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

M. J. TANNENBAUM
Brookhaven National Laboratory
PHENIX Hard-Scattering PWG

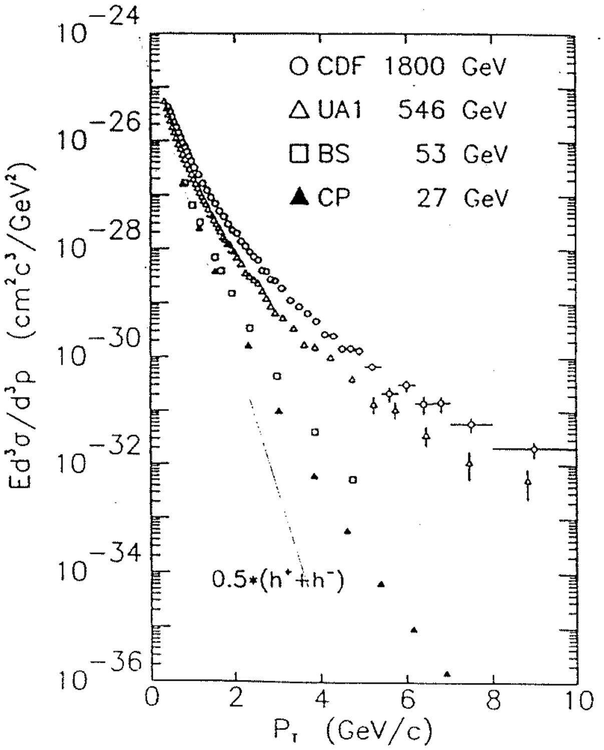


Figure 1: Invariant cross section for non-identified charged-averaged hadron production at 90° in the c.m. system as a function of the transverse momentum p_T compiled by CDF for a range of c.m. energies $\sqrt{s}$.

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

♡ The discovery that the DIS structure function

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

"SCALED" i.e just depended on the ratio

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

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

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

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.

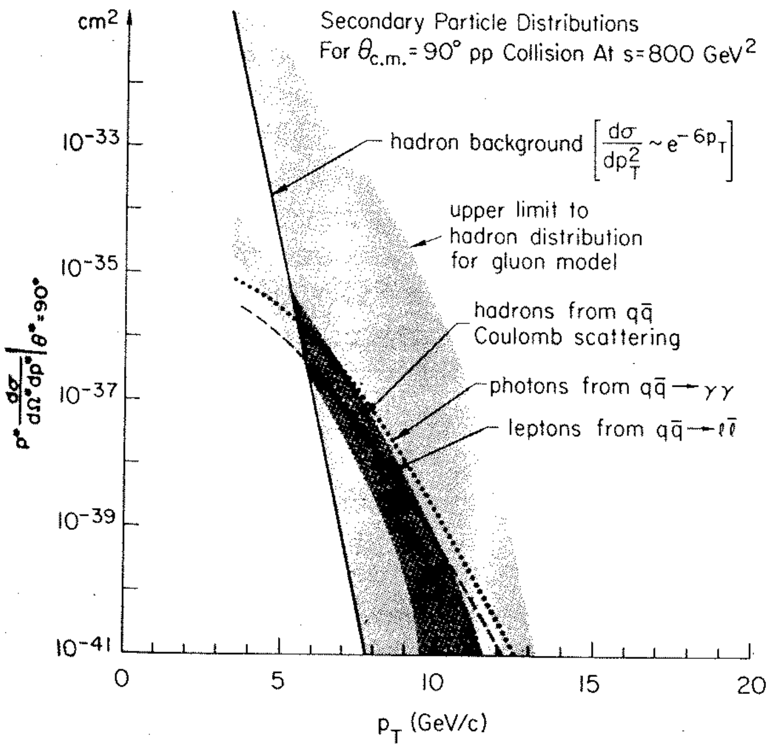


Figure 2: Secondary-particle distributions as calculated in the parton model and compared to diffractive backgrounds for typical NAL conditions.

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:

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

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

♡ Note that $x_{1,2}$ 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 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)

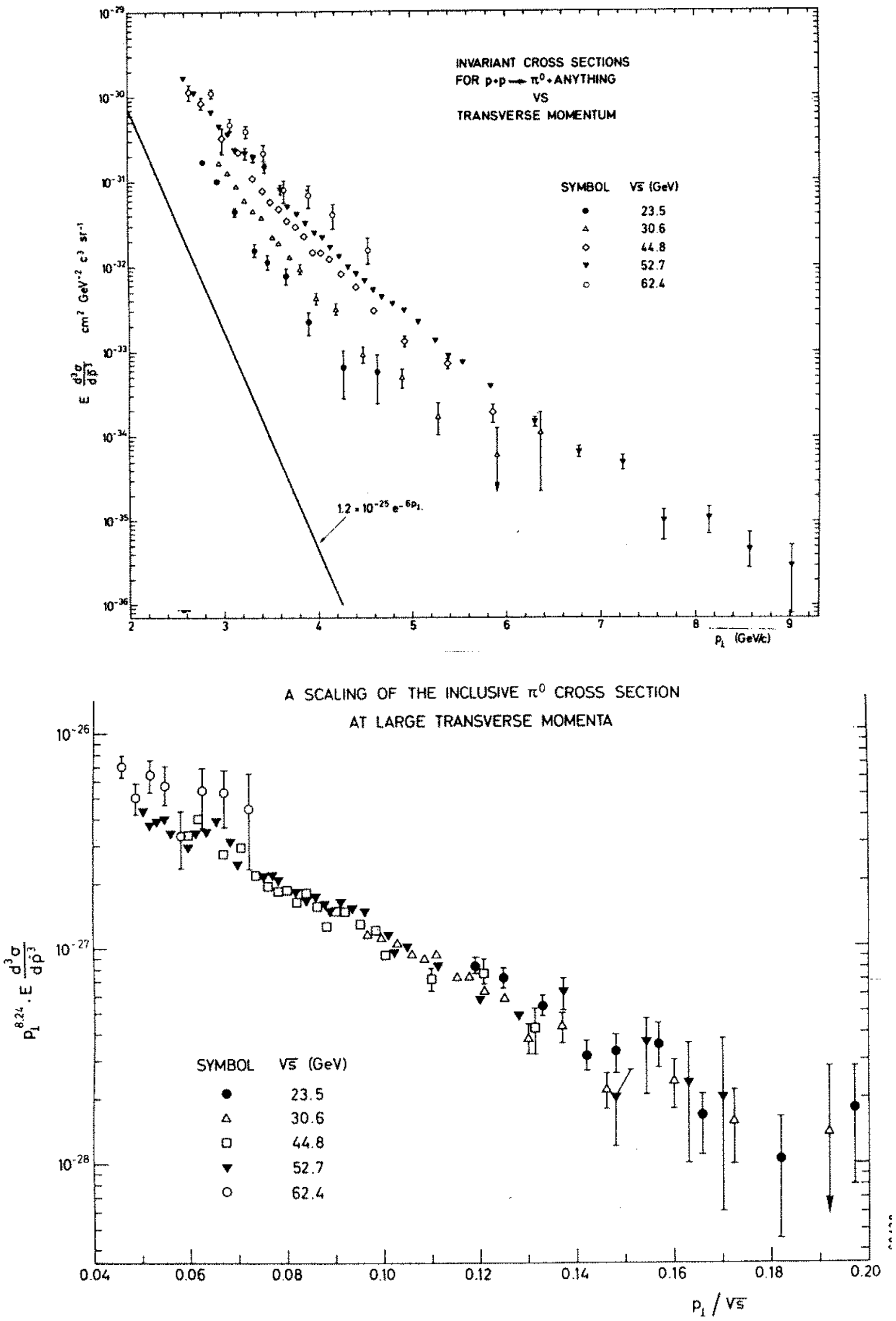


Figure 3: Top(t): CCR transverse momentum dependence of the invariant cross section at five center of mass energies. Bottom(b): The above data multiplied by $p_\perp^n$, using the best fit value of $n = 8.24 \pm 0.05$, with $F = Ae^{-bx_\perp}$, plotted vs $p_\perp/\sqrt{s}$.

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:

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

♡ 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)

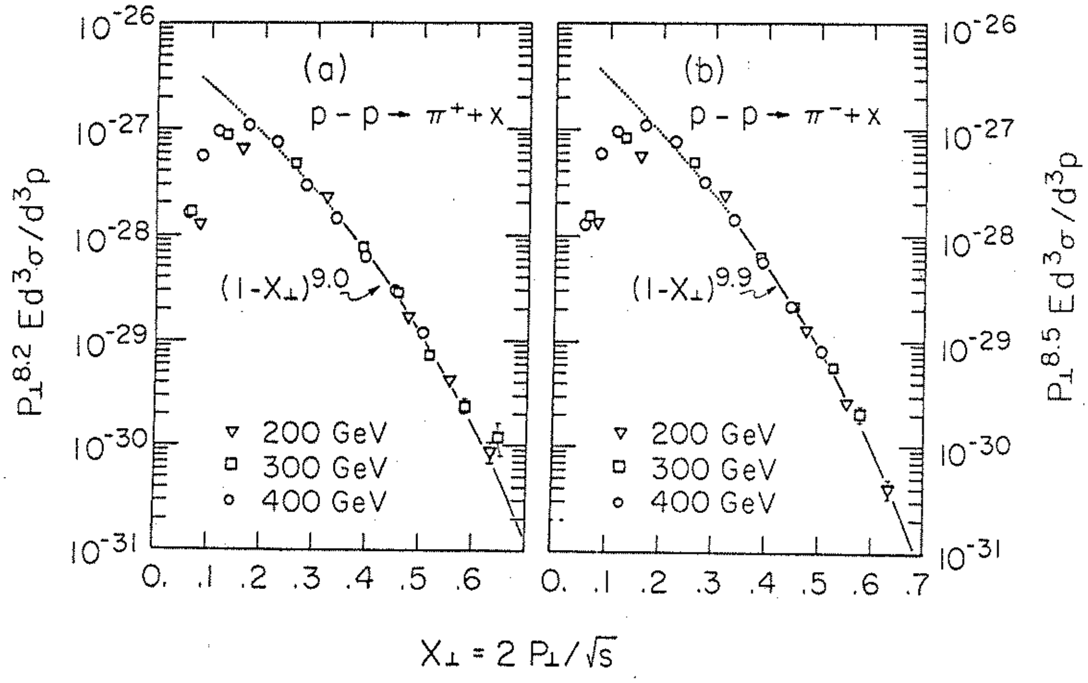


Figure 4: $p_\perp^n Ed^3\sigma/dp^3$ vs x_T for π^+ and π^- production at 90° in the c.m. system for three FNAL incident energies. Best fit $n \sim 8$, $F(x_T) = (1 - x_T)^m$ shown.

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':

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

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)

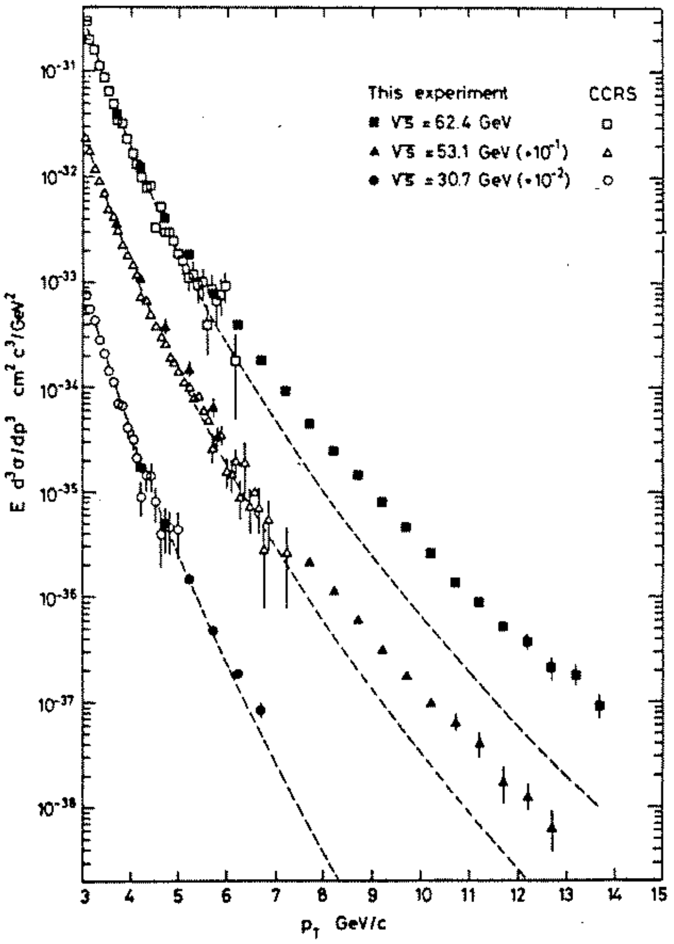


Figure 5: CCOR transverse momentum dependence of the invariant cross section for $p + p \to \pi^0 + X$ at three center of mass energies. Cross sections are offset by the factors noted. Open points and dashed fit are from a previous experiment, CCRS, F. W. Büsser, et al., Nucl. Phys. **B106**, 1 (1976).

♡ $Ed^3\sigma/dp^3 \simeq p_T^{-5.1\pm0.4}(1 - x_T)^{12.1\pm0.6}$, 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,** $n \to 5 = 4^{++}$

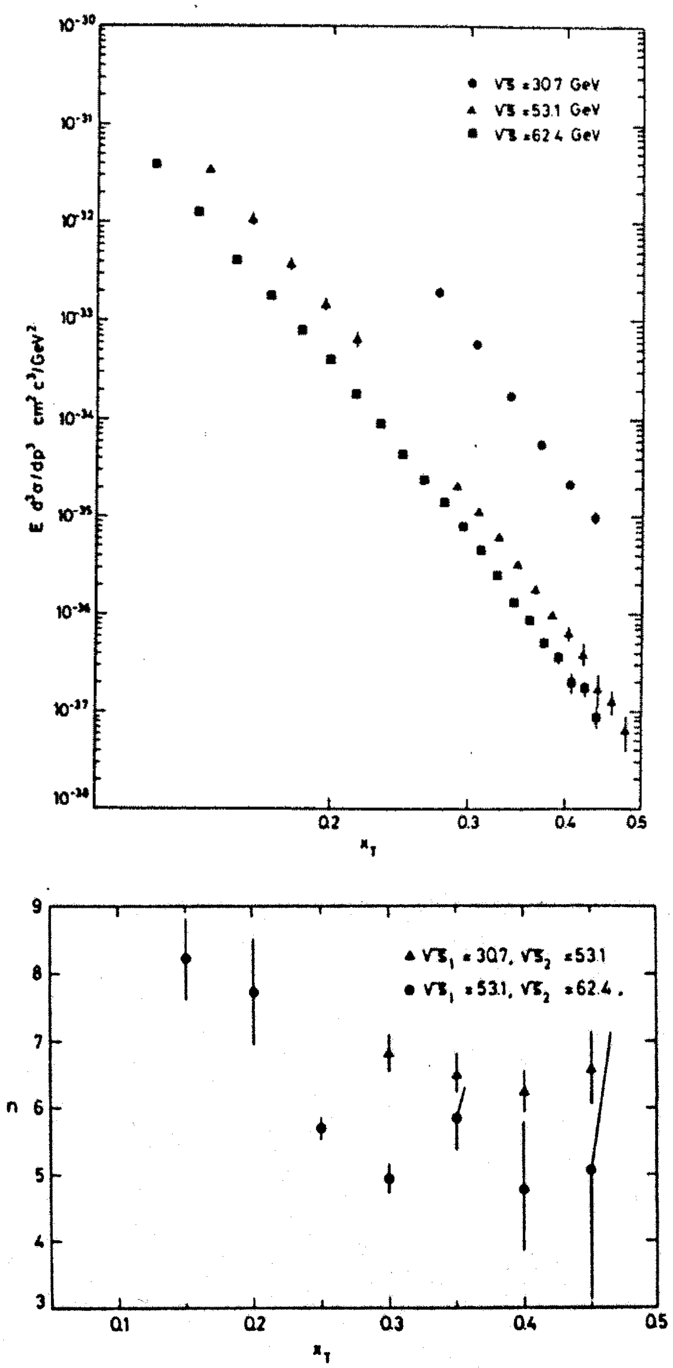


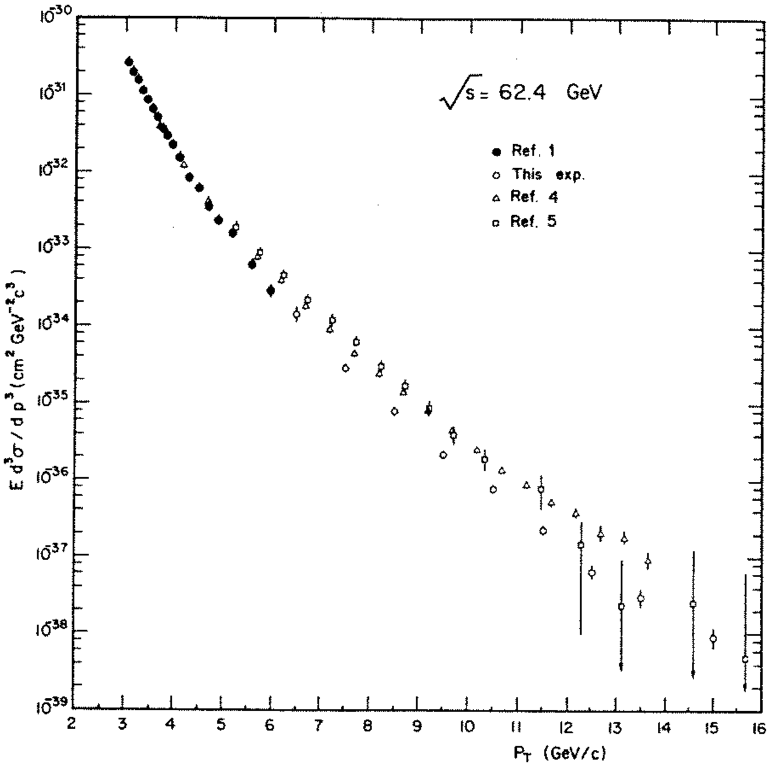
Figure 6: Top(t): CCOR invariant cross section vs $x_T = 2p_T/\sqrt{s}$. Bottom(b): $n(x_T, \sqrt{s})$ derived from the combinations indicated. *The systematic normalization at* $\sqrt{s} = 30.6$ *has been added in quadrature. Note: the absolute scale uncertainty cancels!*

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)



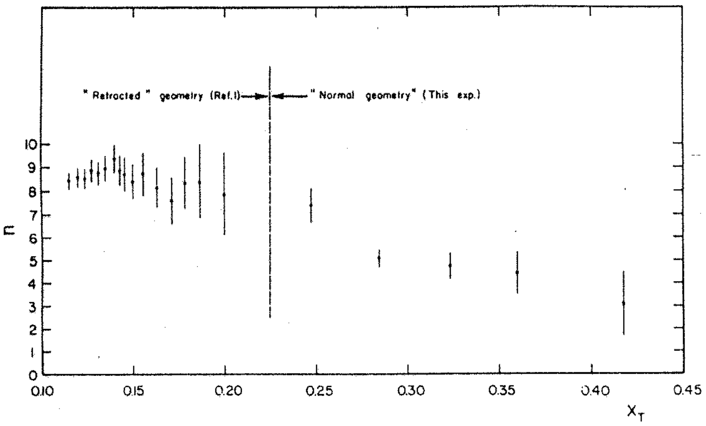


Figure 7: Top(t): Invariant cross section for π^0 inclusive for several ISR experiments, compiled by ABCS Collaboration. Bottom(b): $n(x_T, \sqrt{s})$ from ABCS 52.7, 62.4 data only. There is an additional common systematic error of ± 0.7 in n.

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.