R-H. Hadron physics

Wigner research group

Ferenc Siklér, László Boldizsár, Zoltán Fodor, Endre Futó, Sándor Hegyi, Gábor Jancsó, József Kecskeméti, Krisztián Krajczár, András László, Andrew John Lowe, Gabriella Pálla, Sona Pochybová, Zoltán Seres, János Sziklai, Anna Julia Zsigmond

Quarks and gluons. — Particle physics is our attempt to understand the basic constituents of our world. What is it made of? What are the interactions between the building blocks of matter? Symmetries and gauge theories provide a coherent framework for the electromagnetic, weak, and strong interactions. The last of these, the strong force, acts between quarks and gluons and is described by the theory of quantum chromodynamics (QCD). In most circumstances, it is difficult to perform accurate calculations with QCD because the theory is strongly coupled and consequently has a non-perturbative nature. Results from the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory, later reinforced by those from the Large Hadron Collider (LHC) at CERN, showed unexpected phenomena: suppression of hadrons with high transverse momentum (p_T), and weakening of back-to-back jet correlations. These results indicated that quark matter does not behave like a quasi-ideal state of free quarks and gluons, but like an almost perfect dense fluid.

Our research group studies collisions of nucleons and nuclei, performs basic and advanced measurements, and tests theoretical ideas. We participate in several complementary experiments, both in data taking and physics analysis. Hadron-nucleus collisions are important for the interpretation of the properties of nucleus-nucleus collisions and to uncover the partonic structure of nuclear matter at low fractional momenta. Moreover, these collisions are interesting in themselves for answering questions such as: what is the validity of multiple-collision Glauber-model? Can we get a better understanding of the hadronisation process? This topic is of particular interest for many theorist colleagues in Hungary and worldwide. The energy range (several TeV) of the LHC enables the use of new and more powerful signals and markers. It is also a region that is relevant for understanding cosmic radiation and atmospheric showers. In the past year several members of our research group participated in data taking and calibration of new pPb data at both the Super Proton Synchrotron (SPS) at CERN and at the LHC: data was collected by the NA61 experiment at the SPS at $\sqrt{s}$ = 17 GeV per nucleon pair, and by the ALICE and CMS experiments at the LHC at $\sqrt{s}$ = 5.02 TeV per nucleon pair. The large amount of collected data allowed us to perform the studies proposed at the beginning of the year.

Collision centrality. — To see how much of a heavy ion participates in a collision, a key parameter called centrality must be determined. Centrality is proportional to the number of inelastic proton-nucleon collisions. An estimate of this number is needed when quantities observed in pPb collisions are compared to pp and PbPb results. In the case of heavy-ion collisions, several multiplicity or energy measures are appropriate. They change monotonically with centrality and have a strong correlation due to the high number of particles produced. For pPb collisions, the problem is more complicated: the use of the foregoing methods would result in various biases due to the small number of hadrons created. Our studies show that the number of collisions can be estimated with small bias by measuring the total energy of the produced particles that are projected in the direction of the fragmented Pb nucleus. This finding comes from optimizing the weighted sum of the number of particles produced, where the weights depend on the pseudorapidity of the particle. The best weights are non-zero only for the outer rings of the CMS forward hadronic calorimeter (4 < η < 5). The corresponding averages and standard deviations were calculated using a Glauber-model (Fig. 1).

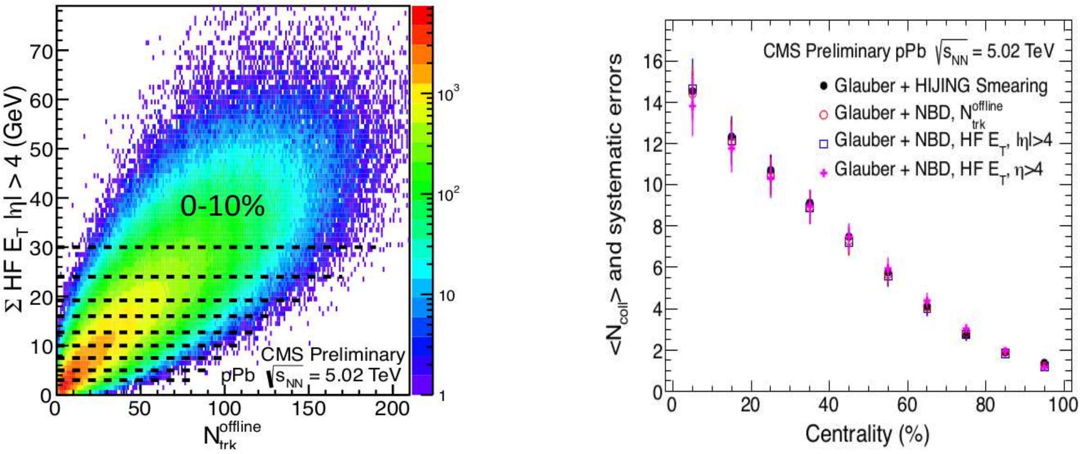
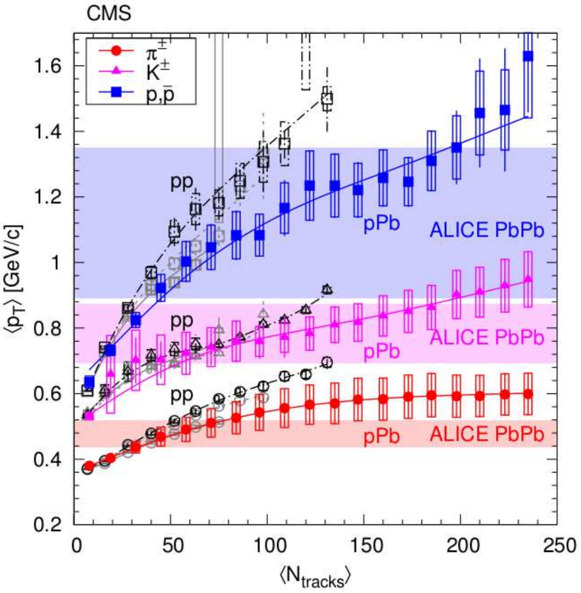


***Figure 1: Left:** The correlation between the number of detected tracks ($N_{trk}^{offline}$) and the energy in the forward calorimeters (E_T) in inelastic pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. **Right:** The estimated number of collisions $\langle N_{coll}\rangle$ and its uncertainty in 10% wide centrality classes. The classifications are based on several measures of centrality.*

In the case of NA61 we can directly detect the slow nucleons (protons and nuclei) using a time projection chamber filled with a special gas mixture. It performs simultaneous range and ionization measurements on each charged particle enabling particle identification and momentum measurement at very low momenta. By counting the number of identified protons, the number of collisions can be estimated.

Momentum distribution of identified particles. — Charged particles created in collisions of nucleons and nuclei are observed by different kinds of tracking detectors (a gas chamber in NA61 and ALICE; a silicon tracker in CMS). With the help of sophisticated algorithms we can reconstruct their trajectories. Simple measures such as the pseudorapidity density can already be directly compared with those from event generators and theoretical calculations. We have measured the spectra of identified charged hadrons produced in pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV using the CMS detector. Charged pions, kaons, and protons were identified from the energy deposited in the silicon tracker and other track information. The yield and spectra of identified hadrons have been studied as a function of the charged particle multiplicity of the event in the range |η| < 2.4. The p_T spectra are well described by fits with the Tsallis-Pareto parametrization. (This observation stresses the role of non-extensive thermodynamics.) The ratios of the yields of oppositely charged particles are close to unity, as expected at mid-rapidity for collisions at multi-TeV energies. The average p_T is found to increase with particle mass and with charged particle multiplicity. The EPOS LHC event generator reproduces several features of the measured distributions. This is a significant improvement from the previous version, which is attributed to a new viscous hydrodynamic treatment of the produced particles. Other studied generators (AMPT, HIJING) predict steeper p_T distributions and much smaller p_T than found in data, as well as substantial deviations in the p/π ratios. Combined with similar results from pp collisions, the track multiplicity dependence of the average transverse momentum and particle ratios indicate that particle production at LHC energies is strongly correlated with event particle multiplicity in both pp and pPb interactions (Fig. 2 left). For low track multiplicity, pPb collisions appear similar to pp collisions. At high multiplicities, the average p_T of particles from pPb collisions with a charged particle multiplicity of N_{tracks} (in |η| < 2.4) is similar to that for pp collisions with 0.55 × N_{tracks}. Both the highest-multiplicity pp and pPb interactions yield higher p_T than seen in central PbPb collisions.



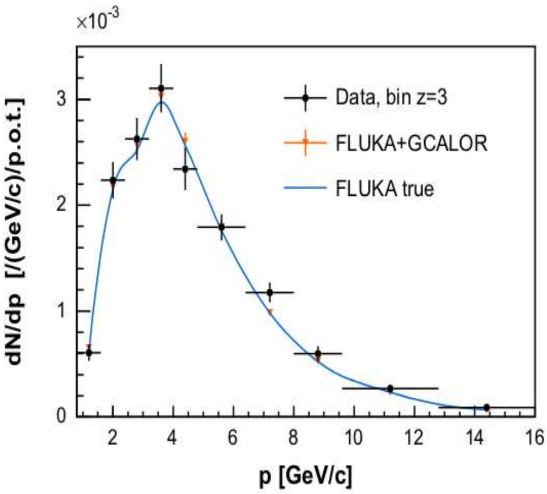


Figure 2: Left: *Average transverse momentum <p_T> of identified charged hadrons (pions, kaons, protons) as a function of the corrected track multiplicity for |η| < 2.4, for pp collisions (open symbols) at several energies, and for pPb collisions (filled symbols) at $\sqrt{s_{NN}}$ = 5.02 TeV. Lines are drawn to guide the eye. The ranges of <p_T> values measured by ALICE in various centrality PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV are indicated with horizontal bands.* ***Right:*** *Spectra of outgoing positively charged pions normalized to the momentum bin size and number of protons on target in the angular interval 40–100 mrad for the central longitudinal bins. Error bars correspond to the sum in quadrature of statistical and systematic uncertainties. Smooth curves show the prediction of the FLUKA simulation.*

Data from hadron-nucleus collisions are valuable for other areas such as atmospheric showers, and consequently for neutrino physics. The T2K long-baseline neutrino oscillation experiment in Japan needs precise predictions of the initial neutrino flux. We have shown that the highest precision can be reached based on detailed measurements of hadron emission from the same target as used by T2K exposed to a proton beam of the same kinetic energy of 30 GeV. The corresponding data were recorded by the NA61 experiment using a replica of the graphite target (Fig. 2 right). In the global framework of accelerator-based neutrino oscillation experiments, it has been demonstrated that high quality measurements can be performed with the NA61 setup. They could lead to a significant reduction of systematic uncertainties on the neutrino flux predictions in long-baseline neutrino experiments.

Momentum distribution at high momenta. — In the presence of the hot and dense medium created in heavy-ion collisions, the yield of high momentum particles is suppressed compared to independent superpositions of nucleon-nucleon collisions. What is the situation in pPb collisions? Do we also see a suppression, or something else? We have measured the spectra of charged particles and the nuclear modification factor for pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV using data taken by the CMS experiment. The results were normalized to a pp reference spectrum derived from a scaled combination of 0.9, 2.76, and 7 TeV pp spectra measured by CMS, as well as 0.63, 1.8, and 1.96 TeV pp spectra measured by CDF. The nuclear modification factor R_{pPb} shows a steady rise to unity until a $p_T \approx 4$ GeV/c, is then constant until approximately 20 GeV/c, and then increases at higher p_T reaching a value around 1.3–1.4 at 70 GeV/c (Fig. 3 left). It is extremely interesting that the rise above unity of R_{pPb} is in the range of p_T where parton anti-shadowing is predicted (with momentum fractions of x = 0.02–0.2). However, the maximum measured value of R_{pPb} is significantly larger than the value expected from anti-shadowing in nuclear parton distribution functions (nPDFs) obtained from globally analysed fits to nuclear hard-process data. The forward-backward asymmetry was also evaluated in various η ranges. Similar anti-shadowing effects are observed in the positive and negative η regions resulting in a ratio close to unity.

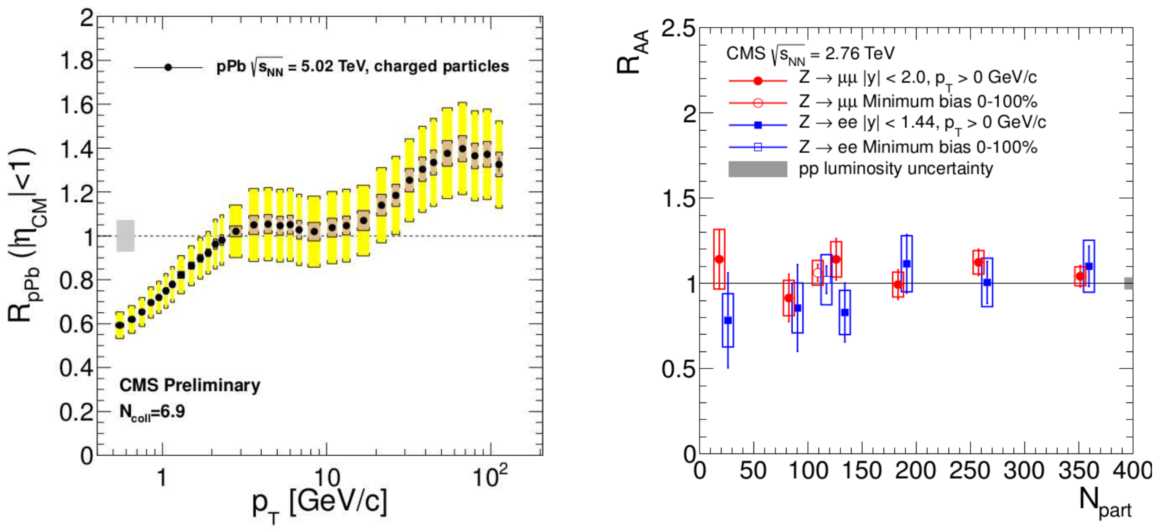


***Figure 3: Left:** The nuclear modification factor (R_{pPb}) of charged particles measured in $\sqrt{s_{NN}}$ = 5.02 TeV pPb collisions as a function of transverse momentum (p_T). **Right:** The nuclear modification factor (R_{AA}) for Z bosons measured in $\sqrt{s_{NN}}$ = 2.76 TeV PbPb collisions, from the decay channels $Z \rightarrow e^+e^-$ (squares) and $Z \rightarrow \mu^+\mu^-$ (dots) as a function of collision centrality (here, the number of participant nucleons N_{part}). The points were shifted for clarity.*

Weak bosons. — By colliding heavy nuclei we can recreate the Universe as it was some microseconds after the Big Bang. In contrast to hadrons, weakly interacting bosons (γ, $W^{\pm}$, Z) can escape the hot and dense medium unchanged. Their decay to lepton pairs is clearly seen by the CMS detector, since its capabilities in this field are excellent. We have studied the production of Z bosons in both dimuon and dielectron decay channels in PbPb and pp collisions at $\sqrt{s_{NN}}$ = 2.76 TeV using the CMS detector. The nuclear modification factor R_{AA} was calculated to study the effect that the medium formed in PbPb collisions has on Z production (Fig. 3 right). We find the R_{AA} for centrality integrated Z-boson production in the dimuon channel to be 1.06 ± 0.05(stat) ± 0.11(syst) and in the dielectron channel to be 1.02 ± 0.08(stat) ± 0.17(syst). Therefore, the production of Z bosons in both decay channels in PbPb collisions is consistent with scaling of the pp cross section with the number of binary collisions. The scaling is seen to hold in the entire kinematic region studied, as expected for a colourless probe that is unaffected by a deconfined quark-gluon plasma. The ongoing study of the properties and the production of these particles created in pPb collisions will be important in the comparison with PbPb interactions.

Grants and international cooperation

OTKA NK 106119, „Attometer physics phenomena: experimental and theoretical studies at the CERN LHC ALICE"

OTKA NK 81447, „Hungary in the CMS experiment of the Large Hadron Collider"

OTKA K 81614, „New analysis methods and tests of quantum chromodynamics at the LHC"

OTKA NK 109703 „Consortional main: Hungary in the CMS experiment of the Large Hadron Collider"

EC FP7 C 262025, „Advanced European Infrastructures for Detectors at Accelerators (AIDA)"

„Wigner research group" support

Publications

Articles

1. Agócs AG et al. incl. Barnaföldi GG, Bencédi G, Bencze G, Berényi D, Boldizsár L, Futo E, Hamar G, Kovacs L, Lévai P, Molnar L, Varga D [50 authors]: R&D studies of a RICH detector using pressurized C_4F_8O radiator gas and a CsI-based gaseous photon detector. ***NUCL. INSTRUM. METHODS A*** 732:(21) pp. 361-365.(2013)

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Conference proceedings

3. Pochybova S: Experimental identification of quark and gluon jets. ***ACTA PHYS. POL. B PROC. SUPPL.*** 6:(2) pp. 539-544. (2013)

See also: R-C.2

CMS collaboration

Due to the vast number of publications of the large collaborations in which the research group participated in 2013, here we list only a short selection of appearences in journals with the highest impact factor.

1. Chatrchyan S et al. incl. Bencze G, Hajdu C, Hidas P, Horvath D, Sikler F, Veszpremi V, Vesztergombi G [2197 authors]: Evidence for associated production of a single top quark and W Boson in pp collisions at $\sqrt{s}$=7 TeV. ***PHYS. REV. LETT.*** 110:(2) Paper 022003. 25 p. (2013)

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4. Chatrchyan S et al. incl. Bencze G, Hajdu C, Hidas P, Horvath D, Sikler F, Veszpremi V, Vesztergombi G [2198 authors]: Measurement of the azimuthal anisotropy of neutral pions in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV. ***PHYS. REV. LETT.*** 110:(4) Paper 042301. 25 p. (2013)

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7. Chatrchyan S et al. incl. Bencze G, Hajdu C, Hidas P, Horvath D, Sikler F, Veszpremi V, Vesztergombi G [2201 authors]: Search for pair production of third-generation leptoquarks and top squarks in pp collisions at $\sqrt{s}$=7 TeV. ***PHYS. REV. LETT.*** 110:(8) Paper 081801. 27 p. (2013)

8. Chatrchyan S et al. incl. Bencze G, Hajdu C, Hidas P, Horvath D, Sikler F, Veszpremi V, Vesztergombi G, Zsigmond AJ [2207 authors]: Search for pair-produced dijet resonances in four-jet final states in pp collisions at $\sqrt{s}$=7 TeV. ***PHYS. REV.***

LETT. 110:(14) Paper 141802. 15 p. (2013)

9. Chatrchyan S et al. incl. Bencze G, Hajdu C, Hidas P, Horvath D, Sikler F, Veszpremi V, Vesztergombi G, Zsigmond AJ [2205 authors]: Search for top squarks in r-parity-violating supersymmetry using three or more leptons and b-tagged jets. ***PHYS. REV. LETT.*** 111:(22) Paper 221801. 16 p. (2013)

10. Chatrchyan S et al. incl. Bencze G, Hajdu C, Hidas P, Horvath D, Sikler F, Veszpremi V, Vesztergombi G, Zsigmond AJ [2224 authors]: Searches for new physics using the $t\bar{t}$ invariant mass distribution in pp collisions at $\sqrt{s}$=8 TeV. ***PHYS. REV. LETT.*** 111:(21) Paper 211804. 16 p. (2013)

11. Chatrchyan S, Khachatryan V, Bencze G, Hajdu C, Hidas P, Horvath D, Sikler F, Veszpremi V, Vesztergombi G, Zsigmond AJ [2211 authors]: Study of the mass and spin-parity of the Higgs boson candidate via its decays to Z boson pairs. ***PHYS. REV. LETT.*** 110:(8) Paper 081803. 15 p. (2013)

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13. Chatrchyan S et al. incl. Bencze G, Hajdu C, Hidas P, Horvath D, Sikler F, Veszpremi V, Vesztergombi G, Zsigmond AJ [2226 authors]: Measurement of the differential and double-differential Drell-Yan cross sections in proton-proton collisions at $\sqrt{s}$ = 7 TeV. ***J. HIGH ENERGY PHYS.*** 2013:(12) Paper 030. 62 p. (2013)

14. Chatrchyan S et al. incl. Bencze G, Hajdu C, Hidas P, Horvath D, Sikler F, Veszpremi V, Vesztergombi G, Zsigmond AJ [2209 authors]: Measurement of the hadronic activity in events with a Z and two jets and extraction of the cross section for the electroweak production of a Z with two jets in pp collisions at TeV. ***J. HIGH ENERGY PHYS.*** 2013: Paper 062. 39 p. (2013)

15. Chatrchyan S et al. incl. Bencze G, Hajdu C, Hidas P, Horvath Measurement of the production cross section for Zγ -> $\gamma\gamma\nu\bar{\nu}\gamma$ in pp collisions at $\sqrt{s}$ =7 TeV and limits on ZZγ and Zγγ triple gauge boson couplings. ***J HIGH ENERGY PHYS.*** (10) Paper 164. 30 p. (2013)

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17. Chatrchyan S et al. incl. Bencze G, Hajdu C, Hidas P, Horvath D, Sikler F, Veszpremi V, Vesztergombi G, Zsigmond AJ [2220 authors]: Measurement of the W-boson helicity in top-quark decays from $t\bar{t}$ production in lepton plus jets events in pp collisions at $\sqrt{s}$ =7 TeV. ***J. HIGH ENERGY PHYS.*** (10) Paper 167. 45 p. (2013)

18. Chatrchyan S et al. incl. Bencze G, Hajdu C, Hidas P, Horvath D, Sikler F, Veszpremi V, Vesztergombi G, Zsigmond AJ [2208 authors]: Measurement of the X(3872) production cross section via decays to $J/\psi\pi + \pi -$ in pp collisions at $\sqrt{s}$=7 TeV. ***J. HIGH ENERGY PHYS.*** 2013:(4) Paper 154. 39 p. (2013)

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20. Chatrchyan S et al. incl. Bencze G, Hajdu C, Hidas P, Horvath D, Sikler F, Veszpremi V, Vesztergombi G, Zsigmond AJ [2199 authors]: Measurement of the λ_b^0 lifetime in pp collisions at $\sqrt{s}$=7 TeV. ***J. HIGH ENERGY PHYS.*** 2013:(7) Paper 163. 31 p. (2013)

21. Chatrchyan S et al. incl. Bencze G, Hajdu C, Hidas P, Horvath D, Sikler F, Veszpremi V, Vesztergombi G, Zsigmond AJ [2189 authors]: Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s}$=7 and 8 TeV. ***J. HIGH ENERGY PHYS.*** 2013:(6) Paper 081. 27 p. (2013)

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24. Chatrchyan S et al. incl. Bencze G, Hajdu C, Hidas P, Horvath D, Sikler F, Veszpremi V, Vesztergombi G, Zsigmond AJ [2196 authors]: Search for microscopic black holes in pp collisions at $\sqrt{s}$=8 TeV. ***J. HIGH ENERGY PHYS.*** 2013:(7) Paper 178. 31 p. (2013)

NA49 Collaboration

1. Anticic T et al. incl. Barna D, Fodor Z, Laszlo A, Palla G, Sikler F, Varga D, Veres GI, Vesztergombi G [73 authors]: System-size dependence of particle-ratio fluctuations in Pb+Pb collisions at 158A GeV. **PHYS. REV. C** 87:(2) Paper 024902. 9 p. (2013)

2. Baatar B et al. incl. Fodor Z, Varga D, Vesztergombi G [24 authors]: Inclusive production of protons, anti-protons, neutrons, deuterons and tritons in p+C collisions at 158 GeV/c beam momentum. **EUR. PHYS. J. C** 73:(4) Paper 2364. 66 p. (2013)

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See also: R-I. NA61/SHINE Collaboration