Introduction to High p_T physics at RHIC Lessons Learned at the CERN-ISR

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November 1, 2001

• 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.

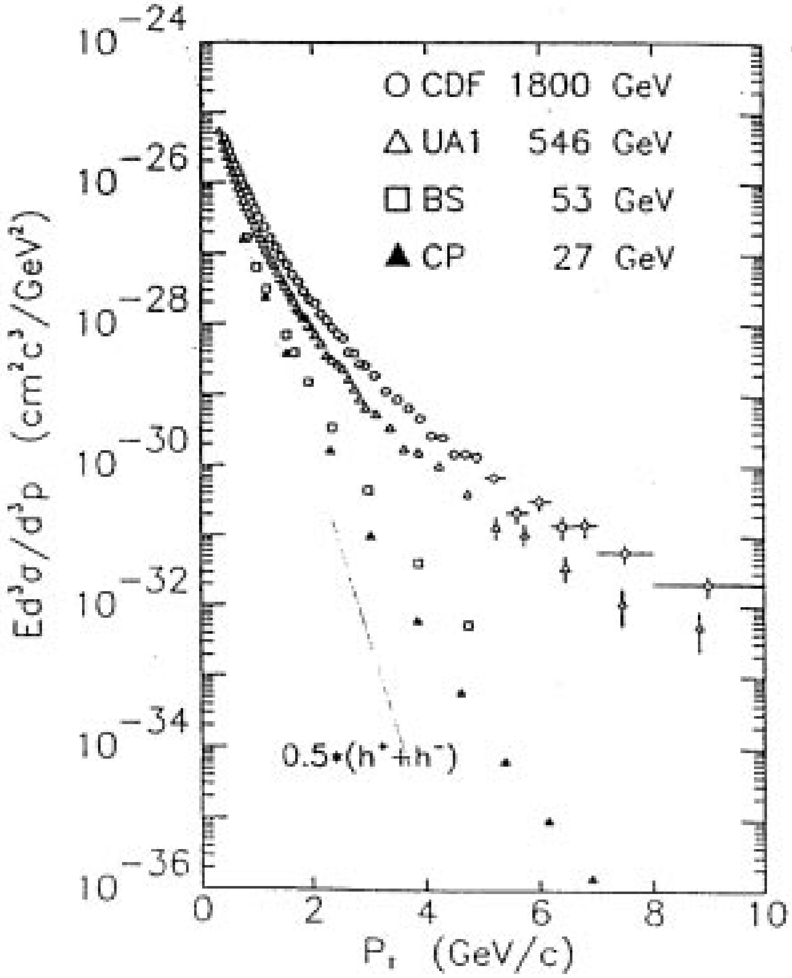
• Scaling arguments allowed the form of the force law between 'partons' to be determined but there was some early confusion caused by initial transverse momentum k_T which distorted the spectra.

• 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.

• In the region of hard scattering ($p_T > 2$ GeV/c) scaling from p-p to nuclear collisions should be simply proportional to the relative number of point-like encounters, corresponding to A (p+A), $A \times B$ (A+B) for the total rate and to T_{AB}, the overlap integral of the nuclear profile functions, as a function of centrality.

• In stark contrast to results at lower c.m. energies, measurements of high p_T π^0 and $(h^+ + h^-)/2$ production at $\sqrt{s_{NN}} = 130$ GeV from PHENIX at RHIC show a huge suppression compared to point-like scaling...

From 1998—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 **!!!**.

Miklos Gyulassy's question at DNP98:

"Can an *OLD TIMER* enlighten me:
Why THEY never found JETS
at FERMILAB (fixed target)?"

A historical review for the *younger folks*!

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

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

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.

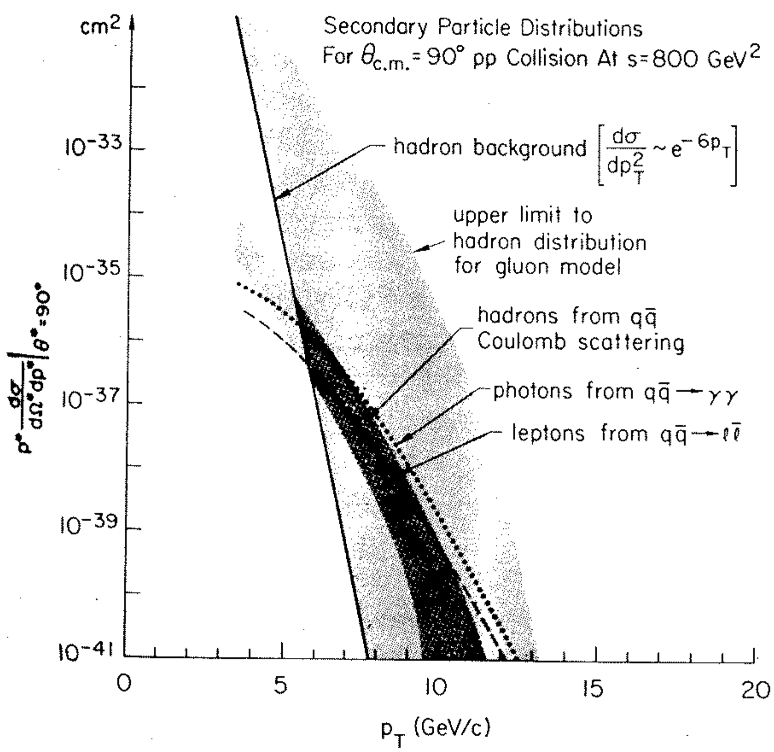


Figure 1: Secondary-particle distributions as calculated in the parton model and compared to diffractive backgrounds for typical NAL conditions.

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 (≫ 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)

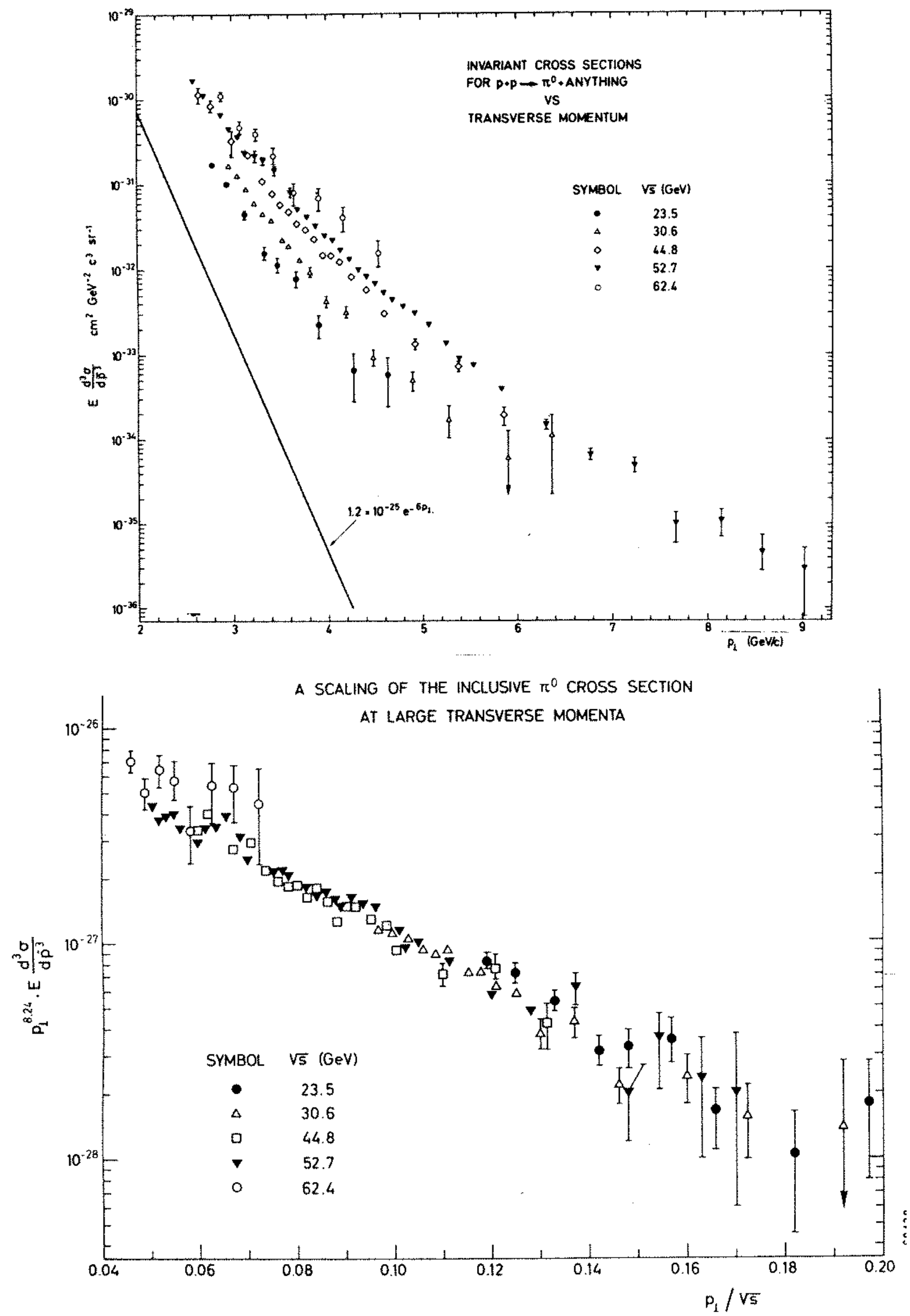


Figure 2: Top(t): CCR transverse momentum dependence of the invariant cross section at five center of mass energies. Bottom(b): The above data multiplied by $p_\perp^n$, using the best fit value of $n = 8.24 \pm 0.05$, with $F = Ae^{-bx_\perp}$, plotted vs $p_\perp/\sqrt{s}$.

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:

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

♡ 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)

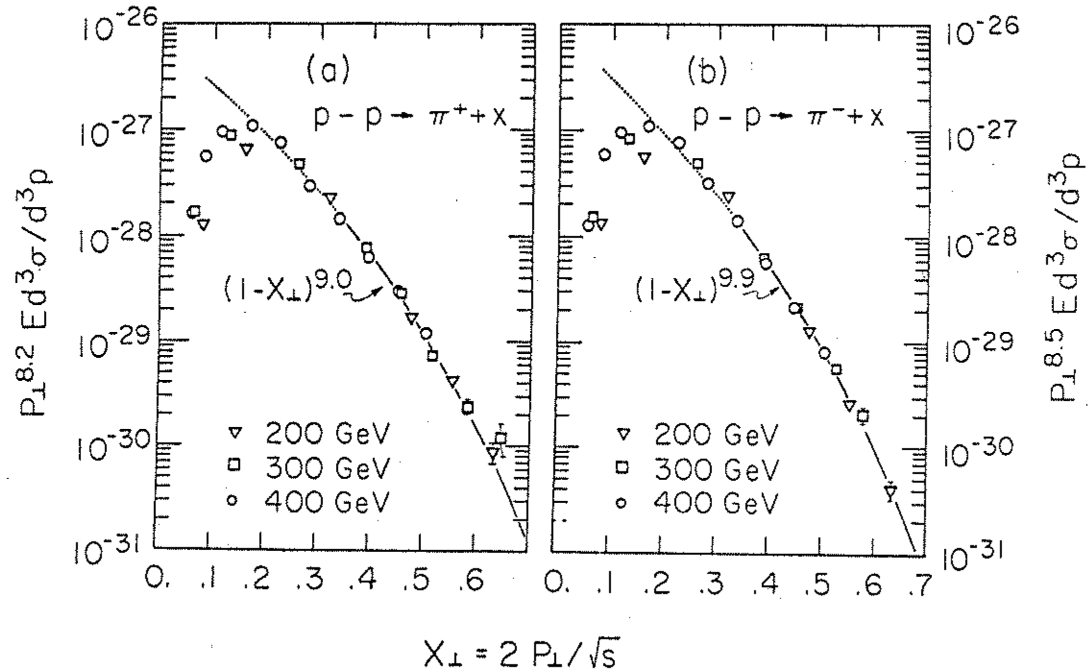


Figure 3: $p_\perp^n Ed^3\sigma/dp^3$ vs x_T for π^+ and π^- production at 90° in the c.m. system for three FNAL incident energies. Best fit $n \sim 8$, $F(x_T) = (1 - x_T)^m$ shown.

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':

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

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)

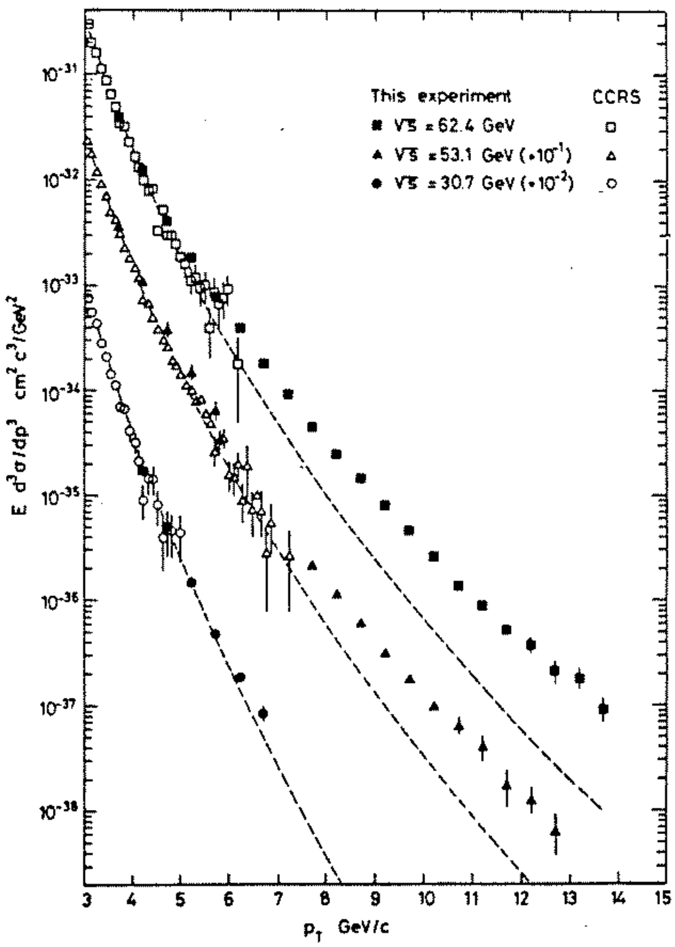


Figure 4: CCOR transverse momentum dependence of the invariant cross section for $p + p \rightarrow \pi^0 + X$ at three center of mass energies. Cross sections are offset by the factors noted. Open points and dashed fit are from a previous experiment, CCRS, F. W. Büsser, et al., Nucl. Phys. **B106**, 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,** $n \to 5 = 4^{++}$

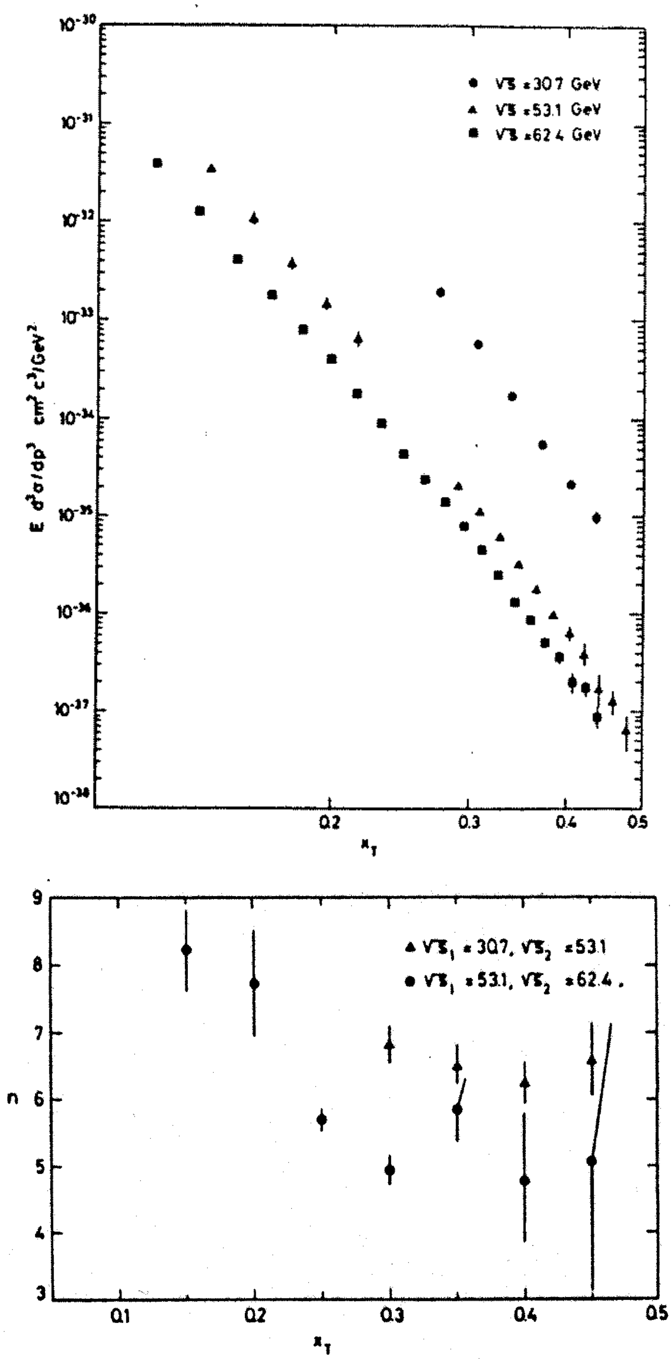


Figure 5: Top(t): CCOR invariant cross section vs $x_T = 2p_T/\sqrt{s}$. Bottom(b): $n(x_T, \sqrt{s})$ derived from the combinations indicated. *The systematic normalization at* $\sqrt{s} = 30.6$ *has been added in quadrature. Note: the absolute scale uncertainty cancels!*

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)

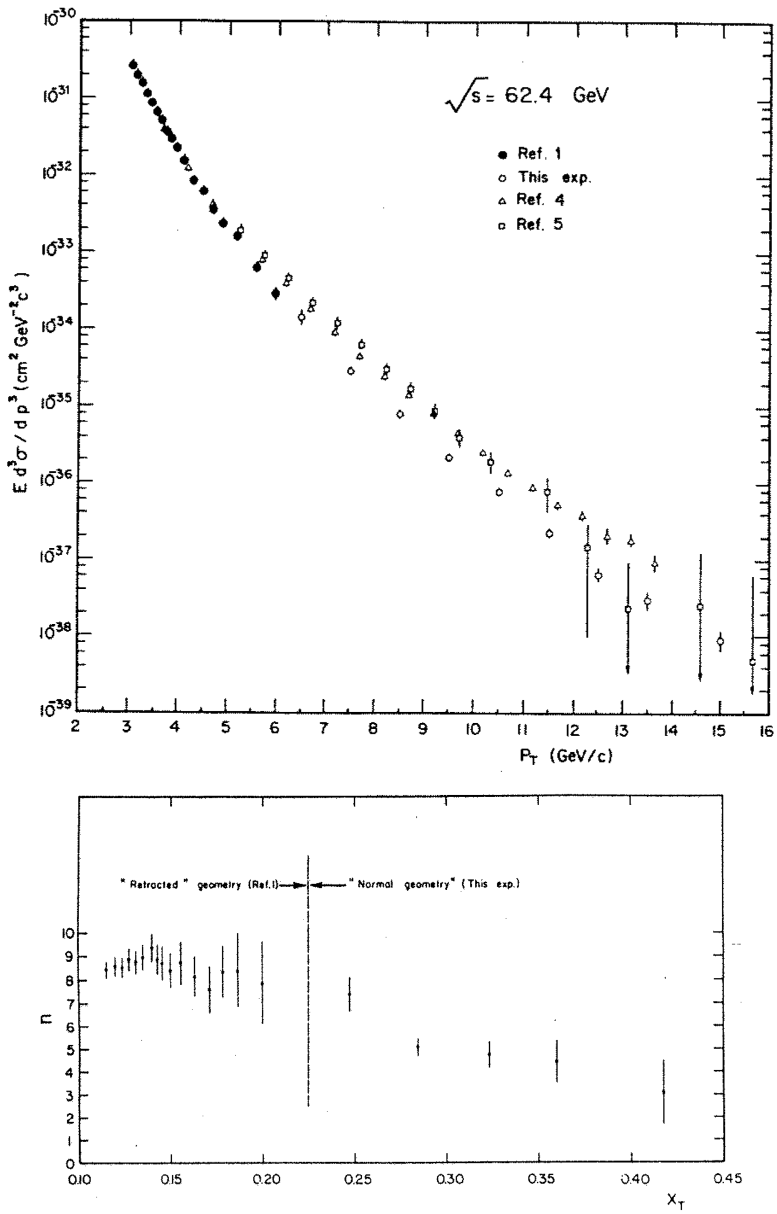


Figure 6: Top(t): Invariant cross section for π^0 inclusive for several ISR experiments, compiled by ABCS Collaboration. Bottom(b): $n(x_T, \sqrt{s})$ from ABCS 52.7, 62.4 data only. There is an additional common systematic error of ± 0.7 in n.

The Answer to Miklos

♡ 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

♡ Jets in 4π Calorimeters at ISR energies or lower invisible below $\sqrt{\hat{s}} \sim E_T \leq 25$ GeV.

♡ A 'phase change' in belief in Jets with UA2 event at 1982 ICHEP in Paris.

QCD

Cross Section in p-p collisions c.m. energy $\sqrt{s}$

The overall p-p reaction cross section
is the sum over constituent reactions

$$a + b \rightarrow c + d$$

$a(x_1)$, $b(x_2)$, are structure functions, the differential probabilities for constituents a and b to carry momentum fractions x_1 and x_2 of their respective protons, e.g. $u(x_1)$,

$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{1}{s}\sum_{ab} a(x_1)b(x_2)\frac{\pi\alpha_s^2(Q^2)}{2x_1x_2}\Sigma^{ab}(\cos\theta^*)$$

$\Sigma^{ab}(\cos\theta^*)$, the characteristic subprocess angular distributions and $\alpha_s(Q^2) = \frac{12\pi}{25}\ln(Q^2/\Lambda^2)$ are predicted by QCD

For fixed x_1, x_2, $\sigma \propto 1/s$—RHIC is optimum

SPIN QCD

The cross-section asymmetry is the sum over constituent reactions

$$A_{LL}(x_1, x_2, \cos\theta^*) = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} \tag{7}$$

$$= \sum_{ab} \frac{\Delta a}{a}(x_1)\,\frac{\Delta b}{b}(x_2)\,\hat{a}_{LL}(a + b \rightarrow c + d) \tag{8}$$

where the helicity asymmetry of $a(x)$ for a polarized proton is

$$\Delta a(x) = a^+(x) - a^-(x)$$

The spin asymmetry of the subprocess

$$\hat{a}_{LL}(a + b \rightarrow c + d)$$

is a fundamental prediction of QCD

which has never been verified—to my knowledge.

quantity. Evidently, for the case of constituent scattering, the Mandelstam invariants $\hat{s}$, $\hat{t}$ and $\hat{u}$ have a clear definition in terms of the c.m. scattering angle:

$$\hat{t} = -\hat{s}\,\frac{(1-\cos\theta^*)}{2} \qquad \text{and} \qquad \hat{u} = -\hat{s}\,\frac{(1+\cos\theta^*)}{2} \quad . \tag{9}$$

The transverse momentum of a scattered constituent is:

$$p_T = p_T^* = \frac{\sqrt{\hat{s}}}{2}\,\sin\theta^* \quad . \tag{10}$$

A naive experimentalist would think of $Q^2 = -\hat{t}$ for a scattering subprocess and $Q^2 = -\hat{s}$ for a Compton or annihilation subprocess.

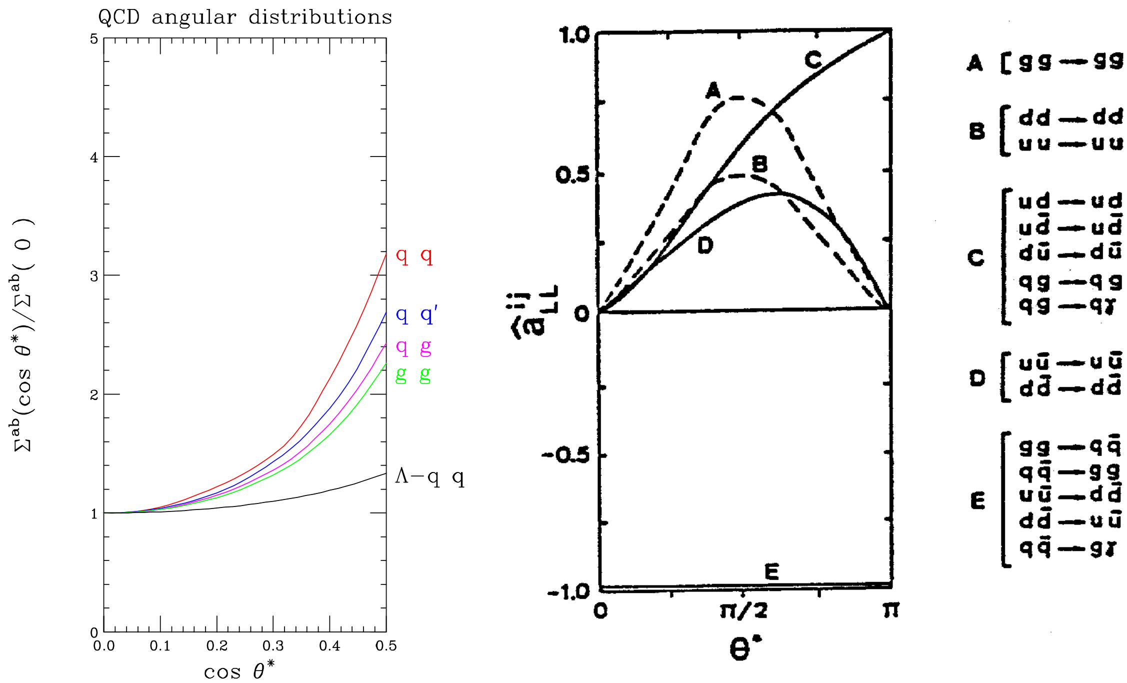


Fig. 2. Characteristic QCD Subprocess angular distributions: (a) scattering; (b) spin asymmetry

7.2. The cross section in $p-p$ collisions

The cross section for hard processes in $p-p$ collisions at c.m. energy $\sqrt{s}$ is taken to be a sum over the constituent reactions. The c.m. system for the constituent scattering is not generally the same as the $p-p$ c.m. system since the constituents have momentum fractions x_1 and x_2 of their respective protons. Thus in the $p-p$ c.m. system, the constituent c.m. system has rapidity, $\hat{y} = \frac{1}{2}\ln\frac{x_1}{x_2}$, and invariant mass-squared, $\hat{s} = x_1 x_2 s$, where

$$x_1 = \sqrt{\frac{\hat{s}}{s}}e^{\hat{y}} \qquad x_2 = \sqrt{\frac{\hat{s}}{s}}e^{-\hat{y}} \quad . \tag{11}$$

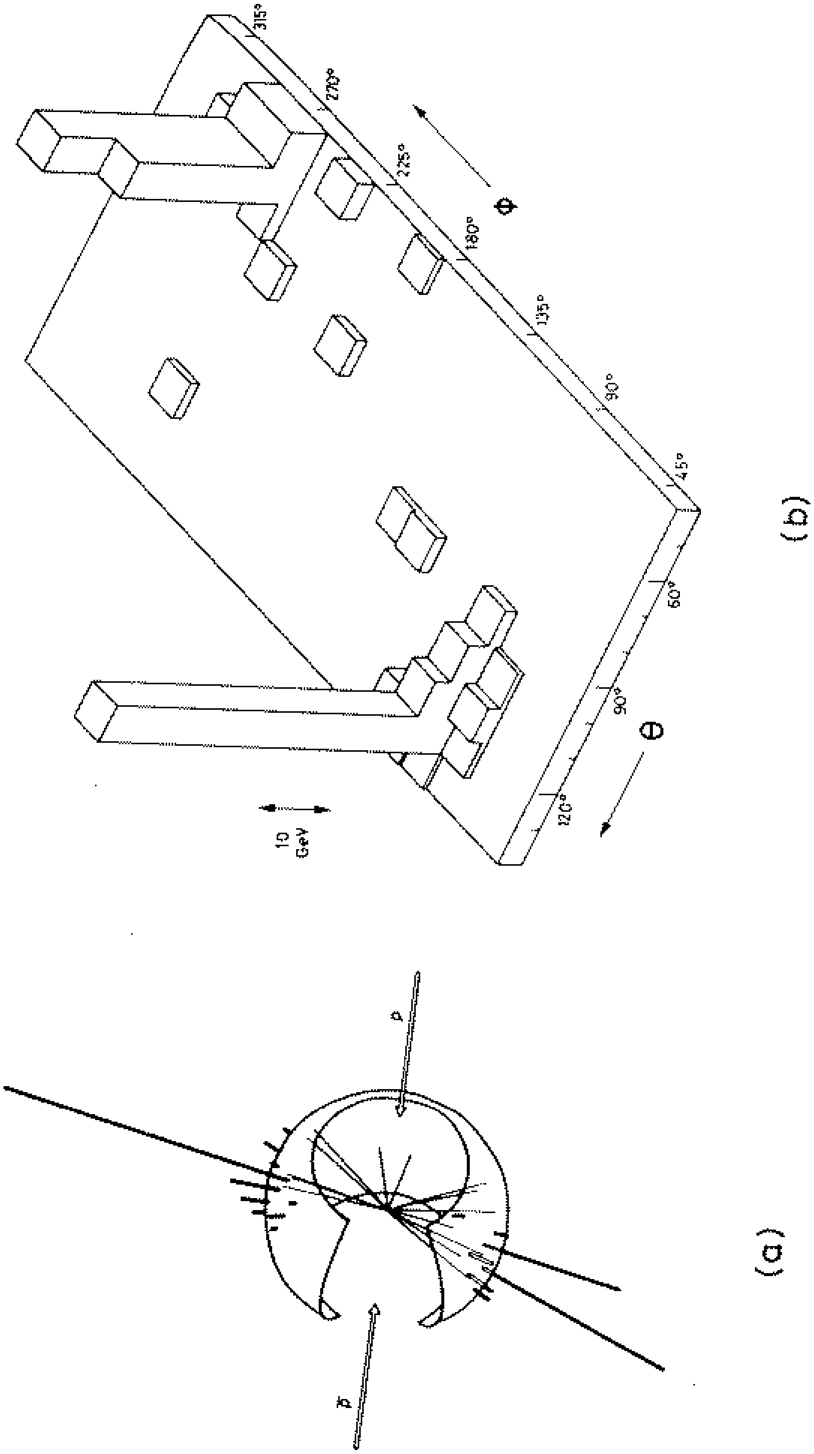
This description and theory is now an important component of

The Standard Model

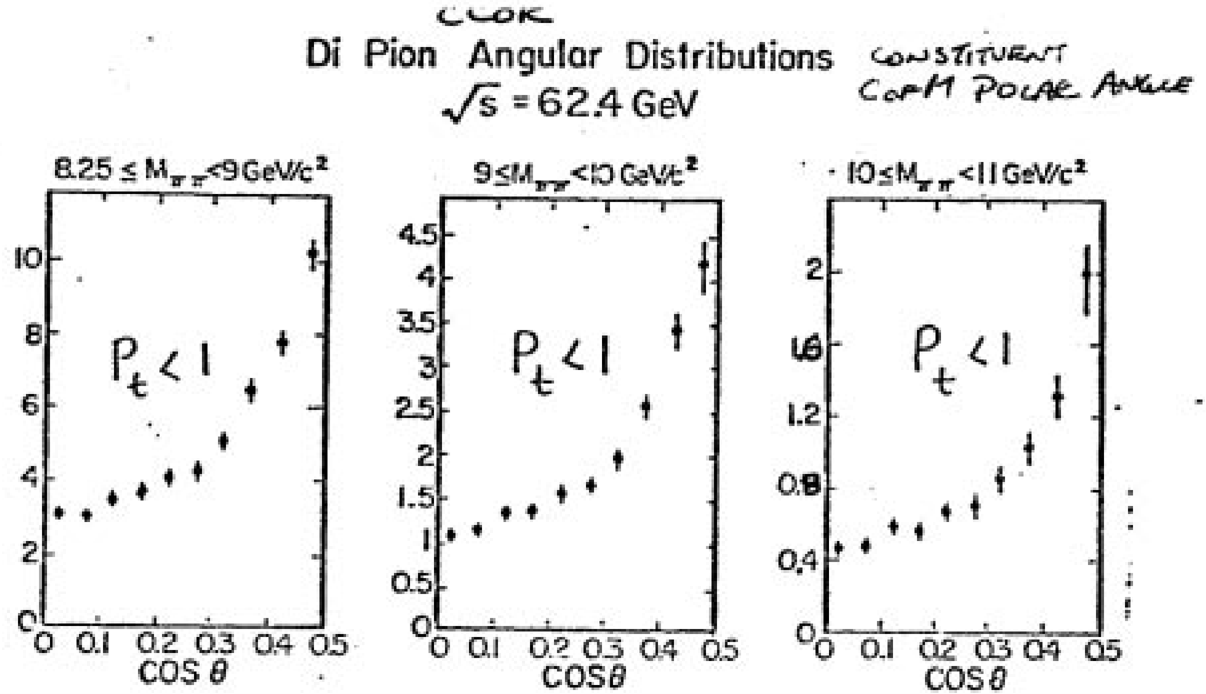
Incredibly, at Snowmass in July 1982, many (if not most) people were skeptical!

The International HEP conference in Paris, three weeks later, changed everything

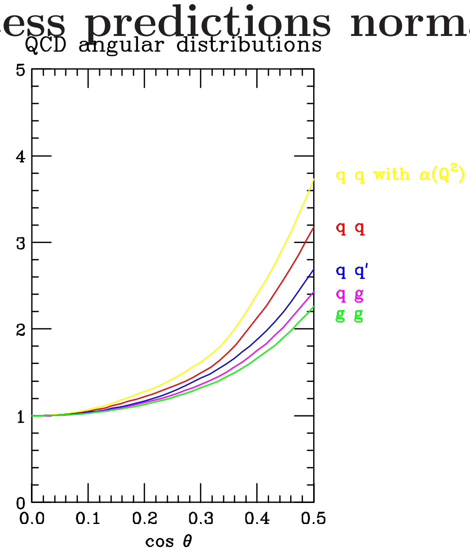
Int'l HEP Conference, Paris, 1982
The UA2 Two-Jet Event



Int'l HEP Conference, Paris, 1982— First measurement of QCD subprocess angular distributions

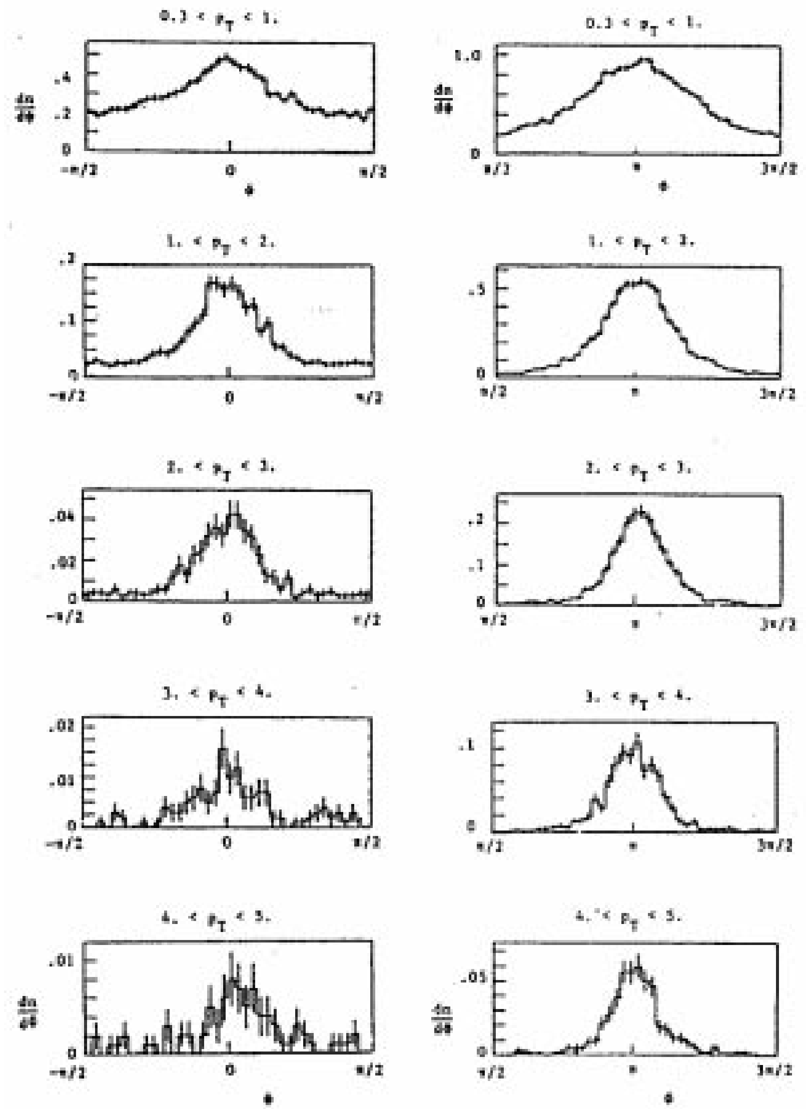


QCD Subprocess predictions normalized at 90°



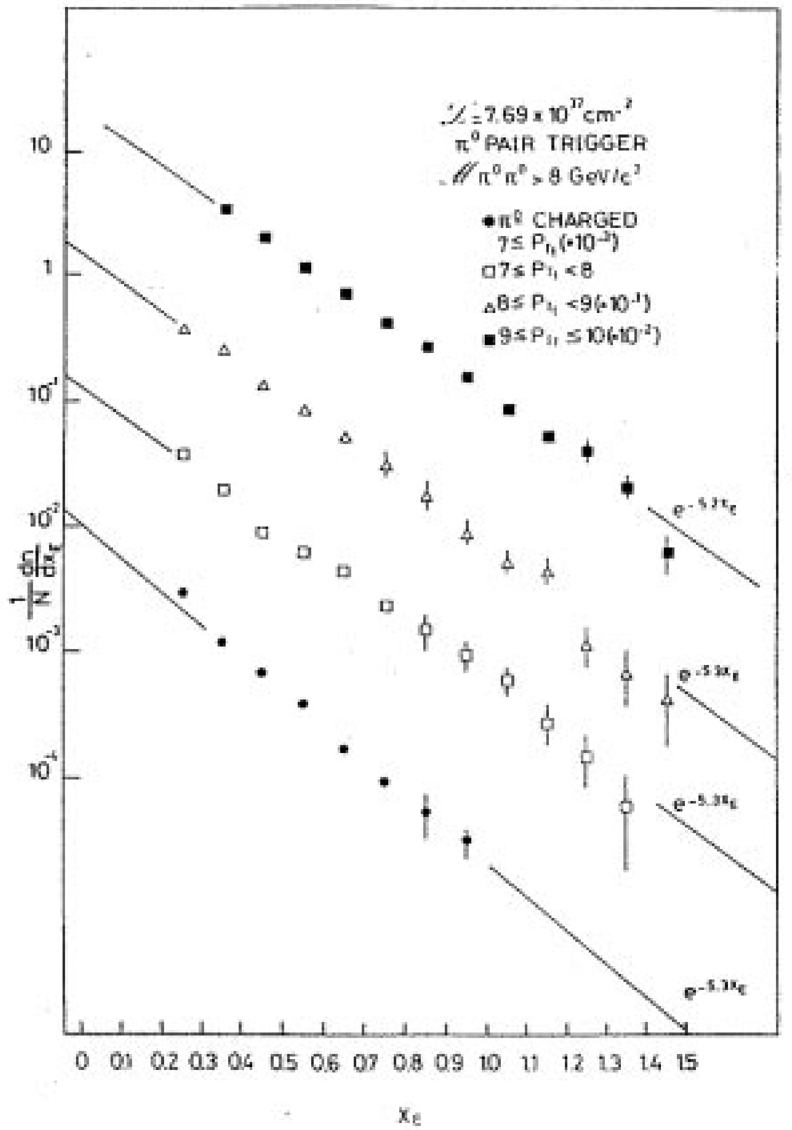
Angular distributions of pairs of nearly back-to-back π^0 as a function of the invariant mass $M_{\pi\pi}$ of the pair. The net P_t of the pion pair is restricted as indicated on the figure and the net rapidity of the di-pion system is restricted to $|Y_{\pi\pi}| < 0.35$. The distribution plotted is 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].

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



Two particle correlation in azimuth of charged particles relative to a triggering neutral with transverse momentum $p_{Tt} \geq 7.0$ 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

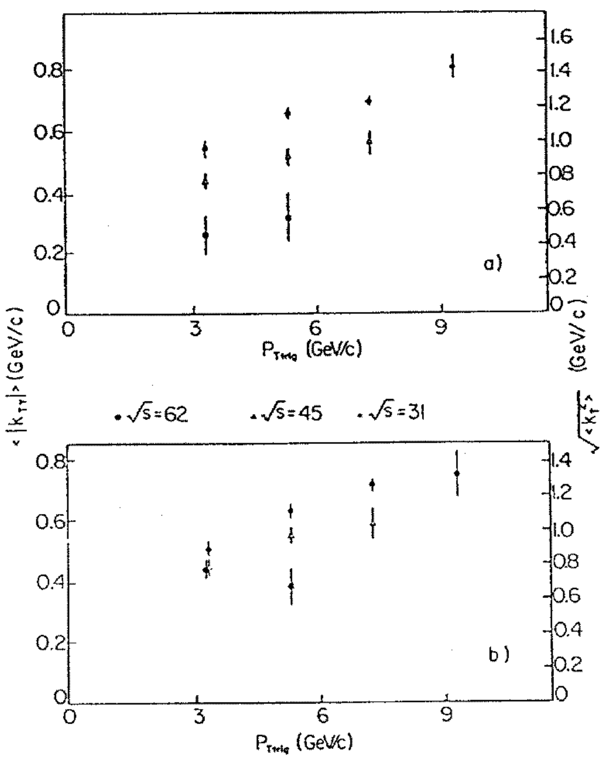
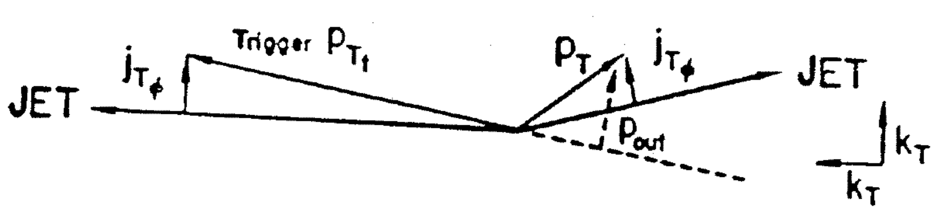


Figure 7: (a) $\langle|k_{Ty}|\rangle$ and $\sqrt{(\langle k_T^2\rangle)}$ as a function of p_{Ttrig} for three different $\sqrt{s}$ values, obtained from back-back correlations. (b) The same using events where the sum of charged paricle transverse momenta on the away side balances p_{Ttrig} [see Phys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



$$\langle|p_{\rm out}|\rangle^2 = \langle|j_{Ty}|\rangle^2 + \ x_E^2(\ \langle|j_{Ty}|\rangle^2 + 2\,\langle|k_{Ty}|\rangle^2\ ) \qquad (9)$$

Hard Scattering is Point-Like From DIS

E. Gabathuler, Total cross-section

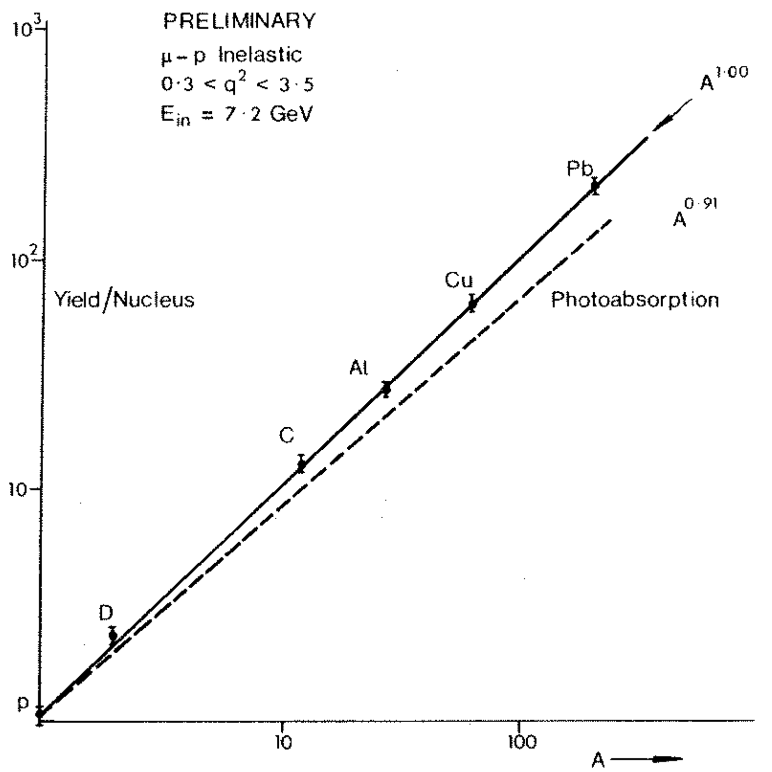


Fig. 14. The *A* dependence of the inelastic muon cross-section as presented by Tannenbaum (see discussion).

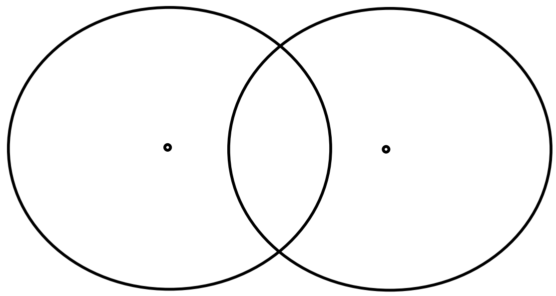
AGS $\mu - A$ scattering data, from E. Gabathuler's talk, [Proc. 6th Int. Symposium on Electron and Photon Interactions at High Energies, Bonn (1973)].

♡ DIS is pointlike $A^{1.00}$ even at modest q^2—no shadowing.
♡ Photoproduction is shadowed—$A^{0.91}$

High p_T in A+B—T_{AB} Scaling

Hard-scattering is a point-like process, with excellent PQCD predictions $\sim 10\%$ for $p-p$ and $\bar{p}-p$ collisions. For p+A or A+A collisions the cross sections should scale by the number of point sources, A for p+A or A^2 for A+A.

As a function of impact parameter, the profile function for a nucleus A



$$T_A(\vec{s}) = \int dz \rho_A(z, \vec{s})$$

is the number of nucleons per unit area along a direction z at a point from the center of the nucleus represented by a 2-d vector $\vec{s}$, where z is perpendicular to $\vec{s}$. For an interaction of nucleus A with nucleus B at impact parameter $\vec{b}$, the nuclear overlap integral $T_{AB}(\vec{b})$ is defined:

$$T_{AB}(\vec{b}) = \int d^2 s T_A(\vec{s}) T_B(\vec{b} - \vec{s}) \quad ,$$

where $d^2 s = 2\pi s ds$ is the 2-dimensional area element. Simply:

$$T_{AB}(\vec{b}) = N_{coll}(\vec{b}, \sigma)/\sigma$$

More precisely, for a certain fraction f of the nuclear interaction cross section for A+B collisions, the semi-inclusive yield is related to the $p-p$ inclusive cross section:

$$\frac{1}{N_f} \frac{d^3 N_f^{A+A}}{p_T dp_T dy d\phi} = \frac{d^3 \sigma^{p-p}}{p_T dp_T dy d\phi} \times \langle T_{AB} \rangle_f \cong \frac{d^3 \sigma^{p-p}}{p_T dp_T dy d\phi} \times \frac{\langle N_{coll}(\sigma_{nn}) \rangle_f}{\sigma_{nn}}$$

What Really Happens in Hadron Scattering

The Anomalous Nuclear Enhancement
aka the 'Cronin Effect'
The unpleasant Nuclear Effect

Due to Multiple Scattering of the initial Nucleons (Constituents?)

Now called k_T broadening.

But don't forget 'shadowing' of the Structure Functions in Nuclei

For latest info see E. Wang and X.-N. Wang nucl-th/0104031

CERN Pb+Pb $\sqrt{s_{NN}} = 17.2$ **GeV**

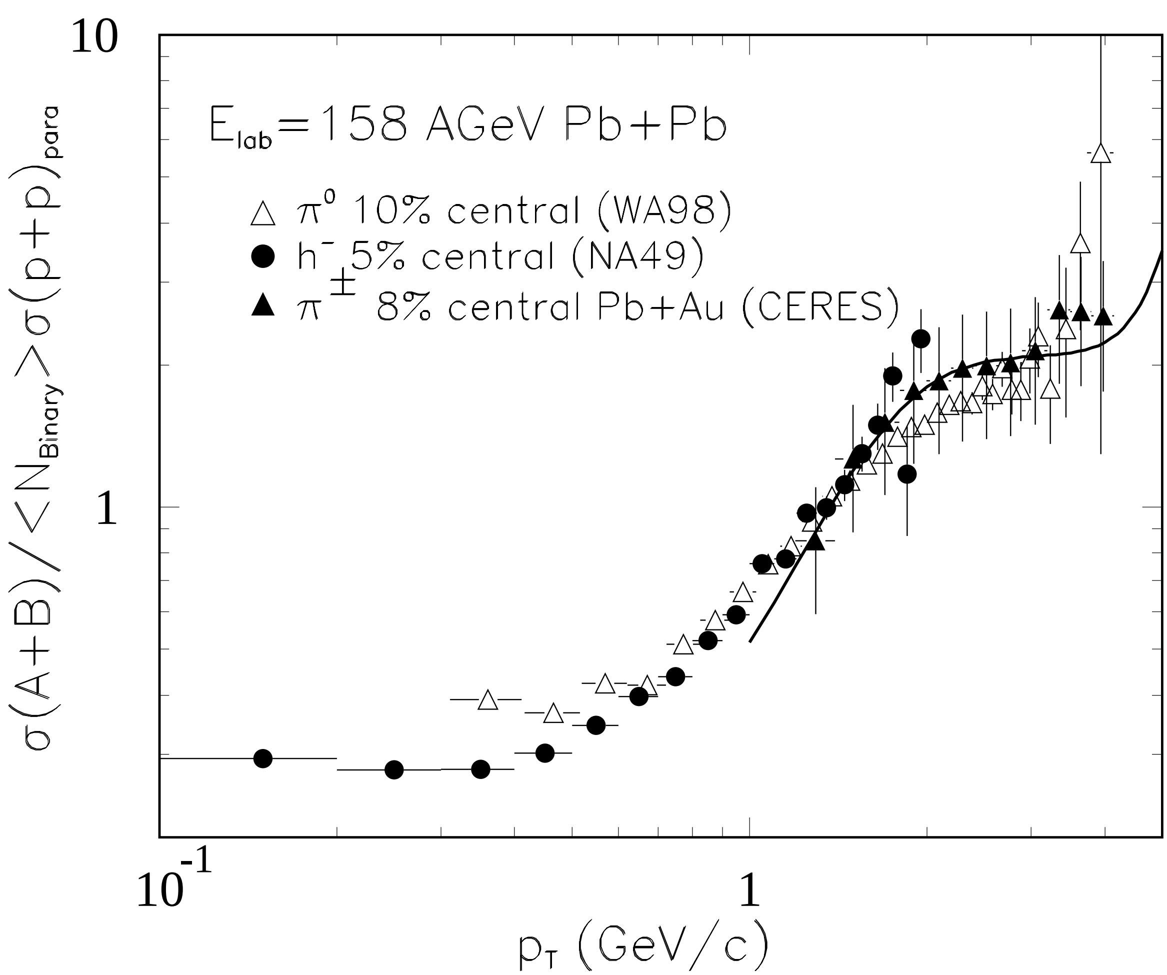


Figure 24: From Wang and Wang nucl-th/0104031

Why is the Cronin Effect 'Unpleasant'?

p_T spectra are very interesting in $p-p$ collisions
but before RHIC were 'tedious' in nuclei

The shapes of the spectra barely change from $p-p$ to $d-d$ to $\alpha-\alpha$ to Au+Au e.g ISR $\sqrt{s_{NN}} = 31$ GeV.

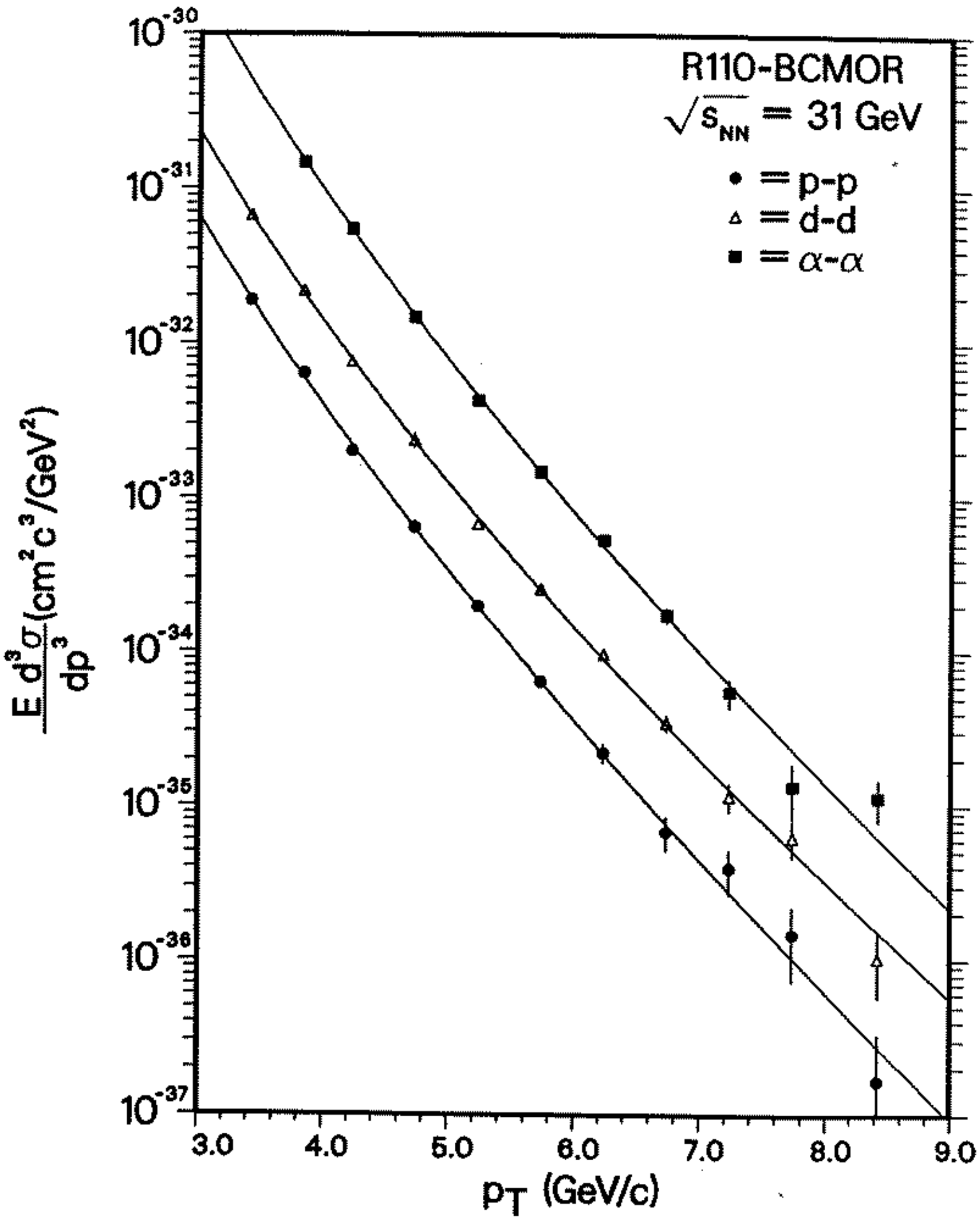
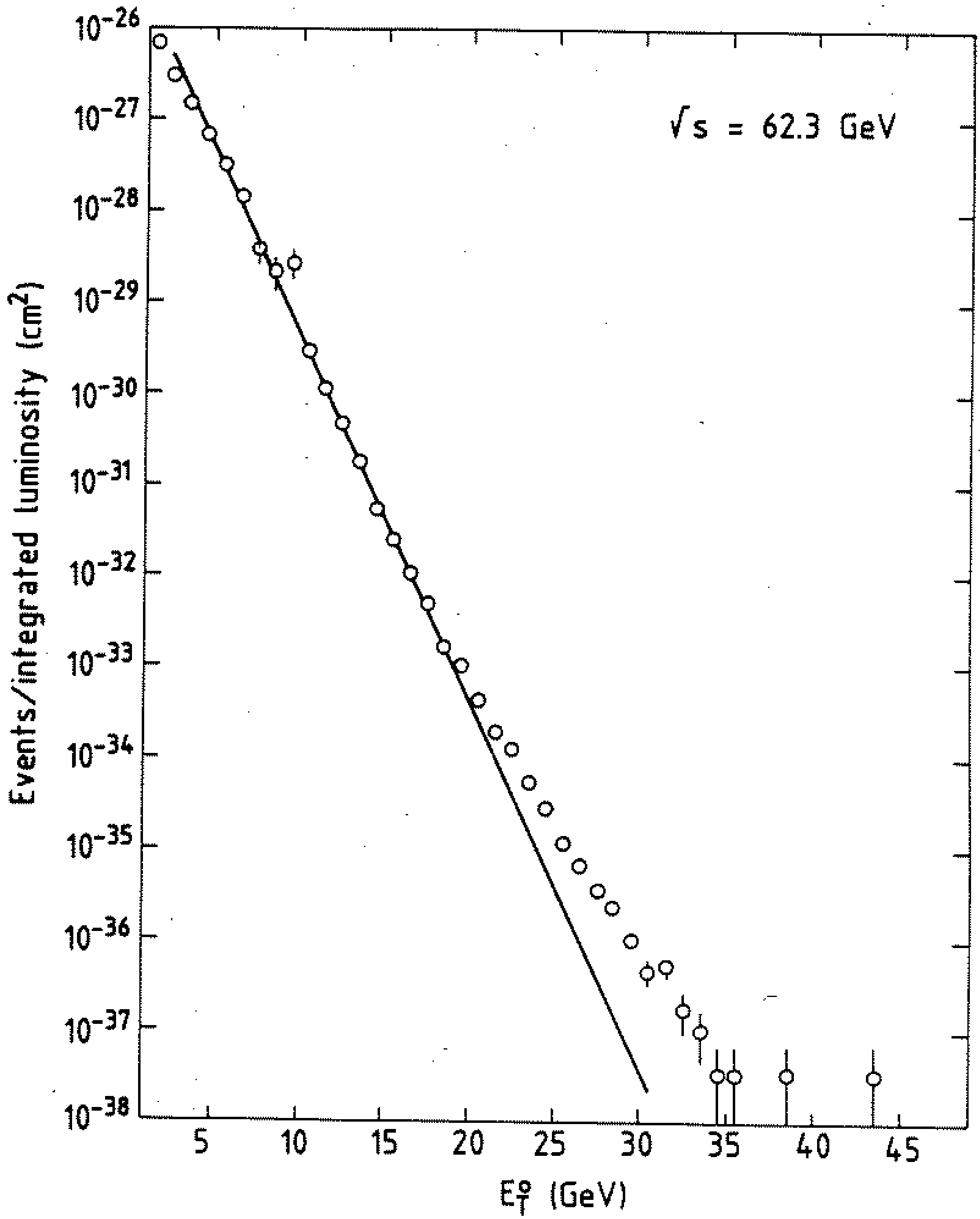
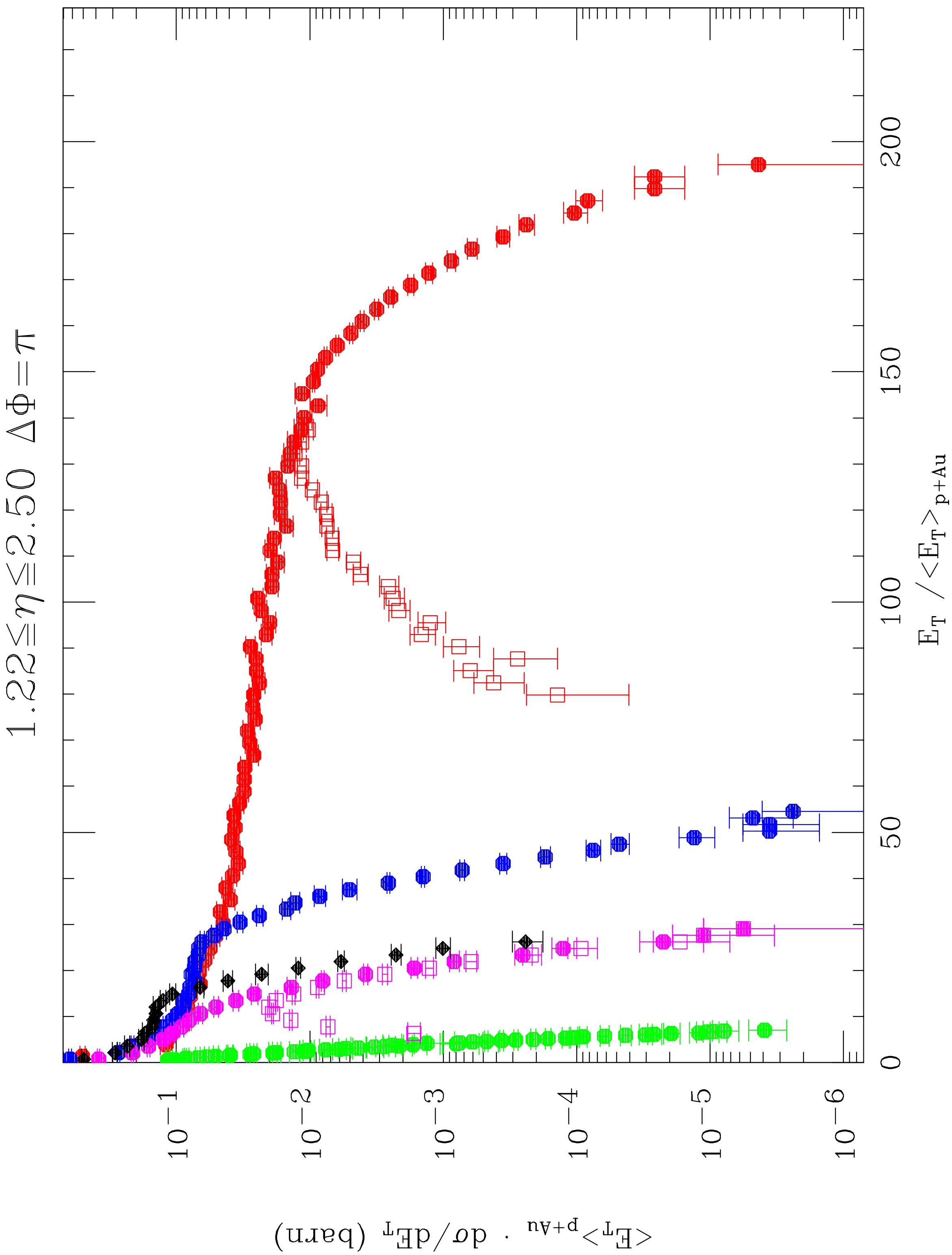


Figure 33: From CCOR Collab, A. L. S. Angelis, et al. PL**B185**, 213 (1987)

E_T Distributions in $p-p$ collisions are Relatively 'Boring'



E_T Distributions have Much More Interesting Effects in collisions of Nuclei



Schematic Nuclear Collision Geometry

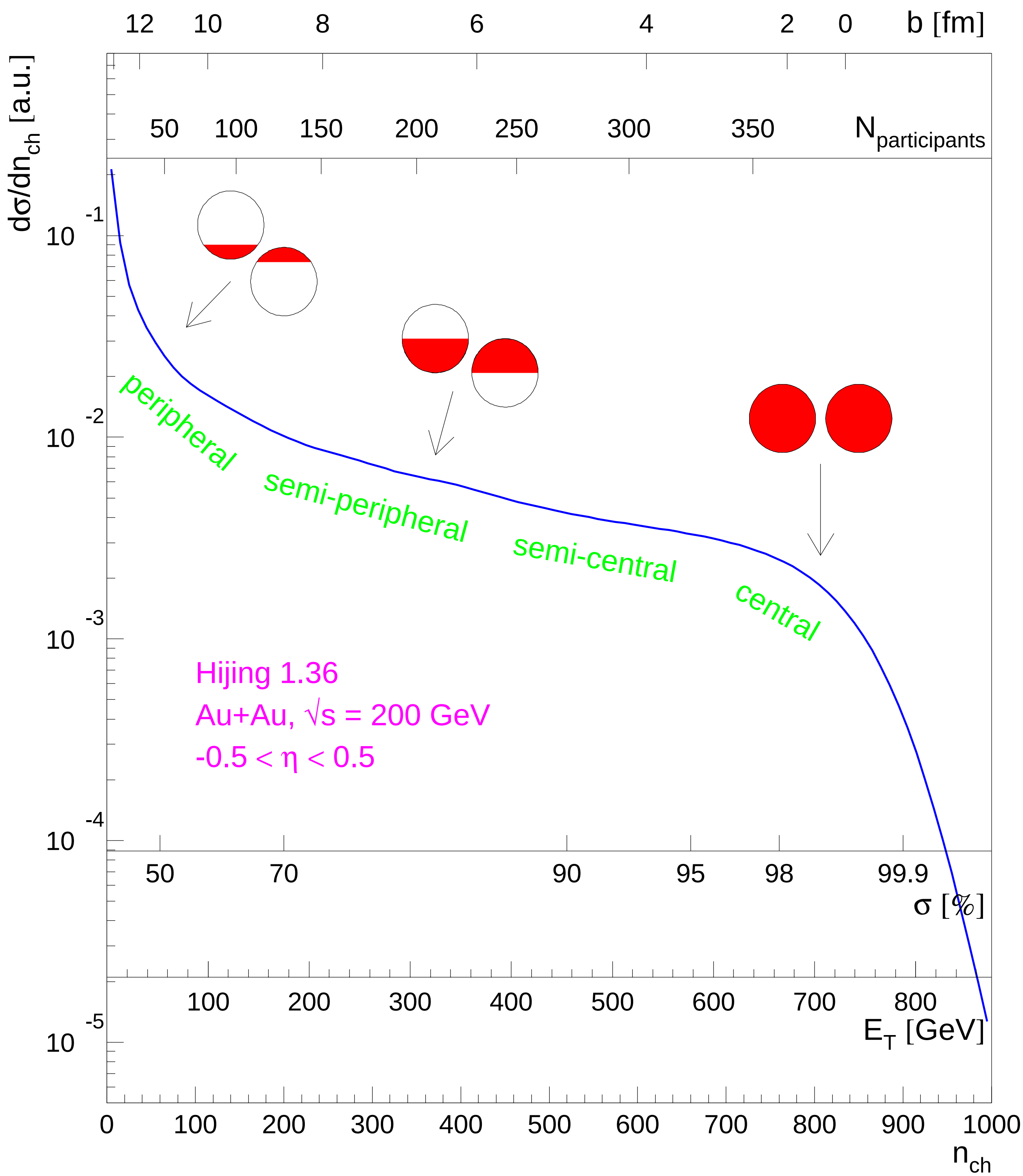
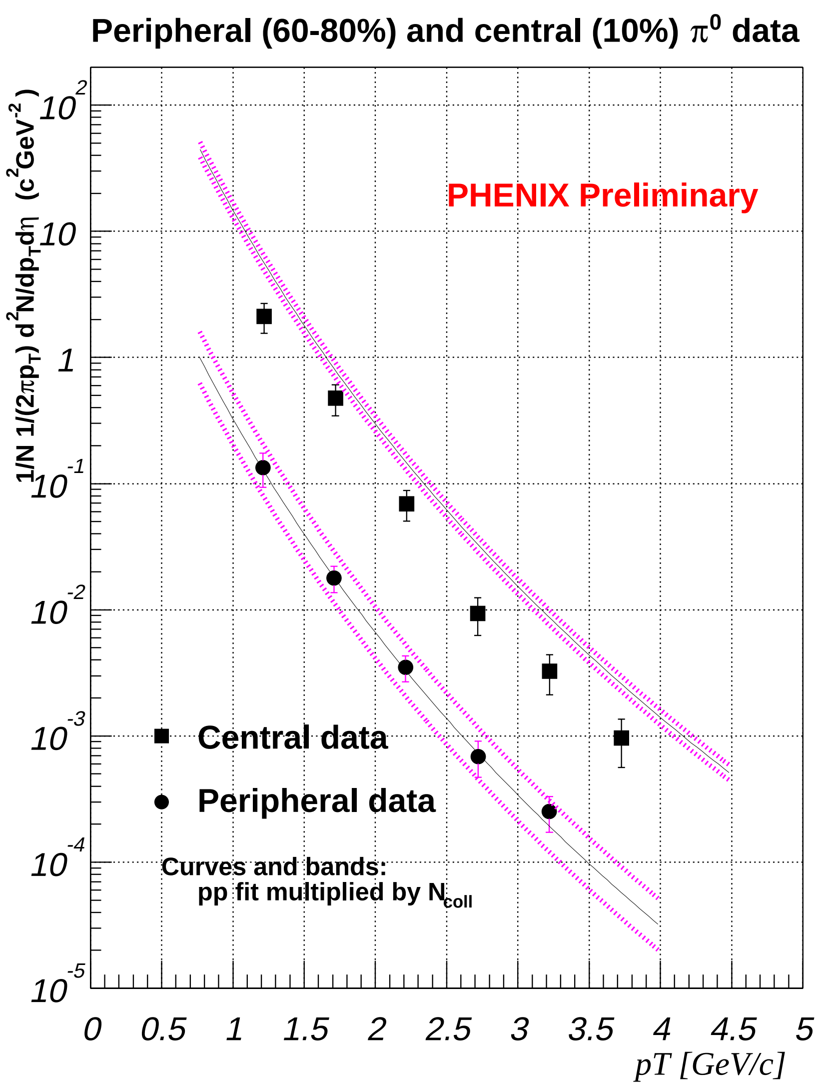


Figure 34: Schematic Nuclear Collision Geometry from Star-Yale

What happens at RHIC—something new!
High $p_T \pi^0$ —PHENIX
Au+Au $\sqrt{s_{NN}}$=130 GeV

π^0 Cent. and Periph.



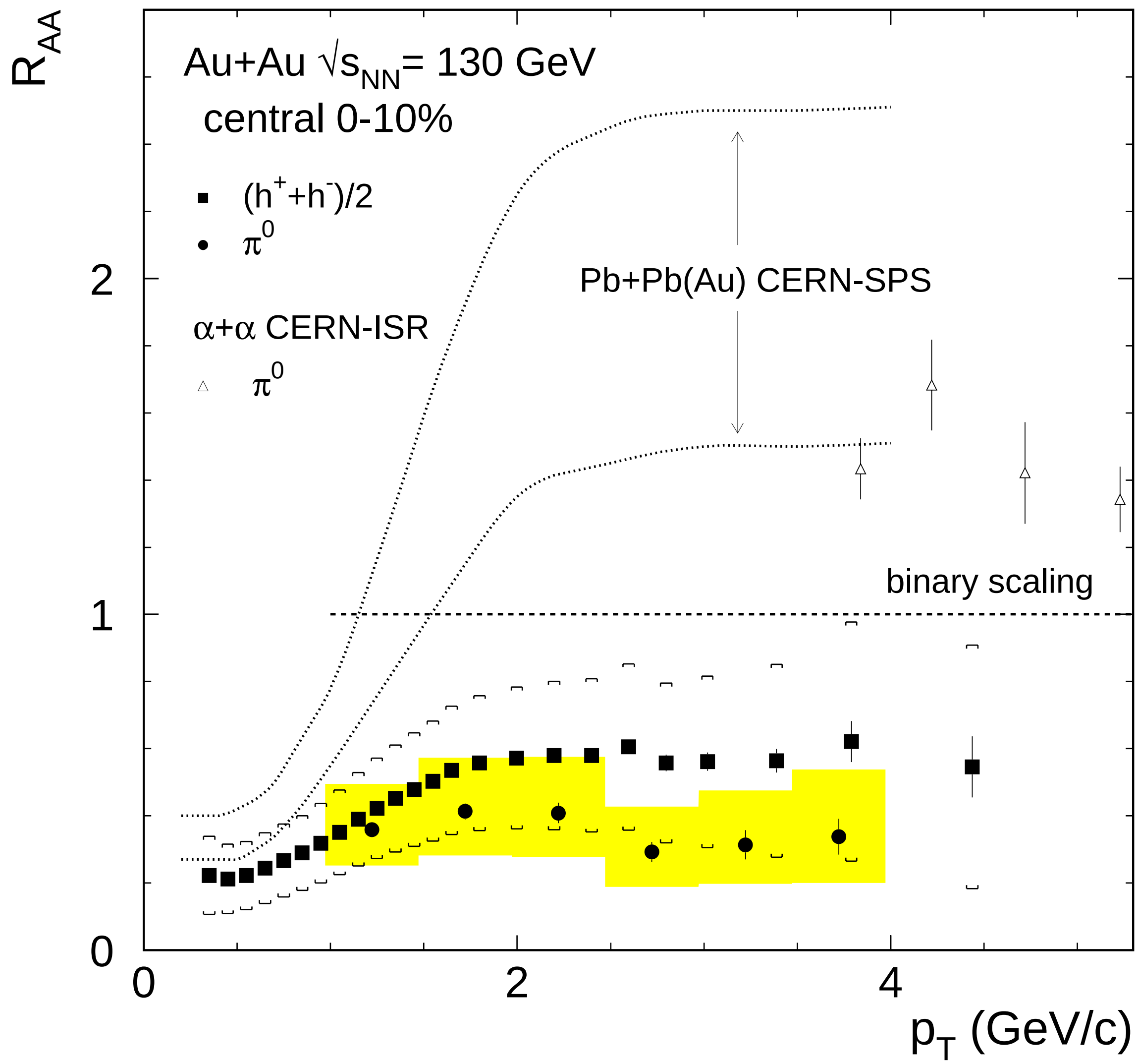
PHENIX central and peripheral π^0 semi-inclusive yield, scaled by $\langle T_{AB} \rangle$ for the centrality class= $\langle N_{coll}(40\text{mb}) \rangle$/40mb

♡ **Central π^0 yield is BELOW the point-like prediction!!**

A New and Interesting High p_T Nuclear Effect

PHENIX π^0 and $(h^+ + h^-)/2$ Central cf. UA1 fit

A defecit for $p_T > 2$ GeV/c—never seen previously!!!



Is this the 'jet quenching' in hot matter predicted by R. Baier, Yu. L. Dokshitzer, A. H. Mueller, S. Peigné and D.Schiff, Nucl. Phys. **B483**, 291 (1997) ?. Too early to say, needs lots more systematic investigation! This year's run at RHIC is presently underway with Au+Au (300 μb^{-1}) and (polarized) p-p (3.5 pb^{-1}) collisions planned at $\sqrt{s_{NN}} = 200$ GeV. Should go to up to $p_T \sim 20$ GeV/c with good p-p comparison if all goes well.

Second Lesson

k_T Issues

• k_T is related to the net transverse momentum of a hard-scattering jet-pair, or a Drell-Yan pair, or a pair of high p_T photons, or the $\gamma+$ Jet pair for direct photon production.

• In leading order QCD or the Quark-Parton model, all the above pairs are coplanar with the incident beam axis: $k_T = 0$.

• However, early Drell-Yan and inclusive high p_T particle studies showed that k_T was measurable and non-zero. Systematic measurements were made at the ISR and Fermilab.

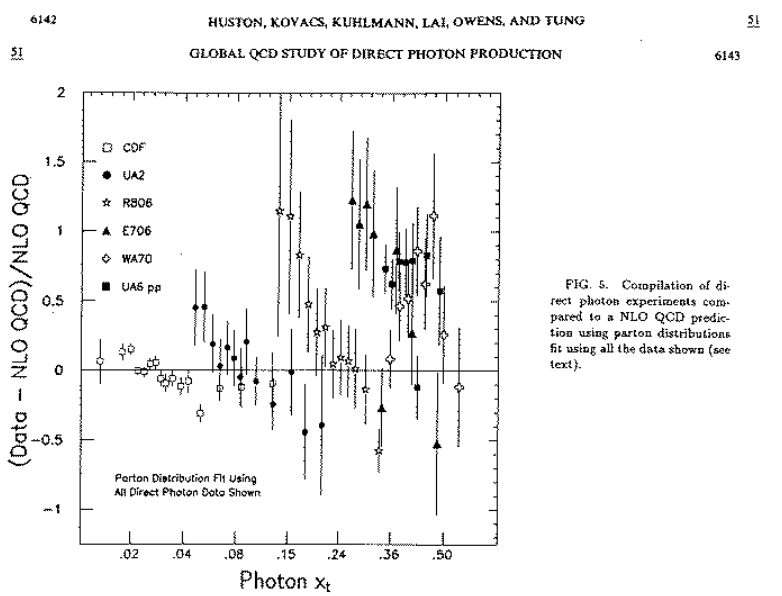
• Some experimentalists and theorists may view the issue of k_T differently—Experimentalists: multi-soft gluon, Gaussian;
Theorists: Hard-NLO gluons, power-law.

• The definitive work on k_T, actually on the p_T distribution of Drell-Yan pairs was made by G. Altarelli, R. K. Ellis and G. Martinelli in Phys. Lett. **151B**, 457 (1985), based on the ISR measurements. $\Rightarrow$ should be incorporated into event generators.

• The effect of k_T on the Gluon Spin structure function is mainly that it leads to an uncertainty in the value of Bjorken x of the inclusive direct photon measurements. This is illustrated and ways to measure k_T are discussed.

k_T and the Gluon Structure Function

• Is the gluon structure function (non-polarized) well known? I looked up a paper [PRL **77**, 446 (1996)] critical of CDF "high p_T jet anomaly", and I present their 'even better than new' gluon structure function below, together with the previous 'standard' by Aurenche, et al. However, a recent paper [Ap1] [L. Apanasevich, et al, PR **D59**, 074007 (1999)] shows that including k_T vastly improves the agreement of the NLO QCD (CTEQ4M) predictions with the data. **But, clearly we must also measure the unpolarized Gluon Structure Function at RHIC!**



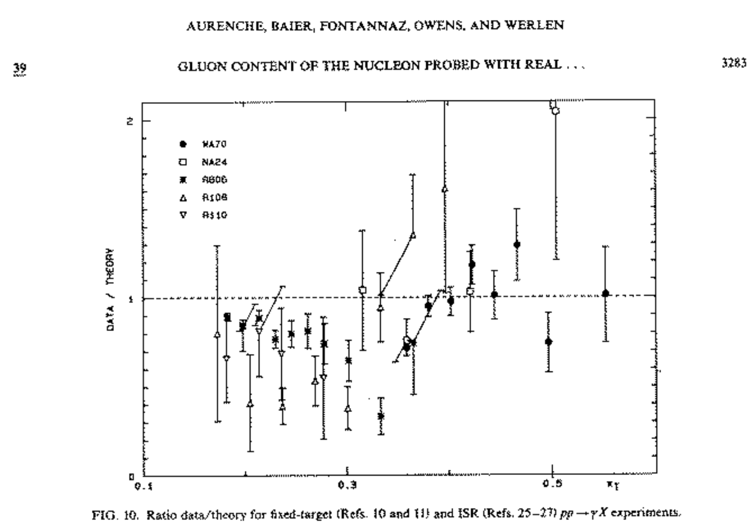


Figure 35: 2 favorite Gluon structure functions (?)

k_T is not a parameter, it can be measured

• In leading order QCD or the Quark-Parton model, the net transverse momentum $\langle p_T \rangle_{\rm pair} = \sqrt{2} \times \langle k_T \rangle$, of a hard-scattering jet-pair, or a Drell-Yan pair, or a pair of high p_T photons, or the $\gamma+$ Jet pair for direct photon production is zero. All the above pairs should be coplanar with the incident beam axis.

• However, early Drell-Yan and inclusive high p_T particle studies showed that k_T was measurable and non-zero.

♡ The history of k_T is worth reviewing as k_T was predicted to be zero by theorists, but was discovered to be non-zero by experimentalists. The CCHK experiment [M. Della Negra, et al., Nucl. Phys. **B127**, 1 (1977)] discovered that back-to-back jets had considerable out of plane transverse momentum $p_{\rm out}$, and proposed that this was due to transverse momentum of partons inside a proton.

♡ This was elaborated by Feynman, Field and Fox, [Nucl. Phys. **B128**, 1, (1997), Phys Rev. **D18**, 3320 (1978)] who introduced the k_T phenomenology of a parton in a proton, which they discussed in terms of 'intrinsic transverse momentum' from confinement which would be constant as a function of x and Q^2, and NLO effects due to hard gluon emission which would vary with x and Q^2, but they used an constant 'effective' k_T to 'explain' the available measurements.

♡ A subsequent ISR experiment, CCOR, showed that k_T for jet-pairs was roughly the same as for Drell-Yan and increased similarly with $\sqrt{s}$ (and p_T) i.e. was not constant. See Fig. 1 in [Ap1].

• The definitive theoretical work on a calculation of k_T in QCD, actually on the p_T distribution of Drell-Yan pairs, was made by G. Altarelli, R. K. Ellis and G. Martinelli in [Phys. Lett. **151B**, 457 (1985)], inspired by the ISR measurements.

Correct k_T for $\sqrt{s} = 200$ GeV

♡ Altarelli, et al., predicted (in 1985) the value of $\langle p_T \rangle_{\rm pair}$ (which they called $\langle q_T \rangle$) for Drell-Yan pairs, which we have seen is the same as for di-hadrons. Interestingly, their predictions go to 200 GeV where the predicted $\langle q_T \rangle = \sigma_{\rm 2partons,2d} = 3.5 \pm 0.2$ GeV/c.

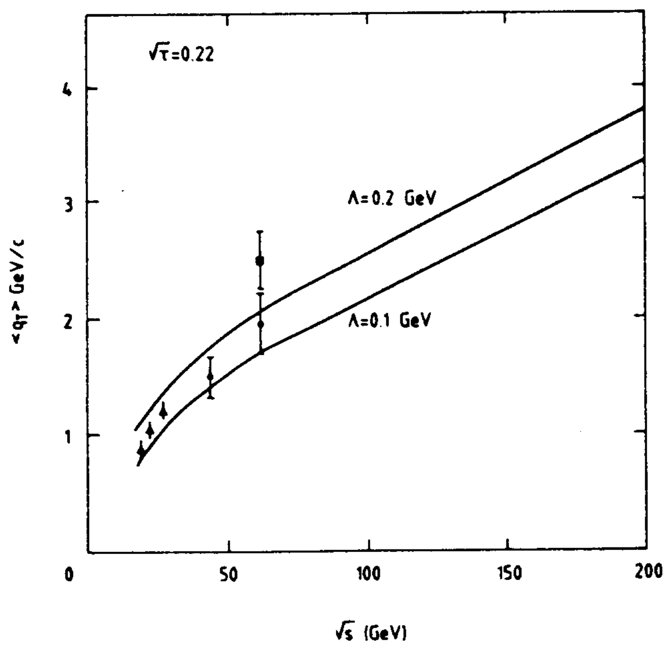


Figure 36: $\langle q_T \rangle$ vs $\sqrt{s}$ at fixed $\sqrt{\tau} = x_1 x_2 = 0.22$. Data shown are ISR and FNAL Drell-Yan. The curves are the theoretical predictions obtained using $\Lambda = 0.1 - 0.2$ GeV. No intrinsic q_T is included. At large values of $\sqrt{s}$, $\langle q_T \rangle$ increases linearly with $\sqrt{s}$. At smaller values, deviations from the linear law are visible, which are due to soft gluon and scaling violation pre-asymptotic effects

♡ Recall from above that

$$\langle k_T \rangle = \langle p_T \rangle_{\rm pair}/\sqrt{2} = 2.5 \text{ GeV/c} \tag{10}$$

$$\sqrt{\langle k_T^2 \rangle} = \langle k_T \rangle \times 2/\sqrt{\pi} = 2.82 \text{ GeV/c} \tag{11}$$

Finally, from Eq. **??** the Gaussian smearing is:

$$\sigma_{\gamma,\rm 1d} = k_T/2 = \sigma_{\rm 1parton,2d}/2 = 1.41 \text{ GeV/c.} \tag{12}$$

Conclusions

♡ There are two important things to note:

◇ $\sigma_{\gamma,1\mathrm{d}} = 1.41$ GeV/c is **much less** than exhibited by PYTHIA.

◇ The direct γ cross section from our proposal has an exponential value $b \simeq 0.40$ between 10 and 20 GeV/c, giving a shift in the p_T spectrum by

$$b\,\sigma^2_{\gamma,1\mathrm{d}}/2 = 0.4 \text{ GeV/c} \tag{13}$$

• This means that at $\sqrt{s} = 200$ GeV/c, x_T is an excellent estimator of Bjorken x to $\approx 3-4\%$ and therefore **PHTHIA's treatment of k_T is WRONG**

• **Of course, to get the Physics Correct, we should all try to measure k_T at RHIC.**

THIS IS MY ANALYSIS
IT SHOULD SERVE AS A CHALLENGE FOR SOMEONE ELSE
TO DO BETTER!