Why Leading Particles Can Be used to Measure Hard-Scattering at RHIC

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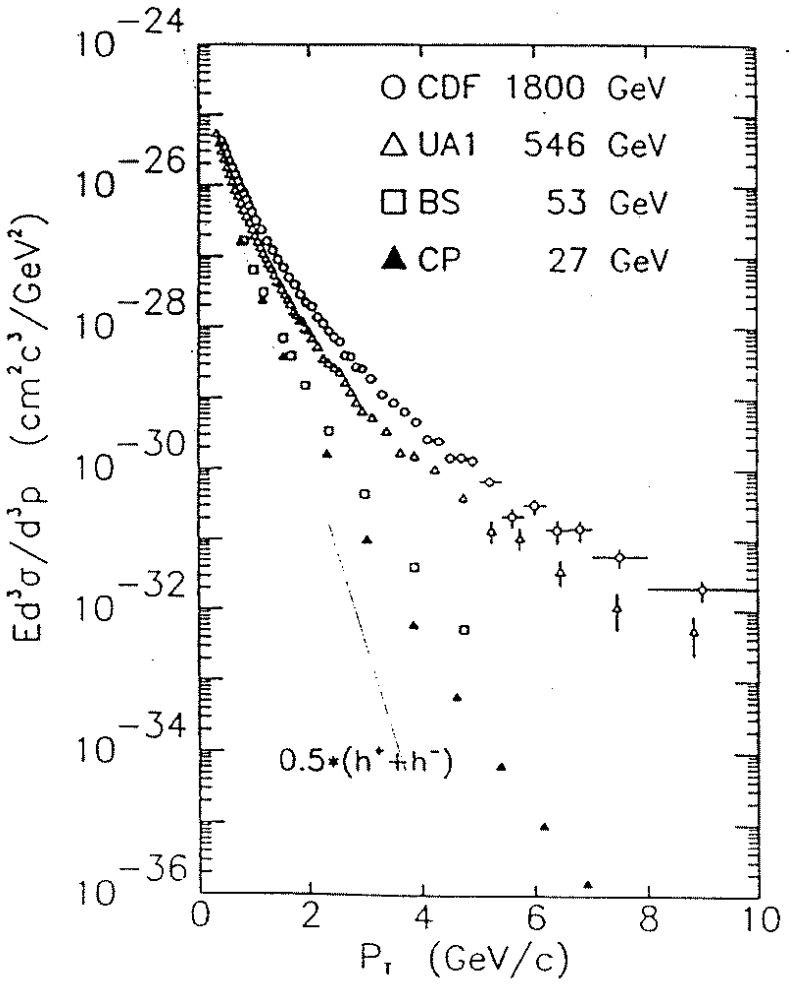
BNL/PHENIX
March 1, 1999

- Hard Scattering in p-p collisions was discovered at the CERN ISR in 1972 by the method of leading particles.
- A very large flux of high p_T pions was observed with a power-law tail which varied systematically with $\sqrt{s}$, the c.m. energy of the collision.
- The huge flux of high p_T particles proved that the partons of DIS strongly interacted with each other.
- Scaling arguments allowed the form of the force law between 'partons' to be determined but there was some early confusion caused by initial transverse momentum k_T which distorted the spectra.
- 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 constituents of the nucleons as described by Quantum Chromodynamics.
- These measurements are illustrated on the following pages.

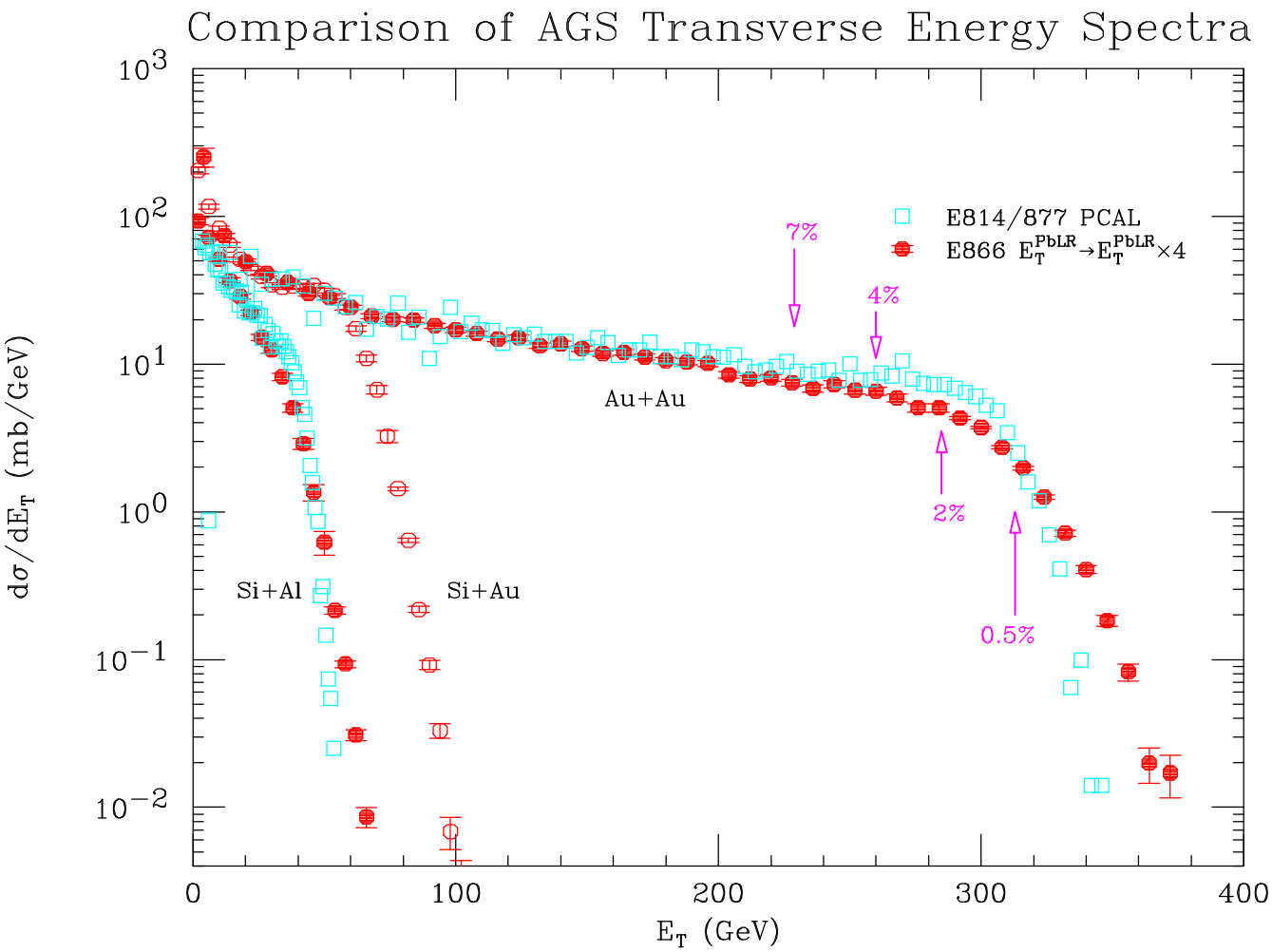
My Best Bet on Discovering QGP
Utilizes semi-Inclusive π^0 or $\pi^{\pm}$ production



Invariant cross section for non-identified charged-averaged hadron production at 90° in the c.m. system as a function of the transverse momentum p_T tablulated by CDF for a range of C.M. energies $\sqrt{s}$. There is an exponential tail (e^{-6p_T}) at low p_T, which depends very little on $\sqrt{s}$. This is 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. **My hope is that the QGP causes the high p_T quarks to lose all their energy and stop, so that the high p_T tail will 'vanish' for central Au+Au collisions**

In RHI central collisions, leading particles are the only way to find jets because in one unit of Δr there is $\pi \times \frac{1}{2\pi}\frac{dE_T}{d\eta} \sim 375$ GeV !!!.

We can use Centrality Cuts
To see if the power-law tail returns at low E_T



Of course, using E_T for centrality may introduce a bias since E_T is dominated by low p_T π^0 and thus may distort the data. Another possibility is to use a gentle $E_T > 70$ GeV (see above) cut to define "not-peripheral" and then use the Zero Degree neutron calorimeter, with "few-neutrons" and "not-peripheral", to define centrality. Also, the PHENIX Silicon Vertex Detector (MVD) may be very useful as a centrality trigger, since we could use the parts of the MVD both inside or outside the EMcal acceptance and see whether these gave different results. **However, I think minimally we will have to run Si+Si to prove the any observed effect, and also p-p and p+Au.**

A Real Theoretical Calculation
X-N. Wang and Z. Huang PRC 55, 3047 (1997)
γ/π^0 is Enhanced!

dot-dashed line. However, one still has to face π^0's about 3 times higher than the direct photons at $p_T = 10$ GeV/c. At larger p_T, the situation improves, but one loses the production rate. Since the isolation cut method normally employed in pp collisions to reduce the background for direct photons does not work any more, the only way one can identify them with high accuracies has to be through the means of improved detectors.

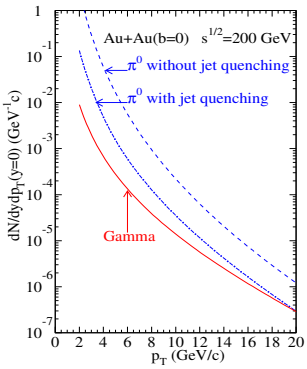


FIG. 13. The spectrum of direct photon production (solid) as compared to π^0 spectrum with (dot-dashed) and without (dashed) parton energy loss ($dE_q/dx = 1$ GeV/fm, $\lambda_q = 1$ fm) in central $Au + Au$ collisions at $\sqrt{s} = 200$ GeV.

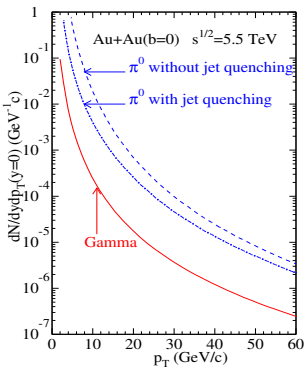


FIG. 14. The same as Fig. 13, except at $\sqrt{s} = 5.5$ TeV.

Similarly, we also list in Table III the number of γ+jet events per year per unit rapidity and unit (GeV) E_T at the LHC energy. We assume a luminosity of $\mathcal{L} = 2 \times 10^{27}$ cm^{-2}s^{-1} with 50 operation days per year for $Au + Au$ collisions. The production rates are reasonably high due to both the high luminosity and collider energy. However, the corresponding background of π^0's is also high (see Fig. 14) which may make the detection of direct photons more difficult.

At the LHC energy, $\sqrt{s} = 5.5$ TeV, the production rate for Z^0+jet becomes large even for reasonably large $P_T^{Z^0}$. Listed in Table IV are the number of Z^0+jet events per year per unit rapidity integrated over $P_T^{Z^0}$ with different low cut-off values. The production cross sections are provided by T. Han based on calculations as described in Ref. [30]. Note that the given Z^0 production rates are integrated ones, thus appearing to be larger than the differential rate of direct photon production at the same transverse momentum. One can detect Z^0 through the dilepton channel which has almost no background in the range of the dilepton invariant mass near M_{Z^0}. One can then apply the same procedure as we have discussed in this paper for direct photon events and measure the modification of the effective jet fragmentation function due to parton energy loss. However, the drawback of using the dilepton channel of Z^0 decay is that the effective number of events via this channel is about 6.7% of the total number of Z^0 events.

E_T^γ (GeV)	7	10	15	20
$dN^{\gamma-jet}/dydE_T$/year	20500	3550	400	70

TABLE II. Rate of direct photon production in central $Au + Au$ collisions at $\sqrt{s} = 200$ GeV, with luminosity $\mathcal{L} = 2 \times 10^{26}$ cm^{-2}s^{-1} and 100 operation days per year.

E_T^γ (GeV)	40	50	60
$dN^{\gamma-jet}/dydE_T$/year	2880	1070	490

TABLE III. Rate of direct photon production in central $Au + Au$ collisions at $\sqrt{s} = 5.5$ TeV, with luminosity $\mathcal{L} = 2 \times 10^{27}$ cm^{-2}s^{-1} and 50 operation days per year.

$P_T^{Z^0}$ (GeV)	> 20	> 40	> 60
dN^{Z^0-jet}/dy/year	21100	7700	3470

TABLE IV. Rate of Z^0 production in central $Au + Au$ collisions at $\sqrt{s} = 5.5$ TeV, with luminosity $\mathcal{L} = 2 \times 10^{27}$ cm^{-2}s^{-1} and 50 operation days per year.

Note the predicted π^0 suppression by jet quenching is a factor of 10—But the direct Gammas are not reduced. Thus γ/π^0 is greater than 10% for $p_T > 3$ GeV/c, (so that even I can make the measurement). **Note that this predicted γ/π^0 is much larger than for p-p collisions since the π^0 background has been suppressed by an order magnitude—if the theorists are right!**

A Systematic Review of measurements of JETS in A+A collisions in PHENIX was recently made by Paul Stankus of ORNL

WWW→ **PHENIX Meetings 9706**

♡ Paul Stankus' conclusion is that "the puzzle will come together over time: and it becomes quite clear that the photon $+\pi^0$ back-to-back measurement will be the one that addresses jet energy loss most directly."

♡ I'm more optimistic about the inclusive γ and inclusive π^0.

♡ Also note that measurements of direct photons in p-p and p+A would be **extremely useful** as a measurement of the Gluon Structure function,

♡ Furthermore, γ-$\pi^{\pm}$ can measure "k_T." Note, that k_T the 'out-of-plane' component of the net p_T of the hard-parton pair, is not merely a parameter, it is a physical quantity which can be measured, but first:

Again, A Real Theoretical Calculation
X-N. Wang and Z. Huang PRC 55, 3047 (1997)

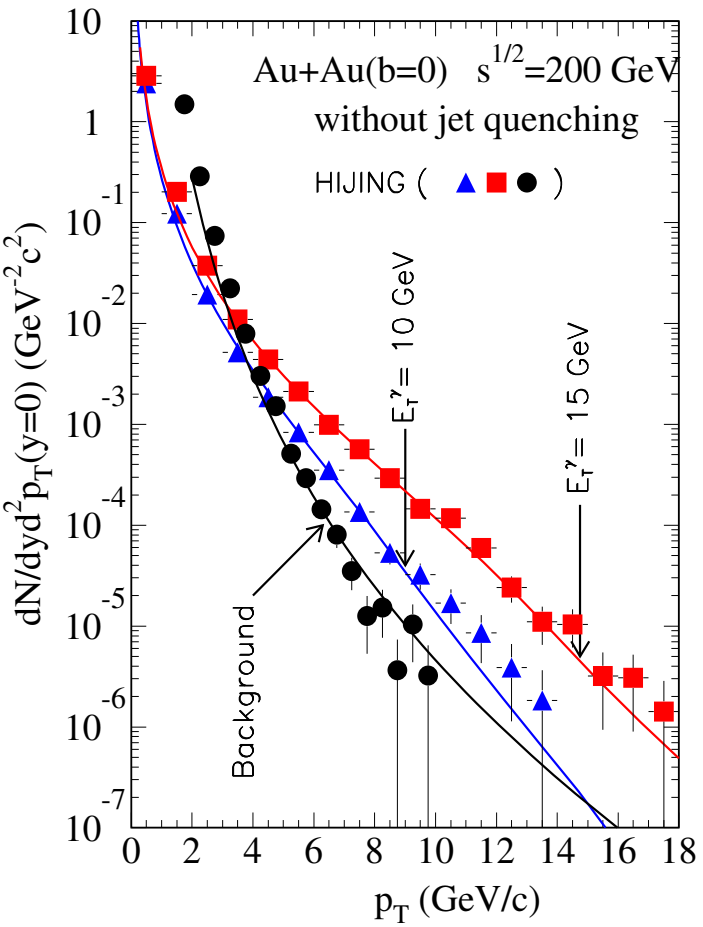
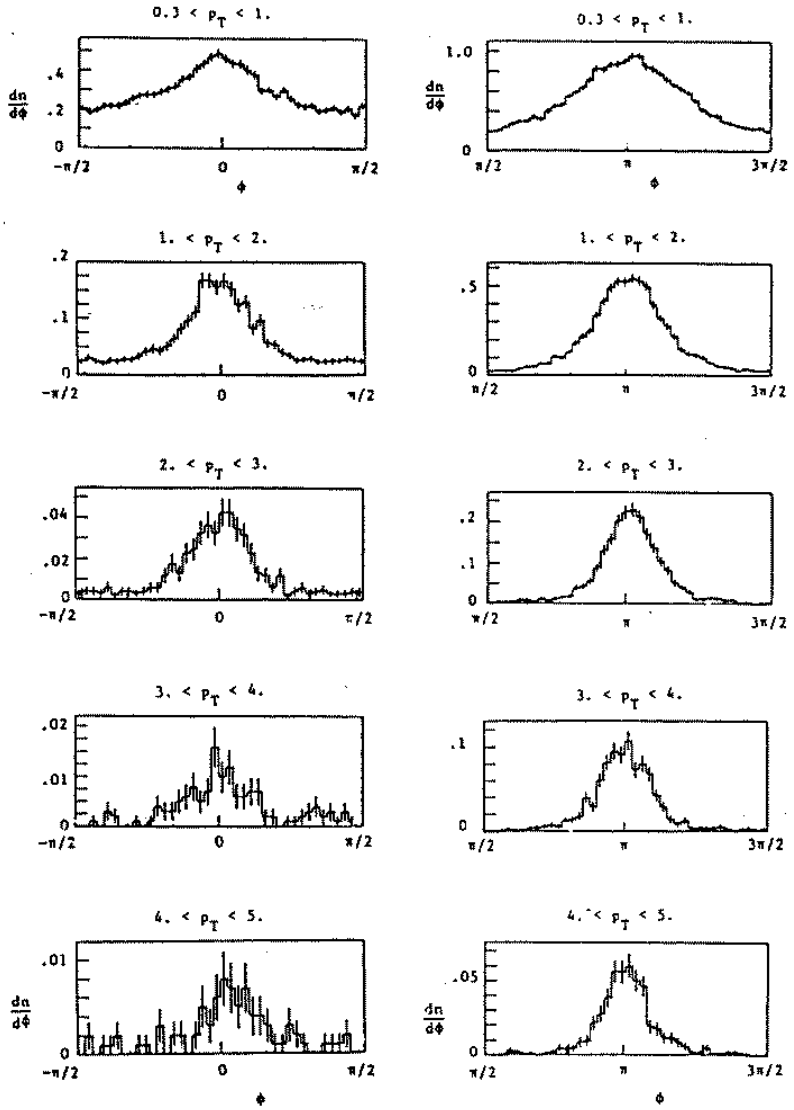


Fig. 4. The differential p_T spectrum of charged particles from the fragmentation of a photon-tagged jet with E_T^γ=10, 15 GeV and the underlying background in central Au+Au collisions at $\sqrt{s}$ = 200 GeV. The direct photon is restricted to $|y| \leq \Delta y/2 = 0.5$. Charged particles are limited to the same rapidity range and in the opposite direction of the photon, $|\phi - \phi_\gamma - \pi| \leq \Delta\phi/2 = 1.0$. Solid lines are HIJING simulation of 20K events.

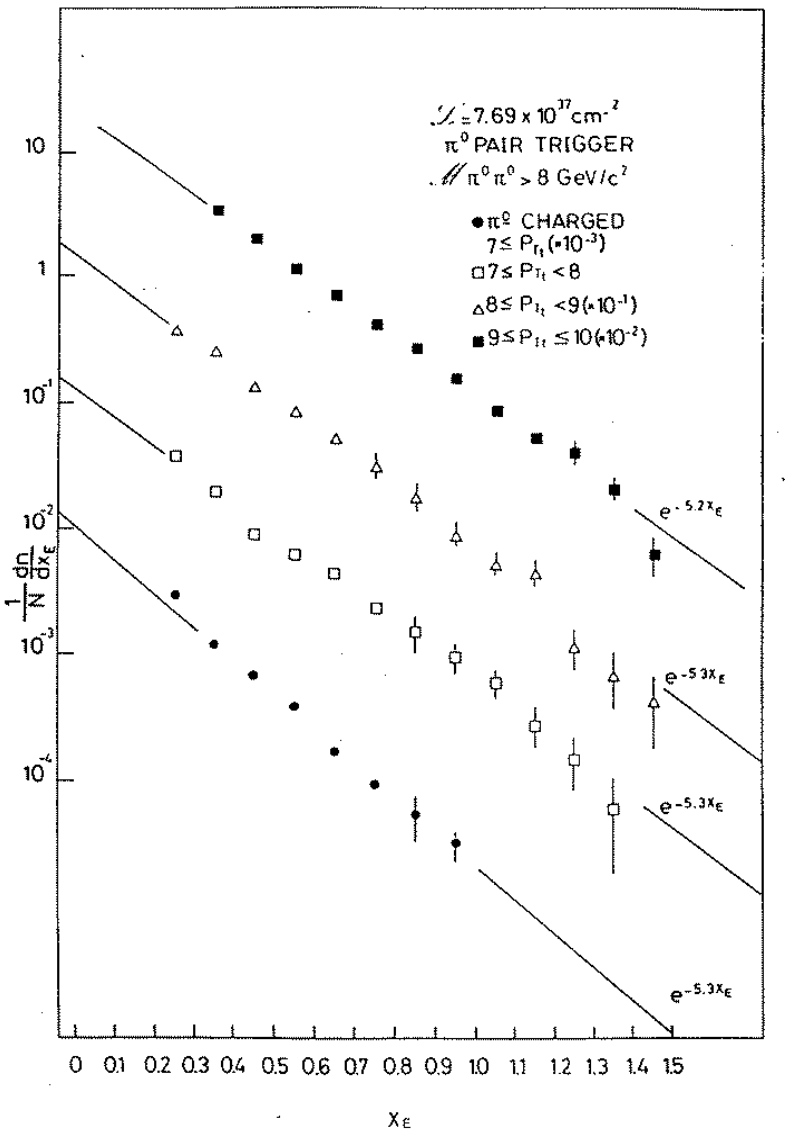
A calculation of charged particles in roughly PHENIX solid angle, opposite from a detected γ or π^0. The γ are direct constituents from the reaction, but the π^0 are the leading fragments of jets. In Au+Au collisions, the key problem is to cope with "background", which is just the p_T spectrum of inclusive charged particles randomly opposite any particle due to the large value of $dn^\pm/d\eta \sim 1000$—the same problem that makes direct detection of jets difficult. Interestingly, **the discovery of hard-scattering in hadron collisons at the CERN ISR and the first measurements of the properties of jets and di-jets were made with leading particles.**

How Everything You Want To Know about JETS can be done in PHENIX with leading particles in each arm c.f. CCOR



Two particle correlation in azimuth of charged particles relative to a triggering neutral with transverse momentum $p_{T\,t} \geq 7.0$ GeV/c which defines the zero of azimuth, $\phi = 0$. Charged particles with $|\eta| < 0.7$ in the same 'arm' as the trigger are on the left and opposite 'arm' to the trigger on the right. As the p_T of the observed charged particle increases, the width of the away side peak (plots on the right) narrows. This effect clearly shows that the jets **are not collinear in azimuth** (they have a net transverse momentum k_T. If there were only fragmentation transverse momentum, then $p_T \times \Delta\phi$ would remain constant which would equal to $< j_T >$, the mean transverse momentum of fragmentation. [See PL 97B (1980) 163 for details]

Measurement of fragmentation function with the same data



Distribution in x_E for a charged pion (or π^0) observed roughly back-to-back to a triggering π^0 of transverse momentum p_{Tt}, 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_{Tt}. **Exercise for students:** What do you have to know about the leading trigger particle to convert from $e^{-5.3x_E}$ to the jet fragmentation variable z $[e^{-6z}]$.

k_T Results from this Data

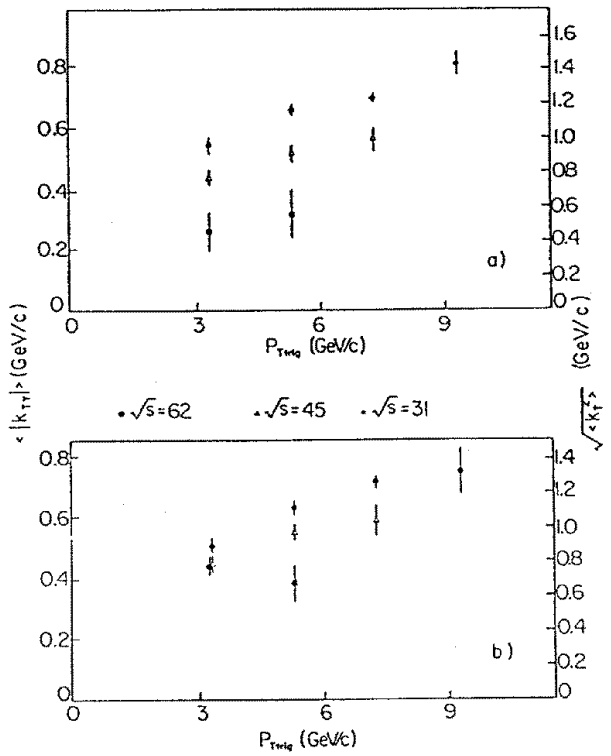
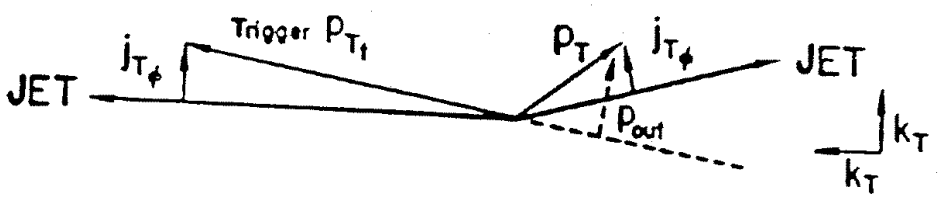
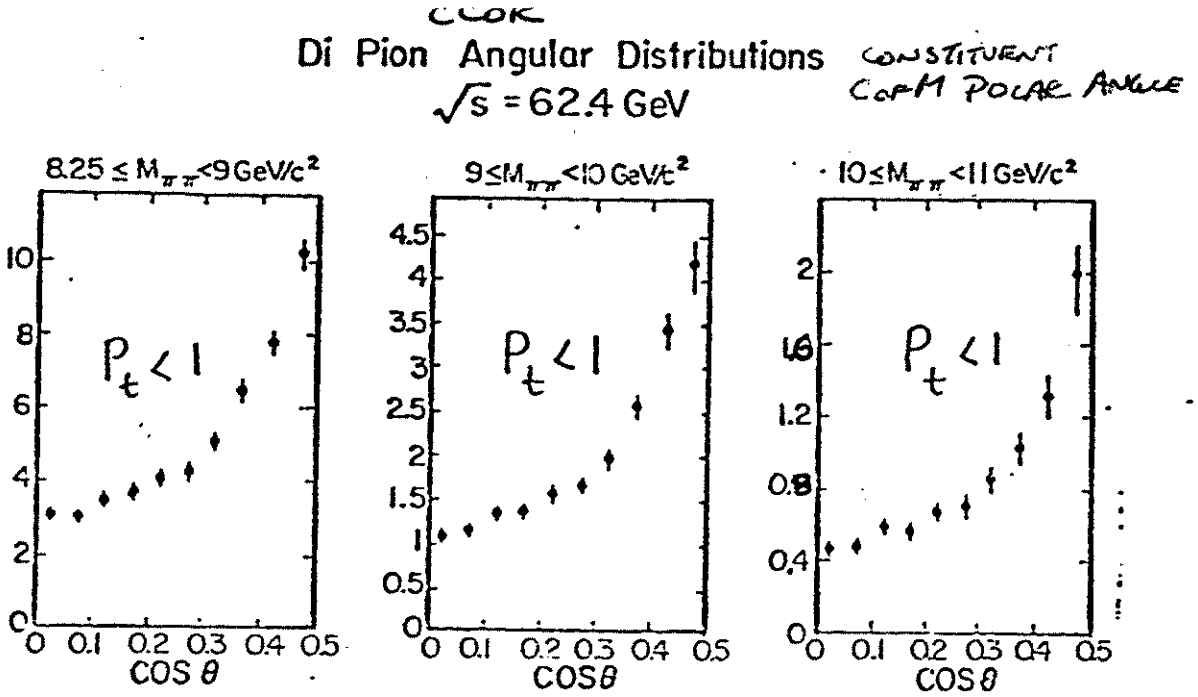


Figure 7: (a) $\langle|k_{Ty}|\rangle$ and $\sqrt{(\langle k_T^2\rangle)}$ as a function of p_{Ttrig} for three different $\sqrt{s}$ values, obtained from back-back correlations. (b) The same using events where the sum of charged paricle transverse momenta on the away side balances p_{Ttrig} [see Phys Lett **97B** (1980) 163].

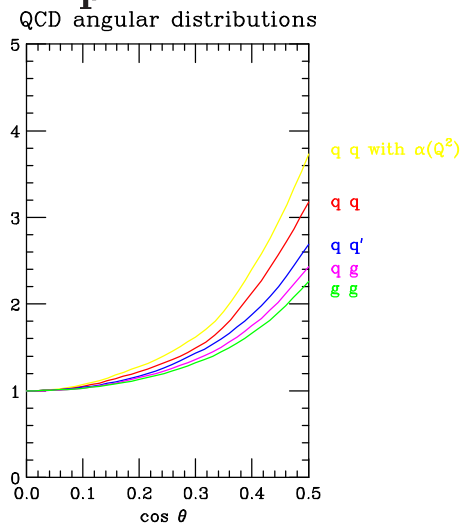


$$\langle|p_{\rm out}|\rangle^2 = \langle|j_{Ty}|\rangle^2 + x_E^2(\,\langle|j_{Ty}|\rangle^2 + 2\,\langle|k_{Ty}|\rangle^2\,) \qquad (1)$$

Same Data Set— First measurement of QCD subprocess angular distributions



QCD Subprocess predictions normalized at 90°



Angular distributions of pairs of nearly back-to-back π^0 as a function of the invariant mass $M_{\pi\pi}$ of the pair. The net P_t of the pion pair is restricted as indicated on the figure and the net rapidity of the di-pion system is restricted to $|Y_{\pi\pi}| < 0.35$. The distribution plotted is the polar angular distribution of the dipion axis in the frame with zero net longitudinal momentum. The important feature of the analysis in these variables, which are more typically used for lepton pairs, is that the di-pion angular distribution at fixed mass corresponds closely to the distribution of scattered partons at fixed $\hat{s}$, thus the data and QCD prediction at the parton level can be directly compared without recourse to a Monte Carlo. [see Nucl Phys **B209** (1982) 284].

As Miklos said at DNP98 after Paul Stankus' back-to-back π^0 talk

"Can an *OLD TIMER* enlighten me: Why THEY never found JETS at FERMILAB (fixed target)?" Part I—Learn Physics from the DATA

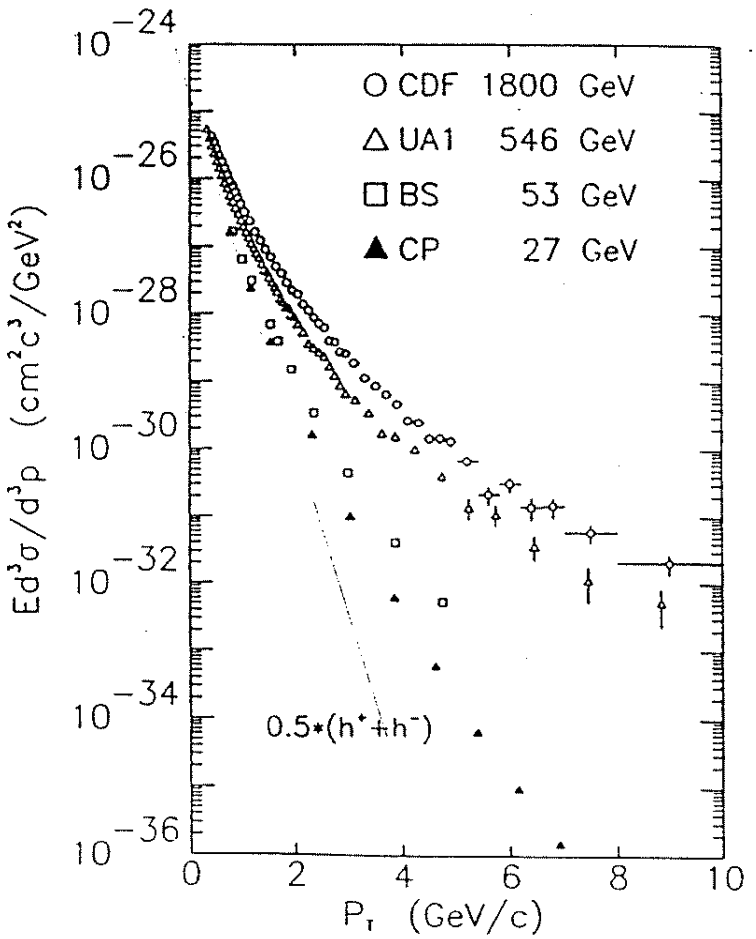


Figure 9: Invariant cross section for non-identified charged-averaged hadron production at 90° in the c.m. system as a function of the transverse momentum p_T compiled by CDF for a range of c.m. energies $\sqrt{s}$.

Bjorken Scaling in Deeply Inelastic Scattering and the Parton Model—1968

♡ The discovery that the DIS structure function

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

"SCALED" i.e just depended on the ratio

$$x = \frac{Q^2}{2M\nu} \tag{3}$$

independently of Q^2 $(\sim 1/r^2)$

♡ as originally suggested by **Bjorken**

♡ 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 $F_2(x)$

BBK 1971

S. M. Berman, J. D. Bjorken and J. B. Kogut
Phys. Rev. **D4** 3388 (1971)
Inclusive Processes at High Transverse Momentum

♡ BBK calculate the inclusive reaction

$$A + B \to C + X \tag{4}$$

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*.*

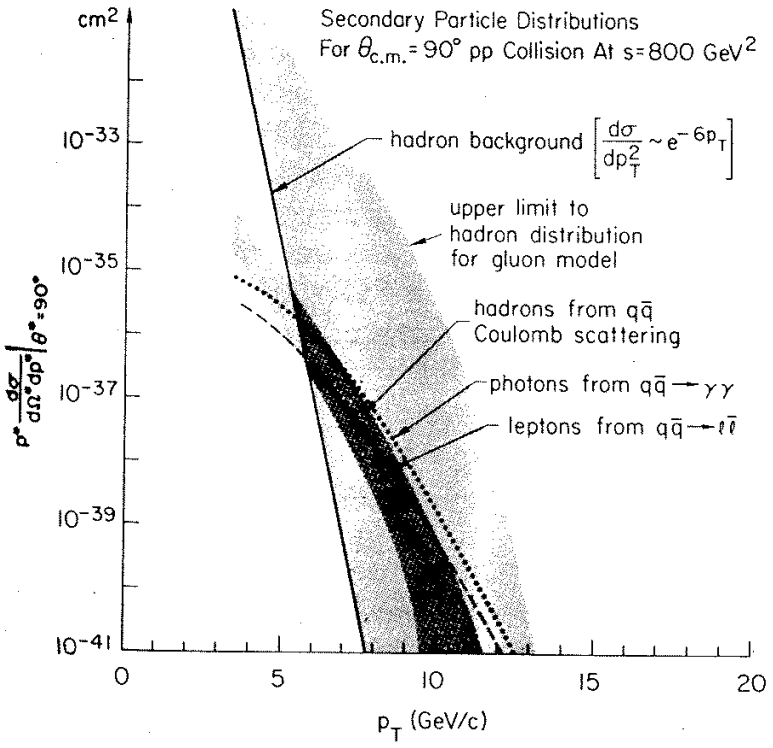


Figure 10: Secondary-particle distributions as calculated in the parton model and compared to diffractive backgrounds for typical NAL conditions.

BBK 1971—continued
The ERA of SCALING

♡ BBK propose a **General Form** for high p_T cross sections, for the **EM** scattering, which must exist:

$$E\frac{d^3\sigma}{dp^3} = \frac{4\pi\alpha^2}{p_T^4}\mathcal{F}(x_1 = \frac{-\hat{u}}{\hat{s}}, x_2 = \frac{-\hat{t}}{\hat{s}}) \qquad (5)$$

♡ The two factors are a $1/p_T^4$ term, characteristic of single photon exchange and a form factor $\mathcal{F}$

♡ Note that $x_{1,2}$ 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. 5 but much larger.

ISR Data, Notably CCR 1972-73

F. W. Büsser, et al., Phys. Lett. **46B** 471 (1973)

Cern **C**olumbia **R**ockefeller

♡ e^{-6p_T} breaks to a power law at high p_T with characteristic $\sqrt{s}$ dependence.

♡ 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. ♡ The data fit $p_\perp^{-n}F(p_\perp/\sqrt{s})$, with $n \simeq 8$

THE CCR DATA—Discovery of "High p_T"

F. W. Büsser, et al., Phys. Lett. **46B** 471 (1973)

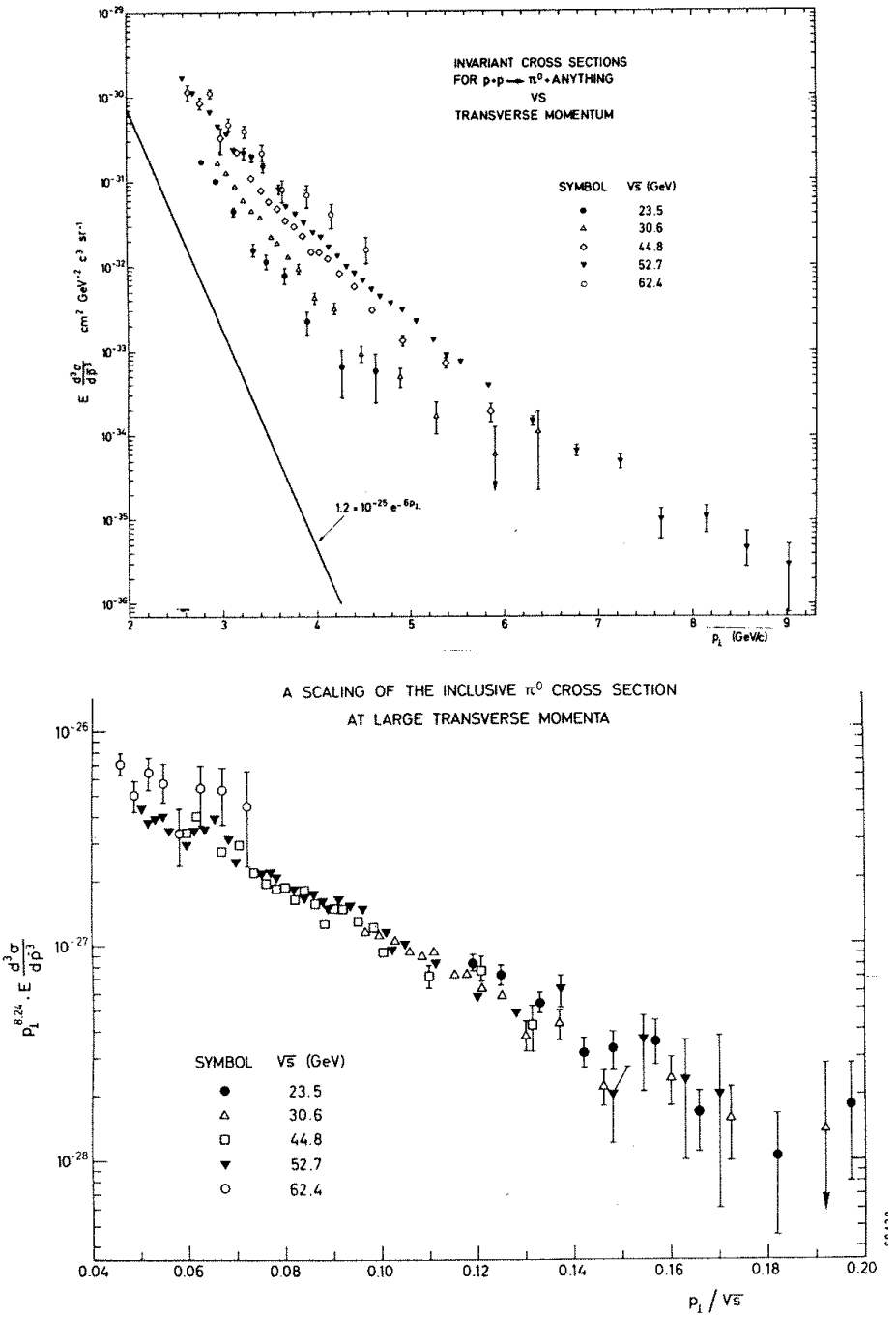


Figure 11: Top(t): CCR transverse momentum dependence of the invariant cross section at five center of mass energies. Bottom(b): The above data multiplied by $p_\perp^n$, using the best fit value of $n = 8.24 \pm 0.05$, with $F = Ae^{-bx_\perp}$, plotted vs $p_\perp/\sqrt{s}$.

Constituent Interchange Model 1972

R. Blankenbecler, S. J. Brodsky, J. F. Gunion
Phys. Lett. **42B** 461 (1972)
Inclusive Processes at High Transverse Momentum

♡ 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 propose a new general scaling form:

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

♡ n gives the form of the force-law between constituents
♡ $n = 4$ for QED or Vector Gluon
♡ Perhaps more importantly, BBG predict n=**8** for the case of quark-meson scattering by the exchange of a quark, **C.I.M.**, as apparently observed.

State of the art—FNAL 1977

D. Antreasyan, J. W. Cronin, et al.,
Phys. Rev. Lett. **38**, 112 (1977)

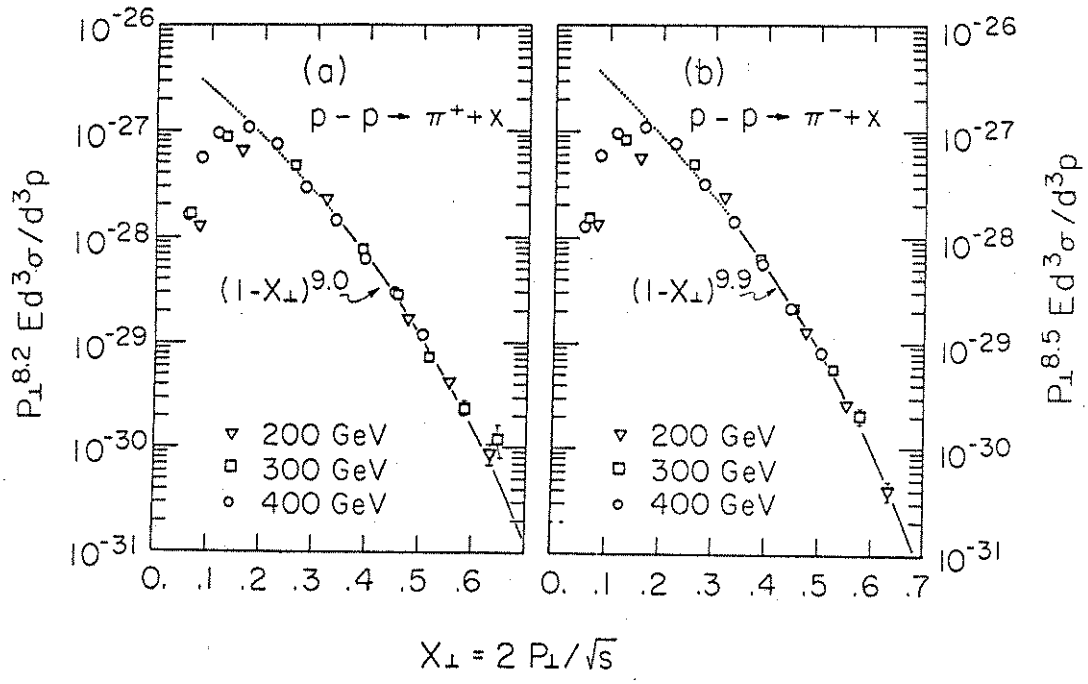


Figure 12: $p_\perp^n E d^3\sigma/dp^3$ vs x_T for π^+ and π^- production at 90° in the c.m. system for three FNAL incident energies. Best fit $n \sim 8$, $F(x_T) = (1 - x_T)^m$ shown.

First prediction using 'QCD' 1975

R. F. Cahalan, K. A. Geer, J. Kogut and Leonard Susskind
Phys. Rev. **D11**, 1199 (1975)

Asymptotic freedom and the "absence" of vector-gluon exchange in wide-angle hadronic collisions

♡ **Abstract:** The naive, pointlike parton model of Berman, Bjorken and Kogut is generalized 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.

♡ An interesting **Acknowledgement:** ... Two of us (J. K. and L. S. also thank S. Brodsky for *emphasizing to us repeatedly* that the present data on wide-angle hadron scattering *show no evidence for vector exchange.*

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

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{p_T^{n(x_T,\sqrt{s})}} F(\frac{p_T}{\sqrt{s}}) = \frac{1}{\sqrt{s}^{n(x_T,\sqrt{s})}} G(\frac{p_T}{\sqrt{s}}) \qquad (7)$$

CCOR 1978—Discovery of "REALLY High $p_T > 7$ GeV/c"

A. L. S. Angelis, et al., Phys. Lett. **79B**, 505 (1978)

See also, A. G. Clark, et al., Phys. Lett. **74B**, 267 (1978)

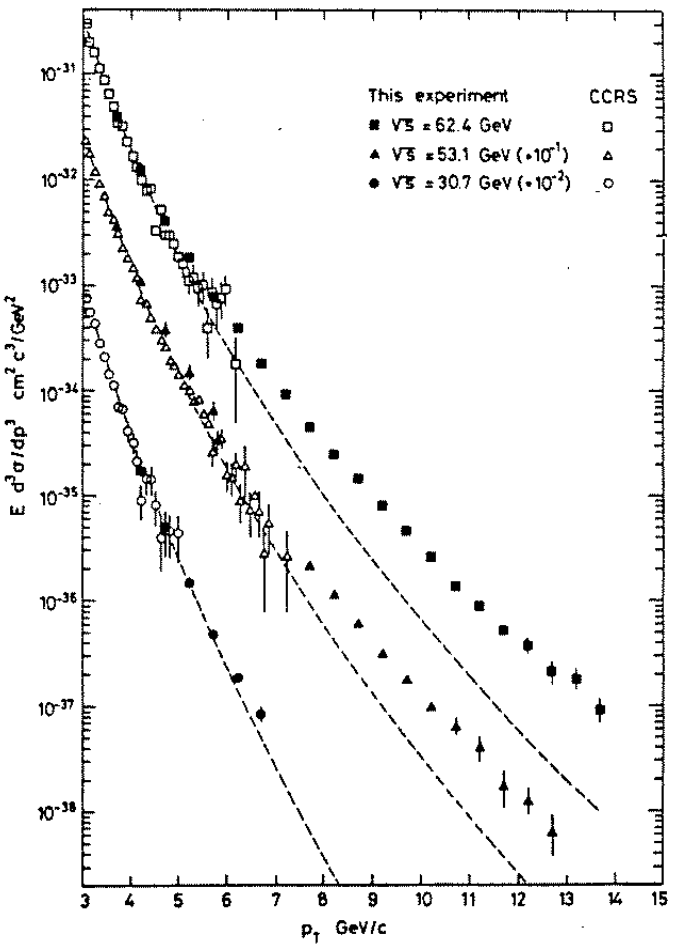


Figure 13: CCOR transverse momentum dependence of the invariant cross section for $p + p \to \pi^0 + X$ at three center of mass energies. Cross sections are offset by the factors noted. Open points and dashed fit are from a previous experiment, CCRS, F. W. Büsser, et al., Nucl. Phys. **B106**, 1 (1976).

♡ $Ed^3\sigma/dp^3 \simeq p_T^{-5.1\pm0.4}(1 - x_T)^{12.1\pm0.6}$, for $7.5 \leq p_T \leq 14.0$ GeV/c, $53.1 \leq \sqrt{s} \leq 62.4$ GeV (including *all* systematic errors).

$n(x_T, \sqrt{s})$ **WORKS,** $n \to 5 = 4^{++}$

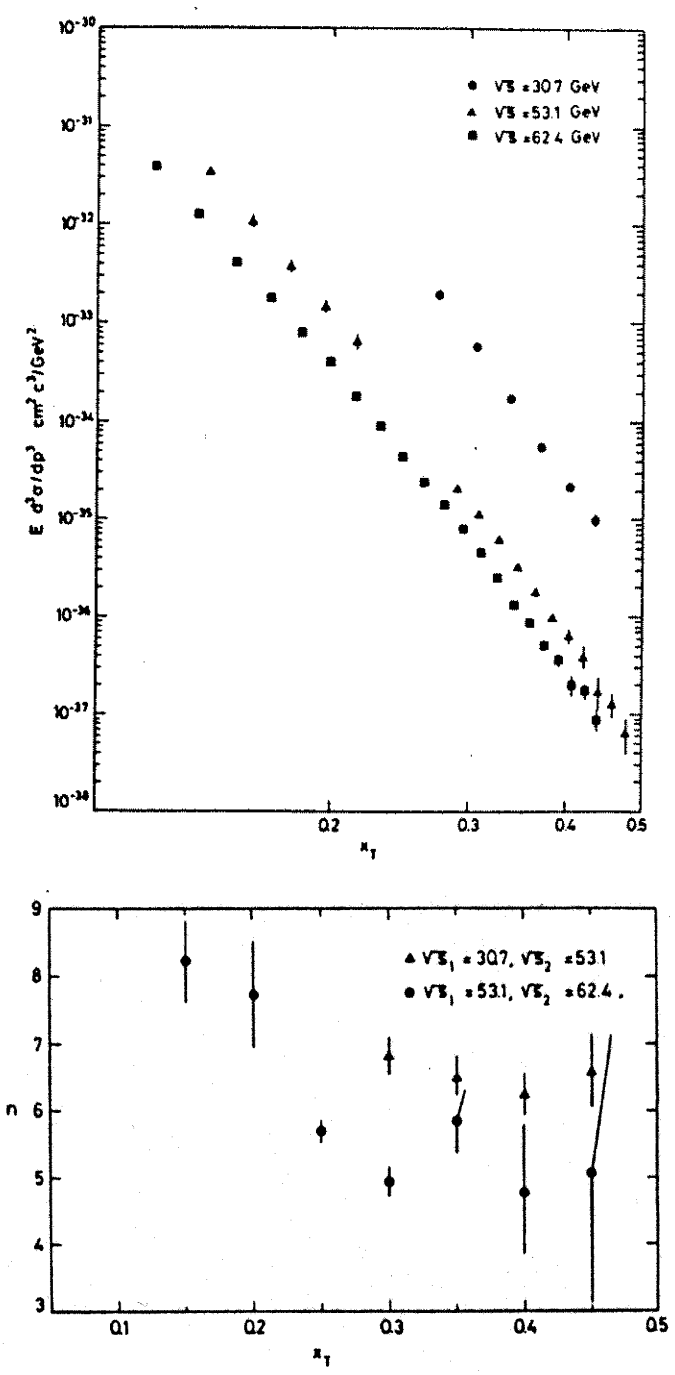


Figure 14: Top(t): CCOR invariant cross section vs $x_T = 2p_T/\sqrt{s}$. Bottom(b): $n(x_T, \sqrt{s})$ derived from the combinations indicated. *The systematic normalization at* $\sqrt{s} = 30.6$ *has been added in quadrature. Note: the absolute scale uncertainty cancels!*

Difficulties with Absolute Cross Sections Due to scale, normalization uncertainties

(How does RQMD do it?)

Athens Brookhaven CERN Syracuse Collaboration

C. Kourkoumelis, et al., Phys. Lett. **84B**, 271 (1979)

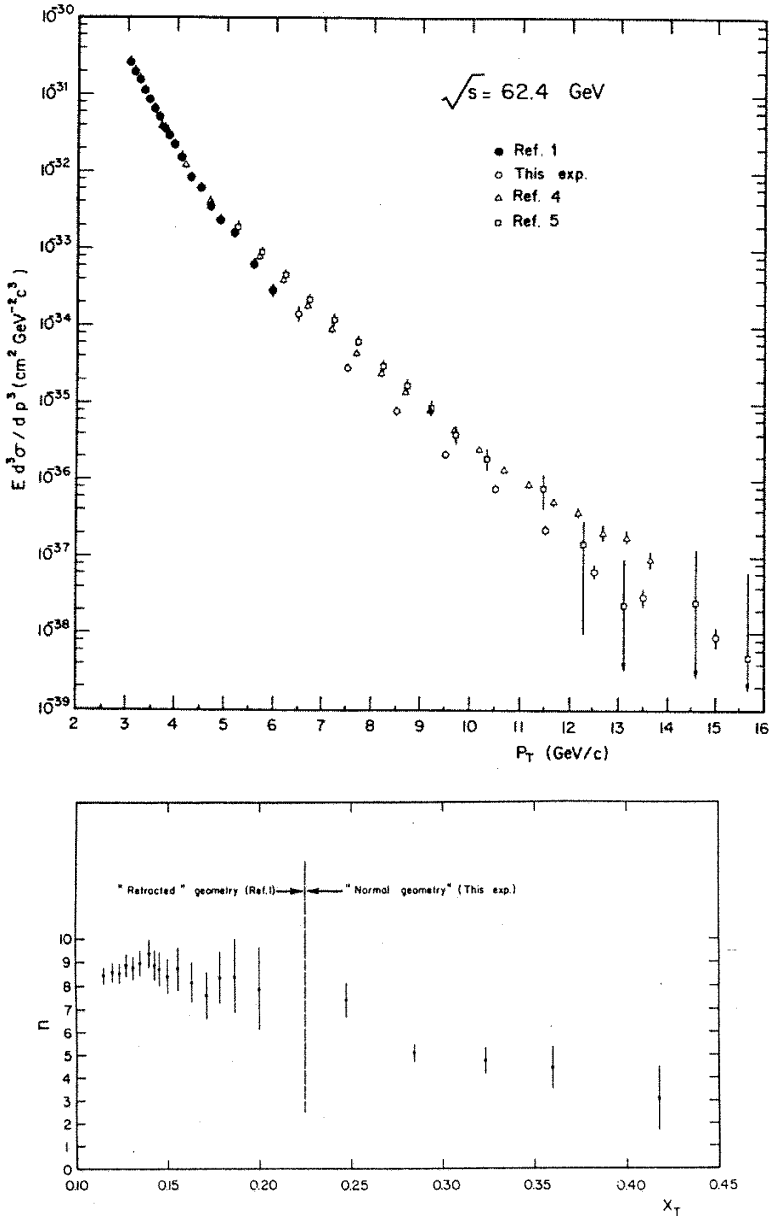


Figure 15: Top(t): Invariant cross section for π^0 inclusive for several ISR experiments, compiled by ABCS Collaboration. Bottom(b): $n(x_T, \sqrt{s})$ from ABCS 52.7, 62.4 data only. There is an additional common systematic error of ± 0.7 in n.

The Answer

♡ Hard-scattering was visible both at ISR and FNAL (Fixed Target) energies by single particle inclusive 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.

♡ 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.

J. F. Owens, E. Reya, M. Glück
Phys. Rev. **D18**, 1501 (1978)
Detailed quantum-chromodynamic predictions for high-p_T processes

J. F. Owens and J. D. Kimel
Phys. Rev. **D18**, 3313 (1978)
Parton-transverse-momentum effects and the quantum-chromodynamic description of high-p_T processes

PartII: Why no Jets at FNAL (fixed target)

See M. J. Tannenbaum Int. J. Mod. Phys. **A4**, 3377-3405 (1989)

Part III: k_T, how to see it, how to avoid it.