Fermi National Accelerator Laboratory

Fermilab-Conf-82-29-T

Workshop on A^{α} Physics
Copies of Transparencies

Unedited Collection
compiled by Lou Voyvodic

Fermi National Accelerator Laboratory

P.O. Box 500, Batavia, Illinois 60510

March 1982

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Fermilab

Fermi National Accelerator Laboratory
P.O. Box 500 • Batavia, Illinois • 60510

February 26, 1982

Workshop on A^{α} Physics

Fermilab, 4 March 1982

Ramsey Auditorium

This one-day workshop will focus on nuclear A-dependent effects in high energy particle production. An effort will be made to stimulate wide-ranging discussions on profitable new directions.

8:30 A.M. Registration

9:00 A.M. Morning Session

HARD SCATTERING - S. Brodsky, Chairman

Experimental Review (H. Frisch, University of Chicago)
Review of Theories and Models, Incisive Measurements
(J. Gunion, University of California, Davis)
(A. Mueller, Columbia University)

1:30 P.M. Afternoon Session I.

SOFT COLLISIONS - W. D. Walker, Chairman

Experimental Review (L. Voyvodic, Fermilab)
Review of Theories and Models, Incisive Measurements
(W. Czyz, INP Cracow and University of Illinois)

3:30 P.M. Afternoon Session II.

Novel Ideas, Heresies, Discussions (Moderator - J. Cronin, University of Chicago)

8:00 P.M. Post-Dinner Session - E. Berger, Chairman

Tevatron Experiments (W. Busza, MIT)
A^{α} Physics (J. D. Bjorken, Fermilab)

- - - - - - - -

Organizing Committee:

E. Berger (ANL), A. Buras (Fermilab), R. McCarthy (SUNY, Stony Brook) and L. Voyvodic (Fermilab).

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HARD SCATTERING - EXPERIMENTAL REVIEW (1)
{H. FRISCH}

A - Dependence

There is something fascinating about science. One gets such wholesome returns of conjecture out of such a trifling investment of fact."

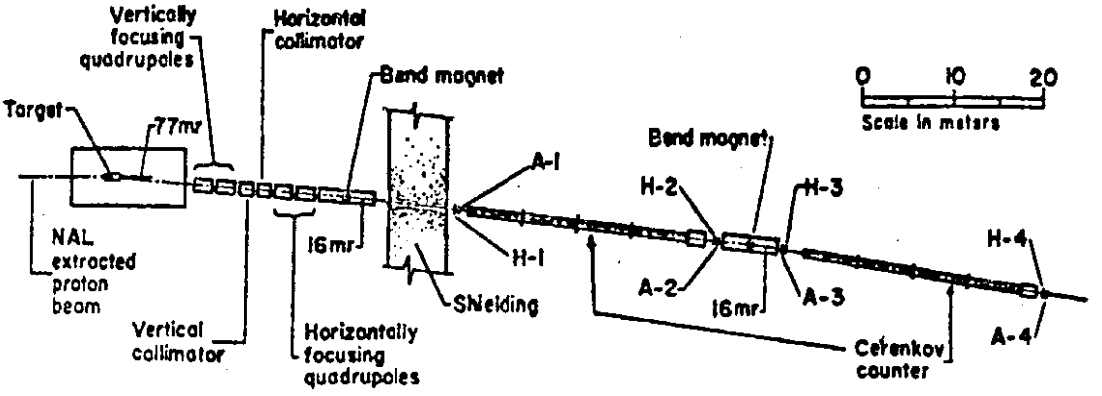
— Mark Twain
Life on the Mississippi
(1896)

High P_T - Single arm experiments

I. C-P collaboration. The first one on A-dependence. It is now old + well known, but it still has a wealth of (quantitatively) unexplained data.

A. Apparatus
B. typical spectra
C. α for $\pi^{\pm}, K^{\pm}, P, \bar{P}$
d. $\Delta\alpha$ for particle ratios.

II. Other experiments



J. W. Cronin, H. J. Frisch, and M. J. Shochet

The Enrico Fermi Institute

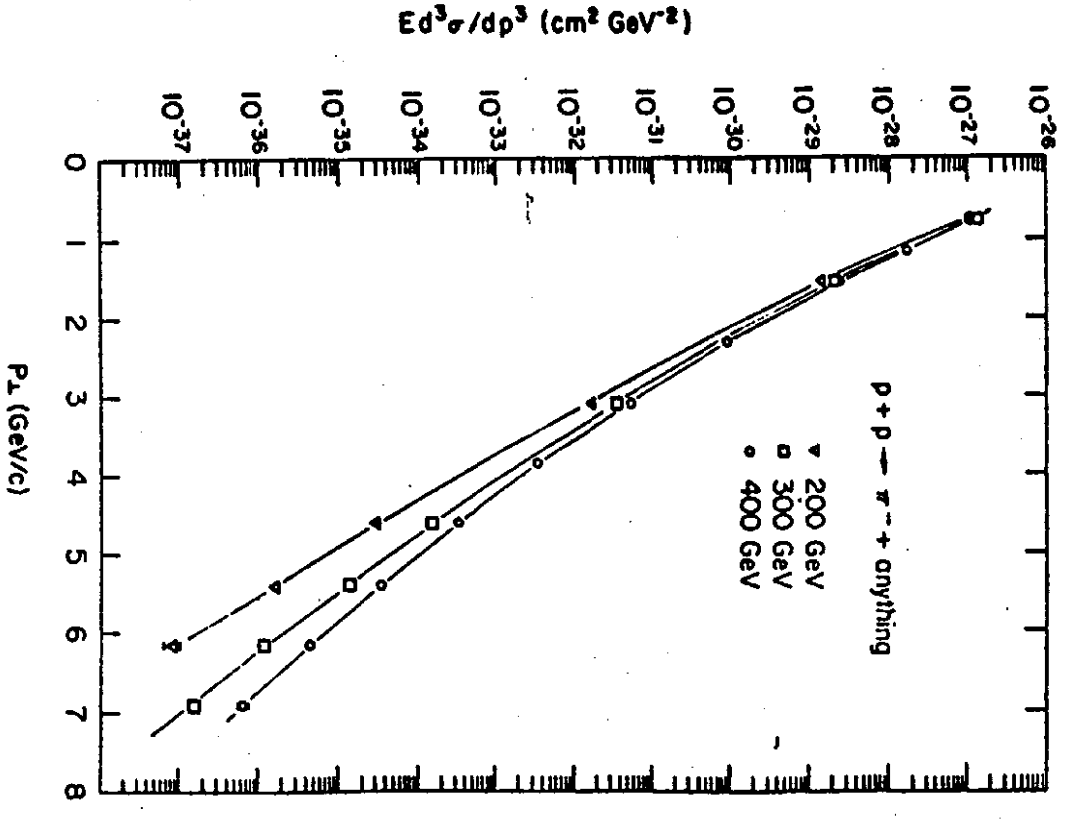
University of Chicago, Chicago, Illinois 60637

and

J. P. Boymond, P. A. Piroué, and R. L. Sumner

Department of Physics, Joseph Henry Laboratories

Princeton University, Princeton, New Jersey 08540

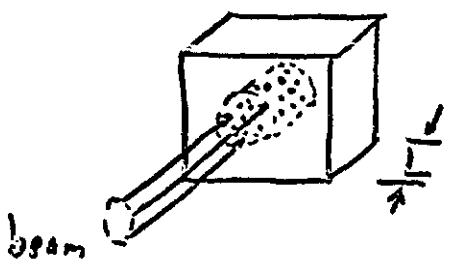


Basics

Cross section per nucleus

$$E\frac{d\sigma_A}{d^3p} = \left[\frac{A}{\rho L N_0}\right]\left[\frac{\text{Yield}}{p^2\left(\frac{\Delta p}{p}\right)\Delta\Omega}\right]\exp\left\{\frac{N_0 L \rho \sigma_{abs}}{A}\right\}$$

where: $A \equiv$ atomic weight (gms/gram-mole)
$\rho \equiv$ density (gms/cm^3)
$L \equiv$ length of target (cm)
$N_0 \equiv$ Avogadro's # (6.023×10^{23} nuclei/gram-mole)

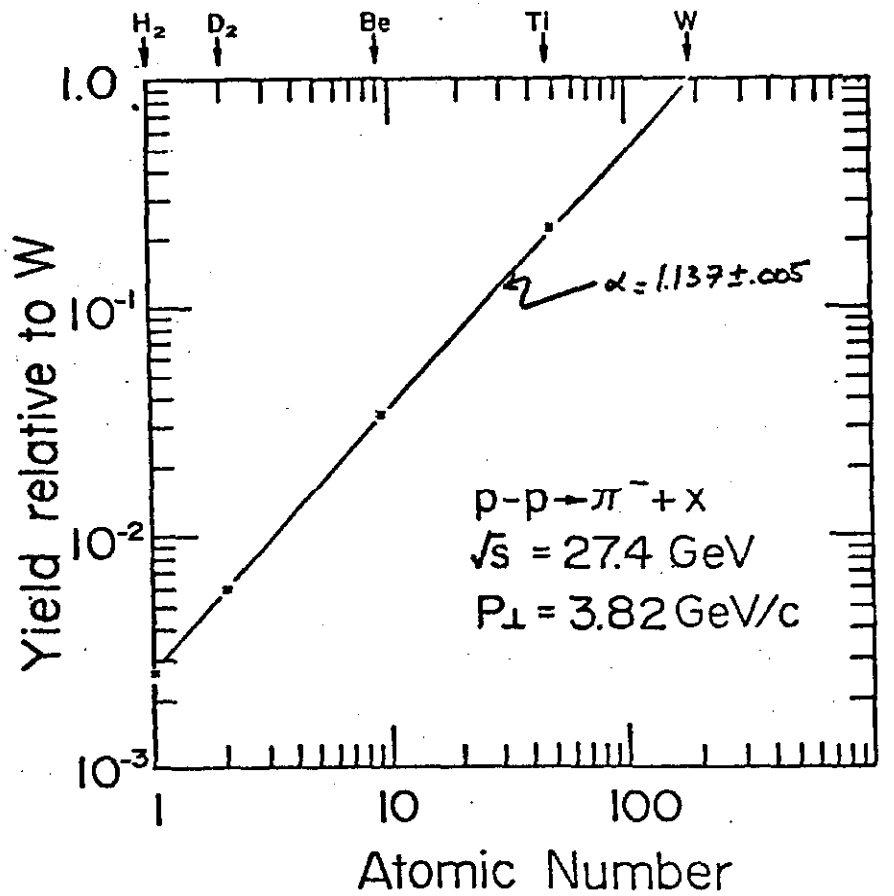


$\frac{N_0}{A}$ = # of nuclei/gram

$\frac{N_0\rho}{A}$ = # of nuclei/cm^3

$\frac{N_0\rho L}{A}$ = # of nuclei/cm^2

Target	A	A/Z	ρ	λ_{abs}	# of nuclei/cm^3 $N_0\rho/A$	L
Be	9.013	2.25	1.84	15"	12.3×10^{22}	.480"
Ti	47.90	2.18	4.54	10.6"	5.7×10^{22}	.341"
W	183.85	2.49	19.3 (gm)	3.9"	6.3×10^{22}	.131"



Because the data look like a straight line on a log-log plot, we parameterized $\sigma(A, p_T) \sim A^{\alpha(p_T)}$ where $\alpha(p_T)$ is the local effective power.

<u>For example</u>, if one measures σ_W and σ_{Be} at a given p_T, to find α:

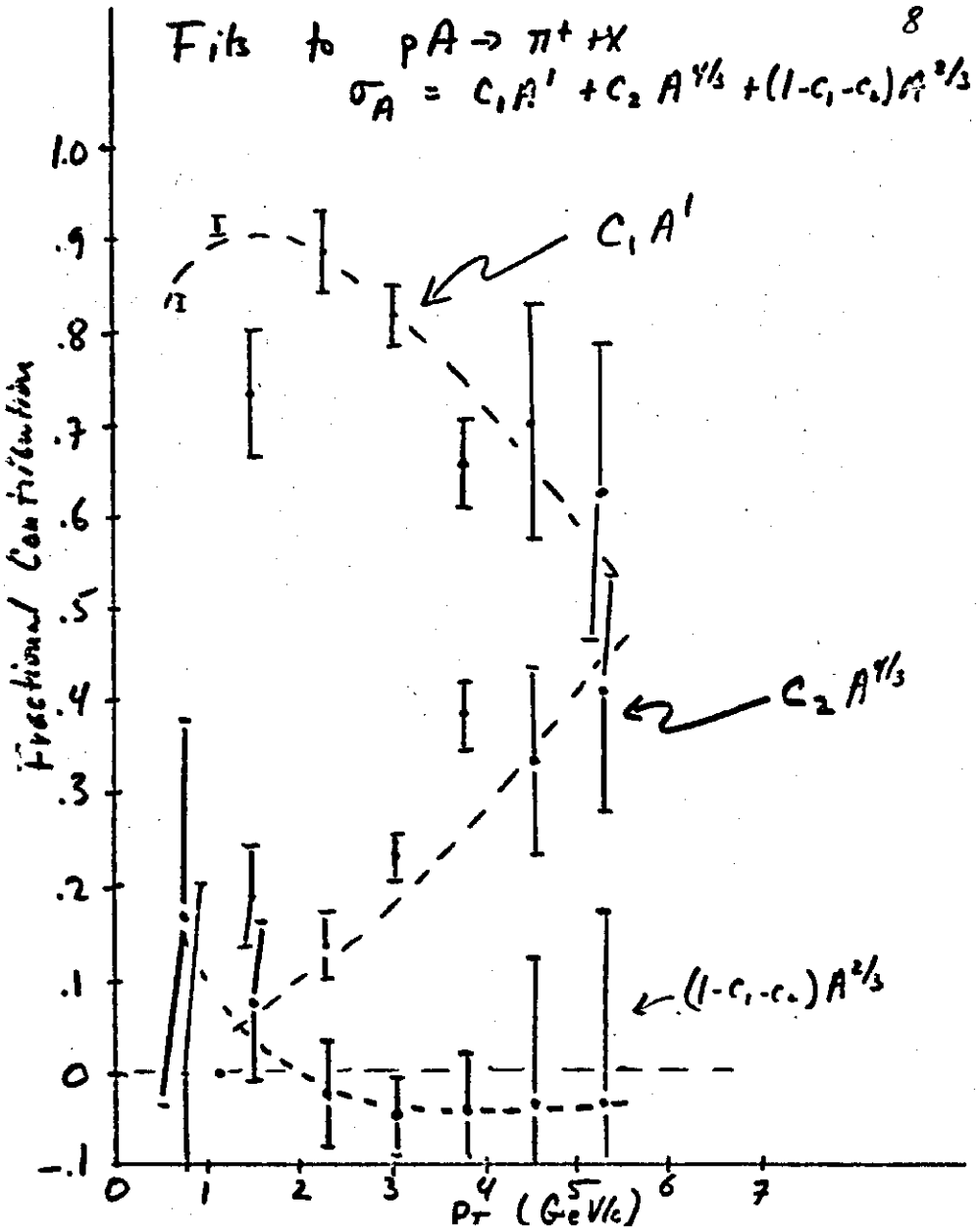
$$\sigma_W/\sigma_{Be} = \left(A_W/A_{Be}\right)^{\alpha}$$

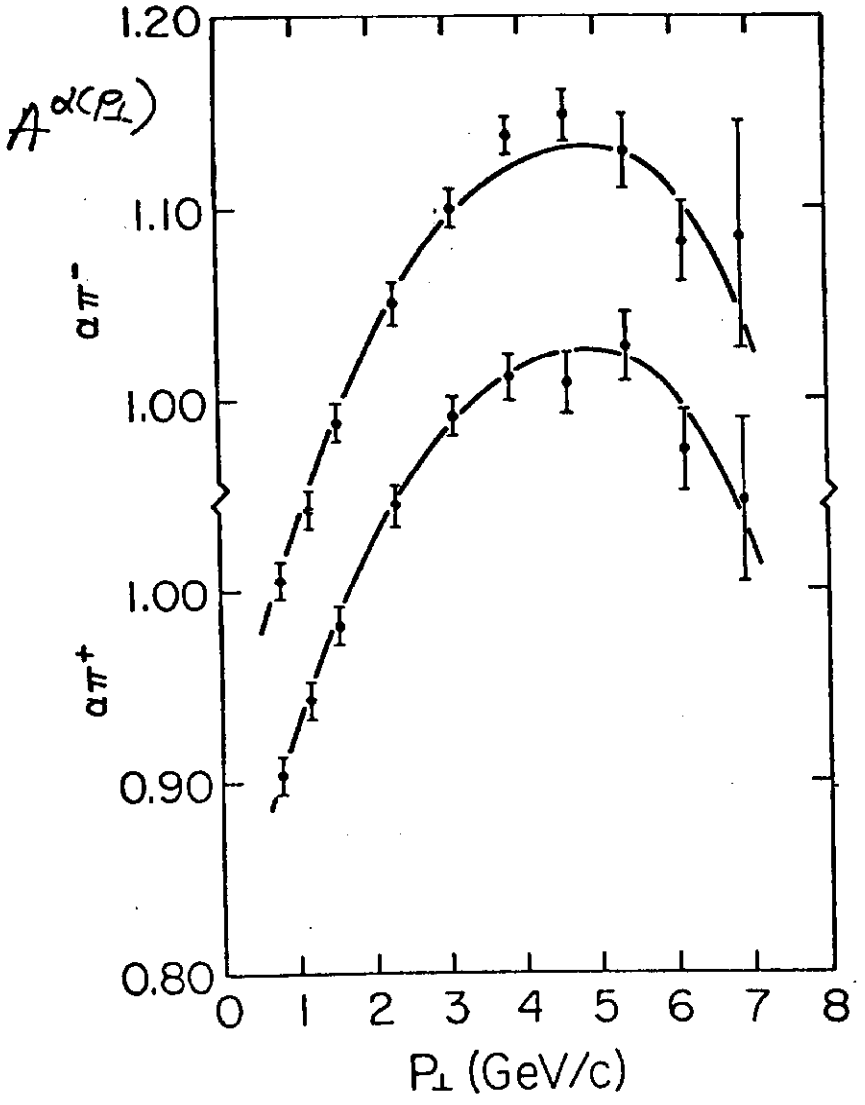
$$\Rightarrow \quad \alpha = \frac{\ln(\sigma_W/\sigma_{Be})}{\ln(A_W/A_{Be})}$$

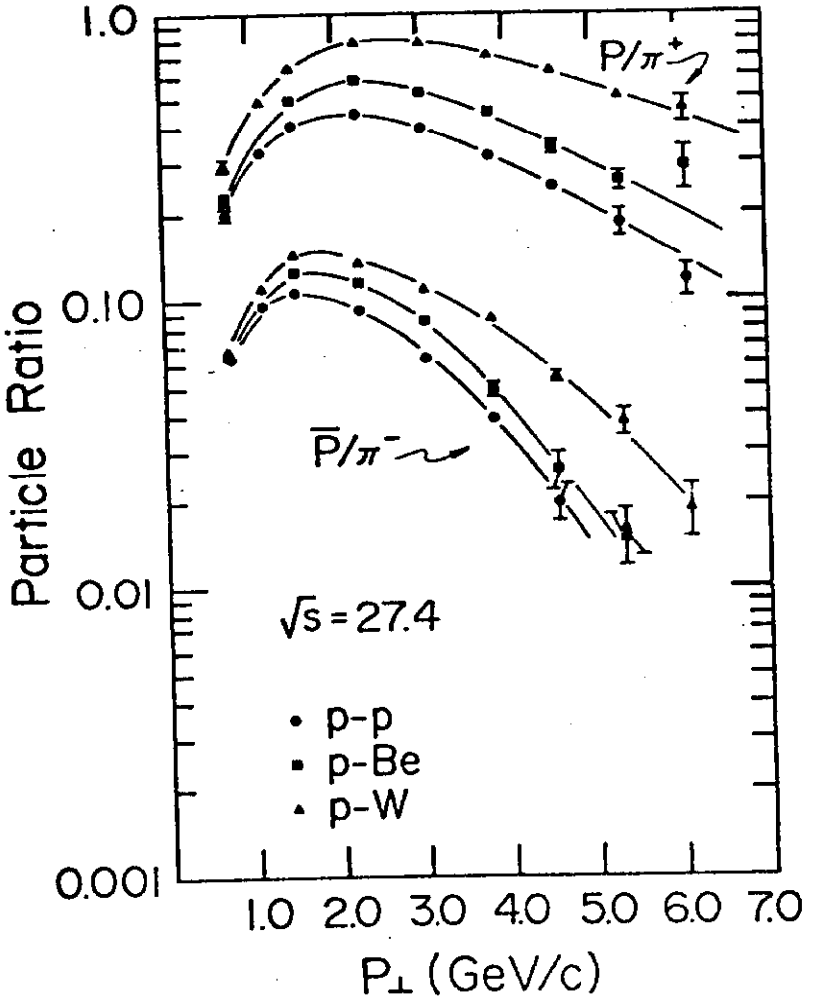
<u>But</u> A^{α} is only a simple parameterization: other forms are <u>not</u> excluded. E.g.

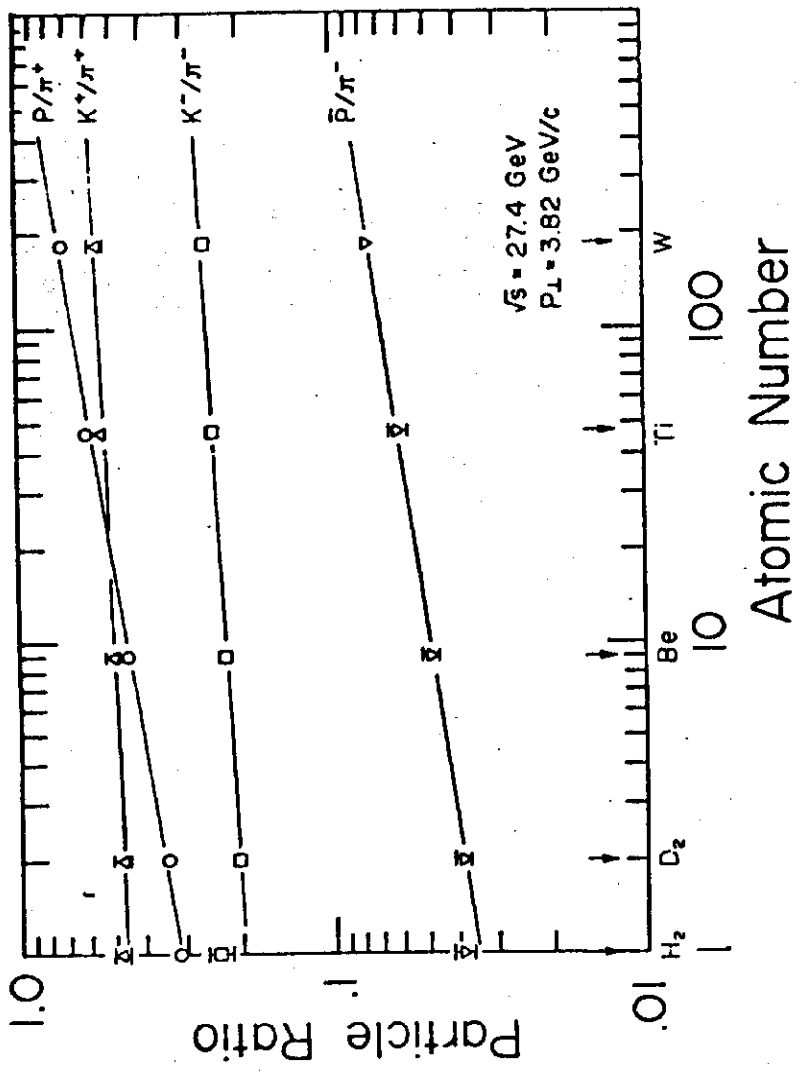
$$\sigma = c_1 A^{2/3} + c_2 A^1 + c_3 A^{4/3}$$

fits the data very well (has excellent χ^2's) A^{α}, however, is easy as a parameterization




$A^{\alpha(P_\perp)}$
$\alpha\pi^-$
$\alpha\pi^+$
1.20
1.10
1.00
1.00
0.90
0.80
0 1 2 3 4 5 6 7 8
$P_\perp$ (GeV/c)


Particle Ratio
1.0
0.10
0.01
0.001
P/π^+
$\bar{P}/\pi^-$
$\sqrt{s} = 27.4$
• p-p
▪ p-Be
▲ p-W
1.0 2.0 3.0 4.0 5.0 6.0 7.0
$P_\perp$ (GeV/c)



If proton production $\sim A^{\alpha_p}$

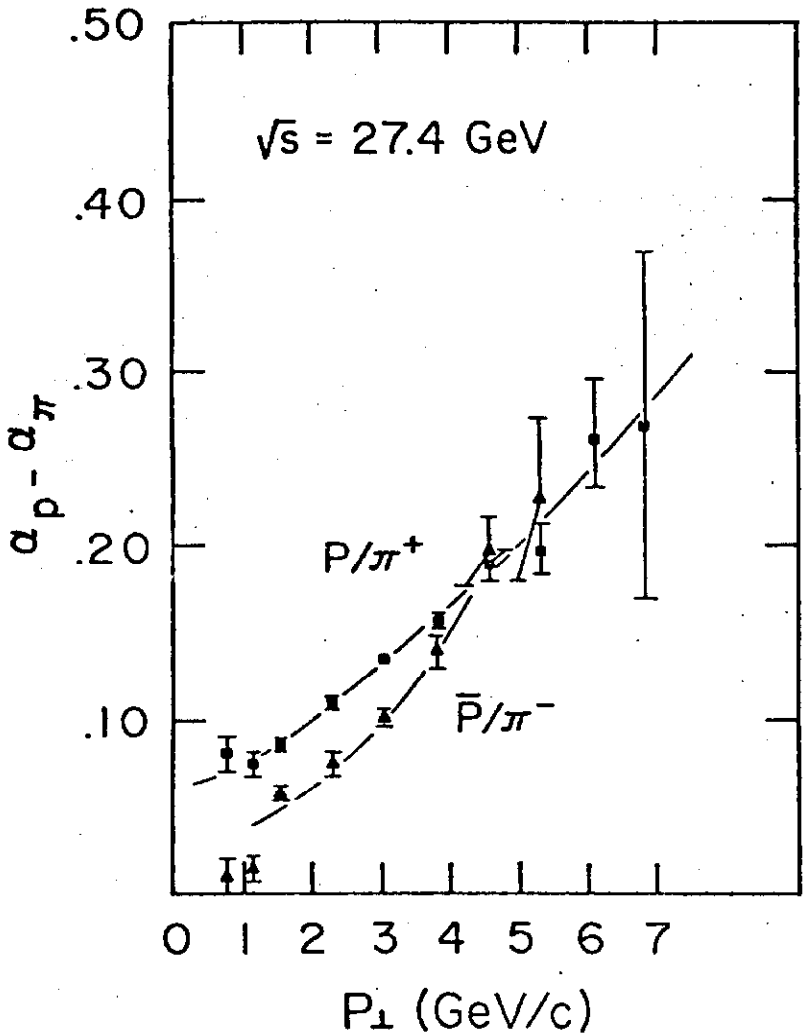
and pion production $\sim A^{\alpha_\pi}$

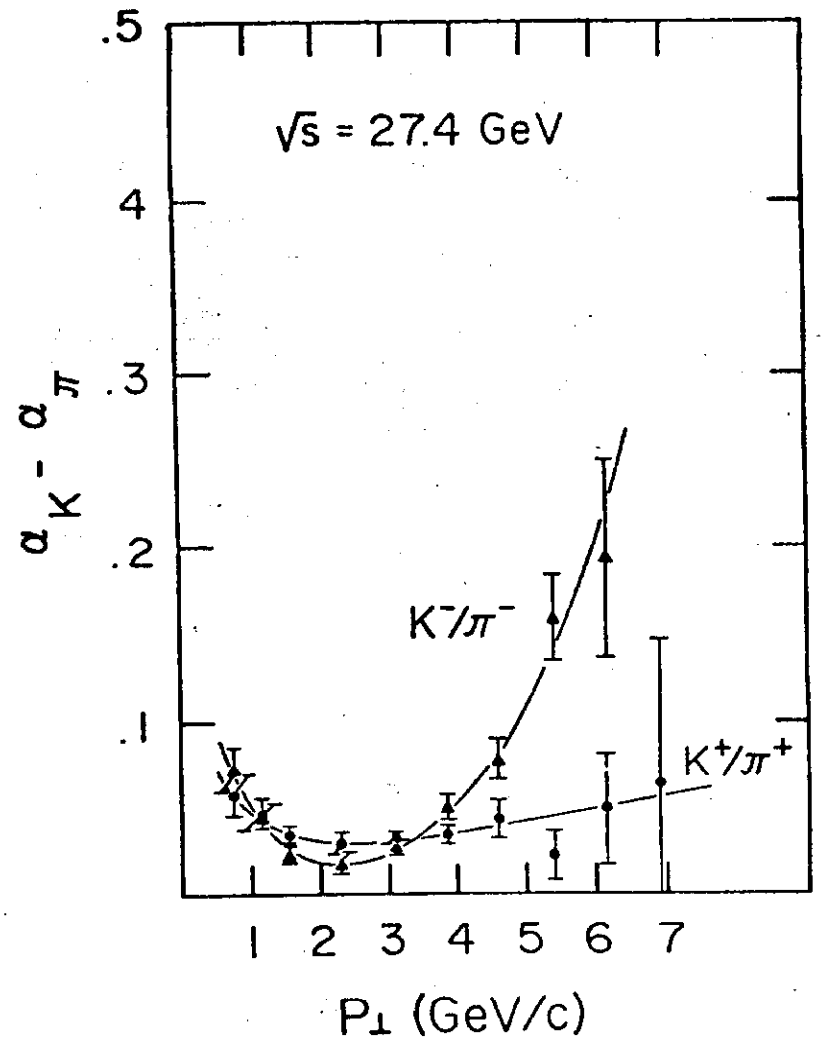
<u>then</u> $$P/\pi \sim \frac{A^{\alpha_p}}{A^{\alpha_\pi}} \sim A^{\alpha_p - \alpha_\pi}$$

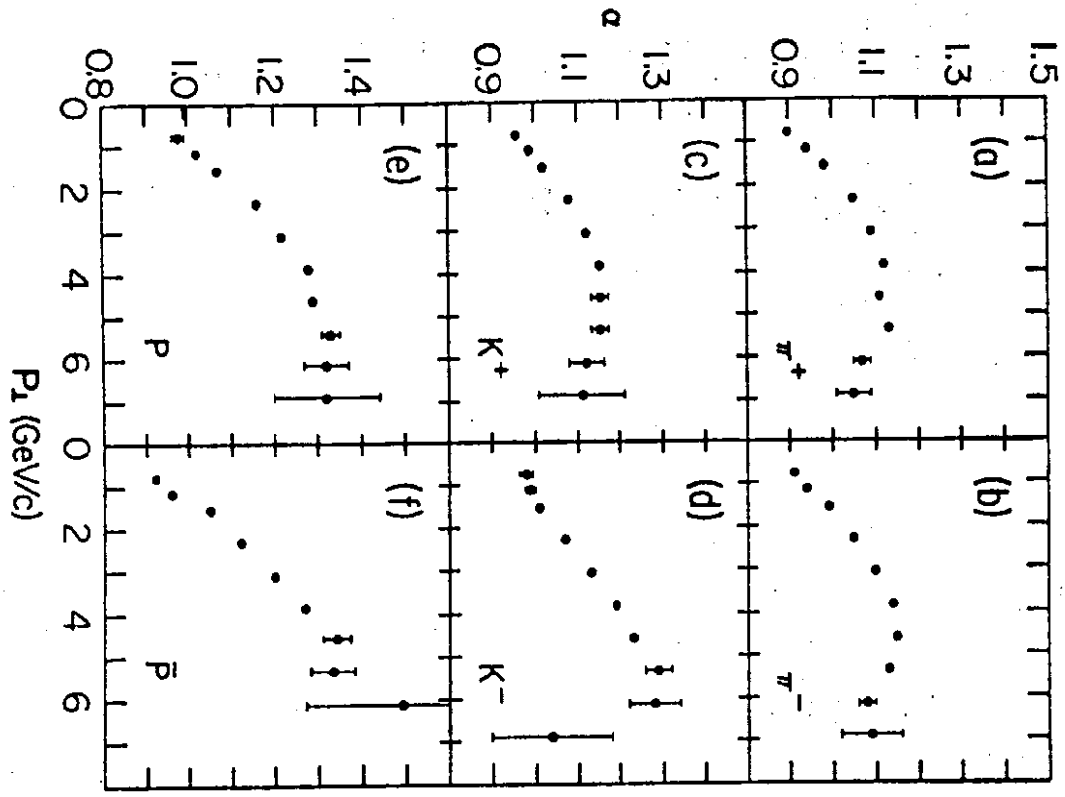
Define $\Delta\alpha = \alpha_p - \alpha_\pi$

$$\boxed{P/\pi(A) \sim A^{\Delta\alpha}}$$

natch


√s = 27.4 GeV
.50
.40
.30
.20
.10
$\alpha_p - \alpha_\pi$
P/π⁺
P̄/π⁻
0 1 2 3 4 5 6 7
P⊥ (GeV/c)


√s = 27.4 GeV
.5
4
.3
.2
.1
$\alpha_K - \alpha_\pi$
K⁻/π⁻
K⁺/π⁺
1 2 3 4 5 6 7
P⊥ (GeV/c)



Other single-arm 'high $P_\perp$' experiments 05/79

Acronyms	Reference	$\sqrt{s}$	$P_\perp$	targets	Comments
MIT/BNL	Becker et al. PRL 37, 1731 (76)	7.43 GeV	0.75 - 2.25	Be, Ti, W	over this limited $P_\perp$ range agrees with our data
Imp College, Rochester, Rutgers	Garbutt et al. Phys Lett 67B, 355 (77)	9.68 - 22.7	0.2 - 2.35	C, W	Ditto - ≤10% Change in α over this $\sqrt{s}$ range
SUNY, Columbia + Fermilab	McCarthy et al PRL 40, 213 (78)	27.4	1.8 - 4.3	Be, W	Agrees double arm data
Purdue UdM Fermilab	Finley et al PRL 42, 1028 (79)	27.4	1 - 2.8	Be Pb	ditto double arm data

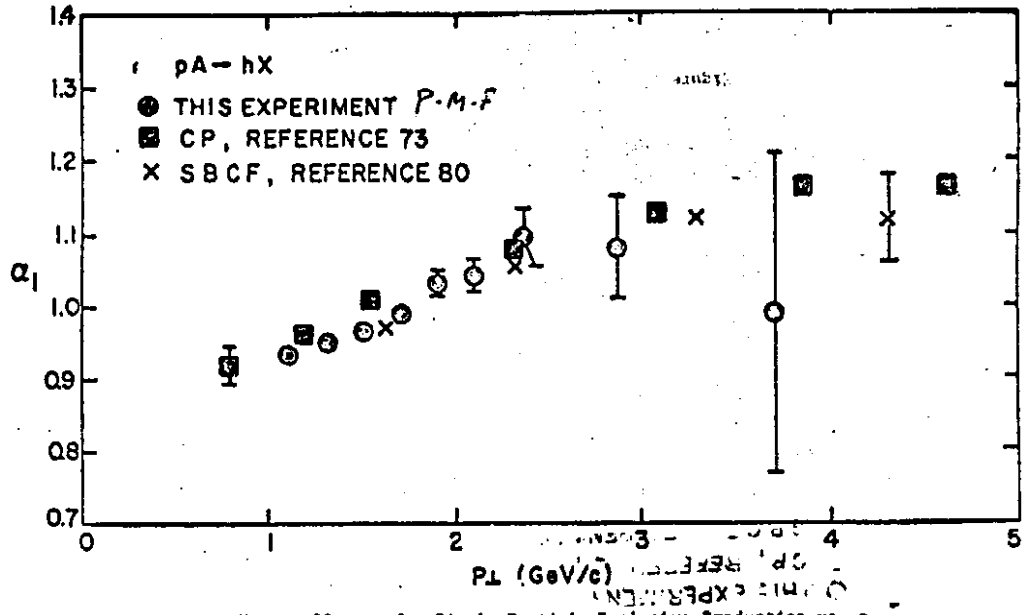


Figure 22. α_1 for Single-Particle Inclusive Production vs. $p_\perp$.

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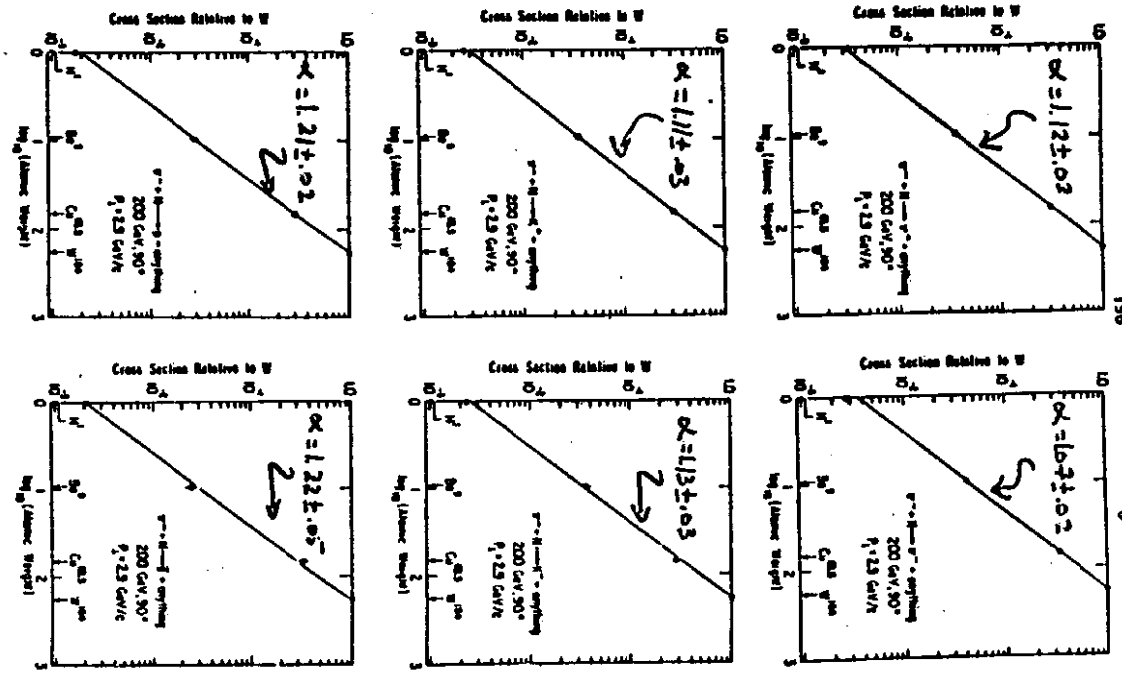

E258 $\pi^- A \to h + X$ Chicago - Princeton

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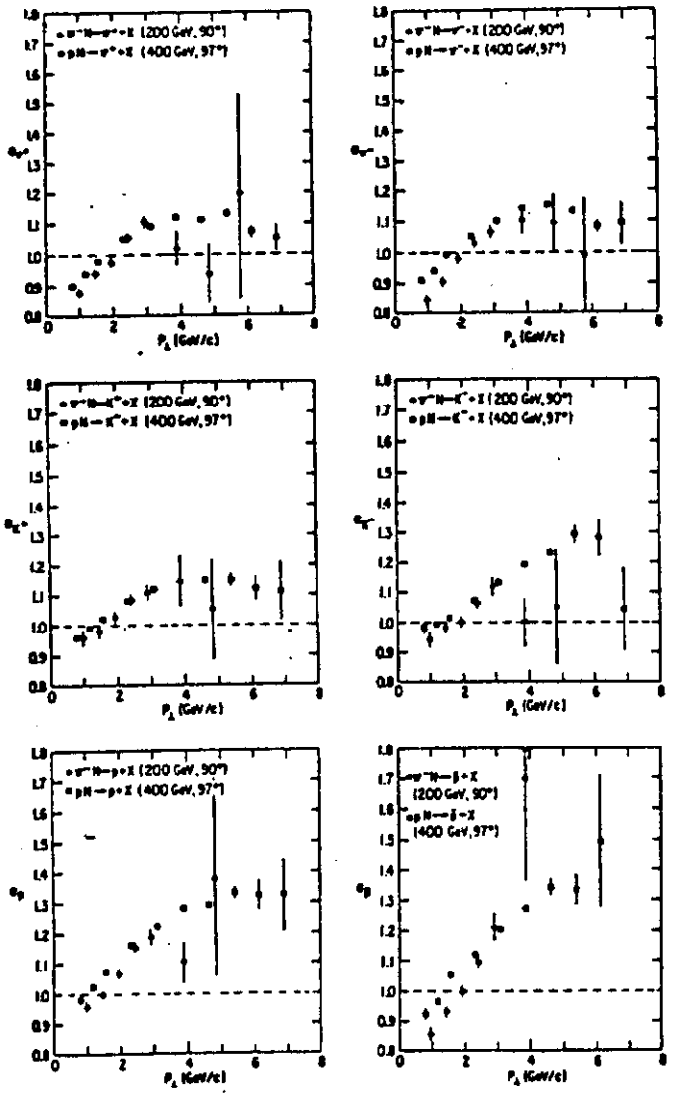
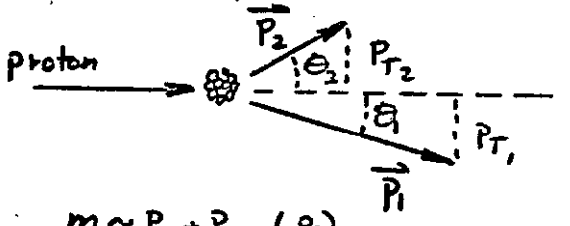


Double-Arm Dihadron Experiments

Look at the production of pairs with large invariant mass (near $x \cong 0$)
(see picture below)

My expectations:

1. If there are high x components in the nucleus, $\alpha(m)$ should increase with mass.
2. Multiple collisions of bare constituents would increase asymmetric events more than symmetric ones. So α would depend on p_T more than on mass
3. Any cascading will increase events at lower p_T and m.



for $\theta_1 + \theta_2 \sim 90°$

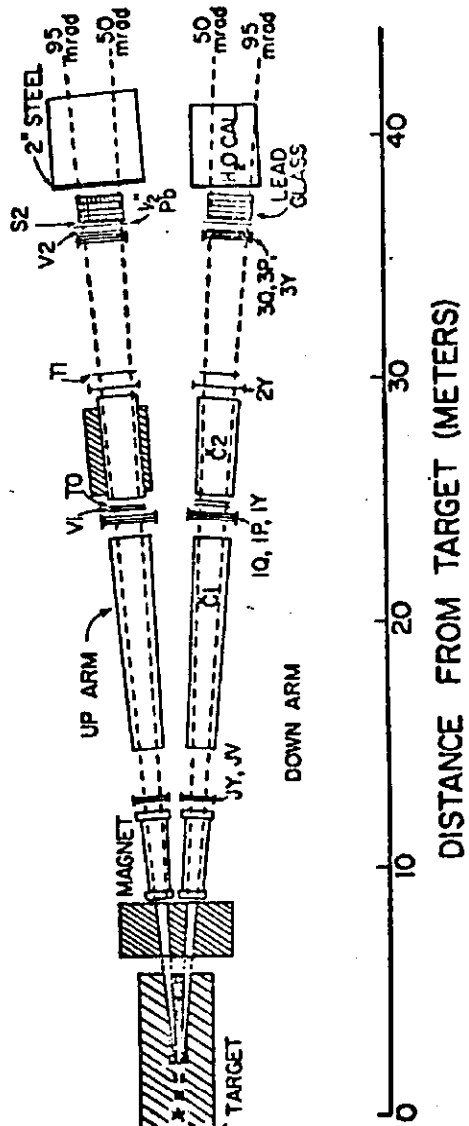
$m \sim P_{T_1} + P_{T_2}$ (Ps)

$P_T \sim P_{T_1} - P_{T_2}$ (Pd)

$-0.2 \leq Y \leq +0.3$

$\Delta\varphi \sim 6^\circ$

THE APPARATUS (TOP VIEW)



R. L. McCarthy, R. J. Engelmann, R. J. Fisk, M. L. Good,[a] A. S. Ito, H. Kichimi, D. M. Kaplan, R. D. Kephart, and H. Wahl[b]
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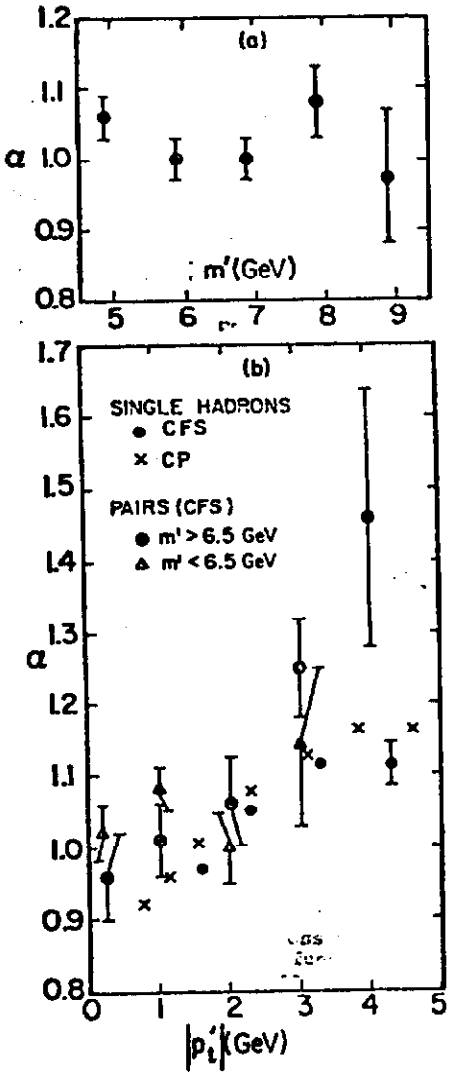
(Received 8 November 1979)



$m' \equiv P_{\perp 1} - P_{\perp 2}$

$P_t' = P_{\perp 1} - P_{\perp 2}$

Particle species dependence SBCF (23)

$p_T < 2.1$ GeV/c $p_T > 2.1$ GeV/c

	π^-	K^-	$\bar{p}$	h^-
π^+	0.99 ± 0.03	1.05 ± 0.09	1.29 ± 0.14	1.00 ± 0.03
	1.08 ± 0.11	1.37 ± 0.46	-	1.12 ± 0.08
K^+	0.98 ± 0.09	1.33 ± 0.17	-	1.05 ± 0.05
	-	-	-	1.24 ± 0.22
p	1.11 ± 0.07	1.58 ± 0.21	1.37 ± 0.13	1.16 ± 0.05
	-	-	-	1.14 ± 0.19
h^+	1.00 ± 0.02	1.11 ± 0.06	1.17 ± 0.07	1.01 ± 0.02
	1.15 ± 0.06	1.52 ± 0.20	1.41 ± 0.43	1.18 ± 0.04

The power α of the A dependence of the invariant dihadron production cross section is given as a function of particle species for $p_t < 2.1$ GeV/c (upper value) and for $p_t > 2.1$ GeV/c (lower value in each box). h^+ denotes all positive hadrons, h^- all negative hadrons.

all m
($m > 4$-5 GeV)

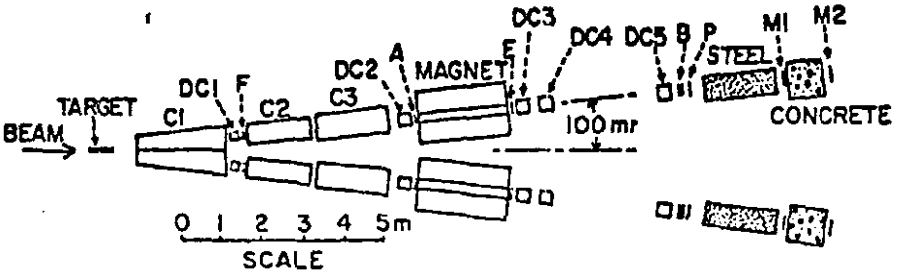
Conclusions from Columbia - Suny - Fermilab Experiment (24)

I. The data are consistent with $\alpha = 1$ as a function of the mass of the pair, for $4.8 \leq m_{pair} \leq 8.8$ G
I.e., there is no anomalous A dependence vs. mass.

II. An anomalous A-dependence is seen for pairs with $p_\perp > 2$ GeV/c (i.e. $\alpha > 1$ for $p_\perp > 2$ GeV)

III Pairs involving heavy particles (especially $K^- + \bar{p}$) have larger values of α.
(Remember, their slopes are steeper)

The results seem qualitatively consistent with the multiple collisions ideas of Kühn and Krzywicki et al, but I don't know about quantitative predictions.



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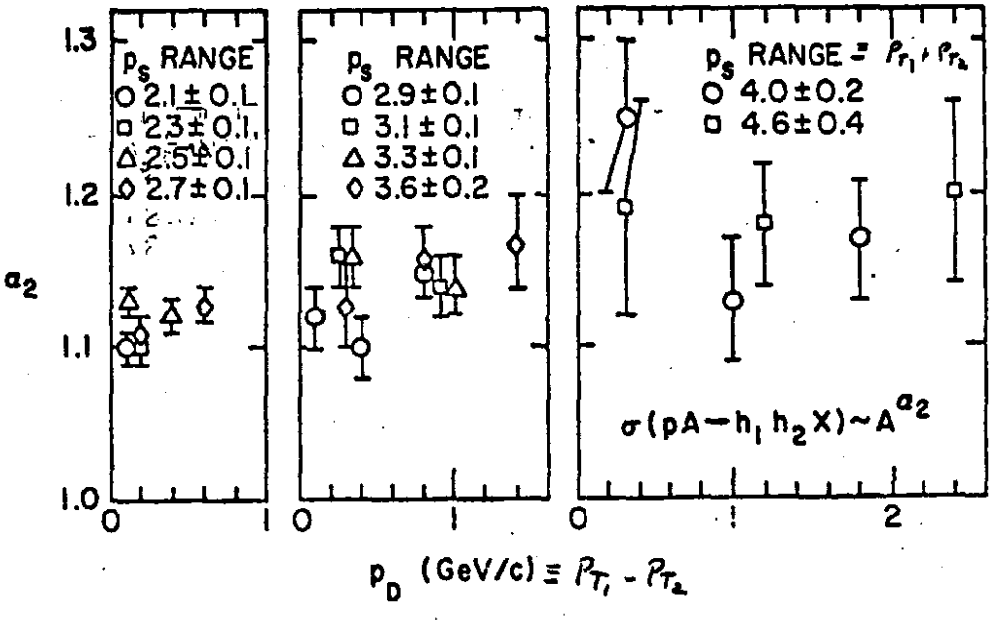

Figure 24. α_2 vs. p_d for Several Ranges of p_s.

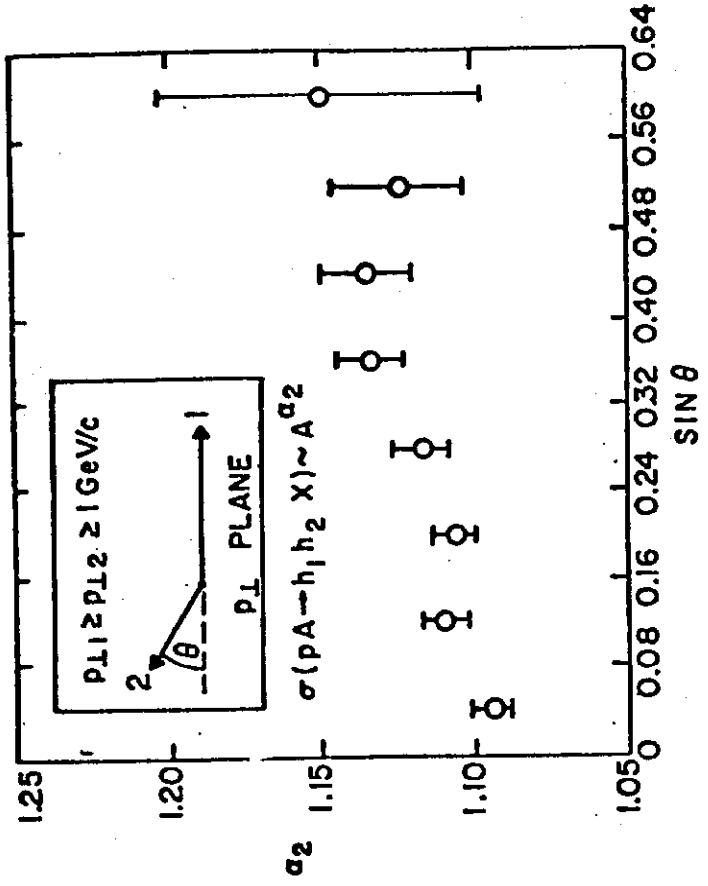

Figure 26. α_2 vs. sin θ.

Production of pairs of different particle types.

— PMF $2 < m < 3.6$ GeV/c^2

E537 – preliminary data

FNAL–Illinois–Indiana–Maryland–Rutgers

— SBCF $4\text{-}5 < m < 8\text{-}9$ GeV/c^2

$pA \to h_1 h_2 + X$; 400 GeV/c

GLOBAL TRIGGER, $\Delta\omega^* \approx 8$ sr

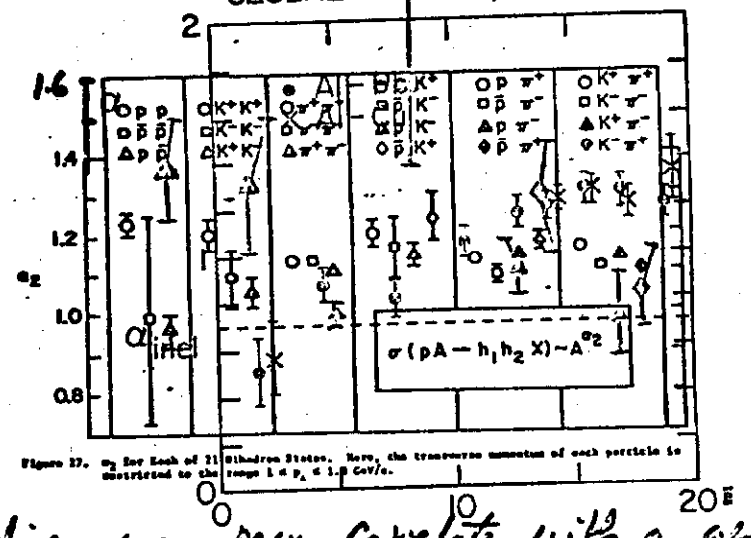

Figure 27. α_2 for Each of 21 Dihadron States. Here, the transverse momentum of each particle is restricted to the range $1 < p_\perp < 1.5$ GeV/c.

The discrepancy may correlate with a general rule of thumb that the steeper the spectrum, the larger the A-dependence. At low p_T, the (single) heavy particles are less steep in p_T than the π's. At high p_T, it's the other way. PMF samples the former; SBCF the latter.

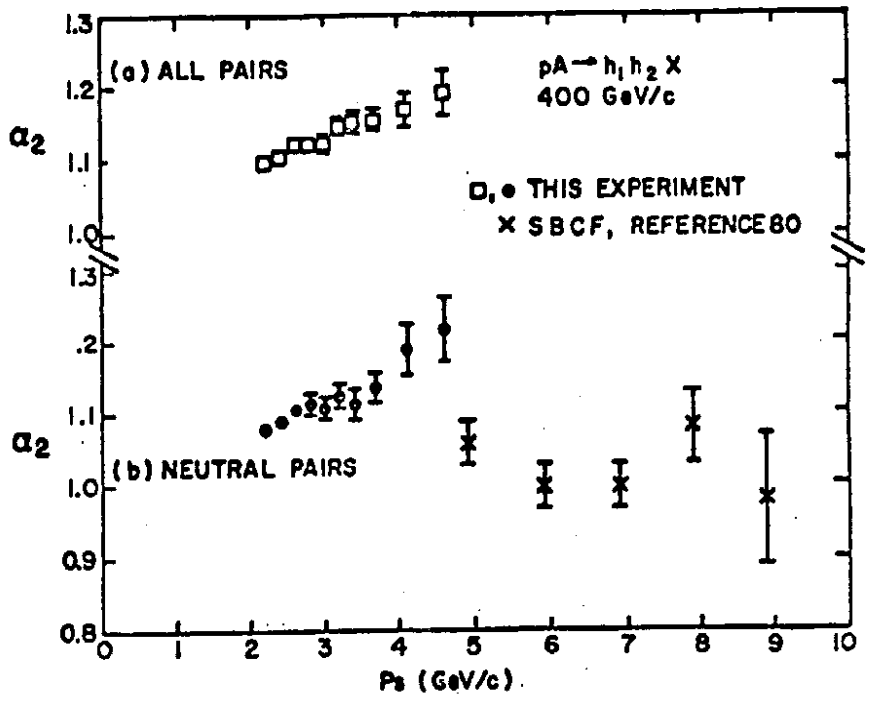

Figure 25. α_2 vs. P_s Integrated Over P_d.

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CUM GRAND SOLIS

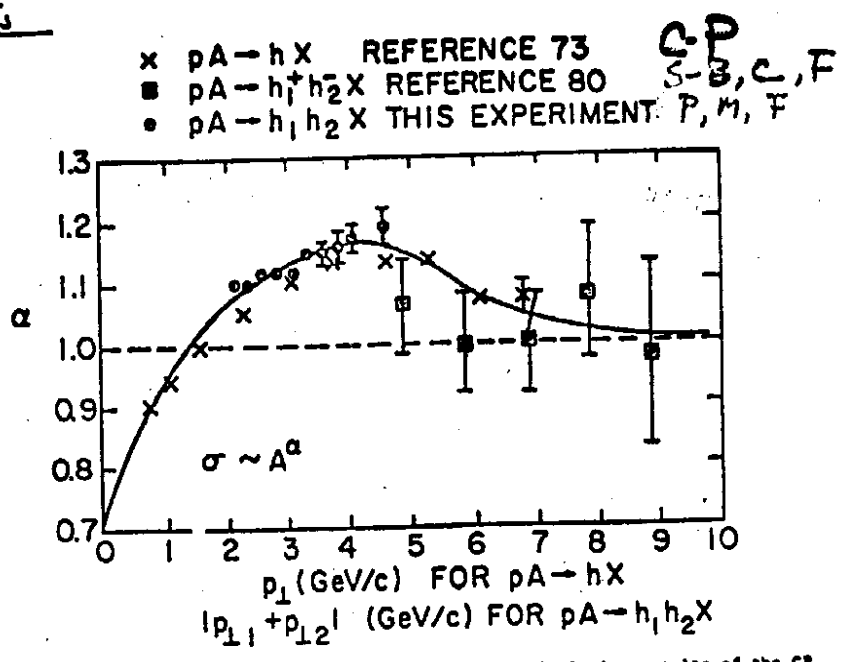

Figure 28. α vs. $p_\perp$ or p_s. The crosses are the single-particle inclusive results of the CP experiment. The boxes are the neutral pair results of SBCF with an additional systematic error of 0.05 added to their quoted error. The circles are the results of this experiment for all charge combinations.

A valiant attempt (D. Finley) to get the results to agree

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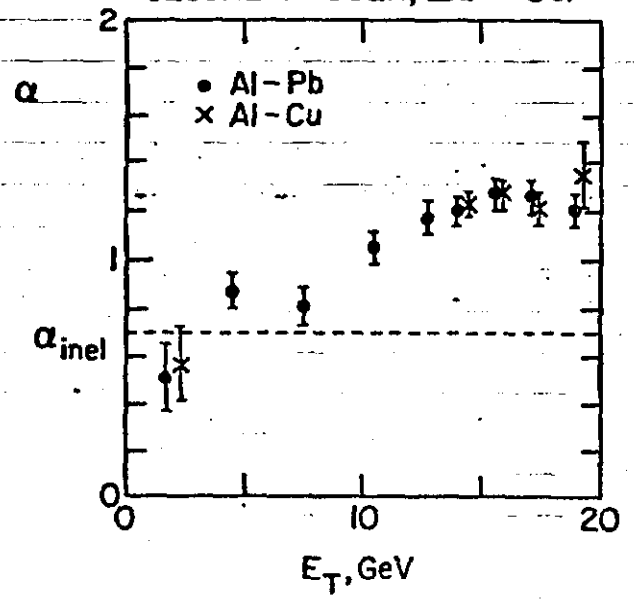
From A. Ziemiński.

E557 – preliminary data
FNAL–Illinois–Indiana–Maryland–Rutgers

$pA \rightarrow (E_T)_{cal} + X$; 400 GeV/c
GLOBAL TRIGGER, $\Delta\omega^* \approx 8$ sr



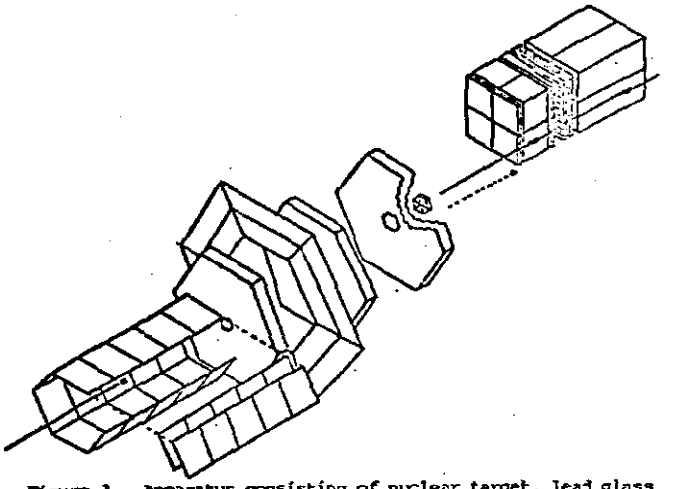


Figure 1. Apparatus consisting of nuclear target, lead glass scintillator shower detector, and non-magnetic vertex detector.

PRELIMINARY RESULTS FOR HIGH X_t π^0 PRODUCTION AND CHARGED PARTICLE CORRELATIONS FOR HADRONIC INTERACTIONS WITH NUCLEAR TARGETS

Bari-Brown-Fermilab-MIT-Warsaw Collaboration
Presented by P. H. Garbincius,
Fermilab, Batavia, Illinois, 60510

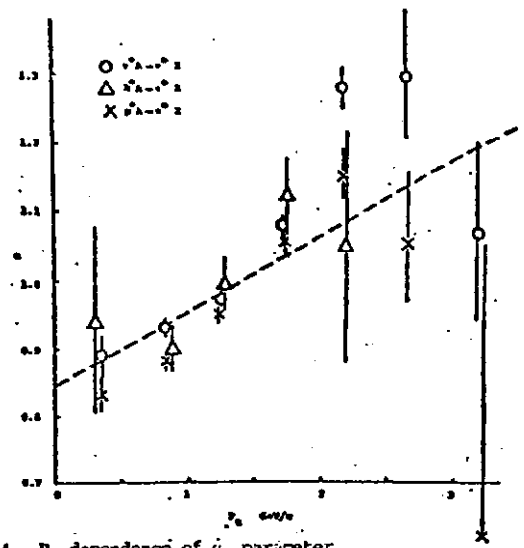


Figure 4. P_t dependence of α parameter.

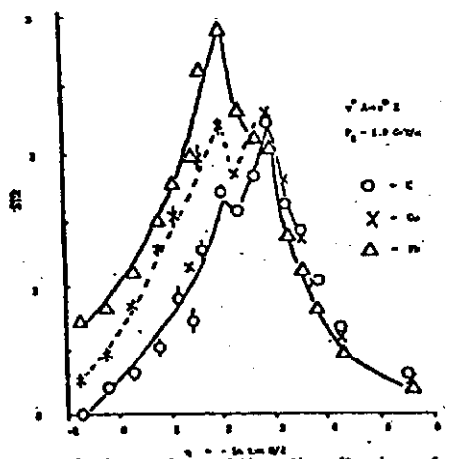


Figure 5. Typical pseudo-rapidity distributions for $\pi^+ A \rightarrow \pi^0 X$ at $P_t = 1.9$ GeV/c.

R110 (CoR)

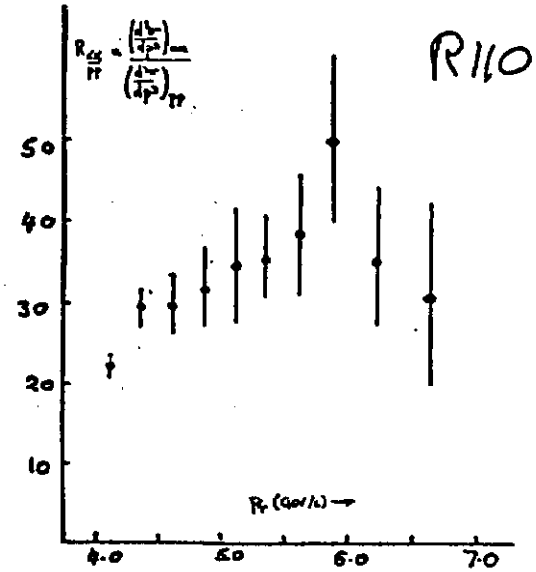


Figure 13

pp data: $A\, f(x_T)\, p_T^{-8.03}$

αp data: $2.41\, A\, f(x_T)\, p_T^{-7.65}$

αα data: $2.67\, A\, f(x_T)\, p_T^{-6.1}$

Table 1 shows directly the ratios of cross-sections versus p_T at the same $\sqrt{s_{NN}}$, as measured in R806. Errors are ± 15%, perhaps ± 20% at the highest p_T.

R806 (ABC)

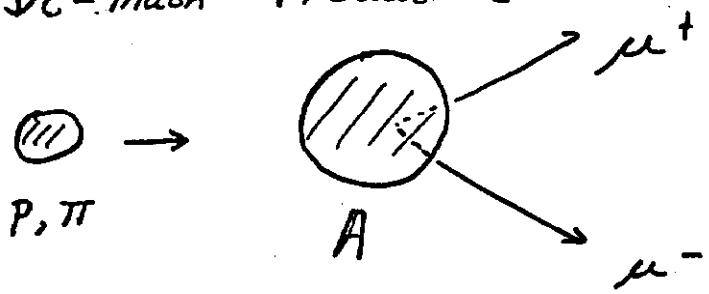
TABLE 1

P_T (GeV/c)	2.5	3	3.5	4	4.5	5	5.5
αp:pp $\sqrt{s}$ = 44	3.3	3.5	3.7	3.9	4.1	4.2	4.4
αα:pp $\sqrt{s}$ = 31	15.1	21.5	28.9	37.2	46.5	-	-

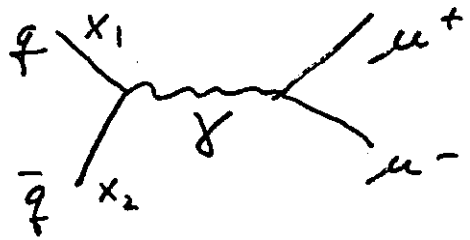
Ratios of Invariant Cross Sections versus p_T.

Clearly for αα collisions the power rises to well over 1.0 (which would give 16). For αp the power is also rising but is not significantly over 1.0 for this data.

Di-muon Production



Drell-Yan process



$$m_{\mu\mu}^2 = x_1 x_2 s$$

$$x_{F_{\mu\mu}} = x_1 - x_2$$

1) By looking in different kinematic regions one can 'pick' x_1 and x_2

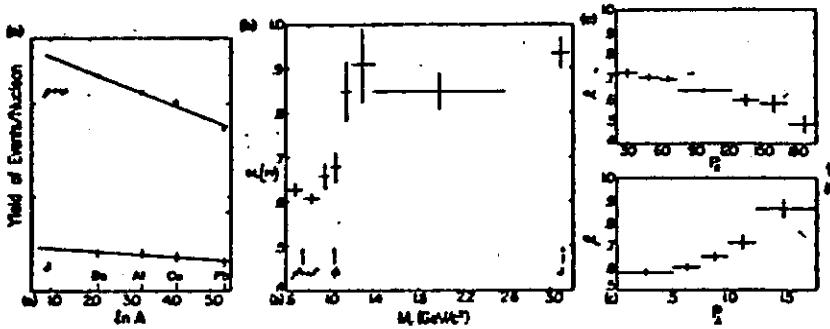
2) The μ's, being leptons, do not interact while leaving the nucleus.

05/79

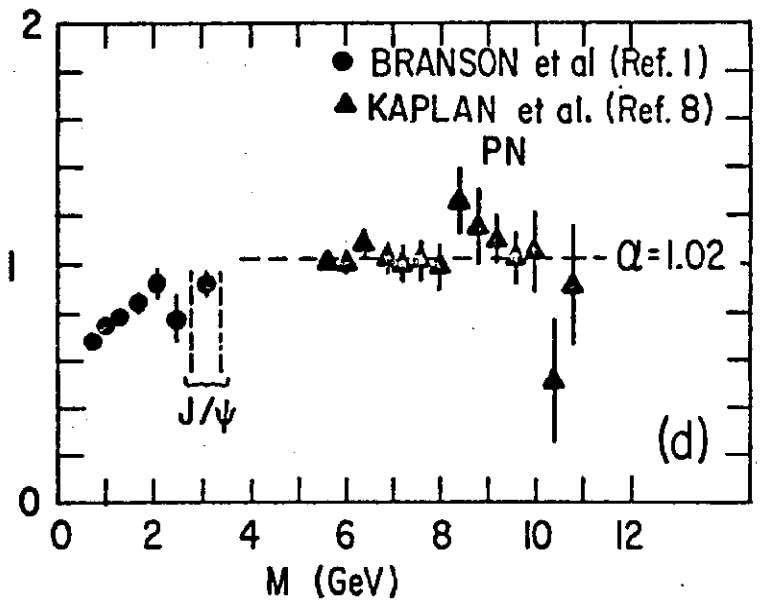
Relevant Di-muon Experiments

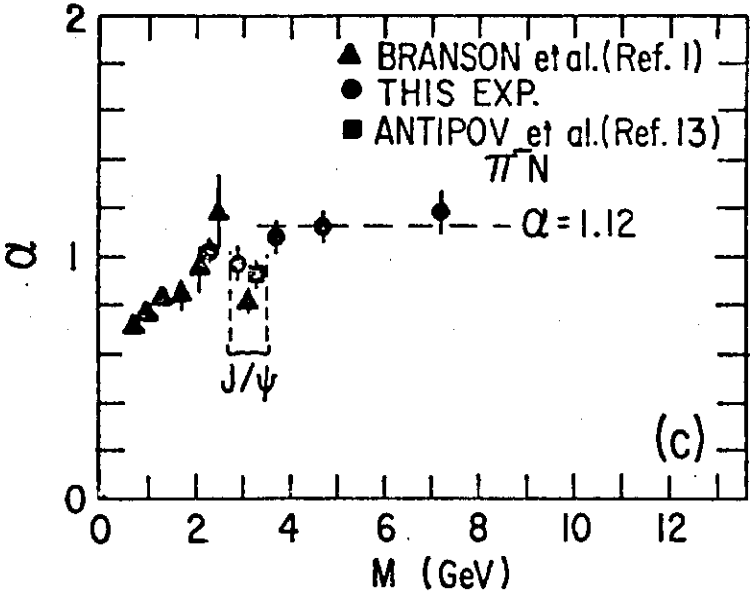
Acronyms	Reference	$\sqrt{s}$ Inc. Particle	target	$m_{\mu\mu}$	α	Comments
Fermilab, Columbia, Hawaii, Illinois	M. Binkley et al PRL 37, 571 (76)	~24.5 GeV neutrons	Be, Al, Cu, Pb	.75 (ρ,ω) to 3.1 (Ψ)	.62±.03 .93±.04	rises with mass
Chicago-Princeton (II)	D. Antreasyan et al PRL 39, 906 (77)	27.4 GeV P	Be, Cu	9 GeV	1.03±0.10	First high mass ($\sigma_{\mu\mu}$, 3) meas
SUNY, Fermilab, Columbia	D.M. Kaplan et al PRL 40, 435 (78)	27.4 GeV P	Be, Pt	5-12 GeV	0.97±.05	
Chicago-Illinois-Princeton	K.J. Anderson et al PRL 42, 944 (79)	20.5 GeV π^- (p)	C, Cu, W	1-7 GeV	1.12±.05	rises with mass up to $m_{\mu\mu}$ ~3
NA3	J. Badier et al (1981) Physics Letters 104B, 335	150 π^-, 200 π^+, 280 π^-	H, Pt	4 →	1.00±.02	use $1/2_1$ Pt roughly mix. jab.
NA10	S. Falciano et al (1981) Physics Letters 103B, 416	280 π^-	C, Cu, W	4.5-8.5 GeV/c	0.97±.01±.02	
CP	A.F. et al, PRD 25 (1982)	225 π^-	Be, Cu, Sn, W	4-8.5 GeV/c	.98±.04	

ρ+ω



(a) A dependence of yields of ρ+ω and J. Straight lines are least-squares fits to the data. Error bars are statistical only. (b) A dependence of the dilepton yield as a function of mass; cross-section per nucleus proportional to $A^{\gamma(M)}$. Vertical bars are statistical errors from least-squares fits. (c) A dependence of the dilepton yield in the ρ+ω mass region as a function of $p_\parallel$ and $p_\perp$ of the pair.




BRANSON et al. (Ref. 1)
THIS EXP.
ANTIPOV et al. (Ref. 13)
$\pi^- N$
$\alpha = 1.12$
J/ψ
(c)
α
M (GeV)
0
1
2
0
2
4
6
8
10
12

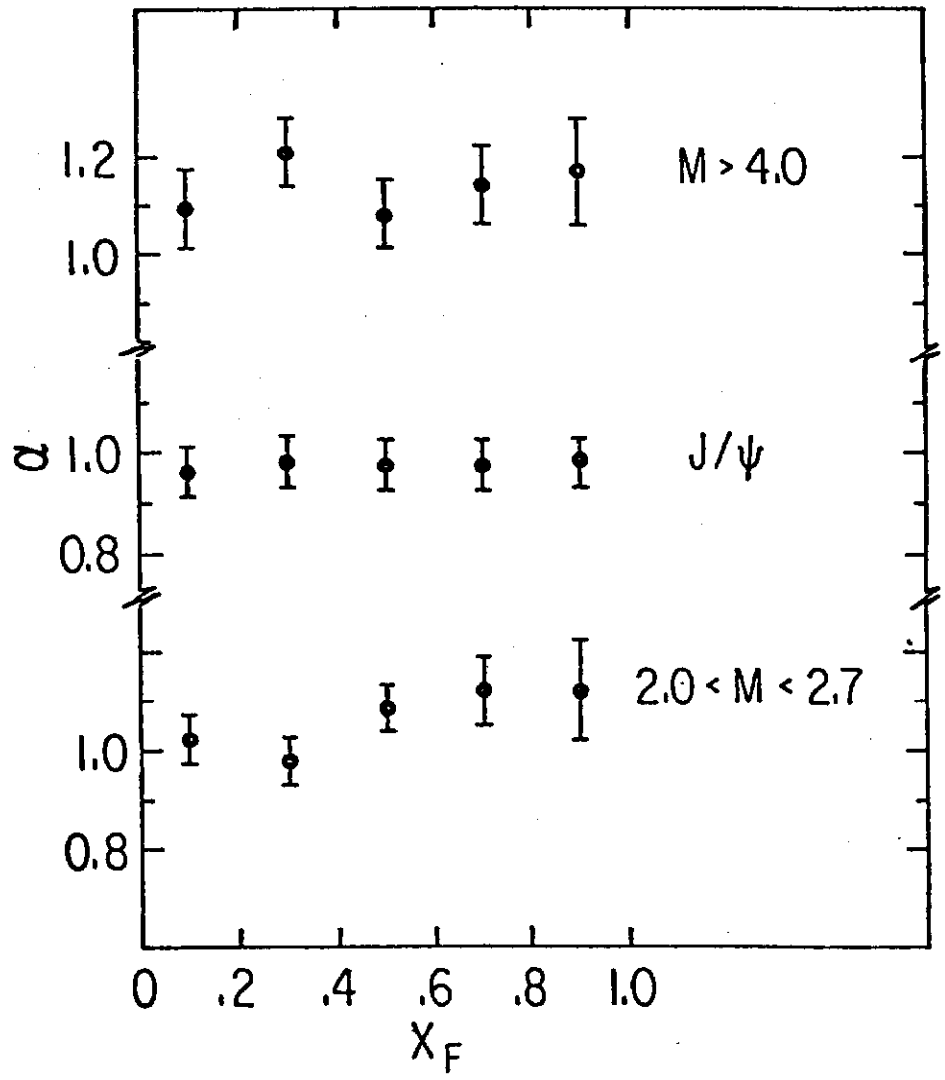

M > 4.0
J/ψ
2.0 < M < 2.7
α
X_F
1.2
1.0
1.0
0.8
1.0
0.8
0
.2
.4
.6
.8
1.0

Fig. 11

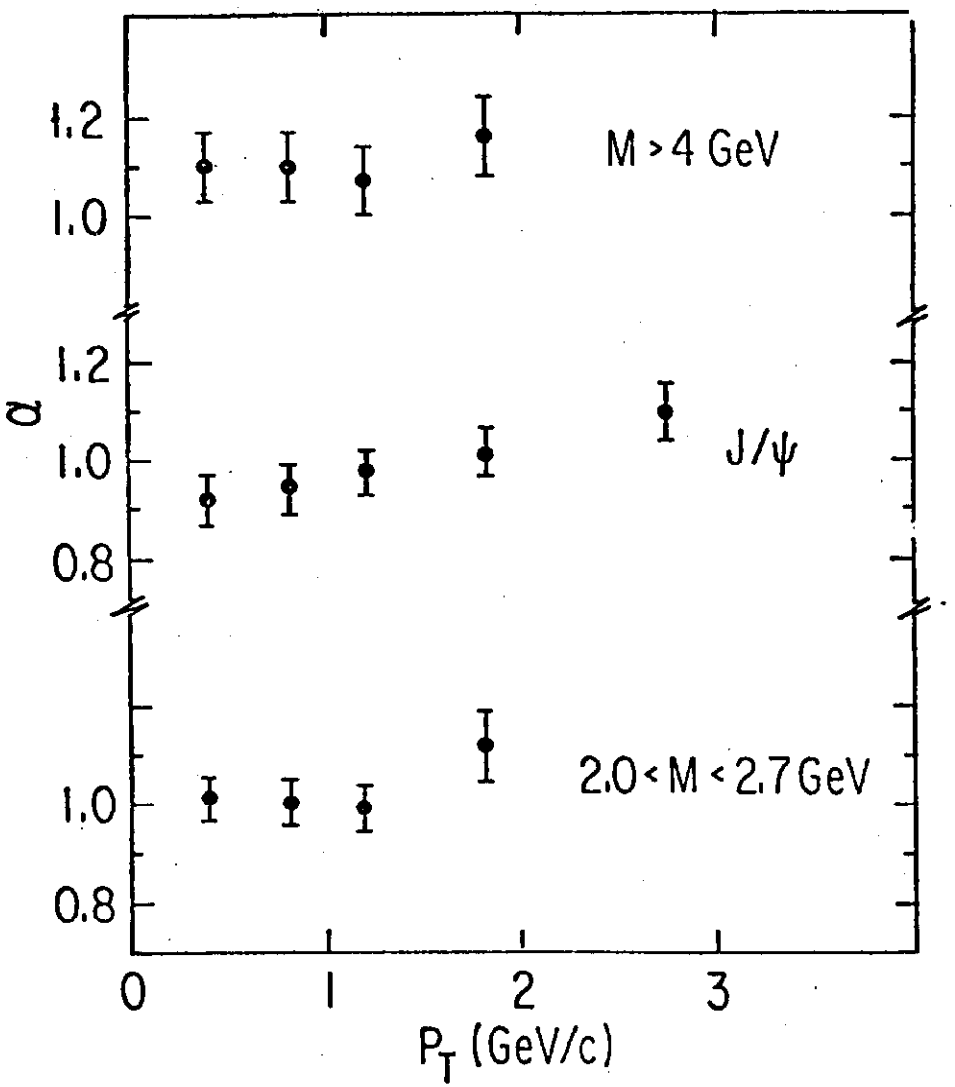


Fig. 10

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Table 2
Comparison between the experimental and the predicted ratio of cross sections on hydrogen and platinum.

Particle	R_{th}	R_{exp}	R_{exp}/R_{th}	α
π^- 200 GeV	1.45	1.35 ± 0.13	0.93 ± 0.15	1.02 ± 0.03
π^+ 200 GeV	0.89	1.13 ± 0.19	1.27 ± 0.25	0.95 ± 0.04
π^-–π^+ 200 GeV	1.92	1.60 ± 0.34	0.83 ± 0.25	1.03 ± 0.05
π^- 150 GeV	1.47	1.47 ± 0.07	1.00 ± 0.10	1.00 ± 0.02
π^- 280 GeV	1.41	1.40 ± 0.07	0.99 ± 0.10	1.00 ± 0.02

not very sensitive to the choice made for the structure functions.

These Drell–Yan predictions can be computed as functions of various parameters and compared to the experimental cross section ratios.

Table 2 summarizes the results for the different energies. The comparison between the experimental and predicted ratio is indicated also for the difference between π^- and π^+ cross sections at 200 GeV. This latter measurement is interesting as, in that case, the possible contribution of hadronic processes to muon pairs production cancels out. α is extracted from: $A^{1-\alpha} = R_{exp}/R_{th}$.

For the experimental ratio, only statistical errors are quoted but for R_{exp}/R_{th} and α systematic errors are included. This systematic error accounts for the uncertainty on the number of nucleons in the targets (7%), the error on the ratio of the acceptances (5%), and the model dependence of the predicted R (5%). Notice also that our results are independent of absolute normalisation problems as our data are taken simultaneously on hydrogen and platinum.

Fig. 2 shows the variation of the experimental ratio R with $\sqrt{\tau} = M/\sqrt{s}$, x_1 and x_2 (x_1 and x_2 are the fractional moments of the incident and target quarks, respectively). The agreement between the experimental points and the theoretical predictions (full lines) is very satisfactory.

We also show in fig. 2 the variation of R with the transverse momentum of the dimuon. No significant variation is observed up to 4 GeV/c.

In conclusion our data on hydrogen and platinum targets are compatible with the absence of nuclear effects, as expected in the Drell–Yan model, this prediction remaining unchanged by QCD corrections. This is found to be true within our experimental errors in the energy interval 150 to 280 GeV/c. The ratio of the

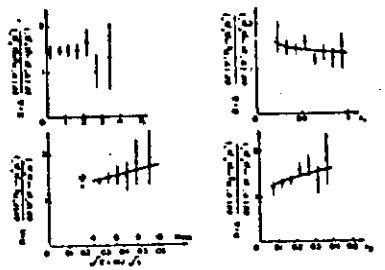


Fig. 2. Hydrogen to platinum cross section ratio (per nucleon) for incident π^- at 150 GeV as functions of P_T, x_1, x_2 and mass.

cross sections, divided by the expected ratio, is 1.00 ± 0.10, or in other words α = 1.00 ± 0.02.

In order to be less sensitive to acceptance corrections and structure function effects, we have performed another measurement using platinum and carbon targets [5] simultaneously. The size of each target has been chosen such as to give the same absorption length for both. To get rid of acceptance problems, the targets have been inverted every 6 hours. In that case the result for α is 0.97 ± 0.05 in good agreement with our previous measurements (the quoted error is statistical only).

Some other experiments have measured α for the dimuon continuum. With incident 400 GeV protons on Be, Cu and Pt targets, the CFS collaboration [6] quoted a result compatible with α = 1 [α = 1.007 ± 0.018 (statistical error) ± 0.028 (systematic error)]. An early determination of α by the CIP collaboration [7], using π^- at 225 GeV/c on C, Cu and W targets gave α = 1.12 ± 0.05. The consequence of this difference from 1 is to multiply the cross section (per nucleon) of dimuon production by a factor 1.8 and therefore to alter the abso-

Conclusions

1. Single particle high p_T production.
   a. $\alpha(p_T)$ rises to >1
   b. depends on particle type
   c. lots of precise data.

2. Dihadron production.
   a. experimental situation isn't so clear
   b. needs a careful job experimentally ($E605^{\pm}$)
   c. needs some thoughtful modelling

3. Dimuon production
   a. $\alpha = 1$ in $\pi^- p$ and pp collisions in kinematic regions explored.
   b. Can be pushed to larger $\tau = \frac{m}{\sqrt{s}}$ and a wider range of x_1 & x_2

It's probably time for a larger investment in facts.

NUCLEAR EFFECTS AT HIGH p_T

$\mu^+\mu^-$ Constraints $\boxed{\text{J. GUNION}}$

Approaches: A) Nucleus $\neq$ A Nucleon

i) Fermi Motion — Kuhn, Fredriksen

ii) QCD coherence — Krzywicki

iii) Fluctons — Lukiyanov...

iv) Tube Models — Dar..., Nasuda, Fredriksen

B) Nucleus = A Nucleon + Dynamical Processes'

i) Intrinsic k_T buildup.

ii) Multiple Hard Scattering

Farrar, Kuhn, Fishbane..., Pumplin-Yen, Krzywicki..., Takegi

iii) Multiple Jet Production

Takagi, Zmushko

Constraints: A) $\mu^+\mu^-$/DI — Factorization; Beam/... attenuation; intrinsic k_T

B) Correlations — Symmetric Pairs

Category A)

All based on $G_{q/A}(x) \neq A\, G_{q/N}(x)$

where $x = \dfrac{p^+_{parton}}{p^+_{Nucleus}/A} = \dfrac{p^+_{parton}}{p^+_{\langle Nucleon\rangle}}$

i) Fermi Motion

$$\Delta x = \frac{p^+_{parton}}{p^+_{\langle Nucleon\rangle} + p_{Fermi}} - \frac{p^+_{parton}}{p^+_{\langle Nucleon\rangle}}$$

$$\sim -\frac{p_F}{M}\, x$$

$\Rightarrow$ too small an effect for reasonable p_F

Also p_F changes slowly with A at higher A.

ii) Coherent Distribution: Extreme-assumes Nucleus = Collection of quarks

$$G^{Coh}_{q/A}(x) \underset{\text{large } A}{\propto} A\, e^{-bx} \qquad b \approx 6$$

$$\text{or} \quad G^{InCoh}_{q/A}(x) \propto A\, (1-x)^{[3+7]}$$

after normalization

$$\frac{G^{Coh}_{q/A}}{G^{InCoh}_{q/A}} > 1 \quad \text{for moderate and high } x.$$

$S_{eff} = \nu S$ $\quad \nu$ = # of nucleons in tube or fluctuation

$G_{q/A}(x) = G_{q/N}(x/\sqrt{\nu})$ in general average over various ν values

Effectively $E\dfrac{d\sigma^{p\nu}}{d^3p}(p_T, x_T) = E\dfrac{d\sigma^{pN}}{d^3p}\left(p_T, \dfrac{x_T}{\sqrt{\nu}}\right)$

or summing over ν's appropriately weighted

$$\frac{\sigma^{pN}_{in}}{\sigma^{pA}_{in}} E\frac{d\sigma^{pA}}{d^3p}(p_T, x_T) = \sum_{\nu=1}^{A} E\frac{d\sigma^{pN}}{d^3p}\left(p_T, \frac{x_T}{\sqrt{\nu}}\right) P_\nu$$

$$\approx E\frac{d\sigma^{pN}}{d^3p}\left(p_T, \frac{x_T}{\sqrt{\nu}}\right)$$

Fortunately all of these approaches are <u>ruled out by deep inelastic and $\mu^+\mu^-$ pair exp</u>

$$\nu W_2^A(x_{Bj}) = A'\, \nu W_2^N(x_{Bj})$$

relative to $\langle N\rangle$

$$\frac{d\sigma^{pA}}{dQ^2_{\mu^+\mu^-}} = A' \frac{d\sigma^{pN}}{dQ^2_{\mu^+\mu^-}} \quad \text{at fixed } Q^2/S_{Nucleus}$$

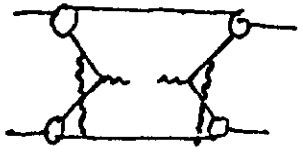
These experimental results are unnatural in category A) models.

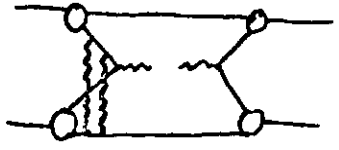
Theory: $G_{q/A}(x) = A\, G_{q/N}(x)$

$\Rightarrow$ A^1 above

$\mu^+\mu^-$ theory review: (Brodsky, Bodwin, Lepage, Mueller) Sopper, Collins, Sterman?

$\boxed{\text{Factorization}}$: (DI $\to \mu^+\mu^-$) violated by (e.g.) initial active-spectator interactions.

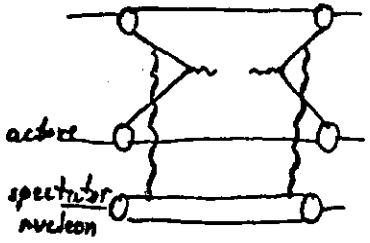
1  $\to$ color $= C_1$

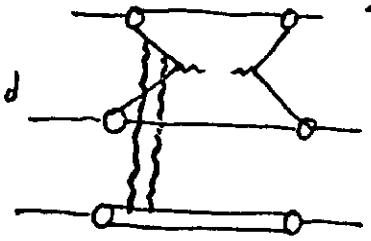
2  $\to$ color $= C_2$

If $C_1 = C_2$ (Abelian theory) then Glauber cuts of 1 + 2 cancel. But $C_1 \neq C_2$ (QCD)

$\Rightarrow$ temporary (Sudhakov suppressed) color enhancement. as $Q^2 \to \infty$

None the less A^1 still expected since



and 

$\to$ same color factor

$\to$ cancellation of interactions with spectator N.

i.e. $\mu^+\mu^-$ probes nucleon by nucleon.

Note: A^1 applies only to $\int d^2Q_T \frac{d\sigma}{dQ^2 d^2Q_T}$!

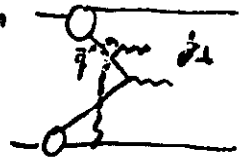
Fixed Q_T is disturbed by momentum ℓ_T transferred by each interactions

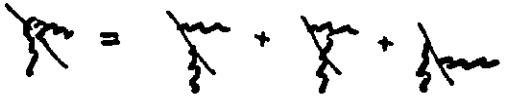
$$(k_T^2)^A_{eff} \sim (k_T^2)_N + \langle \ell_T^2 \rangle_A \propto A^{1/3} \langle \ell_T^2 \rangle_N + \langle k_T^2 \rangle_N$$

$\Rightarrow$ A dependent contribution to $\langle Q_T^2 \rangle$ coming from build up of "primordial" $(k_T^2)^A_{eff}$ inside nucleus

$\boxed{\text{Beam / Jet Attenuation}}$

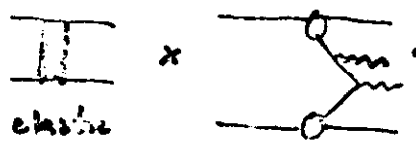
In QCD from radiation from beam object.

eg Beam 



In Abelian theory and Non-Abelian

$j_\perp > l_\perp \Rightarrow$



elastic phase

standard evolution for $j_\perp > l_\perp$ "perturbative part"

But

In QCD color factors of virtual graph and above radiation graph dont match for interactions with $\boxed{\text{active}}$ nucleon $\Rightarrow$ factorization break down and color enhancement (Sudhakov suppressed as Q^2 ...

for $\boxed{\text{spectator}}$ nucleon $\Rightarrow$ color factors match and still get $A^{\perp}$ including bremstrahlung effects.

at $j_\perp < l_\perp$ we are in trouble in both cases ~~notices~~ i.e. there is actual attenuation unless

$$(\Delta p_z)^{\text{spectator}} L_{\text{Target}} << 1$$

equivalent to

$$\sqrt{t_{min}}\; L_{\text{Target}} << 1$$

$$\sqrt{t_{min}} \sim \frac{\Delta M^0_{\text{radiation}}}{2E_{\text{radiation}}} \sim \frac{\ell^{\text{GMP}}}{\sqrt{s}}$$

At high s we are okay over nuclear length (but not over macroscopic target length).

This condition equivalent to Landau–Pomeranchuk coherence length argument

$$\tau^{\text{lab}}_{\text{radiation}} \sim \underbrace{\frac{E}{m_{\text{gg}}}}_{\text{boost factor}} \tau_0$$

or

$$\ell_{\text{radiation}} \sim \frac{E}{m}\, \ell_0$$

$$\overset{m \sim \ell_T}{\sim} \frac{x_F\, s}{M^2 \ell_T^2}$$

ℓ_T^2 = typical off shell mass

if $\ell_{\text{radiation}} >> L_{\text{Target}} \rightarrow$ no radiation

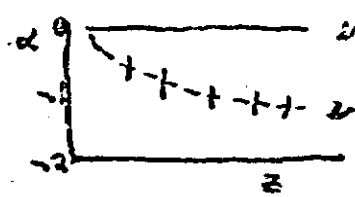
$\rightarrow$ same as above condition.

Radiation takes distance and time to develop!

Radiation length arguments also apply to final state. Should see e.g.

not attenuated if $s \to \infty$ at fixed x.

Experiment? measure $\dfrac{\left(\frac{d\sigma}{dx}\right)^A}{\left(\frac{d\sigma}{dx}\right)^N} \sim A^\alpha$ in current fragmentation region



$z \approx 0.5$ CLAS data

Category B) approaches ignore possible attenuation effects — ok as $s \to \infty$ fixed x_T.

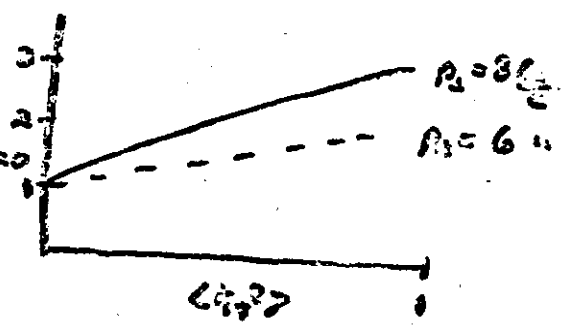
Category B) approaches ignore A^{1} breakdown — (ok for both initial and final state rescatterings as in $\mu^+\mu^-$) — for single hard scattering.

Category B) : A^{1} + Dynamics

i) Intrinsic $\langle k_T^2 \rangle^A_{eff} \propto A^{1/3} \langle k_T^2 \rangle + \langle k_T^2 \rangle_N$

In some high-p_T calculations $\langle k_T^2 \rangle_{eff}$ influences $\sigma \dfrac{d\sigma}{d^3p} \equiv \Sigma$

$$R = \frac{\Sigma^{pp \to hX}\big|_{k_T}}{\Sigma^{pp \to hX}\big|_{k_T=0}}$$



$\approx R \approx a \langle k_T^2 \rangle + 1$

$$\Rightarrow A^{\alpha(A)} \sim \frac{\Sigma^{pA \to hX}}{\Sigma^{pp \to hX}} \sim A \left(\frac{a \langle k_T^2 \rangle^A_{eff} + 1}{a \langle k_T^2 \rangle_N + 1} \right)$$

$$\sim A + c\, A^{4/3}$$

However a_c decreases as p_T increases; data shows opposite

Also Σ less influenced by $\langle k_T^2 \rangle \Rightarrow \alpha_{eff} < \alpha_h$; also opposite data.

Symmetric Pair Production also not influenced by $\langle k_T^2 \rangle_{eff} \Rightarrow \alpha_{pair} < \alpha_n$; Exp.?

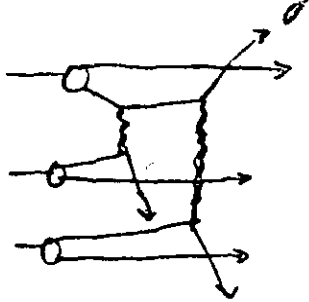
Conclusion: Multiple Scattering / Multiple Jet only approaches yielding

i) $\alpha(p_T) > 1$ increasing with p_T

ii) $\alpha_{Jet} > \alpha_n$

iii) consistency with $A^{\perp}$ for $\mu^+\mu^-$ / DI

Multiple Scattering:



$$\Sigma^{pN\to h}(p_T) = A\,\Sigma^{pp\to h}(p_T) \quad (1)$$

$$+ \underbrace{\frac{A^2}{aR^2}}_{\sim A^{4/3}} \sum_s \int_{k_T^{min}}^{p_T - k_T^{min}} \frac{d^3k}{\sqrt{s}}\, \Sigma^{pN\to s}(k_T) \cdot \Sigma^{sN\to h}(p_T - k_T) \quad (2)$$

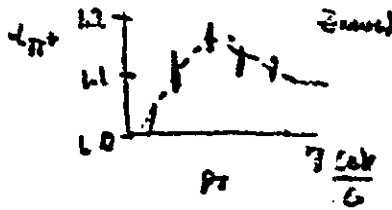
k_T^{min} separates "hard" from "soft".
= parameter of fits

(must have $\sigma_{hard} / \sigma_{soft} \ll 1$ for above [illegible])

Attenuation of quark / gluon beam / jet / secondary neglected

Most authors $s = q$ or g; s = hadron in CTM

Many reasonable fits to data made. E.g.



Zeuchhofit $\underbrace{\hat{s}, \hat{t}}_{\text{hard scattering}} > 7\ \text{GeV}^2$

$\boxed{\text{Note!}}$ For power law behaved Σ's, both (1) and (2) have same asymptotic $\left(\frac{1}{p_T}\right)^n$ behavior.

$\rightarrow \alpha(p_T) \xrightarrow[p_T]{\text{large}}$ constant (until p.s. boundary)

$\alpha(p_T)$ rises at moderate p_T since convolution temporarily splits p_T; as $p_T \uparrow$ splitting becomes asymmetric.

$\alpha(p_T) \to 4/3$ when $p_T \to$ p.s. boundary for single scattering; equivalently $\alpha(p_T)$ rises as $\sqrt{s}$ decreases to p.s. boundary of $2p_T = \sqrt{s}$.

Note 2 More sophisticated approaches distinguish s = quark from s = gluon

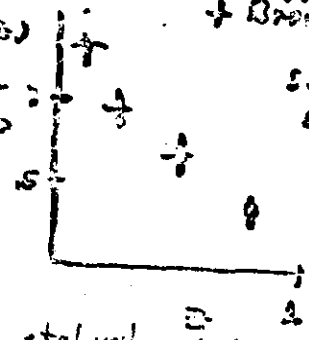
$$\Sigma^{quark} < \Sigma^{gluon} \text{ in QCD}$$

$\Rightarrow$ gluon enhancement.

$\Rightarrow \alpha^{\pi^-,\bar{p}}(p_T) > \alpha^{\pi^+}(p_T)$

$\overset{?}{\Rightarrow}$ since $D_g(z)$ is softer than $D_q(z)$

$$\frac{D_{jet}^{A}(z)}{D_{jet}^{\nu}(z)}$$



+ Bromberg et al. $A = Al$ softer A spectrum

and $d_{jet} > d_h$

Kronicki et al yes! jet trigger enhances g-no trigger constraint

Takagi no! numerically insufficient

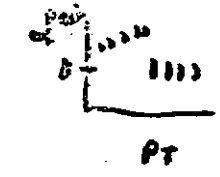
Jet more complicated due to possible low p_T contamination. Nikolaev claims reasonable low p_T contamination $\Rightarrow$ entire $d_{jet} > d_h$ and "soft jet" effect.

Munich Calorimeter experiment interpreted in this way.

Note 3 Further Tests?

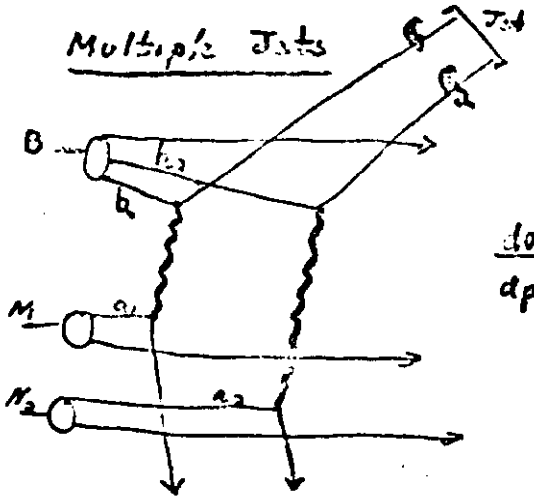
- Multiple Scattering $\Rightarrow$ dilution of opposite side p_T into p_T [illegible] at moderate p_T where splitting occurs
- M S $\Rightarrow$ smaller $\alpha(p_T)$ for symmetric pairs at moderate p_T; asymptotic p_T's $\Rightarrow$ unequal splitting and $\alpha^{pair} \approx \alpha^{single}$

Expt: Take your choice



Caution: Symmetric Pair suppressed, unless $|\vec{p}_T^{\,1} + \vec{p}_T^{\,2}|$ window is big, by T factor.

Multiple Jets



$$\frac{d\sigma^{Jet}}{dp_T} = A \int \frac{d^3p_J}{E_J} \Sigma(p_J)\, \delta(p_T - p_{JT})$$

$$+ \int \frac{d^3p_1}{E_1} \frac{d^3p_2}{E_2} \Sigma(p_1, p_2)\, \delta(|p_{T1} + p_{T2}| - p_T)$$

+ n.s. terms

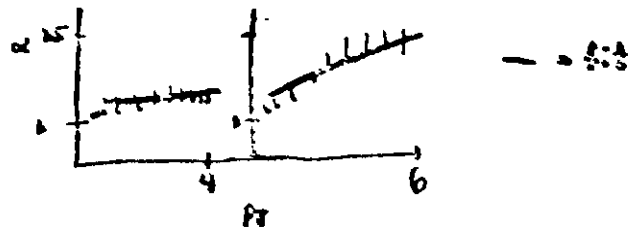
$$\Sigma(p_1, p_2) \propto A^{4/3} \int dx_{a_1}\, dx_{a_2}\, dx_{b_1}\, dx_{b_2}$$

$$G_{b_1 b_2/B}(x_{b_1}, x_{b_2})\; G_{a_1/M_1}(x_{a_1})\; G_{a_2/M_2}(x_{a_2})$$

$$\frac{\hat{s}_1}{\pi} \frac{d\sigma}{d\hat{t}_1}\, \delta(\hat{s}_1 + \hat{t}_1 + \hat{u}_1) \quad \frac{\hat{s}_2}{\pi} \frac{d\sigma}{d\hat{t}_2}\, \delta(\hat{s}_2 + \hat{t}_2 + \hat{u}_2)$$

Extreme assumption (Zmushko) $M\sigma \to$ jets but negligible in s.p. $\Rightarrow \alpha_\sigma > \alpha_h$ since additional $A^{4/3}$ mechanism.
Better (Takagi) C_1 and C_2 separately fragment; still $\Rightarrow \alpha_\sigma > \alpha_h$

good combined fit with n.s. included p_{T1} and $p_{T2} > .25$ GeV/c



? is it impossible for C_1 and C_2 to cohere and fragment collectively?

If not above calculation consistent and σ^{π}_{jet} soft vs σ^{ρ}_{jet}.
Equally well fit as Mikolaev.

Zmushko claims $\alpha^{p\,beam}_{jet} > \alpha^{\pi\,beam}_{jet}$
I don't see where from.

Test! Double Jets at big $\Delta\phi$ should be seen.
Munich experiment could easily have such a double jet contamination even on proton target

Double Jet / Low p_T contamination different realms of same idea; p_{T1} or p_{T2} could be small.

A. MUELLER

A-Dependence and Jet Evolution in Nuclear Matter

Physics of Deeply Inelastic Scattering, μ-Pair Production and hard γ production has many similarities.

I. Deeply Inelastic Scattering in Nuclei

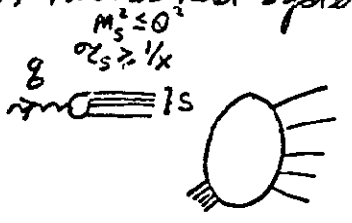
For Lead [Goodman et.al (PRL 47, 293(1981))]

$$\frac{A_{eff}}{A} \approx 0.6 \text{ for } \underbrace{Q^2 \lesssim 2\text{-}3\,\text{GeV}^2,\ \langle\nu\rangle \approx 150}_{x \lesssim 0.01}$$

As much shadowing as for real photons.

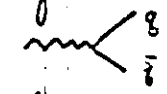
There are two distinct ways to view the process.

(i) Nuclear Rest System

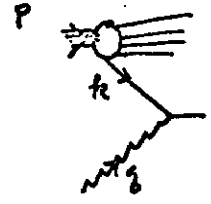


$$\sigma_{\gamma A}^{in} = \sum_S |(\gamma|S)|^2 \sigma_{SA}^{in}$$

Brodsky-Pumplin
Gribov
Bell

When S is expressed in terms of quarks and gluons $(\gamma|S)$ can be calculated. Whether $\sigma_{SA} \sim A$ or $A^{2/3}$ depends on the transverse size of S. Eg:  If quark transverse momentum is large as Q - then $|\underline{b}| \lesssim 1/Q$ and there will be no shadowing when Q^2 is large.

(ii) Fast Nucleon Frame



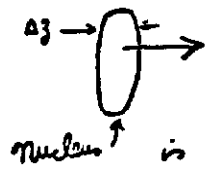
$P = A\,p$ $\qquad k_z = x\,p$

$$q = (\underset{\text{small}}{\overset{t}{q}}, \overset{x,y}{\underset{\text{small}}{q}}, \overset{z}{0})$$

Measure $P_A(x, Q^2)$.

No Shadowing $\Rightarrow P_A(x,Q^2) = A\,P_{\frac{N+P}{2}}(x,Q^2)$

"Naive Parton Model"



Valence quarks occupy size $\Delta z = 2R\frac{m}{p}$

Longitudinal size of sea quark or gluon is $\Delta z = 1/k_z$.

When $1/k_z > 2R\frac{m}{p}$ or $x \le \frac{1}{2Rm} \approx 0.01$ for Lead we expect shadowing.

That is when $x \lesssim \frac{1}{2R_m}$ there is a physical overlap of sea quarks and gluons. We might expect that the normal "equilibrium" density is less than $\sim A^{1/3}\times$ that of a single nucleon.

Naive Parton model can be misleading because struck quark has small transverse size!

To look further consider nuclear evolution

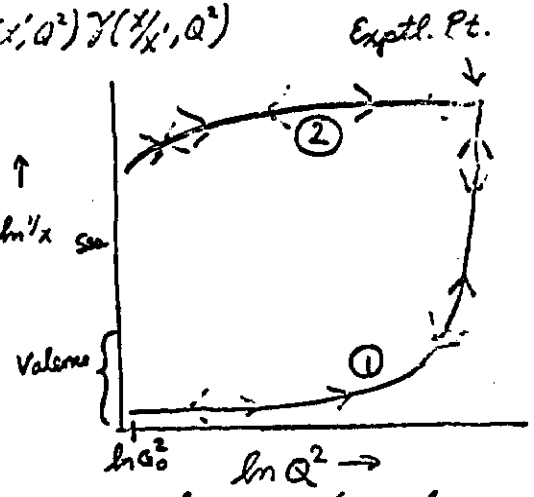
$$\frac{\partial}{\partial \ln Q^2} P(x,Q^2) = -\int_x^1 \frac{dx'}{x'} P(x',Q^2)\,\mathcal{P}(x/x',Q^2)$$

Red shows evolution from nuclear state (ii)

Green shows evolution of individual photon (i)

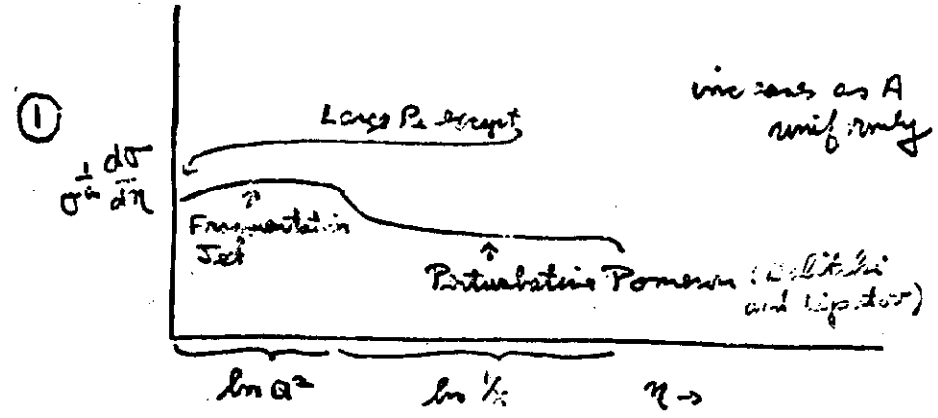
① Clearly $P_A = A P_{\frac{N+P}{2}}$

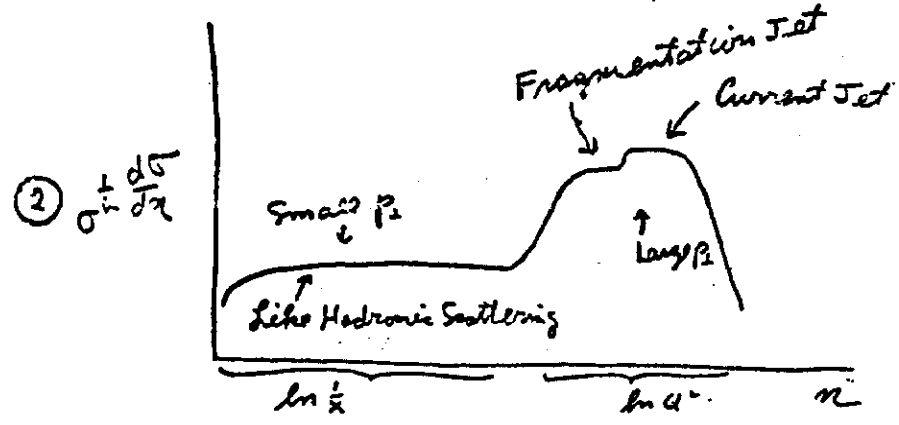
② Shadowing



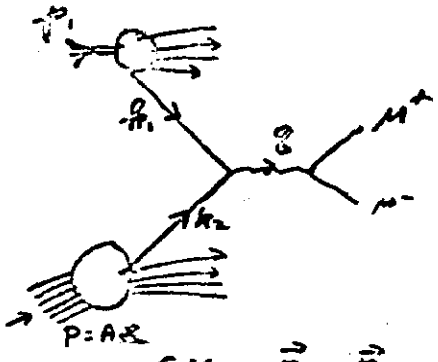
There is a formula giving $P(x,Q^2)$ as sum of all Paths

What about final state





II. μ-Pair Production



$k_{1z} = x_1 p_1$

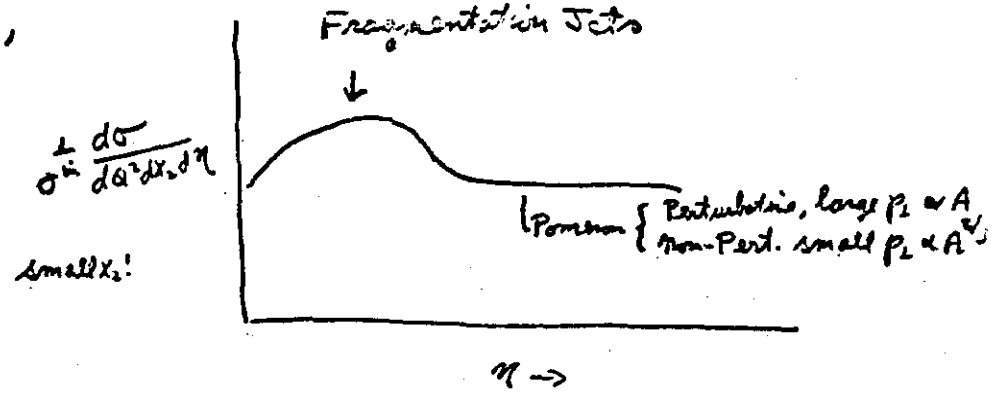
$k_{2z} = x_2 p_2$

$Q^2 = 2 p_1 p_2 x_1 x_2 = x_1 x_2 s$

Shadowing will occur only when x_2 is small, presumably for $x_2 \lesssim 0.01$

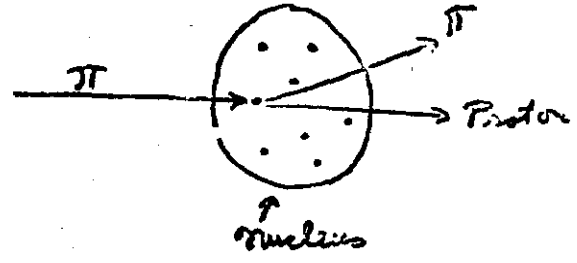
C.M. $\vec{p}_1 = -\vec{p}_2$

μ-pair measures sea distribution of nucleus for small x_2.

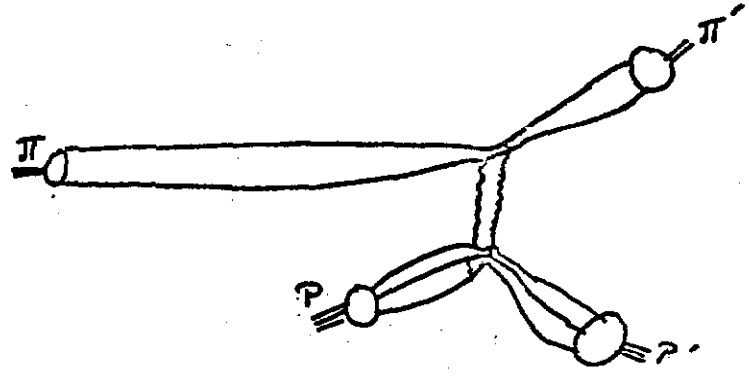


III. $\pi + A \rightarrow \pi' + p' + (A-1)$

nucleus not disrupted



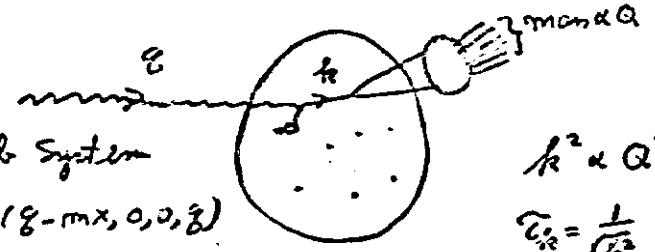
How can this happen? Look at π-p elastic scattering



For a long time before the collision, $\tau \sim p/m$, the π and proton are very small. At time of collision $|\Delta \vec{x}| \sim \frac{1}{\sqrt{-t}}$. π' and p' were functions stay small for long time after collision.

IV Current Jets

Take Deeply Inelastic Scattering on nucleus with x not small.



Lab System

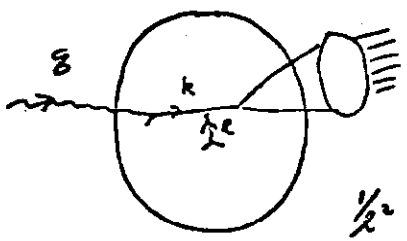
$q = (q - mx, 0, 0, q)$

$Q^2 = 2mqx$

$k^2 \propto Q^2$

$\tau_k = \frac{1}{\sqrt{k^2}} \cdot \frac{k}{\sqrt{k^2}} = O(1)$

Current Jet begins to evolve in the nucleus but interactions with nucleons in the nucleus should not disturb jet.

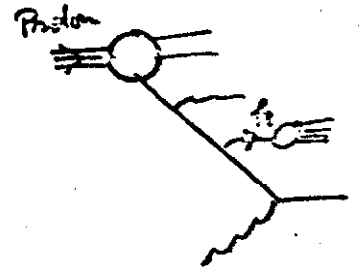


Interaction goes as $1/l^2$ for large l^2. Small l do not modify jet structure.

Current Jets are not significantly modified by nuclei

V Fragmentation Jets

A. Fragmentation Jets in DIS off Nucleons.



$\tau_k \sim \frac{1}{\sqrt{k^2}}$

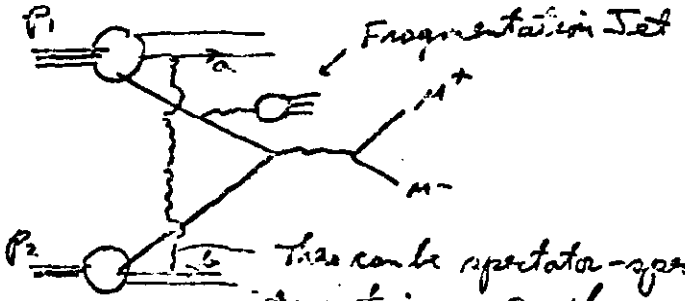
Should be like current jets but more squashed toward $x = 0$.

B. DIS of Nuclei

In above picture k^2 is large. Just like in current jet k should suffer no hard interactions with spectator nucleons.

Fragmentation Jets in DIS are not modified by nuclei.

C. μ-pair production in hadron-hadron collisions



There can be spectator-spectator interactions. If the exchange is a gluon there is not a radical modification of the final state. However, a and b can have an inelastic interaction which is very inelastic.

D. μ-pair production in Hadron-Nucleus Collisions

Now particle 2 is a nucleus. a can have inelastic collisions with many nucleons in nucleus.

In μ-pair production a superposition of fragmentation jet and soft hadronic interactions should occur.

(L. VOYVODIC)

A^α Behavior in Soft Collisions – Experimental Review

Single Particle Yields

$$a + A \rightarrow b_j(\theta, P, m) + X$$

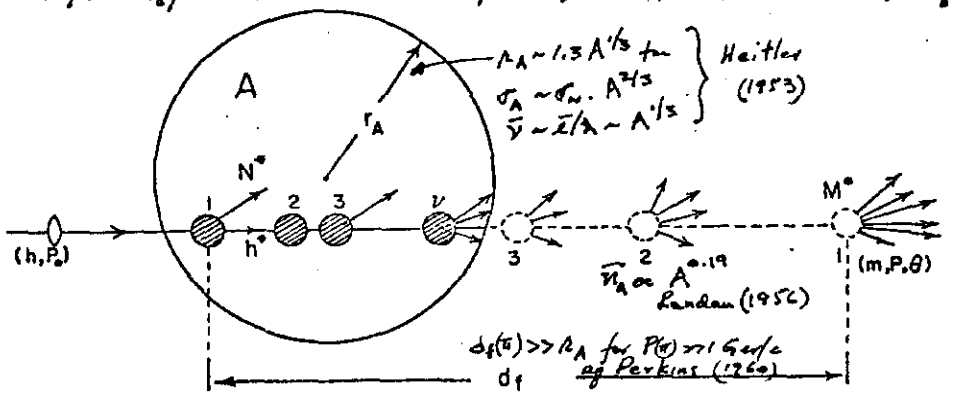
Multiparticle Events

$$a + A \rightarrow (b_1 + b_2 + \cdots b_n) + (N_p + X)$$

"produced" + "nuclear response"

Ancient History & Mythology (~1950 – 1975)

"High Energy Nuclear Collisions are Very Hydrogen-like, show Nuclear Transparency"



Forward hemisphere particles "hydrogen-like", $\frac{d\sigma}{dy} \propto A^{2/3}$;
Some enhancement in target region, $\frac{d\sigma}{dy} \propto A^{\alpha}$
Gottfried, Friedlander etc (~1975)

EXPERIMENTAL METHODS

"4π" – VISUAL
- Nuclear Emulsions (bare, foils, wires ...)
- Bubble Chambers
  HLBC (eg NeH, C_3H_8, CF_3Br, Xe)
  HBC + fields (Fermilab, KEK)
- Streamer Chambers (bare Neltte, foils, gas tubes etc)

"4π" – Electronic Hodoscopes
- Lucite Č (Busza et al) : $\beta \gtrsim 0.90$: $\Delta n/\Delta \eta$
- Lucite Č + CsI(Tl) (Faessler et al) $\beta \gtrsim 0.70$; used N_p to simulate Emulsion N_g

SPECTROMETERS
- Small aperture, single particles, at fixed θ.
- Large (forward) apertures, multiparticles

A^α Parameters:

$$\frac{E\,d^3\sigma}{dp^3} = Y_1 \cdot A^{\alpha(x_F,\,P_T)}$$

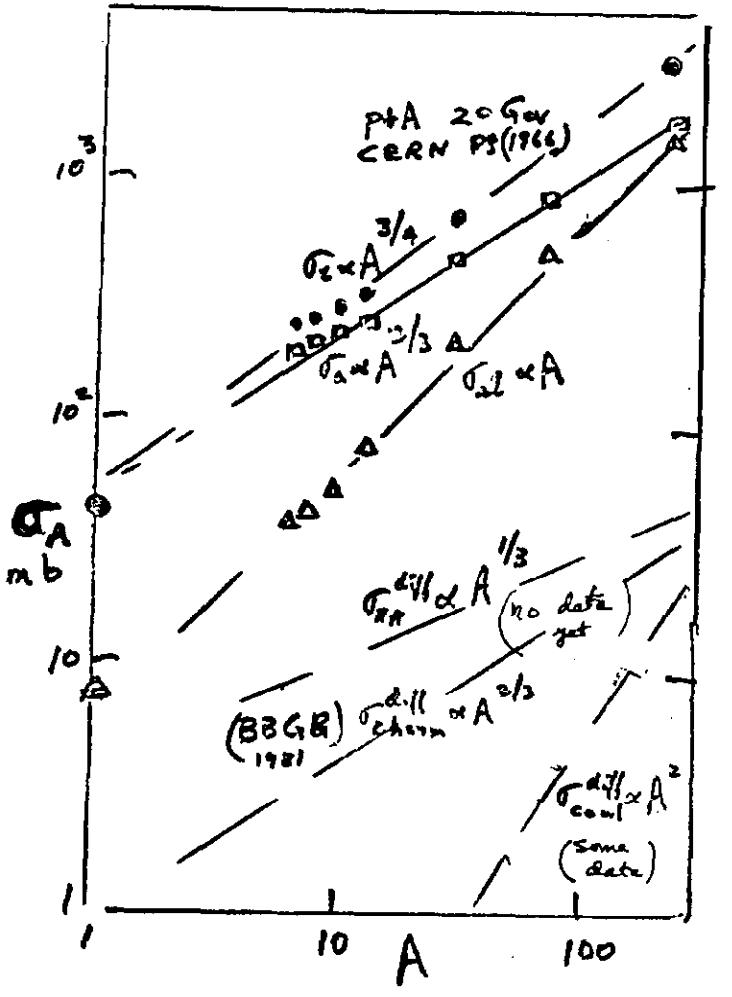
$$\frac{d\sigma}{dy} = f_1 \cdot A^{\alpha(y)}$$

$$\frac{dn}{dy} = g_1 \cdot A^{\beta(y)} = \frac{1}{\sigma_{in}} \cdot \frac{d\sigma}{dy}$$

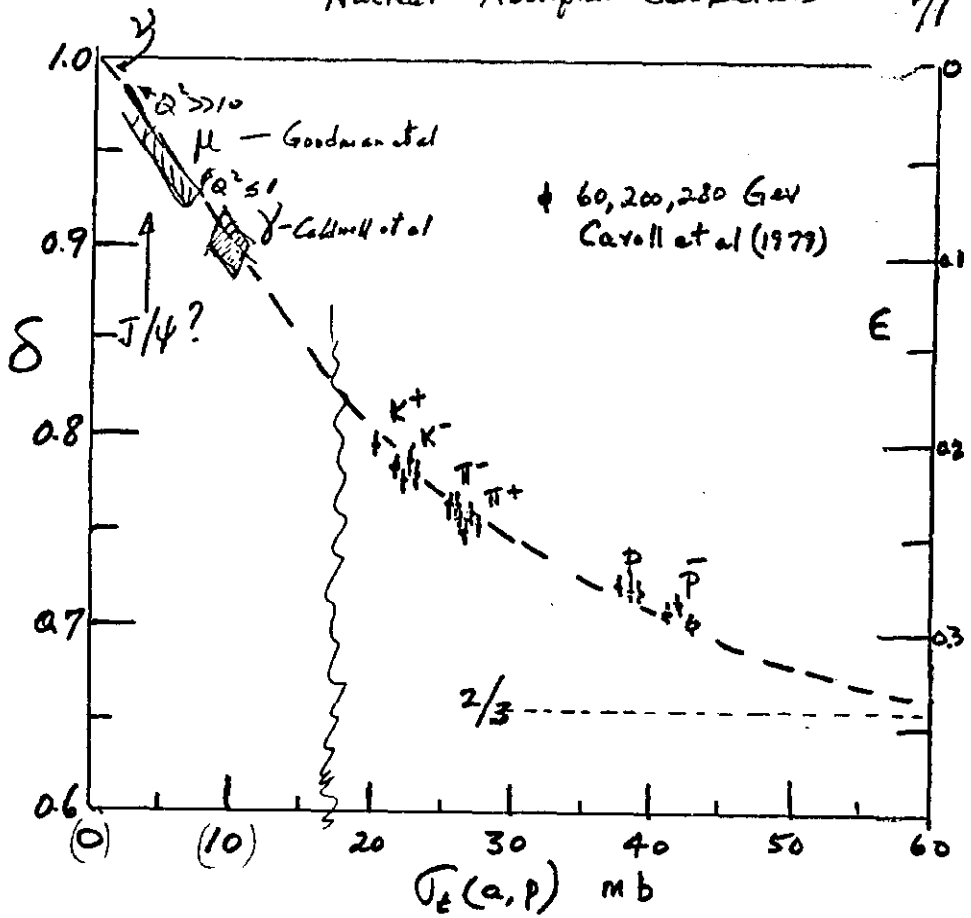
$$\bar{n} = \bar{n}_1 \cdot A^{\gamma} \quad ; \quad D/\bar{n}$$

$$\sigma_{in} = \sigma_1 \cdot A^{\delta} \quad ; \quad \bar{\nu} \propto A^{1-\delta}$$

Nuclear Cross Sections



Nuclear Absorption Cross Sections

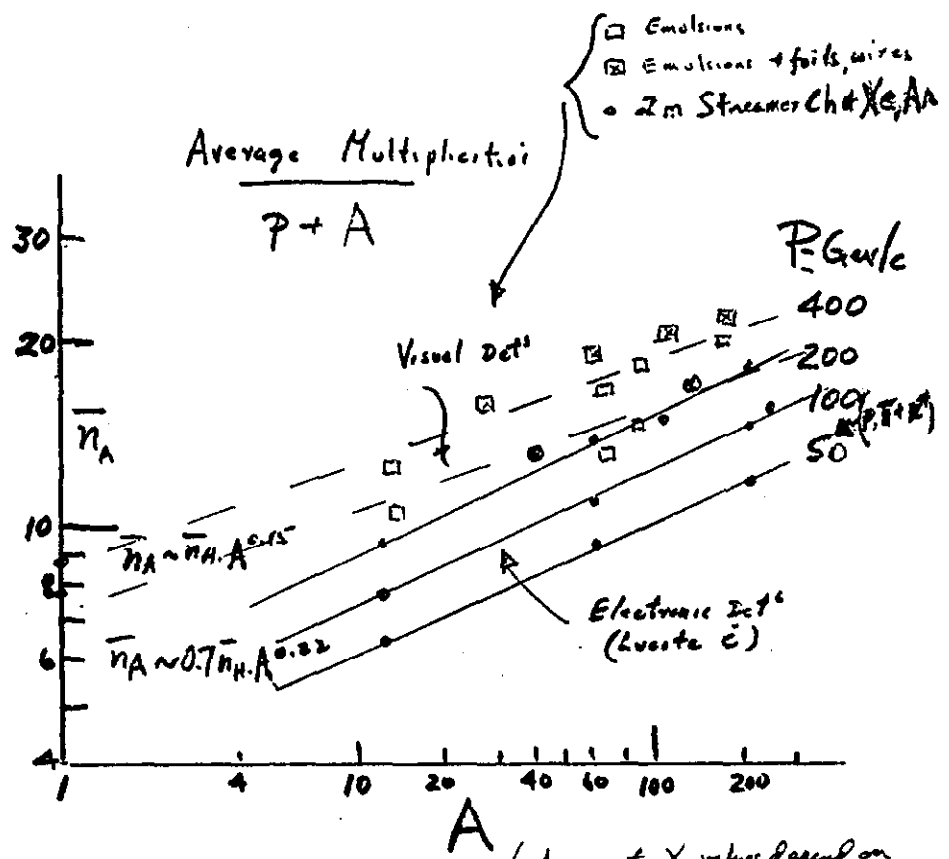


$$\boxed{\sigma_a = \sigma_1 \cdot A^{\delta}}$$

$\sigma_1 \simeq \sigma_t(hp)$ Carroll et al

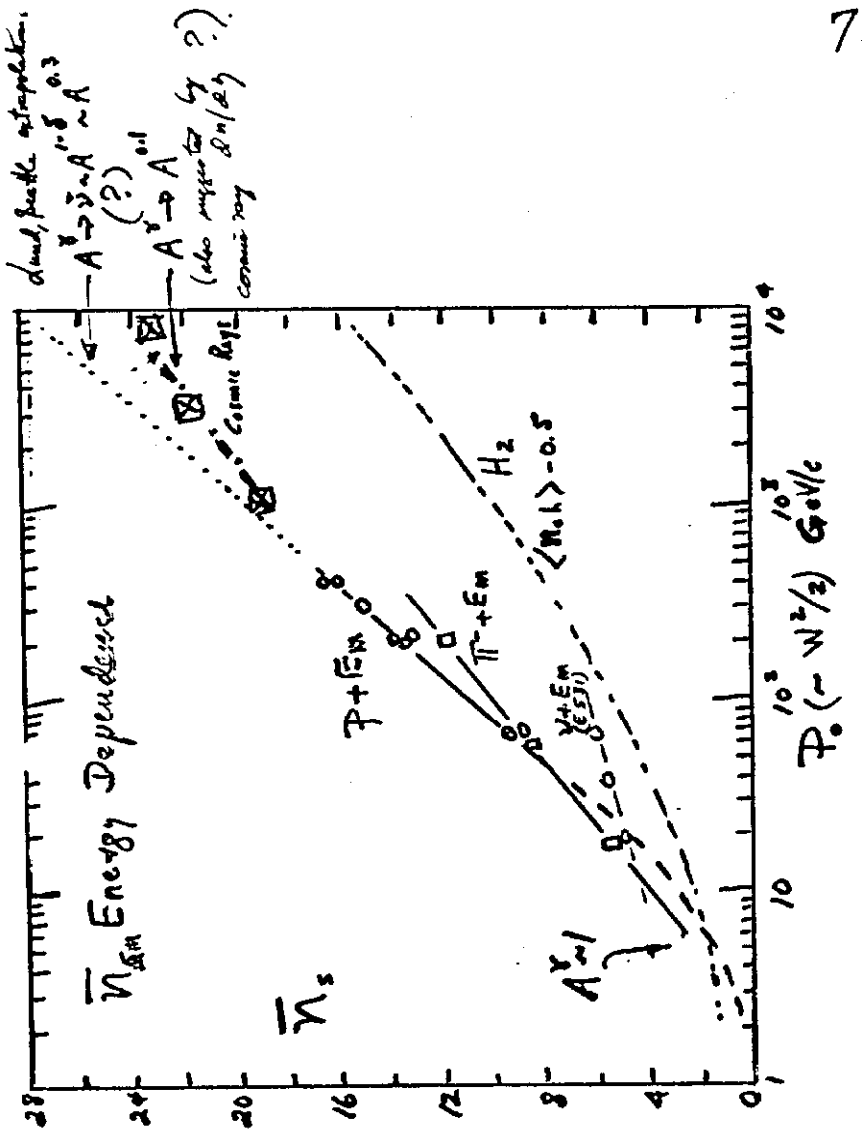
$$\bar{\nu} \simeq \left(\frac{\sigma_{in}}{\sigma_t}\right)_{cp} A^{(1-\delta)} \quad \text{(Glauber)}$$

Average Multiplicities

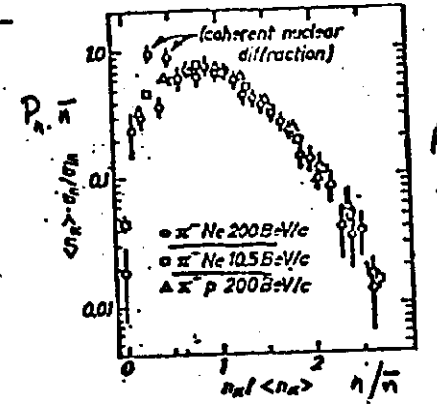


ie $\bar{n}_A = \bar{n}_1 \cdot A^{\gamma}$ (Apparent γ values depend on Experimental methods — indicate problems, systematic errors).

Also find positive particle excess from nuclei — chiefly protons — $\langle n^+ - n^- \rangle$ depends on ionization resolution of detector. Most useful parameters for multiplicities are n^- (ie π^-), and N_g or N_p (associated visible protons, measure collision length for each event).

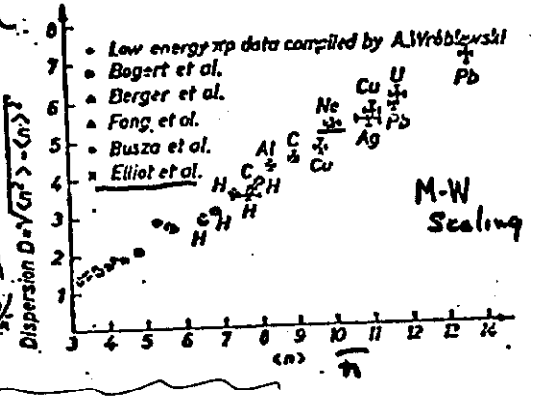


Multiplicity Distributions



KNO Scaling

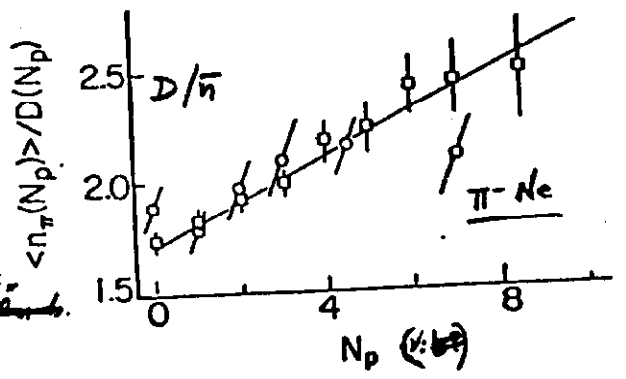
both phenomenon related to presence of short range plus long range correlations ?

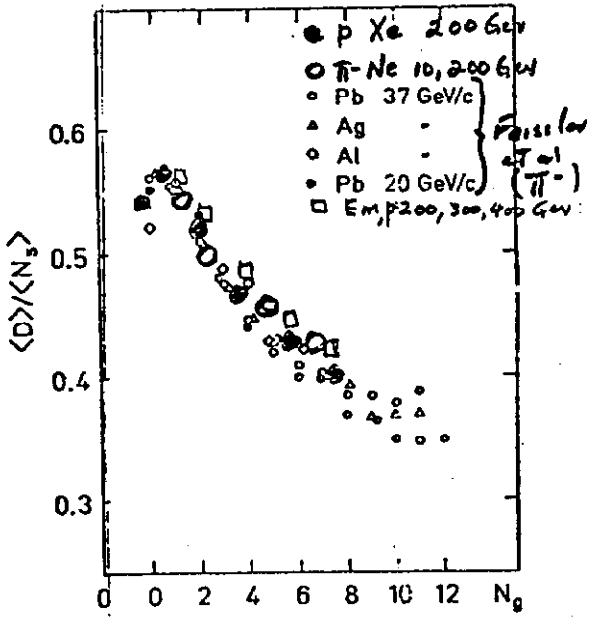


M-W Scaling

Averaging over nuclear collisions for A gives hydrogen-like D/$\bar{n}$

but individual event associated protons show different correlations for individual nuclear thickness ν_i ~~or in fact [illegible]~~

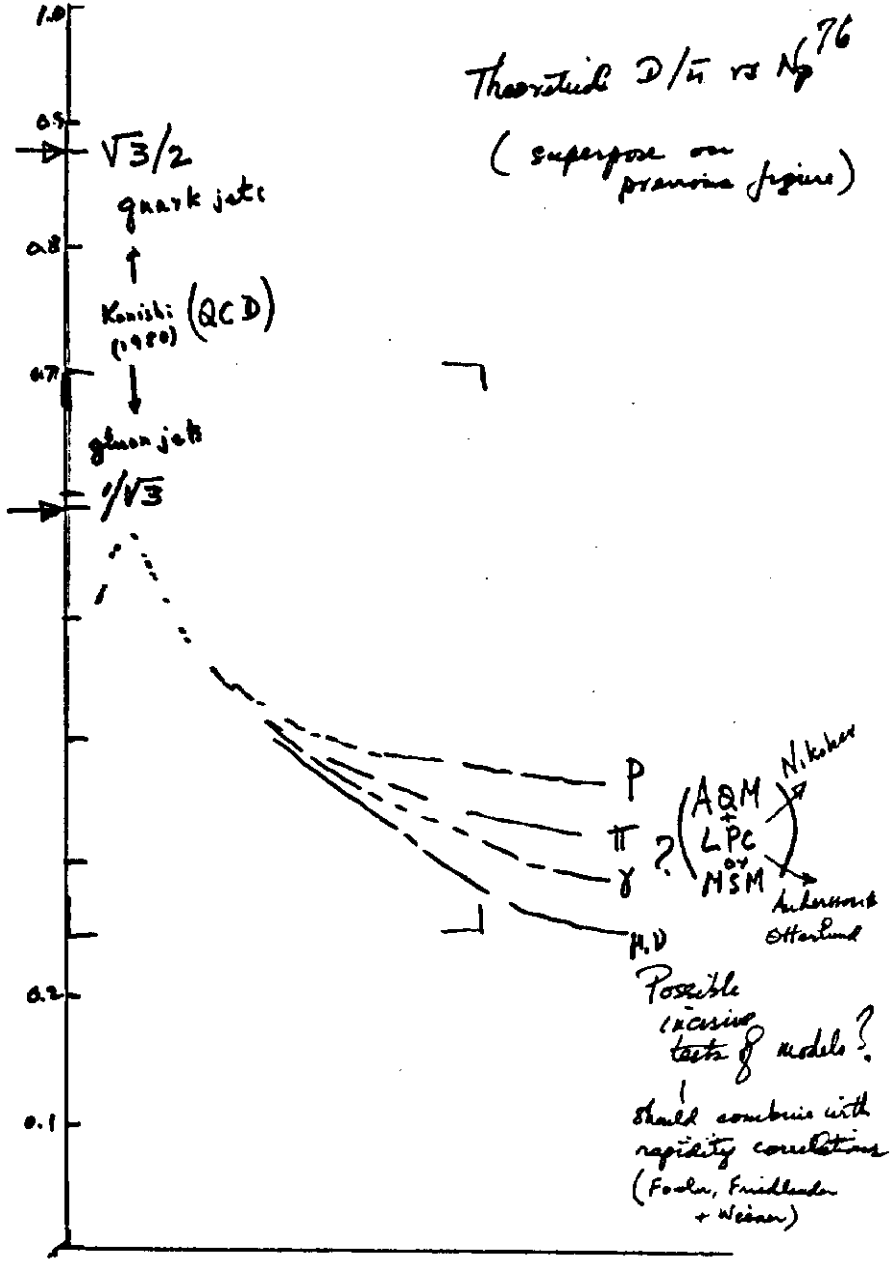




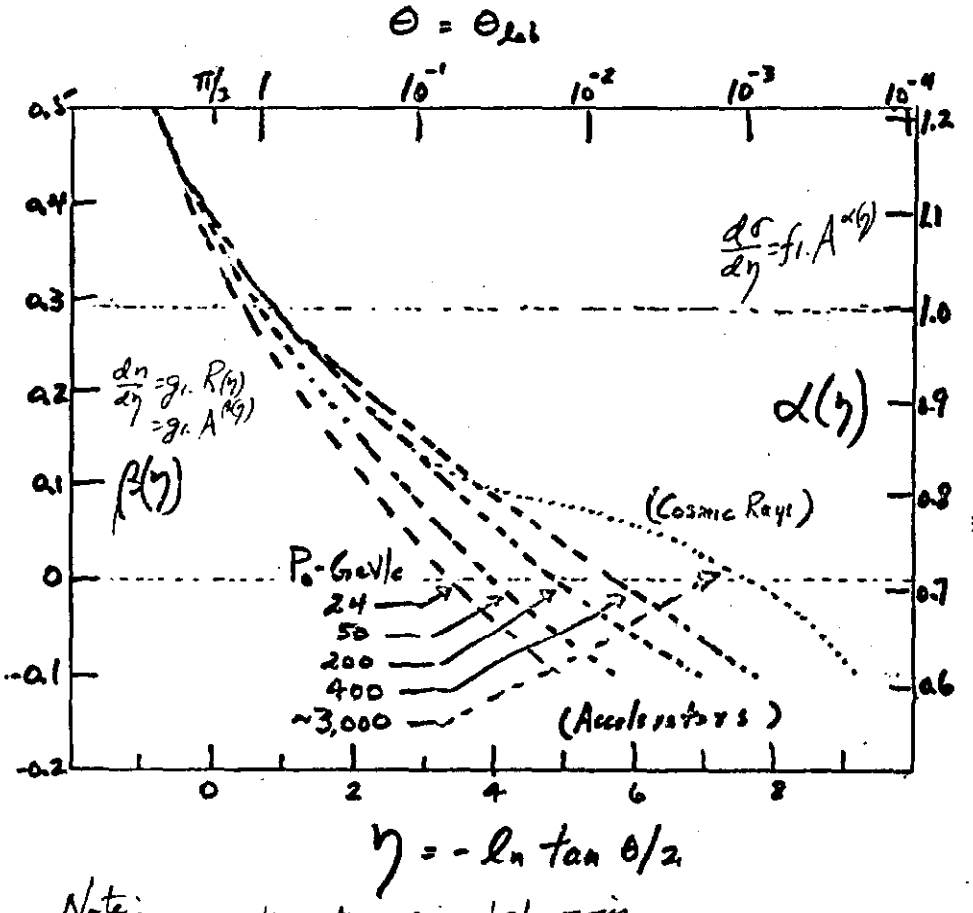
$0.15 \lesssim \beta_p \lesssim 0.7$

$\bar{N}_g(pA) \sim \frac{1}{6} A^{2/3}$

$A_{eff} \sim 16\, N_g^{3/2} \rightarrow 2{,}000$?!!

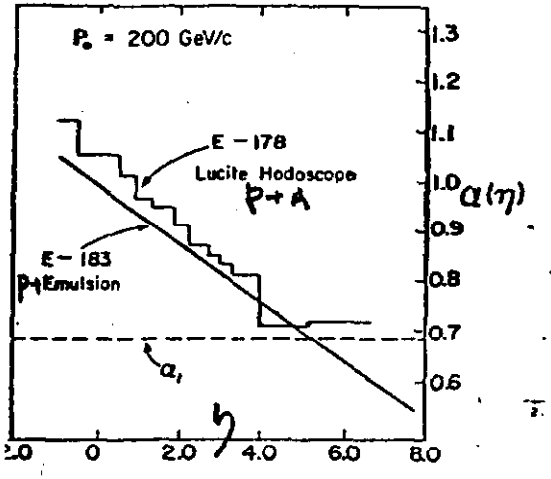


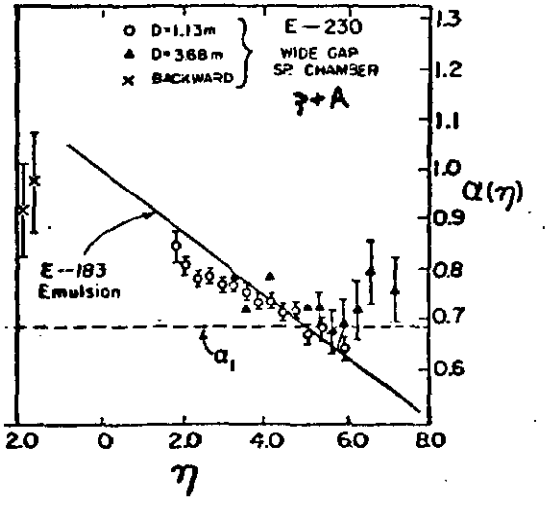
"Rapidity A^{α}" – Hints from P-Emulsion Experiments

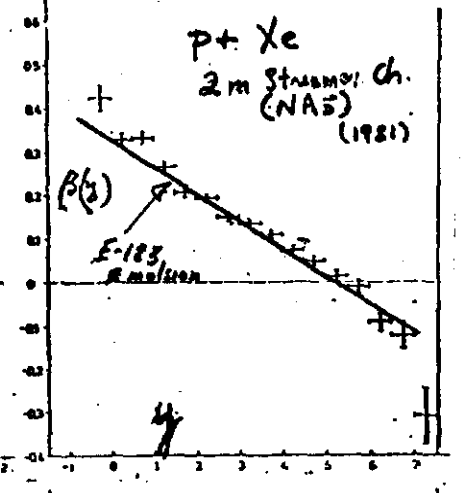


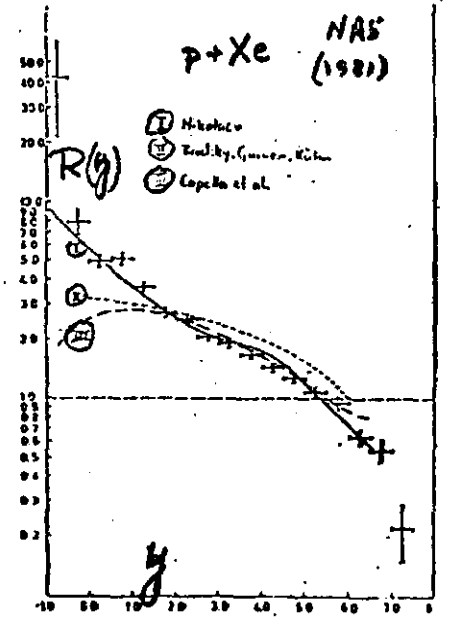
Note:
1) Limiting target region behavior $\alpha > 1$ for $\eta \lesssim 1$, all energies
2) Nuclear depletion in beam fragmentation region $R<1$, $\beta<1$, $\alpha<0$ for $\eta \geq \eta_{max} - 2$ ($y \gtrsim \ln s - 2$)
3) Possible A^{α} plateau in central region ($\eta \sim y \sim \ln \sqrt{s}$) at Tevatron energies ?

200 GeV Rapidities in Different "4π" Detectors

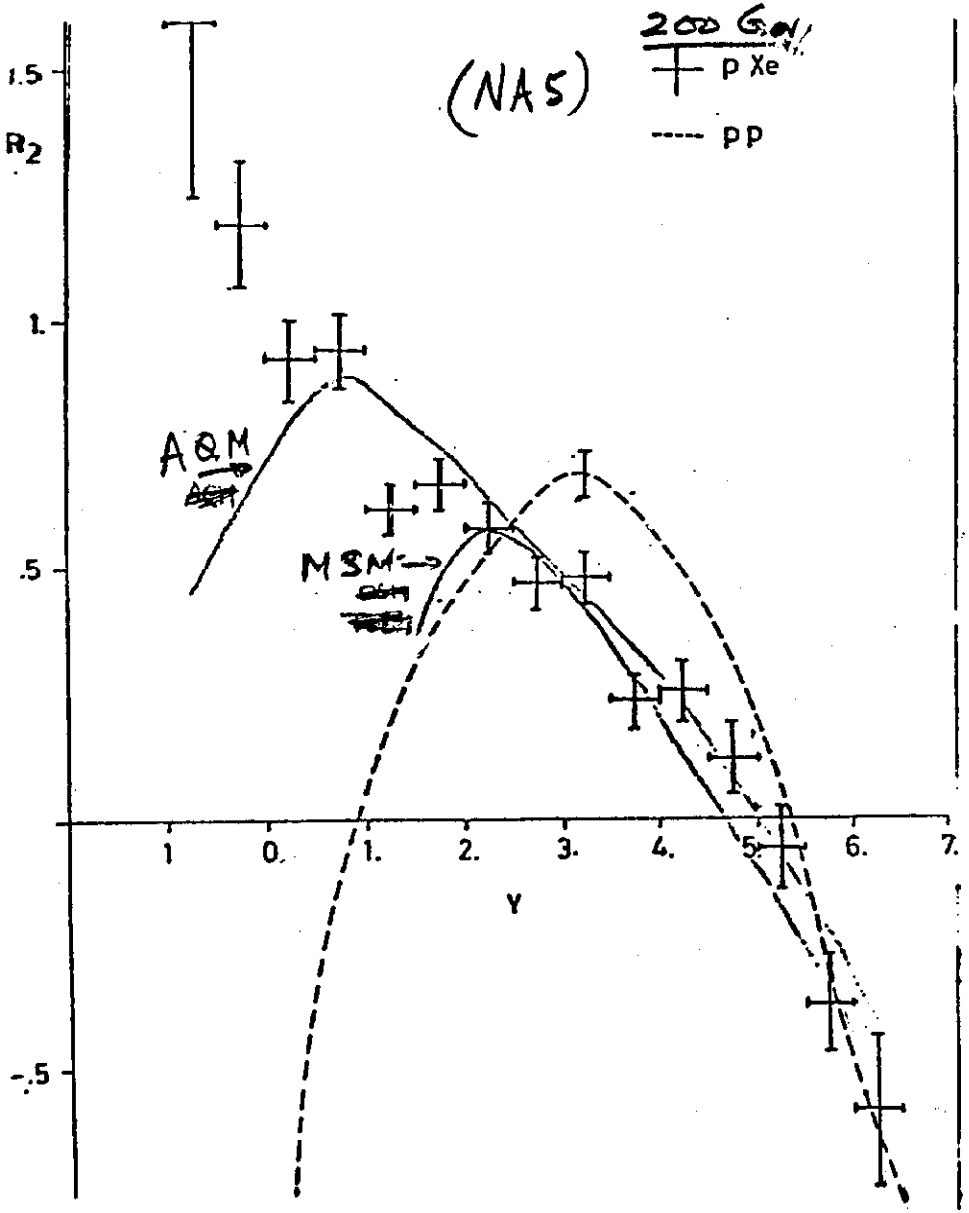




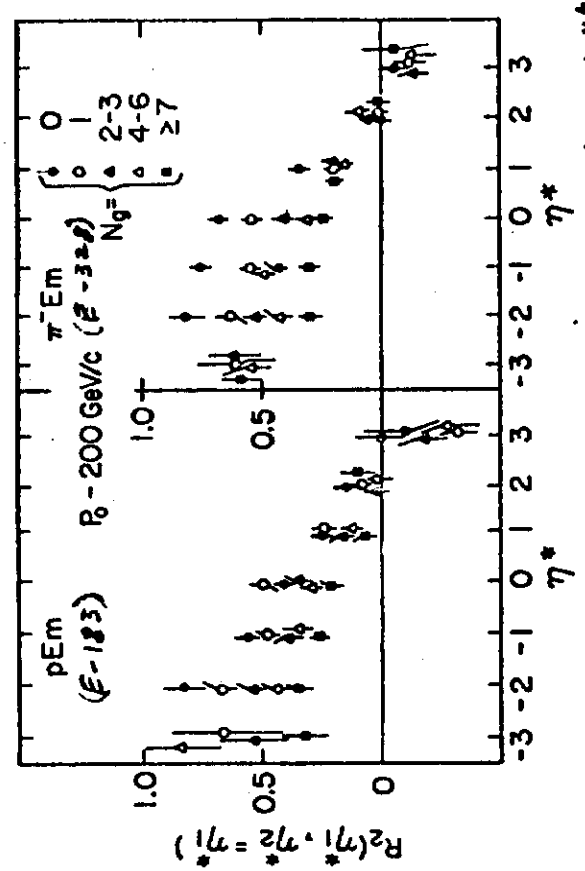




Two Particle Rapidity Correlations 79



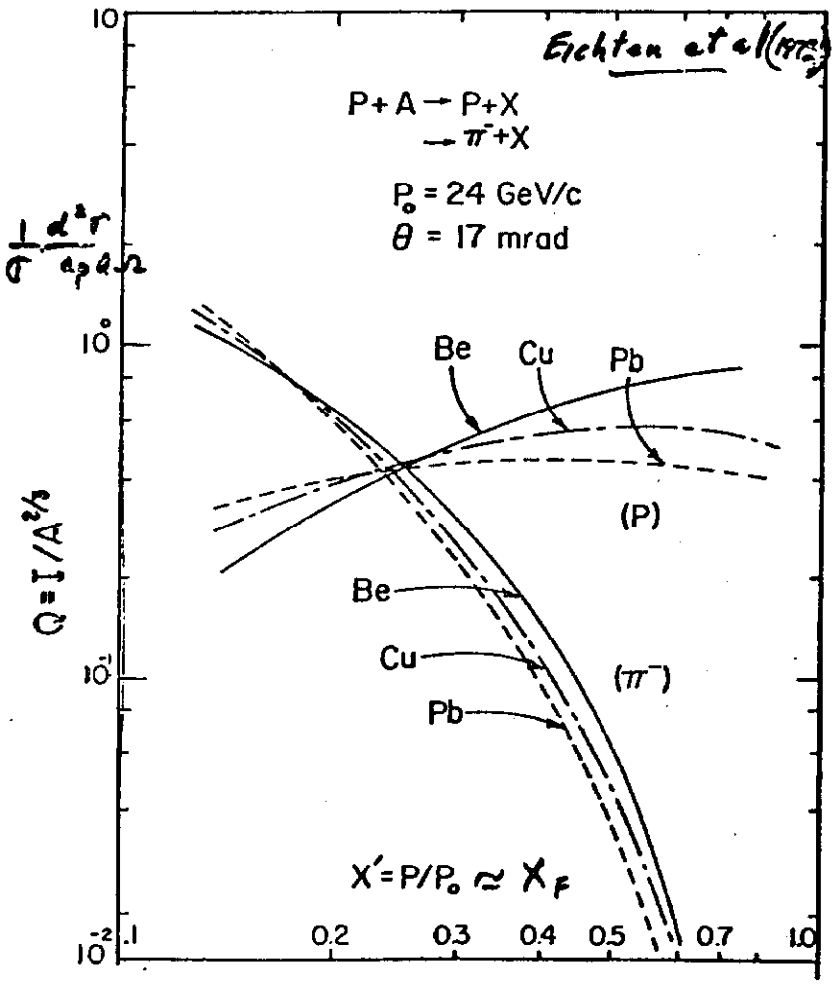
80



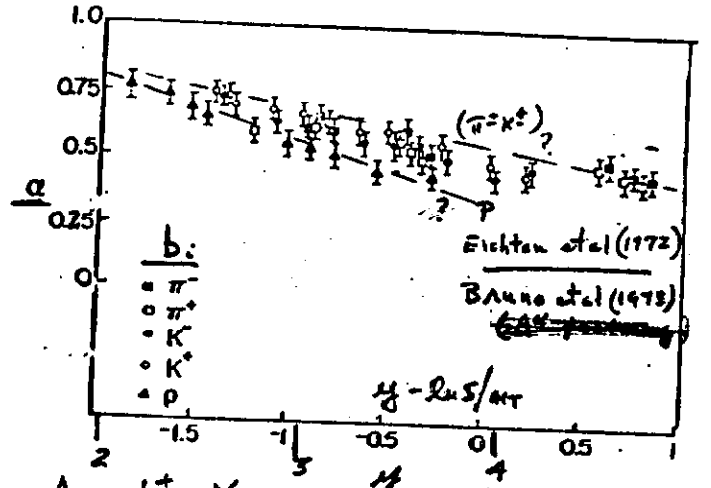
Alma Alta - Leningrad - Moscow - Tashkent Coll^n

Forward Spectrometers —

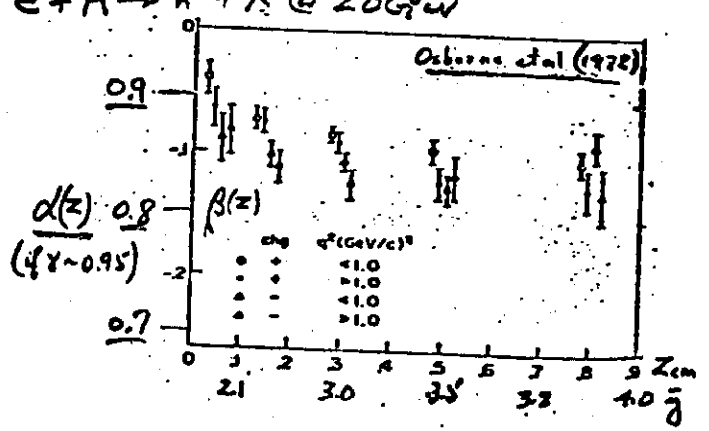
Typical single particle inclusive yields from nuclear targets



P+A → b_i + X @ 24 GeV



e+A → $h^{\pm}$ + X @ 20 GeV

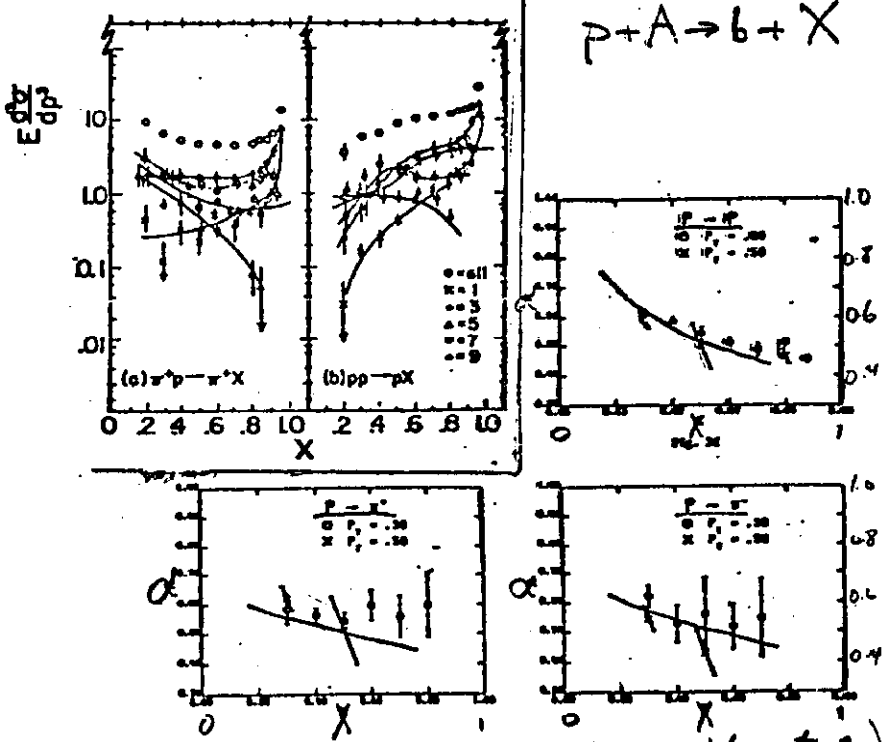


100 GeV
Single Arm Spectrometer (SAS)

$h+p \to b + n_{acc} + X$

Brenner et al (1980)

$p+A \to b+X$

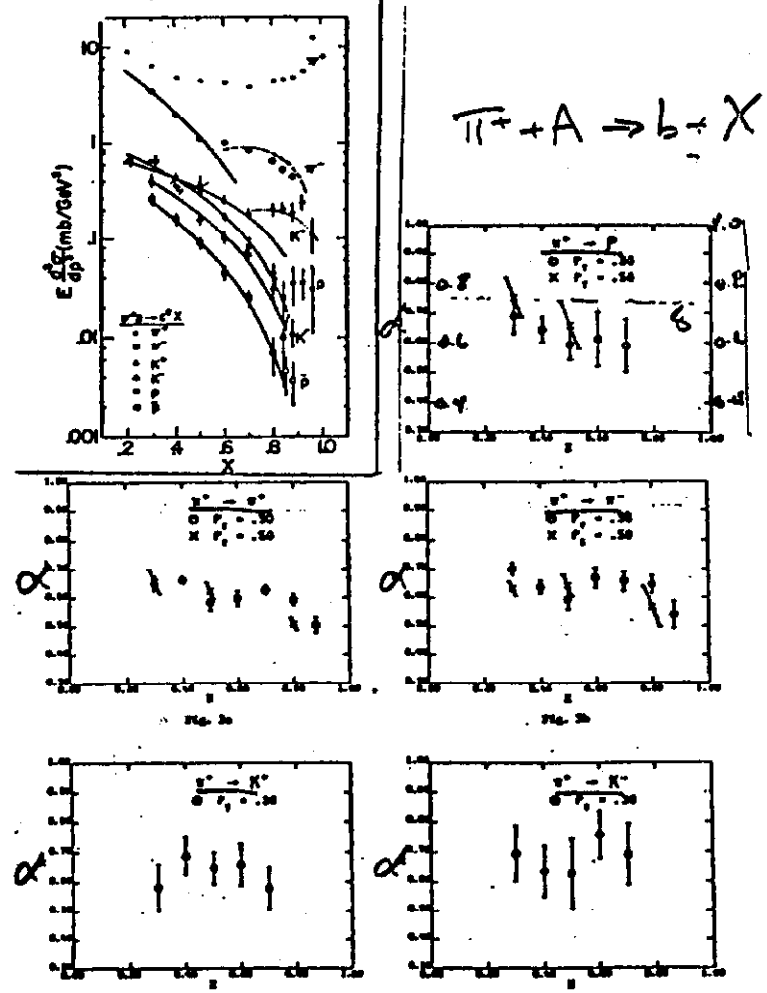


(curves - fits to Eichten et al $p+A$ @ 24 GeV.)

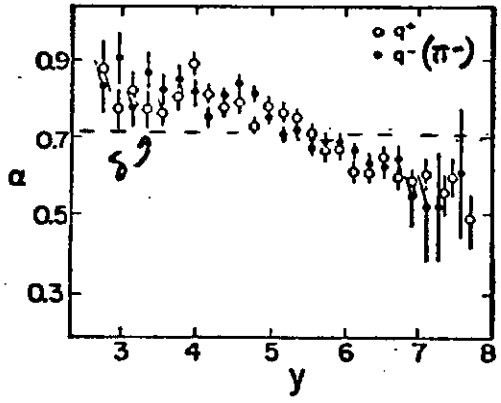
100 GeV (SAS)

$\pi^+p \to b+X$

$\pi^+ + A \to b + X$

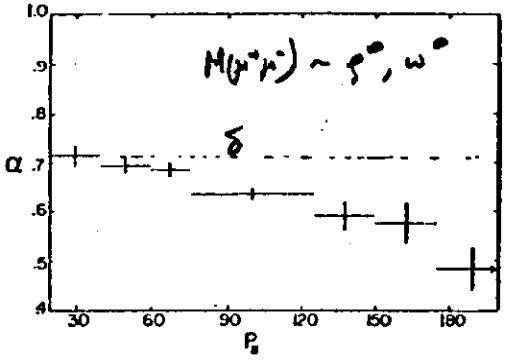


~ 300 GeV



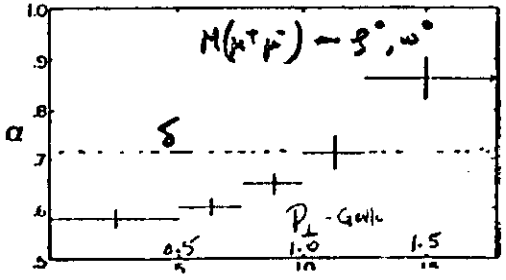
$n + A \to q^{\pm} + X$

Chaney et al (1979)

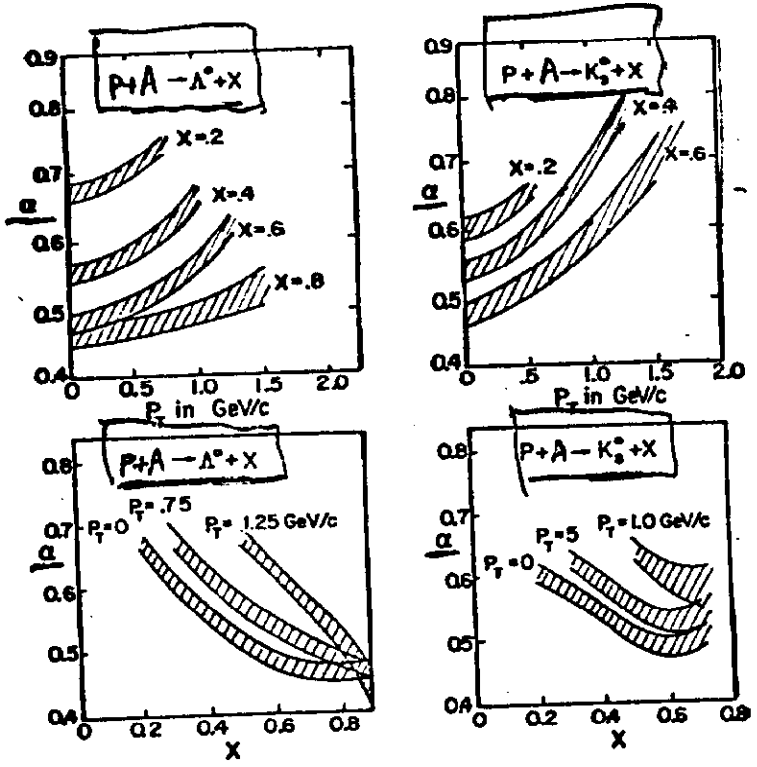


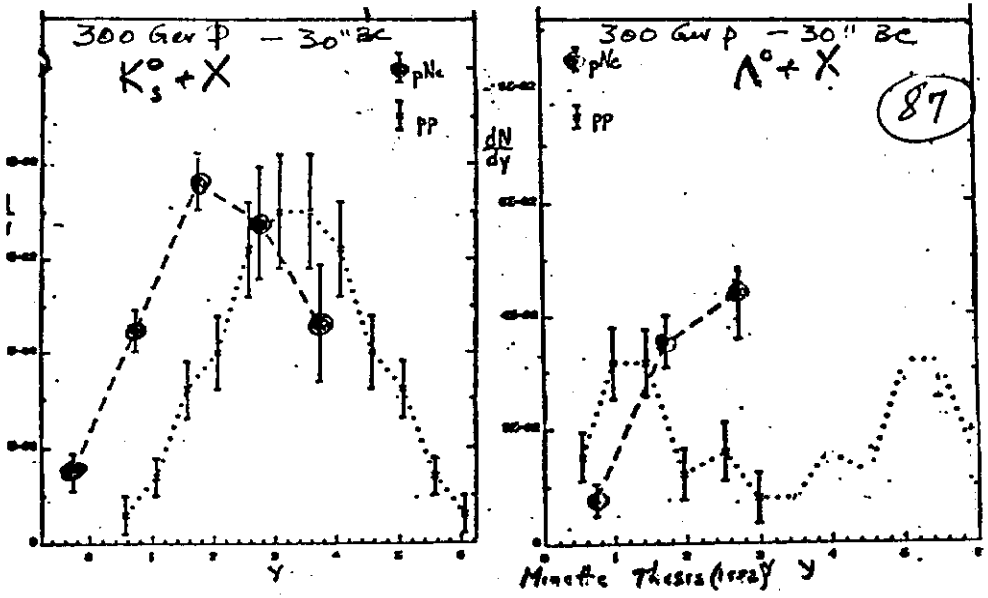
$n + A \to (\mu^+\mu^-) + X$

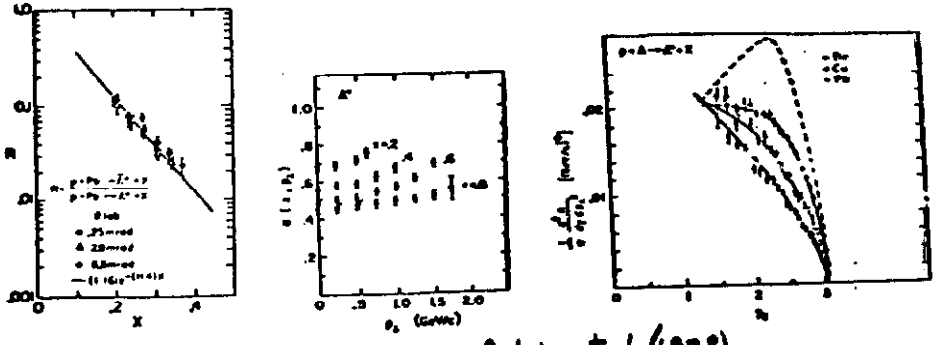
Binkley et al (1976)



300 GeV Skubic et al

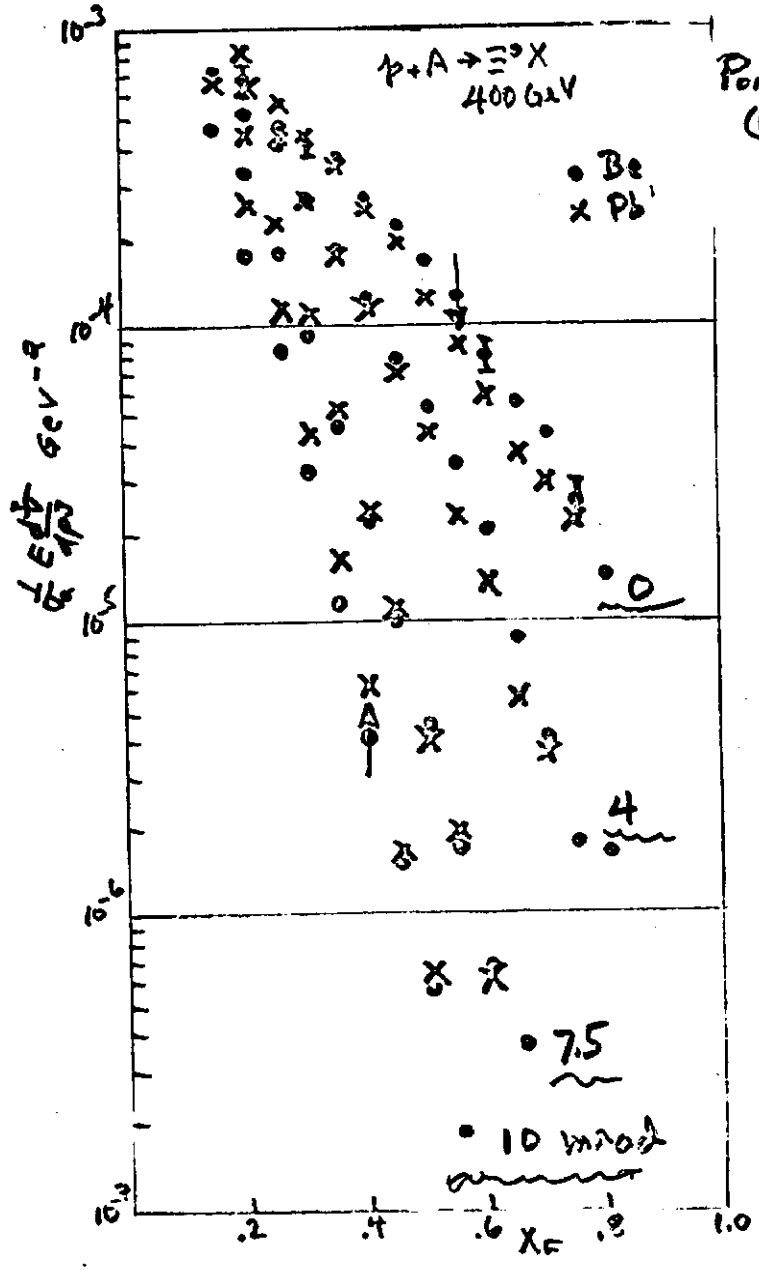




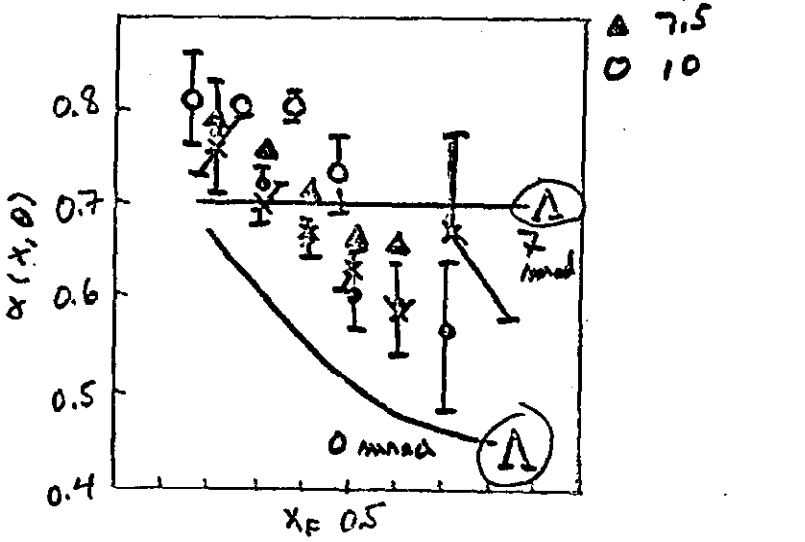


Skubic et al (1978)

Ne Be data (Minette 1982) shows K^0_s enhancement in target region, but Λ^0 depletion in target region ?!?!



$$\frac{\sigma(A_1)}{\sigma(A_2)} = \left(\frac{A_1}{A_2}\right)^{\alpha(x,\theta)}$$



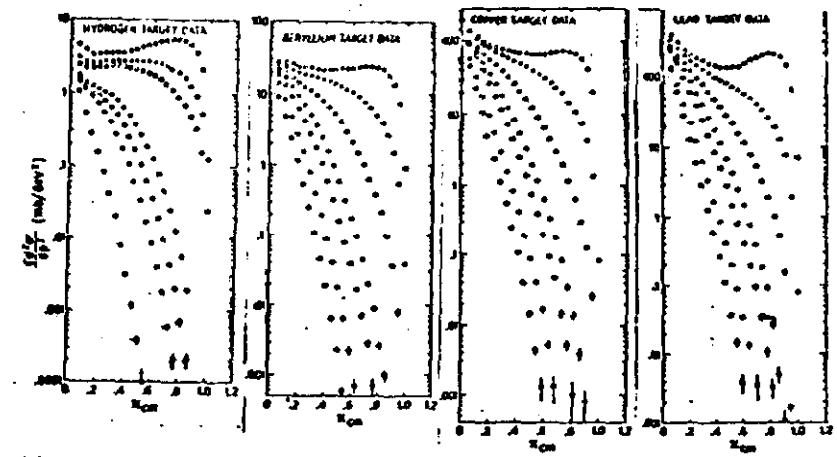


Figure 2: Invariant differential cross sections. Hydrogen data are from 0.7, 1.1, 1.6, 4.0, 5.0, 6.0, and 10.0 mr. The Be, Cu, and Pb data are from 0.7, 1.6, 3.0, 5.0, 6.0, 8.0, and 10.0 mr.

p + A → n + X @ 400 GeV
(L. Jones et al. (1979))

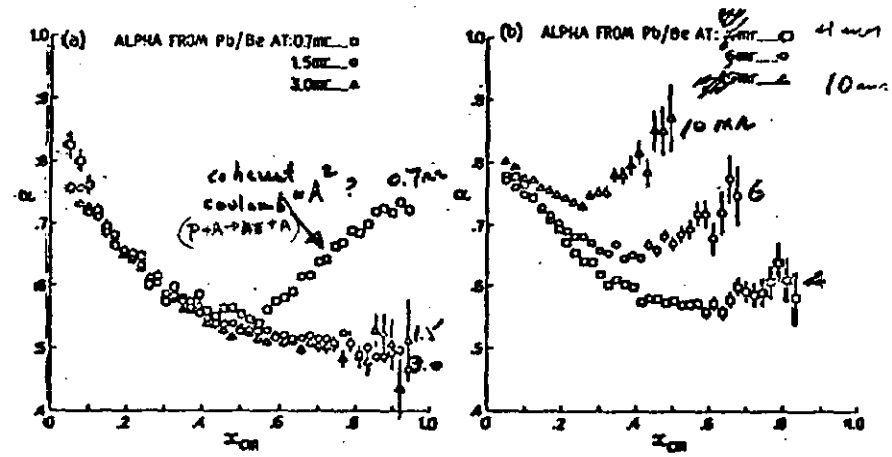
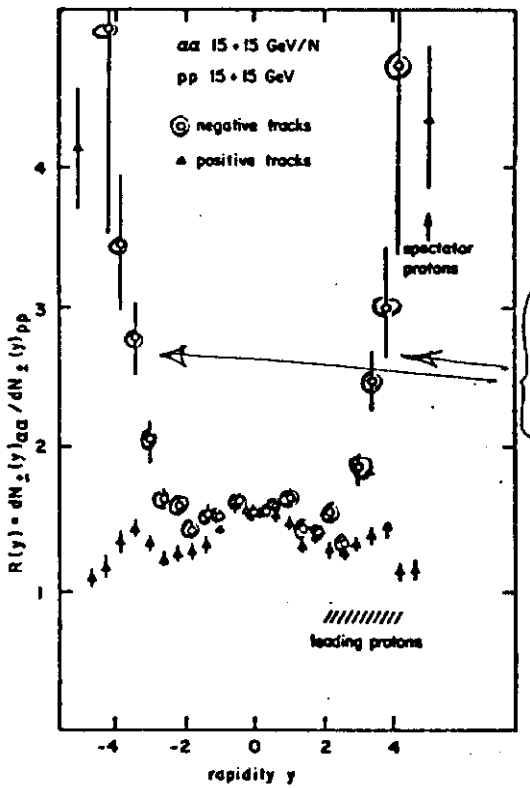


Figure 3: Values of α in the relationship $E\, d^3\sigma/dp^3 \propto A^\alpha$ from the ratio of Pb to Be differential cross sections for different angles and values of x. (α = 0.71 for the total inelastic cross section.)



$n + A \to \pi^- p A$
$\propto A^2$
Coherent Coulomb ?

Fig. 2 Ratio of particle densities in αα collisions to pp collisions versus rapidity y

(via Jacob).

Very Forward Pions
"Superfinetic" - (Nucleus-Nucleus)

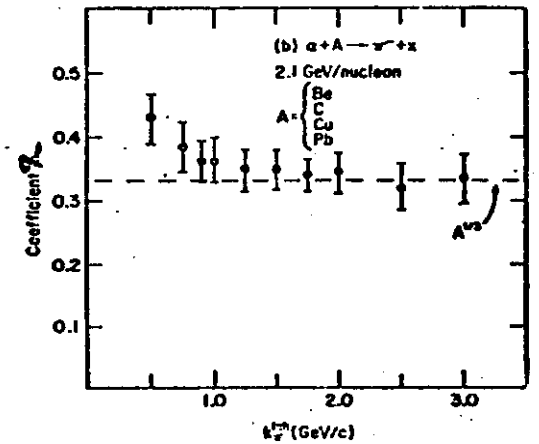
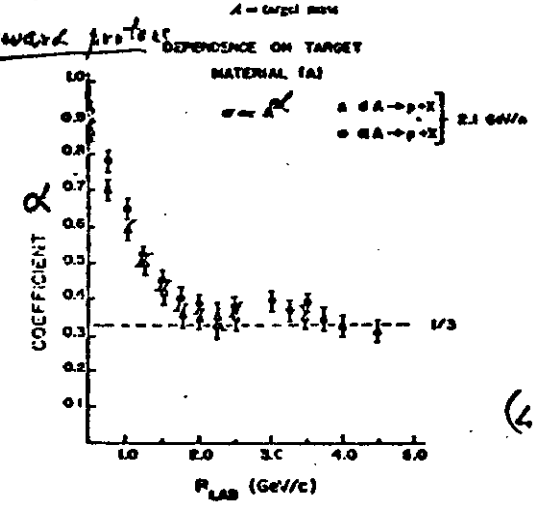


Fig. 17. Dependence of pion production on A. Cross section assumed to have the form: σ ∝ A = target mass

Forward protons

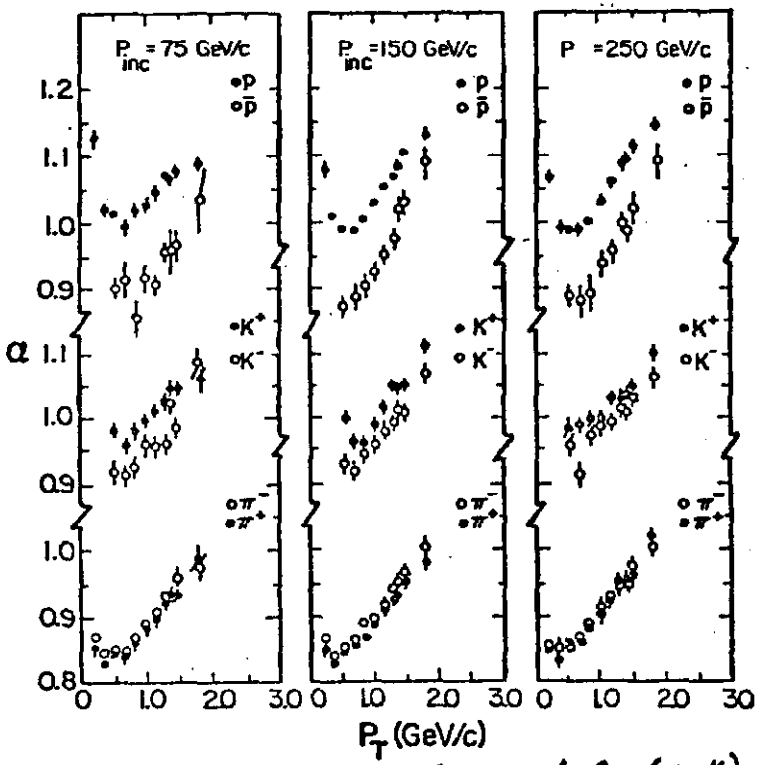


Papp et al (1974)
(L. Schroeder)

[illegible] of deuteron and alpha beam fragmentation to protons on target mass at 2.1 GeV/nu[illegible] [illegible] various targets was fit (best squares) to the form: σ ∝ A^α, A = mass of target

Somewhat backward production
"Medium Collision"

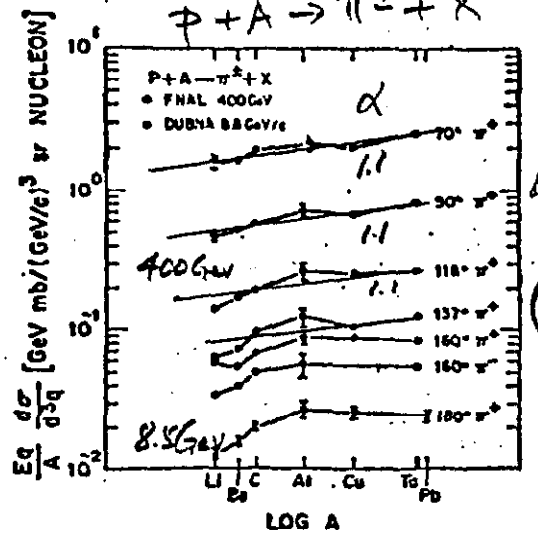
$p + (C, W)$ ITA $\rightarrow b_i^{\pm} + X$ @ 15° ($y = 2$)



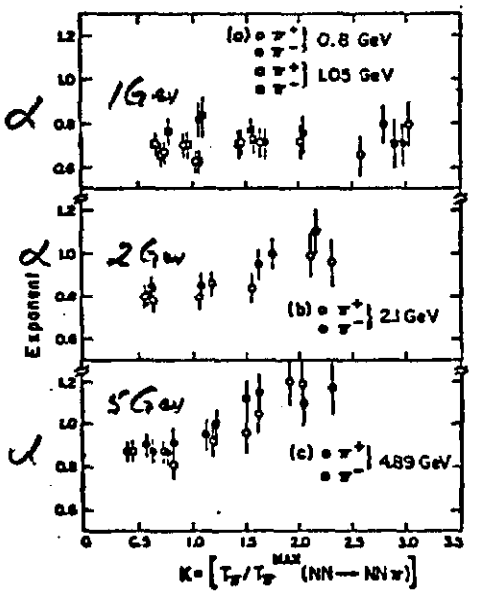
Garbut et al (1974)

Very Backward Pions

$p + A \rightarrow \pi^{\pm} + X$



Nikiforov, Frankel et al (1980)
($P_T \sim 0.5$ GeV)



Schroeder et al (1979)

CONCLUSIONS ON SOFT COLLISIONS A^α DATA

1. Inclusive Cross Sections for produced particles, with incident hadrons 26 to 400 GeV: ~~show~~

(i) A^α shows α increasing with P_T, decreasing with P_L, y, η, X_F.

(ii) Nuclear Enhancement in Target Frag^n Region
$\alpha \gtrsim 1$ for $y \sim \eta \lesssim 0$; $X_F \sim -1$

(iii) Nuclear Attenuation in Beam Frag^n Region
$\alpha \lesssim 1/2$ for $y \sim \eta \sim \ln s$; $X_F \sim +1$

(iv) Central Region ($y \sim \eta \sim \ln \sqrt{s}$; $X_F \sim 0$), A^α behaviour is least well established; little evidence of plateau except for Cosmic Ray data $\gtrsim 1$ Tev.

(v) To first approximation, for secondary hadrons

$$\alpha(y) \simeq 1.0 - K(s) \cdot y$$

$$\alpha(X_F, P_T) \simeq 0.80 - 0.30 X_F + 0.15 P_T$$

2. Differential Multiplicities $\frac{dn}{dy} = \frac{1}{\sigma}\frac{d\sigma}{dy} = g_1 A^{\beta(y)}$,
Average Multiplicities $\bar{n} = \bar{n}_1 \cdot A^\gamma$, and
Absorption Cross Sections $\sigma_A = \sigma_1 \cdot A^\delta$
show appreciable dependence of β, γ, δ on nature of incident particle and its energy. More sensitive experiments still needed.

3. Semi-inclusive Yields (eg $\left(\frac{d\sigma_n}{dy}\right)_A$ at fixed P_T, N_P),
Multiplicity Correlations (eg $(D/\bar{n})_A$ vs N_P), and
Rapidity Correlations (eg $R_{1,2}$ vs y_1, y_2, N_P)
with incident hadrons, photons, leptons
look particularly promising –
for Tevatron chases –

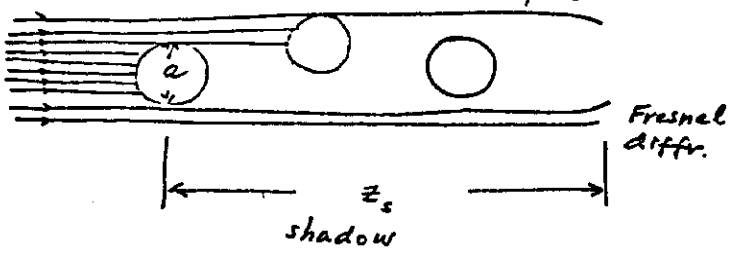
– May yet catch insights into elusive hadronization processes and quark-gluon space-time developments?

– Tests of incisive theories and models?

SOFT COLLISIONS {W. Czyz} 97

1 Diffraction

Elastic interactions → geometrical optics



$$\eta = \frac{z}{ka^2}$$

$\eta \ll 1$ geometrical optics

$\eta \sim 1$ Fresnel diffraction

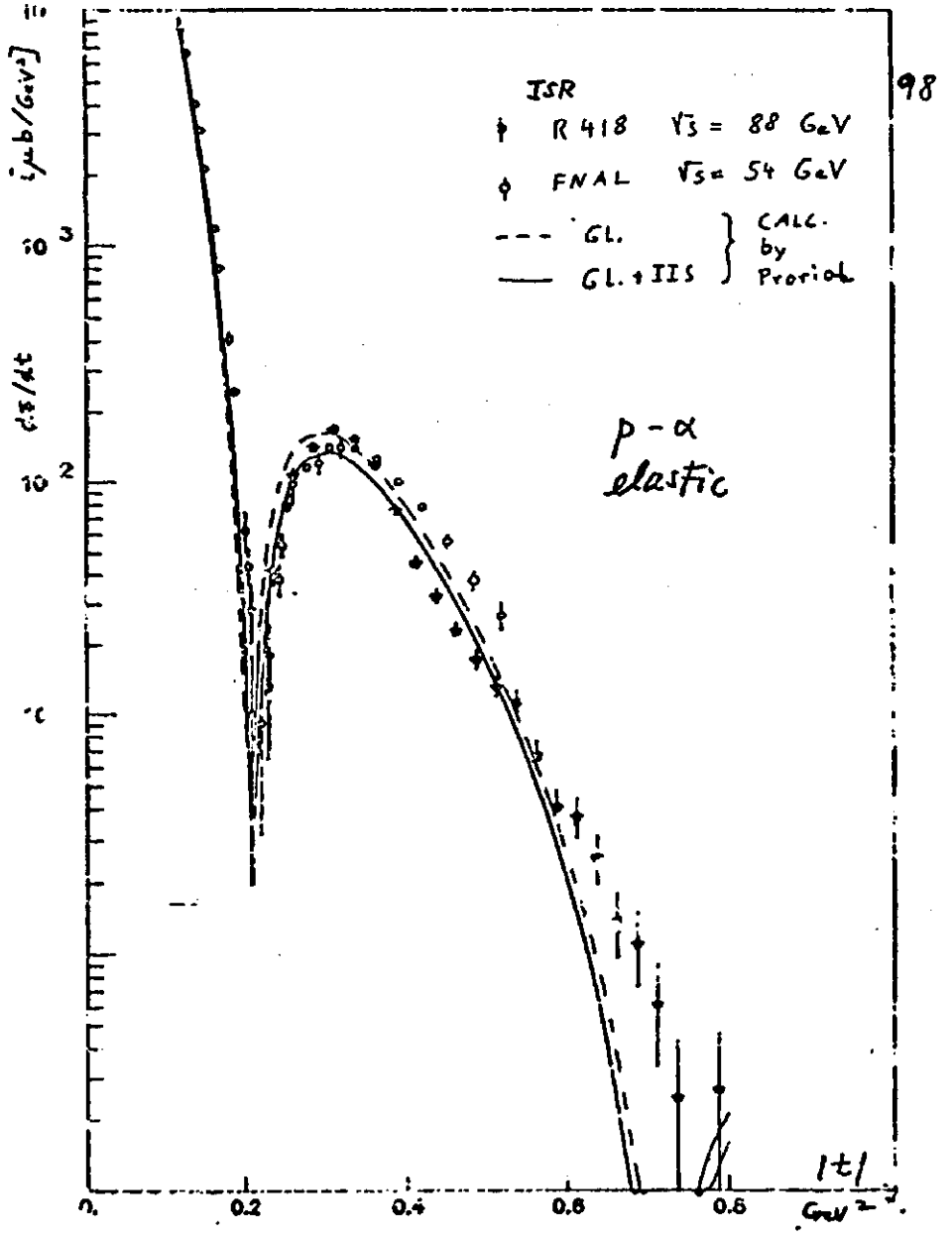
$$z_s \simeq k a^2$$

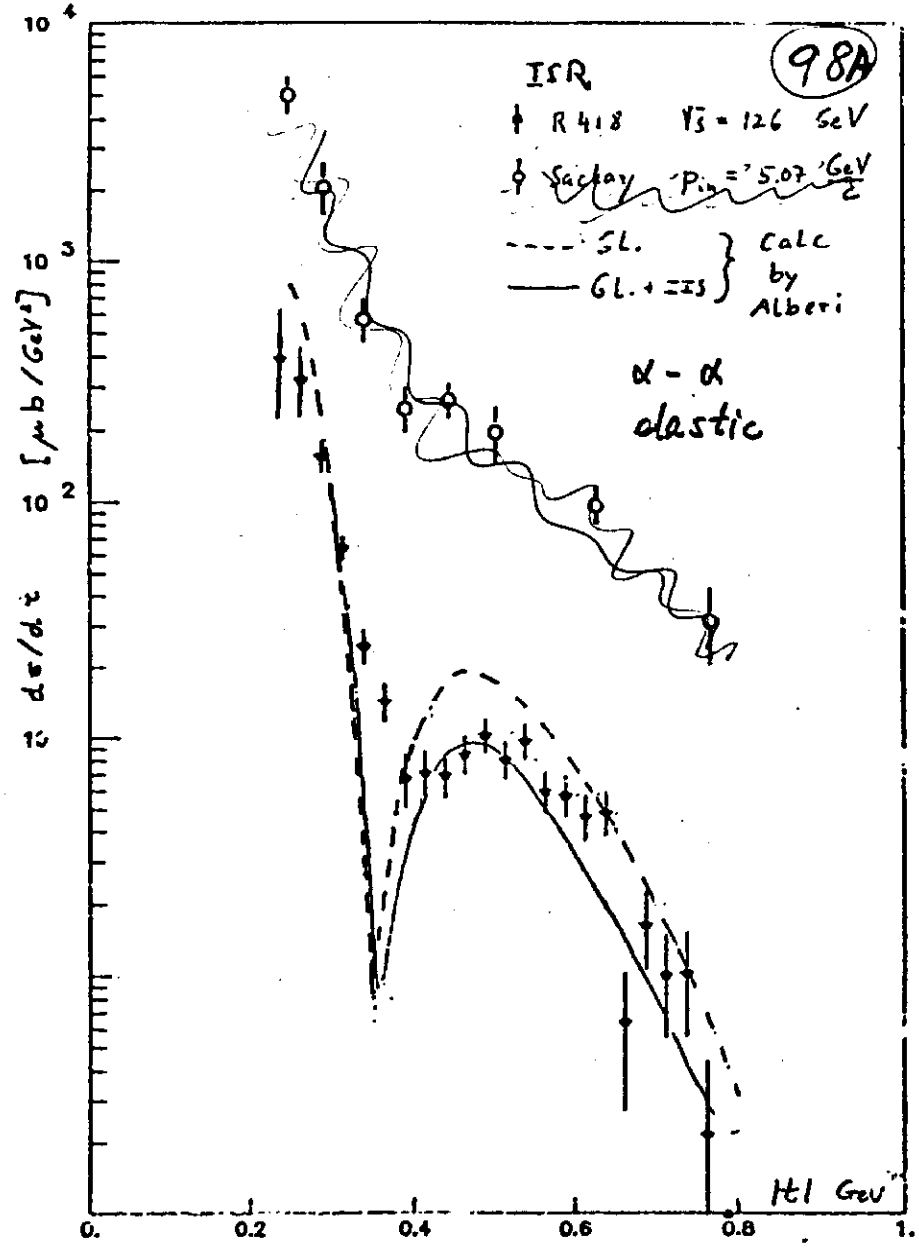
$$K = 500 \text{ GeV} \begin{cases} a = 1 \text{ fm}, & z_s \cong 2500 \text{ fm} \\ a = 0.3 \text{ fm}, & z_s \cong 225 \text{ fm} \end{cases}$$

⟶ Fraunhoffer diffraction

⟶ Glauber Model

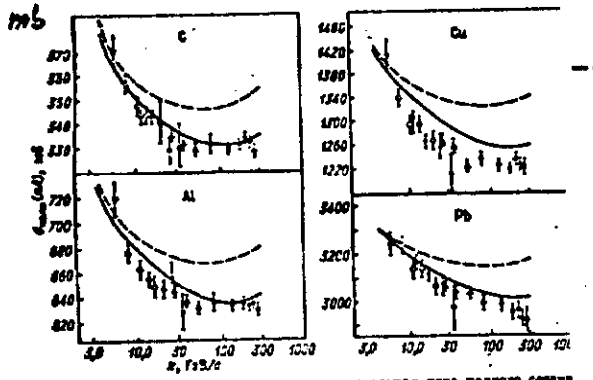
Test it at highest available energies





17

neutron - nucleus σ_T



--- Glauber less than 10% too large

Рис. 14. Зависимость от энергии и атомного номера ядра полного сечения nA-взаимодействия [61]:
— — — — расчет по простой модели Глаубера; ——— — расчет с учетом поправки Карманова — Кондратюка

K_L-nucleus σ_T

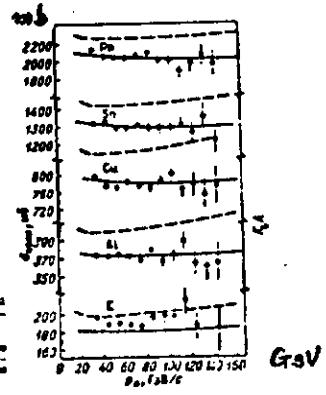


Рис. 15. Зависимость от энергии и атомного номера ядра полного сечения $K_L A$-взаимодействия [62]:
— — — — расчет по простой модели Глаубера; ——— — расчет с учетом неупругих поправок в модели с пассивными экстенциями кварков [74]

Introduce diffractive excitations through the "eigenstates of diffraction"

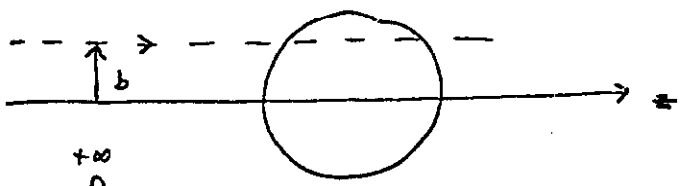
$$\Delta\sigma_T(A) = \sigma_T^G(A) - \sigma_T(A)$$

$$= 2\int d^2b\,\left(1 - e^{\langle i\chi_\ell(b)\rangle}\right) - 2\int d^2b\,\left(1 - \langle e^{i\chi_\ell(b)}\rangle\right)$$

$$= 2\int d^2b\,\underbrace{\left(\langle e^{i\chi_\ell(b)}\rangle - e^{\langle i\chi_\ell(b)\rangle}\right)}_{\geq 0}$$

$$i\chi_\ell(b) = -\tfrac{1}{2}\sigma_{T\ell}(N)\,A\rho(b)$$

$$\sigma_T(N) = \sum_\ell |c_\ell|^2\sigma_{T\ell}(N) = \langle\sigma_{T\ell}(N)\rangle$$



$$\rho(b) = \int_{-\infty}^{+\infty} dz\,\rho(b,z)$$

Approximate expression (Karmanov–Kondratiuk) to second order in $A\rho(b)$:

$$\Delta\sigma_T(A) \simeq (2\pi)^2\int d^2b\; e^{-\frac{1}{2}\sigma_T(N)A\rho(b)}$$

$$\times\;[A\rho(b)]^2\;\left.\frac{d\sigma^{\mathrm{Diff}}(N)}{d^2q}\right|_{q=0}$$

$$\left.\frac{d\sigma^{\mathrm{Diff}}(N)}{d^2q}\right|_{q=0} = \frac{1}{(2\pi)^2}\left[\langle(\tfrac{1}{2}\sigma_{T\ell})^2\rangle - \langle\tfrac{1}{2}\sigma_{T\ell}\rangle^2\right]$$

reasonably good for weak diffraction

agrees with data $\rightarrow$ $\sigma_T(A) \sim$ "$A^{2/3}$"

If diffraction becomes dominant at higher energies (A. White, Fermilab-Conf 82/16 Thy) one expects (Udgaonkar & Gell-Mann, PRL 8, 346 (1962)) $\sigma_T(A) \sim$ "A" $\rightarrow$ re-analyze

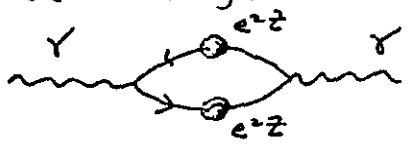
$\longrightarrow$ Measure $\sigma_T(A)$ at higher energies

WHAT ARE THE EIGENSTATES OF DIFFRACTION?

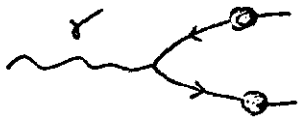
In QED :

Cheng & Wu ; Bjorken, Kogut & Soper (1968-71)

Delbrück scattering:



Pair production



For energies $\gg$ 1 GeV hadronic components become important $\rightarrow$ Shadowing

$$\sigma_{\gamma A} \sim A_{eff}\, \sigma_{\gamma N}$$

$$\frac{A_{eff}}{A} \sim 0.73 \quad (E_\gamma \sim 25 \text{ GeV})$$

$$\sim 0.65 \quad (E_\gamma \sim 130 \text{ GeV})$$

(Caldwell et al. PRL 42, 553 (1979))

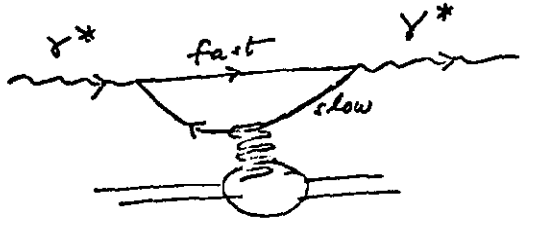
Which variable controls shadowing of virtual photons? Is there shadowing for large Q^2?

Goodman et al, Fermilab-Pub-81/42 exp

$Q^2 = 0.01 - 30.0$ GeV^2

$\nu = 40 - 200$ GeV

Shadowing up to $Q^2 \sim 3$ GeV^2 supports the mechanism of an asymmetric $q\bar{q}$ pair (Bjorken, DESY lectures, 1975)



Asymmetry is essential because the "Chudakov effect"* destroys shadowing for symmetric pairs at large Q^2

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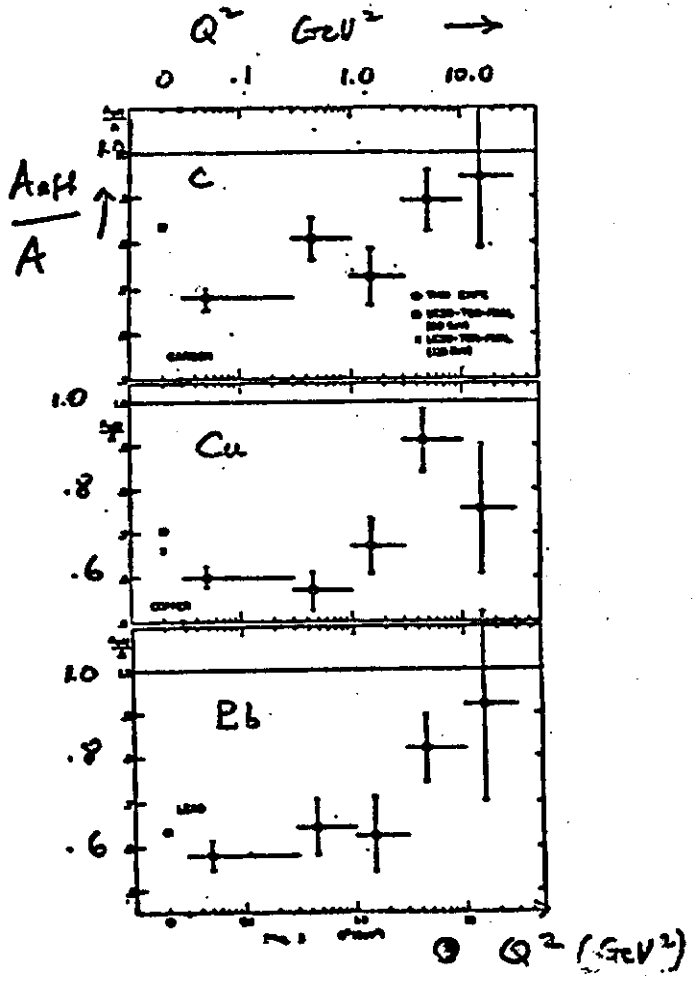
*

$\delta \sim \frac{4\pi m_e c^2}{E_\gamma}$

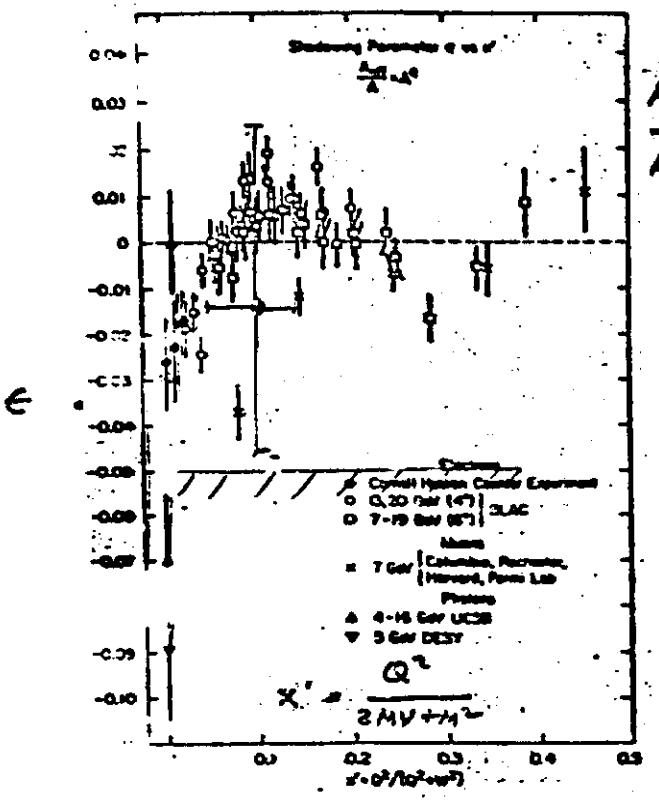
For $\gamma \sim 2\times10^{12}$ GeV Ionisation $< 2 I_e$



Goodman et al., May 1981

Antishadowing ?

- Goodman et al. $\begin{cases} \nu = (40-200)\ \text{GeV} \\ Q^2 = (0.01-30.0)\ \text{GeV}^2 \end{cases}$
- Miller et al. $\begin{cases} \nu = (1-9)\ \text{GeV} \\ Q^2 = (0.2-2.4)\ \text{GeV}^2 \end{cases}$



... of the coefficient ε (in Eq. (3.159)) for ... photoproduction and photoproduction experiments (from ..., 1973).

$$\nu W_2(\nu, Q^2) \xrightarrow{\text{scaling limit}} F_2(x)$$

$$\int dx\, F_2^A(x) = A \int dx\, F_2^N(x)$$

Nikolaev & Zakharov P.L. B55, 39...

For incident hadrons one may expect to see an analogon of the Chudakov effect (Bertsch, Brodsky, Goldhaber, Gunion PRL 47, 297 (1981)):

Very small color neutral objects (components) interact weakly and can be filtered through nuclei.

In analogy with nuclear optics:
($\psi(\xi)$ – wave function of the incident hadr.)

$$\psi'(b,\xi) = S(b,\xi)\,\psi(\xi)$$

$$\equiv \bar{S}(b)\,\psi(\xi) + \overbrace{[S(b,\xi) - \bar{S}(b)]\,\psi(\xi)}^{\text{diffr. excit.}},$$

$$\bar{S}(b) = \int d\xi\, |\psi(\xi)|^2 S(b,\xi)$$

For very small neutral components $S(b,\xi) \approx 1$

$$\frac{d\sigma}{d\xi} = \int d^2b\, (1-\bar{S}(b))^2\, |\psi(\xi)|^2 = \sigma_{el}\, |\psi(\xi)|^2$$

Suppose $c\bar{c}$ component in the proton is very small. We estimate σ^{diff}_{charm}

$$|\psi(\xi)|^2 \longrightarrow P_c$$

$$\sigma^{diffr}_{charm} = P_c\, \sigma_{el}$$

From ISR (Philips, XX. th Conf on High En. Phys. Wisconsin, 1980)

$$\sigma(pp \to c\bar{c}\,X) \sim 0.14\,mb \qquad \sqrt{s} \sim 60\,GeV$$

$$\sigma_{el}(pp) \sim 7\,mb \quad \to \quad P_c \sim 0.02$$

$$\sigma_{el}(pA) \approx \pi R^2 \approx 50\, A^{2/3}\ mb$$

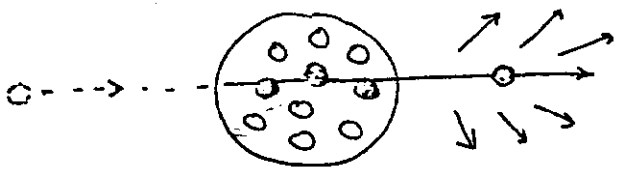
$$\sigma^{diffr}_{charm}(A) \approx 1\,mb\, A^{2/3}$$

for $A^{1/3} = 6$, $\approx 36\,mb$

Considerable difference between ISR and Fermilab (A. Bodek et al UR-804, Dec 1981) which gives ~ few μb for charm prod. in both 350 GeV proton and 278 GeV pion interactions

Diffr. process on nuclear targets can be important in investigations of the internal structure of hadrons and hadronic components of photons

2. NON DIFFRACTIVE PRODUCTION IN HADRON-NUCLEUS INTERACTIONS



All models have to account for

(i) Lack of cascading. Lorentz time dilation:

$$\tau \sim \frac{E}{m}\tau_0 \quad , \tau_0 \text{ - characteristic time}$$

→ production takes place outside of the target

(ii) More than one nucleon is struck. The cross section for striking ν nucleons

$$\sigma_\nu(A) = \int d^2b \binom{A}{\nu}\left[\sigma_{in}(N)\rho(b)\right]^\nu\left[1-\sigma_{in}(N)\rho(b)\right]^{A-\nu}$$

$$\sigma_{in}(A) = \sum_{\nu=1}^{A}\sigma_\nu(A) = \int d^2b\left\{1-\left[1-\sigma_{in}(N)\rho(b)\right]^A\right\}$$

$$\bar{\nu} = \frac{\sum \nu\sigma_\nu(A)}{\sum\sigma_\nu(A)} = \frac{A\sigma_{in}(N)}{\sigma_{in}(A)}$$

+ Optical theorem → Glauber model (nuclear optics we started with)

The Fig suggests

$$R_A = \frac{n_A}{n_N} = \frac{1}{2} + \frac{1}{2}\bar{\nu}$$

which is in reasonable agreement with the data.

General reviews:

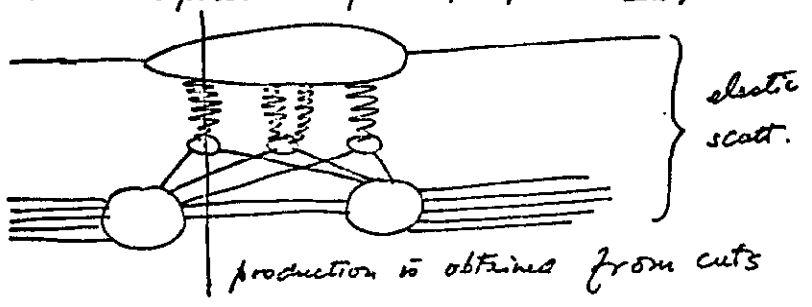
Nikolaev, Sov. J. Part. Nucl. 12, 63 Jan-Feb 1981

Bergstrom & Frederikson, Rev. Mod. Phys. 52, 675 (1980)

Bergstrom, Berlad, Eilam & Frederikson, Phys. Rep.

(I) Reggeon calculus

Review: Capella & Krzywicki, Phys. Rev. D18, 3357 (1978)



The cutting rules (Abramovski-Gribov-Kancheli) give suppression of cascading (i) and σ_{in} (ii)

Typical input : the hadron-nucleon interactions, + probabilistic formulae (e.g. (ii)) + conservation laws

(II) Quark-parton models (with QCD connections)

Reviews: – Brodsky, Inv. talk at Berkeley Workshop on Ultra-Relativistic Collisions, 1979

– Peterson, Inv.-talk at Conf. on Multiparticle Dynamics, Univ. of Notre Dame, Indiana 1981.

The structure of colliding hadrons is introduced through various quark configurations, e.g.

$$|\pi^+\rangle = a^{\pi}_{(2)}|u\bar{d}\rangle + a^{\pi}_{(3)}|u\bar{d}g\rangle + a^{\pi}_{(4)}|u\bar{d}c\bar{c}\rangle + \cdots$$

$$|p\rangle = a^{p}_{(3)}|uud\rangle + a^{p}_{(4)}|uudg\rangle + a^{p}_{(5)}|uudc\bar{c}\rangle + \cdots$$

A simple illustration of this approach was already presented : diffractive charm production.

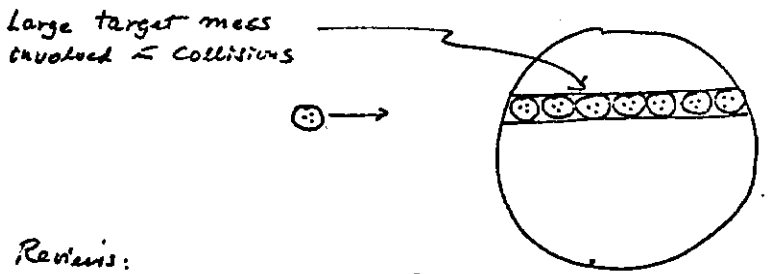
Advantage: various quark configurations are identified as the "eigenstates of diffraction"

$\longrightarrow$ unified approach

Non-diffractive production starts by a soft gluon exchange $\rightarrow$ two colored objects emerge $\rightarrow$ neutralization leads to particle production.

In its simplest version (Anisovich & Shekhter, Białas et al) it can be worked out in the framework of the additive quark model

(III) The Collective tube model



Reviews:

Afek et al, in Proc. Top. Meeting on Multiparticle Production, ICTP, Trieste 1977

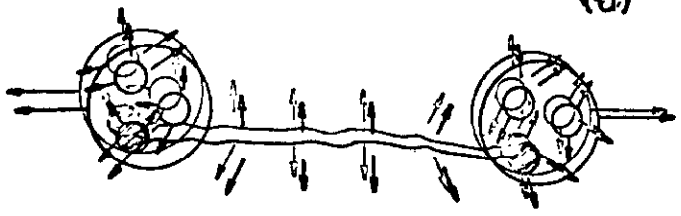
Berlad, Dar & Eilam, 1979 Haifa preprint Technion PH-79-71

- All collisions are collective $\rightarrow$ no cascading
- The prob. of collisions with ν nucleons given by $\sigma_\nu(A)$.
- Quark structure may be introduced.

NUCLEON = NUCLEON COLLISIONS (A. BIALAS, L. LESNIAK + W.C.,

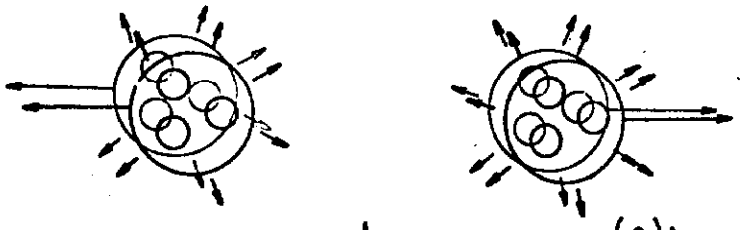
NON DIFFRACTIVE:
COLOUR EXCHANGE

(a)

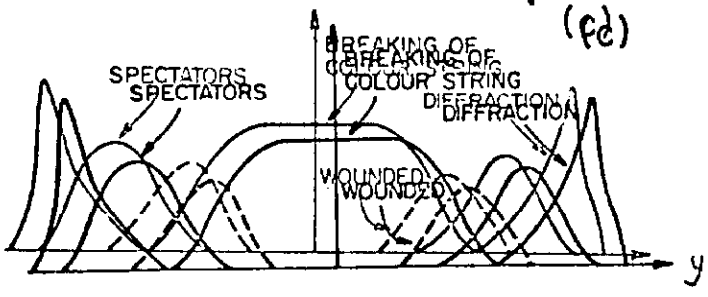


DIFFRACTIVE:
NO COLOUR EXCHANGE

(b)



(c)



3 COMMENTS ON NON DIFFRACTIVE PRODUCTION

(I) The process of <u>inelastic</u> multiple scattering "screens itself":

$$\sigma_{in}(b;A) = 1 - \left[1 - \sigma_{in}(N)\rho(b)\right]^A$$

There are many "self screening" processes.
Inelastic non diffractive processes

$$\sigma_{in}(N) = \sigma_{nd}(N) + \sigma_d(N)$$

$$\sigma_{nd}(b;A) = \sum_{k,k'=0}^{A} \frac{A!}{(A-k-k')!\,k!\,k'!} \left(1-\sigma_{in}(N)\rho(b)\right)^{A-k-k'}$$

$$\times \left(\sigma_{nd}(N)\rho(b)\right)^k \left(\sigma_d(N)\rho(b)\right)^{k'}$$

$$- \sum_{k'=0}^{A} \frac{A!}{(A-k')!\,k'!} \left(1-\sigma_{in}(N)\rho(b)\right)^{A-k'} \left(\sigma_d(N)\rho(b)\right)^{k'}$$

$$= \left[1-\sigma_{in}(N)\rho + \sigma_{nd}(N)\rho + \sigma_d(N)\rho\right]^A - \left[1-\sigma_{in}(N)\rho + \sigma_d(N)\rho\right]^A$$

$$= 1 - \left[1 - \sigma_{nd}(N)\rho(b)\right]^A$$

$\sigma_{in}(N)$ and $\sigma_d(N)$ disappeared

For self screening processes (c) it is easy (de-couple from others) to obtain their A dependences. E.g.

$$\sigma_c(N) \text{ large} \qquad \sigma_c(A) \sim A^{2/3}$$

$$\sigma_c(N) \text{ small} \qquad \sigma_c(A) \sim A$$

Blankenbeckler et al (P.L. 107B, 106 (1981))

(i) observe there is large class of processes c

(ii) state that all probabilistic expressions for inelastic interactions are implied by the cutting rules (AGK) of Reggeon Field Theory.

$\longrightarrow$ TEST OF REGG. FIELD THEORY.

Criteria for selection of partial cross sections

"Criterion C leads to self screening when a superposition of any no of events satisfying C as well as their superposition with any no of events not satisfying C, also do satisfy C. Moreover these are the only events satisfying C."

Examples

- C - all events with one or more particles of a given type (e.g. positively charged) in the interval $y_1 < y < y_2$. If $\Delta = y_1 - y_2$ is small σ_c is small, $\sigma_c(A) \sim A$.

$$\lim_{\Delta \to \infty} \sigma_c(\Delta) \sim A^{2/3}, \quad \underline{\sigma_c(A) \sim A^{\alpha(\Delta)}}$$

- Choosing type of particle as $J/\psi \to \alpha(\Delta) = 1$ because $\sigma_{J/\psi}(N)$ is small.

(Note: if C means one and only one particle of type M within Δ — no self screening)

- Take $pA \to \underset{\text{fast baryon}}{B} + \bar{X}$. C - set of events with no fast isolated baryons. At high energies $\sigma_c(N)$ is small $\to \sigma_c(A) \sim A$. Baryon mult. at x

$$n(x) = \frac{1}{\sigma_{in}(pA)} \frac{d\sigma(pA \to B + \bar{X})}{dx}$$

$$\int_0^1 dx\, n(x) = 1$$

$$\underbrace{\sigma_{in}(pA)}_{\text{we do know } \sim A^{2/3}} = \underbrace{\int_0^{x_0} \frac{d\sigma}{dx}(pA \to B + \underline{X})}_{\text{without fast baryon } \sim A} + \underbrace{\int_{x_0}^{1} \frac{d\sigma}{dx}(pA \to B + \underline{X})}_{\text{must be } \sim A^{\alpha},\ \alpha < \frac{2}{3}}$$

Phenomenon of attenuation of fast secondaries.

— o —

— These are only approximate tests of AGK cutting rules because they apply to very high energies.

— coherent processes are left out

— If Reggeon Field Theory and AGK rules are the Truth, nuclei (in first approximation) will not provide us with new information about hadron - nucleon (non linear) processes. However, they will act as amplifiers of production.

(II) Nucleus – nucleus interactions

Can one obtain high enough densities and temperatures to deconfine quarks and gluons and produce quark-gluon plasma?

— Ahishetty, Koehler & Mc Lerran (P.R. D22, 2793 (1980))
YES

— W.J. Willis (CERN-EP/81-21, March 1981) discusses detection

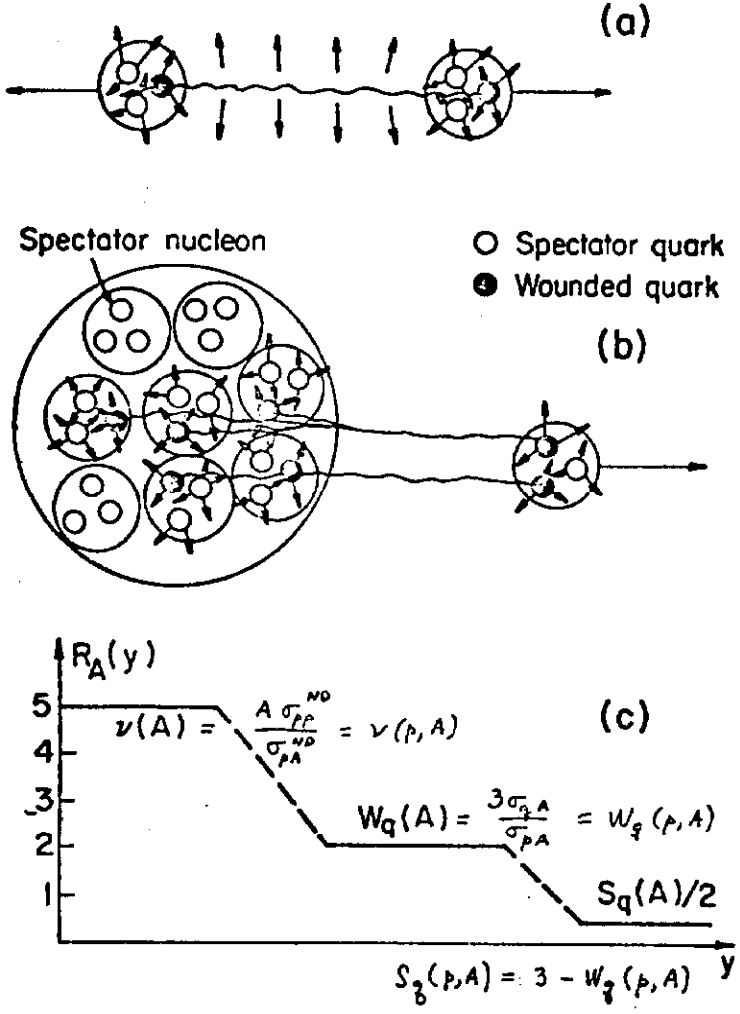
— T.D. Lee (Lecture at the Niels Bohr Inst 1981)
YES

Let us extrapolate hadron – nucleus to nucleus - nucleus collisions.

Use additive quark model

Do it for the relative multiplicities in the central region of rapidities

$$R^{c}_{AB} = \frac{n^{c}_{AB}(y)}{n^{c}_{pp}(y)}$$



M.A. FAESSLER, VERSAILLES, JULY 1981

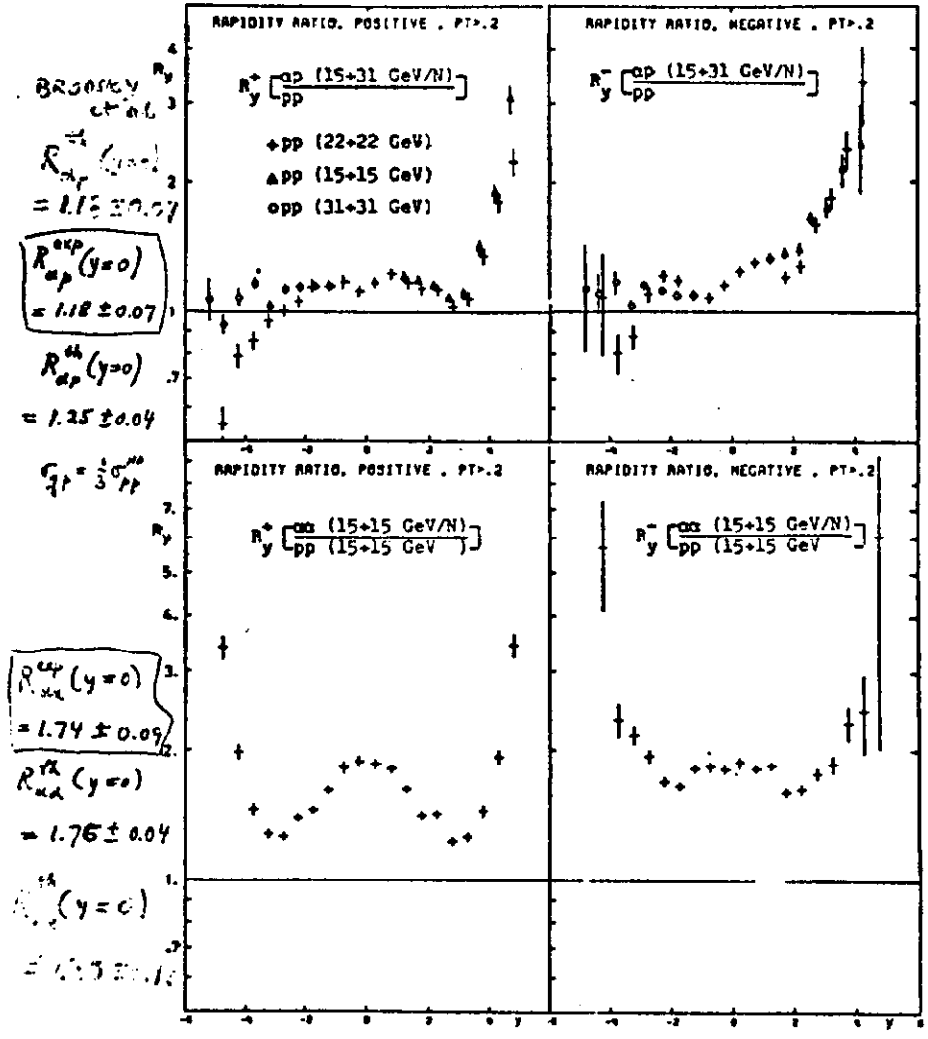
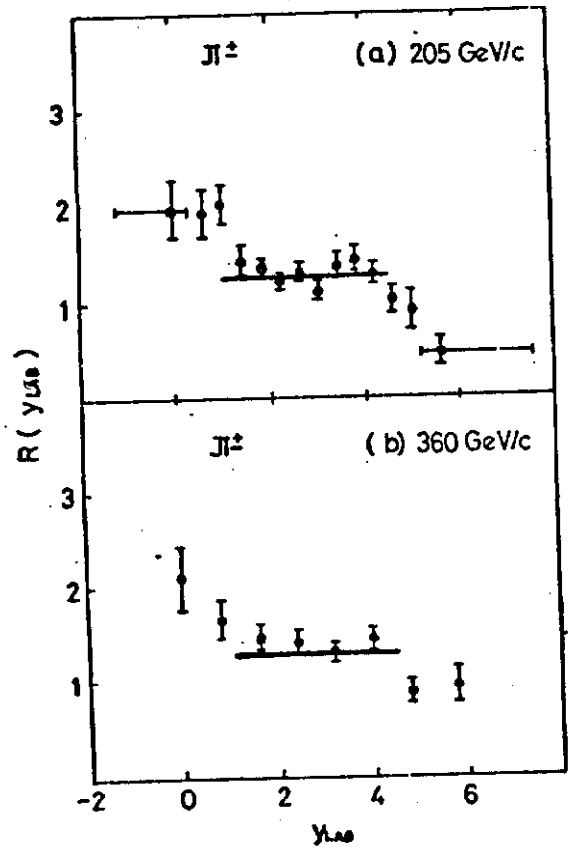
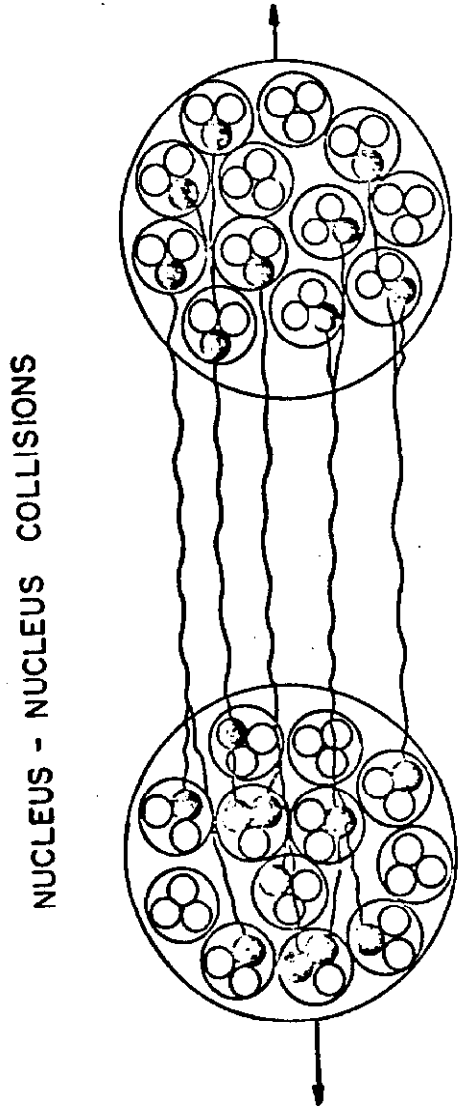


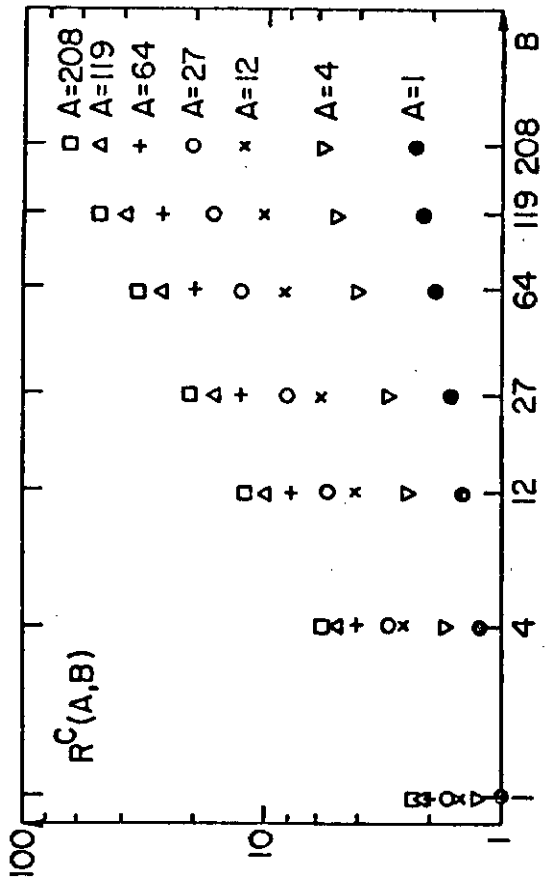
Fig. 6 Ratios [see Eq. (1)] of particle densities as a function of the rapidity $y_{cm} = \frac{1}{2}\ln(E+p_L)/(E-p_L)$ a) $R_y^+(\alpha p/pp)$, b) $R_y^-(\alpha p/pp)$, c) $R_y^+(\alpha\alpha/pp)$, d) $R_y^-(\alpha\alpha/pp)$.

π - deuteron



Z. Phys. C 75-1 (1982) FIG.3
Białas, Czyż, Kisielowska, "Additive Quark Model and..."





- In the central region of y's in α–α collisions a straightforward extrapolation works → no final state interactions seen.
- no measurements for heavier nuclei
- for central collisions of heavy nuclei a hydrodynamic description of the expansion (Landau) is probably appropriate. The initial conditions can be provided by extrapolation of hadron–nucleus production to nucleus–nucleus. These initial condition are different from the ones used by Landau. In his model the two nuclei stop in the c.m. system.

Comments by [J. D. Sullivan] at Fermilab A^{α} Workshop – 4 Mar 1982.

[The material below consists of the comments I made during the workshop, comments I wish I had made. Omitted are comments I wish I hadn't made!].

My remarks will be restricted to the single topic of shadowing in inelastic lepton-nucleus scattering $\ell + A \to \ell' + X$. I have not been actively working on these topics since completing the review G. Grammer and I wrote during 1977 (See: Electromagnetic Interactions of Hadrons, Vol 2, Edited by A. Donnachie & G. Shaw, Plenum (1978)). I remain

very interested in the subject, however.

It has been a pleasure and an inspiration to meet at this workshop many theorists and experimentalists who are excited about exploring high energy physics with the help of nuclear targets (and beams).

Inelastic lepton-nucleus & real photon-nucleus collisions

1) The many attractions of these processes are well known. For our purposes the special feature is the ability to vary two parameters: photon mass squared $-Q^2$, and photon lab energy ν. Simple space-time arguments and more detailed theories predict significant changes in nuclear shadowing as these parameters are varied.

2. $Q^2=0$ and small (compared to $1\,GeV^2$, m_p^2) region:

The existance of ρ, ω, ϕ, the success of the VMD model for real & almost real photon in processes involving nucleon targets, and the confirmed success of the Glauber model (see Czyz's talk) mean that a predictable amount of shadowing for real & almost real photon processes on nuclear targets is inevitable.

For <u>real photons</u> this is confirmed, first in experiments done at SLAC and other (now) low energy electron accelerators and recently at higher energies in experiments at Fermilab (D. Caldwell, et al., PRL 42, 553 (1979); UCSB, Toronto, Fermilab collaboration).

For <u>virtual photons</u>, even for values as small as $Q^2 \leq 0.5\,GeV^2$, the experimental sitatation has been confusing and unsatisfactory for the theoretical models until recently. At the time of the 1977 review with but one exception all data for virtual photons came from electron scattering experiments. In spite of great effort and care by the experimentalists little on no shadowing was observed and, more importantly, the various experiments agreed poorly with one another. The substantial radiative corrections which are present in electron scattering are often blamed for this but I am in no position to judge.

Recently there have been two inelastic muon-nucleus experiments which see substantial shadowing for $Q^2 \neq 0$. Almost too much!

1) A BNL experiment (M. Miller, et al, UR-760 preprint; Rochester, BNL, NSF collaboration [I don't know the published citation.] which covers $0.2 < Q^2 < 2.4$ GeV^2 and $1 < \nu < 9$ GeV.

2) E448 at Fermilab (M. S. Goodman et al, PRL 47, 293 (1981); Harvard, Tufts, Fermilab, Oxford, Chicago, MIT, Mich State; See Goodman's talk here) which covers. $0.01 < Q^2 < 30$ GeV^2 and $40 < \nu < 200$ GeV.

Even though the simplest models (parton point like) fail to describe those data, it is very reassuring nevertheless to see at last definite shadowing for virtual photons!

<u>What are the key issues remaining to be settled?</u>

In my judgement the most fundamental is the question of whether or not nuclear shadowing "scales". By this I mean does shadowing always exist for sufficiently small $x = Q^2/2m\nu$ or, alternatively, when Q^2 exceeds some fixed value is shadowing lost no matter how large we choose ν (wee x).

There are at least two schools of theoretical thought on this subject.

(i) One school (represented here by Bradshy and coworkers) holds that shadowing goes away for Q^2 sufficiently large independent of x (i.e. shadowing doesn't scale). Their arguments are more sophisticated than the old $\rho\omega\phi$ + pt. like model, but their qualitative conclusions are similar. (See Bradshy's remarks this workshop).

(ii) The other school (represented here by Bjorken, Muller and others) holds that shadowing is present for any Q^2 provided x is sufficiently small. The most elegant form of the argument can be phrased in terms of a "correspondence principle". (See various conference talks by Bjorken.)

All schools agree that shadowing is at best a small x phenomena. Clearly some experimental guidance would be very valuable.

There is a variant of school (ii) due to Nicholaev & Zakharov which predicts for x small but slightly larger than the values of x for which shadowing obtains, <u>antishadowing</u> should occur. There is no verdict from experiment yet. Clearly the observation of antishadowing would be spectacular! The presence of logarthmic scale breaking due to QCD, not considered in the crude model of Nicholaev & Zakharov, beclouds the antishadowing issue. (See Muller's talk here for a discussion of some scale breaking effects.)

<u>What physics is revealed by studying shadowing?</u>

Let $q_N^i(x)$ be the quark distribution functions observed in scattering from a <u>nucleon</u> target (suitably isospin averaged) and $q_A^i(x)$ the same for a <u>nuclear</u> target. [We ignore scale breaking effects here.]

The school(i) folks say for sufficiently large Q^2

$$q_A^i(x) = A\, q_N^i(x), \quad \text{all } x$$

whereas school(ii) says (ideally)

$$q_A^i(x) \simeq A^{2/3} q_N^i(x) \quad \text{for, say, } x \lesssim \frac{0.1}{A^{1/3}}, \text{ any } Q^2$$

$$q_A^i(x) = A\, q_N^i(x) \quad \text{for } x \gtrsim \frac{0.1}{A^{1/3}}.$$

The small x shadowing domain corresponds physically to the region in which a quark parton has such a low momentum that its uncertainty principle

confinement exceeds that of a single nucleon and is characteristic of the nuclear size or greater. (This is most easily seen in the virtual photon-nucleus c.m. frame.)

It seems to me quite reasonable that such wee partons would loose their allegiance to individual nucleons and be more properly considered as components of the nuclear system as a whole. The reduction of $q_A^i(x)$ by a factor $A^{1/3}$ (the remaining factor of $A^{2/3}$ is geometrical) comes about if one accepts the notion first articulated by various Russian theorists, that the wee parton sea in nuclear matter saturates at some "equilibrium"

density independent of the details of the system.

Thus shadowing probes the dynamics of wee partons a subject notoriously poorly understood in spite of all our QCD progress.

Thanks again to the organizers for a very exciting workshop.

[B. ROE]

Prompt ν Beam Dump Exp'ts

Signal: ν from short lived particles
Charmed particles $D, F, \Lambda_c \ldots$
+ other?

Background: ν (mainly ν_μ) from π, K decay

To separate:

- Calculate background using μ measurement in shield
- Extrapolate: or Use targets of 2 diff't average densities

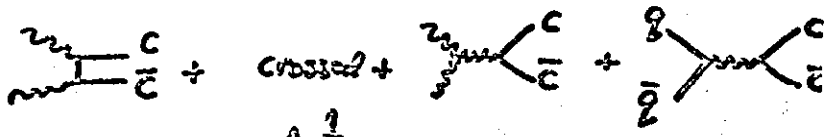
Extrapolate in $\frac{1}{\rho}$ to 0 - Only "prompt" survive

CERN RESULTS

	BEBC ν_μ	ν_e	CHARM
$\sigma_{D\bar{D}}$ (μb)	30±10	17±4	19±6

Central Production

$D\bar{D}$

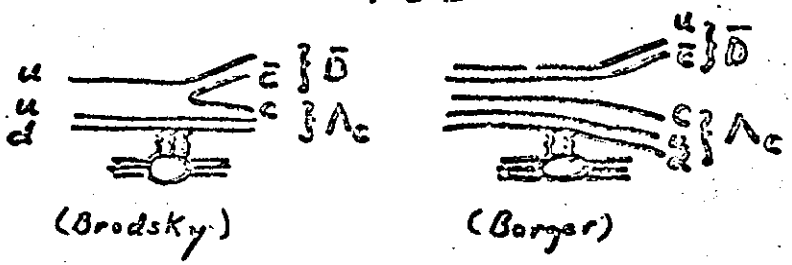


A^{1}

$\sim (1-x)^{n}$ $\quad n = 3-5$; $x = \frac{p_{D\parallel}^{*}}{p_{D\,max}}$

Diffraction Production

$\Lambda_c D$



$A^{2/3}$

$\sim (1-x)^{1}$

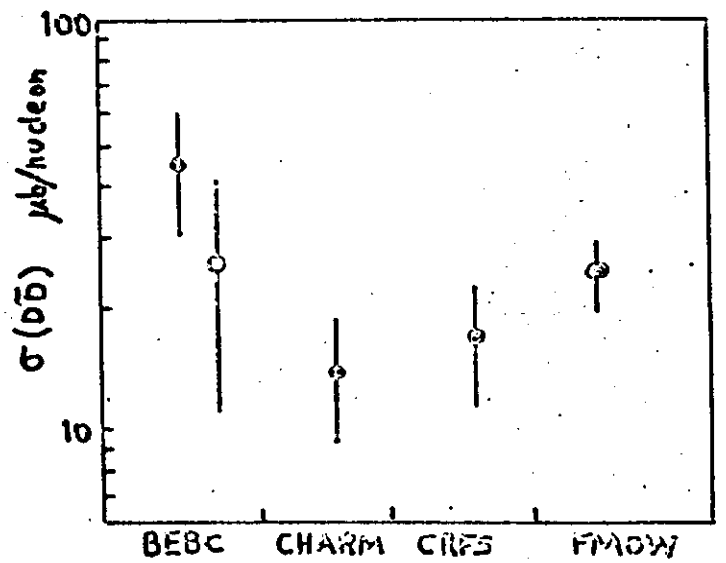
$\sigma(D\bar{D})$ at 400 GeV

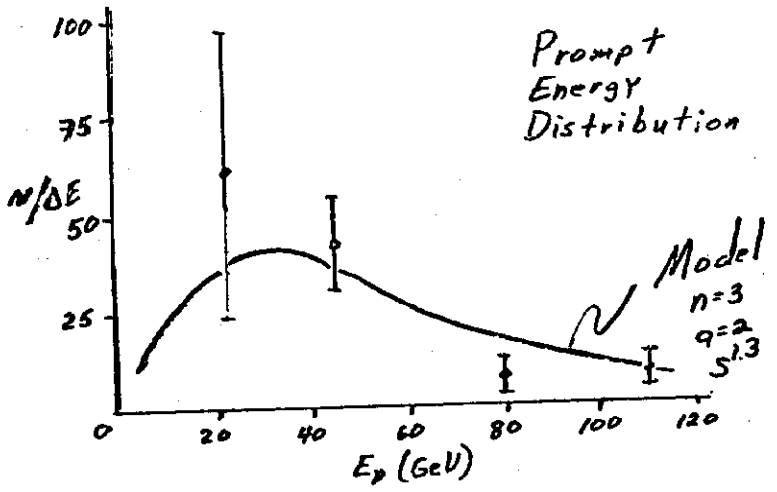
$$E\frac{d^3\sigma}{dp^3} = A(1-|x|)^3 e^{-2p_\perp} s^{1.3}$$

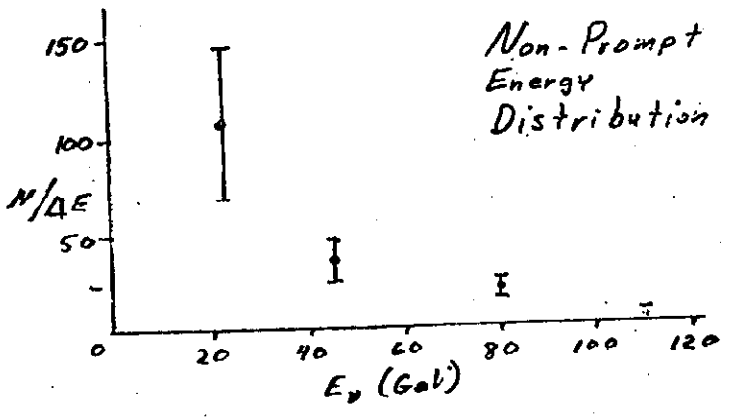
$\varepsilon = 0.3$

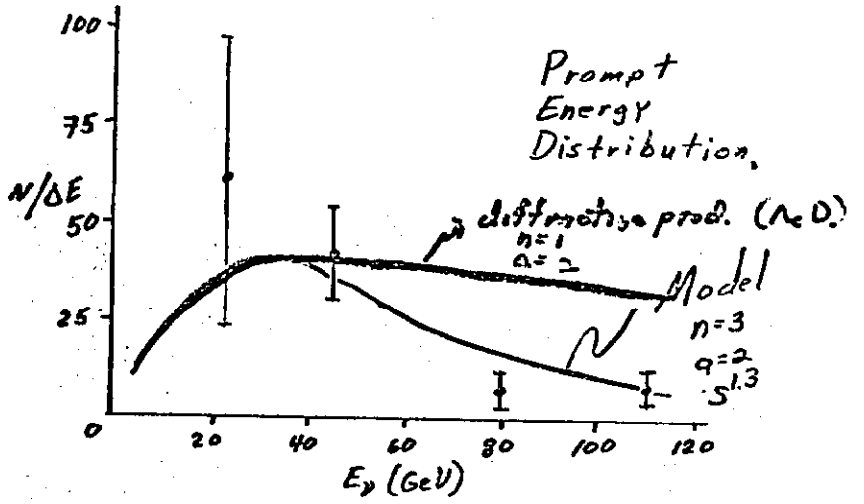
• • ν_μ & $\bar{\nu}_\mu$

o ν_e & $\bar{\nu}_e$




Prompt
Energy
Distribution
Model
n=3
q=2
$S^{1.3}$
N/ΔE
100
75
50
25
0
20
40
60
80
100
120
E_ν (GeV)


Non-Prompt
Energy
Distribution
N/ΔE
150
100
50
0
20
40
60
80
100
120
E_ν (GeV)


Prompt
Energy
Distribution.
diffractive prod. (ΛcD.)
n=1
Model
n=3
q=2
$S^{1.3}$
N/ΔE
100
75
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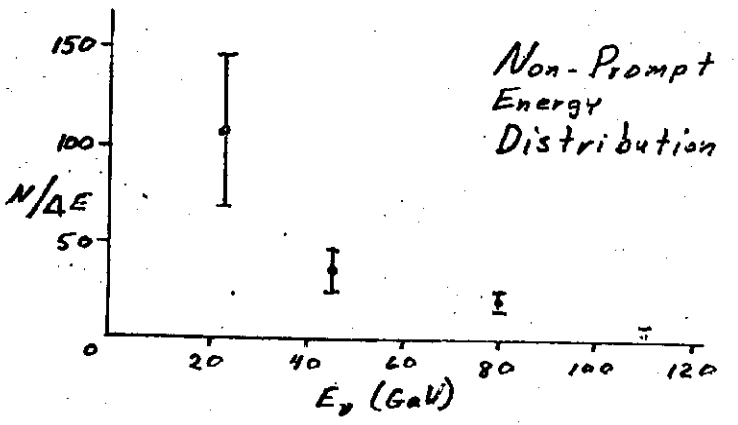
80
100
120
E_ν (GeV)


Non-Prompt
Energy
Distribution
N/ΔE
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100
50
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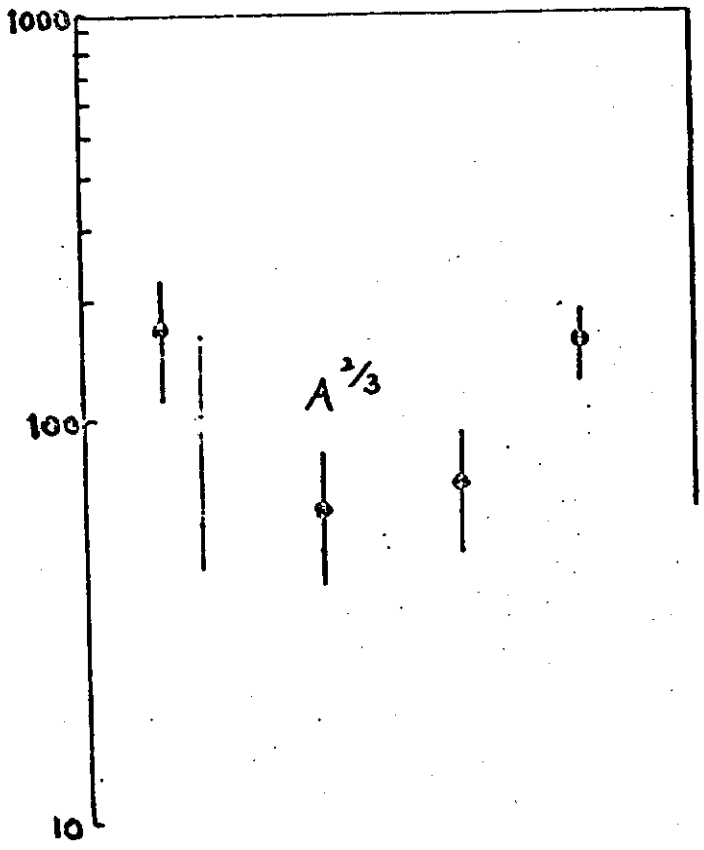
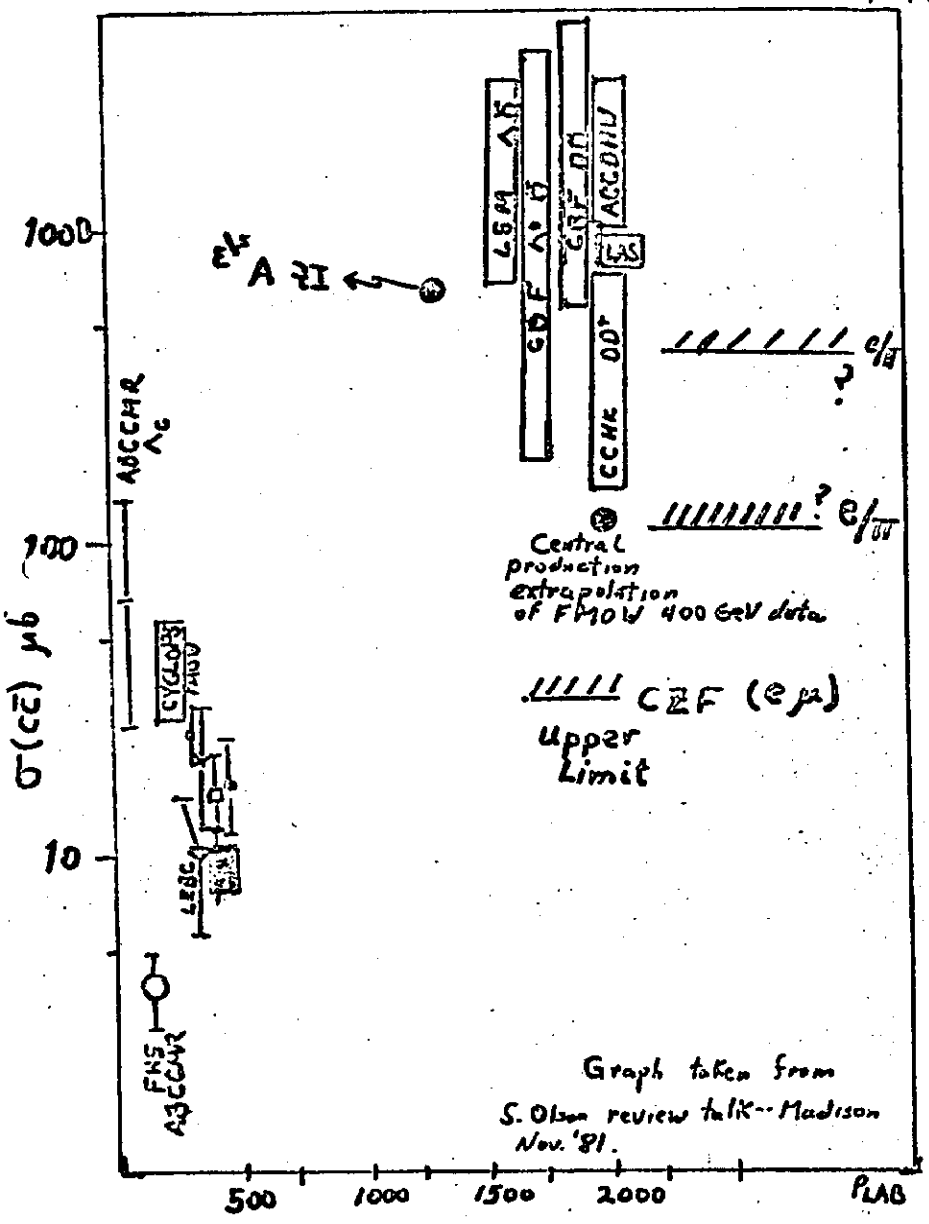
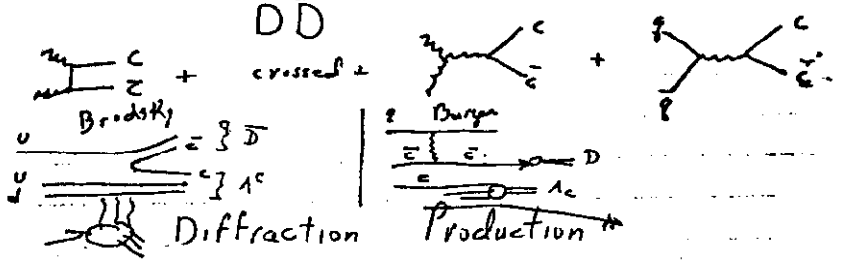
60
80
100
120
E_ν (GeV)


1000
100
10
$A^{2/3}$


1000
100
10
$\sigma(c\bar{c})$ μb
500
1000
1500
2000
P_{LAB}
ABCCMR Λ_c
CYCLOPS
LEBC
FNS ABCCMR
LEM
CBF
CBF DD
ACCDHW
LAS
CCHK
DD+
e/π
?
e/π
Central production extrapolation of FMOW 400 GeV data
CZF (eμ)
Upper Limit
Graph taken from S. Olson review talk -- Madison Nov. '81.

Central Production

$D\bar{D}$



$\Lambda_c D$

diagrams?

$\boxed{E_\nu > 20}$

$\uparrow$

$p_\perp$

$E_\nu > 80$

	$A^{\#}$	$A^{\frac{1}{3}}$
Be	9.01	2.081
Fe	~~63.5~~ 55.85	3.822
Cu	63.54	3.990
W	183.85	5.686

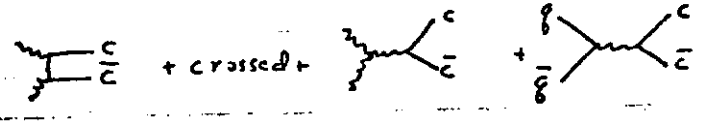
If $A^{\frac{2}{3}}$ not A^1 → mult

CERN	49 / 25	180±60 ν_μ
		100±60 ν_e
BeBC by CHARM	3.990	60±20
EG13	5.686 (16)	140±28
Bodek	3.822 (25)	70±23

expected W to Cu ratio: 1.425 (ratio of rates per POT)

Central Production

$D\bar{D}$

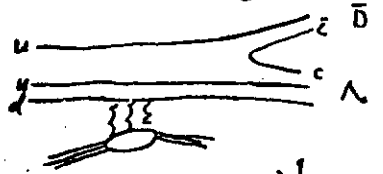


$\sim(1-x)^n$ $n = 3-5$

A^1

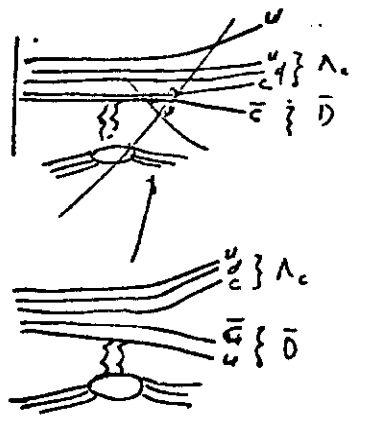
Diffraction Production

$\Lambda_c \bar{D}$



$\sim(1-x)^1$

$A^{\frac{2}{3}}$



ANOMALOUS NUCLEAR ENHANCEMENT AND GLUON FILTERS

U. SUKHATME

Production of particles at large-p_T in hadron-nucleus and nucleus-nucleus collisions.

INPUTS

1. Perturbative QCD framework.
2. Multiple hard scattering in a nucleus

OUTPUTS

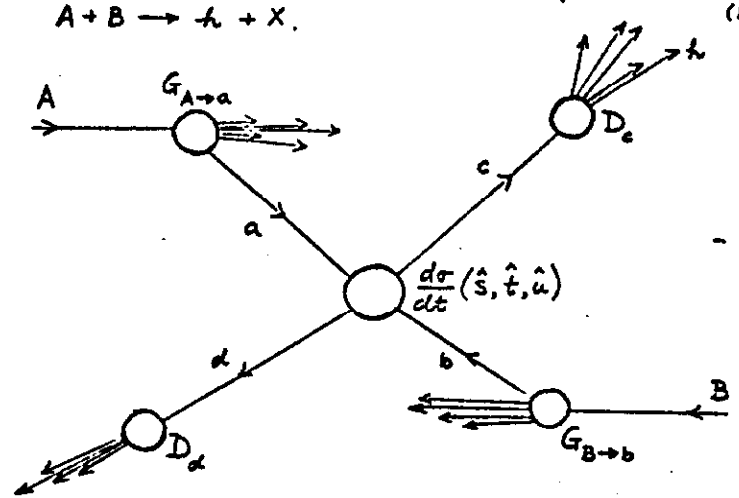
1. Nucleus is a gluon filter.
2. ANE (A^α, $\alpha > 1$).
3. Trigger dependence $\alpha(\overset{\pi^\pm, K^+}{h_F}) \simeq 1.1$, $\alpha(\overset{K^-, \bar{p}}{h_U}) \simeq 1.3$
4. A-dependence in nucleus-nucleus collisions. (enhancement factor shown to be $A_1 A_2^\alpha + A_2 A_1^\alpha - A_1 A_2$)

A. Krzywicki, J. Engels, B. Peterson, U. Sukhatme: Phys. Lett. 85B, 407 (1979).

U. Sukhatme, G. Wilk: SLAC-PUB-2844 (1981), Phys. Rev. D (1982).

Perturbative QCD approach to large-p_T production.

$A + B \to h + X$. (Feynman, Field, Fox)



$s = (p_A + p_B)^2 = E_{cm}^2$; $\hat{s} = (p_a + p_b)^2$

$\hat{t} = (p_a - p_c)^2$; $\hat{u} = (p_a - p_d)^2$; $\hat{s} + \hat{t} + \hat{u} \simeq 0$.

Need (i) parton structure functions G

(ii) parton fragmentation functions D

(iii) hard scattering $\frac{d\sigma}{dt}$

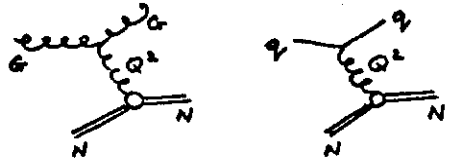
(iv) scaling violations (Q^2 dependence) due to QCD.

$Q^2 = 2\hat{s}\hat{t}\hat{u}/(\hat{s}^2 + \hat{t}^2 + \hat{u}^2)$, symmetric ; $Q^2 \to -\hat{t}$ ($\hat{t} \ll \hat{s}$)

$$E\frac{d\sigma}{d^3p_h}\Big|^{A+B\to h+X}_{(s,\vec{p}_h)} = \sum_{\substack{ab\\cd}} \int d^2k_{1a} \int d^2k_{1b} \int d^2k_{1c} \int dx_a \int dx_b \frac{1}{\pi}\frac{d\sigma}{dt}(\hat{s},\hat{t},Q^2)$$
$$G_{A\to a}(x_a, k_{1a}, Q^2)\, G_{B\to b}(x_b, k_{1b}, Q^2)$$
$$D_{c\to h}(z_c, k_{1c}, Q^2)/z_c .$$

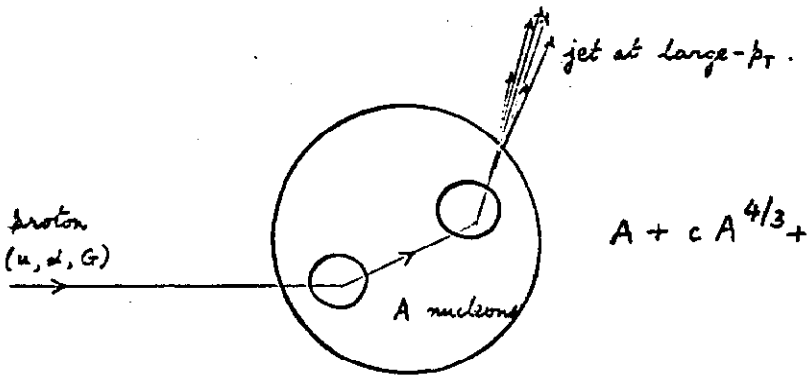
Consider lowest order perturbative QCD contribution to parton-parton hard scattering – single gluon exchange.

$\sigma(G+N) \simeq \frac{9}{4}\sigma(q+N)$ in 1 collision



$\frac{9}{4}$ is color factor.

Gluons interact more strongly with matter than quarks due to the 3G coupling.



$A + cA^{4/3} + \cdots$

Enhance gluon scattering further by allowing the possibility of multiple collisions ⇒ nuclear target.

$\sigma(G+N) \simeq 5\,\sigma(q+N)$ in 2 collisions

Expect observable consequences of 3G coupling, since $A\uparrow$ ⇒ more large-p_T gluon jets.
⇒ <u>nucleus is a gluon filter!</u>

<u>Hadron-nucleus scattering</u>.

$p + A \to h + X$; $p_{LAB} = 400$ GeV/c.

$$\frac{E\frac{d\sigma}{d^3p}(p+A\to G+X)}{E\frac{d\sigma}{d^3p}(p+N\to G+X)} = A + c_2^G(p_\perp)A^{4/3} + c_3^G(p_\perp)A^{5/3} + O(A^2)$$

$$\cong A^{n^G(p_\perp)} \qquad \underline{(n^G \equiv \alpha^G)}$$

c_2^G, c_3^G computations done. ; $k_{T,MIN} = 1.5$ GeV/c.

$p_\perp$ (GeV/c)	5	7	9	11	
$(G/Q)_{pN}$	3	1	.64	.46	
n^G	1.15	1.23	1.21	1.27	ANE and $n^G > n^Q$
n^Q	1.07	1.07	1.06	1.11	
$(G/Q)_{pU}$	9	3	2	1.3	

<u>gluon factory! → especially at the TEVATRON</u>.

<u>Hadron triggers</u>: Fold in fragmentation functions.

n^h has Q, G contributions. $G \to h_x, h_y$ $\quad Q \to h_z$

Particles containing (u,d): $n_{\pi^\pm} \simeq n_{K^+} \simeq n^Q \simeq 1.1$

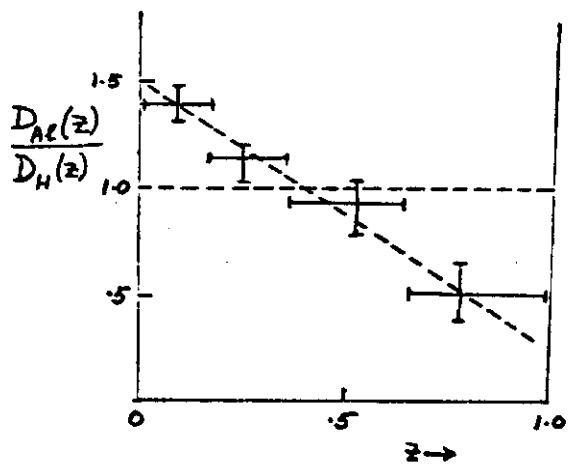
Particles not containing (u,d): $n_{K^-} \simeq n_{\bar p} \simeq n^G \simeq 1.3$

Explains curious trigger dependence of ANE.

Many uncertainties in inputs, but the nucleus as a gluon filter may well be correct.

1. $\alpha(h_v) \neq \alpha(h_F) \Rightarrow$ very reasonable to require 2 types of jets (assuming hadrons come from jets)
$\Rightarrow$ q and g jets in QCD

2. Jets on Al are softer than those on H.
— again suggests gluon jets.



<u>Nucleus - nucleus collisions</u> $(A_1 + A_2 \longrightarrow h + X)$

What type of enhancement? (above $A_1 A_2$).

$I \equiv E \frac{d\sigma}{d^3p}$ (π^0 at 90° in NN CM frame).

$$I_{pA} = \underbrace{A I_{pp}}_{\text{Single scattering}} + \underbrace{A^{\frac{4}{3}} I_D}_{\text{Double scattering}}$$

$$I_{A_1 A_2} = A_1 A_2 I_{pp} + \left(A_1 A_2^{\frac{4}{3}} + A_2 A_1^{\frac{4}{3}}\right) I_D$$

Eliminate the model-dependent quantity $A^{\frac{4}{3}} I_D$.

$$I_{A_1 A_2} = A_1 I_{pA_2} + A_2 I_{pA_1} - A_1 A_2 I_{pp}$$

$$= \underbrace{\left(A_1 A_2^{\alpha} + A_2 A_1^{\alpha} - A_1 A_2\right)}_{\text{Anomalous enhancement factor in } A_1 A_2 \text{ collisions, independent of details of multiple scattering.}} I_{pp}$$

<u>Ex</u>. $\alpha\alpha$ $\quad \frac{I_{\alpha\alpha}}{I_{pp}} = 16\left[2^{2\alpha_{\pi^0}(p_T)-1} - 1\right]$

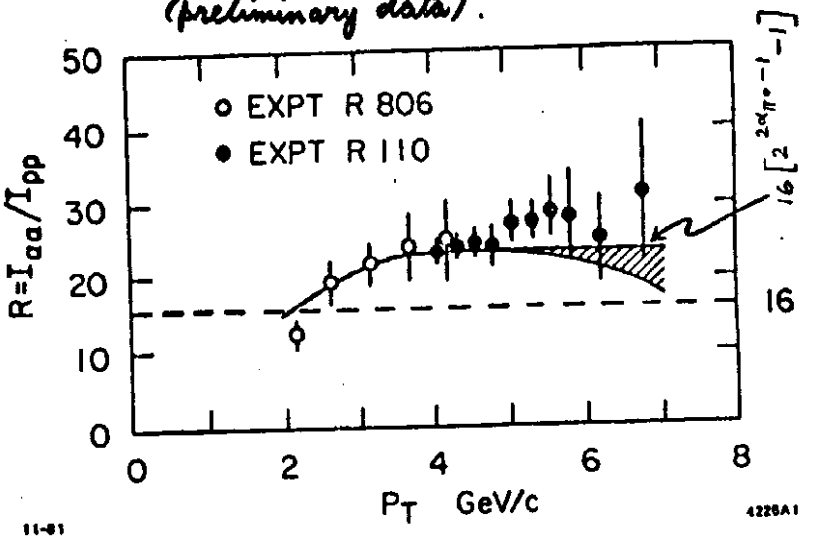
Works rather well, but data is preliminary.

αα collisions – CERN-ISR

15 GeV per nucleon

π^0 trigger at 90° in NN CM frame

(preliminary data).



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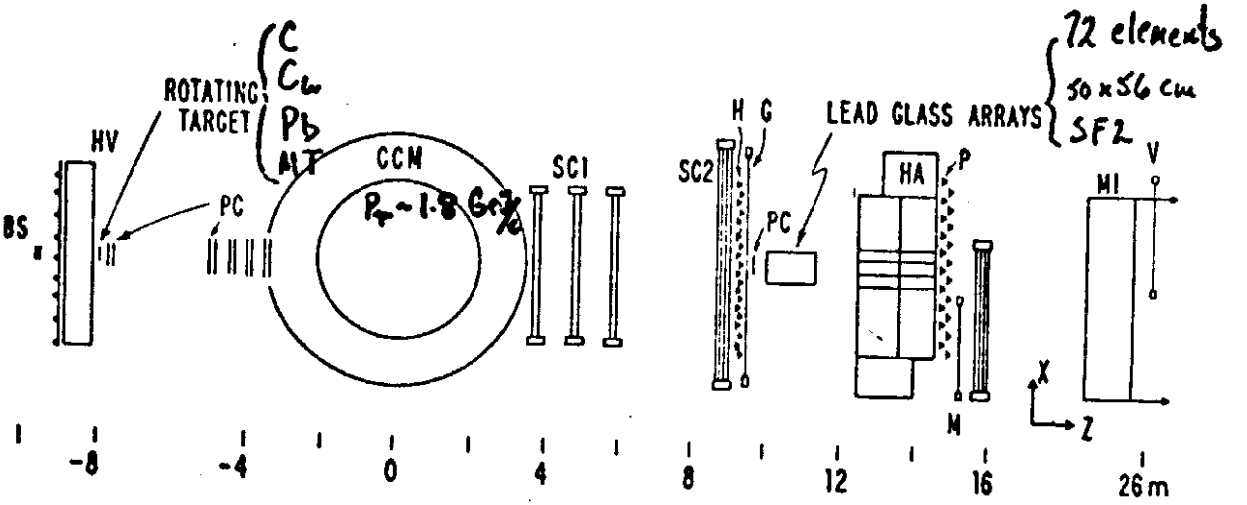
M. Goodman

E448 SHADOWING EXPERIMENTAL APPARATUS



HARVARD, TUFTS, FERMILAB, U. CHICAGO, MIT, MSU

(Goodman et al Phys Rev Lett 47, 293 (1981))

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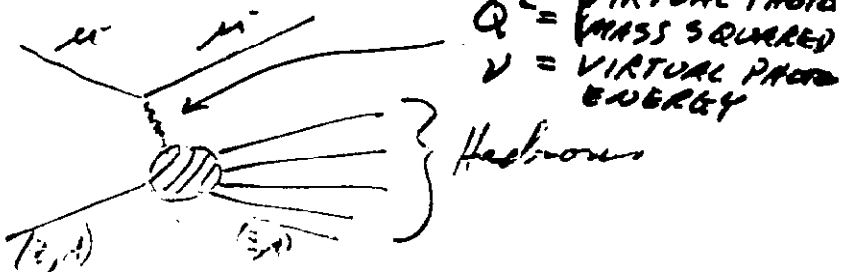
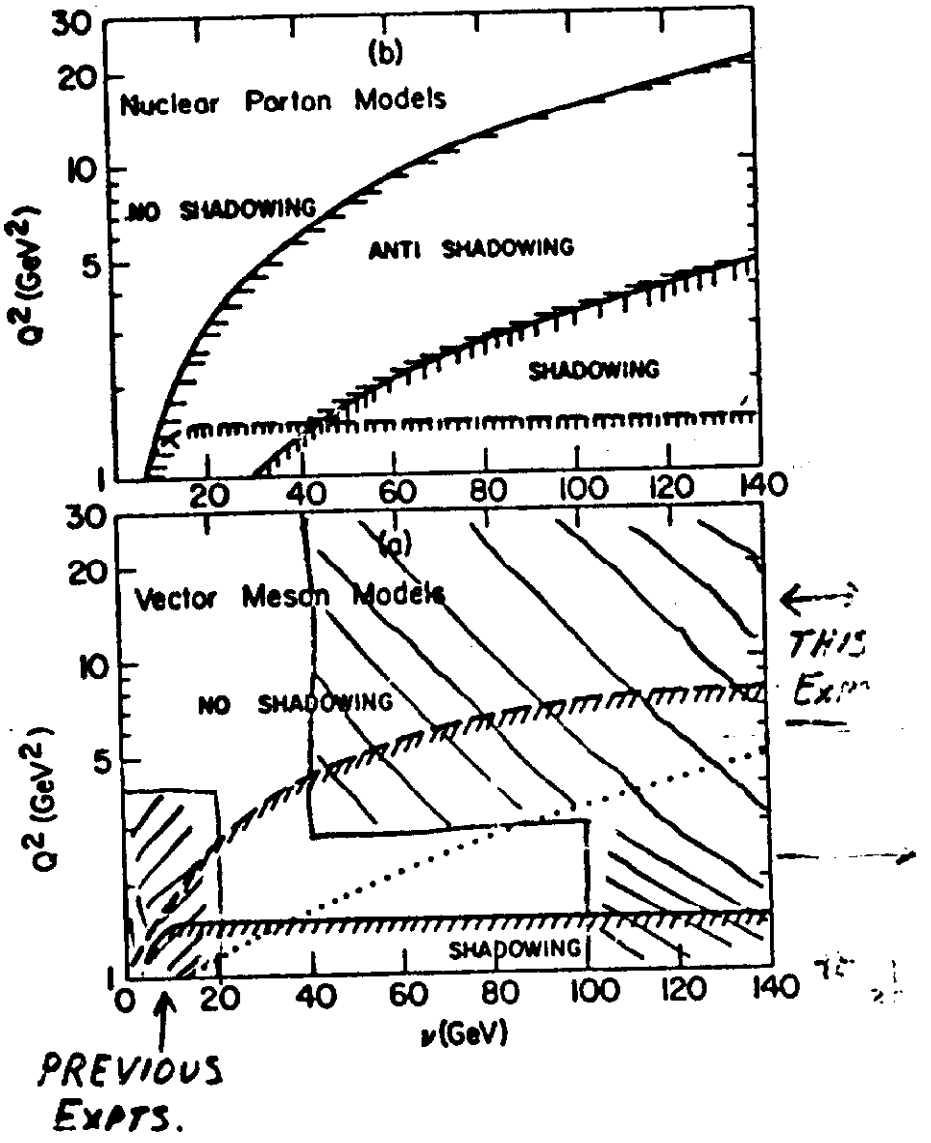
PROCESS OF INTEREST

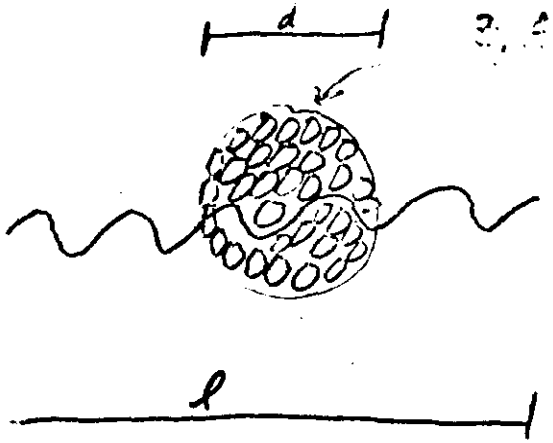


KINEMATIC RANGE OF EXPT:

Q^2 [0.01 – 30.] GeV^2

ν [40 – 200] GeV





$d \sim 2$ Fm C

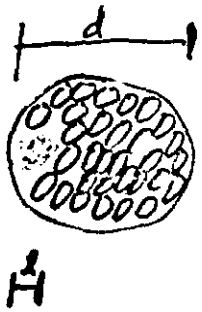
$d \sim 6.5$ Fm Pb

NO SHADOWING

$\ell \gg d$

$\sigma_{\gamma N} \sim A\,\sigma(A=1)$

"BARE PHOTON"



SHADOWING

$\ell \lesssim d$

$\sigma_{\gamma N} < A\,\sigma(A=1)$

$\longrightarrow \sigma_{\gamma N} \sim A^{2/3}\,\sigma(A=1)$

"HADRONIC PHOTON"

DATA:

$$\frac{\sigma(A)}{A} \sim C A^{\rho-1}$$

(NOT GOOD THEORY – OFTEN USED TO SUMMARIZE DATA)

$(\rho-1) = 0 \Rightarrow$ No Shadowing

$$\frac{A_{eff}}{A} \equiv \frac{\sigma(A)}{A\,\sigma(1)} = G(R/\ell)$$

$\ell \gg R$ No Shadowing

R = Nuclear Radius

ℓ = Virtual Photon Mean Free Path

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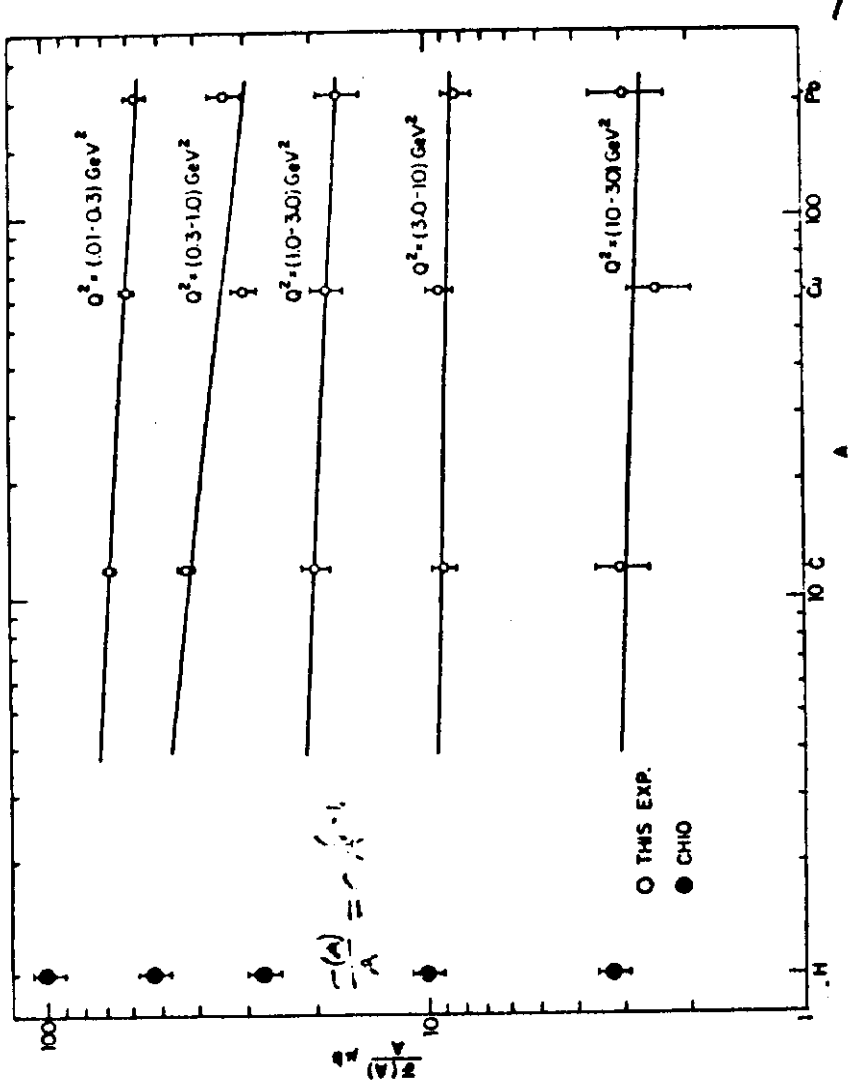

$\frac{A_{eff}}{A}$

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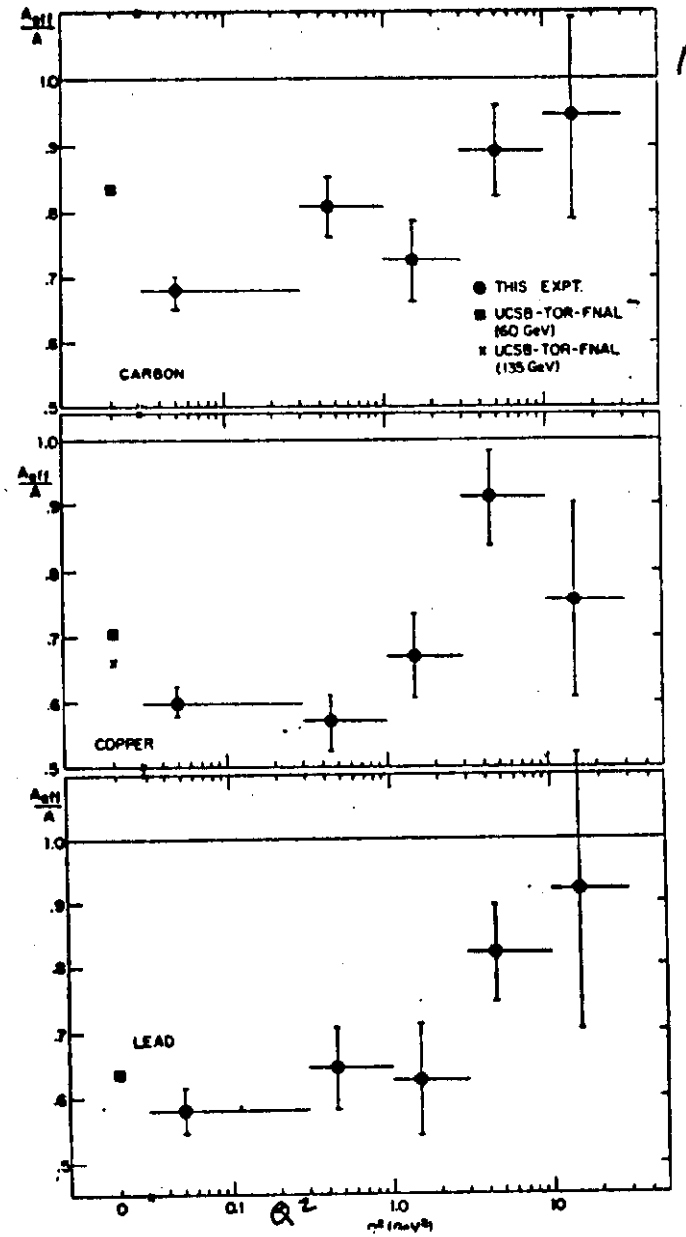
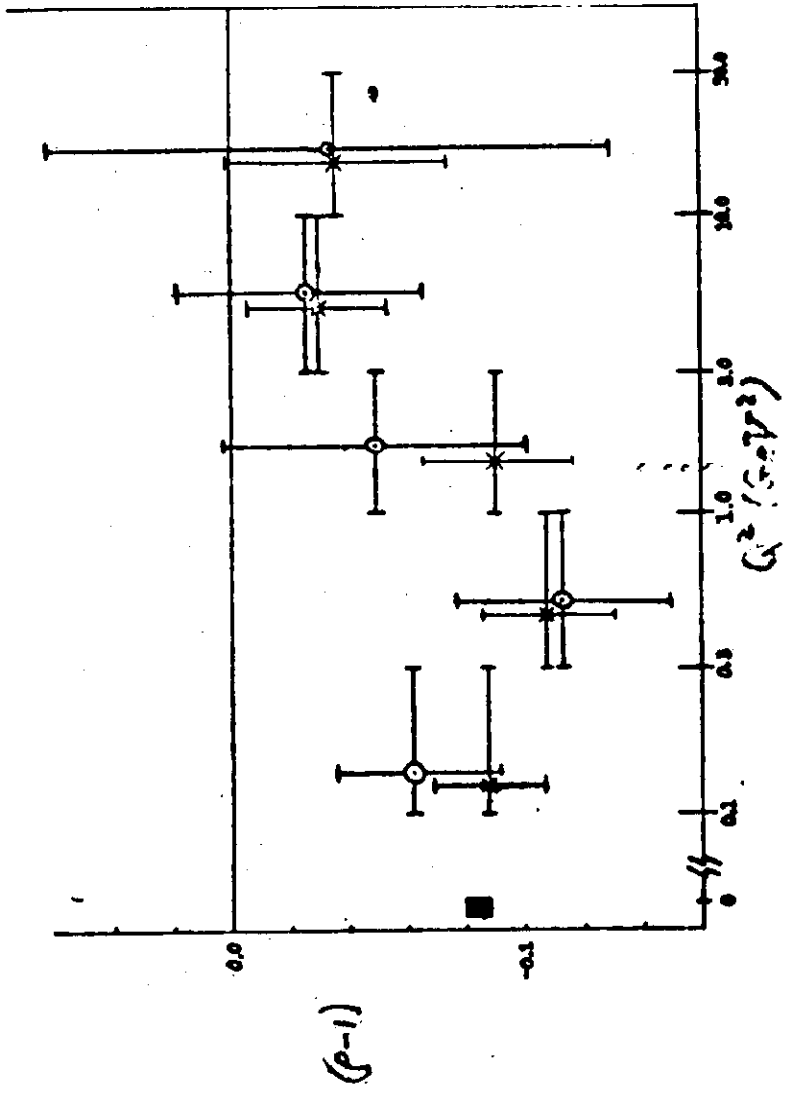




FITTED VIRTUAL PHOTON MEAN FREE PATH

$$\frac{A_{eff}}{A} \sim G(R/\ell)$$

Q^2 (GeV^2)	ℓ
0	$3.4^{+.3}_{-.2}$ Fm
.01 - .3	$2.9^{+.7}_{-.5}$ Fm
.3 - 1.0	$3.5^{+1.4}_{-0.8}$ Fm
1.0 - 3.0	$3.7^{+1.6}_{-0.9}$ Fm
3.0 - 10.	$12.4^{+33.}_{-5.3}$ Fm
10. - 30.	$10.3^{+20.}_{-4.1}$ Fm

R(C) ~ 2.6 Fm

R(Cu) ~ 4.5 Fm

R(Pb) ~ 6.6 Fm

CONCLUSIONS:

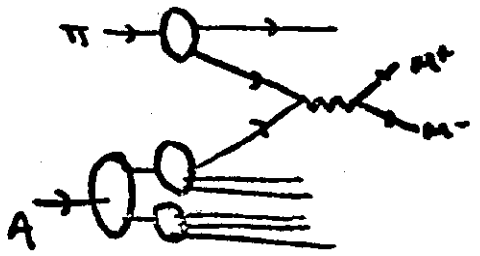
- VIRTUAL PHOTONS SHADOW COMPARABLE TO REAL PHOTONS FOR $Q^2 \lesssim 1\ GeV^2$ AT $\nu \sim 150\ GeV$
- SHADOWING APPEARS TO DIMINISH AS Q^2 INCREASES $\gtrsim 3\ GeV^2$
- Q^2 EXTENT OF SHADOWING GREATER THAN OBSERVED AT LOW ENERGIES
- HIGHER MASS VECTOR MESONS THAN ρ COMPONENT PARTICIPATE IN SHADOWING AT THESE ENERGIES

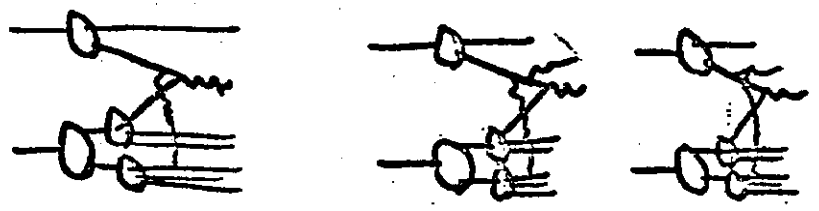
S. BRODSKY

Novel Nuclear Target Effects in QCD

I. Nuclear Corrections to Lepton-Pair Production

G. Bodwin
G. Lepage





Leading twist

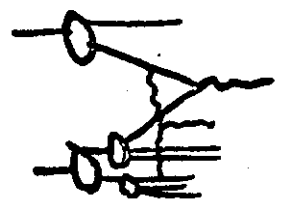
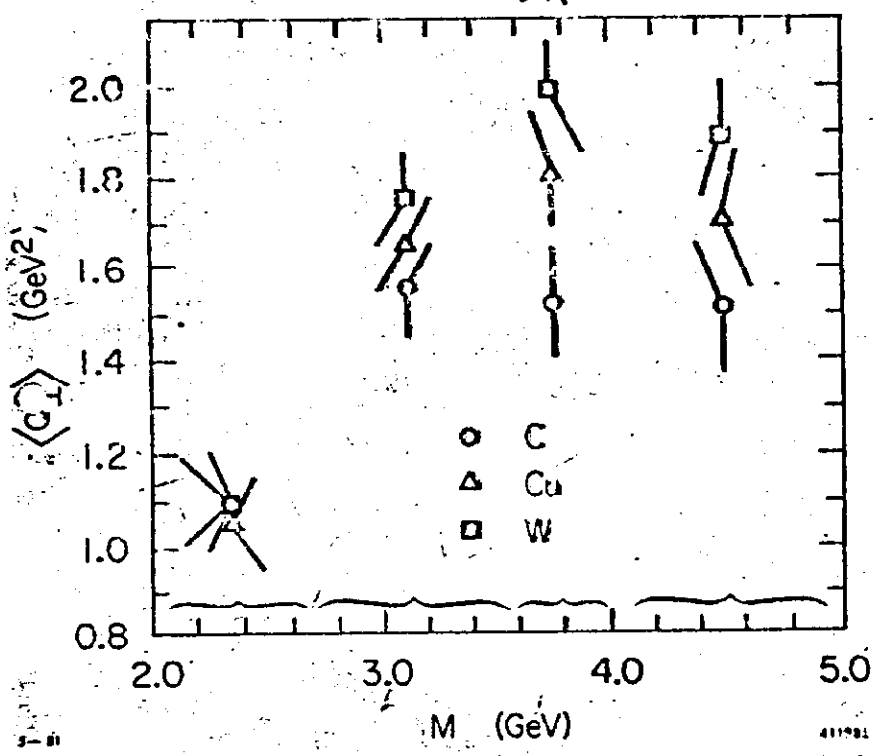


Fig. $\langle Q_\perp^2 \rangle_A$ vs $\sqrt{\langle Q^2 \rangle}$



At $Q_\perp^2 = 0$: depletion $\dfrac{1}{1 + \dfrac{\langle k_\perp^2 \rangle_A}{\langle Q_\perp^2 \rangle}}$

Effect of initial state elastic scattering in nucleus:

$$\frac{d\sigma}{dQ^2 d^2Q_\perp} (HA \to \mu^+\mu^- X)$$

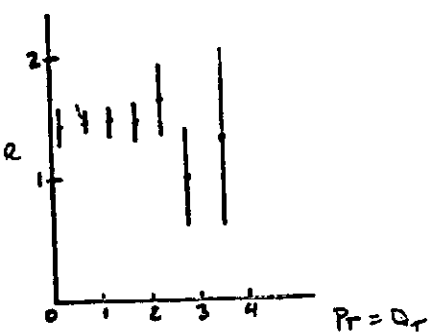
Expect

$$\langle Q_\perp^2 \rangle = \langle Q_\perp^2 \rangle_{A=1} + \langle \ell_\perp^2 \rangle n_{q/N}^{coll} (A^{1/3} - 1)$$

Simple fits to CIP data:

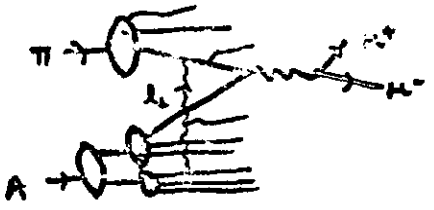
$$\left[\ell_\perp^2 \, n_{q/N}^{coll} \right]^{\frac{1}{2}} \sim 200 \pm 150 \text{ MeV}$$

$$\frac{A \frac{d\sigma}{dp_T}(\pi^- p)}{\frac{d\sigma}{dp_T}(\pi^- p_t)} = R$$



Expect $R(p_T) < 1$ at large $p_T = Q_T$

FNAL Colloq, June, 1981



Pert. Analysis

$A^+ = 0$, LC

+ Coulomb gauge

Eikonal

Initial State Corrections:

change $k_\perp$, color factors

For long target: radiation dessing, secondary beams.

Results:

(1) $\frac{d\sigma}{d^2Q_\perp dQ^2}$ increased at high $Q_\perp$

$\delta\langle Q_\perp^2\rangle \propto A^{1/3}$

(2) $\left(\frac{d\sigma}{dQ^2}\right)_{\pi A} = A\left(\frac{d\sigma}{dQ^2}\right)_{\pi N}$

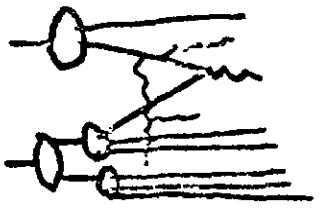
(3) $\left.\frac{d\sigma}{d^2Q_\perp dQ^2}\right|_{Q_\perp=0} \sim \frac{1}{1+\frac{\langle k_\perp^2\rangle}{\langle Q_\perp^2\rangle}}$

4) To eliminate hard radiation induced in target nucleus:

Need $Q^2 \gtrsim x_q \langle k_\perp^2\rangle_A M_N L_A$

$\sim .25\ \mathrm{GeV}^2\ A^{2/3}\ x_q$

$Q^2 \gtrsim 10\ \mathrm{GeV}^2$ for $\bar{U}$



New constit for QCD

5) Radiation induced in central region of A

6) On nucleon target new color factor

$\frac{d\sigma}{dQ^2}(\bar{p}p)$

$$\frac{1}{3} \to \frac{1}{3}\left[1 + (\overset{\leftarrow 9}{C} - 1)|S(Q^2)|^2\right]$$

New scale-breaking pattern. $|S|^2 \sim \frac{1}{3}$ at $Q^2 = 10$

$\sim \frac{1}{10}$ at $Q^2 = 10^{\ldots}$

Sum dbl. logs:

$$|S(Q^2)|^2 = \exp - \frac{C_A}{\beta_0} \ln\left(\frac{\ln Q^2/\Lambda^2}{\ln \lambda^2/\Lambda^2}\right) \ln \frac{Q^2}{\lambda^2}$$

$$C_A = 3, \quad \beta_0 = 11 - \tfrac{2}{3} n_f$$

Numerically: $(\Lambda^2 = .01\ \mathrm{GeV}^2, \quad \lambda^2 = .25\ \mathrm{GeV}^2)$

$$|S|^2 = \begin{cases} \frac{1}{3} & Q^2 = 10\ \mathrm{GeV}^2 \\ 1/6 & 50 \\ 1/10 & 100 \end{cases}$$

$$C = (C_{el} - 1)|S(Q^2)|^2 + 1$$

dom at $Q^2 \to \infty$

1) $C_{el} = C_{el}(\theta)$ (s-dep?)

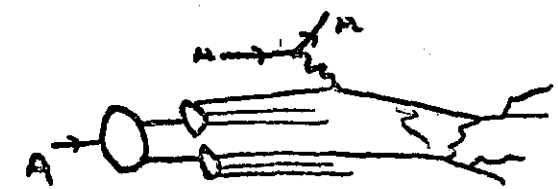
2) $C_{el} \sim \frac{n^2}{2}$?

3) New scale-viol in DIS cross-section

4) Effect is A-indep.

Associated Production A-dep.

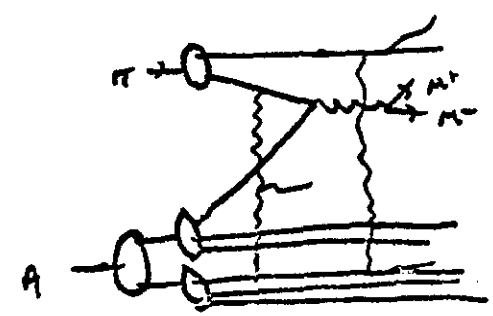
Final States in Deep Inelastic



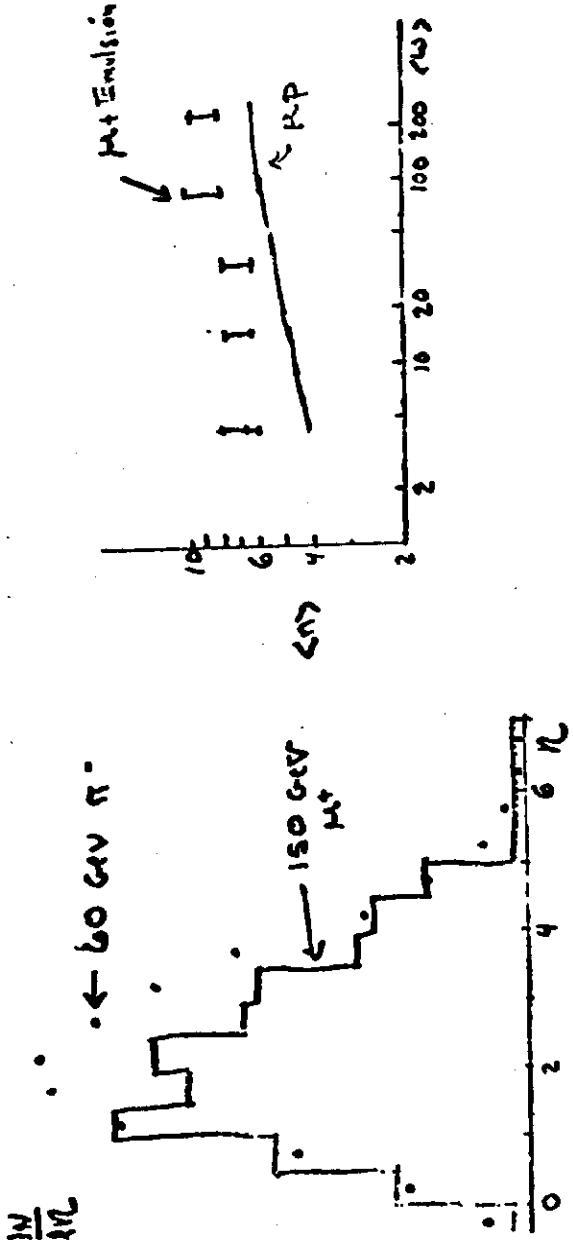
Assoc. mult. increases with $A^{1/3}$

F.S.I. modify $D_{H/q}(z, k_\perp)$ coh. length

radiation loss in nuclear target.



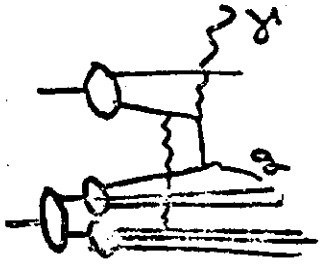
Assoc. mult. increases with $A^{1/3}$.



L. Hand, et al
Cornell, FNAL, Cracow, ..

Emulsion Data

Large p_T cross sections



Direct γ

$$\left(\frac{d\sigma}{d^3p/E}\right)_A \sim A^1 + \underbrace{A^{4/3}\frac{c}{p_T^2}}_{\text{higher twist from ISI}}$$

Similarly, for

$$\frac{d\sigma}{d^3p/E}(pp \to \pi X) \sim A^1 + \underbrace{A^{4/3}\frac{c_\pi}{p_T^2}}_{\text{from ISI, FSI}}$$

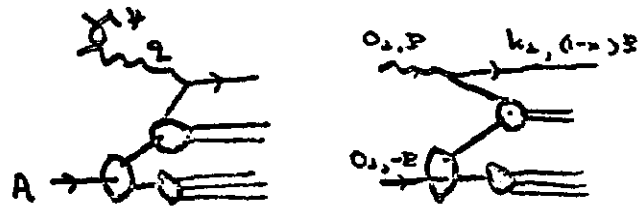
Must have init. and final state ints.

$\mu^+\mu^-$, γ_D sensitive to ISI

Shadowing of Nuclear Structure Functions

SJB + GPL

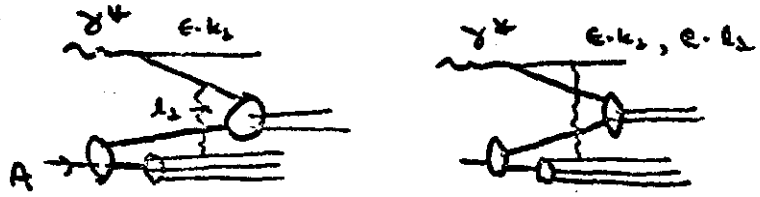
$\gamma^* p$ CM



$\frac{1}{Q^2 + \frac{k_\perp^2}{x(1-x)}}$

leading twist only if $k_\perp^2 \sim O(Q^2)^\epsilon$

shadowing from ISI



$\epsilon \cdot k_\perp$ terms cancel if $Q^2 \gg \frac{l_\perp^2}{x(1-x)}$

$\epsilon \cdot l_\perp$ term is higher twist.

$\therefore$ If $Q^2 \gg \frac{\langle l_\perp^2 \rangle}{x(1-x)} \sim \frac{c}{x_{Bj}}$ very large Q^2, ν if $d \sim \pi$, x sm, $H_e^3 \sim p$

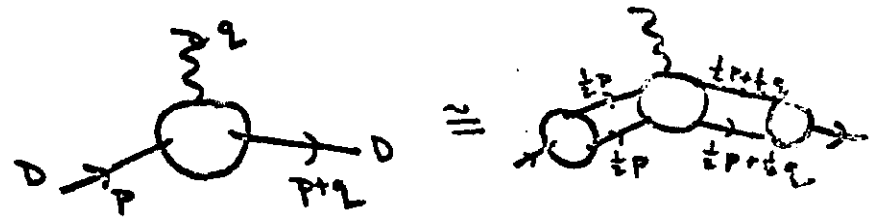
$$F_{2A}(x, Q^2) \Rightarrow A\, F_{2N}(x, Q^2)$$

Corrections from Fermi motion, binding, hadrons etc.

Exclusive Processes involving Nuclear Targets

(Nuclear Reduction)

SJB
B. Chertok



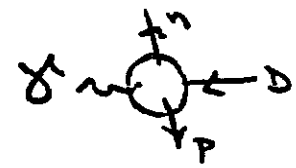
Define "Reduced" Form Factor

$$f_D(Q^2) = \frac{F_D(Q^2)}{F_p\left(\frac{Q^2}{4}\right) F_n\left(\frac{Q^2}{4}\right)}$$

QCD
SJB + GPL

$$\cong \frac{c}{Q^2 + m^2} \sim F_\pi(Q^2)$$

$$f_{He^3}(Q^2) = \frac{F_{He^3}(Q^2)}{F_N^3\left(\frac{Q^2}{4}\right)} \sim F_N(Q^2) \sim \left(\frac{1}{Q^2 + m^2}\right)$$



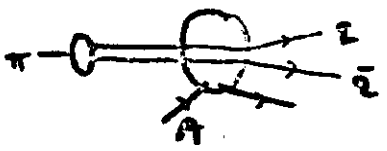
$$\frac{M_{\gamma d \to np}}{F_n(t)\, F_p(u)} \sim M_{\gamma \pi \to \gamma q} \sim \frac{1}{\sqrt{3}} f_\pi$$

Novel Nuclear Target Effects

Diffractive Dissociation

$\pi A \to q\bar{q} A$

G. Bertsch
S.J.
F. Gelbard
B. Gunion



$q\bar{q}$ at $x_1 \sim 0$
~ non-interacting

Predict $\dfrac{d\sigma}{dt_2^2\, d\theta_{cm}}$

normal, A-dep
f_π^2, $\sin^2\theta$

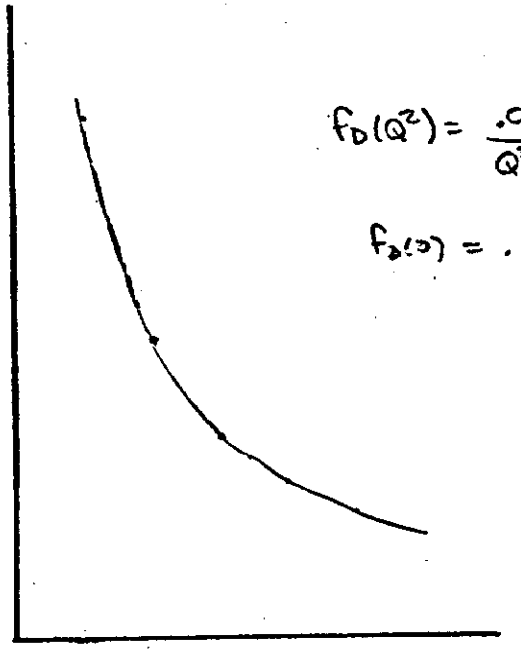
Charm Production in Hadron Collisions

1) $gg \to c\bar{c}$ $\quad \sigma \sim A^1$

+

2) diffractive excitation of intrinsic charm
$\sigma \sim A_T^{2/3}$

$\sigma_{c\bar{c}} \sim P_{c\bar{c}} \cdot \sigma_{el}(A)$



$f_D(Q^2) = \dfrac{.04}{Q^2 + .3\ \mathrm{GeV}^2}$

$f_D(0) = .13$

$$f_D(Q) = \frac{F_D(Q^2)}{[F_p(Q^2/4)]^2}$$

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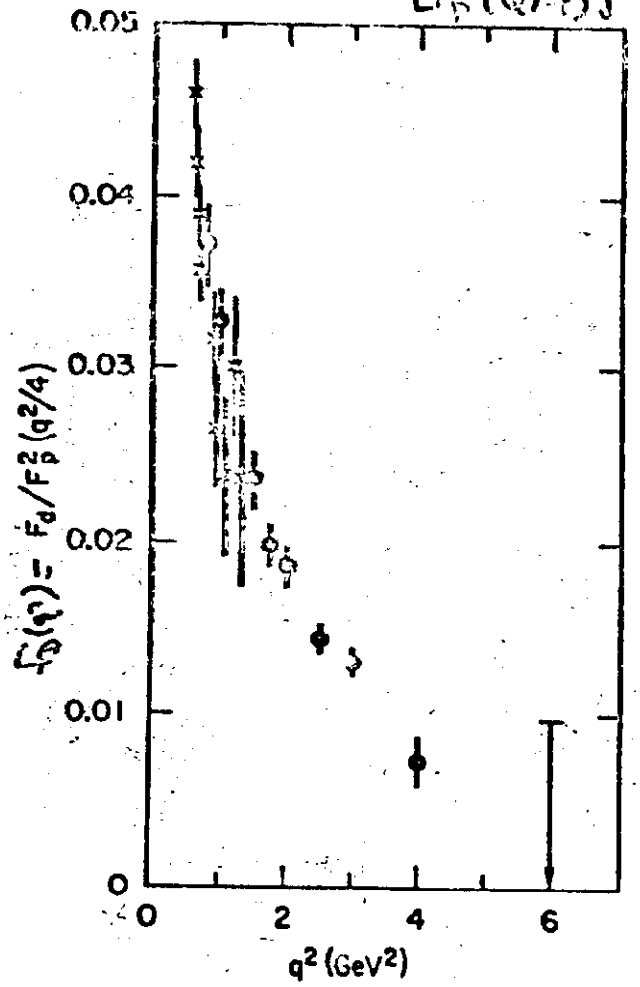

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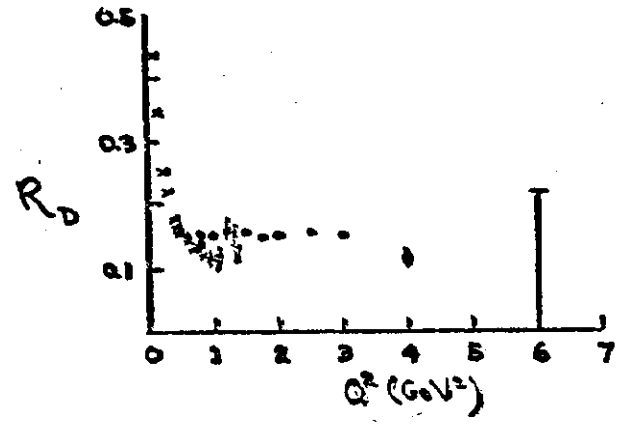
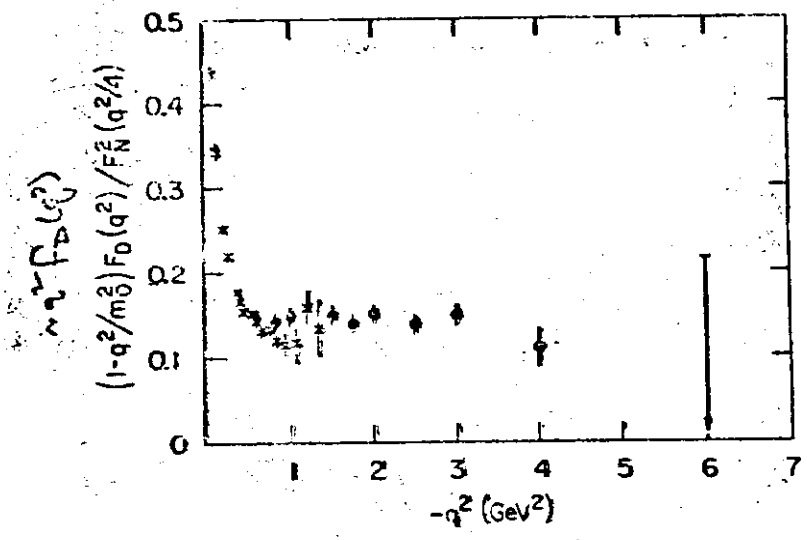


$$F_D(Q^2) = \frac{F_p^2(Q^2/4)}{1 + Q^2/m^2}\, c$$

$$R_D = \frac{F_D^{exp}(Q^2)}{F_D^{QCD}(Q^2)}$$

Production - Lewat 1974 ; B.C.



$m_0^2 = .28$ GeV^2

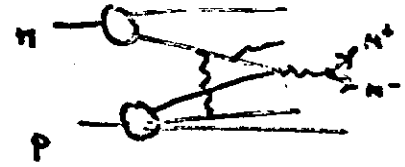
$q^2 f_D(q^2) \to$ const

Predict

$$\left(1-\frac{q^2}{m_0^2}\right) f_D(q^2) = \left(1-\frac{q^2}{m_0^2}\right)\frac{F_D(q^2)}{F_N^2\left(\frac{q^2}{4}\right)}$$

$\to$ const

Initial State Interactions



1) $k_\perp$ distribution disturbed

2) x distrib not affected at $Q^2 > (\ )L$

3) Color factor changed, Q^2 evol. + Sudakov.

New scale breaking pattern

4) A dep $Q_\perp$

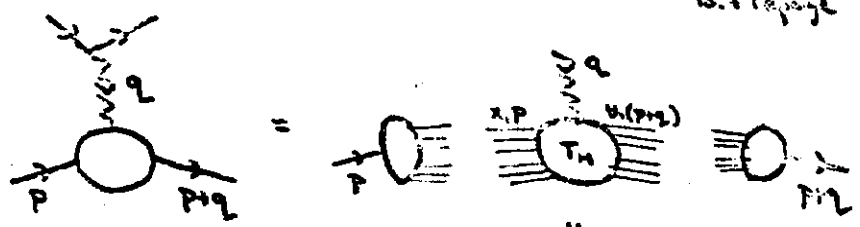
5) A dep assoc. mult.

New phenom. parameters,

measures of q and g prop. thru had.

QCD and Form Factors of Nuclei

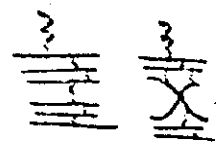
B. + Lepage



$Q^2 = |q^2|$

$$T_H = \left[\frac{\alpha_s(Q^2)}{Q^2}\right]^5 f(x,y)$$

$[\ldots]$



$$F_D(Q^2) = \int [dx][dy]\ \phi^\dagger(x,Q)\ T_H(x,y,Q)\ \phi(y,Q)$$

$$= \left[\frac{\alpha_s(Q^2)}{Q^2}\right]^5 \left[\sum_{n,m=0}^{\infty} b_{nm}\left(\log\frac{Q^2}{\Lambda^2}\right)^{-\gamma_n-\gamma_m}\right]$$

$$\times\left[1 + O(\alpha_s(Q^2), \tfrac{m^2}{Q^2})\right]$$

∴ Predict

- $(Q^2)^5\ F_D(Q^2) \to$ const [modulo logs]

Normalization large despite small $\psi(0)$: $\sim 10^6$ diags

(N-N scattr. large)

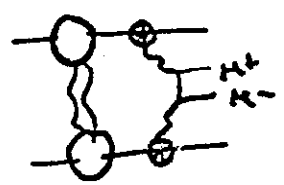
Other Processes

$$\mathcal{M}(k^+A \to k^+A') \propto n_{u/A}\ F_A(Q^2)$$

$$G_{q/A} \sim (A-x)^{2n_s-1} \qquad x \to A$$

$A_1 A_2 \to H X$ large x_2

$pA \to pA\,\mu^+\mu^-$ via $\gamma\gamma$



$\frac{dN}{d^2Q_\perp}$ smeared by ISI

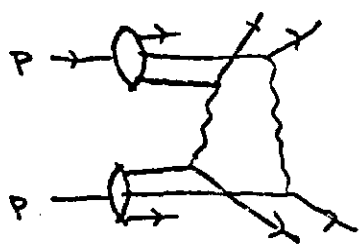
Double Scattering ⇒ Multiple Jets.

Hidden Color

SJC
J. C. [illegible]
Politzer

Large p_T jet production

Double scattering processes



Multiple jet production

Contrib to calorimeter triggers.

High multiplicity.

Suppressed by $\frac{1}{R^2 p_T^2}$ ∴ Higher Twist

Enhanced at $x \to 1$ $\qquad x = E_\perp / E_{TOTAL}$

$$\frac{\sigma_{4jet}}{\sigma_{2jet}} \sim \frac{1}{(1-x)^4} \frac{1}{R^2 p_T^2} A$$

In general multicollisions enhanced at $x \to 1$ and more of initial energy interacts

Is A^α the Correct Parametrization?

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Theoretical models and experimental facts have long dictated that the most suitable (as well as most economical) parametrization of the interactions of elementary particles with nuclei is a simple power law, A^α, where α can be a function of kinematic variables. Total cross sections and other inclusive data support this form and yield $\alpha \approx 2/3$. However, interactions with small cross-sections yield in general $\alpha = 1.0$. In that case the power law dependence is much less justified except as an extension of the well established behavior when $\alpha \approx 2/3$.

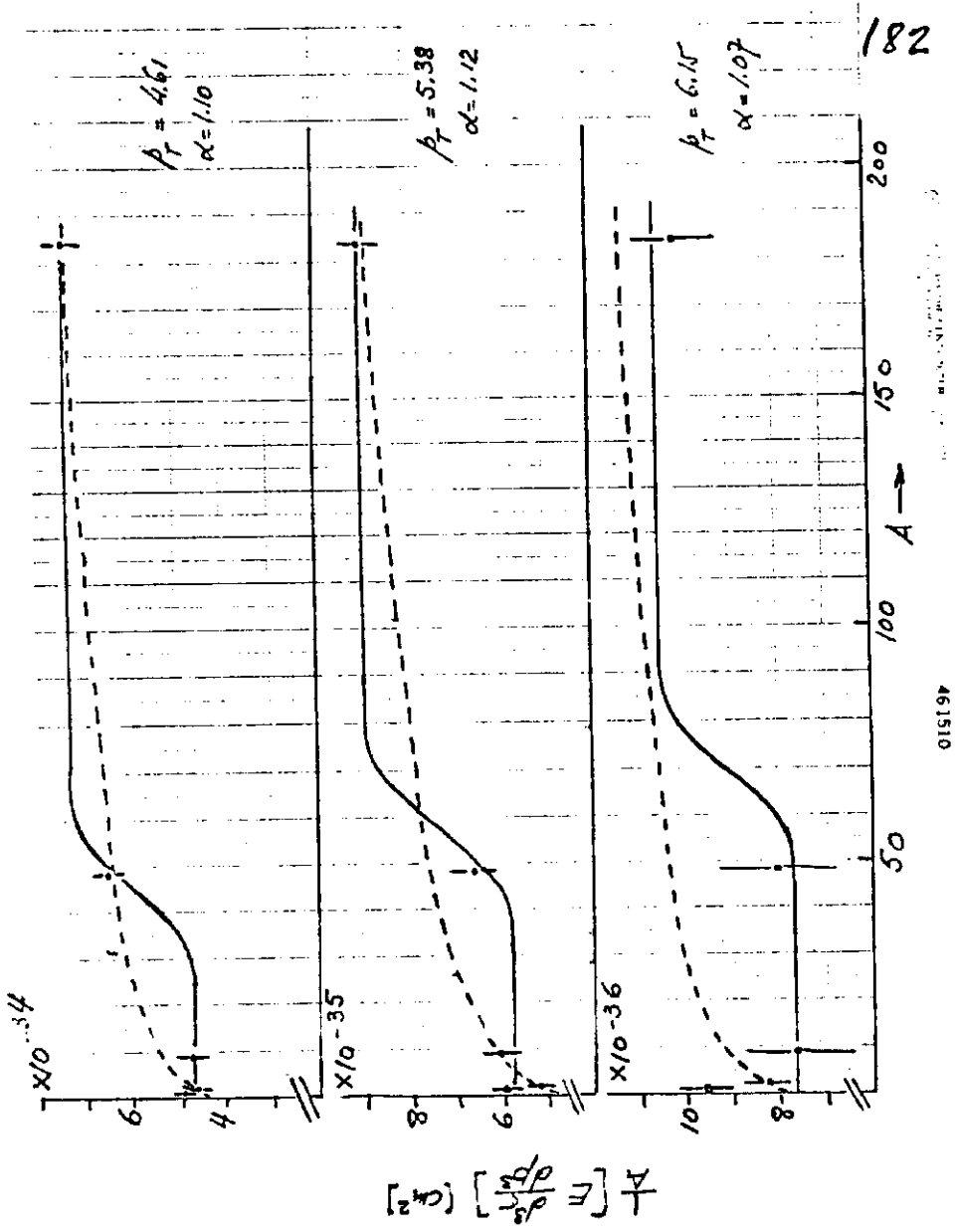
Recently it has been proposed that in very high energy nucleus-nucleus collisions a transition from the nuclear phase to the quark phase of matter may take place[1]. Motivated by these proposals I examined the A-dependence of π^+ production in 400 GeV p-p collisions obtained by the Chicago-Princeton group[2] at FNAL. The data are shown in the figure for $p_T = 4.61$, 5.38 and 6.15 GeV/c where $[E\, d^3\sigma/dp^3]/A$ is plotted vs. A on a linear scale. The dotted curve is the A^α fit using the values of α given by the authors [Fig. 13 of Ref. (2)] and normalized to the deuterium point. The solid lines indicate possible step functions admissible by the data.

It is clear that in order to examine the functional dependence f(A) as contrasted to A^α more data are required, in particular for $10 < A < 100$. Furthermore, the existing high p_T data are far from establishing that the dependence on A follows the familiar power law.

References

(1) R. Anishetty, P. Koehler and L. McLerran, Phys. Rev. D22, 2793 (1980).

(2) D. Antreasyan et al., Phys. Rev. D19, 764 (1979).



R. Weiner

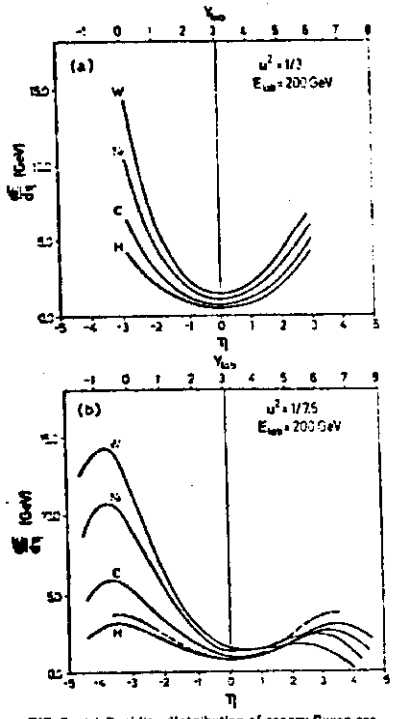
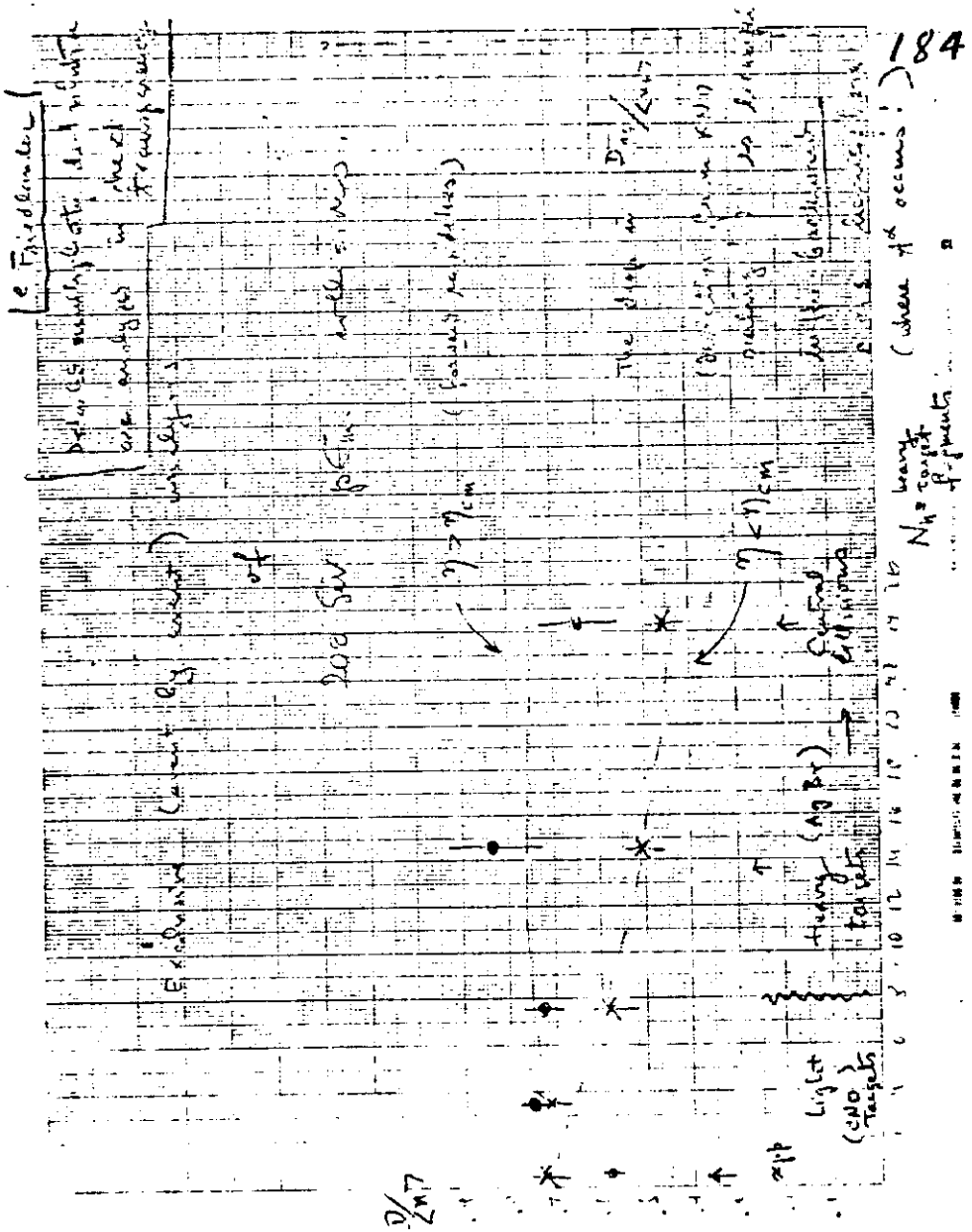


FIG. 7. (a) Rapidity distribution of energy fluxes considered in the central region, $u = 1/\sqrt{3}$ and $E_{lab} = 200$ GeV. (b) The same as in (a) with $u = 1/(7.5)^{1/2}$. The dashed line represents the distribution with $u = 1/\sqrt{3}$ for p-p.

Predictions of the hydrodynamical model for energy fluxes of secondaries as a function of rapidity for two values of the velocity of sound u (from N. Hamada and M. Weiner, Phys. Rev. D18, 1515 (1978))



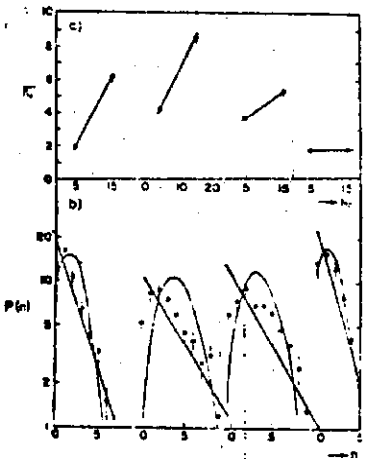


Fig. 1. Proton–nucleus data at 200 GeV. (a) Dependence of local mean multiplicity $\bar{n}_i$ on N_h. (b) Local multiplicity distributions for the case $N_h = 2$–8. Curves: Poisson distributions; straight lines: chaotic distributions.

Dependence of local mean multiplicity $\bar{n}_i$ on N_h → effect of nuclear "transparency"

Local multiplicity distributions for $N_h = 2$–8. Curves: Poisson distributions = coherent meson fields; straight lines: chaotic distributions. Note that only in the forward hemisphere where transparency occurs, the beam is coherent. This is in agreement with self induced transparency.

(Phys Letters 104B, 234 (1981), G.N. Fowler, E.M. Friedlander and R.M. Weiner)

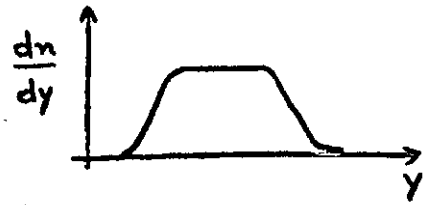
A^{α} & THE TEVATRON

W. BUSZA

1. WHY MEASURE $\frac{1}{\sigma}\frac{d\sigma}{dy}$ FOR Y BETWEEN 4.5 & 5.2?

2. WHY STUDY μ-A COLLISIONS?

3. IF TIME, FEW WORDS ABOUT A^{α} PHYSICS AND HADRON FRAGMENTATION.



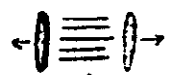
WHY THE PLATEAU?

CONSIDER pp COLLISION IN REST FRAME OF PRODUCED PARTICLE

1. TARGET FRAGMENTATION REGION:

2. PROJECTILE FRAGMENTATION REGION:

3. ANYWHERE IN CENTRAL PLATEAU:



IN ANALOGY WITH ELECTROSTATICS FIELD STRENGTH INDEPENDENT OF VELOCITY & POSITION OF INCIDENT PARTICLES

$\therefore$ IN EVERY FRAME DENSITY OF PRODUCED PARTICLES IS SAME

$\therefore \quad \frac{\Delta N}{\Delta Y} = \text{CONSTANT}$

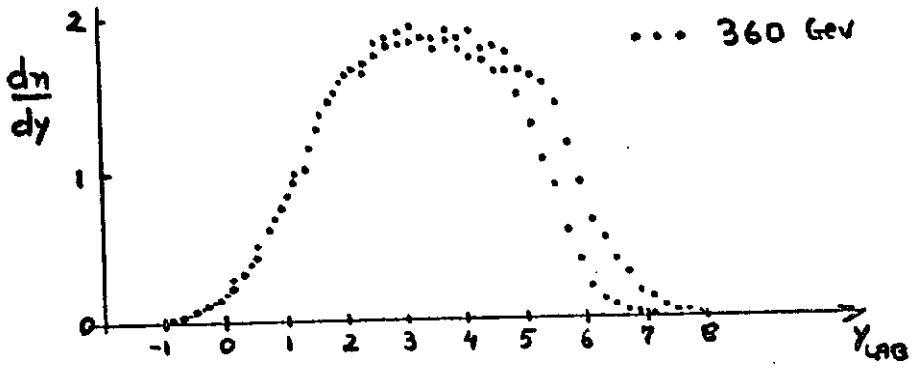
γ	Δy
2	1·4
4	2·1
6	2·5
8	2·8
10	3·0

∴ PROJECTILE & TARGET FRAGMENTATION REGIONS OCCUPY $\Delta Y \simeq 2.5$

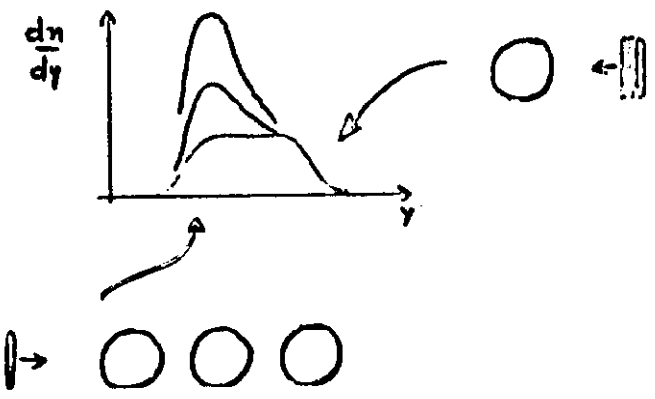
$\pi^- p \to$ CHARGED

••• 200 GeV

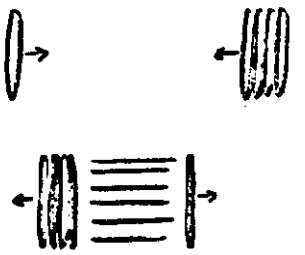
••• 360 GeV



N.B. FOR h-A HAVE:



CONSIDER h-A COLLISIONS AT TEVETRON E's



IS DENSITY OF PARTICLES $\propto$ FIELD STRENGTH?

MAX FIELD?

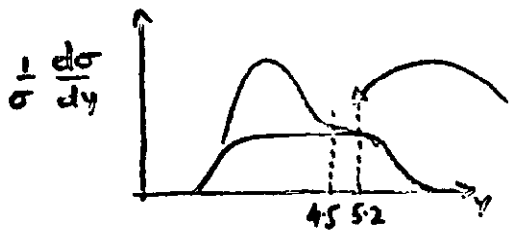
IS THERE SATURATION?

NB. FOR NUCLEUS NEED $\gamma \gtrsim 50$ ∴ $\Delta Y_{MIN} = 4.5$

FOR NUCLEON NEED $\gamma \gtrsim 6$ ∴ $\Delta Y_{MIN} = 2.5$

TEVATRON GIVES TOTAL ΔY FOR p OF 7·6

π 8·6

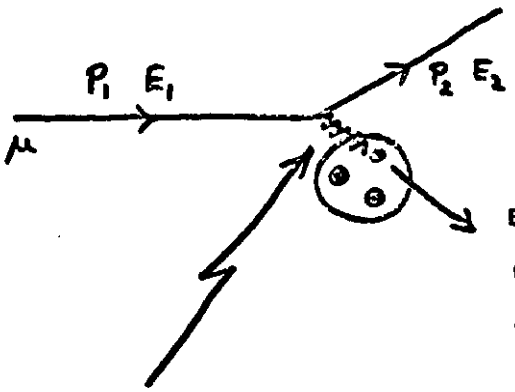


A-DEPENDENCE?

PARTICLE RATIOS?

WHY E665?

$(\mu + A \to \mu' + \text{hadrons} + A')$



ENERGY $\approx \nu = E_1 - E_2$

$$Q^2 = |\vec{P}_1 - \vec{P}_2|^2 - \nu^2$$

$$X_{BJ} \approx \frac{Q^2}{2M\nu}$$

$$\Delta E = \frac{Q^2}{2\nu} = X_{BJ} M$$

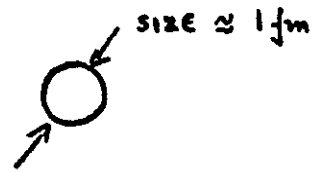
$$\Delta E \Delta t \gtrsim \hbar$$

$$\Delta E \Delta S \gtrsim \hbar c$$

$$\therefore \Delta S \gtrsim \frac{0.2}{\Delta E} \text{ fm} = \frac{0.2}{X_{BJ}}$$

FOR $\Delta S \ll$ HADRON SIZE
i.e. FOR $X_{BJ} \gtrsim 0.4$
} MUST HAVE DIRECT INTERACTION OF PHOTON WITH QUARK

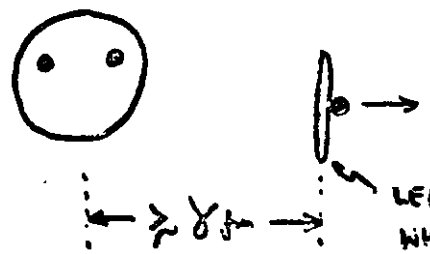
N.B. FOR $X_{BJ} < 0.4$ BUT $Q^2 \gtrsim 1$ INTERACTION MAY ALSO BE DIRECT, BUT FOR $X_{BJ} \gtrsim 0.4$ IT HAS TO BE DIRECT.



$\therefore$ MIN. TIME TO CREATE HADRON $\gtrsim \frac{1 \text{ fm}}{c}$

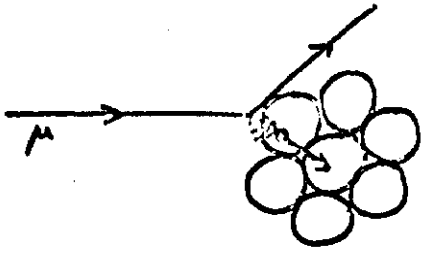
$\therefore$ IN LAB FRAME MIN. TIME $\gtrsim \frac{\gamma}{c}$

OR MIN. DISTANCE $\gtrsim \gamma$ fm $= \frac{E_{LAB}}{\text{MASS}}$ fm.



LEADING HADRON INTO WHICH QUARK FRAGMENT.

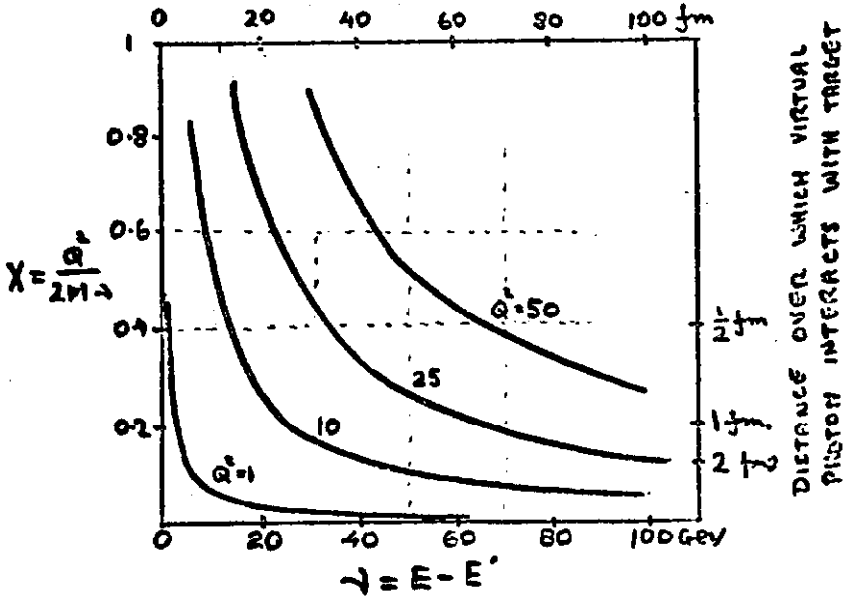
TAGGED QUARK BEAM EXPT:



1. STUDY PRODUCTION RATES AND $P_\perp$ RELATIVE TO PHOTON AXIS OF PRODUCED HADRONS WITH $\gamma \gtrsim 20$ FOR $X_{BJ} \gtrsim 0.4$

2. STUDY PROPERTIES OF VIRTUAL PHOTON e.g. FOR $X < 0.4$ BUT $Q^2 > 1$ IS PHOTON HADRON-LIKE ?

APPROX. DISTANCE IN LAB. OVER WHICH QUARK FRAGMENTS INTO HADRONS



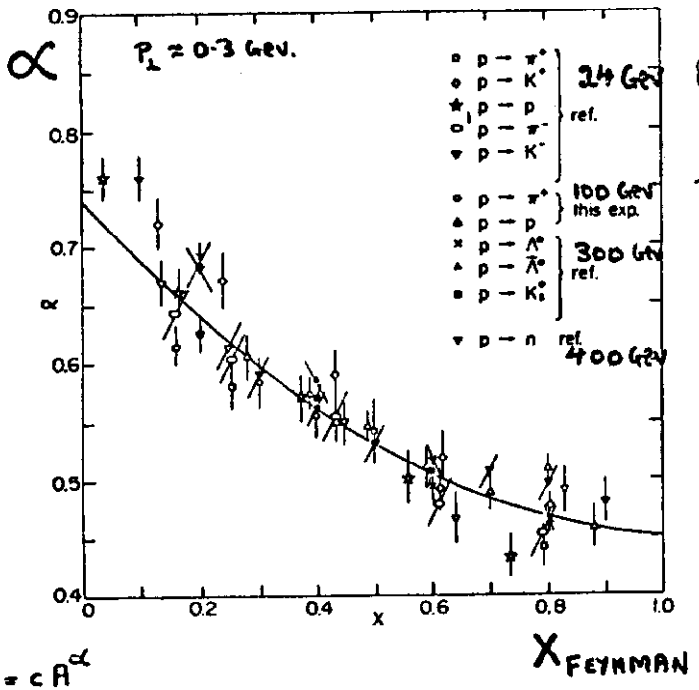
TARGET OR PROJECTILE FRAGMENTATION

RESULTS:

1. FRAGMENTATION INDEPENDENT OF E
2. A^{α} SHOWS FRAG. DOES DEPEND ON PROJECTILE.

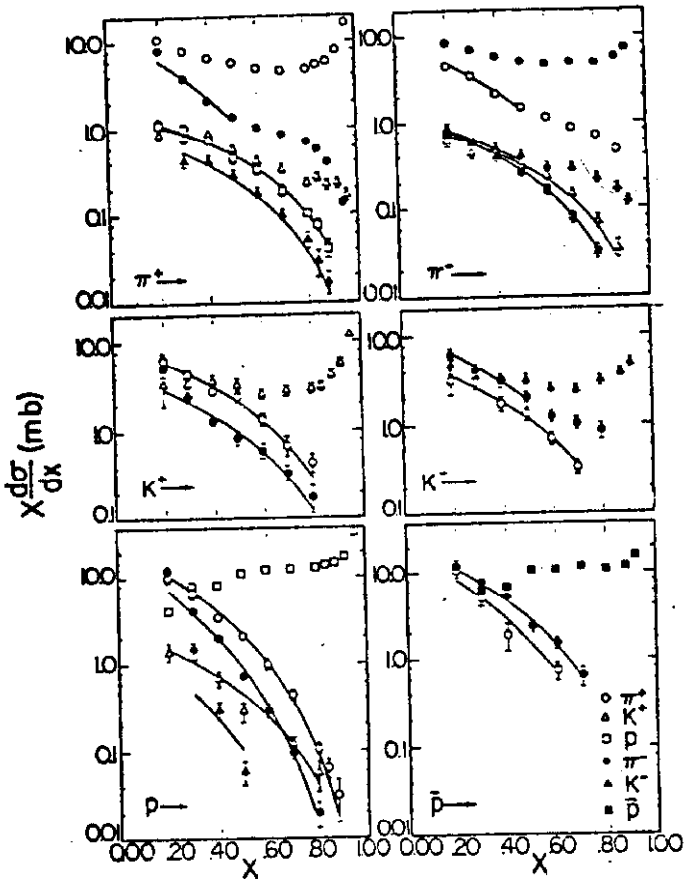
HOW TO RECONCILE POINTS 1, 2 & 3?

3. RATIO OF PARTICLES INDEPENDENT OF A. ONLY FUNCTION OF X. DESPITE FACT THAT X-DEP OF VARIOUS PARTICLES DRAMATICALLY DIFFERENT



$$E\frac{d^3\sigma}{dp^3} = c\,A^{\alpha}$$

100 GeV data, Brenner et al.



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