Introduction to High p_T physics at RHIC

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Abstract

Hard scattering in p-p collisions was discovered at the CERN ISR by the observation of a very large flux of high transverse momentum pions with a power-law tail which varied systematically with the c.m. energy of the collision. This observation in 1972 proved that the partons of deeply inelastic scattering were strongly interacting. Further ISR measurements utilizing inclusive single or pairs of hadrons established that high transverse momentum particles are produced from states with two roughly back-to-back jets which are the result of scattering of point-like constituents of the protons as described by QCD. In the region of hard-scattering, $p_T > 2$ GeV/c, the scaling from p-p to nuclear collisions should be simply proportional to the relative number of point-like encounters, corresponding to A (p+A), A^2 (A+A) for the total rate, and to T_{AA}, the overlap integral of the nuclear profiles, as a function of centrality. Measurements of high p_T pion production in p+A and A+A collisions at FERMILAB and CERN fixed target energies and at the CERN ISR, however, all showed an enhancement compared to the point-like scaling, a phenomenon known as "the Cronin effect". In stark contrast to the results at lower c.m. energies, measurements of high p_T particle production at $\sqrt{s_{NN}} = 130$ GeV at RHIC show a huge suppression compared to point-like scaling. Such an effect has been predicted in QCD, for a sufficiently hot, dense, and colorful medium, due to the interaction of the outgoing partons with the medium. To put the unprecedented RHIC results in context, the nearly 30 year history of this subject, which originated at the CERN ISR, will be reviewed.

1 Introduction

In 1998 [1], in several talks, I indicated that my best bet on discovering the QGP was to utilize semi-inclusive π^0 or $\pi^\pm$ production. In p-p collisions, the invariant cross section for non-identified charge-averaged hadron production at 90° in the c.m. system as a function of the transverse momentum p_T and c.m. energy $\sqrt{s}$ has a characteristic shape (Fig. 1). There is an exponential tail (e^{-6p_T}) at low p_T, which depends very little on $\sqrt{s}$. This is

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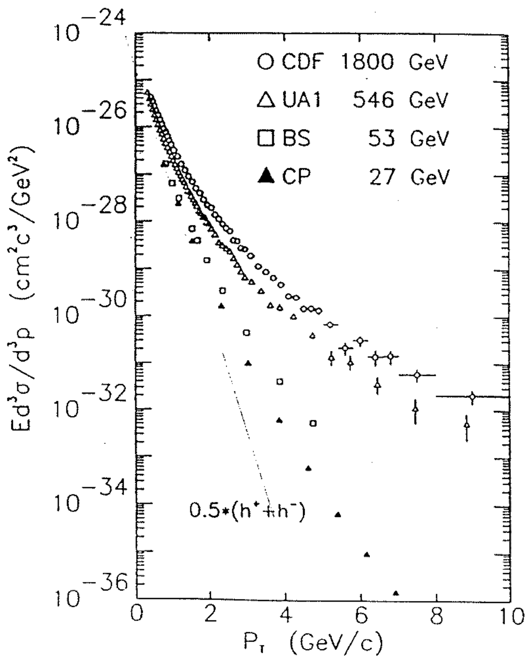

Figure 1: Invariant cross section for non-identified charge-averaged hadron production at 90° in the c.m. system as a function of the transverse momentum p_T compiled by CDF for a range of c.m. energies $\sqrt{s}$.

the soft physics region, where the hadrons are fragments of 'beam jets'. At higher p_T, there is a power-law tail which depends very strongly on $\sqrt{s}$. This is the hard-scattering region, where the hadrons are fragments of the high p_T QCD jets from constituent-scattering. In RHI central collisions, leading particles are the only way to find jets [3] because in one unit of the jet-finding cone, $\Delta r = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, there is $\pi \times \frac{1}{2\pi}\frac{dE_T}{d\eta} \sim 375$ GeV of energy!!

In 1998, I expressed my hope that the QGP would cause the high p_T quarks to lose all their energy and stop, so that the high p_T tail would 'vanish' for central Au+Au collisions. If the power-law tail would return when peripheral Au+Au collisions are selected, then this would be proof of a hot/dense/colorful medium (QGP??) in central Au+Au collisions. This is apparently what we see at RHIC [2]; but my purpose here is to review the experiments and theories which established in the 1970's that hadrons with $p_T > 2$ GeV/c in p-p collisions are fragments of high p_T jets which are the result of scatering of the point-like constituents of the nucleon as described by QCD. [4, 5, 6]

2 Bjorken Scaling and the Parton Model—1968

The discovery that the Deeply Inelastic Scattering (DIS) structure function

$$F_2(Q^2, \nu) = F_2(\frac{Q^2}{\nu}) \tag{1}$$

"SCALED" i.e just depended on the ratio

$$x = \frac{Q^2}{2M\nu} \tag{2}$$

independently of Q^2 as originally suggested by Bjorken [7], led to the concept of a proton composed of point-like **partons**. The probability for a parton to carry a fraction x of the proton's momentum is measured by $F_2(x)$. Berman, Bjorken and Kogut (BBK) [8] then calculated the inclusive reaction

$$A + B \rightarrow C + X \tag{3}$$

when particle C has $p_T \gg 1$ GeV/c. The charged partons of DIS **must scatter electromagnetically**, "which may be viewed as a **lower bound** on the real cross section at large p_T," since the partons of DIS are electrically charged. BBK proposed a general form for high p_T cross sections, for the electromagnetic (EM) scattering:

$$E\frac{d^3\sigma}{dp^3} = \frac{4\pi\alpha^2}{p_T^4}\mathcal{F}(x_1 = \frac{-\hat{u}}{\hat{s}}, x_2 = \frac{-\hat{t}}{\hat{s}}) \tag{4}$$

The two factors are a $1/p_T^4$ term, characteristic of single photon exchange, and a form factor $\mathcal{F}$. Note that $x_{1,2}$ in Eq. 4, where $\hat{s}$, $\hat{t}$ and $\hat{u}$ are the constituent-scattering invariants, are not $x_{\rm BJ}$. The point is that $\mathcal{F}$ **scales**, i.e. is only a function of the ratio of momenta. Vector ($J = 1$) Gluon exchange gives the same form as Eq. 4 but would be much larger.

3 ISR Data, Notably CCR 1972-73

The Cern Columbia Rockefeller (CCR) Collaboration [9] (and also the Saclay Strasbourg [10] and British Scandinavian [11] collaborations) measured high p_T pion production at the CERN-ISR (Fig. 2). The e^{-6p_T} breaks to a power law at high p_T with characteristic $\sqrt{s}$ dependence. The large rate indicates that *partons interact strongly ($\gg$ EM) with each other*, **but,** "Indeed, the possibility of a break in the steep exponential slope observed at low p_T was anticipated by Berman, Bjorken and Kogut. However, the electromagnetic form they predict, $p_\perp^{-4}F(p_\perp/\sqrt{s})$, is not observed in our experiment. On the other hand, a constituent exchange model proposed by Blankenbacler, Brodsky and Gunion, and extended by others, does give an excellent account of the data." [9] The data fit $p_\perp^{-n}F(p_\perp/\sqrt{s})$, with $n \simeq 8$.

4 Constituent Interchange Model (CIM) 1972

Inspired by the *dramatic features* of pion inclusive reactions revealed by "the recent measurements at CERN ISR of single-particle inclusive scattering at 90° and large transverse momentum", Blankenbecler, Brodsky and Gunion [12] proposed a new general scaling form:

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{p_T^n}F(\frac{p_T}{\sqrt{s}}) \tag{5}$$

where n gives the form of the force-law between constituents. For QED or Vector Gluon exchange, $n = 4$, but perhaps more importantly, BBG predict n=**8** for the case of quark-meson scattering by the exchange of a quark (CIM) as apparently observed.

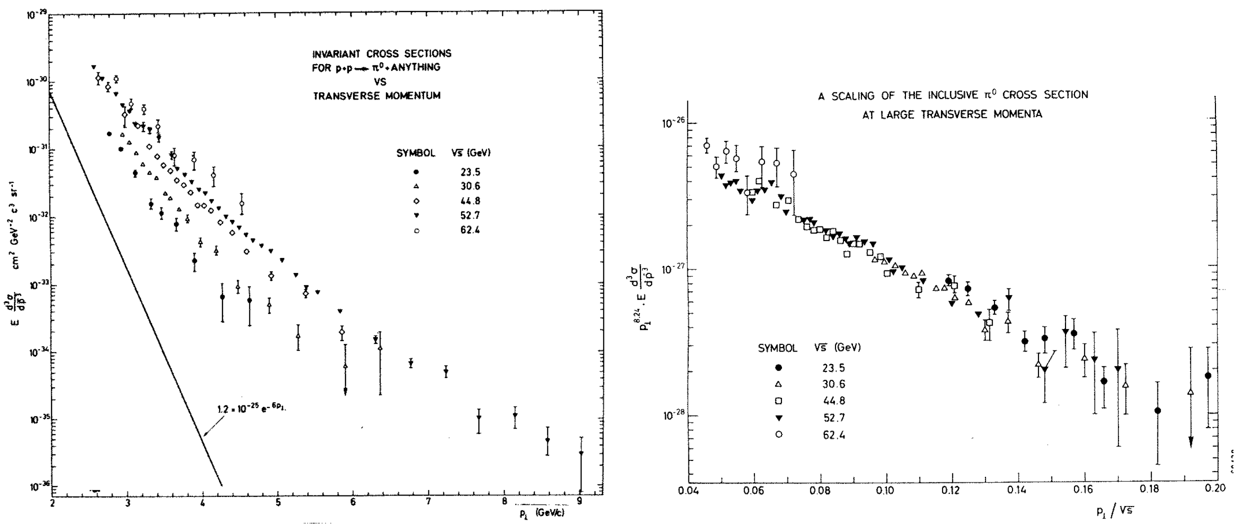

Figure 2: Left: CCR transverse momentum dependence of the invariant cross section at five center of mass energies. Right: The above data multiplied by $p_\perp^n$, using the best fit value of $n = 8.24 \pm 0.05$, with $F = Ae^{-bx_\perp}$, plotted vs $p_\perp/\sqrt{s}$.

5 State of the art at FNAL 1977—but misleading!

The best data at FNAL in 1977 [13] beautifully show the CIM scaling with $n \sim 8$ over the range $0.2 \leq x_T \leq 0.6$, where $x_T = 2p_T/\sqrt{s}$.

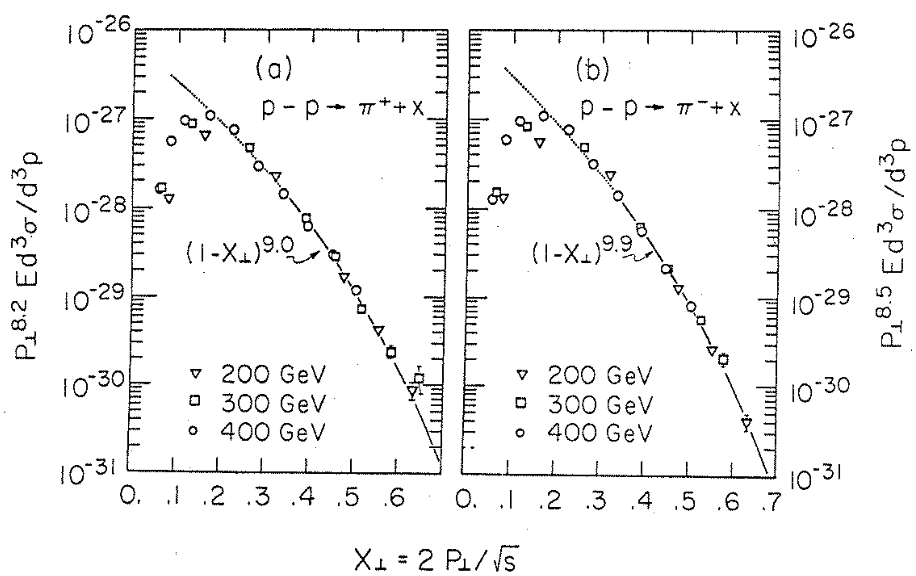

Figure 3: $p_\perp^n Ed^3\sigma/dp^3$ vs x_T for π^+ and π^- production at 90° in the c.m. system for three FNAL incident energies. Best fit $n \sim 8$, $F(x_T) = (1 - x_T)^m$ shown.

6 First prediction using 'QCD' 1975—WRONG!

R. F. Cahalan, K. A. Geer, J. Kogut and Leonard Susskind [14] generalized, in their own words: "The naive, pointlike parton model of Berman, Bjorken and Kogut to scale-invariant and asymptotically free field theories. The asymptotically free field generalization is studied in detail. Although such theories contain vector fields, **single vector-gluon exchange contributes insignificantly to wide-angle hadronic collisions.** This follows from (1) the smallness of the invariant charge at small distances and (2) the *breakdown of naive scaling* in these theories. These effects should explain the apparent absence of vector exchange in inclusive and exclusive hadronic collisions at large momentum transfers observed at Fermilab and at the CERN ISR."

Nobody's perfect, they get *one* thing right! They introduce the "effective index" $n(x_T, \sqrt{s})$ to account for 'scale breaking':

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{p_T^{n(x_T,\sqrt{s})}} F(\frac{p_T}{\sqrt{s}}) = \frac{1}{\sqrt{s}^{n(x_T,\sqrt{s})}} G(\frac{p_T}{\sqrt{s}}) \qquad (6)$$

7 CCOR 1978—Higher $p_T > 7$ GeV/c—$n(x_T, \sqrt{s})$ works, QCD works $n \to 5 = 4^{++}$

The CCOR measurement [15] (Fig. 4) with a larger apparatus and much increased integrated

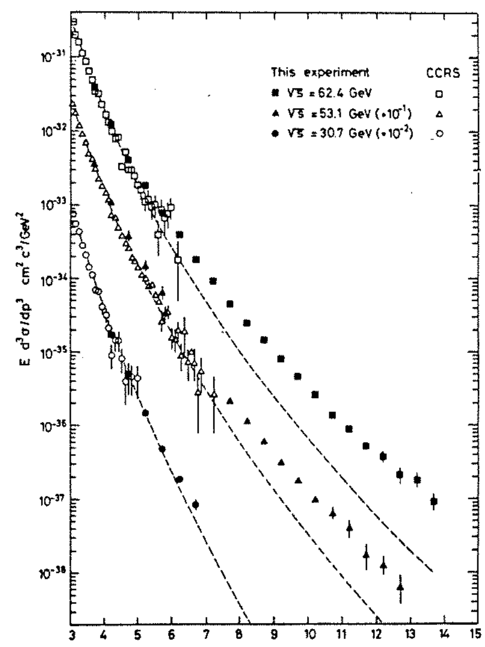

Figure 4: CCOR transverse momentum dependence of the invariant cross section for $p + p \to \pi^0 + X$ at three center of mass energies. Cross sections are offset by the factors noted. Open points and dashed fit are from a previous experiment, CCRS [16].

luminosity extended their previous π^0 measurement [9, 16] to much higher p_T. The p_T^{-8} scaling-fit which worked at lower p_T extrapolated below the higher p_T measurements for $\sqrt{s} > 30.7$ GeV and $p_T \geq 7$ GeV/c.

An important feature of the scaling analysis (Eq. 6) is relevant to determining $n(x_T, \sqrt{s})$— *the absolute p_T scale uncertainty cancels!* In Fig. 5-top-left the CCOR data of Fig. 4 for the 3 values of $\sqrt{s}$ are plotted vs x_T on a log-log scale. $n(x_T, \sqrt{s})$ is determined for any

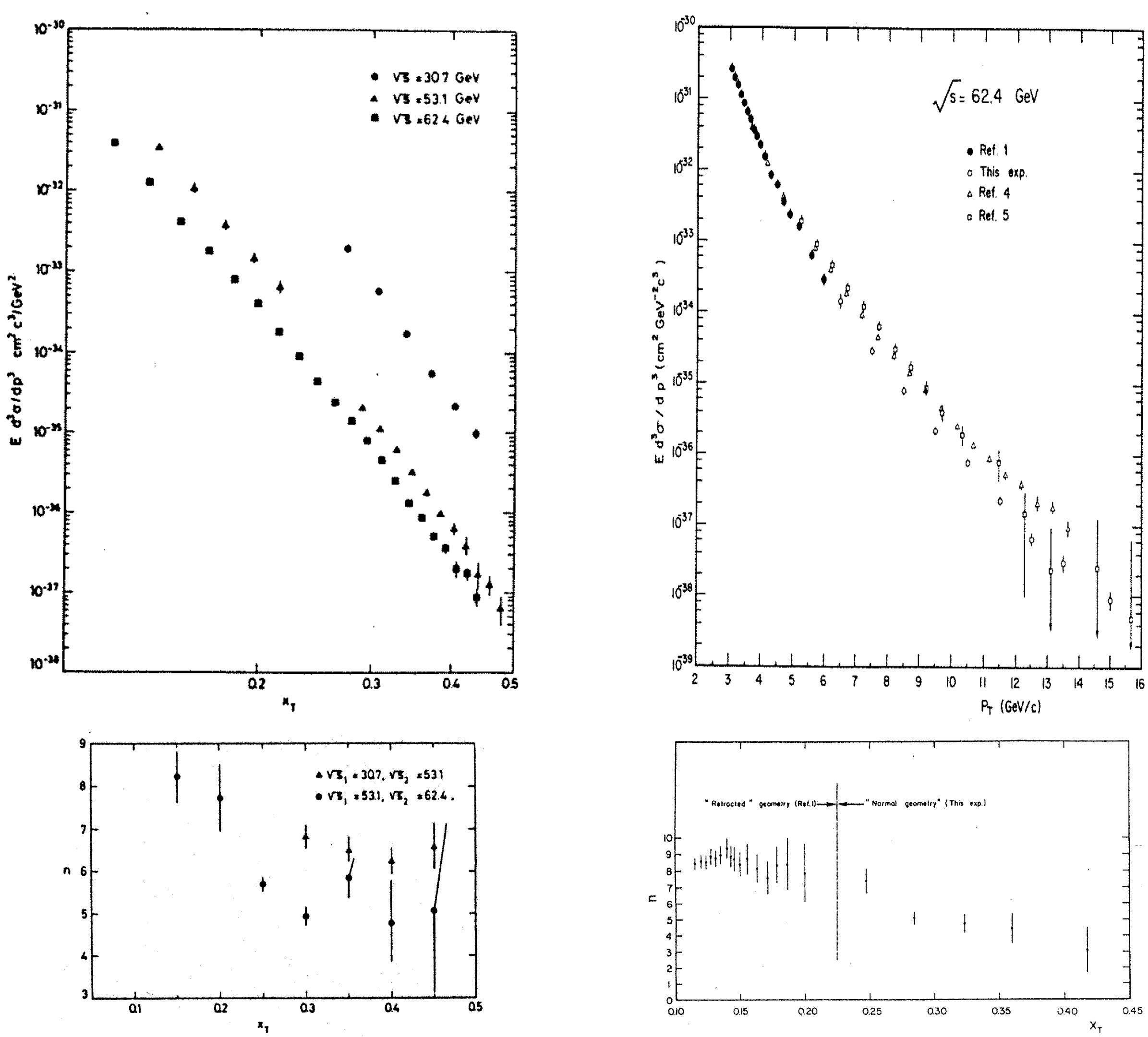

Figure 5: Top-left: CCOR invariant cross section vs $x_T = 2p_T/\sqrt{s}$. Bottom-left: $n(x_T, \sqrt{s})$ derived from the combinations indicated. The systematic normalization error at $\sqrt{s} = 30.6$ GeV has been added in quadrature. There is an additional common systematic error of ± 0.33 in n. Top-right: Invariant cross section for π^0 inclusive for several ISR experiments, compiled by ABCS Collaboration. Bottom-right: $n(x_T, \sqrt{s})$ from ABCS 52.7, 62.4 data only. There is an additional common systematic error of ± 0.7 in n.

2 values of $\sqrt{s}$ by taking the ratio as a function of x_T as shown in Fig. 5-bottom-left. $n(x_T, \sqrt{s})$ clearly varies with both $\sqrt{s}$ and x_T, it is not a constant. For $\sqrt{s} = 53.1$ and

62.4 GeV, $n(x_T, \sqrt{s})$ varies from $\sim$ 8 at low x_T to $\sim$ 5 at high x_T. The new fit [15] is $Ed^3\sigma/dp^3 \simeq p_T^{-5.1\pm0.4}(1-x_T)^{12.1\pm0.6}$, for $7.5 \leq p_T \leq 14.0$ GeV/c, $53.1 \leq \sqrt{s} \leq 62.4$ GeV (including *all* systematic errors). The effect of the absoulte scale uncertainty, which is the main systematic error in these experiments, can be gauged from Fig. 5-top-right [17] which shows the π^0 cross sections from several experiments. The absolute cross sections disagree by factors of ~ 3 for different experiments but the values of $n(x_T, \sqrt{s})$ for the CCOR [15] (Fig. 5-bottom-left) and ABCS [17] experiment (Fig. 5-bottom-right) are in excellent agreement due to the cancellation of the error in the absolute p_T scale.

8 Summary and Conclusion

Hard-scattering was visible both at ISR and FNAL (Fixed Target) energies via inclusive single particle production at large $p_T \geq$ 2-3 GeV/c. Scaling and dimensional arguments for plotting data revealed the systematics and underlying physics. The theorists had the basic underlying physics correct; but many (inconvenient) details remained to be worked out, several by experiment. k_T, the transverse momentum imbalance of outgoing partons (due to initial state radiation), was discovered by experiment. [18] The first modern QCD calculations and predictions for high p_T single particle inclusive cross sections, including non-scaling and initial state radiation was done in 1978, by Jeff Owens and collaborators. [19] Jets in 4π Calorimeters at ISR energies or lower are invisible below $\sqrt{\hat{s}} \sim E_T \leq 25$ GeV [20]; but there were many false claims which led to skepticism about jets in hadron collisions, particularly in the USA. [21] A 'phase change' in belief-in-Jets was produced by one UA2 event at the 1982 ICHEP in Paris [22], but that's another story.

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