R-H. Hadron physics

Wigner research group

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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 in nucleus-nucleus collisions: the suppression of hadrons with high transverse momentum (p_T), and the weakening of back-to-back jet correlations. The created matter did not behave as a quasi-ideal state of free quarks and gluons, but as an almost perfect dense fluid, contrary to the expectations.

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 (ALICE and CMS), both in data taking and physics analysis. In the past year our research group mostly concentrated on the analysis of pPb data recorded at LHC at $\sqrt{s_{NN}}$ = 5.02 TeV energy per nucleon pair. The large amount of collected data allowed us to perform the studies proposed at the beginning of the year.

Size and shape of the created system in pPb collisions

Measurements of the correlation between hadrons emitted in high energy collisions of nucleons and nuclei can be used to study the spatial extent and shape of the created system. The characteristic radii, the homogeneity lengths, of the particle emitting source can be extracted with reasonable precision. We have studied the characteristics of the one-, two-, and three-dimensional two-particle correlation functions in various center-of-mass energy pp, pPb, and peripheral PbPb collisions, as a function of the transverse pair momentum k_T and of the charged-particle multiplicity N_{tracks} of the event [1]. Charged pions and kaons at low p_T and in laboratory pseudorapidity $|\eta| < 1$ were identified via their energy loss in the silicon tracker. The correlation functions were corrected for the Coulomb interaction between particles. The contributions from other, correlated particle emissions (mini-jets, multi-body resonance decays) were also subtracted. The obtained distributions could be fit by an exponential parametrization in the relative momentum of the particle pair, both in one- and in multi-dimensions.

The extracted exponential radii for pions increase with increasing N_{tracks} for all systems and center-of-mass energies studied, for one, two, and three dimensions alike. Their values are in the range 1–5 fm, reaching highest values for very high multiplicity pPb, also for similar multiplicity PbPb collisions. The N_{tracks} dependence of longitudinal (R_l) and transverse radii (R_t) is similar for pp and pPb in all k_T bins, and that similarity also applies to peripheral PbPb if $k_T > 0.4$ GeV/c. In general there is an ordering for the radii, $R_l > R_t$, thus the pp and pPb source is elongated in the beam direction. In the case of peripheral PbPb the source is quite symmetric, and shows a slightly different N_{tracks} dependence. The most visible divergence between pp, pPb, and PbPb is seen in the so called "out" radius (R_o) that could point to the differing lifetime of the created systems in those collisions.

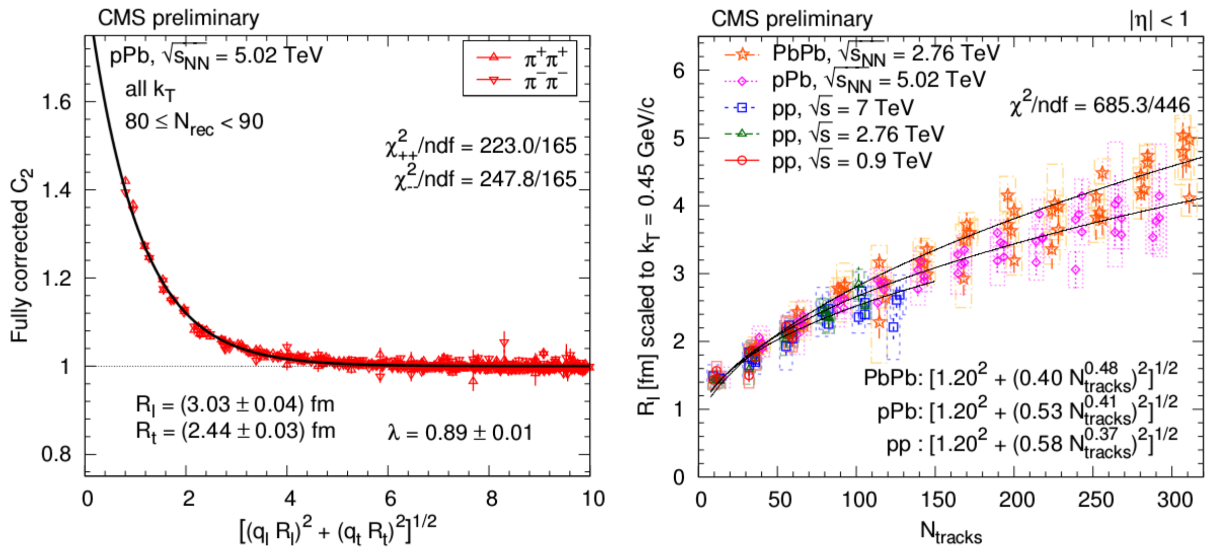
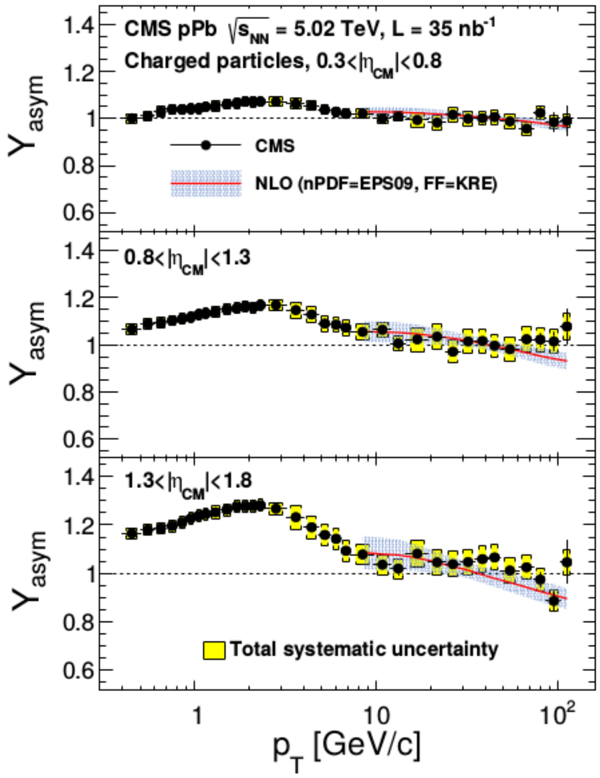


Figure 1. *Left: The like-sign correlation function of pions (red triangles) corrected for Coulomb interaction and cluster contribution (mini-jets and multi-body resonance decays) as a function of the combined momentum, in a selected N_{rec} bins for all k_T. The solid curve indicates a fit with the exponential Bose-Einstein parametrization. Right: The longitudinal radius R_l as a function of N_{tracks} scaled to k_T = 0.45 GeV/c with help of a parametrization.*

The kaon radii also show some increase with N_{tracks}, although its magnitude is smaller than that for pions. Longer lived resonances and rescattering may play a role here. The pion radii decrease with increasing k_T. The dependence of the radii on the multiplicity and k_T factorizes and in some cases appears to be less sensitive to the type of the colliding system and center-of-mass energy. The similarities observed in the N_{tracks} dependence may point to a common critical hadron density in pp, pPb, and peripheral PbPb collisions, since the present correlation technique measures the characteristic size of the system near the time of the last interactions.

Spectra of high p_T charged hadrons in pPb collisions

We have measured the charged-particle spectra in pPb collisions in the transverse momentum range of $0.4 < p_T < 120$ GeV/*c* for center-of-mass pseudorapidities up to $|\eta_{CM}| = 1.8$ [2]. The forward-backward yield asymmetry has been measured as a function of p_T for three bins in η_{CM}. At $p_T < 10$ GeV/*c*, the charged-particle production is enhanced in the direction of the Pb beam, in qualitative agreement with nuclear shadowing expectations. The nuclear modification factor at mid-rapidity, relative to a reference spectrum interpolated from pp measurements at lower and higher collision energies, rises above unity at high p_T reaching an R_{pPb} value of 1.3–1.4 at $p_T \geq 40$ GeV/*c*. The observed enhancement is larger than expected from next-to-leading order (NLO) perturbative QCD predictions that include antishadowing effects in the nuclear parton distribution functions (PDFs) in this kinematic range.



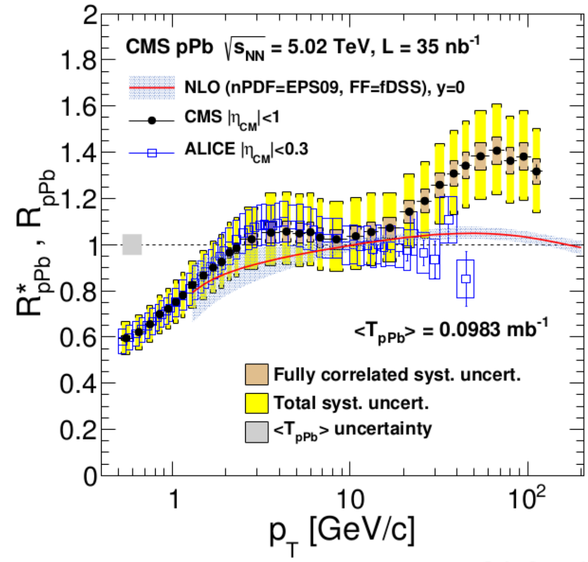


Figure 2. *Left: Charged-particle forward-backward yield asymmetry as a function of p_T for three $|\eta_{CM}|$ intervals. The asymmetry is computed as the charged-particle yields in the direction of the Pb beam divided by those of the proton beam. Right: Charged-particle nuclear modification factors measured by CMS in $|\eta_{CM}| < 1$ (filled circles), and by ALICE in $|\eta_{CM}| < 0.3$ (open squares), are compared to a theoretical prediction.*

The fact that the nuclear modification factor is below unity for $p_T < 2$ GeV/c is anticipated since particle production in this region is dominated by softer scattering processes, that are not expected to scale with the nuclear thickness function. In the intermediate p_T range (2–5 GeV/c), no significant deviation from unity is found in the R_{pPb} ratio. There are several prior measurements that suggest an interplay of multiple effects in this p_T region. At lower collision energies, an enhancement ("Cronin effect") has been observed that is larger for baryons than for mesons, and is stronger in the more central collisions. This enhancement has been attributed to a combination of initial-state multiple scattering effects, causing momentum broadening, and hadronization through parton recombination (a final-state effect) invoked to accommodate baryon/meson differences. Recent results from pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and from dAu collisions at $\sqrt{s_{NN}} = 200$ GeV suggest that collective effects may also play a role in the intermediate-p_T region. Most theoretical models do not predict a Cronin enhancement in this p_T range at LHC energies as the effect of initial-state multiple scattering is compensated by nPDF shadowing.

The observed rise of the nuclear modification factor up to $R_{pPb} \approx 1.3$–1.4 at high p_T, albeit with large uncertainty, is much stronger than expected theoretically. None of the available theoretical models predict enhancements beyond $R_{pPb} \approx 1.1$ at high p_T. In particular, although the p_T range corresponds to parton momentum fractions $0.02 \leq x \leq 0.2$, which coincides with the region where parton antishadowing effects are expected, none of the nPDFs obtained from global fits to nuclear data predict enhancements beyond 10% at the large virtualities of relevance here. We also show the measurement of the ALICE Collaboration, which is performed in a narrower pseudorapidity range than the CMS one, and uses a different method to obtain the pp reference spectrum based on ALICE pp data measured at $\sqrt{s} = 7$ TeV. The difference in the CMS and ALICE R_{pPb} results stems primarily from differences in the charged-hadron spectra measured in pp collisions at $\sqrt{s} = 7$ TeV.

Future direct measurement of the spectra of jets and charged particles in pp collisions at a center-of-mass energy of 5.02 TeV is necessary to better constrain the fragmentation functions and also to reduce the dominant systematic uncertainties in the charged-particle nuclear modification factor.

Spectra of high mass bosons in pPb collisions

We have measured Z boson production cross section in the muon decay channel in pPb collisions [3]. The results are presented in the center-of-mass frame with positive rapidity values corresponding to the proton fragmentation region. The Z boson candidates are selected as an opposite-charge muon pair in the 60–120 GeV/c^2 mass range where both muons have $p_T > 20$ GeV/c and are within the $|\eta_{lab}| < 2.4$ muon detector coverage. The measured inclusive Z boson production cross section in pPb collisions for the range $-2.5 < y_{CM} < 1.5$ is $\sigma_{pPb}(Z\rightarrow\mu\mu) = 94.1 \pm 2.1$ (stat.) $\pm$ 2.4 (syst.) $\pm$ 3.3 (lumi.) nb using the calibrated integrated luminosity. For the same restricted rapidity range, the POWHEG simulation predicts 94.0 ± 4.7 nb after multiplying by the number of nucleons in the Pb nucleus (A = 208), which corresponds to the hypothesis of binary collision scaling in pPb.

The differential cross section as a function of Z boson rapidity is consistent with the theory predictions. The forward-backward ratio, defined as $d\sigma(+y)/d\sigma(-y)$, is expected to be more sensitive to nuclear effects, because normalization uncertainties cancel both in theory and in experiment. Due to the large statistical uncertainties, this measurement is not able to distinguish between different nPDF sets but it can constrain their uncertainties by adding new data points to the global fits in a previously unexplored region of the Q^2−x phase space. The differential cross section as a function of Z boson transverse momentum has been measured and apart from very low transverse momenta it is in good agreement with the predictions from PYTHIA. The results of the presented measurement provide new data points in a previously unexplored region of phase space for constraining nuclear PDF fits.

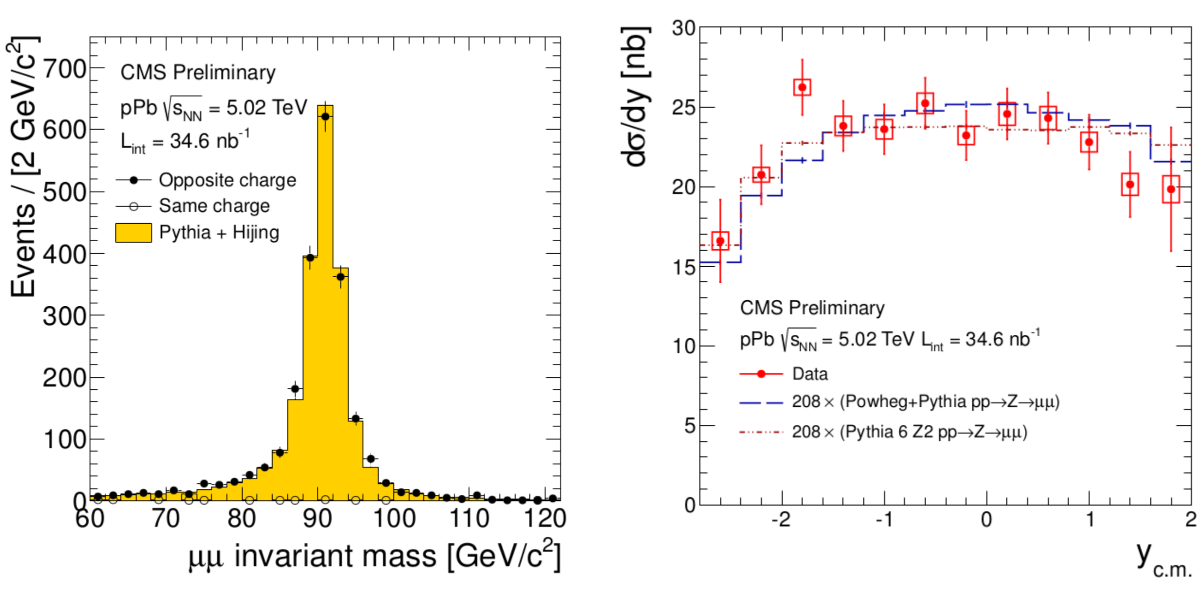


Figure 3. *Left: Invariant mass of selected muon pairs from pPb data compared to a simulation that was normalized to the number of events in data in the sideband mass regions. Right: Differential cross section of Z bosons in pPb collisions as a function of rapidity compared to predictions from POWHEG+PYTHIA generator with CT10NLO PDF set, from PYTHIA generator with Z2 underlying event tune. All theory predictions are scaled by A = 208.*

Thus, Z boson production is unmodified by the hot and dense QCD medium produced in heavy ion collisions, and its yield scales with the number of binary nucleon-nucleon collisions. The nuclear modification factor does not exhibit large deviations from unity showing that nuclear effects are small with respect to the uncertainties of the PbPb measurements. The results were compared to NLO theory predictions with and without nuclear modification, that show hints of nuclear effects but more luminosity is needed to distinguish between different nPDF sets. These measurements set constraints for the global fits of nPDFs in a previously unexplored region of phase space.

Quark and gluon jets

We have studied the proton-to-pion ratio in jets produced in simulated proton-proton collisions at $\sqrt{s}$ = 7 TeV using the Pythia 6.4 Monte Carlo (MC) event generator [4]. We compared the p/π ratio in the selected quark-like and gluon-like jets to a reference sample of tagged quark- and gluon-jets. The contamination in the selected jets significantly influences the observed ratios. Thus, despite the different fragmentation of jets originating from quarks or gluons, we see no difference in the proton-to-pion ratio inside these jets, within the used MC model. To see whether this statement holds, we suggest to proceed with similar study on experimental data.

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.

[1] CMS Collaboration; Femtoscopy with identified charged hadrons in pp, pPb, and peripheral PbPb collisions at LHC energies, CMS PAS HIN-14-013, 2014.

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[2] CMS Collaboration; Nuclear effects on the transverse momentum spectra of charged particles in pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV; arXiv:xxxx.xxxx, submitted to Eur. Phys. J. C.

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[3] CMS Collaboration; Study of Z boson production in the muon decay channel in pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV; CMS PAS HIN-14-003, 2014.

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[4] S. Pochybova; On particle production in jets with quark-like and gluon-like fragmentation; arXiv:1403:0412, 2014.

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