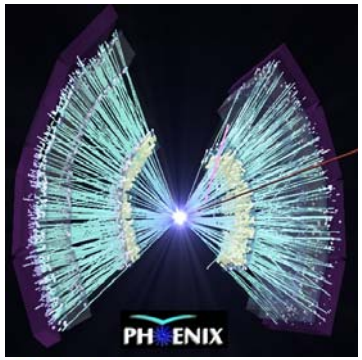
High p_T physics from the AGS to the ISR to RHIC

M. J. Tannenbaum
Brookhaven National Laboratory
Upton, NY 11973 USA



Progress in High-p_T Physics at RHIC
RBRC Workshop, BNL
March 17, 2010

Timeline of hard-constituent Scattering

- 1968--Deeply Inelastic scattering of electrons on protons observed at SLAC. First direct indication of sub-constituents of proton, "partons" as explained by Bjorken scaling [J.D. Bjorken, Phys. Rev. **179**, 1547 (1969)]

- 1971--High p_T scattering of "partons" via QED predicted for p-p collisions by Bjorken, Berman, Kogut [BBK, Phys. Rev. **D4**, 3388 (1971)]

- 1972 First evidence of hard-scattering of constituents discovered at CERN ISR--attention turns from spectroscopy to "high p_T physics"

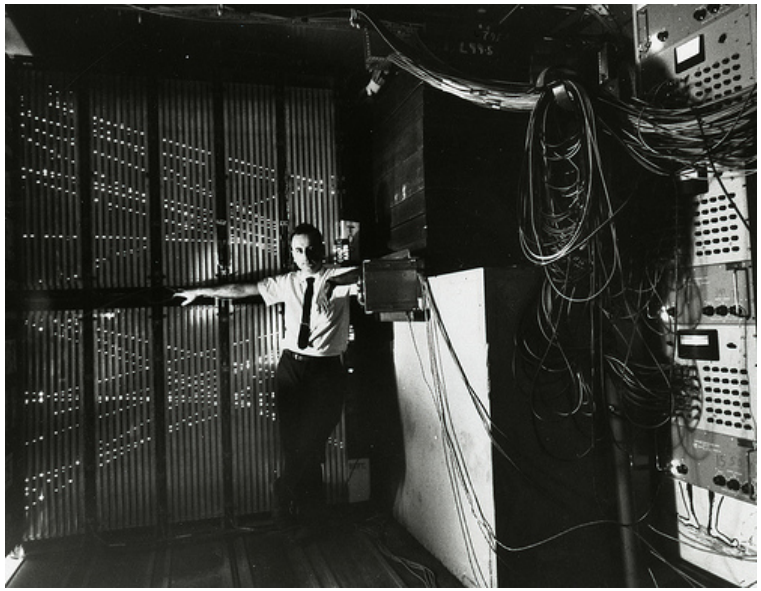
- 1974--J/ψ discovered at BNL and SLAC-people start believing that partons are real and are the same as quarks.

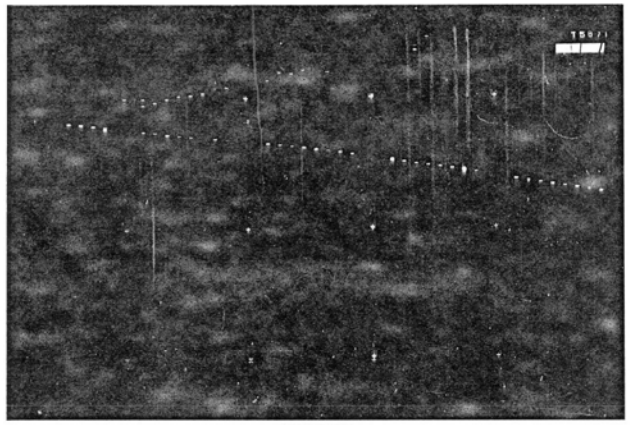
- 1972-1982 properties of hard-scattering and "Jets" mapped out at CERN-ISR for a decade 1975,1977-78 first theory papers on QCD applied to hard-scattering

- 1982-Constituent-scattering Angular distribution measured at ISR in agreement with QCD. (Rutherford scattering of quarks). SppS (UA2)-first observation of unbiased Jets in hadron collisions.

Why were some experiments looking at 90° and not forward in p-p collisions?

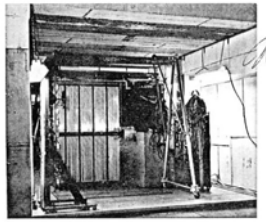
- The first opportunity to study weak interactions at high energy was provided by the development of neutrino beams at the new accelerators in the early 1960's CERN-SpS , BNL-AGS.





Neutrino Event

Columbia (Nevis)



BNL

In Token of Our
Appreciation for
Your Contribution
to the Neutrino
Run September 1961-
June 1962.

"The
Neutrino
Group"

Gordon Danby
Jean-Marc Gaillard
Dino Goulianos
Werner Hayes
Leon Lederman
Mari Mistry
Mel Schwartz
Jack Steinberger

- However, it was soon recognized that the intermediate (weak) boson $W^{\pm}$, might be more favorably produced in nucleon-nucleon collisions.

The ‘Zichichi signature’ for the W boson

Proc. 12th ICHEP, Dubna 1964

MUON-PROTON ELASTIC SCATTERING AT HIGH MOMENTUM TRANSFERS *

R. Cool, A. Maschke
Brookhaven National Laboratory, USA
L. Lederman, M. Tannenbaum
Columbia University, USA
R. Ellsworth, A. Melissinos, J. Tinlot, T. Yamanouchi
University of Rochester, USA
(Presented by J. TINLOT)

We have studied the elastic scattering of negative muons from liquid hydrogen at momentum transfers of 550 MeV/c to 1050 MeV/c ($q^2 = 7$ to 26 fermi^{-2}), using a detecting array of spark chambers and scintillation counters. The experiment was performed at the AGS accelerator of the Brookhaven National Laboratory, and the runs were divided into three stages, of the proton in an aluminum plate spark chamber. One also measures the directions of the recoil proton and the recoil muon. This is equivalent to measuring three independent angles, from which one can infer for each event the value of k, and still overdetermine the scattering event by two degrees of freedom. This redundancy is used to select true scattering

ДИСКУССИЯ DISCUSSION

A. Zichichi

In connection with the problem of observing the production of intermediate bosons, I would like to mention that we have been studying at CERN two schemes:

1) $\bar{p} + p \to W^+ + W^-$, $W^- \to e^- + \nu_e$, $W^+ \to \mu^+ + \nu_\mu$ $\Big\} \to \mu^\pm,\ e^\mp.$

This process is described by the following Feynman diagram

Notice that this process is proportional to α^2 where α is the electromagnetic coupling constant.

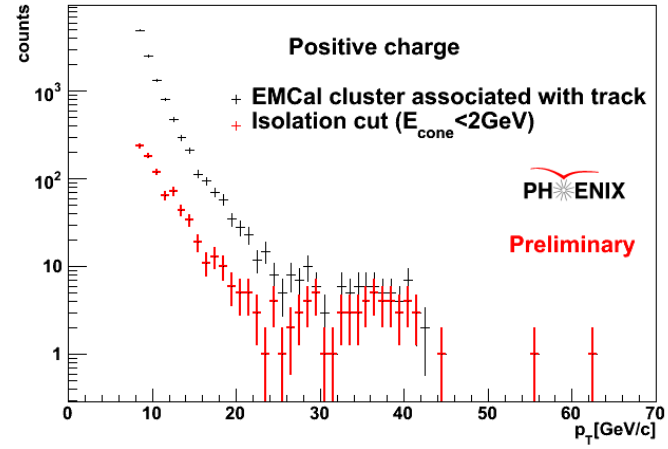
2) The second proposal studied would use the internal target of the proton synchrotron with 10^{12} protons per pulse incident onto the target. The process would be $p + \left(\frac{p}{n}\right) \to W^\pm +$ anything. We would observe the μ's from W-decays. By measuring the angular and momentum distribution at large angles of K and π's, we can predict the corresponding μ-spectrum. We then see if the μ's found at large angles agree with or exceed the expected number. A supplementary check can be made by measuring the polarization of these μ's. The polarization indicates the origin of these μ's. Notice that the cross section for this process goes with $\sqrt{g}$, where g is the β-decay coupling constant.

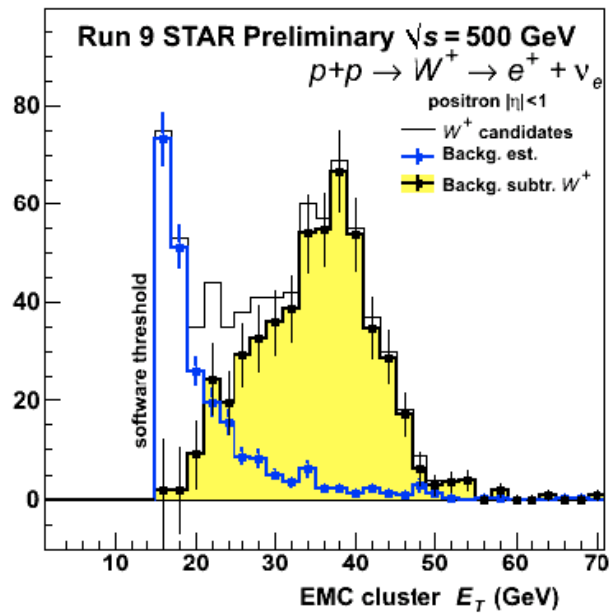
B. Pontecorvo

I would like to use the fact that you are all tired in order to make a remark of linguistic rather than sicentific character. All the speakers used as notations for neutral leptons the letters ν_e and ν_μ. This seems to be a very convenient notation. On the other hand, the terms which are usually used for neutral leptons-electron and muon neutrinos (and even «electron and muon type of neutrino!»), are too cumbersome. True, sometimes for ν_e the word «neutrino» is used and for ν_μ, the word «neutretto». The last term, however, is not very satisfactory since the last thirty years lost of particle including strong interacting particles had been called that way. In addition, it seems to me that both types of neutral leptons should conserve in their «name» the root «neutrino», which is widely associated with the unique

3* 35

PHENIX+STAR 4.0σ Parity Violation

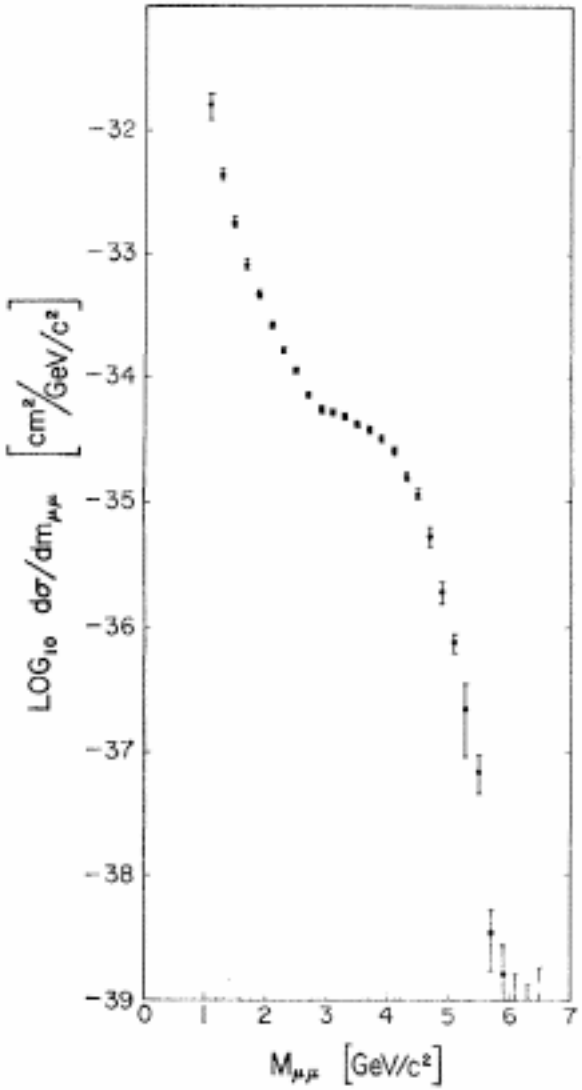




Searches for W boson in p-p collisions

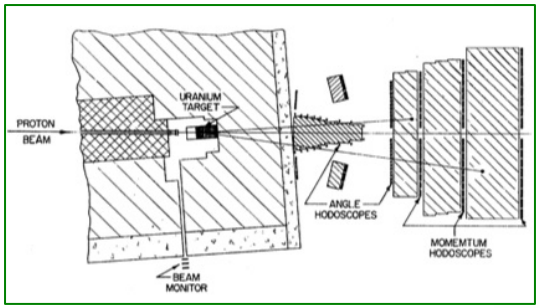
- 1965-1969 Beam dump experiments at ANL-ZGS and BNL-AGS looking for "large angle" muons didn't find any. [ZGS-Lamb, et al PRL **15**, 800 (1965), AGS-Burns, et al, ibid 830, AGS-Wanderer et al, PRL **23**,729(1969)]
- How do you know how many W should have been produced?
- Chilton, Saperstein, Shrauner [PR**148**, 1380 (1966)] emphasize the importance of the timelike form factor, which is solved by
- Y. Yamaguchi [Nuovo Cimento **43**, 193 (1966)] Timelike form factor can be found by measuring the number of lepton pairs e^+e^- or $\mu^+\mu^-$ "massive virtual photons" of the same invariant mass; BUT the individual leptons from these electromagnetically produced pairs might mask the leptons from the $W^{\pm}$.
- This set off a spate of single and di-lepton experiments, notably the discovery by Lederman et al of "Drell-Yan" production at the BNL-AGS, E70 at FNAL and CCR at the CERN-ISR.

AGS-1969-71 Discovery of 'Drell-Yan' and ??



$p+U \rightarrow \mu^+\mu^- + X$

$\sqrt{s_{NN}}=7.4$ GeV



This is why I NEVER plot theory curves on any of my data

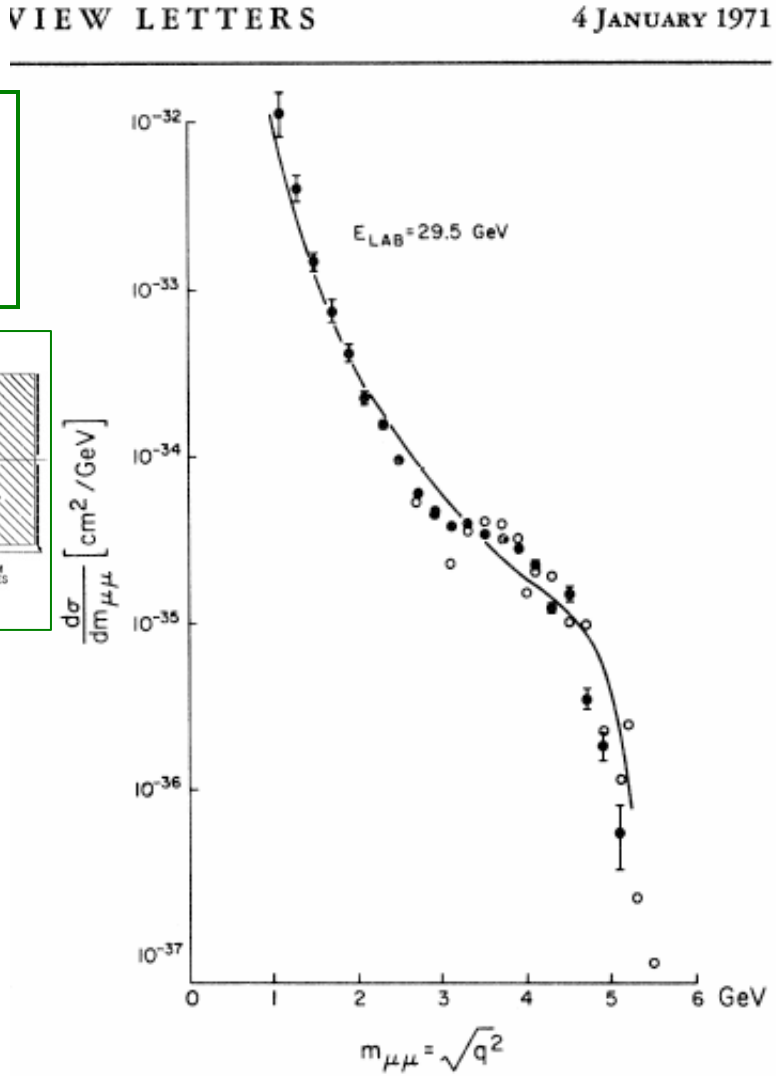


FIG. 2. Experimental cross section of Christenson *et al.*, Ref. 8.

long forgotten

Christenson, Lederman…PRL **25**, 1523 (1970)

`Theory' Altarelli, Brant Preparata PRL **26** 42 (1971)

LML very excited in 1970: AGS-diμ continuum +Bj scaling→W cross section at any √s

Proposal to The National Accelerator Laboratory

E70-(F)NAL

"Study of Lepton Pairs from Proton-Nuclear Interactions; Search for Intermediate Bosons and Lee-Wick Structure"

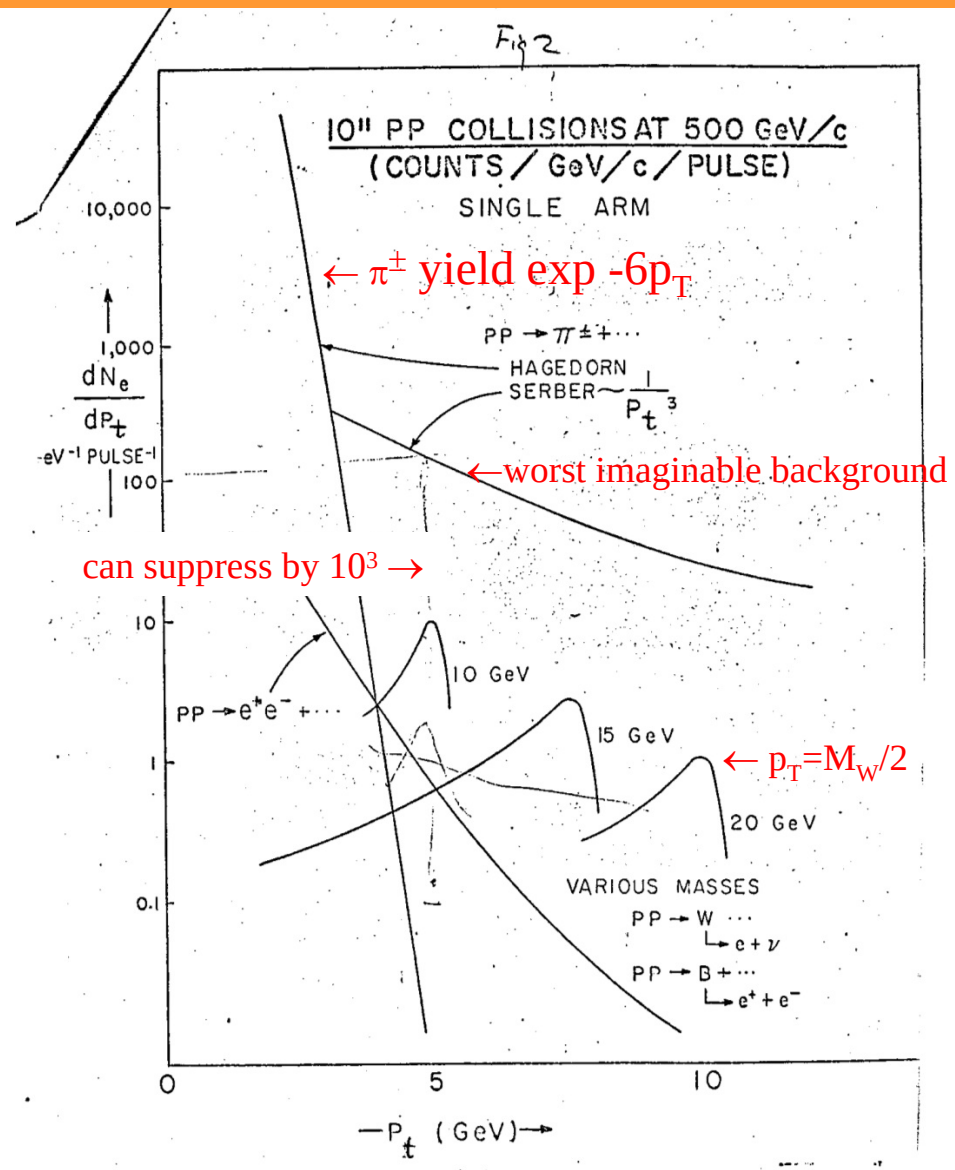
W. LEE, L.M. LEDERMAN, J. APPEL, Columbia University, M. TANNENBAUM, Harvard University, L. READ, J. SCULLI, T. WHITE, and T. YAMANOUCHI, National Accelerator Laboratory.

ABSTRACT

We propose to observe lepton pairs emerging from high energy proton-nuclear collisions. Large effective mass pairs probe the hadronic electromagnetic structure. The continuum mass spectrum will be measured and any resonant structures in the mass range up to ~ 28 GeV will be detected with great sensitivity. The data provides a prediction, via Conserved Vector Current theory, for the production cross section for weak vector bosons and these are also sought in the mass range ~8-25 GeV. We also propose an initial photon-electron beam survey at high transverse momentum which is also a W-search with good sensitivity.

June 17, 1970 + addendum Dec 1970 →

Correspondent: L. M. Lederman, Columbia University



Other Proposals-AGS549-not done !

AGS PROPOSAL

September 14, 1970

AGS-P549

Peter J. Limon, Columbia University, Nevis Labs

A high resolution study of the production of electron pairs in hadronic interactions covering the mass range $0.7\ \mathrm{GeV}/c^2 \leq M_{e^+e^-} \leq 4.5\ \mathrm{GeV}/c^2$.

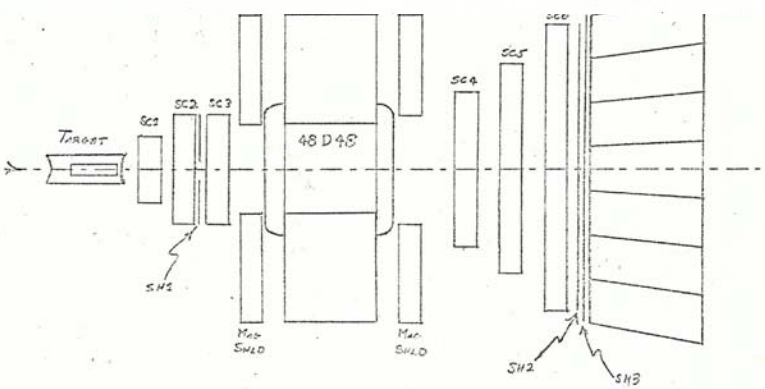
Beam: The "A" target of the S.E.B.

Momentum: 25 GeV/c positive. 20 GeV/c negative.

Run time: 500 hours data taking. 100 hours test.

Detector: Forward leg of the double Vee magnetic spectrometer.

Additional Requirement: OLDF PDP-6/10.



PROPOSAL TO USE THE MULTIPARTICLE MAGNETIC SPECTROMETER TO DETECT LEPTON PAIR PRODUCTION

Peter Limon
Columbia University

Introduction

This letter is being submitted in lieu of a detailed proposal for this experiment. Admittedly, there are many questions which this letter will not answer, and which require further study. We will try to point out what we consider to be the most serious problems. A more detailed proposal will be forthcoming in a few months. The performance of this experiment is contingent upon the results of the detailed study, and approval by the Nevis scientific staff. This letter is organized into three parts:

I. Some reasons for doing the experiment.

II. An outline of the experiment.

III. Estimates of event rate.

It would have found the J/ψ but with NAL, ISR starting up, AGS μ-scattering program doing DIS, potential authors were very busy...

μ-A DIS at AGS (1973)--Hard-Scattering is pointlike

E. Gabathuler, Total cross-section

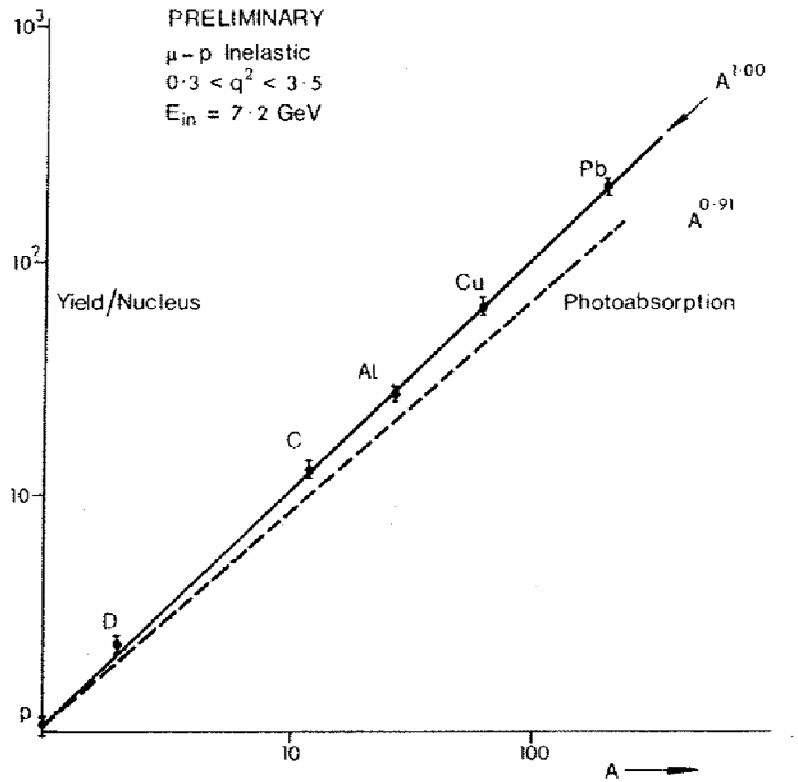


Fig. 14. The A dependence of the inelastic muon cross-section as presented by Tannenbaum (see discussion).

AGS $\mu - A$ scattering data, from E. Gabathuler's talk, [Proc. 6th Int. Symposium on Electron and Photon Interactions at High Energies, Bonn (1973)]. M. May, et al, (M.Murtagh, T.Kirk, MJT) PRL **35**, 407 (1975)

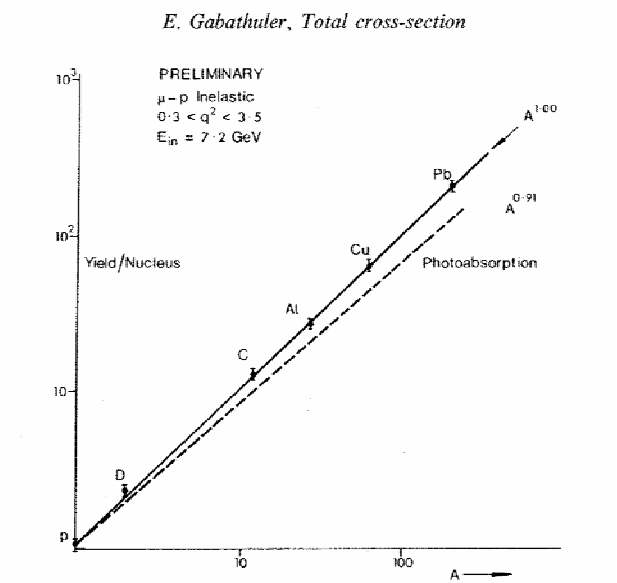
- ♡ DIS is pointlike $A^{1.00}$ even at modest q^2—no shadowing.
- ♡ Photoproduction is shadowed—$A^{0.91}$

M. May, *et al.*,

A Brief History of the EMC effect μ+A DIS

$A^{1.00}$

note disagreement



A dependence of the inelastic muon cross-section as presented by Tannenbaum (see c

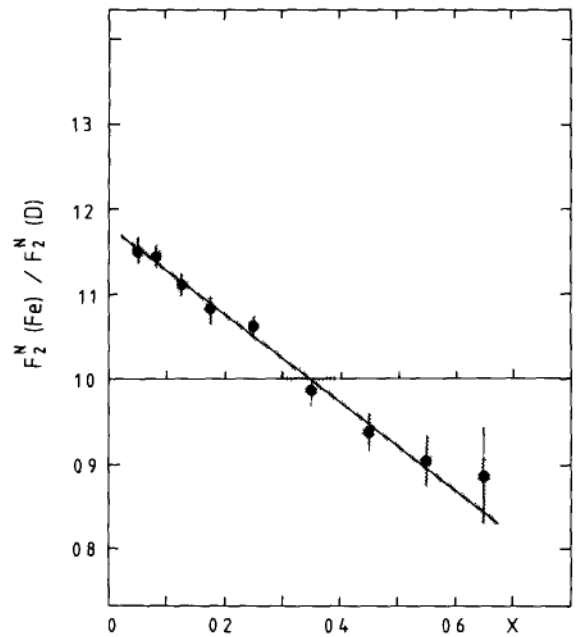
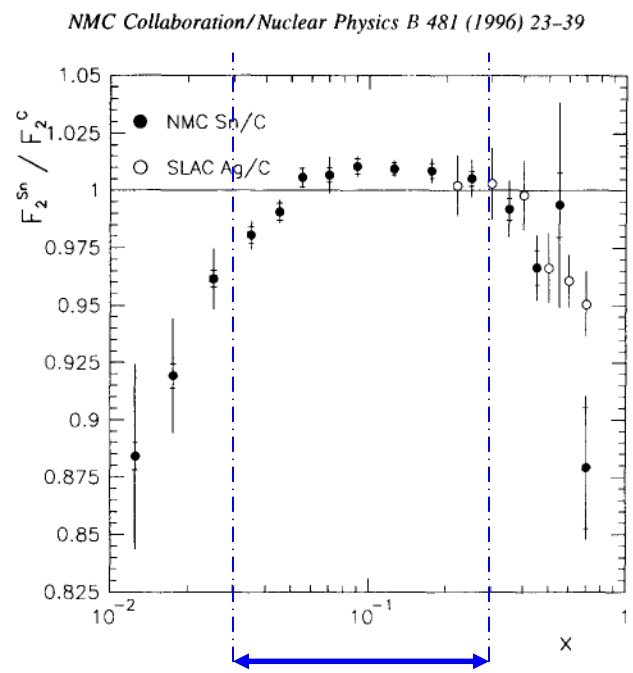


Fig. 2. The ratio of the nucleon structure functions F_2^N measured on iron and deuterium as a function of $x = Q^2/2M_p\nu$. The iron data are corrected for the non-isoscalarity of $^{56}_{26}$Fe,



RHIC range

M.May, et al, PRL 35 (1975) 407. Plot is online result shown by Gabathuler at Electron/Photon 1973

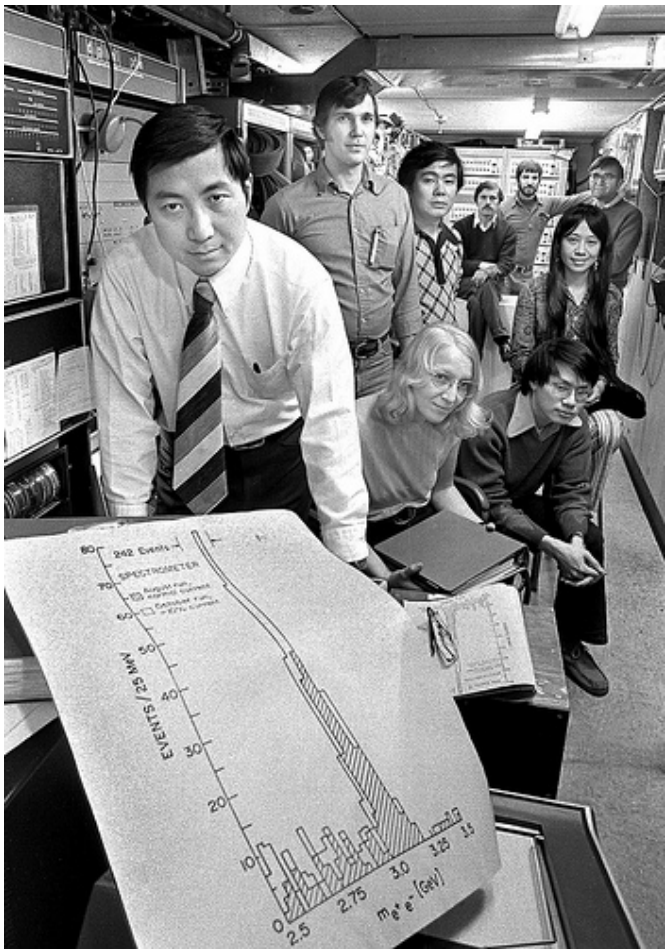
EMC, J.J.Aubert, et al, PLB 123(1983) 275-278

NMC, M.Arneodo, et al, NPB 481(1996) 23-39

$$F_2^A(x,Q^2) \approx AF_2^p(x,Q^2)$$

→ T_{AB} the overlap integral of the nuclear profile functions, as a function of impact parameter b but no such measurements YET in DIS

?? explained by J/ψ in 1974 at AGS + SLAC



VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

This experiment is part of a large program to study the behavior of timelike photons in $p + p \to e^+ + e^- + x$ reactions[1] and to search for new particles which decay into e^+e^- and $\mu^+\mu^-$ pairs.

daily with a thin Al foil. The beam spot size is 3×6 mm^2, and is monitored with closed-circuit television. Figure 1(a) shows the simplified side view of one arm of the spectrometer. The two

Discovery of a Narrow Resonance in e^+e^- Annihilation*

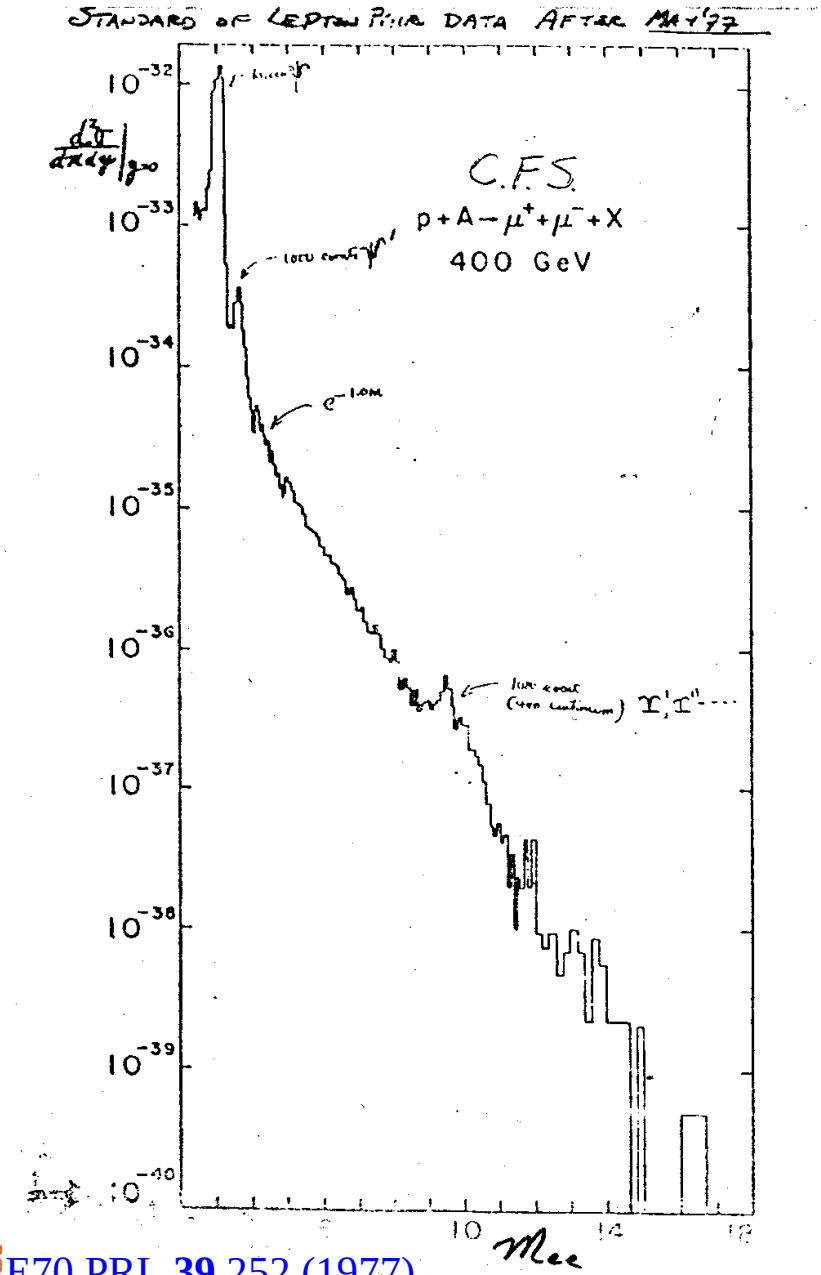
J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

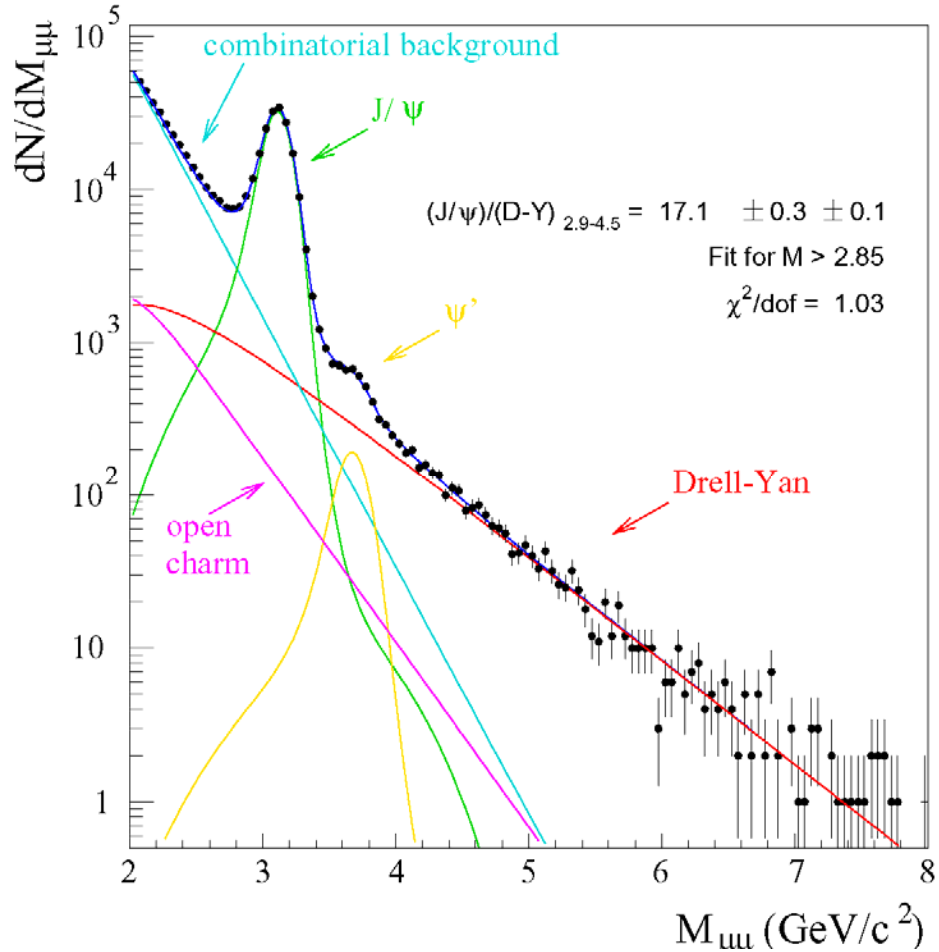
and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720
(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

The whole truth--'Applied HEP'





NA50 PL**B 477**, 28 (2000)

E70 PRL **39** 252 (1977)

The CERN ISR was the first Hadron Collider and made many discoveries and developed many techniques which are in use in Au+Au and p-p collisions at RHIC today.

G. Giacomelli and M. Jacob, Phys. Rept. **55** (1979) 1-132
M. Jacob and K. Johnsen, CERN Yellow Report 84-13

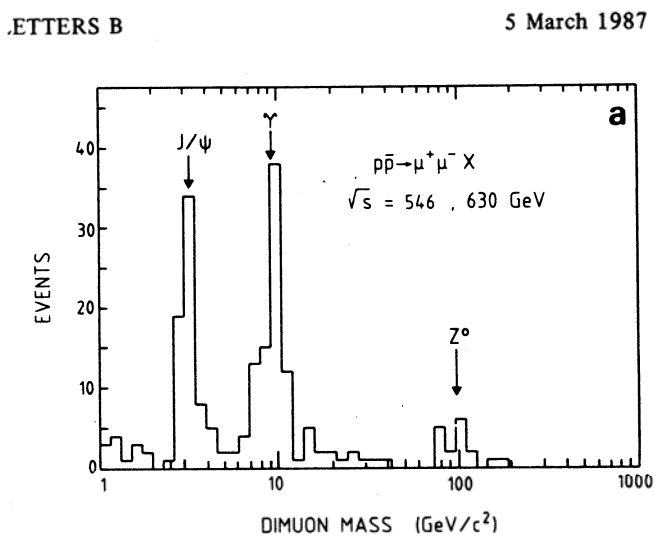
- The rapidity plateau (although several of my RHI colleagues don't believe in a plateau). Will not be discussed in this talk.
- Hard scattering in p-p collisions via particle production at large p_T which proved that the partons of DIS strongly interacted with each other. x_T scaling measurements to find the underlying physics.
- Proof using same-side and away side two particle correlations that high p_T particles in p-p collisions 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 QCD, which was developed during the course of these measurements.

CERN-ISR Discoveries, cont'd

- direct lepton ($e^{\pm}$) production from the decay of (unknown at that time-1974) particles composed of b and c quarks.
- first and only J/Psi cross section measurement for all pair $p_T \geq 0$ at a hadron collider, until PHENIX at RHIC [PRL **92** (2004) 051802] and CDF [PRD **71**(2005) 032001 (15 years after their first publication)]
- direct photon production

J/Psi suppression has been the gold plated signature for the quark gluon plasma in AA

The Road To Success in HEP



$p_T(\mu) \geq 3$ GeV/c, UA1 Phys. Lett. B**186**, 237 (1987)

The Road To Success in HIP

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

♡ The discovery that the DIS structure function

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

"SCALED" i.e just depended on the ratio

$$x = \frac{Q^2}{2M\nu} \qquad (2)$$

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

♡ as originally suggested by **Bjorken** Phys. Rev. **179**, 1547 (1969)

♡ Led to the concept of a proton composed of point-like **partons**. Phys. Rev. **185**, 1975 (1969)

$$\nu = \frac{Q^2}{2Mx}$$

□ The probability for a parton to carry a fraction x of the proton's momentum is measured by $F_2(x)$

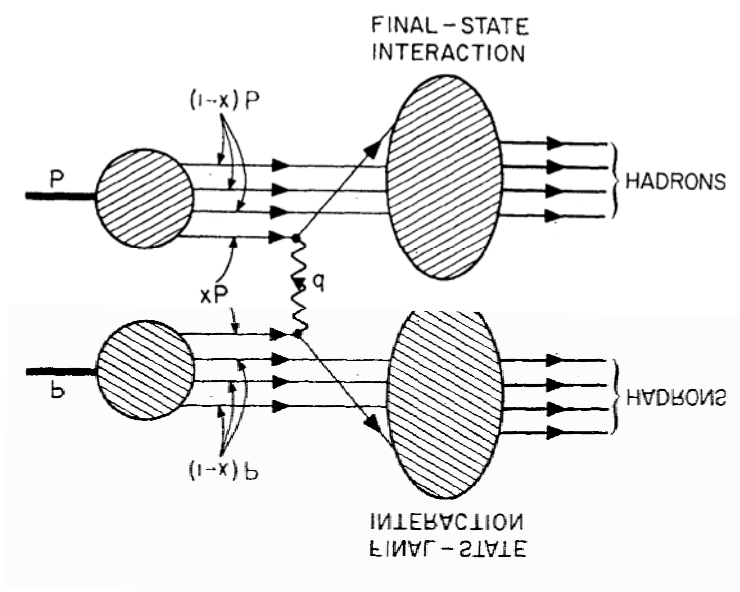
BBK 1971

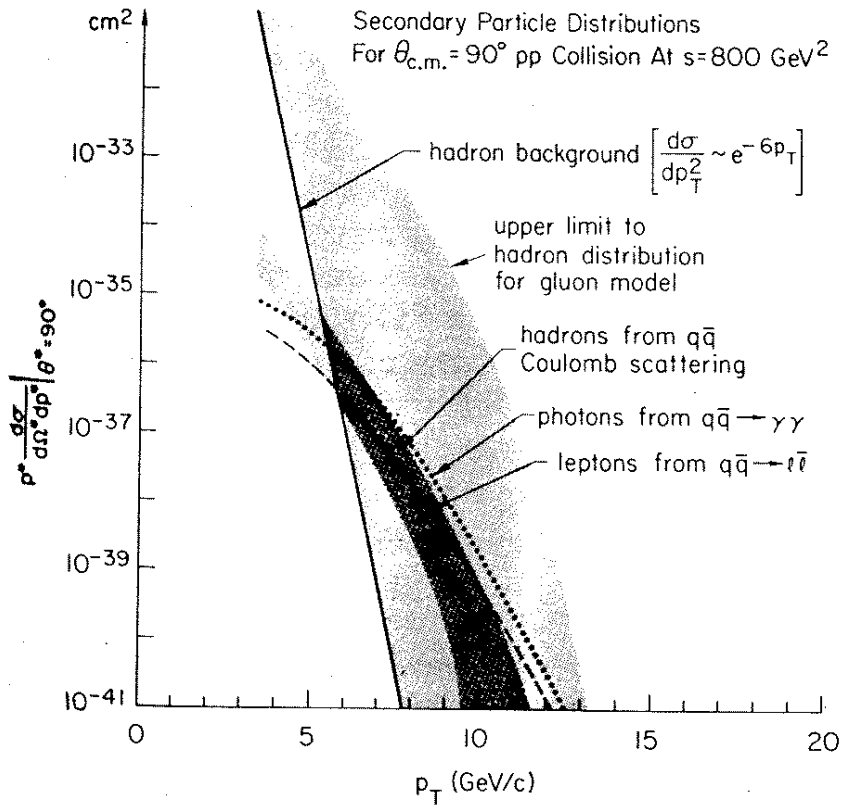
S.M.Berman, J.D.Bjorken and J.B.Kogut, Phys. Rev. **D4**, 3388 (1971)

- BBK calculated for p+p collisions, the inclusive reaction

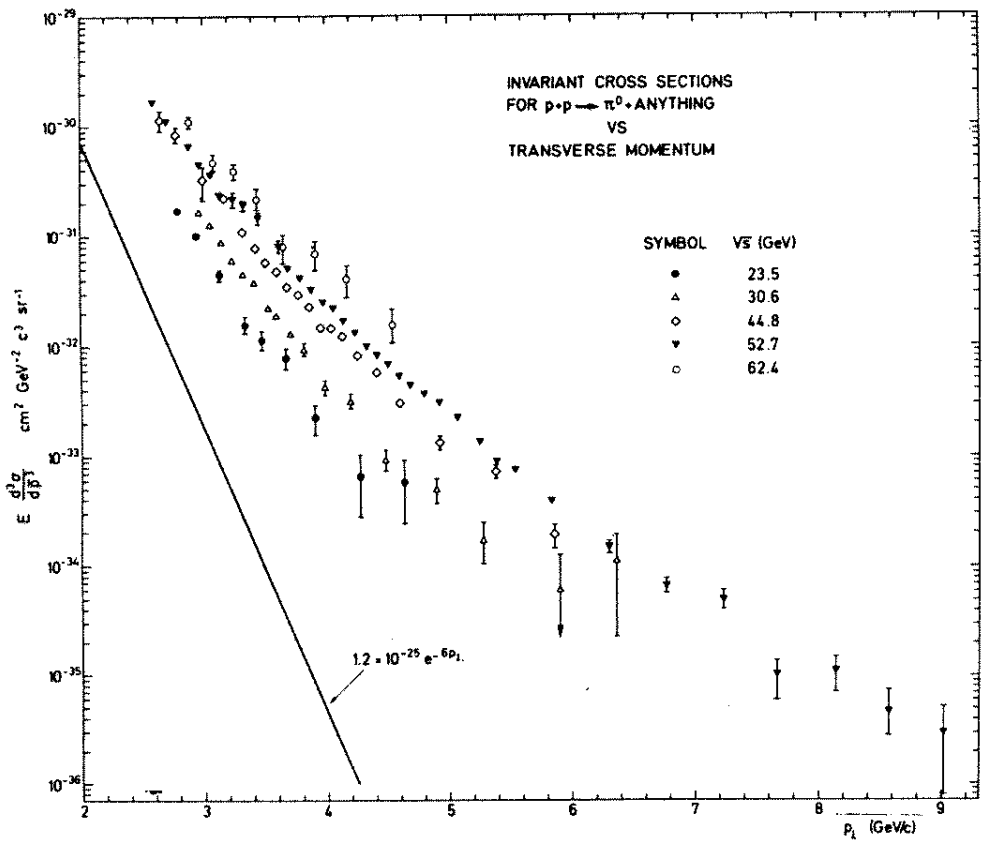
$$A+B \rightarrow C + X \qquad \text{when particle } C \text{ has } p_T >> 1 \text{ GeV/c}$$

  - 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."*





CCR at the CERN-ISR
Discovery of high p_T π^0 production in p-p



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

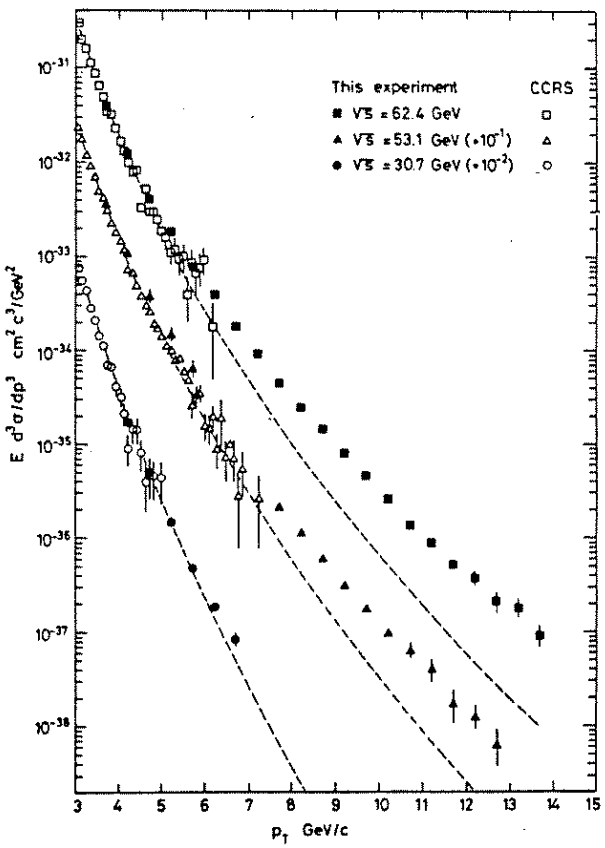
Bjorken scaling PR**179**(1969)1547 → **B**erman**B**j**K**ogut scaling PRD4(71)3388 → **B**lankenbecler, **B**rodsky, **G**union $x_T=2p_T/\sqrt{s}$ Scaling PL **42B**, 461 (1972)

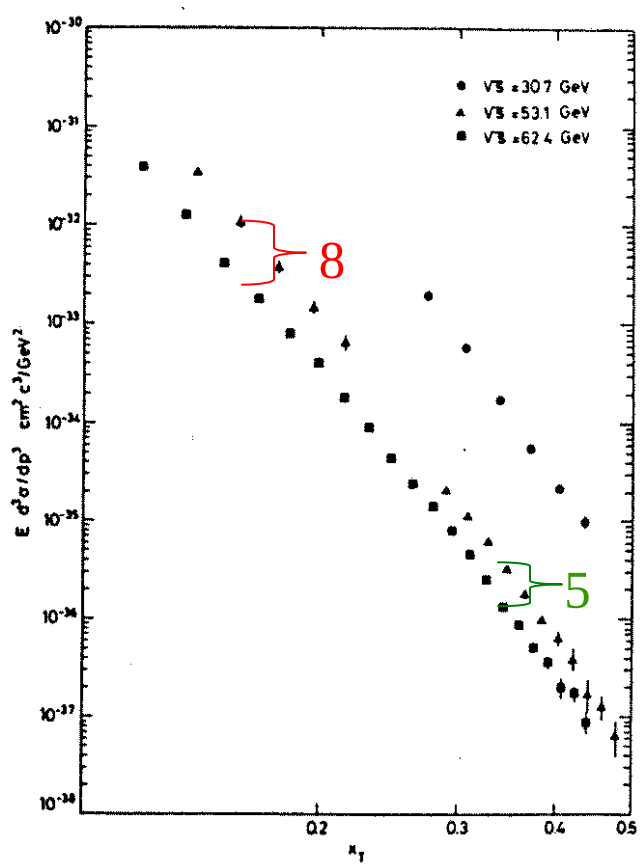
$$E\frac{d^3\sigma}{dp^3} = \frac{1}{p_T^{n_{\rm eff}}}F\left(\frac{p_T}{\sqrt{s}}\right) = \frac{1}{\sqrt{s}^{\,n_{\rm eff}}}G(x_T)$$

$n_{\rm eff}$ gives the form of the force-law between constituents: $n_{\rm eff}$=4 for QED

- e^{-6pT} breaks to a power law at high p_T with characteristic $\sqrt{s}$ dependence
- Large rate indicates that partons interact strongly (>> EM) with other.
- Data follow $x_T=2p_T/\sqrt{s}$ scaling but with $n_{\rm eff}$=8!, not $n_{\rm eff}$=4 as expected for QED

CCOR 1978--Discovery of "REALLY high p_T>7 GeV/c" at ISR





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

QCD: Cahalan, Geer, Kogut, Susskind, PR**D11**, 1199 (1975)

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{\sqrt{s}^{\,n_{\rm eff}(x_T,\sqrt{s})}}G(x_T)$$

$$\left(\frac{\sqrt{s_1}}{\sqrt{s_2}}\right)^{n_{\rm eff}(x_T,\sqrt{s})} = \frac{E\frac{d^3\sigma}{dp^3}(x_T,\sqrt{s_2})}{E\frac{d^3\sigma}{dp^3}(x_T,\sqrt{s_1})}$$

♡ $Ed^3\sigma/dp^3 \simeq p_T^{-5.1\pm0.4}(1-x_T)^{12.1\pm0.6}$

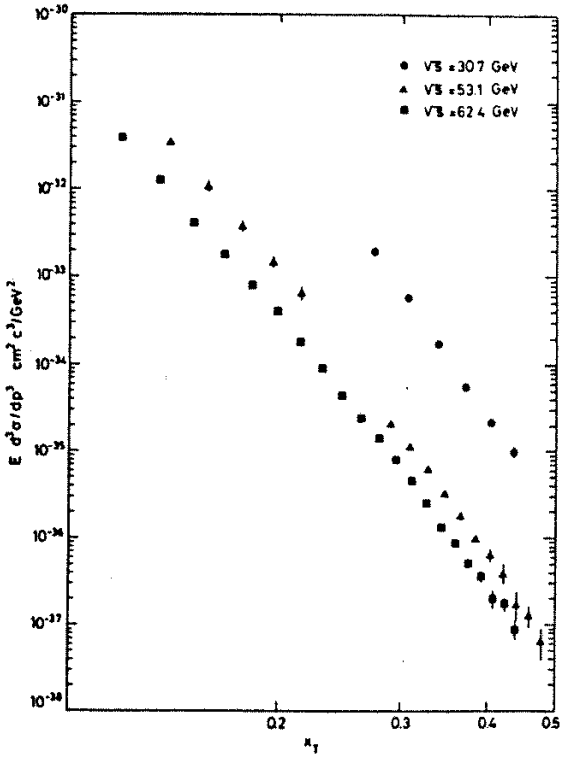
$7.5 \le p_T \le 14.0$ GeV/c,

$53.1 \le \sqrt{s} \le 62.4$ GeV

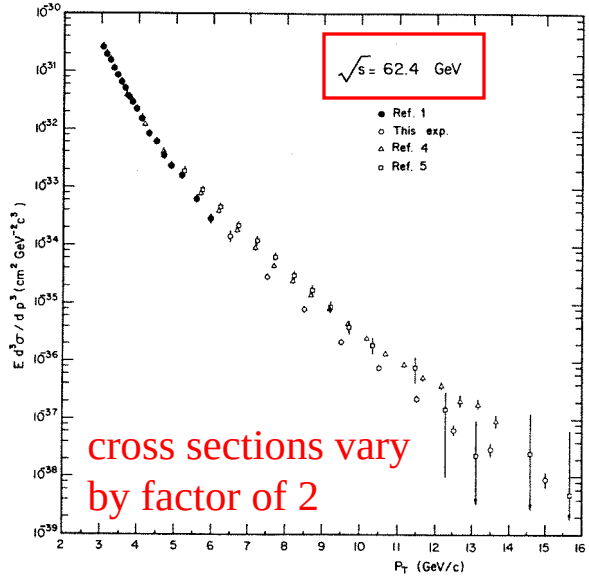
(including *all* systematic errors).

$n_{\rm eff}$=5 (=4^{++}) as predicted for QCD

1978-$n_{eff}(x_T, \sqrt{s})$ WORKS $n_{eff} \rightarrow 5 = 4^{++}$

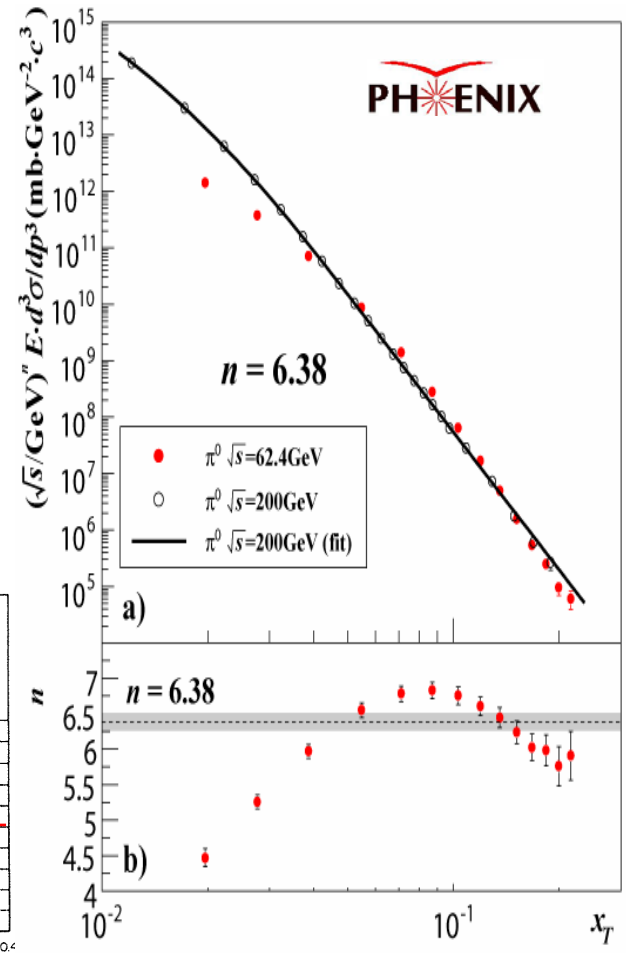


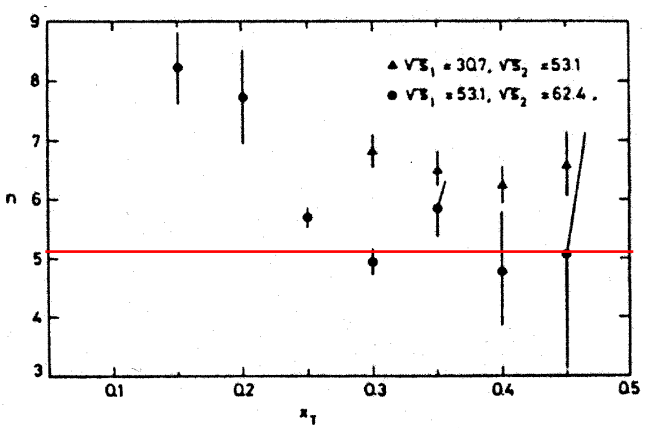
C.Kourkoumelis, et al
Phys.Lett. **84B**, 279 (1979)



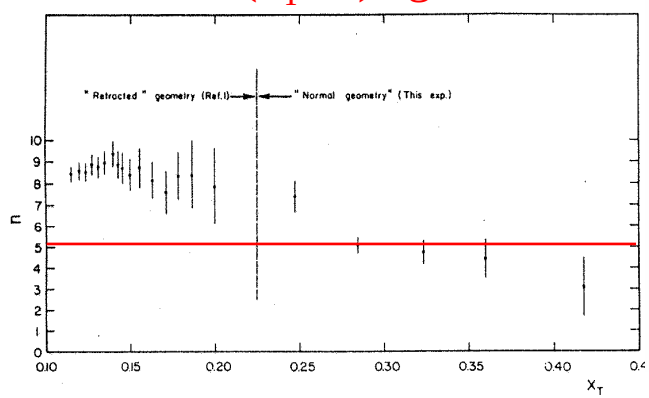
cross sections vary
by factor of 2

A.Adare, et al, PHENIX
PRD**79** (2009) 012003

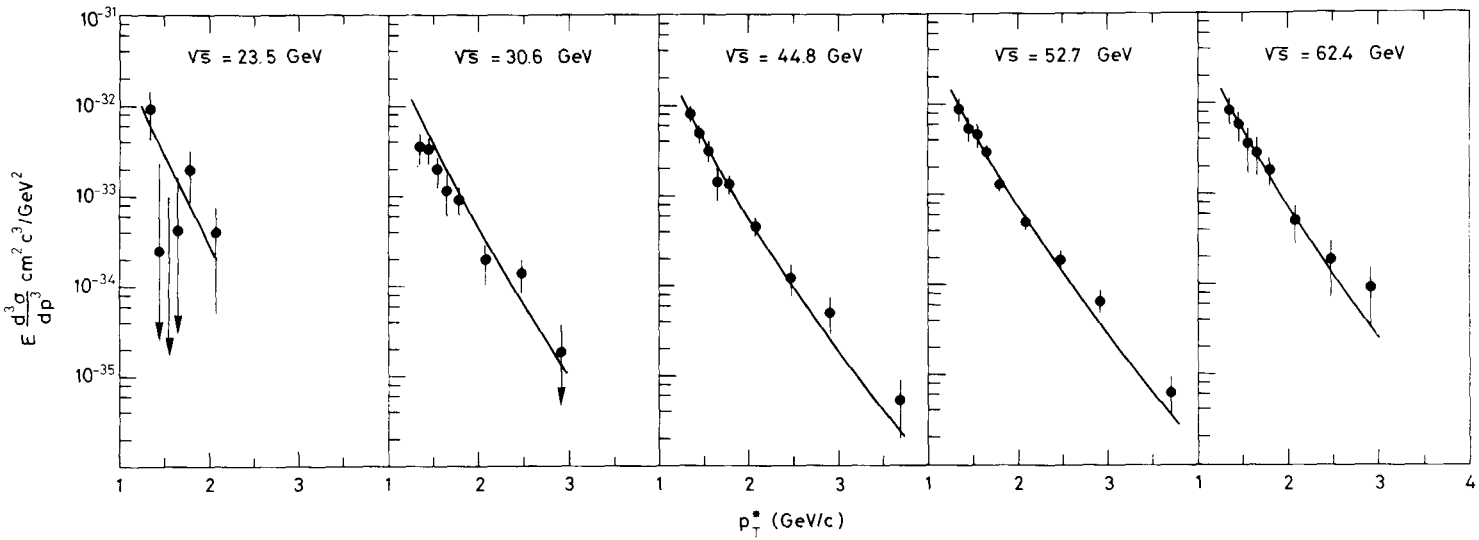




But $n(x_T, \sqrt{s})$ agrees



CCRS-1974 Discovery of direct $e^{\pm}\sim10^{-4}\pi^{\pm}$ at ISR not due to internal conversion of direct photons



CCRS PLB**53**(1974)212; NPB**113**(1976)189

Data points $(e^{+}+e^{-})/2$ lines 10^{-4} $(\pi^{+}+\pi^{-})/2$

- Farrar and Frautschi PRL**36**(1976)1017 proposed that direct leptons are due to internal conversion of direct photons with $\gamma/\pi\sim10$-20% to $e^{+}e^{-}$ ($d\sigma/dm\sim1/m$) for $p_T>1.3$ GeV/c. CCRS looks, finds very few events, sets limits excluding this.

95% confidence level upper limits for a particle of mass m, or a mass continuum, which decays to $e^{+}e^{-}$ with branching ratio B, at $\sqrt{s}$ = 52.7 GeV/c

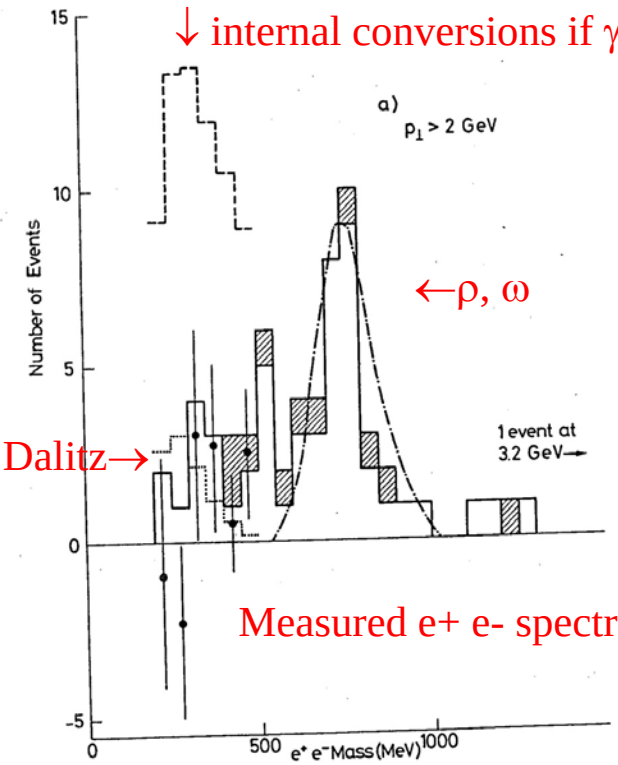
Mass (GeV/c^2)	$B\frac{d\sigma}{dy}(p_T^* > 1.3$ GeV/$c)$ (cm^2)	Fraction of single electron signal
0.400	5.54×10^{-33}	0.064
0.500	8.37×10^{-33}	0.104
0.600	1.64×10^{-32}	0.178

p.s. these direct $e^{\pm}$ are due to semi-leptonic decay of charm particles not discovered until 1976, 2 year later: Hinchliffe and Llewellyn-Smith NPB**114**(1976)45

A later look at direct-γ via internal conversion provides most stringent limit

- L.~Yuan, E.~Amaldi Rome, BNL, CERN PLB **77** (1978) 240 set a limit on real photons using PbGl: $\gamma/\pi^0=0.021\pm0.012$ $3.5<p_T<5.0$ GeV/c
- This corrected a **notoriously wrong** result of $\gamma/\pi^0=0.20\pm0.06\pm0.07$ for $2.8<p_T<3.8$ GeV/c also using PbGl P.Darriulat *et al*, NPB**110** (1976) 365
- The most stringent limit came from (non observation) of low mass e+e- pairs from internal conversion **BNL** CERN SyracuseYale, J. Cobb *et al*, PLB**78** (1978) 519 $\gamma/\pi^0=0.006\pm0.009$ $2<p_T<3$ GeV/c

↓ internal conversions if $\gamma/\pi^0=0.10$



←ρ, ω

e+ e- from π^0 η Dalitz→

Measured e+ e- spectrum

J/Psi and direct $e^{\pm}$

First

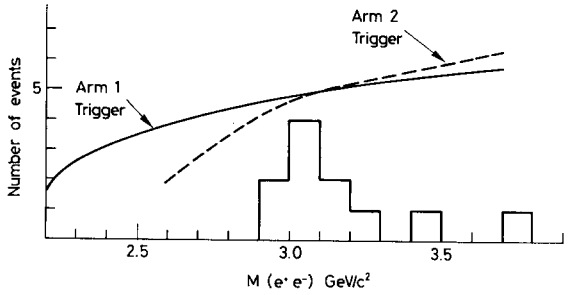


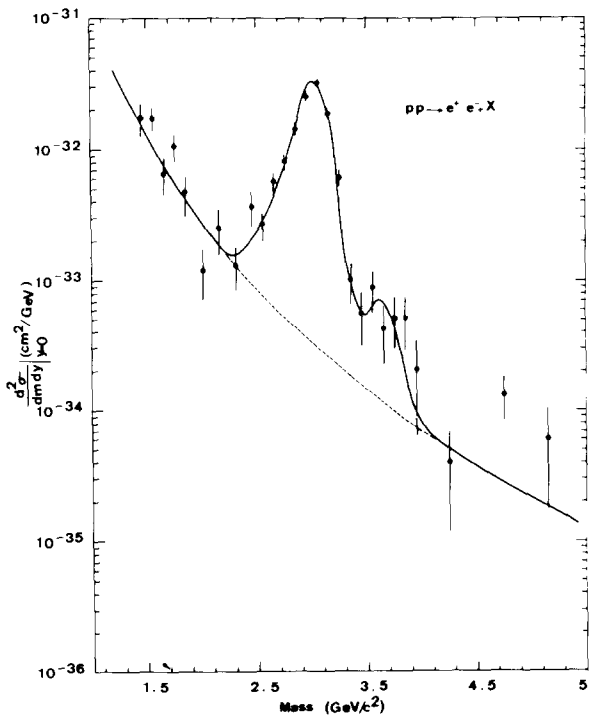
FIG. 2

Fig. 2. Invariant mass distribution for the observed e^+e^- pairs. The curves represent the shapes of the acceptance, as a function of the e^+e^- invariant mass value, for the Arm 1 and Arm 2 triggers, respectively.

CCRS PLB**56**(1975)482
2nd J/Ψ in Europe

Best

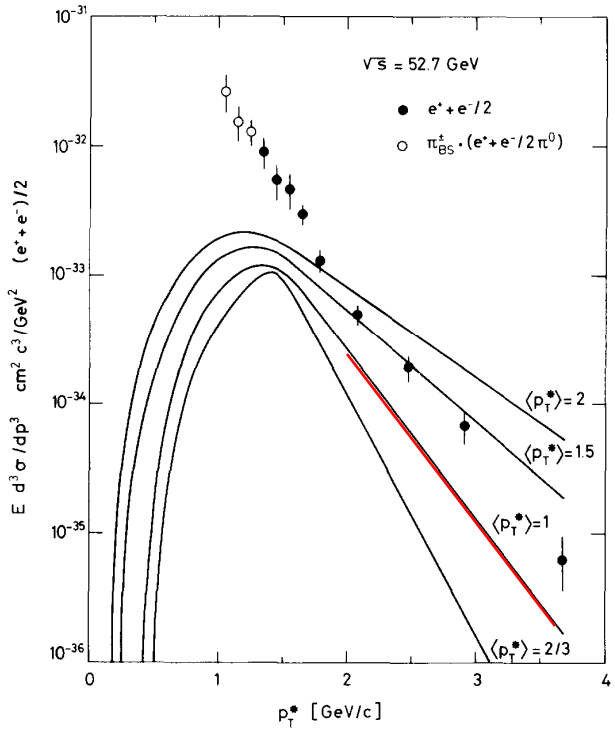
A.G. Clark et al. / Electron pair production at the ISR



CSZ NPB**142**(1978)29
$\langle p_T \rangle$=1.10±0.05 GeV/c

Not cause of direct $e^{\pm}$

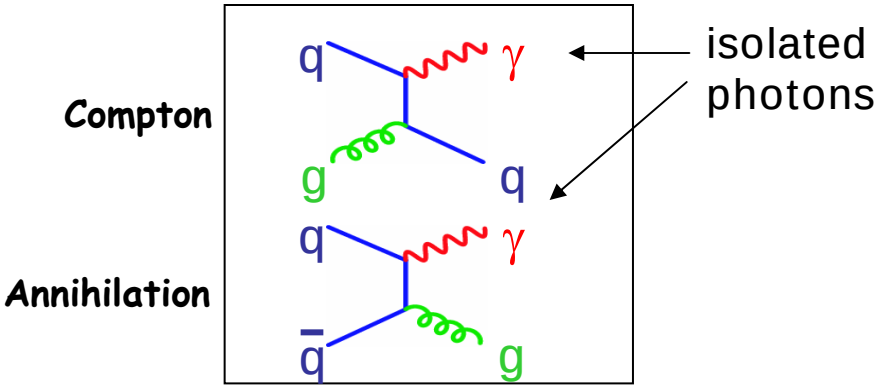
F.W. Büsser et al. / Electrons at the ISR

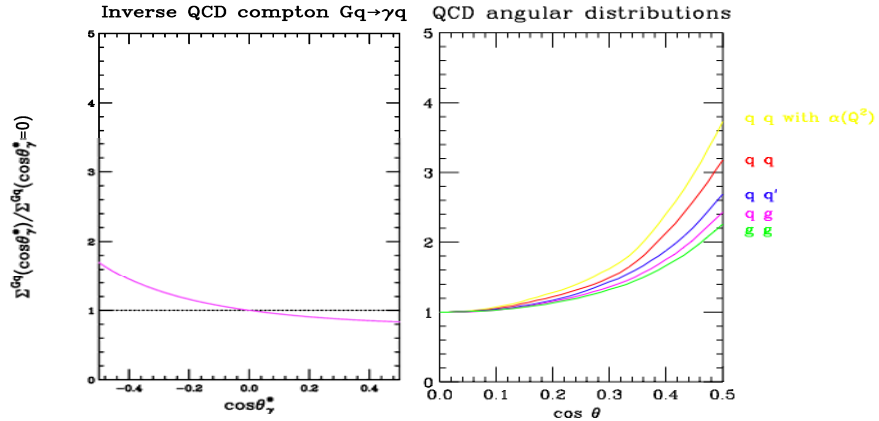


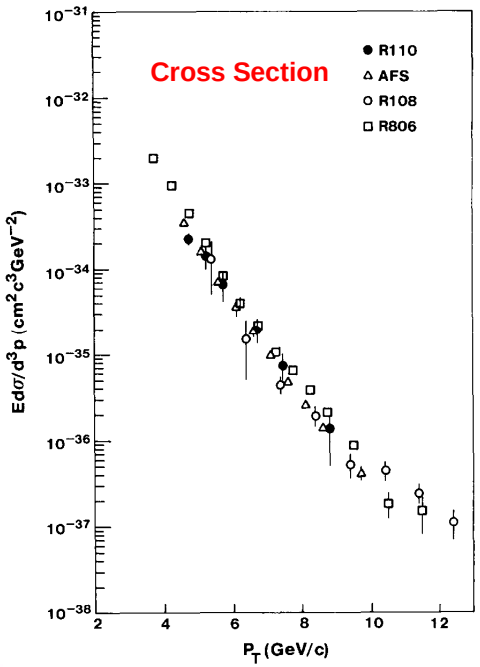
CCRS NPB**113**(1976)189
direct $e^{\pm}$ not due to J/Ψ

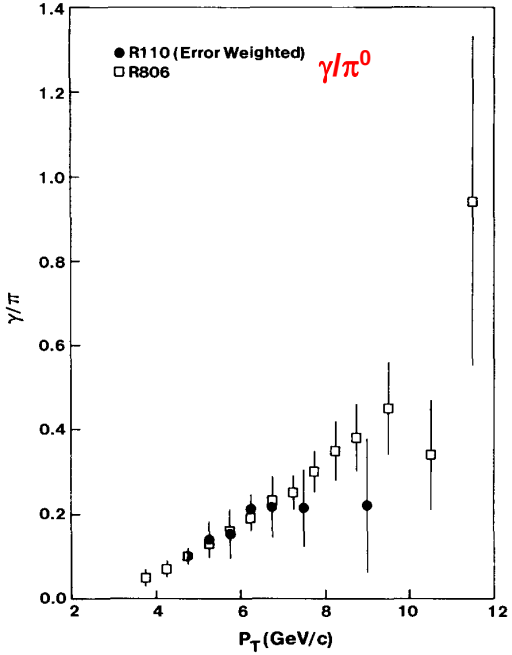
ISR direct photon production + correlations

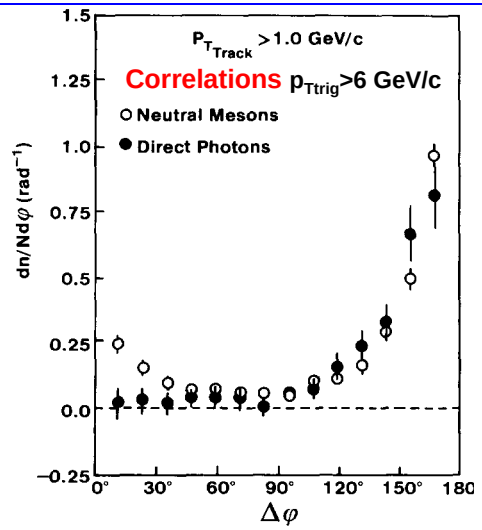
QCD Fritzsch and Minkowski, PLB **69** (1977) 316-320--ISR discovery R806-A^2**B**C-PLB **87**(1979)292.











No evidence for bremss. contribution to direct γ--same side correlation is zero--see CMOR NPB**327**, 541 (1989) for full list of references.

Status of ISR single particle measurements 1978

♡ 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.

k_T is what made $n=4^{++} \rightarrow n=8$

Status of QCD Theory in 1978

- The first modern QCD calculation and prediction for high p_T single particle inclusive cross sections including non-scaling and initial state radiation was done in 1978 by J. F. Owens, E. Reya, M.Gluck, PRD **18**, 1501 (1978), "*Detailed quantum-chromodynamic predictions for high-p_T processes*," and J.F. Owens, J. D. Kimel, PRD **18**, 3313 (1978), "*Parton-transverse-momentum effects and the quantum-chromodynamic description of high-p_T processes*".

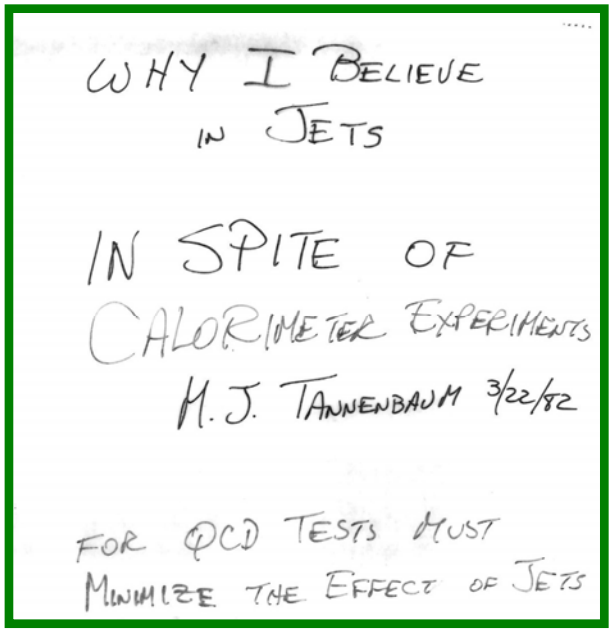
- This work was closely followed and corroborated by Feynman, Field, Fox PRD **18**, 3320 (1978), "*Quantum-chromodynamic approach for the large-transverse-momentum production of particles and jets*."

- Unfortunately jets in 4π Calorimeters at ISR energies or lower are invisible below $\sqrt{\hat{s}} \approx E_T \leq 25$ GeV, which led to considerable confusion in the period 1980-1982.

QCD and Jets
are now a cornerstone of the standard model

- Incredibly at the famous Snowmass conference in July 1982, many if not most people were skeptical

e.g. MJT Seminar 3/22/82


WHY I BELIEVE
IN JETS

IN SPITE OF
CALORIMETER EXPERIMENTS
M.J. TANNENBAUM 3/22/82

FOR QCD TESTS MUST
MINIMIZE THE EFFECT OF JETS

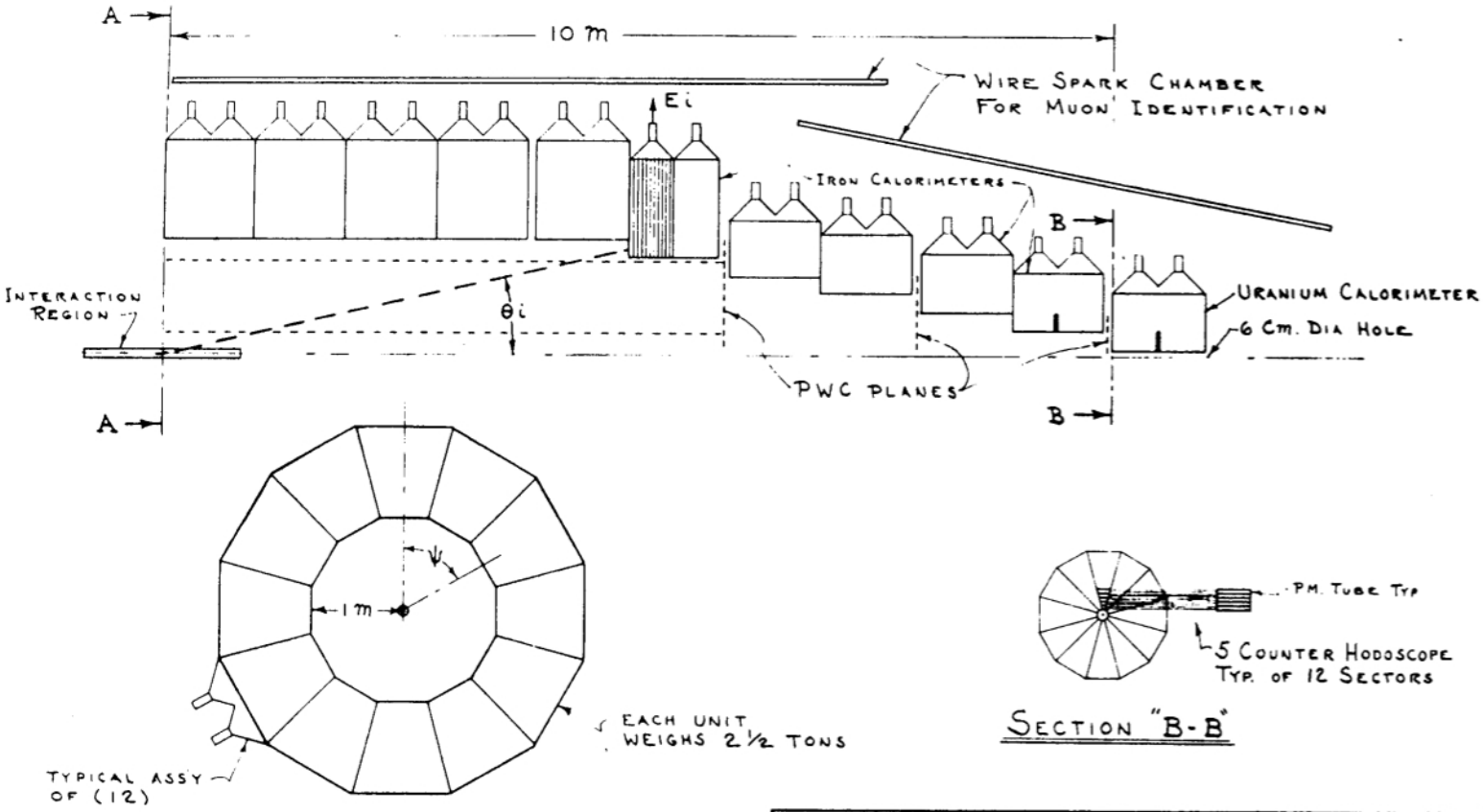
- The International HEP conference in Paris, three weeks later, July 26--31, 1982 changed everything.

Why nobody (in the U.S.) believed in jets

- In 1972-73, soon after hard-scattering was discovered in p-p collisions, Bjorken PRD**8** (1973) 4098 and Willis (ISABELLE Physics Prospects-BNL-17522) proposed 4π hadron calorimeters to search for jets from fragmentation of scattered partons with large p_T realizing that a substantial increase in rate would be expected in measuring the entire jet at a given p_T rather than just the leading fragment. (Bjorken's parent-child effect)
- It took until 1980 to get a full azimuth $\Delta\eta\sim\pm0.88$ ($\Delta\Theta\sim\pm45^o$) calorimeter but meanwhile experiments were done with smaller back-to-back calorimeters each with aperture $\Delta\Phi\sim\pm45^o$ $\Delta\eta\sim\pm0.55$ and many new trigger biases were discovered, for instance, jets wider than the calorimeter aperture would deposit less energy than narrow jets of the same p_T and be suppressed by the steeply falling spectrum$\Rightarrow$jet structure is dominated by the calorimeter geometry [e.g. see M. Dris NIM **158** (1979) 89]

Willis 'impactometer' from Isabelle Study 1972

4π hadron calorimeter non-magnetic detector. Sound familiar?

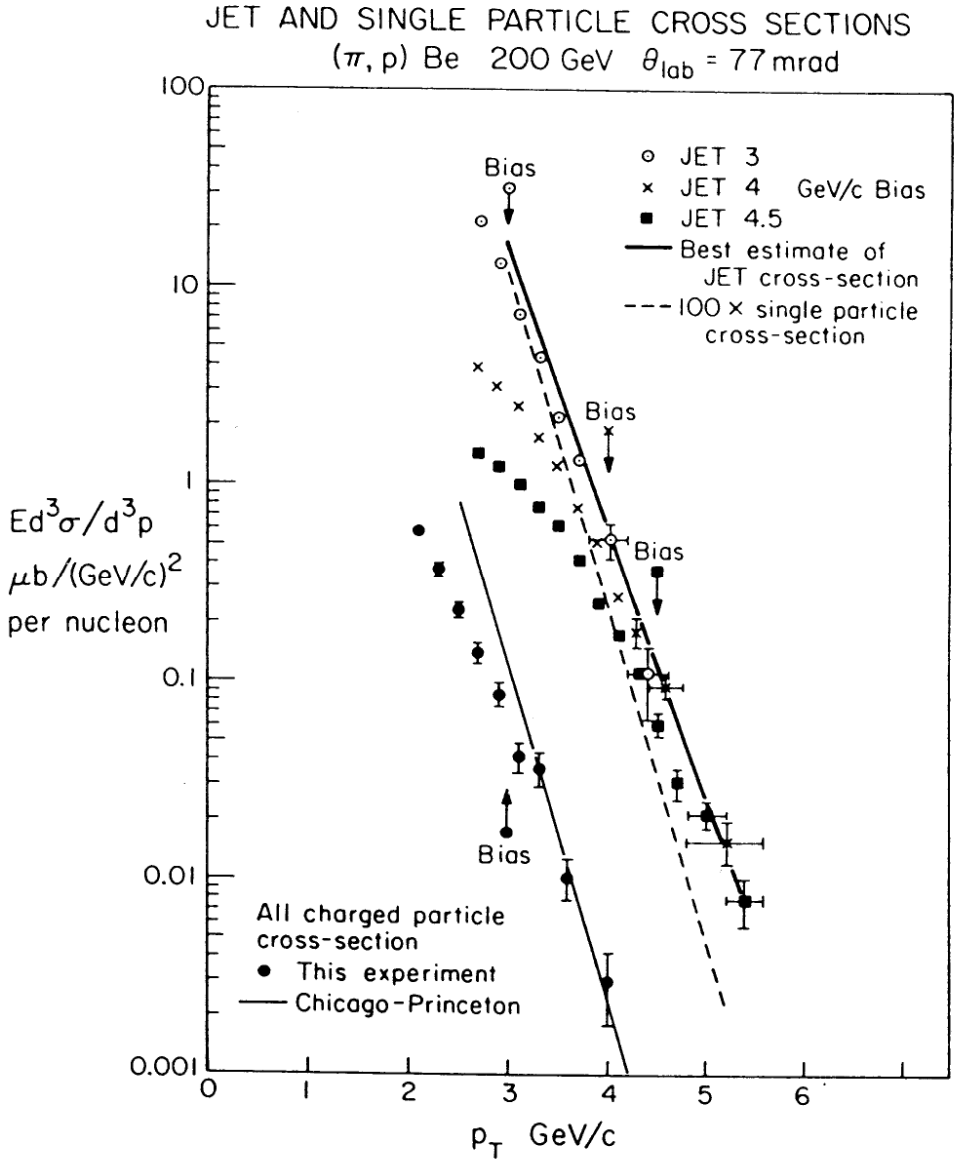


Impactometer

For 200 GeV Protons on P or E

Measures $\pi\psi = \sum_i E_i \sin\theta_i$ $\leftarrow E_T$

(In)famous FNAL E260 found "Jets" (1977)



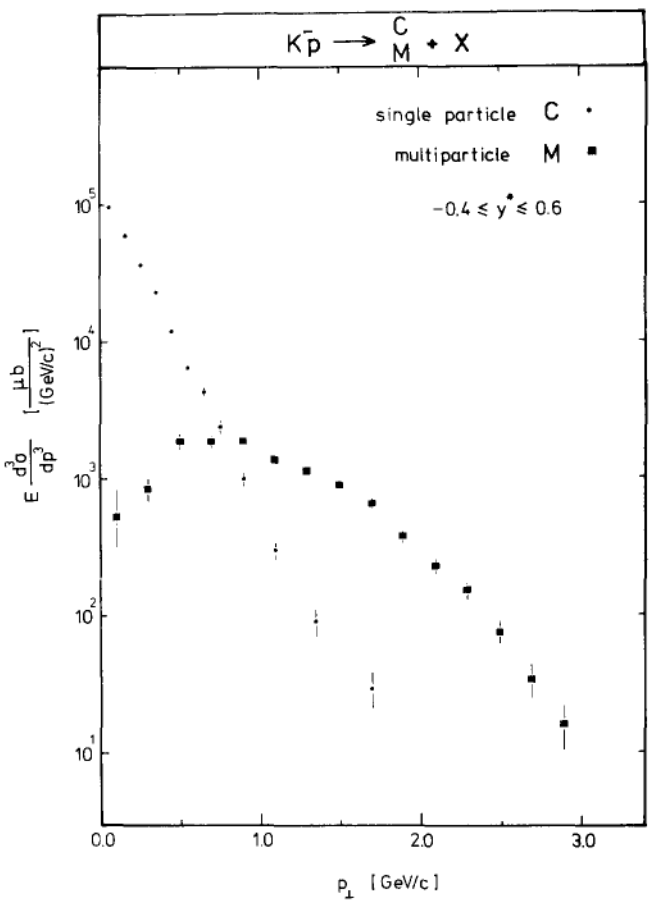
- In each of 2 back to back calorimeters with $\Delta\Phi \sim \pm 45^o$ $\Delta\eta \sim \pm 0.36$ (same as PHENIX) the invariant cross section of several particles with a vector sum p_T is much larger than a single particle of the same p_T. The authors took this as evidence for the exactly back-to-back in azimuth jets of constituent scattering⇒Never let an interested theorist collaborate on an experiment.

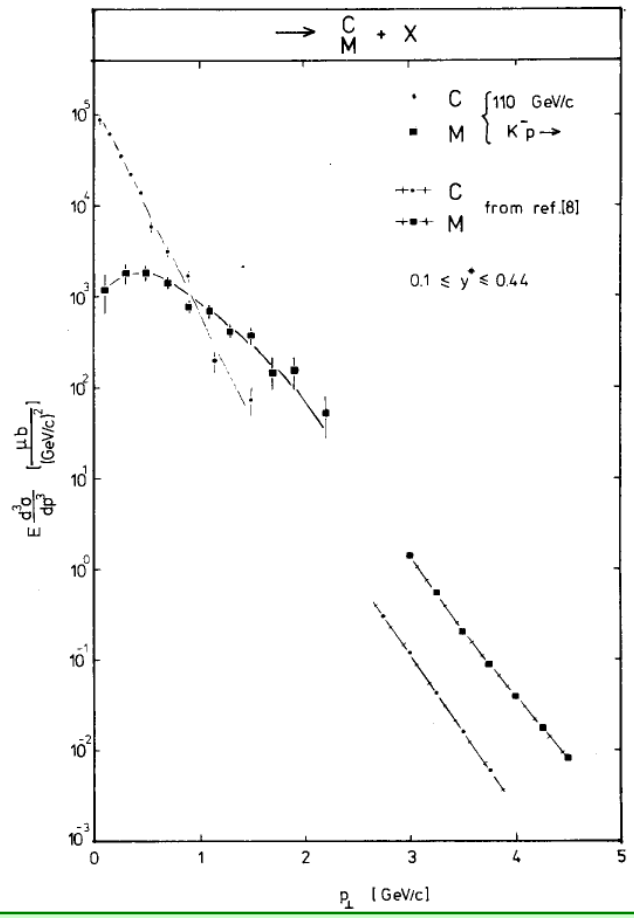
C.Bromberg et al E260, PRL 38 (1977)1447, NPB134 (1978) 189

But, experiments with different apertures got different results

- The first 4π experiment was a bubble chamber(!) 110 GeV/c K^- on p

[M. Deutschmann, et al, ABCCLVW collab, NPB**155** (1979)307]



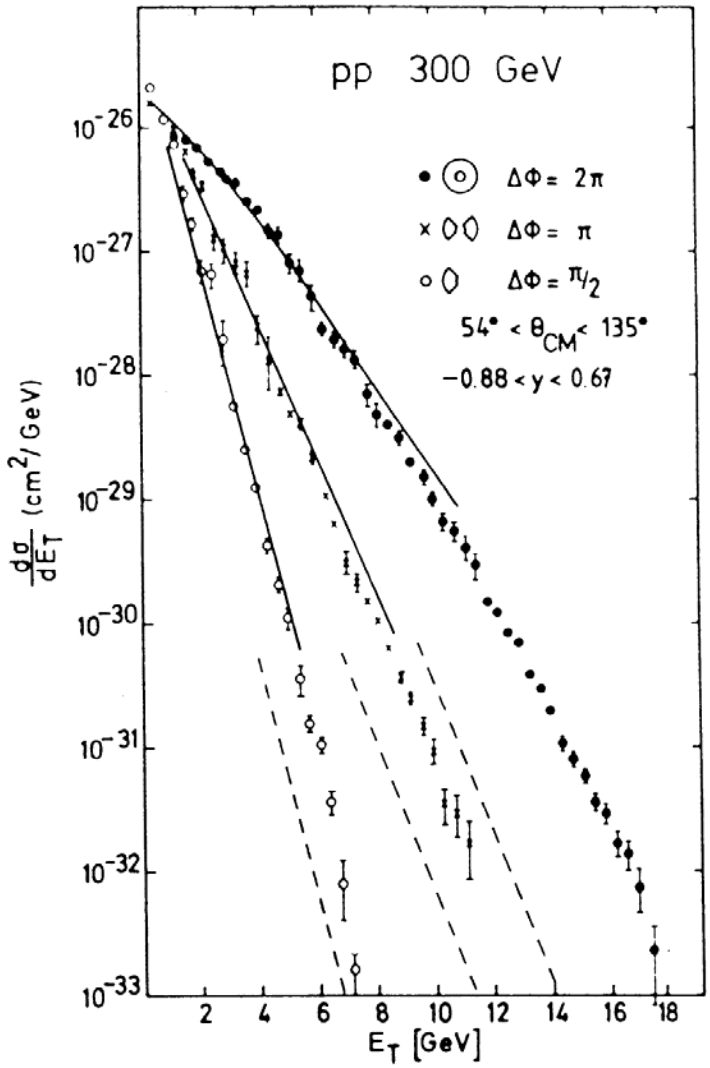


- multiparticle cross section for p_T> 1.5 GeV/c >> single particle
- Data extrapolate nicely to those of E260 [8] in slope and magnitude.
- But ``principal axis" analysis of the data shows "the vast majority of events with large p_T multiparticle systems DO NOT exhibit jet-like structure."

For more (confusion): see MJT AIP Conf Proc **59**, 263-309 on scitation.aip.org

NA5-the coup-de-grâce to jets (1980)

- Full azimuth calorimeter -0.88<η*<0.67 (→ NA35, NA49)



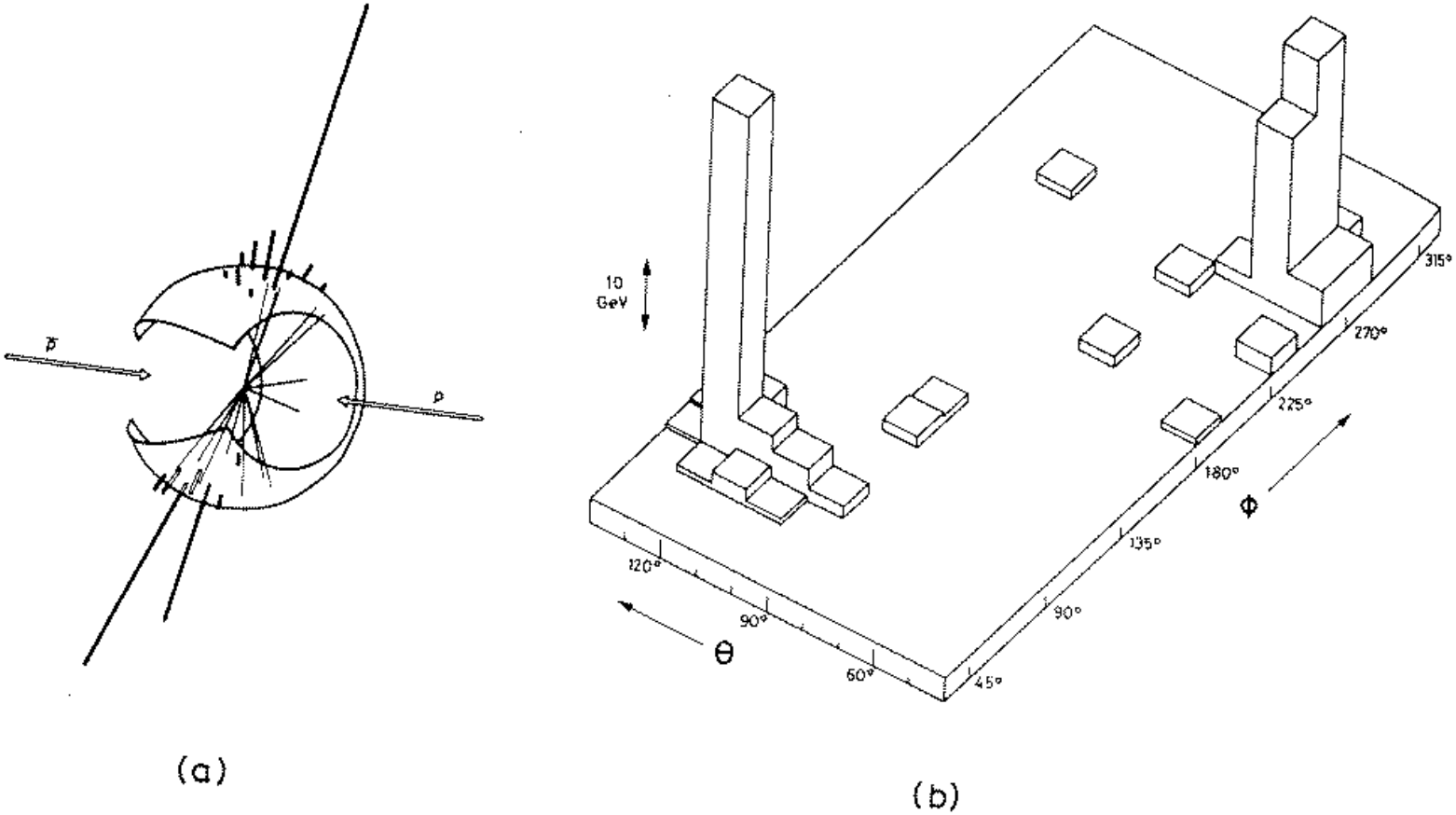
- plus triggered in two smaller apertures corresponding to E260.
- No jets in full azimuth data
- All data way above QCD predictions-------
- The large E_T observed is the result of "a large number of particles with a rather small transverse momentum"--the first E_T measurement in the present terminology.

K. Pretzl, Proc 20th ICHEP (1980)
C. DeMarzo et al NA5, PLB**112**(1982)173

For more on E_T see MJT IJMPA **4** (1989)3377

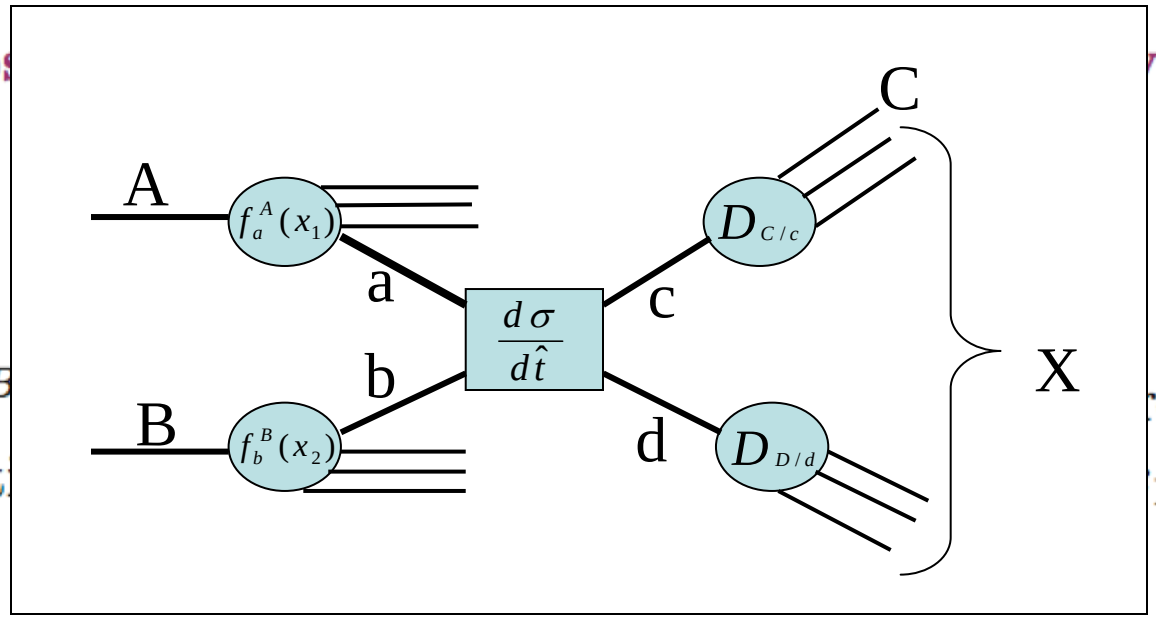
Back to-THE UA2 Jet-Paris 1982

From 1980--1982 most high energy physicists doubted jets existed because of the famous NA5 E_T spectrum which showed NO JETS. This one event from UA2 in 1982 changed everybody's opinion.



LO-QCD in 1 slide

Cros … $\sqrt{s}$



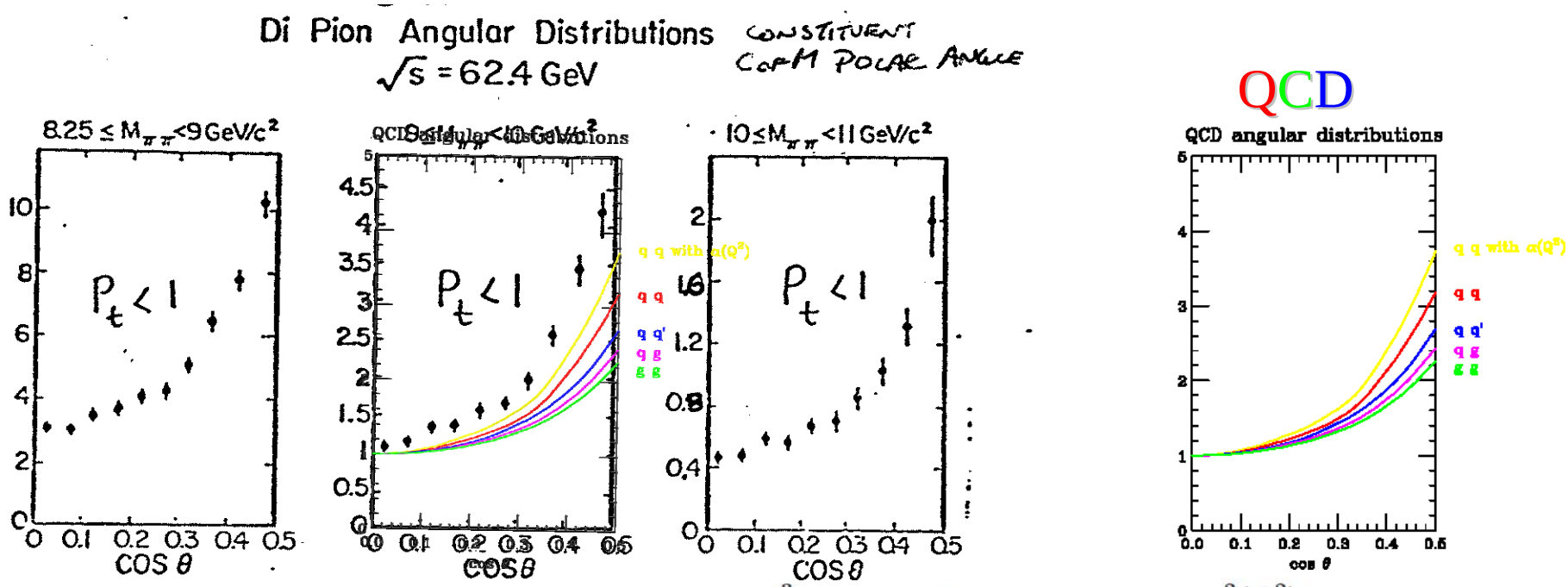
$f_a^A(x_1)$, f_b^B … robabilities for const … $_1$ and x_2

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

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

Also Paris1982-first measurement of QCD subprocess angular distribution using π^0-π^0 correlations

DATA: CCOR NPB 209, 284 (1982)

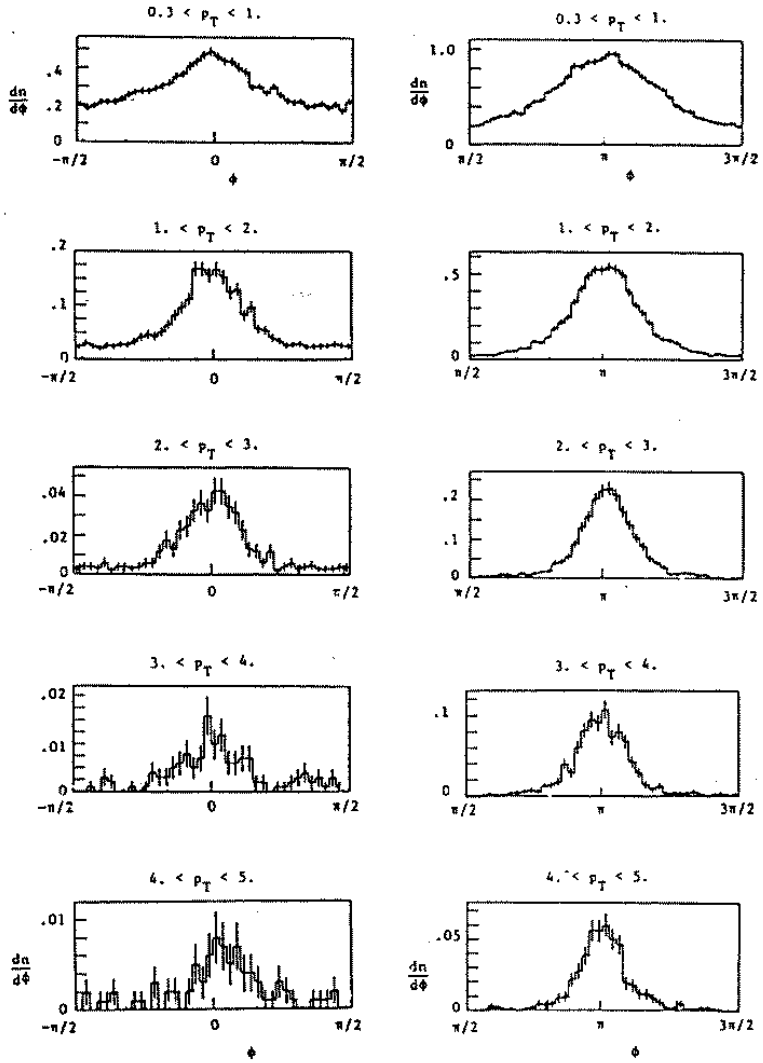


$$\frac{d^3\sigma}{dx_1 dx_2 d\cos\theta^*} = \frac{1}{s}\sum_{ab} f_a^A(x_1) f_b^B(x_2) \frac{\pi\alpha_s^2(Q^2)}{2x_1x_2}\Sigma^{ab}(\cos\theta^*)$$

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

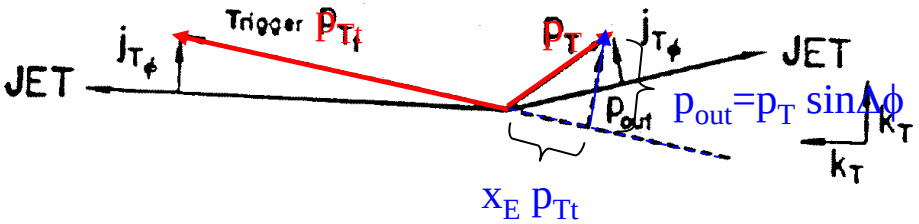
At the CERN ISR from 1975-1982 two-particle correlations showed unambiguously that high p_T particles come from jets

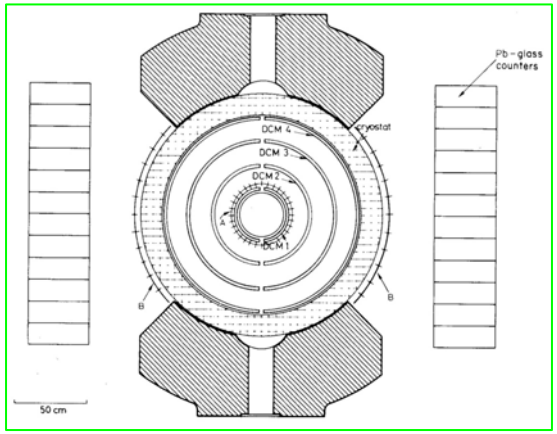
How everything you want to know about JETS was measured with 2-particle correlations



CCOR, A.L.S.Angelis, et al
Phys.Lett. **97B**, 163 (1980)
PhysicaScripta **19**, 116 (1979)

p_{Tt} > 7 GeV/c vs p_T





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.

Feynman Field & Fox to the rescue

♡ 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.

k_T and NLO are distinct---e.g. Drell Yan

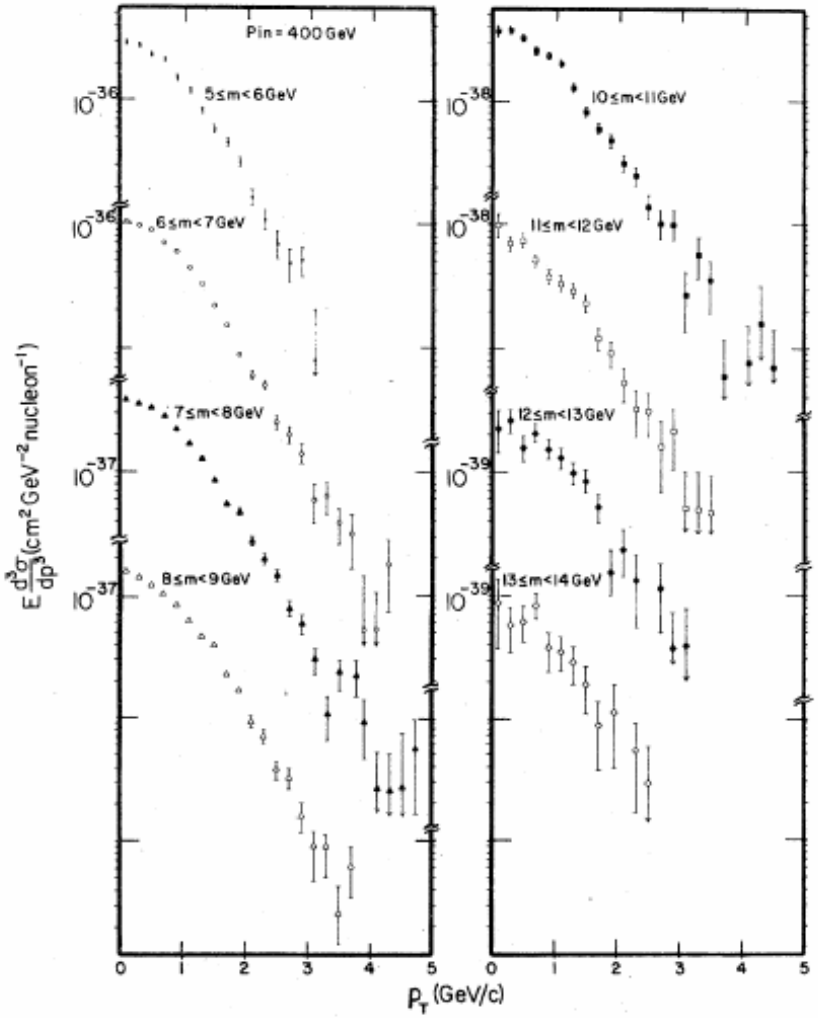
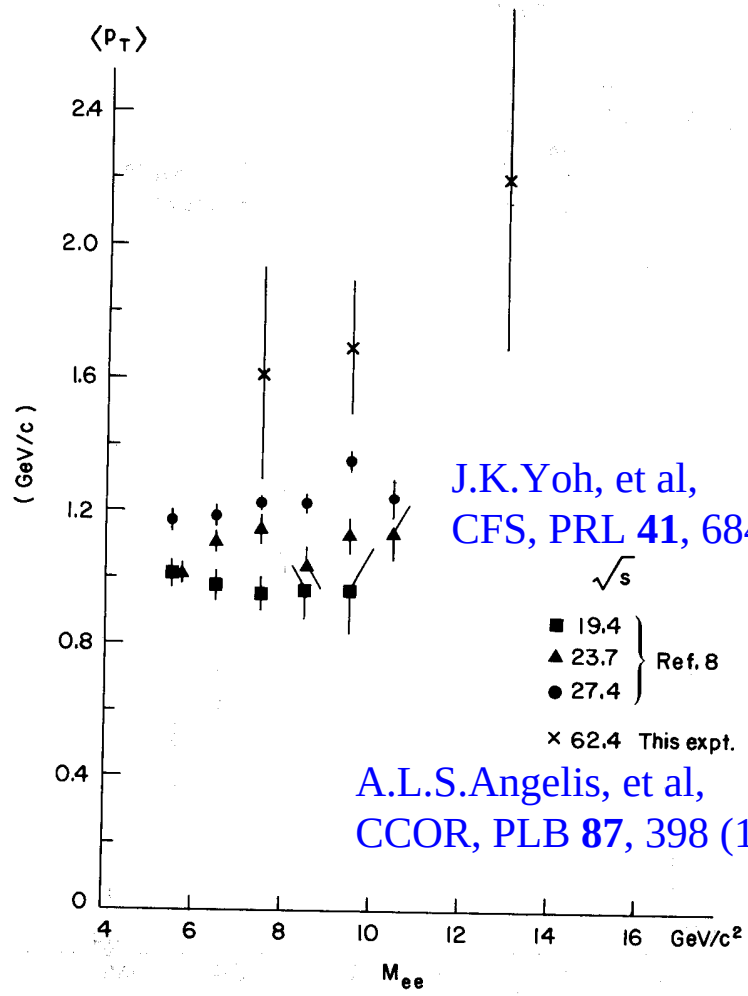


FIG. 12. Invariant yield of dimuons as a function of the transverse momentum p_T of the muon pair for 400 GeV incident protons.

A.S.Ito, et al, PRD23,604 (1981)



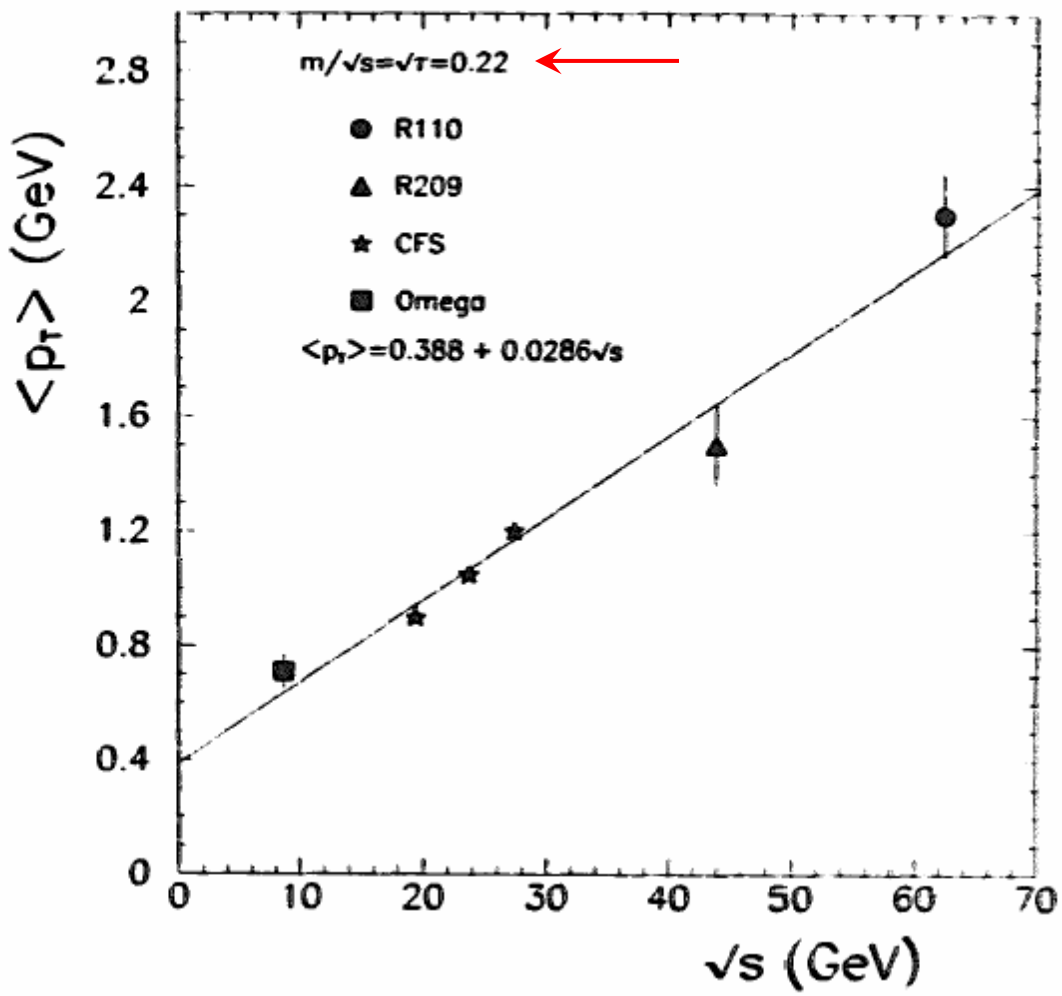
J.K.Yoh, et al,
CFS, PRL **41**, 684 (1978)

A.L.S.Angelis, et al,
CCOR, PLB **87**, 398 (1979)

Note Gaussian shape, no power-law tail!

$\langle p_T \rangle (=\sqrt{2}k_T)$ vs $\sqrt{s}$ in Drell-Yan

A.L.S. Angelis et al. / Massive electron pairs CMOR, NPB348, 1 (1991)



Feynman, Field and Fox said that x_E distribution from single particle or Jet measures D(z)

38 *R.P Feynman et al. / Large transverse momenta*

FFF Nucl.Phys. **B128**(1977) 1-65

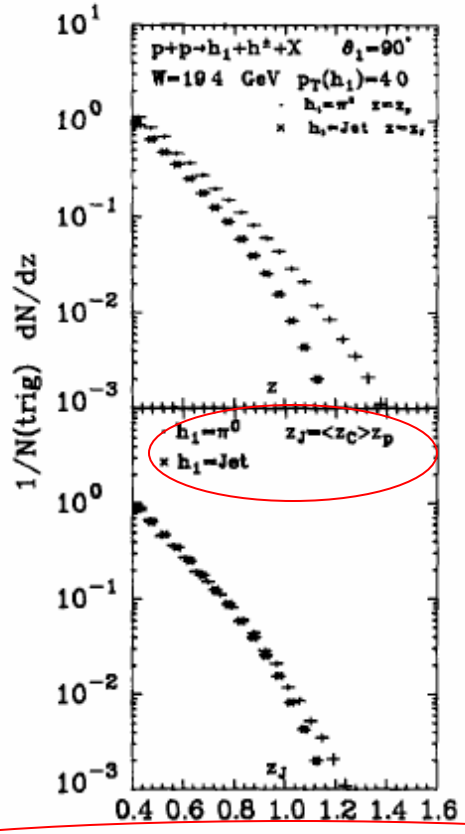


Fig. 23. Comparison of the π^0 and jet trigger away-side distribution of charged hadrons in pp collisions at $W = 19.4$ GeV, $\theta_1 = 90°$, and $p_\perp$ (trigger) = 4.0 GeV/c from the quark-quark scattering model. The upper figure shows the single-particle (π^0) trigger results plotted *versus* $z_p = -p_x(h^\pm)/p_\perp(\pi^0)$ and the jet trigger plotted *versus* $z_J = -p_x(h^\pm)/p_\perp(\text{jet})$ (see table 1). In the lower figure, we plot *both versus* z_J, where for the jet trigger $z_J = z_J$ but for the single-particle trigger $z_J = \langle z_c \rangle z_p$. The away hadrons are integrated over all rapidity Y and $|180° - \phi| \leq 45°$ and the theory is calculated using $\langle k_\perp \rangle_{h\to q} = 500$ MeV. • $h_1 = \pi^0$, × h_1 = jet.

"There is a simple relationship between experiments done with single-particle triggers and those performed with jet triggers. The only difference in the opposite side correlation is due to the fact that the 'quark', from which a single-particle trigger came, always has a higher $p_\perp$ than the trigger (by factor $1/z_{trig}$). The away-side correlations for a single-particle trigger at $p_\perp$ should be roughly the same as the away side correlations for a jet trigger at $p_\perp$ (jet)= $p_\perp$ (single particle)/ $<z_{trig}>$".

As measured at the ISR by Darriulat, etc.

P. Darriulat, et al, Nucl.Phys. **B107** (1976) 429-456

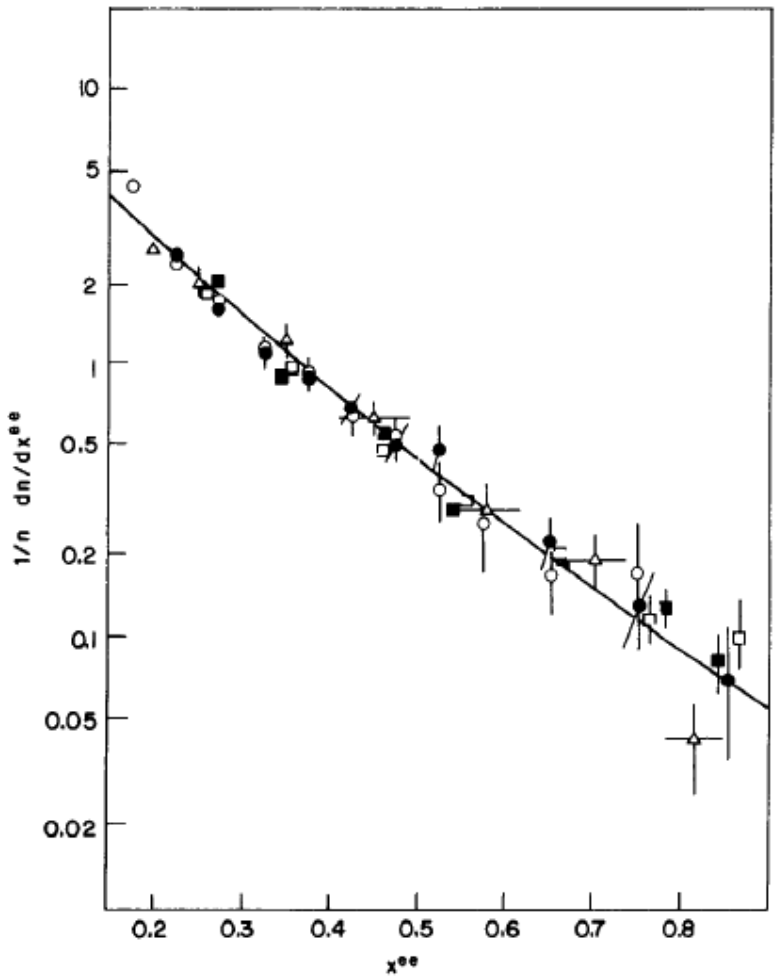


Figure 21 Jet fragmentation functions measured in different processes: ν-p interactions (*open triangles*, Van der Welde 1979); e^+e^- annihilations (*solid line*, Hanson et al 1975); and pp collisions (*full circles* CS, $p_T < 6$ GeV/c, *open circles* CS, $p_T > 6$ GeV/c, *full squares* CCOR, $p_T > 5$ GeV/c, *open squares* CCOR, $p_T > 7$ GeV/c).

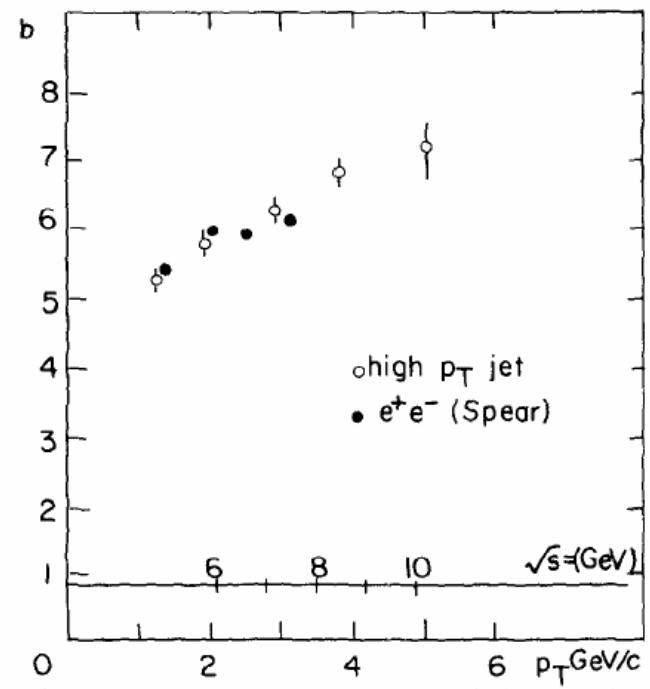
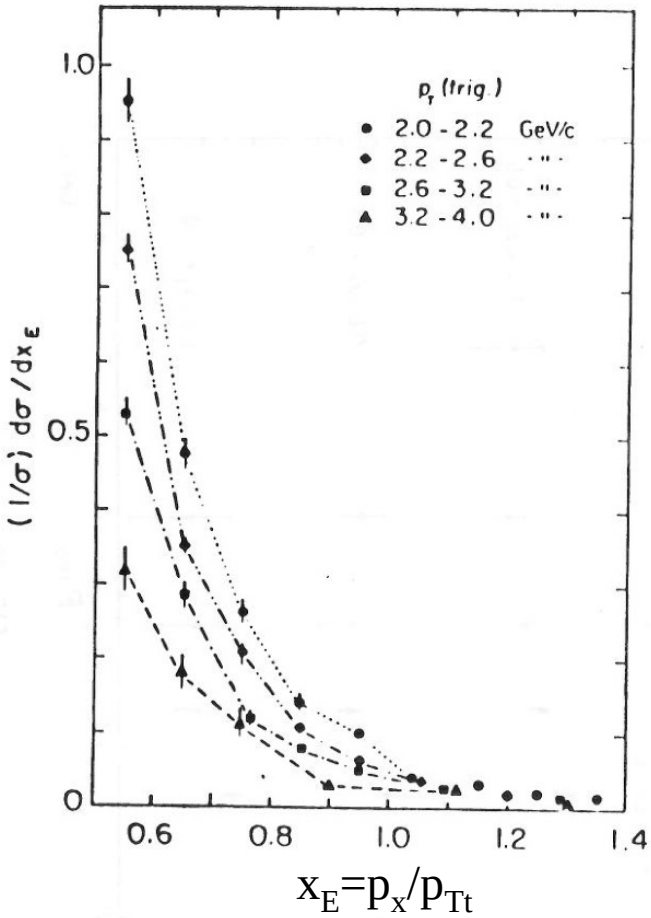


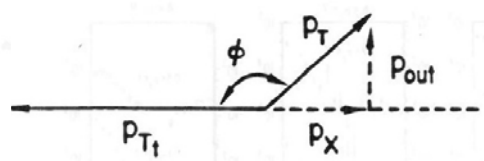
Figure 19 The slopes b obtained from exponential fits to the jet fragmentation function in the interval $0.2 < z < 0.8$ in e^+e^- annihilation (*full circles*) and LPTH data of the BS Collaboration (*open circles*).

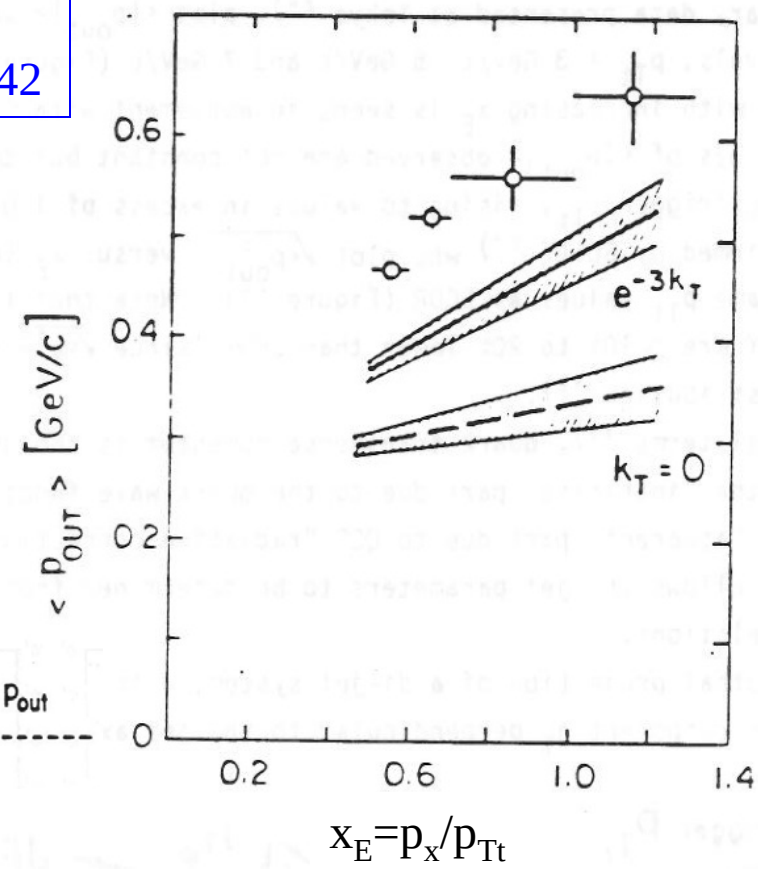
Figures from P. Darriulat, ARNPS **30** (1980) 159-210 showing that Jet fragmentation functions in νp, e^+e^- and pp (CCOR) are the same with the same dependence of *b* (exponential slope) on "$\hat{s}$"

Bit first, CCHK discovered k_T by lack of x_E scaling



CCHK
NP**B127**(1977) 1-42

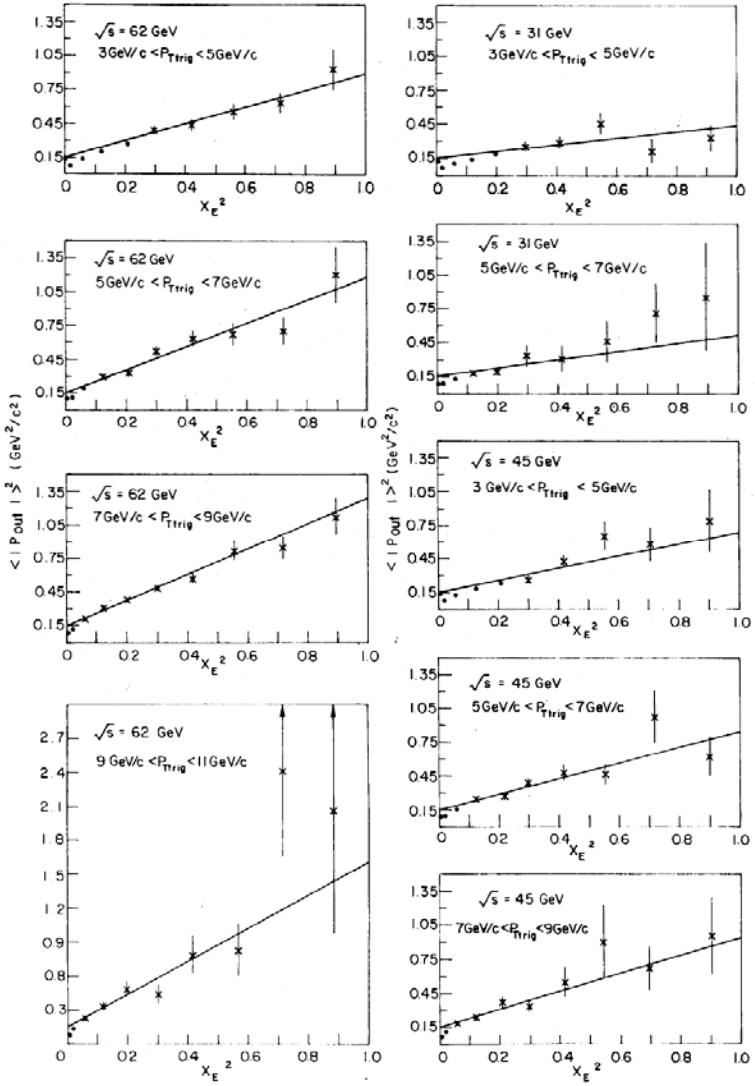


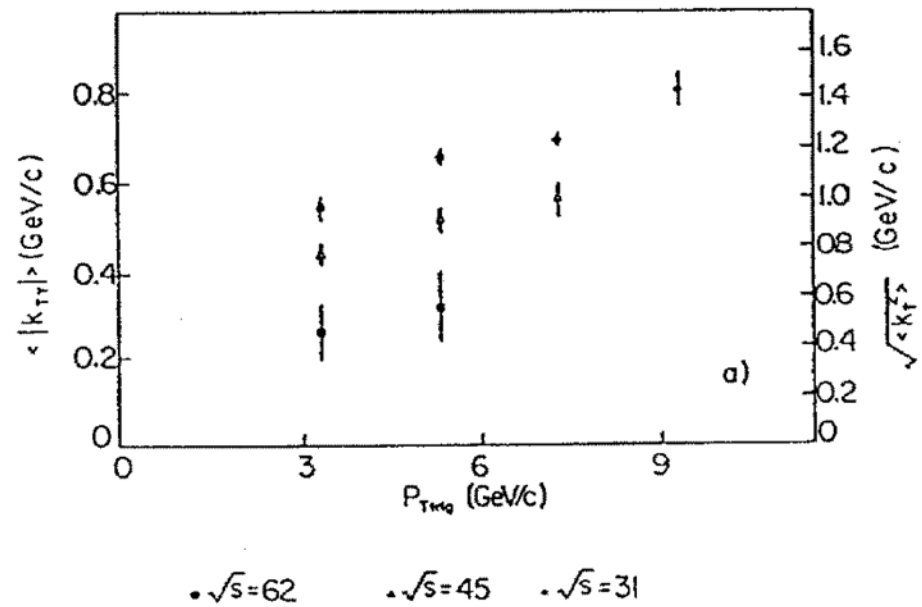


Cern-College de France, Heidelberg, Karlsruhe (CCHK) collab. found that x_E distributions were not universal for $2<p_{Tt}<4$ GeV/c and attributed this to the large out of plane momentum p_{out} which was not constant with x_E as in fragmentation but increased with increasing x_E as if the di-jets were not collinear due to initial state k_T

CCOR $<|p_{out}|>^2$ vs x^2_E --k_T not constant

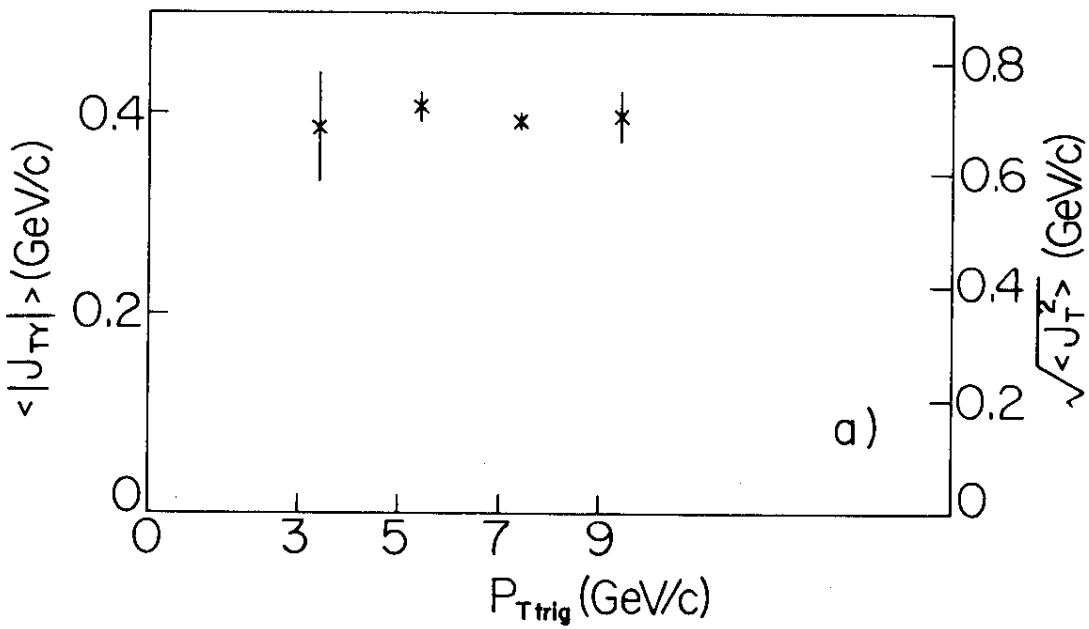
$$\langle |p_{out}| \rangle^2 = x_E^2[2\langle |k_{Ty}| \rangle^2 + \langle |j_{Ty}| \rangle^2] + \langle |j_{Ty}| \rangle^2$$





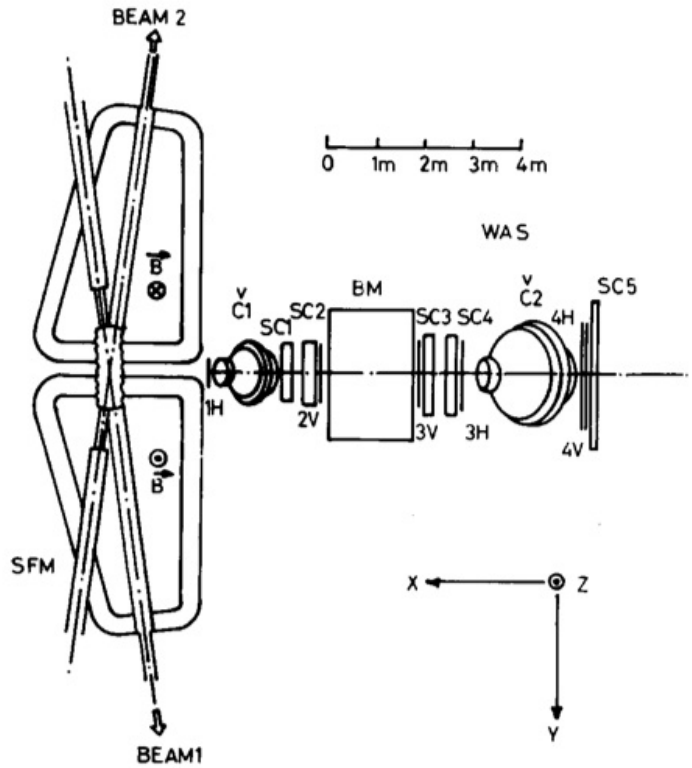
CCOR PL**B** 97 (1980) 163
k_T varies with p_{Tt} and √s
Not intrinsic !

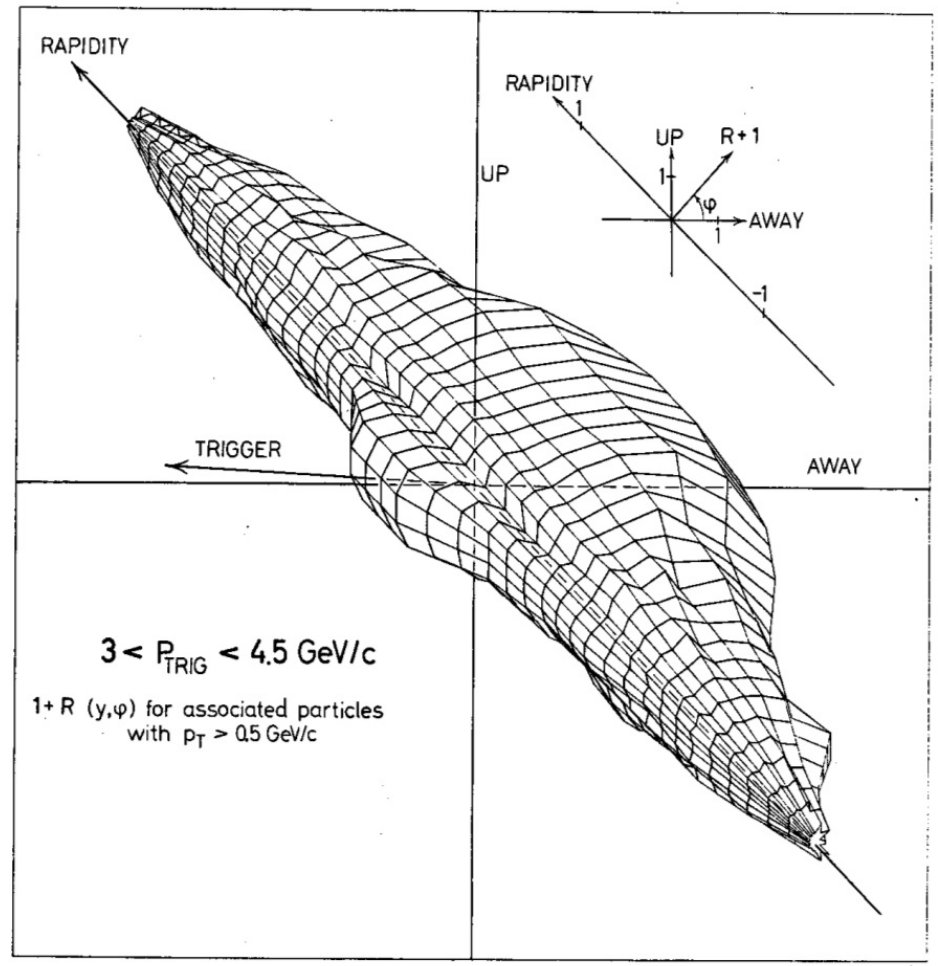
But j_T is constant-independent of p_{Tt} and $\sqrt{s}$ Characteristic of jet fragmentation



- it took the $e^+ e^-$ people several more years to get this correct--- because they didn't understand the seagull effect: ($j_T < p_T$)

British French Scandinavian "Ridge"



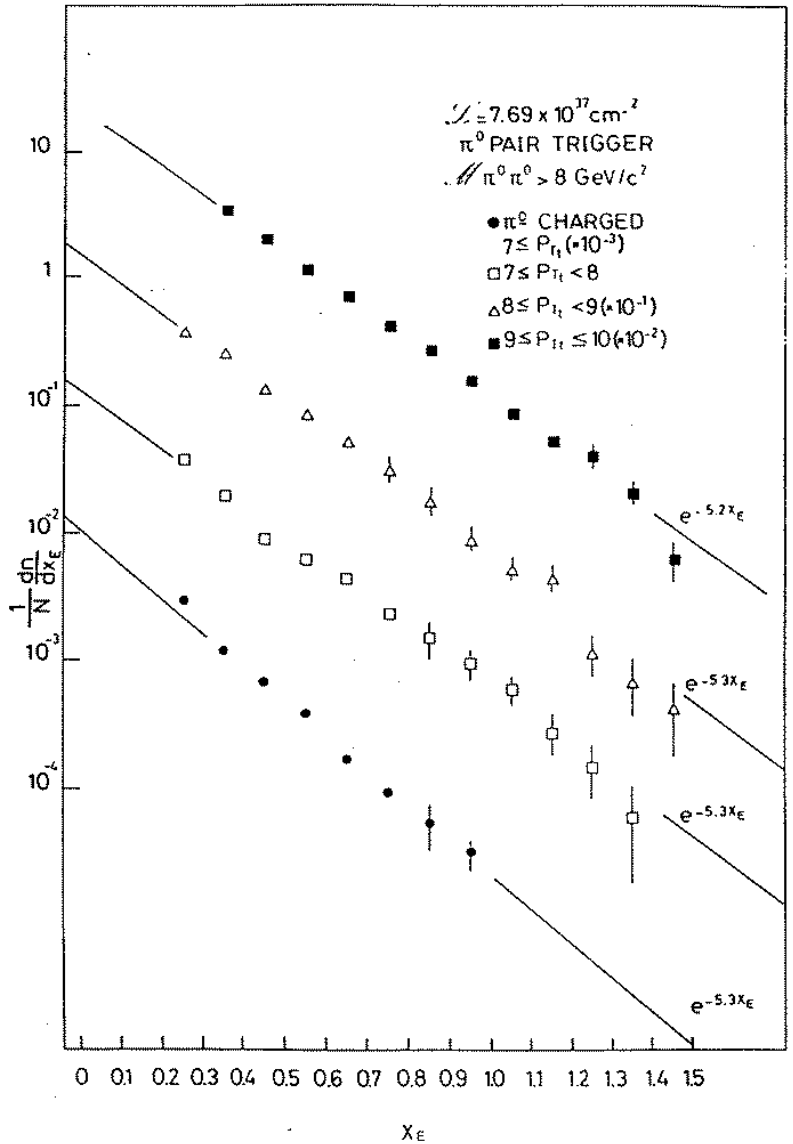


Split Field magnet, horrible magnetic field uniformity. Track recon took ~5 yrs to develop + 1 hour of CDC7600 per hour of data! Great acceptance when it finally worked.

BFS
NP**B145**(1978) 308

For the past decade these single and two-particle techniques were used exclusively at RHIC for hard-scattering, with outstanding results...

x_E distribution measures fragmentation fn.



$$x_E \sim z/\langle z_{trig}\rangle$$

$\langle z_{trig}\rangle$=0.85 measured

$$\Rightarrow D^q_\pi(z) \sim e^{-6z}$$

- independent of p_{Tt}

See M. Jacob's talk Proc. EPS 1979 Geneva (CERN). p512

Regarding George Sterman's talk, this plot from 1979 showed that there were NO di-jets each of a single particle as claimed by another ISR exp't (p511) since there was no peak at x_E=1

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':

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