CONFERENCE SUMMARY*

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In this summary I briefly discuss some of the many interesting talks presented at this symposium.

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1. Introduction

To review the content of 75 interesting talks in a brief summary is apparently not possible. I therefore necessarily have to concentrate on a limited subsample, and apologise to all of you, who have presented valuable contributions, which I am not able to cover.

The QCD Lagrangian is simple, but the solution is very complicated. Not even the vacuum is understood. Quarks and gluons are always in a *medium*, also when in vacuum. We can compare with QED. In a medium the solutions to the simple Maxwell's equations exhibit strange phenomena, like lightning or superconductivity. The medium implies new degrees of freedom: massive electrons, phonons, quasiparticles in superconductors, spin waves, rotons, polarons, plasmons, *etc.* Also topological defects appear: monopoles, vortex lines, fractional charges. In liquid ^{3}He there are several different phases depending on temperature, pressure, and magnetic field. These phases are characterised by different effective field theories, which exhibit gauge symmetry and general relativity. At lower energy some symmetries get broken (just as in the Standard Model) and the result depends critically on the symmetry of the medium. Lorentz invariance is here a low energy phenomenon, which is broken at higher energies (*cf.* the talk by Teshima).

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Also in QCD different degrees of freedom are active in different media, *e.g.* in vacuum, inside nuclear matter, in a hadronic soup, or in a quark-gluon plasma. In the laboratory the two latter media are not in equilibrium, and the properties depend on both $\boldsymbol{r}$ and t. At this symposium results from different reactions have been presented: e^+e^-, ep, eA, hh, hA, AA, going from a more simple situation to higher and higher complexity. In this summary I will follow the same route from simpler towards more complicated environments.

2. "No medium"

At very short distances the medium is less important. Here perturbative QCD is expected to work well, with a coupling $\alpha_{\rm s}$ running as predicted by asymptotic freedom. That this is indeed the case was demonstrated by *Metzger*, who showed results from the LEP QCD Working group. Determinations of $\alpha_{\rm s}$ at different energies and from different observables give consistent results. He also gave a warning that power corrections do not give a fully reliable description of non-perturbative effects for shape variables. That perturbative QCD really works here was also shown by the results presented by *Gwenlan* for 3 jet events in DIS and by *Przybycień* for $F_{2,c}^{\gamma}$. Both these results were well described by NLO calculations.

3. In vacuum

It was suggested by 't Hooft that the QCD vacuum behaves like a dual superconductor. This means that the colour electric field is concentrated in fluxtubes or strings, which then implies quark confinement. The string hadronization model, in which a gluon acts as a transverse excitation on a string stretched between a quark and an antiquark, works very well for e^+e^--annihilation. A basic assumption in this model is that there is only one type of string, stretched between a colour triplet and an antitriplet, and the same type of string should also describe hadronization in *e.g.* DIS. *Zawiejski* presented results for BE correlation in DIS, and showed that both the source radius r and the strength parameter λ measured in DIS agree with the corresponding results in e^+e^-. No Q^2-dependence is observed, neither on the current nor on the target side in the Breit frame. The source is also elongated in the longitudinal direction, as previously seen at LEP, and consistent with the string model.

In the string model π^0 pairs (or two pions in an $I = 0$ state) can be produced as neighbours in rank, and therefore the correlation is expected to have a smaller radius. This is consistent with data, although the experimental results are not conclusive due to the large errors. Difficult to understand within the string picture is, however, the small radius for the (negative) correlation for protons and Λ. *Alexander* presented here results around 0.1 – 0.2 fm. This is, however, consistent with expectations based on the generalised Gottfried–Bjorken hypothesis, connecting the space-time position for a produced hadron to its 4-momentum (Białas, Zalewski *et al.*).

An interesting and important question concerns the possibility of *string interaction.* How wide are the strings? How close can they be before they interact? In a type I superconductor there is a rapid transition between the outside vacuum condensate and the interior of the fluxtube, with an approximately constant field. The width of such a fluxtube is expected to be of the order of 1 fm, and we would expect a large interaction between overlapping fluxtubes. In a type II superconductor the vortex lines have a rather thin core, inside which the condensate is destroyed. The field here extends further out into the condensate, and two such vortex lines interact strongly only when the thin cores overlap.

van Remortel showed results from $e^+e^- \to W^+W^-$ where both Ws decay hadronically. The two W decay with a distance in space and time of the order 0.1 fm, and it would be natural to expect some crosstalk between the two decay systems, some effect of colour reconnection or modification of the Bose–Einstein correlation. Here results for BE correlations were presented, and effects of a crosstalk is hardly seen, although there is a weak indication that a limited modification of the correlation corresponds to a larger source size. *Metzger* showed results from 3-jet events in e^+e^--annihilation, where the two string segments attached to the gluon conceivably could interact with each other. Also here the strings seem to interact very weakly.

String percolation was studied by *Pajares* and *Ranft.* In a string picture for nucleus-nucleus collisions many strings are stretched within a limited area. They may then fuse to form "ropes", with a larger effective string tension, which is expected to cause higher transverse momenta. In this formalism it is possible to describe both observed multiplicities and $p_\perp$-distributions. These observables can, however, also be described by other models, and more work is therefore needed to find discriminating observables.

Heavy quark hadronization exhibits some problems. In the process $c \to \psi$ it is unclear how the colour disappears if the $c\bar{c}$ system is produced in a colour octet state. *Pakhlov* showed that the ratio $(e^+e^-\to\psi c\bar{c})/(e^+e^-\to\psi X)$ is around 60%, which is much larger than expected from perturbative QCD. *Sciaba* showed that b fragmentation is well described by the string model (including the "Bowler correction", which accounts for the reduction in string area for massive quarks), but the cross section for $\gamma\gamma \to b\bar{b}$ is twice as large as expected.

Related to both the vacuum and "no medium" are the results shown by *Campana* on gluon fragmentation. Theoretical calculations for the multiplicity in gluon jets are usually presented for one hemisphere of a colour neutral two-gluon system. Here the maximum $p_\perp$ allowed for subjets is of the order of the total jet energy. In experimental 3-jet events the gluon jets are biased by the constraint that the subjet $p_\perp$ necessarily is limited by the resolution used in the jet finding algorithm. Campana showed that it is possible to extract results for "unbiased" gluon jets, and that these results interpolate smoothly between results for unbiased jets at 5 GeV in Υ-decay and at 40 GeV from events with two parallel heavy quark jets opposite to a gluon jet in Z-decay.

Possibly one could say that the results on the proton form factor also are related to the vacuum condensate. *Negrini* presented data in the timelike region up to 14 GeV^2, from $p\bar{p}$ collisions with a gas-jet target. For large s the result is well described by the "QCD behaviour" $G_M \propto 1/(s^2 \ln(s/\Lambda^2))$.

4. Dense gluonic state

An introduction to low-x physics and saturation was presented by *Arnesto.* At small x the phase space for $k_\perp$-ordered chains, à la DGLAP, becomes small. Thus $k_\perp$-non-ordered ladders become more important, and the $k_\perp$-factorization formalism and BFKL evolution become relevant. At small x gluonic ladders are expected to dominate, and give a fast increase for the parton densities. The structure function F_2 does indeed grow like a power for small x, as predicted by BFKL, but the data can also be reproduced by DGLAP evolution assuming a sufficiently singular non-perturbative input gluon density. Further insight into the true nature of the parton evolution can be obtained from a direct determination of the gluon density and more exclusive observables including jets or single hadrons in the forward direction.

Determinations of the gluon density differ significantly between different fits to experimental data. To better constrain the fits we need experimental data for the longitudinal structure function, F_L, which is more directly connected to the gluon density. Some new results from H1 were presented for a limited set of x-values by *Łobodzińska.* However, for a determination of the x-dependence further data from running with lower proton energy is needed.

Analyses of the $k_\perp$-factorization formalism were presented by *Jung*, who showed MC results for the CCFM and the LDC models, implemented in the Cascade and the LDCMC event generators. More inclusive observables are well described within the collinear factorization formalism. However exclusive observables involving a large rapidity separation, *e.g.* forward jets at

HERA, are badly reproduced in calculations based on collinear factorization, and much better described in a $k_\perp$-factorized formalism (*cf.* also the talk by *Magill*). This is also the case for heavy quark production at the Tevatron, although, as shown by *Oliver*, the production of b-quarks at HERA is also well reproduced by NLO calculations with collinear factorization.

At small x the gluon density becomes very large, and an essential question is if, or when, non-linear terms in the evolution become important, and the gluon density saturates. A possible indication is given by a scaling property predicted by a saturation model, saying that a single scale, $\tau = \frac{Q^2}{Q_0^2}(\frac{x}{x_0})^\lambda$, should dominate the structure at low-x. This scaling property is strikingly well satisfied by experimental data. The effects of non-linear terms in the evolution were discussed by *Staśto*, who studied solutions to the the Balitsky–Kovchegov equation, and showed how these terms suppress the gluon density for small x and small $k_\perp$. The gluon density is also important in hh and AA collisions, and saturation is expected to show up earlier in nuclei. However, saturation is *not* seen in dA collisions at RHIC, as demonstrated by *Steinberg*.

Knowledge of the gluon density for small x is also essential for an understanding of minimum bias events and minijets in high energy pp collisions. This is important, not only as an interesting question in itself, but also because a good understanding of these features is necessary for a reliable interpretation of possible signals for "new physics" at LHC. *Korytov* presented data for minimum bias events at the Tevatron, and showed that results from a tuned PYTHIA MC agrees well with experimental data. The main parameters in the tuning are the cut-off, $p_{\perp\min}$, for soft subcollisions and the proton matter distribution. *Butter* showed extrapolations to LHC, which indicate an enhanced underlying event activity almost by a factor of 3 compared to the Tevatron. *Szczurek* applied the $k_\perp$-factorization formalism to hh collisions, and showed how the density of low-$p_\perp$ minijets is stabilized in this formalism.

A very interesting idea was presented by *Pirner*, who discussed the possibility of a new 2nd order phase transition between a dipole gas and a dipole liquid at high gluon densities. The basic properties of this transition and the critical point are here determined by the Z_3 symmetry in SU(3).

5. Cold nuclear matter

An introductory review to propagation in (cold) nuclear matter was presented by *Pirner*. Important questions concern the properties of gluon radiation, parton rescattering, string loss, and hadron absorption. *van der Nat* showed results on quark propagation from eA collisions at HERMES. Large attenuation is observed for small ν, and a strong A-dependence.

The results are not fully described by any model. In nuclear absorption models we expect an A-dependence $\propto A^{1/3}$, while for models based on pQCD it is expected to be $\propto A^{2/3}$. The data indicate a power closer to 2/3, which thus favours the QCD-based models.

Comparisons of π^+/π^- ratios in pp, np, and AA collisions were presented by *Rybicki*. For leading particles, where valence quarks dominate, these ratios are similar. Thus the valence quarks in a nucleus and valence quarks in a nucleon propagate in the same way inside nuclear matter.

Gottschalk presented results from the SELEX experiment on doubly charmed baryons produced in pA and $\Sigma^- A$ collisions. Possible signals for 5 different states are observed. The states are still waiting for confirmation from other experiments.

6. Dense (hot?) matter

A large part of the symposium was devoted to the properties of matter at very high density in high energy heavy ion collisions, where the most important questions are: Has the system reached thermal equilibrium, and has it passed a phase transition to a quark-gluon plasma? *Gaździcki* summarised the signals for deconfinement, which have been observed at the CERN SPS accelerator: The kink in the number of produced pions per wounded nucleon, the strangeness enhancement, and the step in the slope parameters at $s_{NN}^{1/4} \approx 2$ GeV$^{1/2}$.

A wealth of new data from RHIC were presented, together with comparisons to model calculations. A review of particle spectra was presented by *Calderon*, who demonstrated that thermodynamical models with flow fit almost too well. The $p_\perp$ distributions fall off as exponential (blueshifted) thermal spectra for almost 4 decades, with a small tail of faster particles from high $p_\perp$ jets. Also particle ratios are well described by models with flow in the form of a Hubble expansion (meaning that the expansion velocity is proportional to the distance to the centre of the collision), followed by a fast freeze-out. Successful models with this property include *e.g.* the Blast–Wave model (*Lisa*), the Kraków model discussed by *Broniowski*, and the Buda–Lund model presented by *Ster*.

The tail of faster particles from jet fragmentation dominates for $p_\perp >$ 5 GeV. Very noticeable is here the absence of an away side jet in Au+Au collisions. This is consistent with the formation of dense matter, where only hard partons created close to the surface, and moving radially outwards, can escape and produce observable jets. This feature is in striking contrast to d+Au collisions, in which the away side jet is very similar to the corresponding jets in pp collisions.

Further insight into the properties of the flow of the dense matter can be obtained from resonance production. *Fachini* presented data for K^* and ϕ production, which show much less dependence on centrality than kaons and (anti)protons. Thus $\langle p_\perp \rangle$ is essentially independent of the total multiplicity of charged particles, and thus to the centrality of the collision. The reason for this is not clear. It was suggested that for K^* rescattering dominates at peripheral collisions, while regeneration becomes significant for central collisions. ϕ mesons, which have a smaller radius, appear not to follow the same collective outward flow as the pions, kaons, and protons.

Bose–Einstein correlations contribute essential constraints to the models for heavy ion collisions. Indications for thermalization are here obtained also in fixed target experiments. *Alexander* showed how the radius grows linearly with $A^{1/3}$. This agrees with expectations from a classical Hanbury Brown–Twiss effect, and thus supports the formation of a thermalized system. *Appelhäuser* presented data from CERES, which show that $R_{\rm long}$ depends linearly on the transverse mass $m_t = (m_\pi^2 + k_t^2)^{1/2}$. This is consistent with a Hubble expansion, for which Sinyukov has derived the relation $R_{\rm long} = \tau_f \cdot \sqrt{T_f/m_t}$. Assuming a temperature T_f = 160–120 MeV the data correspond to a lifetime $\tau_f \approx$ 7–8 fm/c.

The RHIC experiments have produced a large amount of data on Bose–Einstein correlations. Of particular interest is the angular anisotropy, which was discussed by *Heinz* and by *Lisa*. For non-central collisions the initial interaction region is not axially symmetric. This also gives an asymmetric expansion, and different source radii for particles moving in, or perpendicular to, the event plane. Clear oscillations in the asimuthal angle are observed at all k_t, and this information can be used for a time-space separation of the freeze-out. A detailed analysis indicates that the flow velocity grows proportional to t, and the values for the longitudinal source size $R_{\rm L}(m_t)$ are then consistent with a freeze-out time $\tau_0 \sim 9$ fm/c.

Kisiel showed how emission asymmetries and radial flow are reflected in correlations for non-identical particles. Double ratios are taken for πK pairs with $(\vec{v}_\pi - \vec{v}_K)\cdot(\vec{v}_\pi + \vec{v}_K)$ positive and negative and with $k_{\rm out}$ also positive and negative (where $k = p_1 - p_2$). A clear deviation from unity is observed in data from STAR, while no such asymmetry is seen in corresponding data for $k_{\rm side}$ or $k_{\rm long}$. The result is interpreted as a shift of 5 fm in *either* x or t.

As conclusion the RHIC data on particle flow and BE correlations are well described by thermal models based on Hubble expansion followed by a sudden freeze-out, where the time for the chemical freeze-out is the same as for the thermal freeze-out. Whether the medium in the flow is a plasma or a hadron soup is a much more complicated question, which I think at present does not have a clear answer. One here has to extrapolate from the freeze-out time in order to determine the properties of the initial conditions, which are not directly accessible. A warning was here given by Broniowski: It makes a large difference if resonances are included in the freeze-out or not, which makes it difficult to determine the freeze-out temperature with any certainty. Within the Kraków model an analysis including heavy resonances at $T = 165$ MeV and also including experimental cuts, agrees approximately with a simple model without resonances at $T = 110$ MeV.

7. Other topics

7.1. *Diffraction*

The basic nature of diffraction is still not known to us. What is the Pomeron? Just a pole or a cut in a complex plane? Is it 2 gluons, a gluon ladder, or is it many gluons? Does it have a $q\bar{q}$ content? I will here only mention the presentation by *Golec-Biernat*, who showed that there is indeed a close connection between the dipole picture of diffractive DIS and the Ingelman–Schlein model for the Pomeron.

7.2. *Special tools*

Koch described how event-by-event correlations can be used to illuminate basic dynamic properties, and preliminary applications of this method to πp and Kp scattering were presented by *Wu*. Possible information from events with very high multiplicity (VHM events) was discussed by *Sissakian* and *Kokoulina*.

7.3. *Cosmic rays*

Introductions to cosmic ray physics were given by *Lipari* and *Engel*, with special emphasis on the problems related to the "knee" in the spectrum around 10^6–10^7 GeV. The conclusion by *Haungs* is that the knee is caused by light primary elements, that the composition becomes heavier above the knee, and that no "new" physics is needed. Interesting results from the very large AGASA extensive air shower detector were presented by *Teshima*. 11 events are recorded above 10^{11} GeV, although protons above this energy are expected to disappear due to collisions with photons in the microwave background radiation, via the reaction $p\gamma \to \Delta \to N\pi$. If those events are confirmed (and cannot be explained as the tail of standard contributions), it calls for some unconventional explanation. Here Teshima suggested that special relativity may be violated at high energies, while *Sarkar* instead proposed the existence of massive relic particles in the halo of our galaxy.

8. Thanks

Finally, on behalf of all participants, I want to thank the organizers and the secretaries for a very successful and very well organized symposium, with perfect conditions in a nice atmosphere.