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WOUNDED NUCLEONS, WOUNDED QUARKS, AND RELATIVISTIC ION COLLISIONS*

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A concept of wounded nucleons and/or wounded quarks plays an important role in parametrizing and to some extent explaining many a feature of the relativistic ion collisions. This will be illustrated in a historical perspective, up to and including the latest developments.

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1. Hadron–nucleus collisions

Thirty years ago Andrzej Białas introduced the concept of a wounded nucleon, that is a nucleon that has interacted at least once. The Wounded Nucleon Model [1] — as usual — started from experimental observations concerning high energy hadron–nucleus interactions (see Fig. 1). A series of Fermilab experiments [2], a European NA5 experiment [3] and lots of emulsion data have led to a somewhat surprising regularity: the average charged particle multiplicity increases in such collisions more slowly than the number of individual nucleon–nucleon collisions. This number, denoted usually by ν is given by

$$\nu = \frac{A\sigma_{hp}}{\sigma_{hA}} \tag{1}$$

and the data gives the following dependence of the ratio of charged particles produced in hadron–nucleus collision to that for hadron–proton collision:

$$R = \frac{\langle n\rangle_{hA}}{\langle n\rangle_{hp}} = \frac{(1+\nu)}{2}\,. \tag{2}$$

This is just the ratio of the number of participants in hadron–nucleus (1 from hadron and ν from nucleus of mass A) and hadron–proton (2). The Wounded

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Nucleon Model, WNM, states that particle production in a nuclear collision is the superposition of independent contributions from the wounded nucleons in the projectile and target. Thus one can just measure particle production in elementary collisions, count the wounded/participating nucleons in the target, and obtain the total particle multiplicity in hadron–nucleus collision. This is a rather strong statement, as one could expect that after each new hit, the nucleon would be less prone to produce new particles.

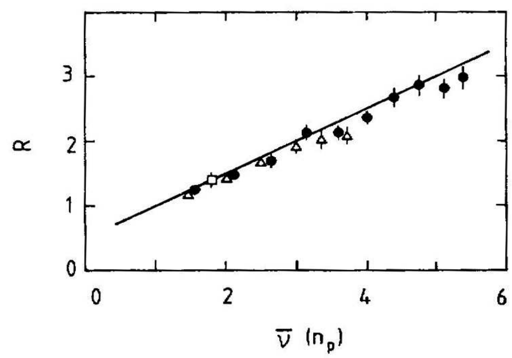

Fig. 1. The ratio of charged particle multiplicity in p–A collisions to that in p–p collisions *vs* the average number ν of projectile collisions. A line shows Eq. (2), Ref. [3].

In Fig. 2 [4] we observe a remarkable success of the model. The ratio of the total charged particle multiplicity from hadron–nucleus collisions, normalized to this multiplicity in elementary collisions, remains directly proportional to half the number of participants. This holds both for the AGS energy range and the RHIC data on d–Au at 200 GeV/c. Note that not only we have the proportionality to the number of participants, but also the scaling with elementary collisions data.

At the time when new experiments on nucleus–nucleus collisions were planned, new ideas appeared, originating from the wounded objects concept. Białas *et al.* [5] and Anisovitch *et al.* [6] have suggested that it is rather the number of wounded quarks in the colliding objects that determines the produced particle multiplicity. Thus the ratio of particle multiplicity in nucleus–nucleus collision to that in elementary collision would be given by

$$R_{AB} = \frac{\nu_{AB}}{\nu_{qA}\nu_{qB}}\,. \tag{3}$$

From the concept of wounded quarks to specific model predictions — it can be a long way. One can calculate the number of wounded quarks assuming a hypothetical value of quark–quark cross section, and a spatial distribution

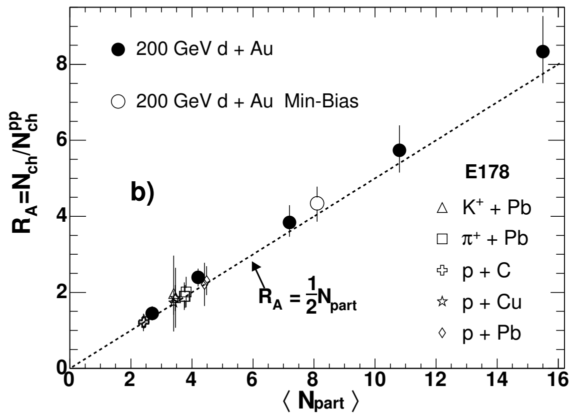

Fig. 2. The ratio of the total charged particle multiplicity in hadron–nucleus and deuteron–nucleus collisions to that in hadron–proton collisions at the same energy, as a function of the number of participants, Ref. [4].

of nuclear matter — and hence quarks — in the colliding objects. The second step, particle production from a wounded quark, is open for many assumptions.

In 1982 Białas [7] has given specific predictions for nuclear collisions, based on the Additive Quark Model, AQM. In this model, particle production would originate from three sources: breaking of the color strings between quarks from the projectile and the target, fragmentation of the wounded quarks, and fragmentation of the spectator quarks.

I cannot refrain here from quoting one of the first nucleus–nucleus collision data, compared to 'wounded nucleons' and 'wounded quarks' model predictions. These were the results of a series of JINR Dubna experiments with proton, deuteron, alpha and carbon beams at 4.2 GeV/N (the highest energy nuclear beams at the time), incident on tantalum target [8]. The ratio of multiplicities from C–Ta to that from d–Ta was measured as 3.6 ± 0.2, while the model gave 3.0, and the ratio of α–Ta to d–Ta was 1.7 ± 0.1 while the model predicted 1.6.

With the first data on particle production from really high energy nucleus–nucleus collisions, an attempt at parametrizing produced particle multiplicities in terms of wounded objects was undertaken by Kadija *et al.* [9]. They have shown a consistent parametrization of production rates of negative hadrons — proportional to the number of wounded nucleons, and neutral kaons — proportional to the number of wounded quarks — as shown in Fig. 3. This was at the epoch when the highest energy was CERN SPS 200 GeV/N, and the 'heavy ion' was an oxygen, and at most — sulphur.

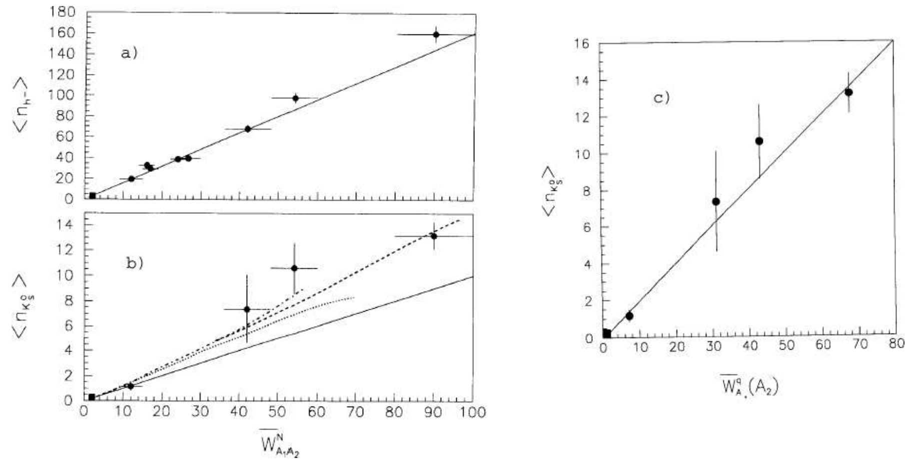

Fig. 3. The average negative hadron multiplicity (a) and neutral kaon multiplicity (b) from $A1$–$A2$ collisions at 200 GeV/N *vs* the number of nucleon participants. Part (c) shows the kaon multiplicity *vs* the number of wounded quarks, Ref. [9].

With the advent of higher statistics, higher energy and higher mass numbers of colliding nuclei, such simple parametrizations are not common. Yet a 'wounded object' concept has some very interesting come-backs. Based on the data from RHIC, $\sqrt{s}$ 200 GeV/N d–Au, a new version of the WNM was proposed by Białas and Czyż [10] (actually, it was presented for the first time at the Zakopane School 2 years ago!). The basic assumption is that particle production can be represented as the superposition of independent contributions from wounded w nucleons in the projectile and the target. This applies not only to the total charged particle multiplicity, but to the longitudinal spectra as well. The density of particles in nucleus A–nucleus B collision is given by

$$\frac{dN_{AB}}{dy} = w_A F_A(y) + w_B F_B(y) \tag{4}$$

and the model requires

$$F_B(y) = F_A(-y) \tag{5}$$

(F is the contribution from a single wounded nucleon).

The first consequence is that

$$R_{AB}(y=0) = \tfrac{1}{2}(w_A + w_B)\,. \tag{6}$$

This has been very well checked by RHIC data, as shown in Fig. 4.

For the full (pseudo) rapidity range, the authors construct symmetric and antisymmetric components:

$$G(\eta) = \frac{dN(\eta)}{d\eta} \pm \frac{dN(-\eta)}{d\eta} \tag{7}$$

and compare the model with data on symmetric and antisymmetric part of spectra for several centralities of d–Au, as measured by the PHOBOS experiment at RHIC. This is illustrated in Fig. 5. Given rather large experimental uncertainties, the parametrization of multiplicities and spectra is very reasonable. The authors stress that the contribution from one wounded nucleon extends over almost full rapidity range.

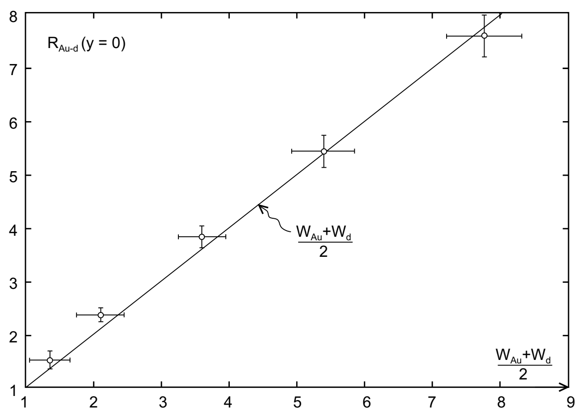

Fig. 4. Charged particle multiplicity at midrapidity for deuteron–gold collisions at 200 GeV/N compared with the predictions of the Wounded Nucleon Model, Ref. [10].

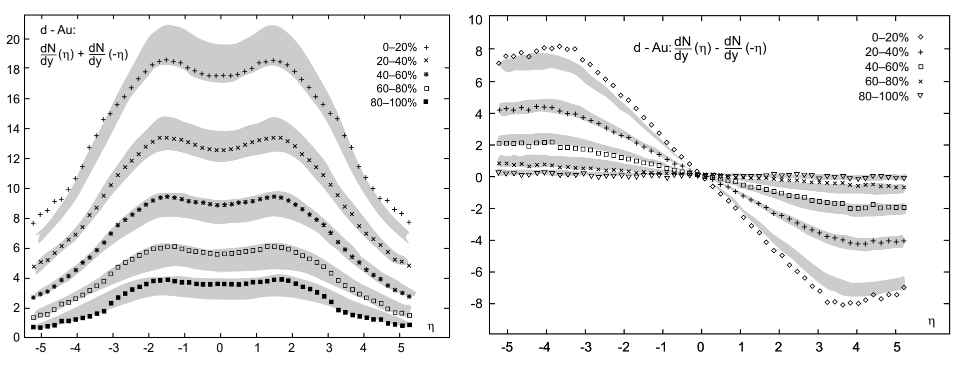

Fig. 5. Symmetric and antisymmetyric part of the d–Au inclusive cross section compared with the predictions of the Wounded Nucleon Model, Ref. [10].

An interpretation is given in a paper by Białas and Jeżabek [12]. The authors propose a two step particle production: multiple color exchanges between partons from the projectile and the target, and subsequent particle production from color sources created in the first step. In authors' interpretation, a reasonable description of data by the model implies some sort of saturation — the number of color sources per unit rapidity is independent of the number of color exchanges between the projectile and the target.

Thus for global characteristics of particle production in hadron–nucleus collisions the WNM works surprisingly well. One should stress that this applies to the total charged particle multiplicities. A more differential study of identified particles, such as strangeness carrying mesons and baryons, can not be described as a simple superposition of hadron–nucleon collisions [11].

2. Nucleus–nucleus collisions

For the 'true' nuclear collisions, when two heavy nuclei collide, the Wounded Nucleon Model does not work. This is clearly seen from Fig. 6 [13], which shows the total charged particle multiplicity per participant pair for several centralities of Au–Au collisions at four RHIC energies. To the first approximation, thus normalized multiplicity is flat as a function of the number of participants — but it clearly exceeds the multiplicity from proton–proton collisions.

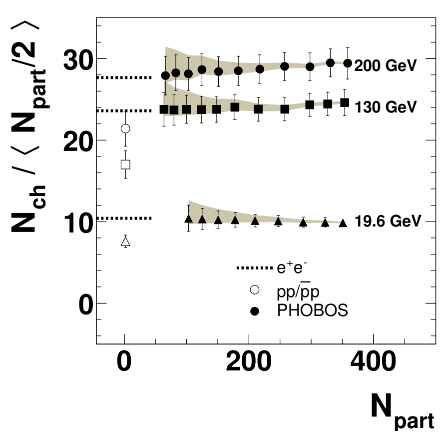

Fig. 6. Total charged particle multiplicity per participant pair for Au–Au collisions at four RHIC energies, *vs* the number of nucleon participants. Notice the p–p points lying systematically lower, Ref. [13].

Still, the proportionality of these multiplicities to the number of participants holds. Various approaches to specific choice of 'effective energy' for proton–proton collisions were used. In Fig. 7 we see a clear proportionality of nuclear multiplicities normalized to proton–proton multiplicity to the number of participants, both for Au–Au and d–Au collisions — but the protonic multiplicity is taken at twice the Au energy per nucleon [13]. This supposedly accounts for the leading baryon effect. Fig. 8 again shows this proportionality — but with Au–Au data normalized to the multiplicity in e^+e^- collisions [14]: an apparently unexpected universality in particle production from vastly different objects. The surprising scaling of particle production in nuclear collisions with the number of participating nucleons extends to other characteristics, such as rapidity spectra and even transverse distributions. Fig. 9 shows a comparison of pseudorapidity distributions for Cu–Cu and Au–Au collisions, measured for the same number of participating nucleons, at 62.4 and 200 GeV/N, by the Phobos Collaboration [15], with the distributions practically identical. This geometric scaling works also for transverse spectra, and, surprisingly enough, extends even for transverse momenta as high as 6 GeV/c, as illustrated in Fig. 10 [16].

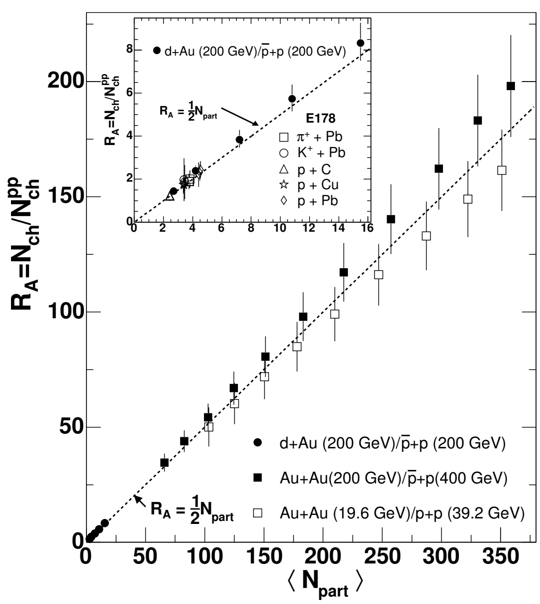

Fig. 7. Ratios of the total particle multiplicity for nucleus–nucleus collisions for several energies, over the multiplicity in p–p collisions, *vs* the number of participating nucleons. For Au–Au interactions the p–p data is taken at twice the cms energy, Ref. [13].

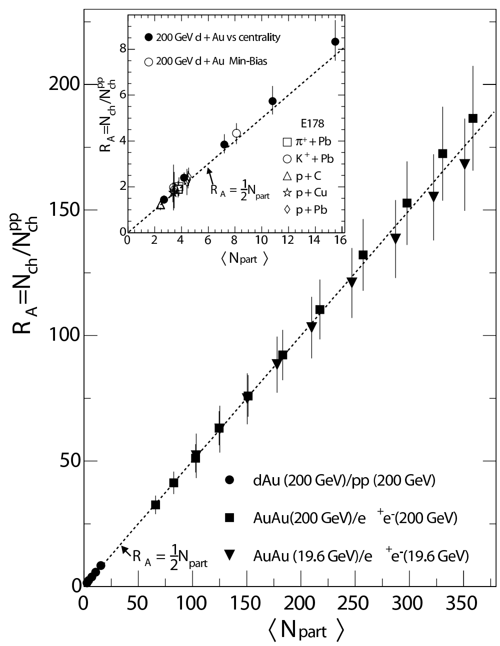

Fig. 8. Same as Fig. 7, but the Au–Au data points are normalized to the multiplicity from $e^{+}e^{-}$ collisions at the same energy, Ref. [14].

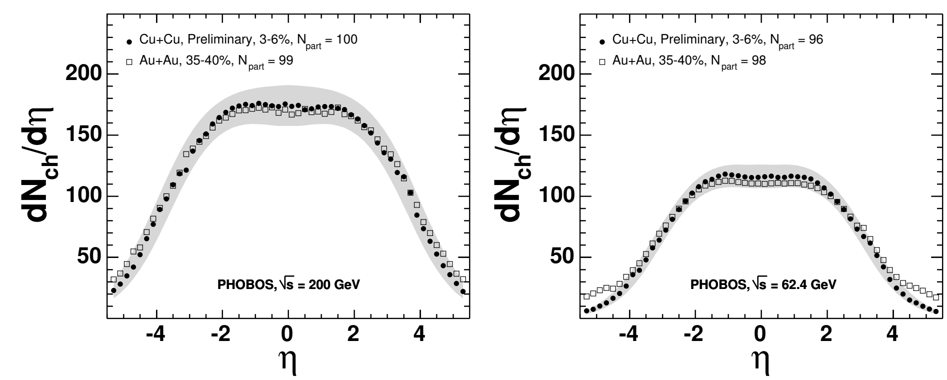

Fig. 9. Charged particle pseudorapidity distributions for Cu–Cu and Au–Au collisions, measured at the same centrality (number of nucleon participants) Ref. [15].

There is a recent revival of the wounded quark parametrization ideas. Eremin and Voloshin [17] draw attention to the fact that midrapidity density of charged particle production in nuclear collisions, normalized to p–p data, shows an increase with the number of nucleon participants, as seen in Fig. 11. The authors calculate both numbers: of nucleon and quark

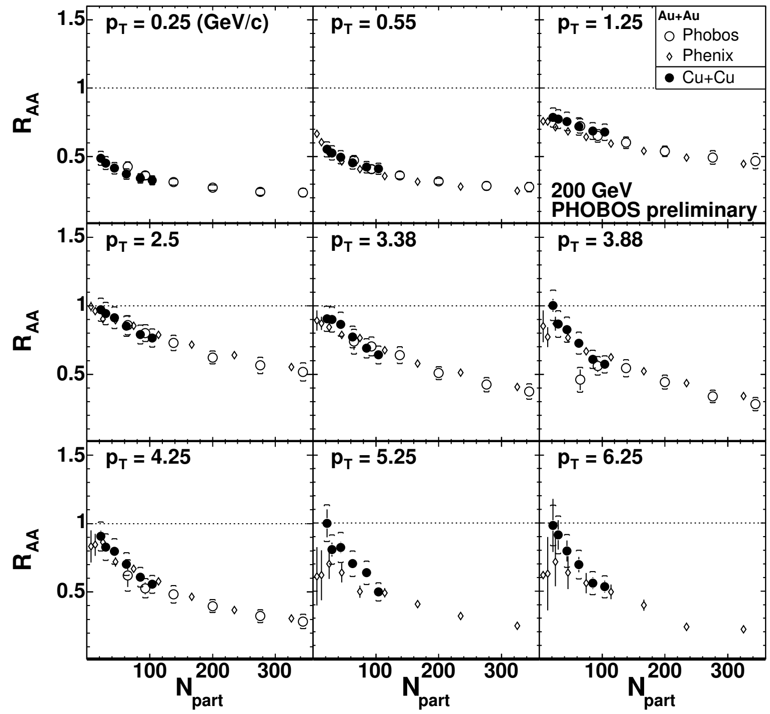

Fig. 10. Nuclear modification factor in bins of p_T, *vs* N_{part} for Cu–Cu and Au–Au at $\sqrt{s}$ 200 GeV/N, Ref. [16].

participants, using Nuclear Overlap Model of Eskola *et al.* [18] — see the illustration in Fig. 12. Then they parametrize the RHIC Au–Au results for midrapidity particle density with the calculated participant numbers. As seen from Fig. 13, scaling by quark participants flattens out the centrality dependence — this results from relative increase in the number of interacting constituent quarks in more central collisions.

Netrakanti and Mohanty [19] have applied the same idea also to the SPS data at $\sqrt{s}$ 17.2 GeV/c on charged particles and γ production in Pb–Pb collisions (WA98), illustrated in Fig. 14. Bhaskar De and Bhattacharyya [20] have analyzed the NA49 data on identified particle production. They claim to observe a better and more unified description of midrapidity density yields for various secondaries with the quark participant picture. A word of caution is in order here. The treatment of the NA49 data is somehow inconsistent, the authors mixing the integrated yields with midrapidity yields for different particles. In a forthcoming study [21] the data from NA49 will be consistently compared with constituent quark scaling.

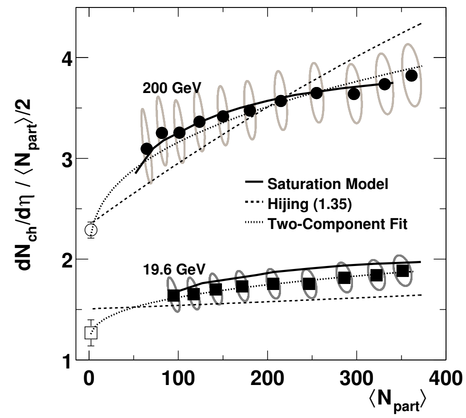

Fig. 11. Midrapidity charged particle multiplicity per participant pair for Au–Au collisions *vs* the number of participants, Ref. [13].

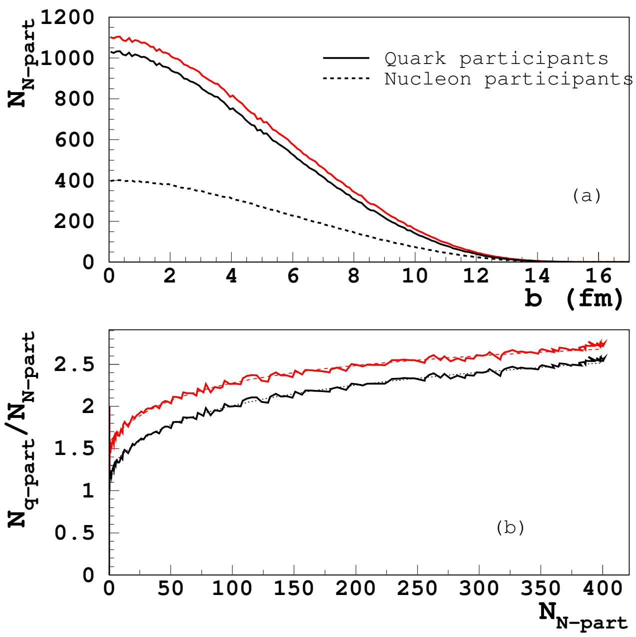

Fig. 12. (a) Calculated number of quark (solid line) and nucleon (dashed) participants *vs* impact parameter. (b) Ratio of quark to nucleon participants vs the number of nucleon participants. Two sets of lines correspond to two values of quark–quark cross section, Ref. [17].

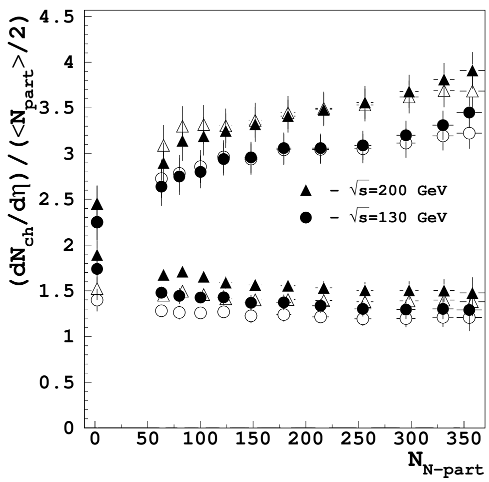

Fig. 13. Midrapidity charged particle multiplicity per nucleon (upper) and quark (lower) participant pair, *vs* centrality. Results for quark participants are shown for σ_{qq} 4.5 mb (solid) and 6 mb (open symbols) Ref. [17].

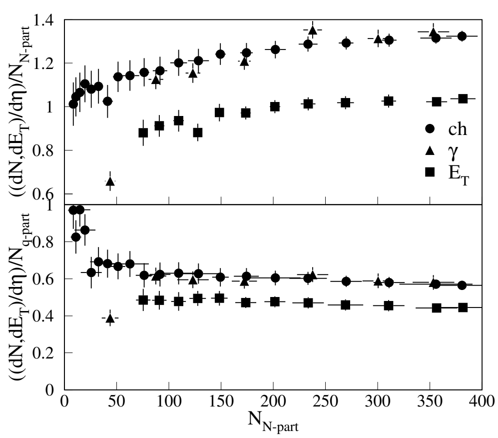

Fig. 14. Midrapidity charged particle, gamma quanta and transverse energy density from Pb–Pb collisions at SPS, per nucleon (upper) and quark (lower) participant *vs* the number of nucleon participants, Ref. [19].

Let it be stated here, that a detailed study of strange particle production in light and heavy ion collisions [22] has definitely ruled out a simple nucleon participant scaling.

The energy dependence of particle production in nuclear collisions, compared with this dependence of the production in elementary collisions, is a subject of another attempt at a description in terms of nucleon vs quark participants. The author, Nouicer [23] looks at the energy dependence of particle density per participant pair in central nucleus–nucleus collisions *vs* the same quantity in proton–proton collisions. In terms of nucleon participants, the two sets of data follow distinct lines, as seen from Fig. 15. With the normalization to the participant constituent quarks, both lines coincide. Yet a very debatable point arises. As first pointed out by Barbara Wosiek, the author normalizes proton–proton data by the number of quark participants for 'most central' collisions while the *pp* data comprise all minimum bias interactions. Normalization by 'minimum bias' number of quark participants disturbs the common trend of data, as indicated by large points in Fig. 15.

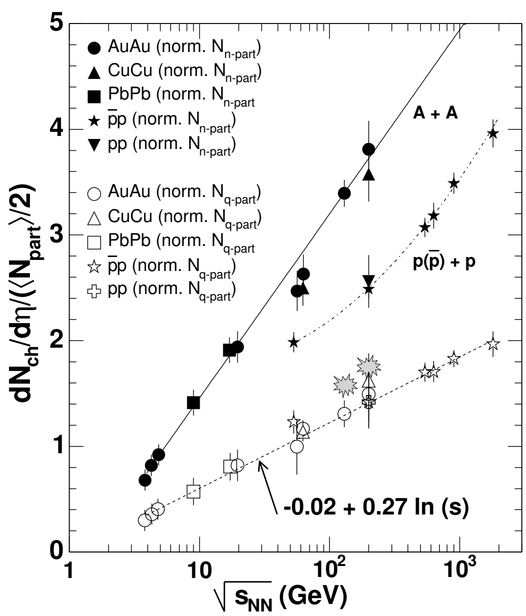

Fig. 15. Particle density per quark (open symbols) an nucleon (solid points) participant pair for central nucleus–nucleus collisions as a function of energy, and for proton–proton collisions. Two large points are calculated with number of quark participants from minimum bias *pp* collisions, Ref. [23].

3. Conclusions

In summary, the very idea of particle production originating from elementary constituents has a long history. The success of the Wounded Nucleon Model in the description of general characteristics of hadron–nucleus collisions in the wide energy range is remarkable. A more detailed study, *e.g.* strange particle production, does not follow the strict WNM predictions.

For heavier colliding objects, the Model fails. Attempts at a parametrization in terms of wounded quark participants seems to simplify the picture (but not to explain it!).

Obviously, the central heavy ion collisions are not a simple superposition of nucleon–nucleon collisions. At the same time, the observed dominance of 'constituent scaling' in the production of particles from very different colliding objects, at very different energies, remains a puzzle.

I would like to express my cordial thanks to Barbara Wosiek, for numerous enlightening discussions, in particular on the PHOBOS data, and helping me in securing many experimental plots. This work was partially supported by the Polish State Committee for Scientific Research (KBN) under grant No 1 P03B 006 30.

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