Summary (autoreferat)

1. Name

Adam Bzdak

2. Scientific degrees

- Ph.D. in physics (with distinction), Jagiellonian University, Kraków, 2007
  Thesis: Double pomeron exchange production processes in an effective model
- M.Sc. in physics (with distinction), Jagiellonian University, Kraków, 2003
  Thesis: Investigation of pion distribution amplitude in the nonlocal chiral quark model

3. Research appointments

12/2014 –	AGH University of Science and Technology, Kraków, Poland
05/2011 – 09/2014	RIKEN BNL Research Center, Brookhaven National Laboratory, Upton NY, USA
09/2009 – 05/2011	Lawrence Berkeley National Laboratory, Nuclear Science Division, Berkeley CA, USA
05/2008 – 09/2009	The Henryk Niewodniczański Institute of Nuclear Physics PAN, Kraków, Poland
09/2007 – 02/2008	University of Alberta, Edmonton, Canada

4. Scientific accomplishments related to habilitation thesis

Below I list and discuss the series of papers titled "Initial conditions and evolution of matter in nucleus-nucleus, proton-nucleus and proton-proton collisions".

H-1. A. Bzdak, G. L. Ma
"Elliptic and triangular flow in p+Pb and peripheral Pb+Pb collisions from parton scatterings"
Phys. Rev. Lett. **113**, 252301 (2014)

H-2. A. Bzdak, P. Bozek, L. McLerran
"Fluctuation induced equality of multi-particle eccentricities for four or more particles"
Nucl. Phys. A **927**, 15 (2014)

H-3. P. Bozek, A. Bzdak, V. Skokov
"The rapidity dependence of the average transverse momentum in p+Pb collisions at the LHC: the Color Glass Condensate versus hydrodynamics"
Phys. Lett. B **728**, 662 (2014)

H-4. A. Bzdak, V. Skokov
"Decisive test of color coherence in proton-nucleus collisions at the LHC"
Phys. Rev. Lett. **111**, 182301 (2013)

H-5. A. Bzdak, V. Skokov
"Average transverse momentum of hadrons in proton-nucleus collisions in the wounded nucleon model"
Phys. Lett. B **726**, 408 (2013)

H-6. A. Bzdak, D. Teaney
"Longitudinal fluctuations of the fireball density in heavy-ion collisions"
Phys. Rev. C **87**, 024906 (2013)

H-7. A. Bzdak, V. Skokov
"Anisotropy of photon production: initial eccentricity or magnetic field"
Phys. Rev. Lett. **110**, 192301 (2013)

H-8. A. Bzdak
"Symmetric correlations as seen in central Au+Au collisions at $\sqrt{s} = 200A$ GeV"
Phys. Rev. C **85**, 051901 (2012)

H-9. A. Bzdak, V. Skokov
"Event-by-event fluctuations of magnetic and electric fields in heavy ion collisions"
Phys. Lett. B **710**, 171 (2012)

H-10. A. Bzdak
"Forward-backward multiplicity correlations in the wounded nucleon model"
Phys. Rev. C **80**, 024906 (2009)

H-11. A. Bialas, A. Bzdak
"Wounded quarks and diquarks in high energy collisions"
Phys. Rev. C **77**, 034908 (2008)

Summary of the above-listed papers [1]

One of the most important problem in relativistic nucleus-nucleus (A+A), proton-nucleus (p+A) and proton-proton (p+p) collisions is the initial state, i.e., to uncover the properties of matter created in the first few moments after a collision. Can we describe the produced matter in terms of quarks and gluons, or perhaps we need other effective degrees of freedom (fields, constituent quarks, etc.)? Do we create the strongly coupled quark-gluon plasma that subsequently evolves according to hydrodynamics (see, e.g., [1])? What are the microscopic properties of this matter? What kind of experimental observables are needed to uncover its properties? There are many questions, to some of them we have preliminary answers however, in my opinion, our understanding of this problem is still far from being satisfactory.

Below I present several papers to illustrate my attempts at investigating the hot matter produced in relativistic A+A, p+A and p+p interactions.

The simplest assumption in heavy-ion physics is the superposition of elementary proton-proton collisions. In other words, we assume that physics in A+A, p+A and p+p is the same and the only difference comes from different numbers of elementary nucleon-nucleon collisions, which can lead to rather nontrivial effects. Let us illustrate this assumption in the context of the number of produced particles, N_{ch}, at mid-rapidity, $y = 0$. We can naturally consider two models. In the first one we assume that the number of produced particles is proportional to the number of inelastic nucleon-nucleon collisions, N_{coll}. It turns out that this assumption works well for particles with high transverse momentum, p_t, but fails for low p_t particles (of the order of 500 MeV). This leads to the wounded nucleon model [2], where the number of particles is proportional to the number of wounded nucleons, N_{part}, i.e., nucleons that suffer at least one inelastic collision. It turns out this assumption works very well for low p_t particles in p+A collisions at various energies [3–5]. As far as A+A collisions are concerned, the wounded nucleon model results in too small number of produced particles. In Au+Au collisions at RHIC N_{ch} scales faster that N_{part} but slower than N_{coll} [6]. It is commonly believed that indeed wounded nuclons are mostly responsible for particle production in A+A however, there is a small contribution from jet fragments that scale like N_{coll} [7]. This two-component model can satisfactory describe A+A data at various energies.

In Ref. [H-11] we explained the A+A data at all rapidities without the N_{coll} term. We assumed that the initial condition in A+A, p+A and p+p collisions is dominated by constituent quarks and diquarks, and the number of particles in the final state is simply proportional to the number of wounded quarks and diquarks (quarks and diquarks that underwent at least one inelastic collision). Each quark and diquark is characterized by a given rapidity fragmentation function. This model automatically results in N_{ch} growing faster that N_{part} since there is a different number of wounded quarks and diquarks in a proton that underwent one inelastic collision, and a proton that underwent several collisions. We were able to explain simultaneously both Au+Au, d+Au and p+p data at RHIC for all rapidities and centralities. We also argued that a model with three constituent quarks cannot describe data, it results with too large number of produced particles. It would be interesting to investigate the q-d model in the context of new LHC data on p+A collisions.

[1] Here I focus on the main ideas without discussing technical details.

The long-range rapidity correlations are very useful in studies of the initial state in hadronic collisions [8]. Particles with different rapidities quickly become separated in space and thus any dynamical correlation between them must be created in the initial stage of evolution, when particles are close to each other (the larger separation in rapidity, the earlier a given correlation should be generated [9]). Unfortunately, there are many sources of correlations, present from the very begging, which are not particularly interesting from the initial state point of view. For example, correlations due to momentum and energy conservation, baryon conservation, etc.

In Ref. [H-10] the long-range rapidity correlations in A+A interactions due to fluctuations of the number of wounded nucleons were investigated. It is rather straightforward to understand this mechanism: a large number of particles at rapidity y_1 triggers events with a large N_{part}, and consequently with a large number of particles at some arbitrary rapidity y_2. On the other hand, a small number of particles at y_1 triggers a small number of participants and consequently a small number of particles at y_2. Obviously, this correlation is independent of the rapidity separation between particles and is always present in A+A experiments. As shown in Ref. [H-10] this mechanism is present in STAR data [10] on the long-range multiplicity correlation coefficient and it is important to remove this source to properly interpret the measured data. A possible method is to measure the forward-backward correlation coefficient at a fixed number of particles at midrapidity (in this way we substantially reduce fluctuations of N_{part} [11]).

In Ref. [H-8] I showed that the forward-backward correlation coefficient, b, cannot be larger than 0.5 if measurement is performed at a fixed number of particles at midrapidity, and the forward and backward bins are located symmetrically around $y = 0$. The STAR data [10] in central Au+Au collisions show that b is about 0.6, which is not yet understood. As shown in Ref. [H-8], it is equivalent to the situation, where two bins located symmetrically around $y = 0$ are stronger correlated than two bins (with much smaller rapidity distance) located asymmetrically around $y = 0$. It means that the two-particle correlation function depends not only on the rapidity difference, $y_1 - y_2$, but also on the rapidity sum, $y_1 + y_2$. Similar conclusions were obtained in Ref. [12]. This effect is observed for the first time and we hope that new results from the LHC will shed some more light on this issue.

Motivated by Ref. [H-8], in Ref. [H-6] we proposed to study rapidity fluctuations of the fireball longitudinal shape. This idea is similar to fluctuations of the fireball in the transverse direction, which lead to nontrivial azimuthal correlations. We proposed to expand the measured two-particle rapidity correlation function in a series of the Chebyshev polynomials, where each polynomial and its coefficient represents a different component of the fireball's fluctuating rapidity density. This is analogous to the elliptic and triangular [13] flow coefficients extracted from the two-particle azimuthal correlation function. It turns out that fluctuations in the fireball longitudinal shape lead to specific rapidity correlations. For example, an event-by-event difference between the number of wounded nucleon in the left- and right-going nucleus naturally leads to an asymmetric single particle distribution, dN/dy, and consequently to the long-range rapidity correlations depending on $(y_1 + y_2)^2 - (y_1 - y_2)^2$ [H-8], where y_1 and y_2 are rapidities of two particles. This idea is relatively new and we are hoping for its practical applications at the LHC.

An important aspect of studies on the initial stage in heavy-ion physics is an enormous magnetic field created just after a non-central A+A collision [14]. The origin of this field is easy to understand: a A+A interaction is a collision of two electrically charged objects moving with relativistic velocities. The strength of this field is quite surprising, in Au+Au collisions at 200 GeV (per nucleon-nucleon pair) it roughly equals 10^{18} Gauss. In Ref. [H-9] for the first time the electric and magnetic fields were calculated taking into account fluctuating positions of individual nucleons inside a nucleus. It was shown that in each event we have an enormous magnetic field not only in the direction perpendicular to the reaction plane, but also in the longitudinal direction. This paper is now very often cited in the context of the QCD topological effects (see, e.g., [15] for a review). In addition, we proposed an experimental method to measure the electric conductivity of the initial medium. The idea is based on the observation that in the initial stage of A+A collision very strong electric fields can generate electric currents in the initial medium.

The initial magnetic field in A+A collisions can generate substantial elliptic flow coefficient for direct photons v_2^γ. The PHENIX collaboration at RHIC measured [16] v_2^γ, which surprisingly is comparable with the elliptic flow coefficient for pions, v_2^π. This result is very surprising, indeed. Photons practically do not interact with each other and only weekly interact with quarks, thus the measured large value of v_2^γ is difficult to understand. An interesting idea was proposed in Ref. [17], where the authors considered interaction of gluons with the magnetic field, which naturally leads to the emission of photons in a direction perpendicular to the reaction plane, producing a non-zero elliptic flow coefficient. Rough estimations suggest that this mechanism is of the right order of magnitude and possibly could explain the PHENIX data.

In Ref. [H-7] we proposed a way to determine whether v_2^γ originates from the initial magnetic field, or it is a consequence of the fireball elliptical shape present in A+A interactions. Our idea can be summarized in several points. First we choose a relatively narrow centrality class defined, e.g., by the number of particles in the mid-rapidity region. Given the centrality class, in each event we measure the value of the elliptic flow, v_2^π, for pions. It is commonly accepted that v_2^π reflects the initial elliptical shape of the fireball in the transverse direction. Due to the fluctuations in positions of the participants, we obtain a broad range of v_2^π [18]. Finally, we measure the elliptic flow for photons v_2^γ for different values of v_2^π. If v_2^γ results solely from the initial eccentricity then it should be proportional to v_2^π. On the contrary, if the magnetic field dominates v_2^γ, it should be independent of v_2^π. As shown in Ref. [18] the magnetic field, at a fixed centrality, is largely independent of the fluctuating shape of the fireball. This technique is currently studied by the PHENIX Collaboration.

Relativistic proton-nucleus and high-multiplicity proton-proton collisions allow for detail studies of the initial state and subsequent evolution of hot matter created in these interactions. Several experimental results [19–26] suggest that in these collisions small droplets of the quark-gluon plasma are produced, which subsequently evolve according to the equations of relativistic hydrodynamics [27–34]. This interpretation is not fully satisfactory and other interesting ideas, based on quantum chromodynamics, are discussed, e.g., the color glass condensate (CGC) [35, 36], or the AMPT model (cascade of partons) [37, 38]. In the papers [H1-H5] I investigated proton-proton and proton-nucleus collisions using many different techniques.

In Ref. [H-5] we investigated the transverse momentum of produced pions, kaons and protons in p+A collisions as a function of the number of produced particles. Our goal was to check whether a simple superposition of nucleon-nucleon collisions can explain the CMS and ALICE Collaborations data published in [39, 40]. They found that the average transverse momenta of pions, kaons and protons grow with the number of produced particles, which is consistent with hydrodynamics. Exactly the same effect is observed in p+p collisions and it is natural to investigate if both effects are somehow related. We performed our calculations in the wounded nucleon model, which is well suited to describe multiplicity distributions in p+A. We found that the average transverse momentum of particles measured in p+A is larger that expectations from the incoherent superposition of nucleon-nucleon collisions. The difference is small for pions (100 MeV) and grows with particle mass (300 MeV for kaons and 500 MeV for protons). It suggests that in p+A collisions we see some new physics (in comparison to p+p) and this physics depends on particle mass. This conclusion is consistent with hydrodynamics, where particles gain transverse momentum due to the radial flow present in hydrodynamic evolution. Recent hydrodynamic calculations, performed in Ref. [31], confirmed our findings. It is worth mentioning that alternative partial explanation can be found in the CGC framework, where the saturation scale grows with the number of produced particles, thus shifting produced gluons into the higher transverse momenta [41].

In Ref. [H-4] we proposed a new test of the CGC framework in p+A interactions. In the wounded nucleon model the number of produced particles at mid-rapidity grows linearly with the number of participants. This assumption was verified at the RHIC energies. In the CGC framework the situation is quite different. Here classical chromoelectric fields from different nucleons overlap so that the strength of the nucleus chromoelectric field grows slower than N_{part}. It originates from the non-linear QCD effects present in the saturation regime. By increasing the number of wounded nucleons the system gradually approaches the dense limit and the QCD processes $g + g \to g$ tend to slow down the growing strength of the classical gluonic field. It turns out that the number of produced particles at mid-rapidity in p+A grows as logarithm of the number of wounded nucleons. For example, for $N_{part} = 20$ the difference between CGC and the wounded nucleon model is roughly a factor of two, which could be tested experimentally. Unfortunately in p+A collisions there are serious difficulties in extracting the average number of participants at a given centrality (this problem is not present in A+A), thus we proposed to measure the number of produced particles at mid-rapidity vs. the number of produced particles close to a nucleus fragmentation region. The latter is proportional to the number of participants in both frameworks (in this region particles originate from a nucleus large-x partons, where we do not expect to have saturation effects.

Another way to test possible CGC effects in p+A collisions is measurement of the transverse momentum of produced hadrons as a function of rapidity. As shown in Ref. [H-3], the mean transverse momentum of particles in hydrodynamics is larger on a nucleus side than on a proton side (in central collisions). It stems from the fact that the larger number of particles on a nucleus side makes hydrodynamic evolution more effective. In the CGC framework we observed quite the opposite effect, which is easy to understand: particles produced on a nucleus side originate from a nucleus large-x gluons. Particles on a proton side originate from a nucleus low-x gluons. The saturation scale is larger for low-x gluons (high density of gluons). Consequently, particles going in a nucleus direction have smaller transverse momentum than particles going in a proton direction. In the CGC framework the average transverse momentum of produced particles is closely related to the saturation scale that explains the effect found in Ref. [H-3]. We hope that this observation will help to distinguish between competing models of p+A.

One of the strongest arguments in favor of collectivity (hydrodynamics, cascade models) in p+A collisions is an approximate equality of four-, six- and eight-particle elliptic flow cumulants. In a collective scenario multi-particle azimuthal correlations originate form the same *global* source (fireball), in contrast to, e.g., correlations form resonance decays, which are *local*. In Ref. [H-2] we demonstrated that in p+A interactions the elliptic (and triangular) flow coefficient extracted from the two-particle correlation function is larger than the one extracted from the four-particle correlation function, which in turn is approximately equal to the flow coefficient obtained from the six- and eight-particle correlation functions. Similar conclusions were also obtained in Ref. [42]. This observation is not trivial since higher order flow cumulants are very sensitive to details of the spacial distribution of matter created in p+A. Such relation between higher order flow cumulants is not obvious in the CGC framework, where, e.g, the four-particle cumulant seems to have the wrong sign [43]. Preliminary CMS data on multi-particle flow cumulants [44] in p+A and peripheral A+A collisions clearly support the collective scenario in such interactions.

Recent experimental results at RHIC and the LHC [19–26] demonstrate striking similarity between high-multiplicity p+p, p+A, d+A and A+A collisions. The latter is usually described by hydrodynamics, indicating that a strongly interacting matter (quark-gluon plasma) is produced. The matter in the fireball behaves as nearly perfect fluid and the system is not far from local thermal equilibrium. Recent hydrodynamic calculations [27–34] in p+A and d+A interactions reproduced the experimental data, indicating that also in these small systems the strongly interacting fireball is produced. This interpretation is interesting but not fully satisfactory. For example, the elliptic flow coefficient is large up to 5 GeV (transverse momentum), where it is not easy to justify hydrodynamics. Systems created in p+A and particularly in p+p collisions are rather small and it is not obvious to what degree the systems reach local thermal equilibrium. Another problem of hydrodynamics is its effective nature, namely, the model has many parameters and it is not obvious whether the apparent success of hydrodynamics reflects the fact that indeed its is the right language to describe p+A, or it reflects its flexibility to fit data.

In Refs. [H1] and [38] we simulated p+p, p+A and peripheral A+A collisions in the AMPT model, where the rigorous assumptions of hydrodynamics are not needed. We showed that the incoherent elastic scattering of partons, with a reasonable partonic cross-section of $1.5 - 3$ mb is sufficient to understand a great deal of p+p, p+A and peripheral A+A data. We also argued that the average number of collisions per parton is roughly two, which can explain why hydrodynamics is so effective in describing p+A data.

5. Other accomplishments

I author or co-author 40 publications (excluding published conference proceedings), 28 of them where published after Ph.D. Additional three papers are now under consideration in PRL, PRC and PLB. The full list of my papers can be found elsewhere.

Since 2003 I have been working on various aspects of high-energy hadronic physics. In particular, I was involved in (i) searching for the QCD critical point via. cumulants of net-baryon number [45,46] (Refs. [47,48]), (ii) interpretation of RHIC data in context of the chiral magnetic effect [49] (e.g., Ref. [15]), (iii) exclusive Higgs boson production via. double pomeron exchange (e.g., Refs. [50, 51]) (iv) odderon physics in processes of exclusive J/ψ production (Ref. [52]), (v) studies of pion distribution function in the chiral quark model (Ref. [53]). In Refs. [54, 55] I studied the square-root of the Dirac equation, which allowed to derive supersymmetry together with the Maxwell and Yang-Mills equations. I find these papers particularly interesting.

Parametric summary of my papers

Web of Knowladge:
427 citations (excluding self-citations)
h-index = 14.

Conference talks

1. 11-th Polish Workshop on Relativistic Heavy-Ion Collisions, Warsaw, 01/2015
   Centrality dependence of high energy jets in p+Pb collisions at the LHC

2. The 30th Winter Workshop on Nuclear Dynamics, Galveston TX, USA, 04/2014
   Saturation, hydrodynamics and parton scatterings in p+p and p+A collisions

3. Frontiers of Hadronic Physics: Brains Recirculate Two, Brookhaven National Laboratory, USA, 03/2014
   Multi-particle eccentricities in A+A and p+A collisions

4. APS Meeting, Denver CO, USA, 04/2013
   LPV and Chiral Magnetic Effect: Status and open questions

5. Brain Workshop, Brookhaven National Laboratory, USA, 03/2013
   Making sense of the ridge in pp and pA

6. CPOD 2013, Napa CA, USA, 03/2013
   Baryon number conservation and limited acceptance vs. cumulants of net proton distribution, and a few slides about v_2 splitting

7. Quark Matter 2012, Washington, D.C., USA, 08/2012
   Baryon number conservation and limited acceptance vs. cumulants of net proton distribution

8. The first heavy ion collisions at the LHC - HIC10, CERN, 08/2010
   Local parity violation - measurement, new observable and alternative contributions

9. The Berkeley School 2010, Berkeley CA, USA, 06/2010
   Remarks on possible local parity violation in heavy ion collisions

10. RHIC and AGS Annual Users' Meeting, Brookhaven National Laboratory, USA, 06/2010
    Remarks on possible local P-violation in heavy ion collisions

11. Joint Workshop, Brookhaven National Laboratory, USA, 12/2009
    Remarks on possible P-violation in heavy ion collisions

12. Epiphany 2009, Kraków, 01/2009
    Forward-backward multiplicity correlations in proton-proton and nucleus-nucleus collisions

13. International NA49 Collaboration Meeting, Kraków, 05/2008
    Wounded quarks and diquarks

14. IV Polish Workshop on Relativistic Heavy-Ion Collisions, Kraków, 05/2007
    Wounded quarks and diquarks in heavy ion collisions

15. Workshop on Low-x Physics, Lisbon, 06/2006
    Exclusive J/ψ production in pp and $p\bar{p}$ collisions and the QCD Odderon

16. Cracow School of Theoretical Physics, Zakopane, 05/2006
    Exclusive J/ψ production in pp and $p\bar{p}$ collisions and the QCD Odderon

17. Rencontres De Moriond, 40th anniversary, QCD and high energy hadronic interactions, Włochy, 03/2006
    Exclusive J/ψ production in pp and $p\bar{p}$ collisions and the QCD Odderon

18. Workshop on Low-x Physics, Sinaia, 07/2005
    Inclusive and exclusive double diffraction

19. The Future of Forward Physics at the LHC, Manchester, 12/2004
    Inclusive and exclusive double diffraction

I gave several seminars (invited) at: University of Illinois at Chicago, Stony Brook University, McGill University, Yale University, The City College of New York and Argonne National Laboratory.

Teaching and public outreach

1. Two of my papers were selected as RIKEN Research Highlight and were presented, e.g., in phys.org
   http://phys.org/news/2013-08-experimental-interacts-high-energies.html
   http://phys.org/news/2013-12-protons-ions-quark-gluon-plasma-liquid.html

2. 2007/2008, University of Alberta, 15 hours. Classes in statistical physics with 3D simulations using Visual Python (VPython).

3. 2003 – 2006, Jagiellonian University, three years, 90 hours each: basic physics for mathematicians and biologists, laboratories for biologists, wave phenomena for computer scientists.

Grants

1. Grant NCN UMO-2013/09/B/ST2/00497 (2014-), Investigation of the hadronisation process by analysis of inter particle correlations, investigator
2. Grant NCN, N202 125437 (2009-2012), Description and evolution of matter created in high energy collisions, investigator
3. PhD Grant (promotorski), MNiSW, N202 060 31/3199 (2006-2007), Double pomeron exchange processes in an effective model, investigator

Other

1. The Foundation for Polish Science, the KOLUMB fellowship, 2009
2. The Foundation for Polish Science, the START stipend, 2006 and 2007.

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