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# SUMMARY OF DISCUSSIONS AT THE "HIGH $p_T$" SESSION

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## Abstract

A summary of the discussion at the HIGH $p_T$ session is presented. There was a clear consensus at this session that Jets and Jet Phenomena in Relativistic Heavy Ion collisions would best be studied using leading particles, in the same way that these phenomena were originally mapped out in $p-p$ collisions. The new topic of "Jet Quenching in Nuclei" was extensively discussed. It was clear that this proposed phenomenon could also be studied by measuring fragmentation functions in Deeply Inelastic Lepton-Nucleus Scattering; but there was controversy over whether the effect should be seen in proton-Nucleus reactions. Other hard-scattering phenomena, including "Mini-jets", single particle inclusive production, the "Cronin Effect", and direct photon production, are mentioned.

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## 1. Introduction

The four talks presented in the "HIGH $p_T$" session represent a comprehensive summary of the field. The talks of Sosnowski, Seyboth, and Lissauer represent reviews of subject matter covering two decades of research, roughly the 1970's to the present. Plumer's material is much newer, representing a trend in the 1990's for Nuclear physicists to become more interested in hard-processes, in addition to the usual "thermalized" ("soft") low $p_T$ processes.

It is difficult to present a full summary of all the points of discussion, so I have made a selection of subjects: that were not touched upon in the main presentations; that are very contentious; where the consensus of the high energy community is still in doubt; or where old ideas have shown a renaissance, or have been forgotten.

## 2. Jets and Jet Phenomena via Leading Particles

Sosnowski presented a beautiful exposition of the formalism of high $p_T$ particle and jet production in $p-p$ collisions, tracing the development from the original discovery at the CERN ISR, in 1973, of an unexpectedly large yield of hadrons produced at high transverse momenta, in contradiction to the "commonly held beliefs" of the period; and introducing all the arcana of the subject including non-scaling structure and fragmentation functions, variation of the QCD coupling constant with "$Q^2$", transverse momentum of partons ($k_T$), jet fragmentation transverse momentum, the quark and di-quark structure of jets from leading particles, jets in calorimeters, the pedestal effect (an increase in the minimum bias level under jets as seen in the $dE_T/d\phi$ distribution [1]), multi-jet production.

A most interesting observation was Sosnowski's warning to beware of models that predict the data—several models may reproduce the experimentally observed result. He reminded us of a statistical, cylindrical phase space model which could predict many of the features of high $p_T$ particle production. It is now generally accepted that the QCD-corrected Quark Parton Model well describes high $p_T$ particle and jet production, to within a factor of 1.5 $\sim$ 2 ("the $K$ factor"—which is taken to be due to next-to-leading order QCD effects).

Lissauer emphasized the necessity of detecting jets, via leading particles, in heavy ion collisions. For central Au+Au collisions at RHIC, the expected multiplicity density, $dn/dy|_{y=0}$ is 1000 charged particles per unit of rapidity. At a $<p_T>\simeq$ 350 MeV/c, this corresponds to a transverse energy of 350 GeV/unit of rapidity from "soft" physics—or a "pedestal" of 60 GeV in the typical cone of "radius", $\Delta R=\sqrt{\Delta\eta^2+\Delta\phi^2}\simeq 0.6$, used to define jets in calorimeters [2]. Perhaps jet-finding algorithms could be improved. However, this seems like much too difficult a way to proceed. Also, there remains a mistrust of jet-finding algorithms—which have the tendency to always find fluctuations that look like jets, even when there are no jets [3]. Since it is virtually impossible to generate a high $p_T$ single particle by pile-up or by a statistical fluctuation, there is a general consensus that jets and jet phenomena, in relativistic heavy ion collisions, should be detected and analyzed via leading particles, in the same way that high $p_T$ and jet phenomena were originally discovered and their properties mapped out in $p-p$ collisions [4]

It should be emphasized that jet cross section studies are not in general tests of QCD, since they require knowledge of the structure functions of the incident hadrons—which must be obtained from deeply inelastic lepton scattering (DIS). However, DIS provides only minimal constraints on the gluon structure function [5]—which can best be obtained from measurements of direct photon production in hadron collisions, as discussed by Seyboth.

The study of jets, via leading particles, requires the additional knowledge of the "fragmentation" function. However, I should point out that this presented no problem to the theorists of the 1970's [6]. Furthermore, the fragmentation function can be measured by analyzing the same-side or opposite side charged particles, produced in association with high $p_T$ single particles—the so called "$p_{\rm out}$ vs $x_E$" distributions, mentioned by Sosnowski. Just to show the generation of Nuclear and Particle physicists, coming of age in the 1990's, that the effect is really clear in the data, it is worthwhile to present a typical distribution of the azimuthal correlation of charged particles to a high $p_T$ ($\geq$ 7.0 GeV/c) $\pi^0$ used as a trigger [7](see fig. 1). Also the fragmentation function deduced from opposite side leading $\pi^0$'s at the ISR [8] is shown (see fig. 2), represented in the variable $x_E$. At the ISR, the fragmentation function of jets was typically $e^{-6.2z}$, so that the average particle carried 16% of the jet energy. However, due to the steeply falling spectrum, a selected high $p_T$ single particle carried typically 85% of the energy of its parent jet. This "parent-daughter" or "trigger-bias" effect is an interesting exercise in contitional probability, which should be repeated at the relevant $\sqrt{s}$ by everyone contemplating spending years studying jets.

A conclusion of this discussion was that the theorists should try to calculate their predictions in terms of single or multiple leading particles, as well as in terms of jets or partons. (This applies to Plumer's presentation, also, and will be reiterated below.) Some examples in the literature include: Frank Paige's effort on jet detection at RHIC [9], using only particles with $p_T \gtrsim$ a few GeV/c; Lorella Jones' attempt to classify jets according to the correlation of the leading particles [10]; and Gosta Gustafson's statement at this meeting that he could separate gluon and quark jets using "neural network" analysis of the fragments.

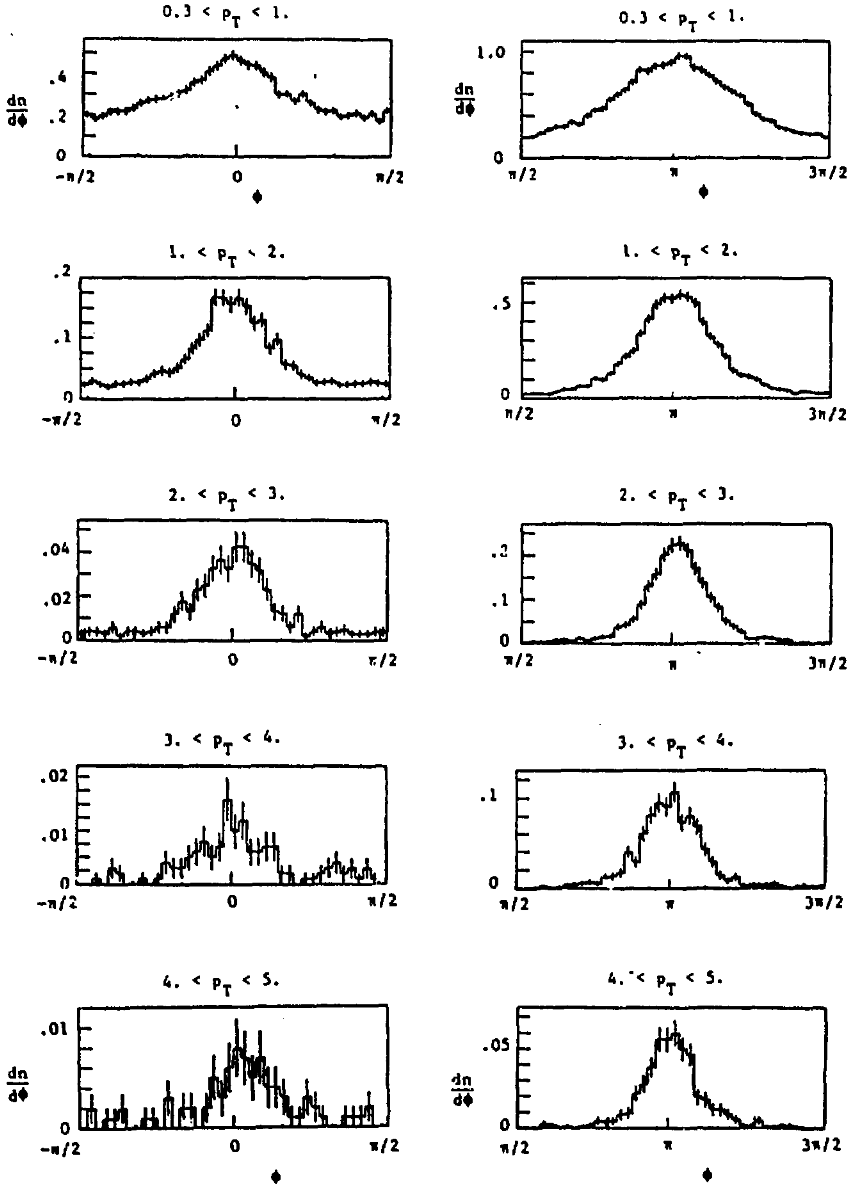

Figure 1. Two-particle correlation in azimuth of charged particles relative to a triggering neutral with transverse momentum $p_{T_t} \geq 7.0$ GeV/c, at $\phi$=0. The correlation is shown for five intervals of charged particle transverse momentum, $p_T$. The particles are produced near 90° in the c.m. system, with the charged particles restricted to $|\eta| < 0.7$. The plot is split into two halves, the trigger side (left) and the away side (right). The vertical units in all cases are particles per radian per trigger, but the size of the vertical scale is adjusted separately for each subplot [7]. Note that each subplot has a peak on top of a flat background. The flat background is consistent with the minimum bias "pedestal"; and the peaking in both the same and opposite side hemispheres is due to jets. From the development of the widths of the peaks as a function of $p_T$, this figure clearly shows that the two jets are not collinear in azimuth. This is easy to see by comparing the opposite side (right hand) plots for $1 \leq p_T \leq 2$ and $2 \leq p_T \leq 3$ GeV/c. If there were only fragmentation transverse momentum, then $p_T \times \Delta\phi$ should be constant; or $\Delta\phi$, the width of the peak, should be inversely proportional to $p_T$. In fact, the width of the peak barely changes with $p_T$, showing that it is $k_T$, the net transverse momentum of the di-jets, that is the dominant cause of the azimuthal width.

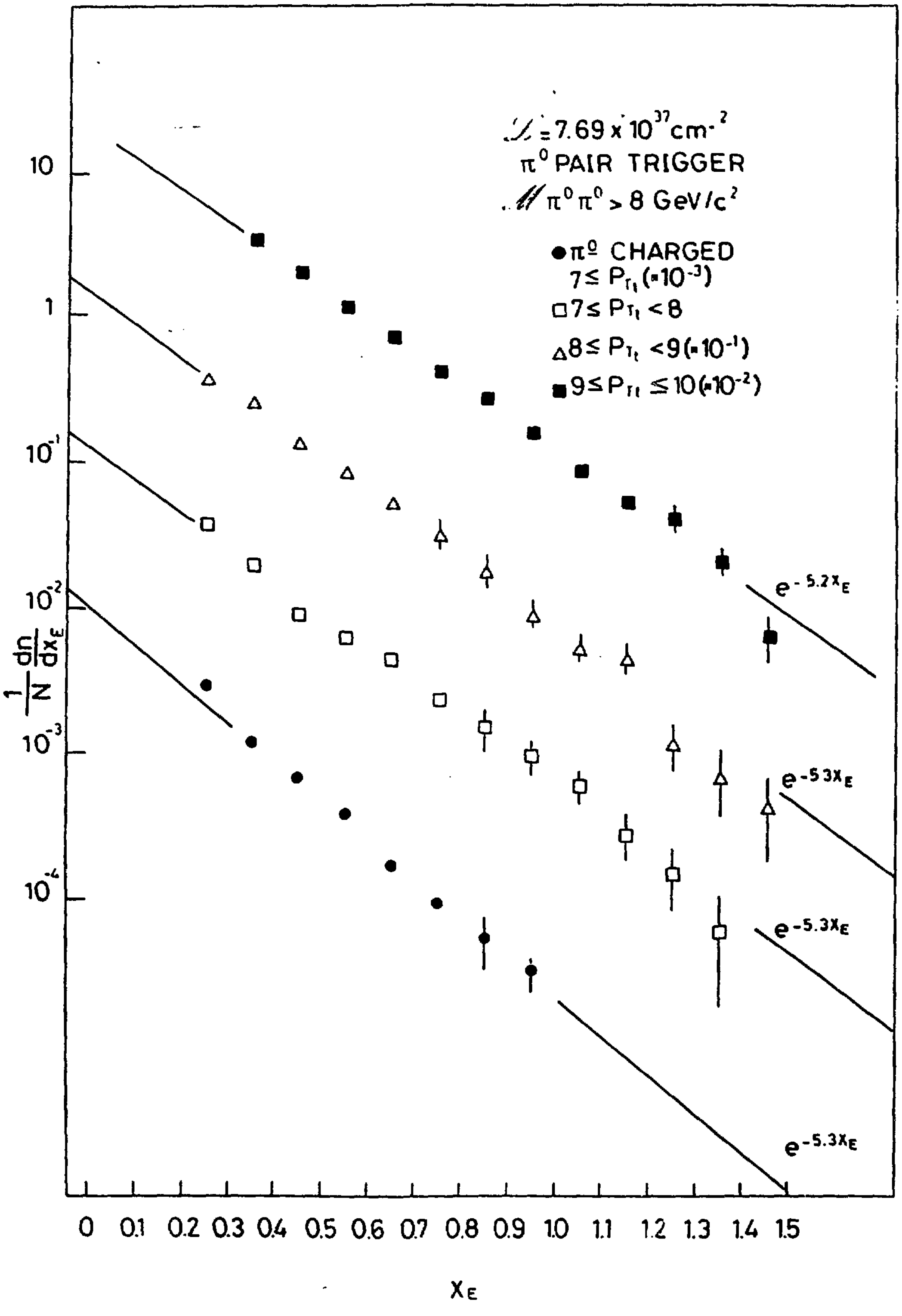

Figure 2. Distribution in $x_E$, for a second $\pi^0$ observed roughly back-to-back to a triggering $\pi^0$ of transverse momentum $p_{T_t}$, where both pions have $|\eta| < 0.5$ in the c.m. system. $x_E$ is the ratio of the component of the $p_T$ of the second pion, opposite in azimuth to the triggering pion, divided by $p_{T_t}$ [8,7].

To close this section, it is worthwhile to report an interesting discussion, stimulated by Stroeble, on whether it matters, when you trigger on a high $p_T$ photon, if the photon is direct, or is from a $\pi^0$—since in both cases the photon is the result of a hard scattering, and the opposite jet is unbiased. The answer, in simple terms, is that direct photons are produced by the QCD-Compton reaction:

$$g + q \rightarrow \gamma + q$$

so that the recoil jet from a direct photon is a fragmenting quark; while leading $\pi^0$'s, at RHIC, may tend to be more produced by gluon-gluon reactions, so that the associated jet may be from a gluon. Also, there should be a fundamental difference in the constituent scattering angular distribution in the two cases: the direct-photon production should exhibit the characteristic Compton distribution; while $g - g$ scattering should have the $\hat{t}$-channel pole, characteristic of Rutherford Scattering. (See further discussion in section 4.)

## 3. Jets in Nuclei, Jet Quenching and the Utility of e+A and p+A Phenomena

Plumer reviewed the use of QCD hard-scattering-jets as probes of dense nuclear matter and the QGP. He discussed two principal effects: one of which, Jet Acoplanarity, is "conventional" in the sense that it is consistent with the understanding of hard-collisions in nuclei, dating from the original Cronin Effect in 1975 [11]; while the other, Jet Quenching, is work done this year (1990), so that it was new to most of the audience, and, consequently, aroused a considerable discussion.

In the QCD-parton approach, high-$p_T$ single particles are the leading fragments of jets produced by a large momentum transfer quasielastic scattering of point-like constiuents of the nucleon. Thus, the nucleon is already treated as a transparent composite object in this picture (since the parton interaction cross sections are small), so that the extension to the collisions of nuclei was thought to be straightforward—the cross sections should just go like $A_1 \times A_2$, where the $A_i$ are the atomic masses of the two nuclei. Single particle inclusive measurements, at Fermilab, indicated, instead, an "anomalous nuclear enhancement" (the Cronin Effect)—the cross section for high $p_T$ particle production in p+A collisions was proportional to $A^\alpha$, with $\alpha > 1$. This effect is now well understood as being caused by smearing of the steeply falling hard-scattering $p_T$ spectrum—due to multiple scattering of the constituents, in the nucleus [12]. A qualitative feature of this explanation is that the Cronin Effect should vanish ( i.e. the cross section should go like $A^1$ ), for back-to-back hadron pairs (or jet pairs)—while the net-$p_T$ of the jet-pair (described in terms of $k_T$ or $p_{\text{out}}$)

should increase. Alternatively, the net-$p_T$ distribution of the hadron or jet pair should show a strong $A$ dependence. This is the same effect as "Jet Acoplanarity", discussed by Plumer. These features are indeed shown by all the data [13]. In fact, a recent preprint by E690 [14], clearly shows the increasing acoplanarity of jet pairs, with increasing target atomic mass A, in p+A collisions. Of particular note is that, for jet pairs, the increase of $k_{T_\eta}$, from $0.9 \pm 0.2$ GeV/c in $p-p$, to $2.0 \pm 0.2$ GeV/c in p+Pb, for 400 GeV incident protons, is much larger than the corresponding increase measured in "Drell-Yan" at comparable energies [15]—indicating a clear effect of final state interactions for hadronic partons, although the data are otherwise qualitatively explained by constituent multiple scattering.

By contrast, the proposed Jet Quenching [16,17] is supposed to be due to *the loss of energy*, $dE/dx \simeq 1$ Gev/fm, of the partons *in the final state*, after scattering, as they pass through the nuclear matter—the energy loss is predicted to be much reduced in the presence of the QGP. The effect is supposed to be maximal for jets with relatively low $p_T \lesssim 20$ GeV/c. The predictions are presented in terms of the scalar sum of the $p_T$'s of the back-to-back jets, so that the Cronin Effect is minimized.

Needless to say, the idea of energy loss in nuclear matter provoked enormous discussion, since it was generally believed that one of the main underpinnings of the whole QCD-parton approach, as well as of the understanding of hadron interactions in nuclei, is that a struck nucleon or parton is relatively unaffected by being struck again [18], except for picking up a little momentum transverse to its trajectory [12]. This opened up a whole host of questions. Gustafson asked if the quenching effect would be different for heavy and light quarks. Schukraft pressed the point of whether the effect should be seen in p+A and lepton-nucleus collisions.

Plumer responded that he expected no such effect in p+A, since the ( 90° c.m ) jets are produced at central rapidity, while the nucleus remains well separated, at the target rapidity. This is quite different from the case of lepton-nucleus scattering, where the struck quark essentially goes forward (and thus must pass through the entire target nucleus), so that the effects of parton energy loss should be seen—by measuring apparent changes in the fragmentation function. A strong conclusion of this discussion was that parton $dE/dx$ effects should be looked for—by measurements of the fragmentation functions in lepton-nucleus scattering. Also, experimentalists and theorists should study p+A data, carefully, to see whether any $dE/dx$ effects are expected, or observed. It was pointed out, by many, that even a fraction of a GeV extra energy loss would be very apparent in the Cronin Effect, which deals with precision measurements of particles in the range $2 \lesssim p_T \lesssim 6$ GeV/c, and a very steeply falling spectrum.

Another lively discussion was precipitated by Lissauer, who also raised the topic in his lecture, concerning the apparent washing out of the "Jet Acoplanarity" effect by a "rapidity cut" along the jet axis. Since the jets are roughly at 90°, this cut (made by the theorists, allegedly to simulate the effect *of experimental cuts*, but, of course, made in a way that makes it impossible for experimentalists to know what the theorists are predicting) corresponds roughly to what experimentalists would call "a $p_T$ cut on particles included in the jet". Lissauer claimed that the reason the effect appeared to wash out was due to a poor "jet definition" cut by the theorists.

This is patently clear to any experimentalist. It is obvious that if you miss $n$ particles of a jet, you make an error in momentum, transverse to the jet, of $\sqrt{n} \times <j_T>$, where $<j_T>$ is the mean transverse momentum of jet fragmentation. The clearest case occurs when you use only the leading particle—then you are off from the jet direction by only one unit of $<j_T>$ (see figure 1). A long discussion on jet definition ensued, with the conclusions that:

- Theorists should first present their work in theoretical quantities, either at the parton or jet level, and explain what the effect is: e.g. what is $k_T$ for $p-p$ collisions and how much does it increase for the case of ordinary A+A collisions, dense nuclear matter, or the QGP;
- then, they should look at the effect using the leading particles in jets;
- then, in addition, they can do whatever they prefer.

## 4. Unresolved problems in direct photon production

### 4.1 Experimental

Kampert's talk, on the latest WA 80 data, shows that there is no direct photon signal in Relativistic Heavy Ion collisions, for 200 GeV/u O+Au. The result, $\gamma/\pi^0 \leq 15\%$ (90% cl), for $0.5 \leq p_T \leq 2.5$ GeV/c, is now compatible with the experience in High Energy Physics. Lissauer noted that, in the lower $p_T$ region, where background rather than counting rate is the problem, it is better to measure direct photons by detecting internally converted low mass $e^+e^-$ pairs, even though there is a penalty in rate of a factor $(\alpha/\pi) \times (dm/m)$, where $m$ is the invariant mass of the pair. Such an experiment was done at the ISR, with the result [19]:

$$\frac{\gamma}{\pi^0} = (0.6 \pm 0.9)\,\%$$

for $2 \leq p_T \leq 3$ GeV/c, at $\sqrt{s} \simeq 55$ GeV.

A place where experiment is still lacking was brought out in the discussion—direct photon production in p+A collisions. This is a good place to look for modifications of the gluon structure function of the incident proton in the nuclear medium. Thus, configurations would have to be devised which select a gluon from the proton and a quark from the nucleus. This is an interesting possibility for p+A or d+A at RHIC, and could also be done at Fermilab in fixed target experiments.

Another topic, where more data would help, concerns a demonstration that direct photon production is really the result of the QCD Compton effect. The only real tests of the QCD matrix elements of constituent scattering come from angular distributions measured with leading $\pi^0$'s from jet-pairs (as shown by Sosnowski and Lissauer) or with the jet pairs directly [20]. It is generally accepted, by anyone who has done such a measurement, that pair measurements are the cleanest way to test QCD—both of the outgoing hard-scattered constituents are measured, allowing the constituent kinematics to be reconstructed [21]. Seyboth showed the recent UA2 measurement of the direct-$\gamma$–jet angular distribution—with a clear difference from the case in which the $\gamma$-ray comes from a $\pi^0$. Of course, this is only a first step. Better data and more theoretical attention are required to see whether $\gamma$-jet coincidence studies could provide tests of QCD with *real* precision ($\sim 1\%$), or alternatively, could probe the fundamental limitations of the theory. After all, direct photon production is one of the few reactions where a fundamental constituent of the theory is directly accessible and can be measured extremely well.

### 4.2 Theoretical Issues

Peter Seyboth's presentation on the status of direct photon production was a model talk—all the experimental results were given and the various techniques were explained. The theory was clearly explained, also. However, only one theoretical point of view was given, that of Aurenche, et al [5]. The method of Aurenche, et al., troubles me for several reasons, two of which were touched upon by Seyboth. Firstly, from the data/theory plot, it is clear that the prediction at the ISR is consistently high by 30%, and well above the experimental errors, for $x_T \lesssim 0.35$. Secondly, the method of the "Principle of Minimal Sensitivity", used to apparently eliminate the dependence of the calculation on two unknown scales, is unfortunate, because it hides the fact that there are considerable theoretical uncertainties in the results—what we experimentalists would call "systematic errors." Egregiously, these errors are not indicated on the theoretical predictions. We have a clue that something is fishy because the "optimized scales" are small fractions of any reasonable "$Q^2$" scale in the problem, like $p_T^2$, $\hat{s}, \hat{t}$, etc. A clearer example of the theoretical uncertainties in leading and next-to-leading order calculations is given by Baer, et al., in a recent article [22]. Interestingly enough, there is a very large theoretical uncertainty (considerably more than a factor of 2), for $p_T = 20$ GeV/c photons, at $\sqrt{s} = 630$ GeV. This also serves as an answer to a question, raised by Sosnowski, on whether the "hardness" of a collision is measured by $p_T$ or $x_T$. The neat answer, told to me by Frank Paige [23], is that QCD perturbation theory works for large $p_T$. When $x_T$ is also "large" then lowest order is adequate; for "small" $x_T$, more orders are needed, and "sums over terms involving $\log x_T$ are required" [23].

## 5. Mini-Jets—and the MJT Theoretical Challenge

### 5.1 Mini-Jets are ISR Jets

Mini-jets tend to be viewed as controversial by many experimentalists —I don't believe that they were mentioned in any of the experimental talks. This stems from the sordid history of jet algorithms—which tend to find jets even when there aren't any [3]. The situation will clearly be much worse in RHI collisions.

I have no problem understanding mini-jets. In my opinion, mini-jets are simply ISR jets, i.e. 5-15 GeV jets, and therefore are best seen by single particle inclusive production. From the nice compilation by CDF [24] of the $h^+ + h^-$ single particle inclusive spectra (figure 3), it is evident that the cross section increases by orders of magnitude in the range 2 to 3 GeV/c, with increasing $\sqrt{s}$, whereas for $p_T \lesssim 1$ GeV/c, the cross section stays constant, and is well represented by $e^{-6p_T}$, from AGS fixed target energies (including RHI collisions) to Tevatron Collider energies.

It seems to me that this big increase is evidence for mini-jet production. However, Lissauer says that it may be simply the result of feed-down—due to the increased high $p_T$ jet production with increasing $\sqrt{s}$. This needs a more quantitative argument. Whatever the cause of the enhancement, there is clearly a blurring of the boundary between "hard" and "soft" physics with increasing $\sqrt{s}$.

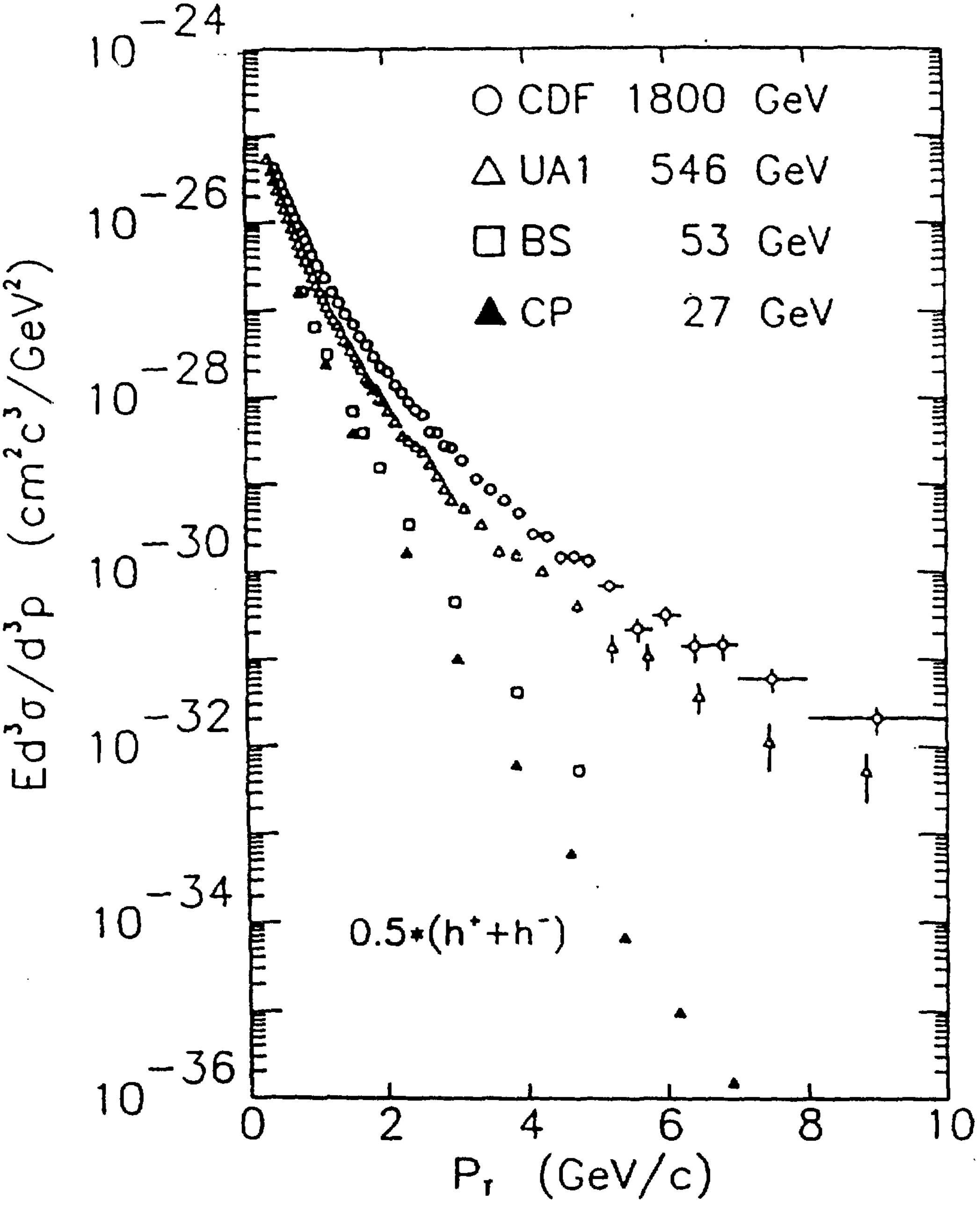

Figure 3. $\sqrt{s}$ dependence of inclusive cross sections for charge-averaged hadron production $0.5 \times (h^+ + h^-)$ near 90° in the c.m. system as a function of the transverse momentum. The data were compiled by the CDF collaboration [24].

### 5.2 The MJT Challenge

Since we know the $h^+ + h^-$ spectra in $p - \bar{p}$ collisions at $\sqrt{s}$=200 GeV, from UA1 measurements [25], we therefore have no need of theoretical predictions of these spectra for $p - p$ collisions at RHIC. We do, however, need the theorists to tell us what the single particle inclusive spectra will be *in A+A collisions*. My challenge is for theorists to present us with such predictions, for at least the following cases: a) with no QGP or Jet Quenching; b) with QGP and no Jet Quenching; c) for Jet Quenching and no QGP; d) for QGP with Jet Quenching; and any other other conditions that we are likely to encounter in A+A collisions. I am happy to note that some theorists have already begun thinking in this direction [17].

It is also important to consider whether the predictions will depend on the identity of the final state particles, since many QGP predictions involve strangeness. The benefit of using identified particles, even at collider energies, was shown in Oh's presentation of the C0(E735) data at the FNAL collider—the systematics of the pions and protons turned out to be completely different. Particularly striking is that the "Van Hove signature" for the QGP [26] is still alive: the $<p_T>$ of identified $\pi^\pm$ saturates as a function of $dn/dy$, and does not show any evidence of the second rise predicted for a phase transition. The systematics of the produced $p^\pm$ are completely different, and are not understood at this time.

There may also be other surprises. No $p - p$ data exist for $\sqrt{s} > 63$ GeV. The $p - \bar{p}$ data are very useful—but, one should not forget that charge symmetry between $\pi^\pm$ and $p^\pm$ is enforced in $p - \bar{p}$ collisions, but there is no such constraint acting for proton-proton or nucleus-nucleus reactions. We will thus have to do our homework at RHIC, with lots of $d - d$ (and $p - p$) comparison runs, before we are sure of a new effect in A+A interactions.

### 6. Conclusion

As eloquently pointed out by Sosnowski, the commonly held beliefs of the period were completely overturned during the lifetime of the CERN ISR, leading to the present set of commonly held beliefs: the "Standard Model", or for our particular interest, Quantum Chromodynamics. It will be interesting to see whether the same thing happens at RHIC.

I look forward to another great period of discovery!

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