analysis in order to approximately double the analysis sensitivity. We provided a member for the Publication Committee of the CMS Experiment at CERN and played an important role in publishing CMS results of low-x Quantum Chromodynamics (QCD) studies. We hold leadership positions, a group convenor and a deputy project manager, in the CMS Tracker project.

The stable operation of the T2\_HU\_Budapest grid site continued in 2018. Our site is used extensively by the entire CMS collaboration including our group for reconstructing collision data in physics analyses. The disk capacity committed to CMS has increased to 1 PB.

We proposed a general concept of bosonic operator orderings and generalized Wick's theorem transforming any ordering into any other one. We pointed out how Planckian scale challenges the validity of the massive body Schrödinger equation.

**Work on instrumentation.** — The group created a test setup for developing the CMS Phase 2 Upgrade Inner Tracker data-acquisition system, and started to develop firmware in order to calibrate and read out the new sensors that are being designed for the upgraded detector. We have constructed a test-beam telescope to be used for the high rate tests of the new Phase 2 Tracker chips; commissioned the telescope and took the first data using the Phase 2 Outer Tracker chip prototypes at the Super Proton Synchrotron (SPS) at CERN.

The SPS Diffuser designed and constructed by our group was successfully installed and tested in the CERN SPS accelerator, and delivered the expected performance in terms of loss reduction. The conceptual design of a high-field extraction septum magnet for the Future Circular Collider was completed, which uses the combination of a superconducting magnet and a passive superconducting shield.

**Outreach.** — An education program was organized by Wigner RCP at CERN with the leadership of our group: the annual Hungarian Teachers Programme (18-25 August 2018) for 21 physics teachers. For the teachers we organized a meeting on December 8 at Wigner RCP with the lecturers. We also participated in the organization of the annual Hands-on Particle Physics Master-classes on two occasions with 22 high-school students attending each session. We have also participated in the organization of two scientific seminars on particle physics for the

Celebration of Hungarian Science on particle physics at the Hungarian Academy of Sciences and at the Roland Eötvös University. In addition to conference talks and university teaching, many popular lectures were given by our group.

## Grants

NKFIH K-124850 Consortial assoc.: The Standard Model and beyond: Searching for New Physics with the CERN LHC CMS experiment (V. Veszprémi, Cs. Hajdu, D. Horváth, T. Vámi, 2017-2021)

NKFIH K-124945 Research and development of novel technologies for particle accelerators (D. Barna, 2017-2021)

Pallas Athene Foundations HTP-2018 (D. Horváth)

FQXi-MGA-1707 Gravity related modifications of non-relativistic quantum theory (L. Diósi, 2017)

## International cooperation

CMS Collaboration (over 200 institutes)

University of Tokyo, Japan

RIKEN, Wako, Japan

Max-Planck-Institut für Quantenoptik, Germany

Università di Brescia & Istituto Nazionale di Fisica Nucleare, Italy

## Publications

### Articles

1. Diósi L: Wick theorem for all orderings of canonical operators. *J PHYS A-MATH THEOR* **51**:36 365201/1-6 (2018)
2. Diósi L: Fundamental irreversibility: Planckian or Schrödinger-Newton? *ENTROPY* **20**:7 1-5 (2018)
3. Giunchi G, Barna D, Bajas H, Brunner K, Nemet A, Petrone C: Relaxation phenomena in a long MgB<sub>2</sub> tube subjected to transverse magnetic field, at 4.2 K. *IEEE T APPL SUPERCON* **28**:4 1-5 (2018)

### Others

4. Horváth D: Új felfedezések a CERN Nagy Hadronütköztetőjénél: furcsa részecskék (New inventions at the LHC of CERN: strange particles, in Hungarian). *FIZIKAI SZEMLE* **68**:7-8 219-224 (2018)
5. Horváth D, Trócsányi Z: Müon: mi az és mire jó? (Muon: what is it and what good is it?, in Hungarian) *FIZIKAI SZEMLE* **68**:5 147-153 (2018)
6. Horváth D: Magyar tanárok és diákok részecskefizikai oktatása a Cern-ben (Hungarian teachers and students learn particle physics at CERN, in Hungarian). *FIZIKAI SZEMLE* **68**:4 124-130 (2018)

### **ATLAS collaboration**

Due to the vast number of publications of the large collaborations in which the research group participated in 2018, here we list only a short selection of appearances in journals with the highest impact factor. Wigner author in the collaboration is József Tóth.

1. Aaboud M et al. (ATLAS Collaboration) [2892 authors]: Search for low-mass dijet resonances using trigger-level jets with the ATLAS detector in pp collisions at  $\sqrt{s} = 13$  TeV. **PHYS REV LETT** **121**:8 081801/1-20 (2018)
2. Aaboud M et al. (ATLAS Collaboration) [2886 authors]: Measurement of the soft-drop jet mass in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector. **PHYS REV LETT** **121**:9 092001/1-21 (2018)
3. Aaboud M et al. (ATLAS Collaboration) [2870 authors]: Search for the decay of the Higgs boson to charm quarks with the ATLAS experiment. **PHYS REV LETT** **120**:21 211802/1-20 (2018)
4. Aaboud M et al. (ATLAS Collaboration) [2887 authors]: Search for a structure in the  $B_s^0 \pi^\pm$  invariant mass spectrum with the ATLAS experiment. **PHYS REV LETT** **120**:20 202007/1-19 (2018)
5. Aaboud M et al. (ATLAS Collaboration) [authors]: Search for high-mass resonances decaying to  $\tau\nu$  in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector. **PHYS REV LETT** **120**:16 161802/1-20 (2018)
6. Aaboud M. et al. (ATLAS Collaboration) [2929 authors]: Combination of the searches for pair-produced vectorlike partners of the third-generation quarks at  $\sqrt{s} = 13$  TeV with the ATLAS detector. **PHYS REV LETT** **121**:21 211801/1-20 (2018)
7. Aaboud M. et al. (ATLAS Collaboration) [2924 authors]: Search for resonant and nonresonant Higgs boson pair production in the  $b\bar{b}\tau^+\tau^-$  decay channel in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector. **PHYS REV LETT** **121**:19 191801/1-24 (2018)
8. Aaboud et al. (ATLAS Collaboration) [2900 authors]: Search for supersymmetry in final states with charm jets and missing transverse momentum in 13 TeV pp collisions with the ATLAS detector. **J HIGH ENERGY PHYS** **2018**:9 050/1-44 (2018)
9. Aaboud M et al. (ATLAS Collaboration) [2913 authors]: Measurements of b-jet tagging efficiency with the ATLAS detector using  $t\bar{t}$  events at  $\sqrt{s} = 13$  TeV. **J HIGH ENERGY PHYS** **2018**:8 089/1-47 (2018)
10. Aaboud M et al. (ATLAS Collaboration) [2869 authors]: Search for flavour-changing neutral current top-quark decays  $t \rightarrow qZ$  in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector. **J HIGH ENERGY PHYS** **2018**:7 176/1-41 (2018)
11. Aaboud M et al. (ATLAS Collaboration) [2870 authors]: Search for pair production of heavy vector-like quarks decaying into high- $p_T$  W bosons and top quarks in the lepton-plus-jets final state in pp collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector. **J HIGH ENERGY PHYS** **2018**:8 048/1-41 (2018)
12. Aaboud M et al. (ATLAS Collaboration) [2903 authors]: Search for exclusive Higgs and Z boson decays to  $\phi\gamma$  and  $\rho\gamma$  with the ATLAS detector. **J HIGH ENERGY PHYS** **2018**:7 127/1-37 (2018)
13. Aaboud M et al. (ATLAS Collaboration) [2902 authors]: Search for pair production of up-type vector-like quarks and for four-top-quark events in final states with multiple b-jets with the ATLAS detector. **J HIGH ENERGY PHYS** **2018**:7 089/1-68 (2018)

14. Aaboud M et al. (ATLAS Collaboration) [2900 authors]: Search for Higgs boson decays to beyond-the-Standard-Model light bosons in four-lepton events with the ATLAS detector at  $\sqrt{s} = 13$  TeV. **J HIGH ENERGY PHYS 2018:6 166/1-51 (2018)**
15. Aaboud M et al. (ATLAS Collaboration) [2885 authors]: Search for top-squark pair production in final states with one lepton, jets, and missing transverse momentum using  $36 \text{ fb}^{-1}$  of  $\sqrt{s} = 13$  TeV  $pp$  collision data with the ATLAS detector. **J HIGH ENERGY PHYS 2018:6 108/1-96 (2018)**
16. Aaboud M et al. (ATLAS Collaboration) [2874 authors]: Search for supersymmetry in final states with missing transverse momentum and multiple b-jets in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector. **J HIGH ENERGY PHYS 2018:6 107/1-58 (2018)**
17. Aaboud M et al. (ATLAS Collaboration) [2874 authors]: Search for long-lived charginos based on a disappearing-track signature in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector. **J HIGH ENERGY PHYS 2018:6 022/1-48 (2018)**
18. Aaboud M et al. (ATLAS Collaboration) [2903 authors]: Measurement of inclusive jet and dijet cross-sections in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector. **J HIGH ENERGY PHYS 2018:5 195/1-47 (2018)**
19. Aaboud M et al. (ATLAS Collaboration) [2880 authors]: Measurement of differential cross sections and  $W^+/W^-$  cross-section ratios for  $W$  boson production in association with jets at  $\sqrt{s} = 8$  TeV with the ATLAS detector. **J HIGH ENERGY PHYS 2018:5 077/1-60 (2018)**
20. Aaboud M et al. (ATLAS and CMS Collaborations) [5098authors]: Combination of inclusive and differential  $t\bar{t}$  charge asymmetry measurements using ATLAS and CMS data at  $\sqrt{s} = 7$  and 8 TeV. **J HIGH ENERGY PHYS 2018:4 033/1-68 (2018)**
21. Aaboud M et al. (ATLAS Collaboration) [2907 authors]: Search for heavy resonances decaying into a  $W$  or  $Z$  boson and a Higgs boson in final states with leptons and  $b$ -jets in  $36 \text{ fb}^{-1}$  of  $\sqrt{s} = 13$  TeV  $pp$  collisions with the ATLAS detector. **J HIGH ENERGY PHYS 2018:3 174/1-53 (2018)**
22. Aaboud M et al. (ATLAS Collaboration) [2906 authors]: Measurement of the Higgs boson coupling properties in the  $H \rightarrow ZZ^* \rightarrow 4\ell$  decay channel at  $\sqrt{s} = 13$  TeV with the ATLAS detector. **J HIGH ENERGY PHYS 2018:3 095/1-60 (2018)**
23. Aaboud M et al. (ATLAS Collaboration) [2904 authors]: Search for  $W W/W Z$  resonance production in  $\ell\nu qq$  final states in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector. **J HIGH ENERGY PHYS 2018:3 042/1-45 (2018)**
24. Aaboud M et al. (ATLAS Collaboration) [2893 authors]: Searches for heavy  $ZZ$  and  $ZW$  resonances in the  $\ell\ell qq$  and  $\nu\nu qq$  final states in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector. **J HIGH ENERGY PHYS 2018:3 009/1-53 (2018)**
25. Aaboud M et al. (ATLAS Collaboration) [2904 authors]: Search for dark matter and other new phenomena in events with an energetic jet and large missing transverse momentum using the ATLAS detector. **J HIGH ENERGY PHYS 2018:1 126/1-53 (2018)**

**See also: R-F CMS Collaboration (Hajdú C, Horváth D, Vámi T)**