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pp, pA and $\alpha\alpha$ Collisions and the Understanding of the Quark-Gluon Plasma

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pp, pA AND αα COLLISIONS AND THE UNDERSTANDING OF THE QUARK-GLUON PLASMA*

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ABSTRACT

Global characteristics of heavy ion collisions at high energy are now understood at some level such that the challenging search for Quark-Gluon plasma signatures becomes of more importance. Some features of pp, pA and αα interactions at $\sqrt{s} \leq 62$ GeV are selected to illustrate potential consequences for, and problems of, investigations of the Quark-Gluon plasma.

I. INTRODUCTION

First results from high energy heavy ion experiments have revealed so far the more global features of these collisions$^{1)}$. They are compatible with a picture of parallel independent nucleon-nucleon interactions which probably create a sufficiently high energy density for a phase transition to a Quark-Gluon Plasma (QGP). Starting from this basic knowledge one can now search for the QGP manifesting itself through deviations from "conventional" nucleon-nucleon physics. Comparisons will be usually done with measurements from pp, pA and $\alpha\alpha$ collisions supplemented by Monte Carlo simulation to estimate "trivial" nuclear effects like e.g., collision geometry, Fermi motion etc. A good understanding of the relevant features of these reactions is therefore mandatory. It is the aim of this paper to sketch the current understanding of some selected features of pp, pA and $\alpha\alpha$ collisions and to point out some implications for the QGP search.

II. LONGITUDINAL SPECTRA OF BARYONS

A measurement of the energy degradation of leading baryons in pA collisions is expected to give a good estimate of the beam momentum which yields the largest baryon density at $x_F \approx 0$, i.e. the most effective "stopping" of the projectile. Inclusive cross sections for neutron and proton production in pp collisions at p_{lab} = 24 GeV/c (fig. 1) differ significantly for $|x_F| \geq 0.7$ $^{2)}$. Hence, an optimal determination of "stopping" requires a measurement of longitudinal (and transverse) spectra for both neutrons and protons. Previous experiments$^{3)}$ did not fulfil these requirements sufficiently. However, all analyses based upon identified protons are consistent$^{4)}$.

Since the beam momenta of current experiments are now known anyway, being basically defined by the available accelerators, further more detailed measurements seem to be of little immediate practical importance. They would provide, nevertheless, a better understanding of the propagation of baryon number in nuclear matter and would therefore help to improve models.

Especially, a measurement of baryon densities at $x_F \approx 0$ is of prime interest, since it is here that the QGP should eventually dominate. A direct determination of the baryon density requires detection and identification of at least protons, neutrons and lambdas as well as of their antiparticles. An approximate method can be used to estimate the net baryon density at small $|x_F|$. From fig. 1 and ref.$^{1)}$ one concludes that the shapes of the longitudinal spectra of p, n and Λ resemble each other for $|x_F| \leq 0.7$. This can probably be understood as a consequence of the ud-diquarks involved in the production process$^{5)}$ which combine with u, d or s quarks, respectively. In addition the shapes of the longitudinal spectra for $\bar{p}$ and $\bar{\Lambda}$

production seem to be similar$^{5)}$. Hence one can estimate the baryon density dn_B/dx_F for nucleon-nucleon collisions according to the following ansatz:

$$\frac{dn_B}{dx_F} \approx \alpha_h(x_F)\,\frac{dn}{dx_F}\,(h) - \beta_{\bar{h}}\,(x_F)\,\frac{dn}{dx_F}(\bar{h}),\ h = p,n,\Lambda,$$

$$\text{where } \alpha_h\,(x_F) = \left(\frac{dn}{dx_F}(p) + \frac{dn}{dx_F}(n) + \frac{dn}{dx_F}(\Lambda)\right)\left(\frac{dn}{dx_F}\,(h)\right)^{-1} \text{ and}$$

$\beta_{\bar{h}}(x_F)$ is defined likewise for the antiparticles $\bar{h}$. The functions $\alpha_h(x_F)$ and $\beta_{\bar{h}}(x_F)$ should not depend strongly on x_F and can be derived from measurements or from appropriate models$^{5)}$. The above ansatz is expected to hold also for pA collisions, since the dependence of $d\sigma/dx_F$ on A tends to be the same for p, n and $\Lambda^{6)}$; even for heavy ion (AA') collisions one should get reasonable estimates of dn_B/dx_F. This method would yield dn_B/dx_F from a measurement of (anti-) lambda production only. In this respect it is also reassuring that the maximum of the semiinclusive differential cross section $d\sigma_n/dx_F$ tends to depend on the number of charged particles, n_c, in about the same way for Λ production in pp collisions$^{7)}$ and p production in $\alpha\alpha$ collisions $^{8)}$.

III. THERMAL EQUILIBRIUM IN PP COLLISIONS

Based on an intuitive approximation an analysis of multiplicity distributions $P_n(\Delta y)$ in fixed intervals, Δy, of rapidity y was carried out in ref. $^{9)}$. $P_n(\Delta y)$ was obtained from a convolution of a negative binomial distribution describing a thermal source and of a Poisson distribution corresponding to independent radiation of gluons off valence quarks. Good agreement with the data was found. It was speculated that the thermal behaviour dominating at small $|\,y\,|$, may be due to gluon-gluon interactions. This may, at least qualitatively, be consistent with data on negative particle production in $\alpha\alpha$ and pp collisions$^{10)}$, where the different isospin of p and α is only reflected at $|\,y\,| \geq 2.5$, corresponding to a range of Bjorken-x where valence quarks dominate the nucleon structure functions.

One may wonder whether there is direct evidence from differential distributions for thermal behaviour in the central region. Actually, the inclusive distributions of transverse momenta p_T from $\pi^{\pm}$ (fig. 2), $K^{\pm}$ and $^{(}\bar{p}^{)}$ production obtained long ago at the ISR$^{10)}$ are consistent with an exponential $\exp(-aE_T)$, where $E_T = \sqrt{m^2 + p_T^2}$, which approximates a thermal distribution$^{12)}$ with a temperature T given by the parameter a. Other data from the ISR tend to spoil this simple picture. As demonstrated in fig. 3a$^{10)}$, semiinclusive p_T distributions deviate from the inclusive ones. In particular, one finds an excess of about 20%

for $p_T \leq 0.25$ GeV/c from events with large charged multiplicities n_c. In a thermodynamic picture this would suggest different temperatures for different values of n_c, with lower temperatures for higher multiplicities. A recent analysis shows also that the shape of inclusive p_T spectra depends on $\sqrt{s}$, with a rather strong increase at $p_T \leq 0.25$ GeV/c (fig.3b,[13]). Again one would be lead to the conclusion that there is no unique value of T. A simple thermodynamical description seems to be rather artificial under these conditions. Note that the excess of events with $p_T \geq 1$ GeV/c at large n_c (fig. 3a) and $\sqrt{s}$ (fig. 3b) may be a straightforward consequence of hard parton scattering.

It may be appropriate to recall what was once more common knowledge. In fig. 4 the contribution of various resonances to the inclusive pion yield is shown as function of p_T^2 for π^+p interactions at 16 GeV/c[14]. More than 50% of all pions are decay products of resonances. Probably, one should rather talk about thermal distributions for the directly produced hadrons, i.e. for resonances. It is interesting to note that pions with $p_T \leq 0.25$ GeV/c originate mainly from ω (and η) decay. In the absence of badly needed data on resonance production as function of n_c and of $\sqrt{s}$ one may consult corresponding data from K°_s and Λ production in fig. 5[15]. The average multiplicities $< K^\circ_s >$ and $< \Lambda >$ do depend on $\sqrt{s}$ and on $n_- = 1/2\ (n_c - 2)$. There is no a priori reason why resonances should behave in a different way. This might then be at the origin of the observed features of inclusive pseudoscalar meson production. It should be mentioned also that production of resonances during hadronization of the QGP may reduce problems of entropy conservation[16].

Instead of a conclusion there remains the question if a thermal equilibrium develops in nucleon-nucleon collisions.

IV. SIGNATURES OF THE QGP

1) Average transverse momenta

The average transverse momentum of secondaries, which may reflect a temperature, is predicted to rise initially as a function of dn/dy, then a more or less pronounced plateau is expected signalling a mixed phase due to a phase transition and, finally, $< p_T >$ should rise again in the quark-gluon phase[17a]. Whereas details depend on the particular model, stronger dependences are generally expected for heavier particles due to hydrodynamic transverse flow[17b]. It is instructive to have a look at the corresponding data obtained from pp,pA and $\alpha\alpha$ collisions. In pp collisions at $p_{lab} = 19$ GeV/c[18], $< p_T >$ decreases with increasing $< n_c >$ as intuitively expected from phase-space considerations. For pp collisions at $\sqrt{s} = 19$ GeV, $< p_T >$ is independent of dn/dy for dn/dy ≤ 10 followed by a significant decrease which is not found for pA collisions at the same beam momentum (fig.6a[19a]). In pp collisions at the ISR the increase of $< p_T >$ with dn/dy is found to be stronger at higher energies (fig.6a [19b]).

Surprisingly, the same dependence is found for pp collisions at $\sqrt{s}$ = 62 GeV and $\alpha\alpha$ collisions $\sqrt{s_{NN}}$ = 31 GeV. Particle identification was not attempted in any of the investigations mentioned. One may therefore wonder whether the $\alpha\alpha$ data could be explained on the basis of a larger fraction of baryons.

From these data it follows that quantitative differences must be established between nucleon-nucleon and AA' collisions at various energies, a measurement of trends is not sufficient to argue for the QGP. Also particle identification is called for in order to reduce possible ambiguities of interpretation.

2) Electromagnetic Probes

Scaling hydrodynamics predicts that the yield of direct photons and lepton pairs is proportional to $(dn/dy)^2$ 20). The yield of e^+ with $0.12 < p_T < 0.4$ GeV/c and of e^+e^- pairs with mass $M_{e+e-} \leq 0.6$ GeV was actually found recently to depend on $(dn/dy)^2$ in pp collisions21). Such a measurement requires an excellent rejection of hadrons, and it has to cope with a large background from non-direct sources22).

Decays of ρ, ω, η and tensor mesons23) give rise to such a background flux. Since not all decays can be uniquely identified experimentally, a certain fraction has to be subtratced using Monte Carlo methods. Consequently, a reliable measurement of direct leptons and γ at small p_T or of lepton pairs with small invariant masses requires a detailed knowledge of the production characteristic of resonances (section III). Especially in heavy ion collisions there is a complete lack of relevant data so far.

At higher dilepton masses M, e.g. $M \leq 3$ GeV, , another background process may be of importance, i.e. production and semileptonic decays of $D\bar{D}$ pairs. For pp collisions at $\sqrt{s}$ = 27 GeV calculations based upon a model of correlated $D\bar{D}$ production with $\sigma(D\bar{D}) = 7\ \mu b$ and an average rapidity separation $\Delta y\ (D\text{-}\bar{D}) = 0.5$ indicated that the measured inclusive dilepton yield may be saturated just by charm decays24). Recently, $\sigma(D\bar{D}) = 14.6 \pm 2.0\ \mu b$ and $\Delta y\ (D\text{-}\bar{D}) = 1.02 \pm 0.12$ was measured25); this would correspond to even larger dilepton fluxes such that there seems to be an unsolved problem already in pp collisions. The dependence of $\sigma(D\bar{D})$ on A in pA collisions is not well known either26). In AA' collisions more than one $D\bar{D}$ pair may be produced such that a lepton from one $D\bar{D}$ pair and an antilepton from another pair may form a dilepton system of large invariant mass. The resulting distribution of M from these combinations should resemble that expected from uncorrelated $D\bar{D}$ production in pp collisions24). It was shown for the latter case that the measured dilepton flux depends strongly on geometrical acceptance.

From this discussion one concludes that charm background to direct dilepton pairs in AA' collisions is very hard to estimate reliably. One would prefer to have a measurement of $\sigma(AA' \rightarrow D\bar{D} + X)$ to guide Monte Carlo simulations. Note that relative suppression of $D\bar{D}$ production in AA' collisions is also one of the proposed QGP signatures.

3) Strangeness

A large abundance of s and $\bar{s}$ quarks is expected in the QGP, especially for baryon rich plasmas$^{16)}$. It is, however, very difficult to predict the resulting abundances of all species of strange hadrons. One tends to anticipate nevertheless that (anti-) baryons containing more than one strange quark may be more sensitive probes.

In pp collisions, production of K°_S and Λ is rather well measured and quite well understood theoretically$^{5)}$. However, there are only very limited data on Ξ and Ω production as shown in fig. $7^{27)}$. If anything, only a strong dependence on $\sqrt{s}$ of Ξ and Ω production may be extracted from the data. This suggests that, if a QGP is formed in AA' collisions at $p_{lab} \leq 60$ GeV/c/A, a potential exhancement of strangeness may be more pronounced than at $p_{lab} =$ 200 GeV/c/A.

4) Large Transverse Momentum Processes

The inclusive yield of hadrons h ($\pi^\pm$, $K^\pm$, p, $\bar{p}$) at high p_T in pA collisions depends on A in the following way: $\sigma(pA \rightarrow h + X) = K\sigma\,(pp \rightarrow h + X)\,A^{\alpha(p_T)}$. The exponent α was measured to exceed unity for $p_T \geq 1.5$ GeV/c$^{28)}$ indicating "collective" effects. The theoretical explanation is based upon the picture of multiple parton scattering in nuclear matter$^{29)}$. Single parton scattering is known to be at the origin of mesons produced at large p_T in pp collisions. Keeping in mind that the QCD scattering matrix elements are basically of "Rutherford" shape, it is intuitively clear that multiple small angle scattering is more economic than a single large angle process. Predictions from this simple scheme are compatible with the data on π° production at large p_T in $\alpha\alpha$ collisions (fig. 8a,$^{30)}$). However, much more detail, e.g. on event structure, is needed for pA collisions before one can proceed to use high p_T processes as a diagnostic tool$^{31)}$ for QGP formation in AA' collisions.

In fig.8b the inclusive yield of K^+ and p relative to π^+ is given for pp, dd and $\alpha\alpha$ collisions at the ISR $^{32)}$. For $\alpha\alpha$ collisions larger values of this ratio are found than for pp and dd interactions. Presumably, protons are responsible for this trend, since it is not observed for the antiparticles$^{32)}$. It may be a consequence of the fact that protons at high p_T are predominantly produced by hard scattering of diquarks$^{33)}$. In this case the diquark form factor tends to favour multiple scattering over single large angle scattering even more than for quark and gluon scattering yielding mesons at large transverse momenta.

If diquarks were bound objects with a radius of about 0.3 fm, they would probably "melt" in a QGP due to the Debye screening of colour charge$^{34)}$. In this case a substantial reduction of proton, neutron and Λ yields at large p_T relative to mesons would signal the formation of a "deconfined" phase of strongly interacting matter in AA' collisions$^{35)}$.

V SUMMARY

Selected features of pp, pA and $\alpha\alpha$ collisions and their relation to heavy ion collisions were briefly discussed excluding topics which were anticipated to be treated in detail during this meeting (rapidity fluctuations, Bose-Einstein interference, suppression of J/ψ). A simple method to estimate the baryon density in the central region was suggested. The question of thermalisation in nucleon-nucleon collisions was addressed and left unanswered. Finally, the "melting" of protons at high transverse momentum was proposed as a new signature of deconfinement.

One realizes that there is not always an adequate body of relevant data from pp and pA interactions or no sufficient understanding thereof. In order to reduce potential ambiguities of the interpretation of so-called QGP signatures, detailed measurements of production properties of π^+, K^+, p, Ξ, Ω (and their antiparticles), in pp and pA interactions as well as of resonances and of charmed particles in heavy ion collisions would be welcome. Hence the search for the QGP should also revive some interest in non-perturbative phenomena in pp and pA collisions.

VI ACKNOWLEDGMENTS

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FIGURE CAPTIONS

Fig 1 Invariant cross section versus x_F a) for p at different fixed values of p_T andb) for n.

Fig 2 Invariant cross section for π^+ versus p_T in the ISR energy range.
The solid curve is at fit to exp $(- aE_T)$ for $p_T < 0.4$ GeV/c.

Fig 3 a) Ratio of semiinclusive p_T distributions to the inclusive distribution for pp collisions at $\sqrt{s} = 62$ GeV;
b) Ratio of cross sections for negative particles from pp collisions at two energies as function of p_T.

Fig 4 Dependence on $p_T{}^2$ of the relative contribution of pions from resonances to the inclusive yield.

Fig 5 Average multiplicities of K°_S and Λ as function of n_- for pp collisions various beam momenta.

Fig 6 Average transverse momentum as function of dn/dy for a) pA collisions at 200 GeV/c and b) pp, pp, dd, $\alpha\alpha$ collisions at the ISR.

Fig 7 Invariant cross sections versus x_F for $\Sigma^\pm$, Ξ^-, Ω^- production at various beam momenta.

Fig 8 a) Ratio of measured cross section for inclusive π° production in $\alpha\alpha$ and dd collisions to a fit to pp data;
b) Ratio of yield of heavy hadrons to pions as function of p_T for pp, dd and $\alpha\alpha$ collisions at the ISR.

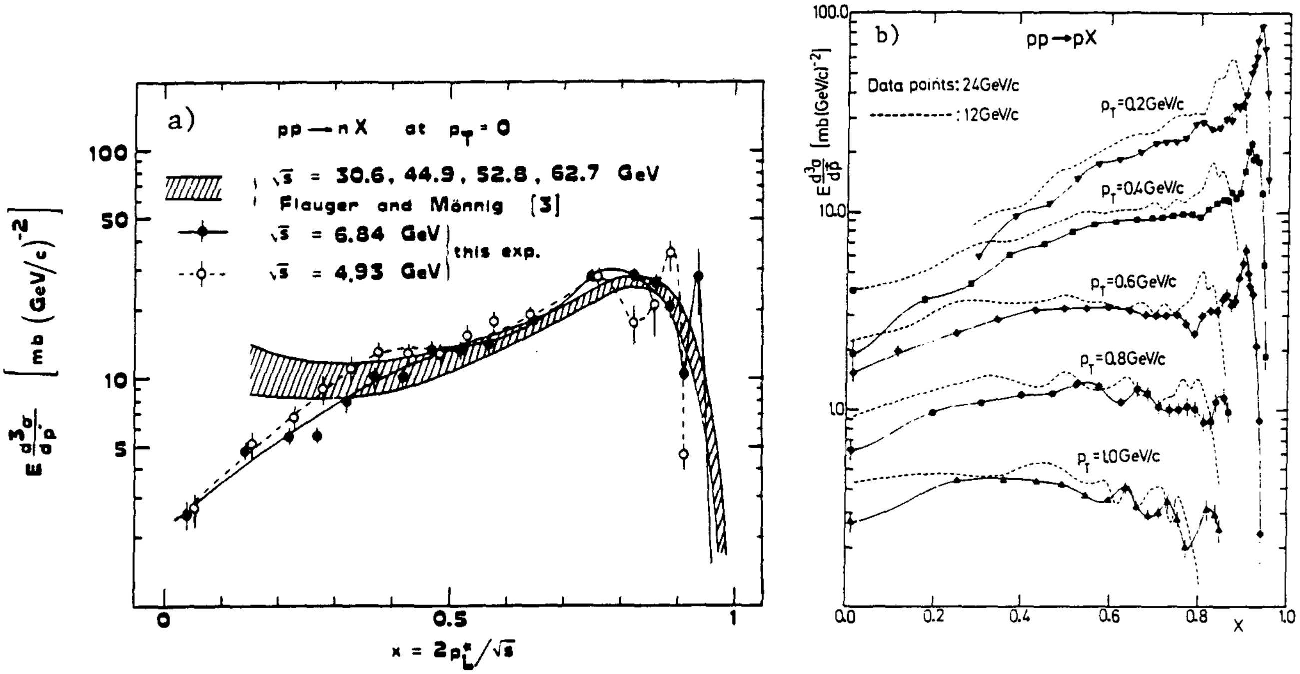

Fig 1: Invariant cross section versus x_F a) for p at different fixed values of p_T and b) for n.

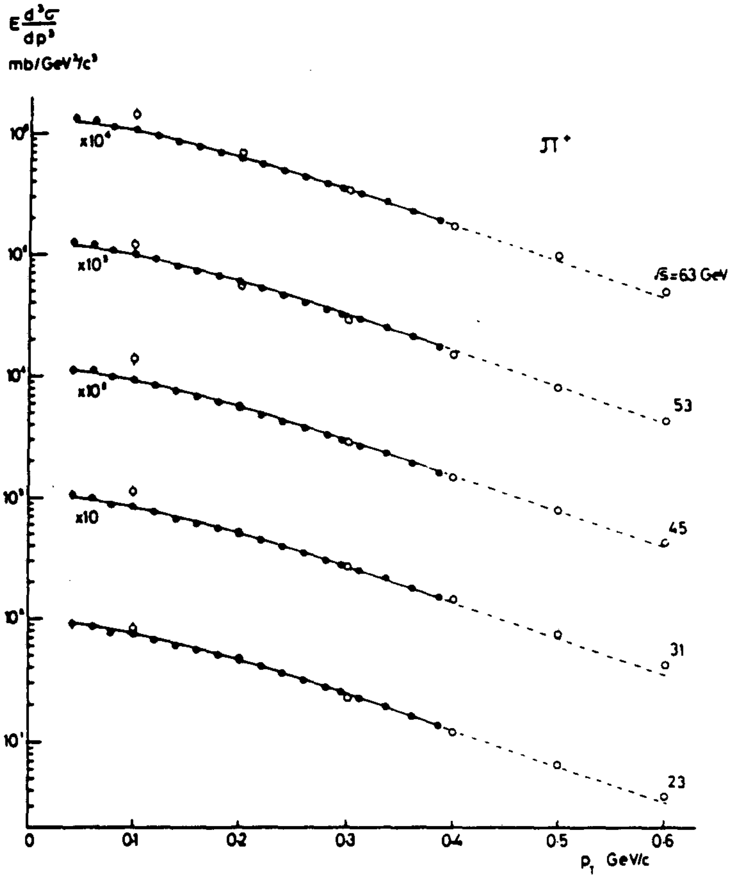

Fig 2: Invariant cross section for π^+ versus p_T in the ISR energy range. The solid curve is at fit to exp (- aE_T) for $p_T < 0.4$ GeV/c.

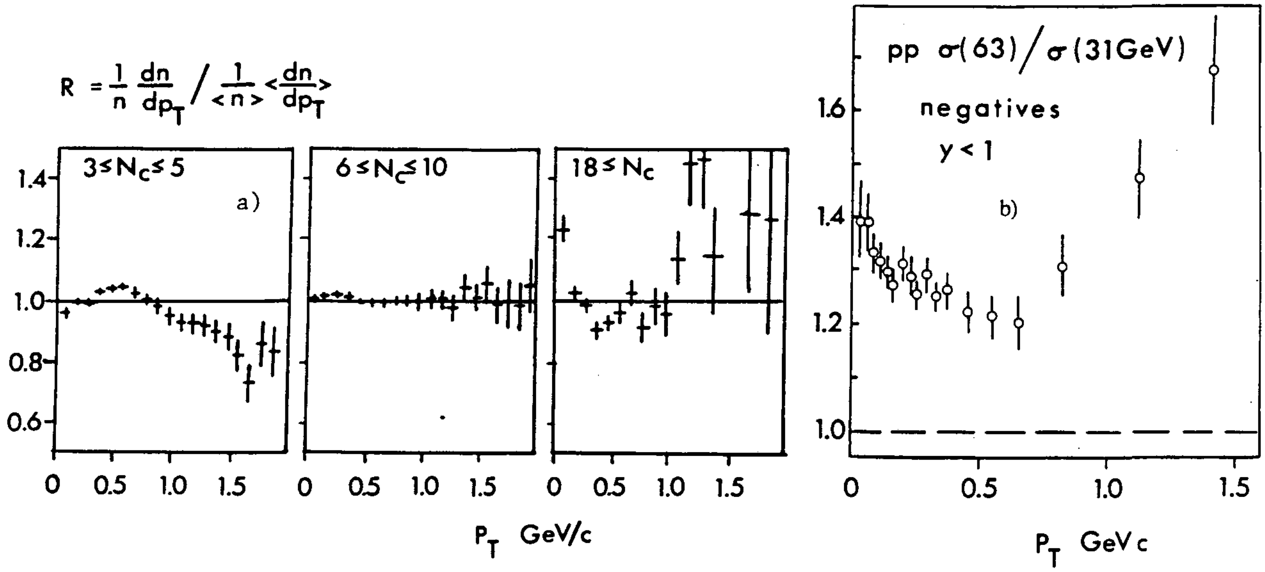

Fig 3: a) Ratio of semiinclusive p_T distributions to the inclusive distribution for pp collisions at $\sqrt{s} = 62$ GeV.
b) Ratio of cross sections for negative particles from pp collisions at two energies as function of p_T.

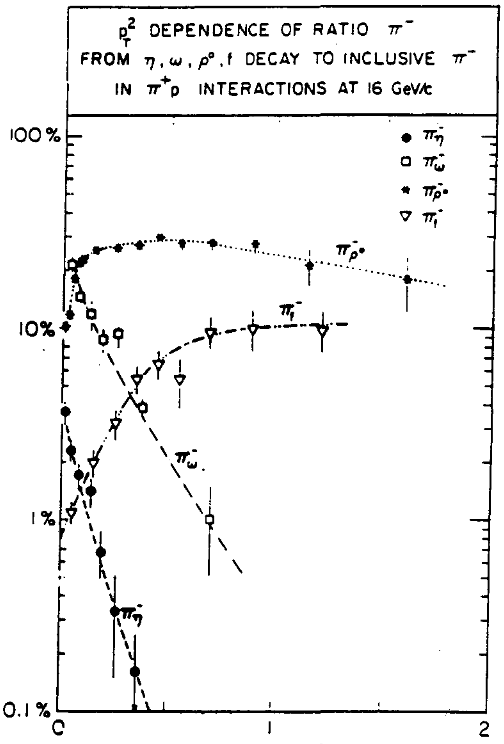

Fig 4: Dependence on $p_T{}^2$ of the relative contribution of pions from resonances to the inclusive yield.

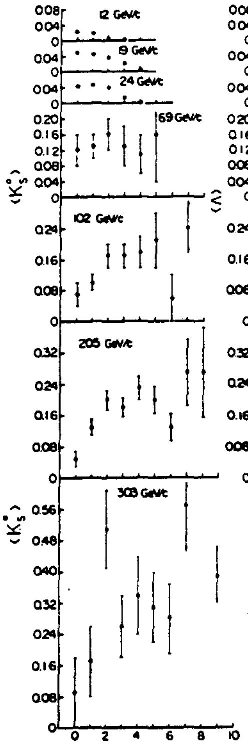

Fig 5: Average multiplicities of K°_S and Λ as function of n for pp collisions various beam momenta.

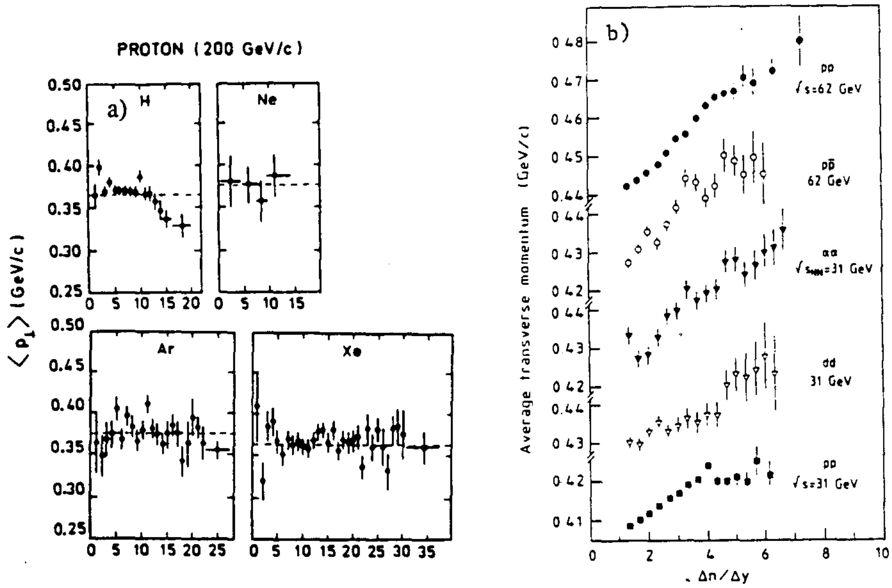

Fig 6: Average transverse momentum as function of dn/dy for a) pA collisions at 200 GeV/c and b) pp, p$\bar{p}$, dd, αα collisions at the ISR.

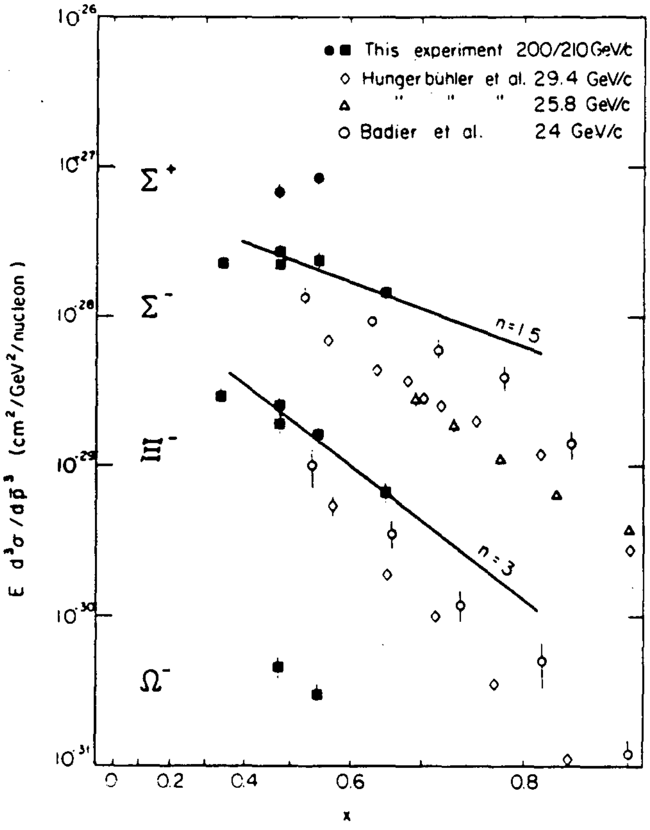

Fig 7: Invariant cross sections versus x_F for $\Sigma^\pm$, Ξ^-, Ω^- production at various beam momenta.

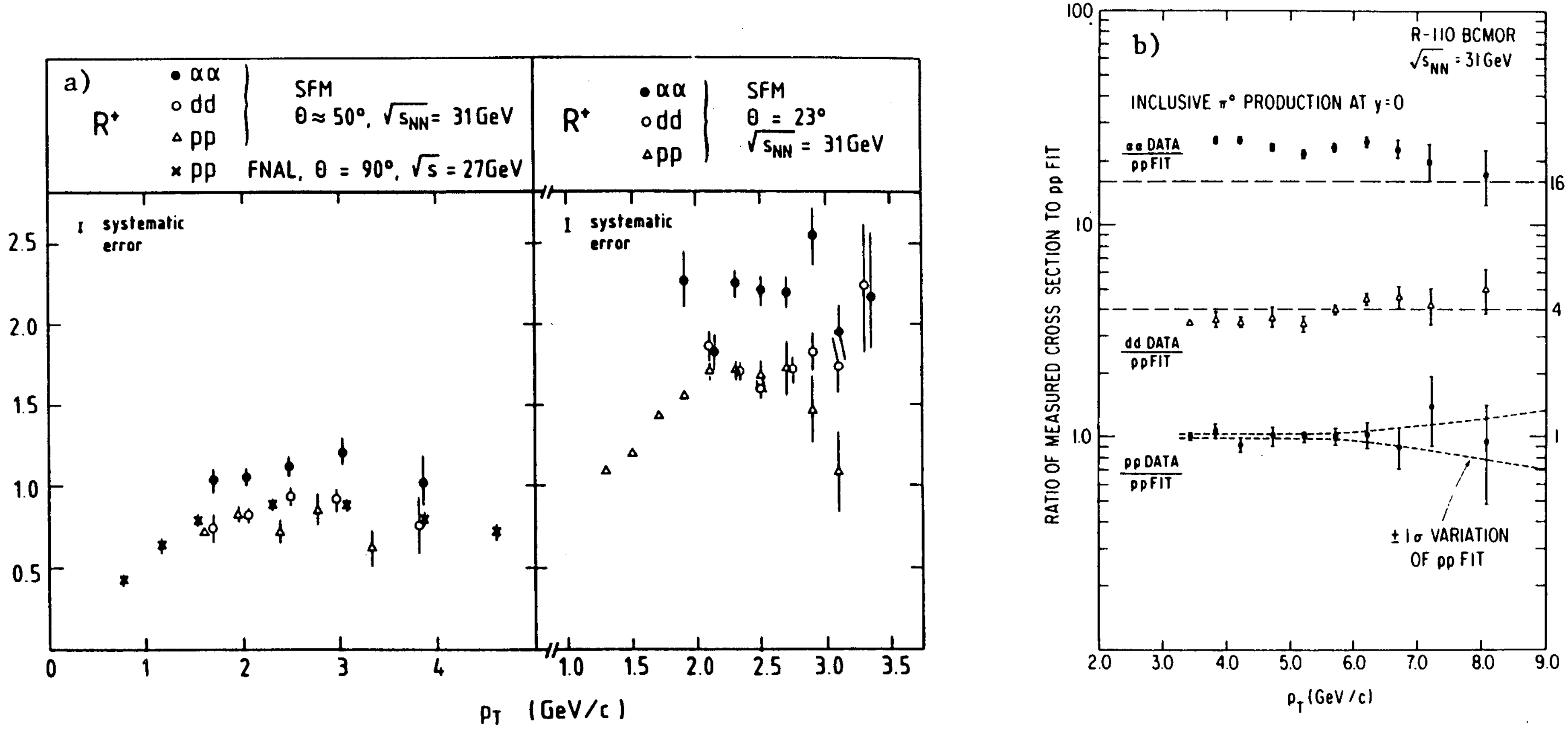

Fig 8: a) Ratio of measured cross section for inclusive π° production in αα and dd collisions to a fit to pp data.
b) Ratio of yield of heavy hadrons to pions as function of p_T for pp, dd and αα collisions at the ISR.