R-H. Hadron physics

Wigner research group

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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 nonperturbative 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 as a quasi-ideal state of free quarks and gluons, but as 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 (ALICE and CMS), both in data-taking and physics analysis. In the past year our research group concentrated mostly 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 and 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. 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 multi-dimensions.


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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 their highest values for very high multiplicity pPb and 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 indicate the differing lifetime of the created systems in those collisions.
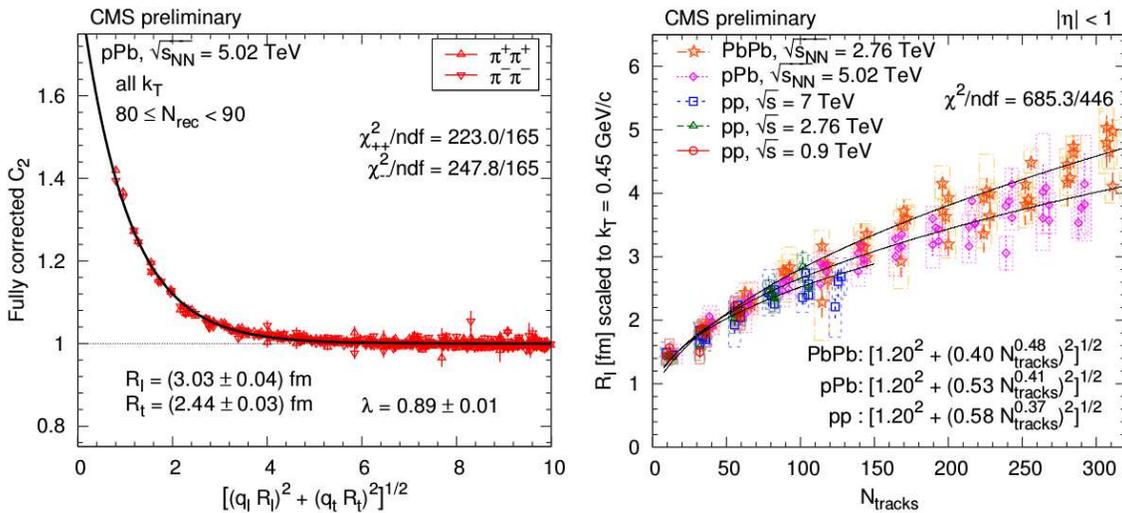

Figure 1. Left: *The like-sign correlation function of pions (red triangles) corrected for Coulomb interaction and cluster contribution (mini-jets and multi-body resonance decays) as a function of the combined momentum, in a selected N_{rec} bins for all k_T. The solid curve indicates a fit with the 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 $|\eta_{CM}| = 1.8$. 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 anti-shadowing effects in the nuclear parton distribution functions (nPDFs) in this kinematic range.
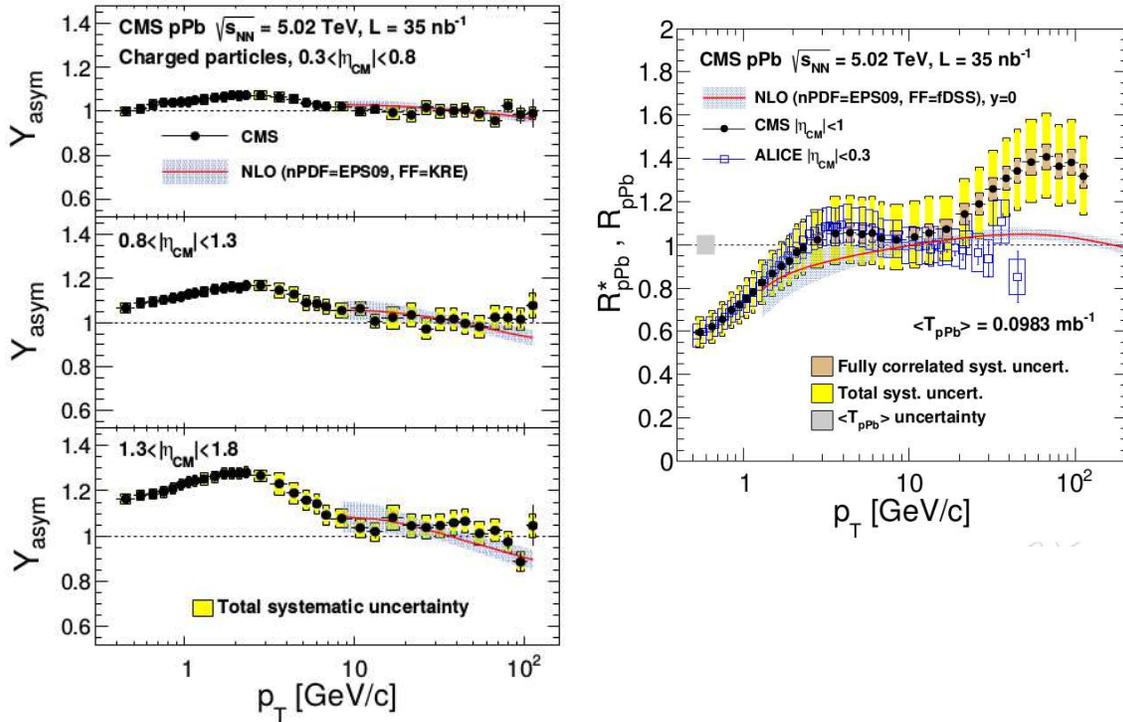

Figure 2. Left: *Charged-particle forward-backward yield asymmetry as a function of p_T for three $|\eta_{CM}|$ intervals. The asymmetry is computed as the charged-particle yields in the direction of the Pb beam divided by those of the proton beam. **Right:** Charged-particle nuclear modification factors 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 anti-shadowing 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 the Z boson production cross section in the muon decay channel in pPb collisions. 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 ± 2.1 (stat.) ± 2.4 (syst.) ± 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.
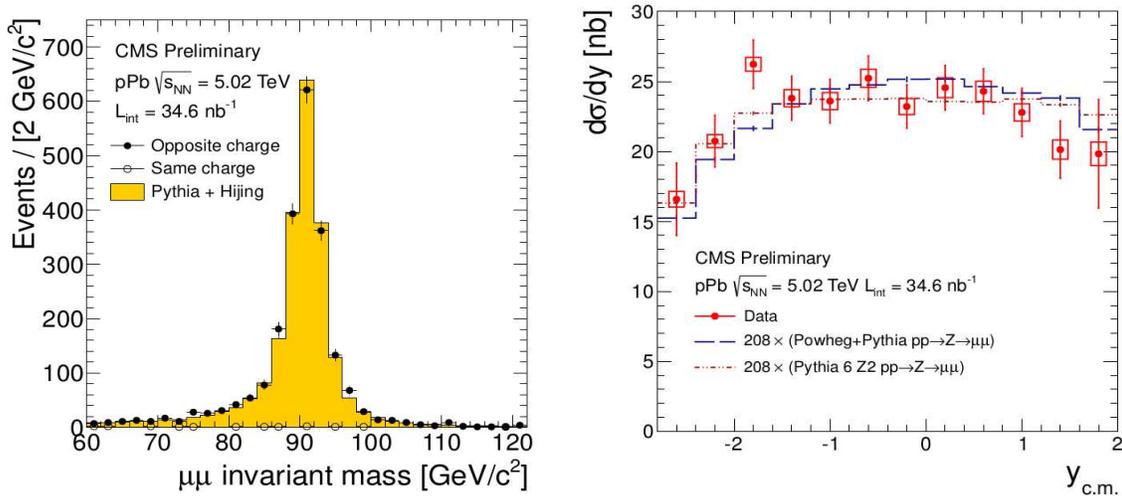
Figure 3. Left: *Invariant mass of selected muon pairs from pPb data compared to a simulation that was normalized to the number of events in data in the signal mass regions.* ***Right:*** *Differential cross section of Z bosons in pPb collisions as a function of rapidity compared to predictions from POWHEG+PYTHIA generator with CT10NLO PDF set, from PYTHIA generator with Z2 underlying event tune. All theory predictions are scaled by A = 208.*

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 unable 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.

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 pPb 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 √s = 7 TeV using the PYTHIA 6.4 Monte Carlo (MC) event generator. 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 proceeding with similar study using experimental data.

Grants

Publications

Articles

1. Münzer R et al. incl. <u>Fodor Z</u>, <u>Kecskemeti J</u>, <u>Seres Z</u> (67 authors): SiΛvio: A trigger for Λ-hyperons. **NUCL INSTRUM METH A**, 745: pp. 38-49. (2014)

See also: R-I.3,

CMS collaboration

Due to the vast number of publications of the large collaborations in which the research group participated in 2014, here we list only a short selection of appearences in journals with the highest impact factor.

1. Chatrchyan S et al. incl. <u>Bencze Gy</u>, <u>Hajdu Cs</u>, <u>Hidas P</u>, <u>Horvath D</u>, <u>Sikler F</u>, <u>Veszpremi V</u>, <u>Vesztergombi Gy</u>, <u>Zsigmond AJ</u> [2200 authors]: Evidence for the direct decay of the 125 GeV Higgs boson to fermions. ***NATURE PHYSICS*** 10: pp. 557-560. (2014)

2. Bodwin GT et al. incl. <u>Bencze Gy</u>, <u>Hajdu Cs</u>, <u>Hidas P</u>, <u>Horvath D</u>, <u>Sikler F</u>, <u>Veszpremi V</u>, <u>Vesztergombi Gy</u>, <u>Zsigmond AJ</u> [2200 authors]: Fragmentation contributions to J/ψ production at the Tevatron and the LHC. **PHYS REV LETT**, 113:(2) Paper 022001. (2014)

3. Chatrchyan S et al. incl. <u>Bencze Gy</u>, <u>Hajdu Cs</u>, <u>Hidas P</u>, <u>Horvath D</u>, <u>Sikler F</u>, <u>Veszpremi V</u>, <u>Vesztergombi Gy</u>, <u>Zsigmond AJ</u> [2200 authors]: Search for top squark and higgsino production using diphoton higgs boson decays. **PHYS REV LETT**, 112:(16) Paper 161802. 15 p. (2014)

4. Chatrchyan S et al. incl. <u>Bencze Gy</u>, <u>Hajdu Cs</u>, <u>Hidas P</u>, <u>Horvath D</u>, <u>Sikler F</u>, <u>Veszpremi V</u>, <u>Vesztergombi Gy</u>, <u>Zsigmond AJ</u> [2202 authors]: Search for top-quark partners with charge 5/3 in the same-sign dilepton final state. **PHYS REV LETT**, 112:(17) Paper 171801. 16 p. (2014)

5. Chatrchyan S et al. incl. <u>Bencze Gy</u>, <u>Hajdu Cs</u>, <u>Hidas P</u>, <u>Horvath D</u>, <u>Sikler F</u>, <u>Veszpremi V</u>, <u>Vesztergombi Gy</u>, <u>Zsigmond AJ</u> [2200 authors]: Search for flavor-changing neutral currents in top-quark decays t →zq in pp collisions at √s = 8TeV. **PHYS REV LETT**, 112:(17) Paper 171802. 16 p. (2014)

6. Chatrchyan S et al. incl. <u>Bencze Gy</u>, <u>Hajdu Cs</u>, <u>Hidas P</u>, <u>Horvath D</u>, <u>Sikler F</u>, <u>Veszpremi V</u>, <u>Vesztergombi Gy</u>, <u>Zsigmond AJ</u> [2202 authors]: Measurements of t t̄ spin correlations and top-quark polarization using dilepton final states in pp collisions at √s = 7TeV. **PHYS REV LETT**, 112:(18) Paper 182001. 16 p. (2014)

7. Chatrchyan S et al. incl. <u>Bencze Gy</u>, <u>Hajdu Cs</u>, <u>Hidas P</u>, <u>Horvath D</u>, <u>Sikler F</u>, <u>Veszpremi V</u>, <u>Vesztergombi Gy</u>, <u>Zsigmond AJ</u> [2209 authors]: Measurement of inclusive W and Z boson production cross sections in pp collisions at √s = 8TeV. **PHYS REV LETT**, 112:(19) Paper 191802. 17 p. (2014)

8. Chatrchyan S et al. incl. <u>Bencze Gy</u>, <u>Hajdu Cs</u>, <u>Hidas P</u>, <u>Horvath D</u>, <u>Sikler F</u>, <u>Veszpremi V</u>, <u>Vesztergombi Gy</u>, <u>Zsigmond AJ</u> [2207 authors]: Observation of the associated

production of a single top quark -and a W boson in *pp* collisions at √s = 8TeV. **PHYS REV LETT**, 112:(23) Paper 231802. 16 p. (2014)

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12. Chatrchyan S et al. incl. <u>Bencze Gy</u>, <u>Hajdu Cs</u>, <u>Hidas P</u>, <u>Horvath D</u>, <u>Sikler F</u>, <u>Veszpremi V</u>, <u>Vesztergombi Gy</u>, <u>Zsigmond AJ</u> [2207 authors]: Measurement of Higgs boson production and properties in the WW decay channel with leptonic final states. **J HIGH ENERGY PHYS**, 2014:(1) Paper 096. 86 p. (2014)

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14. Chatrchyan S et al. incl. <u>Bencze Gy</u>, <u>Hajdu Cs</u>, <u>Hidas P</u>, <u>Horvath D</u>, <u>Sikler F</u>, <u>Veszpremi V</u>, <u>Vesztergombi Gy</u>, <u>Zsigmond AJ</u> [2202 authors]: Studies of azimuthal dihadron correlations in ultra-central PbPb collisions at √s $_{NN}$=2.76 TeV. **J HIGH ENERGY PHYS**, 2014**:**(2) Paper 088. 38 p. (2014)

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18. Chatrchyan S et al. incl. <u>Bencze Gy</u>, <u>Hajdu Cs</u>, <u>Hidas P</u>, <u>Horvath D</u>, <u>Sikler F</u>, <u>Veszpremi V</u>, <u>Vesztergombi Gy</u>, <u>Zsigmond AJ</u> [2224 authors]: Measurements of the tt¯ charge asymmetry using the dilepton decay channel in pp collisions at s√ = 7 TeV. **J HIGH**

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See also: R-B. ALICE Collaboration, R-I. NA61/SHINE Collaboration