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Strangeness suppression in proton-proton collisions

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Can the yield of a strange particle serve as the smoking gun for the creation of a quark-gluon plasma? In order to answer this question one has first to understand strange particle production in elementary *pp* reactions. Here one observes a big difference between BNL RHIC and CERN SPS energies. The mass yield distribution is much steeper at SPS than at RHIC. Surprisingly the form of the mass yield for (e^+e^-) annihilation, which is almost energy independent, agrees perfectly with *pp* reactions at RHIC. After having verified that the recently advanced NEXUS approach reproduces well the existing data, we interpret the results: strangeness is suppressed in proton-proton collisions at SPS energy as compared to electron-positron (e^+e^-) annihilation due to the limited masses of the strings produced in the reaction.

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I. INTRODUCTION

Strangeness enhancement in ultrarelativistic nucleus-nucleus collisions has been proposed as a signal for the formation of a quark-gluon plasma [1]. Therefore at CERN Super Proton Synchrotron (SPS) energies strangeness production has been investigated in detail and it is as well a major part of the BNL Relativistic Heavy Ion Collider (RHIC) research program. When one talks about strangeness enhancement one has first to specify the point of reference, which are usually proton-proton reactions. How meaningful is this point of reference? If one compares the presently available 4π multiplicities of antibaryons measured in heavy ion reactions at SPS energy (17.3 GeV) [2] with the ones observed in e^+e^- annihilation at 91 [3] or at 29 GeV [4,5], one does not find strangeness enhancement. If one compares, however, to *pp* data at 19.4 GeV [6] one finds such an enhancement, despite of the fact that particle production seems to be universal in all kinds of elementary high energy reactions.

Obviously it is necessary to understand this difference before one can talk about strangeness enhancement in heavy ion collisions. Becattini *et al.* [7] have suggested that in these reactions hadron gas fireballs in thermal and chemical equilibrium (for nonstrange hadrons) are formed. Only the production of strange hadrons is suppressed by a constant factor. Based on this assumption the particle yields can be described by 3 fit parameters, the temperature, the freeze out volume and a strangeness suppression factor. Fitting these parameters to measured particle multiplicities, they describe all published data on particle production in e^+e^- annihilation and *pp* reactions. The constant temperature they found is interpreted as freeze out temperature and the different reactions differ only by the freeze out volume. Thus they conclude that phase space and not dynamics dominates the particle production, a result which allows immediately to extrapolate the results to heavy ion data.

Particle production has been studied for a long time in phenomenological approaches such as the dual parton model [8], the Venus [9] or the PYTHIA-Lund models [10] or in the ultrarelativistic quantum molecular dynamics (URQMD) [11] approach. In these models the constituents of the hadrons interact and form strings as in e^+e^- annihilation which decay subsequently into hadrons. It is the purpose of this Brief Report to show that in the framework of these models (which reproduce not only the yields but also the momentum space distribution of the particles) the above mentioned experimental observation finds a completely different albeit very physical explanation. We will show that the string mass distribution and hence the momentum distribution of the partons in the hadrons explains the strangeness suppression in *pp* relative to e^+e^- annihilation. Therefore the similarity of e^+e^- annihilation with heavy ion reactions, where basically the same process takes place as in *pp*, is all but evident. We base our consideration on the NEXUS model but the observations are in fact more general, any string based model should arrive at the same conclusions.

II. THE NEXUS MODEL AND THE ROLE OF STRING FRAGMENTATION

Before we start with an analysis of the physics of multiplicities of different hadrons we explain the basic features of our approach (NEXUS) which describes simultaneously high energy electron-positron annihilation and hadron-hadron scattering. The details may be found in Ref. [12].

The common feature between hadron-hadron collisions and electron-positron annihilation is the creation of strings which finally produce observable hadrons. In the former case the exchange of a Pomeron leads to the formation of two strings, in the latter a string is spanned between the quark-antiquark created by the decay of a virtual photon or a *Z* boson. At low energies the string just consists of two partons at the end points, at higher energies perturbative gluons appear in initial or final state radiation which are mapped onto the string as the so-called kinks.

Once a string is created it evolves according to the Nambu-Goto Lagrangian for a classical relativistic string. In

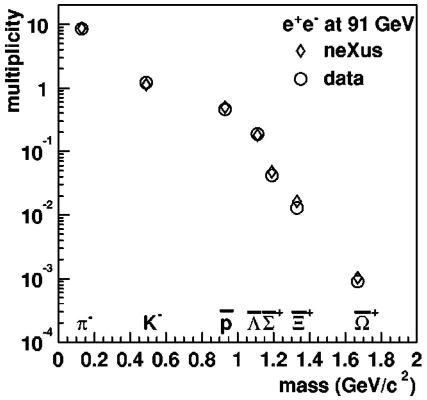

FIG. 1. Results for e^+e^- annihilation at 91.2 GeV compared with data from the Opal Collaboration [3].

order to produce hadrons we use the area law of Artru and Menessier. Here, the probability of the string to break is proportional to the invariant area swept over in Minkowski space. The breaking is then determined by one parameter, the break probability. If it is small, the string breaks at later times, producing less but heavier fragments and vice versa. Flavor production is governed by two additional parameters, the probability to create a strange quark-antiquark pair (otherwise up or down pairs are created in equal fractions) and the probability to create a diquark-antidiquark pair. The former therefore governs strangeness production, the latter baryon production and the combination of both rules the creation of hyperons. The decay of strings can be seen as a longitudinal (one dimensional) microscopic phase space decay, therefore is more difficult to produce heavier particles than lighter ones.

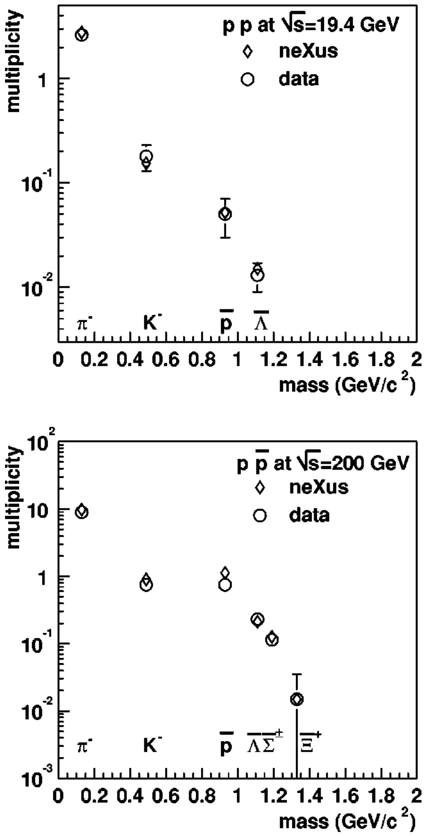

FIG. 2. Comparison of the model with data for proton-proton collisions at $\sqrt{s}=19.4$ GeV [6] and anti-proton-proton collisions at $\sqrt{s}=200$ GeV [13].

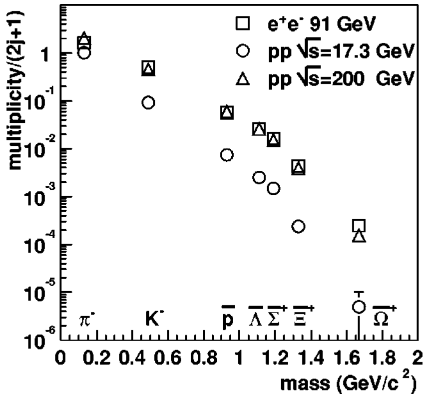

FIG. 3. Particle yields (without resonance decays) of different reactions calculated with NEXUS.

In Fig. 1 we show particle yields of e^+e^- annihilation from our model compared with data from the OPAL Collaboration [3]. The two parameters for strangeness and diquarks have been adjusted to fit these data, and the model is capable to describe a multitude of data. One can convince oneself in reference [12] that also event shapes and differential spectra are reproduced nicely. The same model applied to hadron-hadron collisions gives the results shown in Fig. 2. Here we compare two energies which are close to the ones we are going to use for our analysis. Furthermore we consider only negatives or antibaryons as produced particles, results for the other particles agree in a similar way with data. We can conclude that for e^+e^- annihilation as well as for *pp* and antiproton-proton ($p\overline{p}$) collisions NEXUS agrees with the experimentally observed particle yields.

III. INTERPRETATION OF RESULTS

We are now going to interpret the above-mentioned results based on NEXUS calculations. In Fig. 3 we show multiplicities of particles produced in *pp* collisions at 17.3 GeV (SPS) and at 200 GeV (RHIC) as compared with e^+e^- at 91.2 GeV. In order to examine the mechanism of particle production on the level of strings we do only consider particles directly produced by strings, resonance decays are switched off. To account for spin degeneracy we divide the obtained multiplicity by the factor $2j+1$. First of all one sees that the particle yields fall roughly exponentially with the particle mass. This is a simple phase-space effect: heavier particles are more difficult to produce. Striking is the unexpected similarity of *pp* at 200 GeV with e^+e^- at 91.2 GeV. As described above, the formation of strings is quite different in *pp* as compared to e^+e^- reactions. The spectra obtained for 17.3 GeV is considerably steeper. We see as well very little difference between strange and non-strange hadrons, all fall on a common curve.

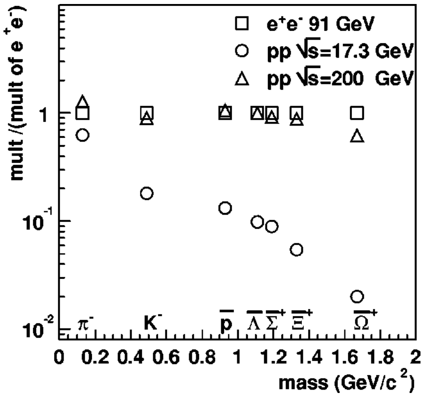

FIG. 4. The multiplicities of particles normalized to e^+e^- at 91.2 GeV. Proton-proton collisions at 200 GeV are very similar to e^+e^-; at 17.3 GeV a suppression of heavier particles is noticeable.

This effect can be seen clearer in Fig. 4, where the multiplicities are plotted normalized to the ones of e^+e^-. The ratio for *pp* interactions with respect to e^+e^- at RHIC energies is close to one. Only the heaviest particle—the Omega—is slightly suppressed in *pp*. At SPS energies the yields for *pp* collisions show a completely different behavior: the ratio with respect to e^+e^- falls off strongly as a function of the mass.

Where does this effect come from? No new physics enters between the two energies, with exception of the minijets which are more abundant at higher energies. But this influences only differential spectra like that of transverse momenta and not the relative abundance of particles.

The answer becomes quite clear when we look at the masses of the strings which finally produce the particles. Figure 5 shows the distribution dn/dm of string masses produced at the two different energies. We leave out the case of e^+e^- since here we have in most cases one string of mass 91.2 GeV. Only if a quark-antiquark pair is produced during the final state radiation, we end up with more than one string. This process is however much less important than gluon radiation. In *pp* interactions most of the strings have still low masses, which is a direct consequence of parton distribution functions peaking at low *x*. But the evolution of the tails is quite different. Whereas at 17.3 GeV the distribution is steeply falling with almost no strings at all above 10 GeV, the strings for *pp* at 200 GeV reach much higher masses.

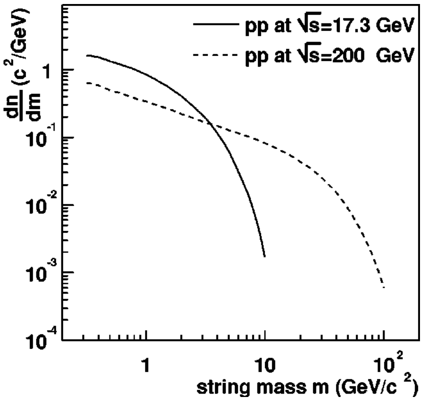

FIG. 5. The distribution of string masses for two reactions *pp* at 17.3 and 200 GeV.

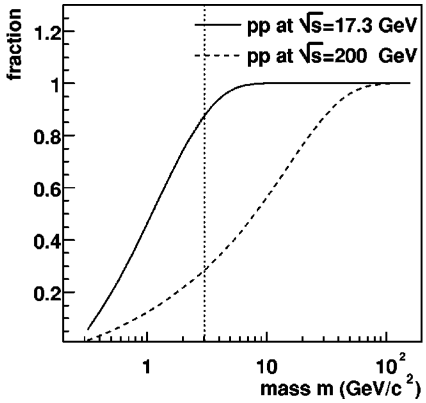

FIG. 6. Integrated string masses: Shown is the relative fraction of strings below a certain mass *m*. The line at 3 GeV shows the threshold for Ω production.

More conclusive is Fig. 6 where we see the corresponding cumulative distributions, i.e., the fraction

$$F(m)=\frac{\int_0^m \frac{dn}{dm'}\,dm'}{\int_0^\infty \frac{dn}{dm'}\,dm'}$$

of strings with masses below *m*. At 17.3 GeV 50% of strings are lighter than 1 GeV, at 200 GeV the fraction is only 10%. Strings below 1 GeV cannot produce any baryons. If we want to create a $\bar{\Omega}$ given a s-$\bar{d}$ string, we will find in addition a $\bar{\Xi}$, since we have to break the string with the creation of a ss-$\overline{ss}$ pair. Therefore the minimum mass is above 3 GeV in the best case scenario, where one strange quark is already given by the initial string. Consequently, it is hard to create Ω's at low beam energies since only 10% of the strings have the necessary mass, whereas at RHIC energies 70% of the strings could kinematically produce Ω's.

IV. CONCLUSIONS

We can conclude that the different string masses at different beam energies are responsible for a possible suppression of heavy hadrons in *pp* collisions as compared to e^+e^- annihilation. If the hadron mass is small as compared to the typical string energy the hadron multiplicity ratios reach asymptotic values. A further increase of the string energy leads only to an overall increase of the produced hadron multiplicity leaving their relative ratio unchanged. If the string mass becomes comparable to the hadron masses, the production of these hadrons is suppressed due to the very limited phase space available. It is therefore not the strangeness but the fact that strange hadrons are heavier than their nonstrange counterparts what causes the apparent strangeness suppression.

Employing a string fragmentation model which describes the kinematical variables as well the multiplicities of particle species in e^+e^-, *pp* and $p\bar{p}$ collisions allows to interpret the particle yields in physical terms without touching the claim that data can be well fitted using the functional forms of a grand canonical description.

ACKNOWLEDGMENTS

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