Comparative study of high-energy nuclear interactions

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Quarks and gluons

Particle physics is our attempt to understand the basics 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 theory of quarks and gluons (QCD), is quite difficult to calculate, due to the strong coupling we are left with perturbative calculation methods. The results from RHIC (Brookhaven), later reinforced by LHC (Geneva) measurements, showed unexpected phenomena: suppression of hadrons with high transverse momentum (p_T), and weakening of back-to-back jet correlations. The matter did not behave as a quasi-ideal state of free quarks and gluons, but as an almost perfect dense fluid.

The aim of our research group is to study collisions of nucleons and nuclei, to perform basic and advanced measurements, and to test 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. Also, these collisions are interesting in themselves. What is the validity of multiple-collision Glauber-model? Can we get a better understanding of the hadronization process? The topic is of particular interest for many theorist colleagues in Hungary and worldwide. The energy range (several TeV) of the LHC enables using new, more powerful signals and markers. It is also a relevant region for the cosmic radiation and atmospheric showers. In the past year several members of our research group participated in the data taking and calibration of new pPb data both at CERN SPS (17 GeV per nucleon pair; NA61) and LHC accelerators (5.02 TeV; ALICE and CMS). The large amount of collected data allowed us to perform the studies proposed at the beginning of the year.

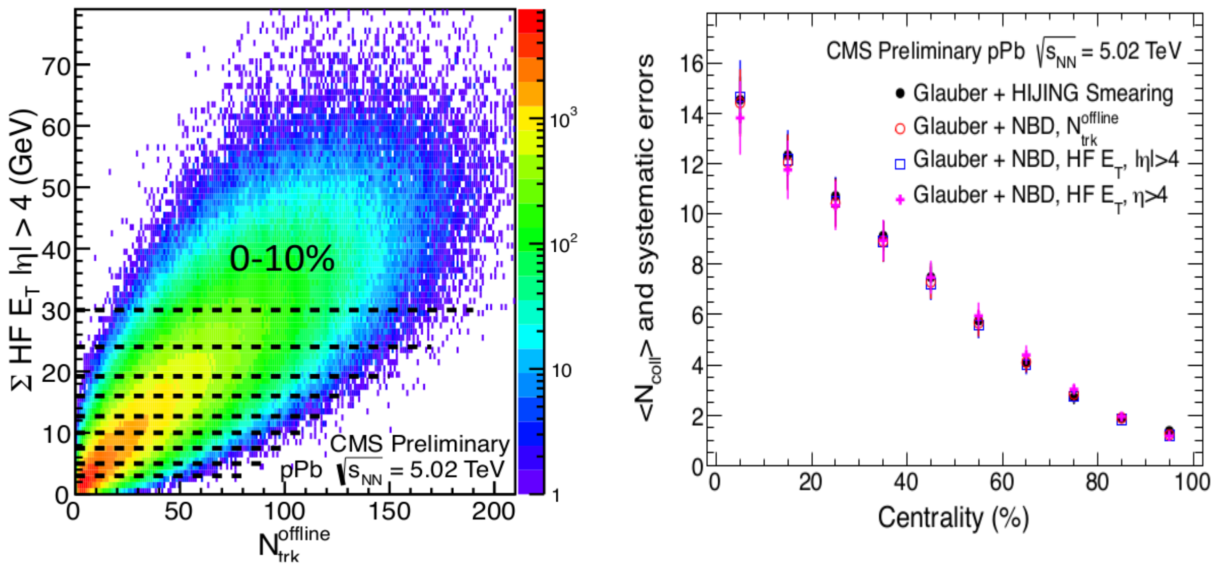

Figure 1: *Left:* The correlation between the number of detected tracks ($N_{trk}^{offline}$) and the energy in the forward calorimeters (E_T) in inelastic pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. *Right*: The estimated number of collisions <N_{coll}> and its uncertainty in 10% wide centrality classes.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

Collision centrality

One of the important tasks is to determine the centrality of a pPb collision, or 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 produced particles. 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 created hadrons. Our studies show that by measuring the total energy of the produced particles, flying in the direction of the fragmented Pb nucleus, the number of collisions can be estimated with small bias [1]. This finding comes from optimizing the weighted sum of the number of produced particles, 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 ($4 < \eta < 5$). The corresponding averages and standard deviations were calculated using a Glauber-model (Fig. 1-left).

In the case of NA61 we could 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 allowing for particle identification and momentum measurement at very low momenta. By counting the number of identified protons, the number of collisions can be estimated.

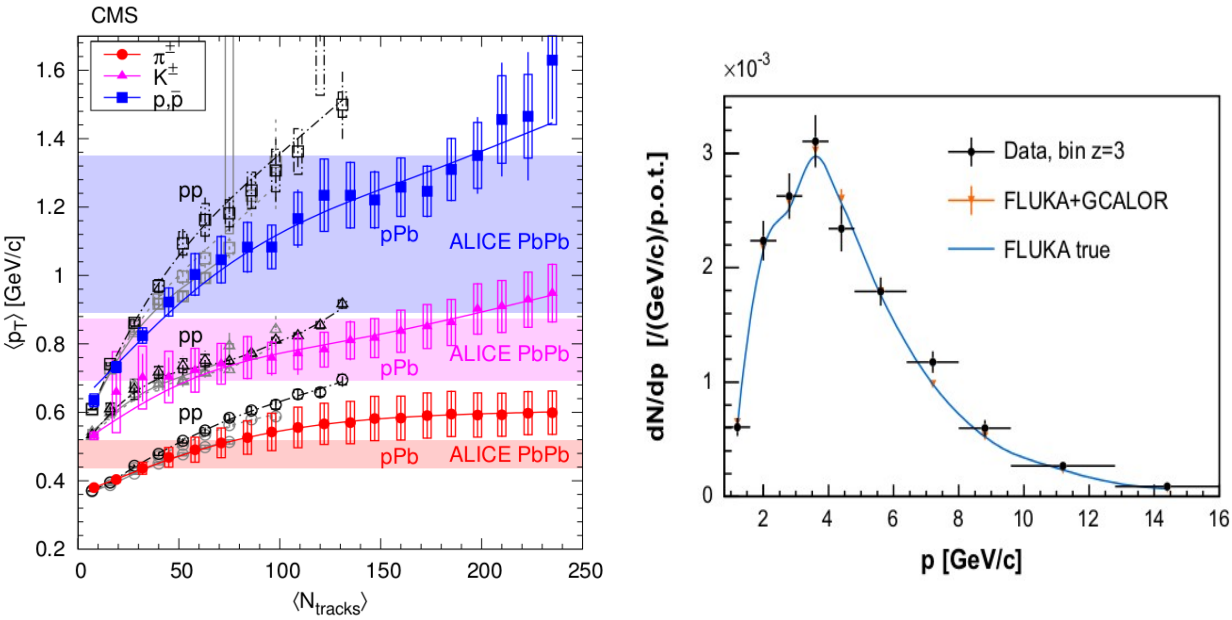

Figure 2: *Left:* Average transverse momentum $<p_T>$ of identified charged hadrons (pions, kaons, protons) as a function of the corrected track multiplicity for $|\eta| < 2.4$, for pp collisions (open symbols) at several energies [5], and for pPb collisions (filled symbols) at $\sqrt{s_{NN}} = 5.02$ TeV, from Ref. [3]. 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 [6] 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, from Ref. [7]. Error bars correspond to the sum in quadrature of statistical and systematic uncertainties. Smooth curves show the prediction of the FLUKA simulation.

Momentum distribution of identified particles

Charged particles created in collisions of nucleons and nuclei are observed by different kinds of tracking detectors (gas chamber in NA61 and ALICE, silicon tracker in CMS). With the help of sophisticated algorithms we can reconstruct their trajectories. Already simple measures such as the pseudorapidity density [2] allow for direct comparisons with event generators and other theories. We have measured the spectra of identified charged hadrons produced in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using the CMS detector [3]. 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 $|\eta| < 2.4$. The p_T spectra are well described by fits with the Tsallis-Pareto parametrization. (This observation can stress the role of non-extensive thermodynamics [4].) The ratios of the yields of oppositely charged particles are close to one, as expected at mid-rapidity for collisions at multi-TeV energies. The average p_T is found to increase with particle mass and the charged particle multiplicity. The EPOS LHC event generator reproduces several features of the measured distributions, a significant improvement from the previous version, 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 [5], 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). 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 $|\eta| < 2.4$) is similar to that for pp collisions with $0.55 \times N_{tracks}$. Both the highest-multiplicity pp and pPb interactions yield higher p_T than seen in central PbPb collisions [6].

Data from hadron-nucleus collisions are valuable for other areas such as atmospheric showers, and through that 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 [7]. In the global framework of accelerator-based neutrino oscillation experiments, it is demonstrated that high quality measurements can be performed with the NA61 setup. They would lead to a significant reduction of systematic uncertainties on the neutrino flux predictions in long-baseline neutrino experiments.

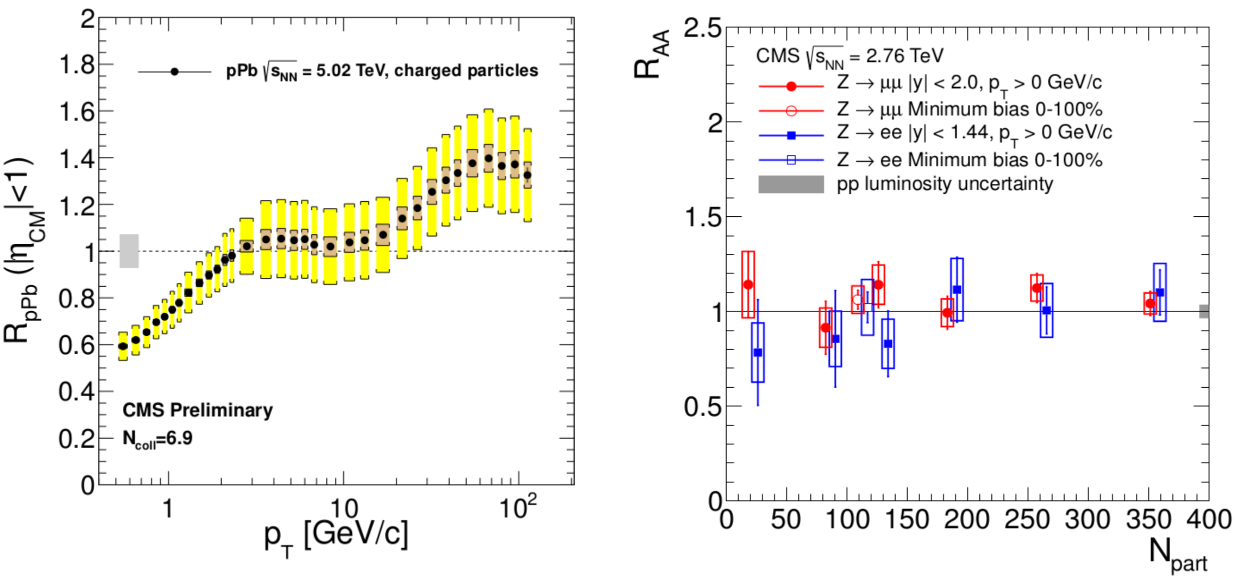

Figure 3: *Left:* The nuclear modification factor (R_{pPb}) of charged particles measured in $\sqrt{s_{NN}} = 5.02$ TeV pPb collisions as a function of transverse momentum (p_T), from Ref [8]. *Right:* The nuclear modification factor (R_{AA}) for Z bosons measured in $\sqrt{s_{NN}} = 2.76$ TeV PbPb collisions, 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}), from Ref. [9]. The points were shifted for clarity.

Momentum distribution at high momenta

In the presense 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 the charged particles and the nuclear modification factor for pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV using data taken by the CMS experiment [8]. 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 at a $p_T \approx$ 4 GeV/c, is flat to 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 analyzed 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.

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 [9]. The nuclear modification factor R_{AA} was calculated in order to study the effect, that the medium formed in PbPb collisions has on the Z production. We find the R_{AA} for the 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 colorless 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.

References

In the case of collaboration papers, proofs (internal notes or conferences notes) of invididual contributions from our research group are indicated after "Internal reference". Public documents are hyperlinked.

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