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H4.SMR 346/36

SCHOOL ON
NON-ACCELERATOR PHYSICS
25 April - 6 May 1988

HIGH ENERGY HADRON - HADRON INTERACTIONS

by

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HIGH ENERGY HADRON-HADRON INTERACTIONS

(NOT REALLY NON-ACCELERATORS, BUT LOW p_t - PHYSICS RELEVANT)

1. TOTAL CROSS SECTIONS

ALL RISING AS $\ln^2 s$ $\quad (s = E_{cm}^2)$

2. ELASTIC CROSS SECTIONS

$\sigma_{EL} = \int \frac{d\sigma}{dt} dt$ FOLLOWS BEHAVIOUR OF σ_{TOT}

$O = \frac{2\sigma_{EL}}{\sigma_{TOT}} \simeq 0.4 \Rightarrow$ PROTON TRANSPARENT

3. DIFFERENTIAL ELASTIC CROSS SECTIONS

$|t| < 10^{-3}\,GeV^2$ COULOMB SCATTERING

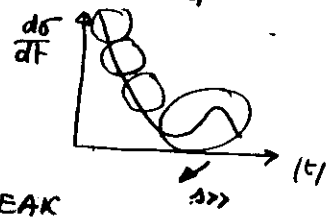
$10^{-3} < |t| < 10^{-2}$ COULOMB-NUCLEAR INTERFERENCE

$|t| > 10^{-2}$ NUCLEAR SCATTERING

LARGE ANGLE SCATTERING

NUCLEAR SCATT. low-t

$\frac{d\sigma}{dt} = A\, e^{bt}$



$b \sim \ln s \Rightarrow$ SHRINKING OF DIFFRACTION PEAK

$\rho = \left.\frac{Re\,F}{Im\,F}\right|_{t=0}$ BECOMES POSITIVE AT LARGE s

4. INELASTIC INTERACTIONS - CHARGED MULTIPLICITIES

a) AVERAGE CHARGED MULTIPLICITY

$\langle n_{ch} \rangle = A + B \ln s + C \ln^2 s$

$\left.\begin{matrix} pp \\ \bar{p}p \end{matrix}\right\} = (2.5 \pm 0.6) - (0.2 \pm 0.2) \ln s + (0.18 \pm 0.01) \ln^2 s$

AT $\sqrt{s} = 62$ GeV pp $\quad \langle n_{ch} \rangle = 4.5\,\pi^- + 5\,\pi^0 + 5.5\,\pi^+ + 0.4 K^- + 0.25 \bar{K}^0 + 1.9\,p + 0.7\,n + 0.07\,\bar{n} + \ldots$

b) MULTIPLICITY DISTRIBUTIONS

KNO SCALING: PLOTS OF $\sigma_n \langle n \rangle / \sigma_{in} = P_n \langle n \rangle$ VERSUS $z = n/\langle n \rangle$ SUGGESTED A "UNIVERSAL DISTRIBUTION", INDEP. OF $\sqrt{s}$, η, πN-NN, ...

RECENT DATA FROM $S p\bar{p}S$ DISAGREE WITH KNO

MULTIPLICITY DISTRIBUTIONS ARE NOW FITTED TO NEGATIVE BINOMIAL FUNCTIONS

$$P_n(\bar{n}, k) = \frac{(n+k-1)!}{n!\,(k-1)!} \frac{\bar{n}^n k^k}{(\bar{n}+k)^{n+k}}$$

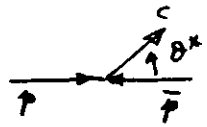
SIMPLEST INTERPRETATION IS IN TERM OF A TWO-STEP PROCESS: FIRST ARE PRODUCED "ANCESTORS" WHICH DECAY IN "CLANS" OF PARTICLES

NUMBER OF ANCESTORS $\bar{N} = k \ln\left(1 + \frac{\bar{n}}{k}\right)$

NUMBER OF PARTICLES PER CLAN $\bar{n}_c = \frac{\bar{n}}{k}\left[\ln\left(1 + \frac{\bar{n}}{k}\right)\right]^{-1}$

5. INELASTIC INTERACTIONS { VARIABLES / CROSS SECTIONS

INCLUSIVE DISTRIBUTIONS $\bar{p}+p \to c+X$



-VARIABLES

$s = E_{cm}^2$

$p_t = p \sin\vartheta = p^* \sin\vartheta^*$

$y = \frac{1}{2} \ln \frac{E+p_{\parallel}}{E-p_{\parallel}} \Rightarrow \eta_{cm} = -\ln \operatorname{tg} \frac{\vartheta^*}{2}$

$x_F = p_{\parallel} / p_{\parallel\,max}$

- INVARIANT CROSS SECTIONS

$f = E \frac{d^3\sigma}{dp^3}$

$= f(s, p_T, y, x)$

- SINGLE SPECTRA

$f = f(p_T)$

$f = f(y)$

$f = f(x)$

3. $\langle p_T \rangle = F(\rho)$ $\qquad \rho = dN/dy$

pp, $\bar{p}p$, dd, $\alpha\alpha$

$\sim 10^6$ events in pp, $\sqrt{s} = 31, 44, 62$ GeV

a) FOR ONE EVENT $\bar{p}_T = \frac{1}{M} \sum_i^M |p_T|_i$

" ALL " $\langle \bar{p}_T \rangle = \frac{1}{N} \sum_i^N \bar{p}_{T\,i}$

b) IN $0.3 < p_T < 0.8$ GeV/c

$f = d^3\sigma / d^3\vec{p} = A\, e^{-B p_T}$, $\langle \bar{p}_T \rangle = 2/B$

- CENTRAL REGION ($|y| < 1.5$)

$\langle p_T \rangle$ INCREASES WITH ρ 4

AMOUNT OF INCREASE INCREASES WITH $\sqrt{s}$

INCREASE $\alpha\alpha > dd > pp = \bar{p}p$

SHAPE OF INCREASE

NO FACTORIZATION IN (y, p_T)

- FRAGMENTATION REGION 6

$\langle \bar{p}_T \rangle$ DECREASES WITH INCREASING ρ 7 8

6. SHORT RANGE RAPIDITY CORRELATIONS

TWO PARTICLES

$$R_2^{ab}(y_1,y_2) = \frac{\rho_2^{ab}(y_1,y_2)}{\rho_1^a(y_1)\,\rho_1^b(y_2)} - 1$$

$$\rho_1^a(y_1) = \frac{1}{\sigma_{in}}\,\frac{d\sigma_{in}^a(y_1)}{dy_1}$$

$$\rho_2^{ab}(y_1,y_2) = \frac{1}{\sigma_{in}}\,\frac{d^2\sigma_{in}^{ab}(y_1,y_2)}{dy_1\,dy_2}$$

FIND STRONG SHORT RANGE CORRELATIONS IN PARTICULAR FOR $(+-)$ COMBINATIONS.

FIND $pp = \bar{p}p$

THREE PARTICLES

$$K_3^{abc} = \frac{\rho_3^{abc} + 2\rho_1^a\rho_1^b\rho_1^c - \rho_2^{ab}\rho_1^c - \rho_2^{bc}\rho_1^a - \rho_2^{ca}\rho_1^b}{\rho_1^a\,\rho_1^b\,\rho_1^c}$$

$$\rho_3^{abc}(y_1y_2y_3) = \frac{1}{\sigma_{in}}\,\frac{d^3\sigma_{in}^{abc}}{dy_1\,dy_2\,dy_3}$$

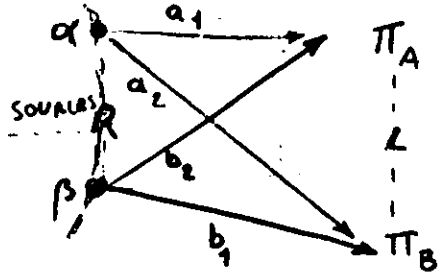
CLUSTER MODEL - TWO STEP PROCESS

$\phi + p \to c_1 + c_2 + \ldots + c_m \Rightarrow$ RESONANCES

$\hookrightarrow \pi_1\pi_2 \ldots$

7. BOSE-EINSTEIN CORRELATIONS

(COCCONI-KOPILOV-GOLDHABER)



ASTRONOMY: $L \ll R$ (INTERFERENCE AT AT OBSERVER)

PARTICLES: $L \gg R$ (INTERFERENCE AT AT EMISSION)

$$A \approx e^{ikA_1}\,e^{ikb_1} + e^{ika_2}\,e^{ikb_2}$$

$\alpha \to A$, $\beta \to B$ $\qquad$ $\alpha \to B$, $\beta \to A$

(ONE DOES NOT KNOW WHICH SOURCE GAVE WHICH π). CORRELATIONS IN INTENSITY

$$I \approx |A|^2 = 2\,(1 - \cos KR\Theta)$$

IF "VOLUME" SOURCE (π FROM ρ_1^0..)

$$I = \gamma\,(1 + \alpha\, e^{-\beta q_t^2})$$

$q_0 = E_1 - E_2$, $q_t = |\vec{p}_{\pi 1} - \vec{p}_{\pi 2}|$ IN PLANE $\perp$ TO $\vec{p}_{\pi 1} \cdot \vec{p}_{\pi 2}$

($\alpha \sim m_{\pi\pi}$)

α = CHAOTICITY PARAMETER $0 < \alpha < 1$

$R = 0.197\sqrt{\beta}$ (RADIUS OF EMITTING REGION)

CHOICE OF UNCORRELATED BACKGROUND ($I = N_L/N_U$)

B.E. CORRELATIONS HAVE BEEN OBSERVED IN HIGH ENERGY pp AND $\bar{p}p$ INTERACTION ($\alpha \sim 0.45$, $R \sim 1.1$ fermi). THEY ARE EQUAL WITHIN ERRORS.

T13
T12

R DEPENDS ON CENTRAL $\rho = dN/dy$

DEPENDENCE INCREASES WITH $\sqrt{s}$ 15

APPROXIMATELY AS $\langle \bar{p}_T \rangle$ 16

R_T , R_L — $\rightarrow$ $\leftarrow$ y

$\Delta\vec{p} = \vec{p}_1 - \vec{p}_2$ $\quad R_T \begin{cases} \Delta p_x > \Delta p_y \\ \text{''} > \Delta p_z \end{cases}$ OR $\begin{cases} \Delta p_z > \Delta p_y \\ \text{''} > \Delta p_x \end{cases}$

IN PP INTERACTIONS AT $\sqrt{s} = 62$ GeV FIND

$\begin{cases} R_L > R_T \\ \text{BOTH INCREASE WITH } n \end{cases}$

(R_L IS NOT WELL DETERMINED FOR $R_L \gtrsim 1.5$ fm)

COMPARISON WITH νD_{2H} 17

RAPIDITY FLUCTUATIONS

(HOT SPOTS) $\Rightarrow$ NOT ABOVE STATISTICAL TAILS

CONCLUSIONS

MAIN FEATURES OF LOW-p_T PHYSICS HAVE BEEN MEASURED UP TO $\sqrt{s} \simeq 1.8$ TeV.

σ_{TOT} RISING

PROTON TRANSPARENT

TWO SLOPES IN $d\sigma/dt$ ($\Rightarrow$ "ONION STRUCTURE"?)

$\bar{n} = A + B \ln s + C \ln^2 s$

TWO STEP PICTURE OF PARTICLE PRODUCTION

KNO SCALING $\rightarrow$ NEGATIVE BINOMIAL

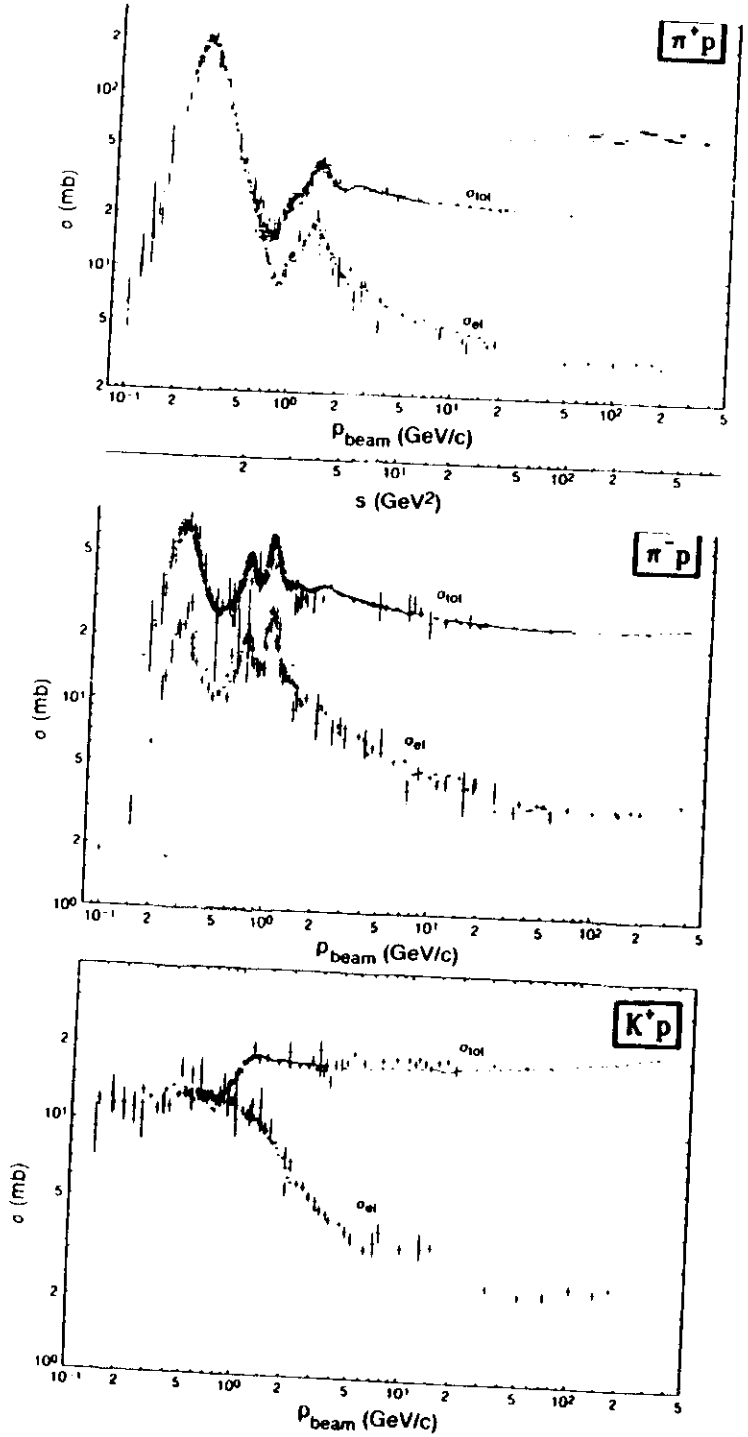
$\langle p_T \rangle \sim 0.35$ GeV/c $\Rightarrow$ RISING

$f = F(p_T)\, F(y) \Rightarrow$ NO FATORIZATION

$\bar{p}_T = f\left(\rho = \frac{dN}{dy}\right)$

RAPIDITY CORRELATIONS (SHORT RANGE)

BOSE-EINSTEIN ''



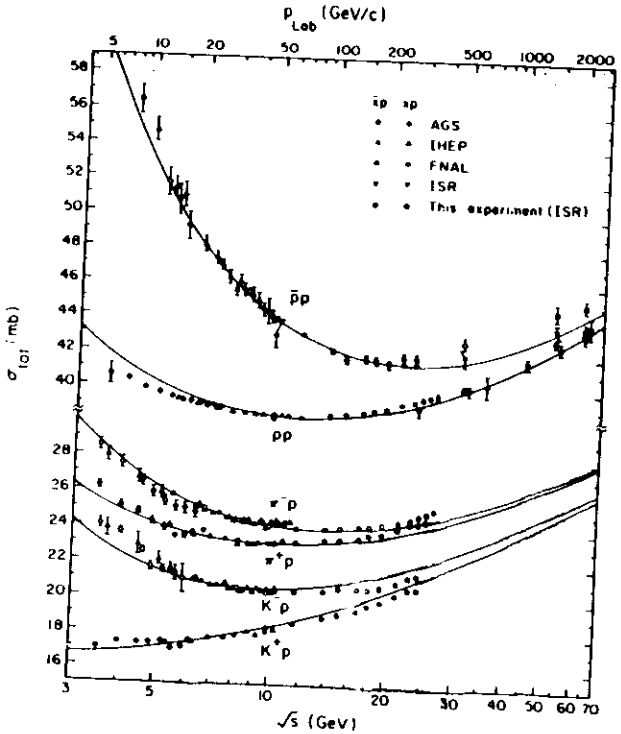


Fig. 16. Compilation of hadron-proton total cross sections. The data were taken from this experiment and from refs. [9] (AGS), [10] (IHEP), [17] (FNAL), [16] (ISR p̄p) and [20] (ISR, pp). The curves were computed according to Lipkin's parametrization (see text).

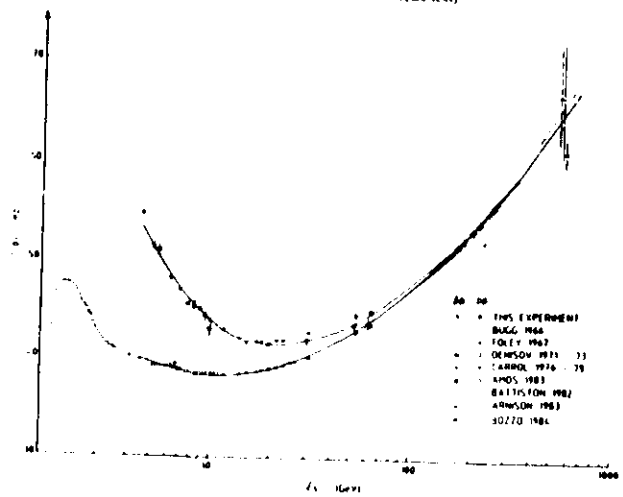
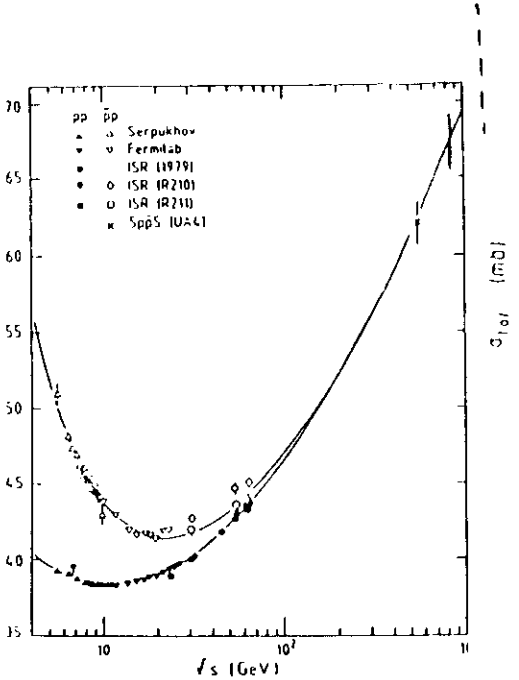
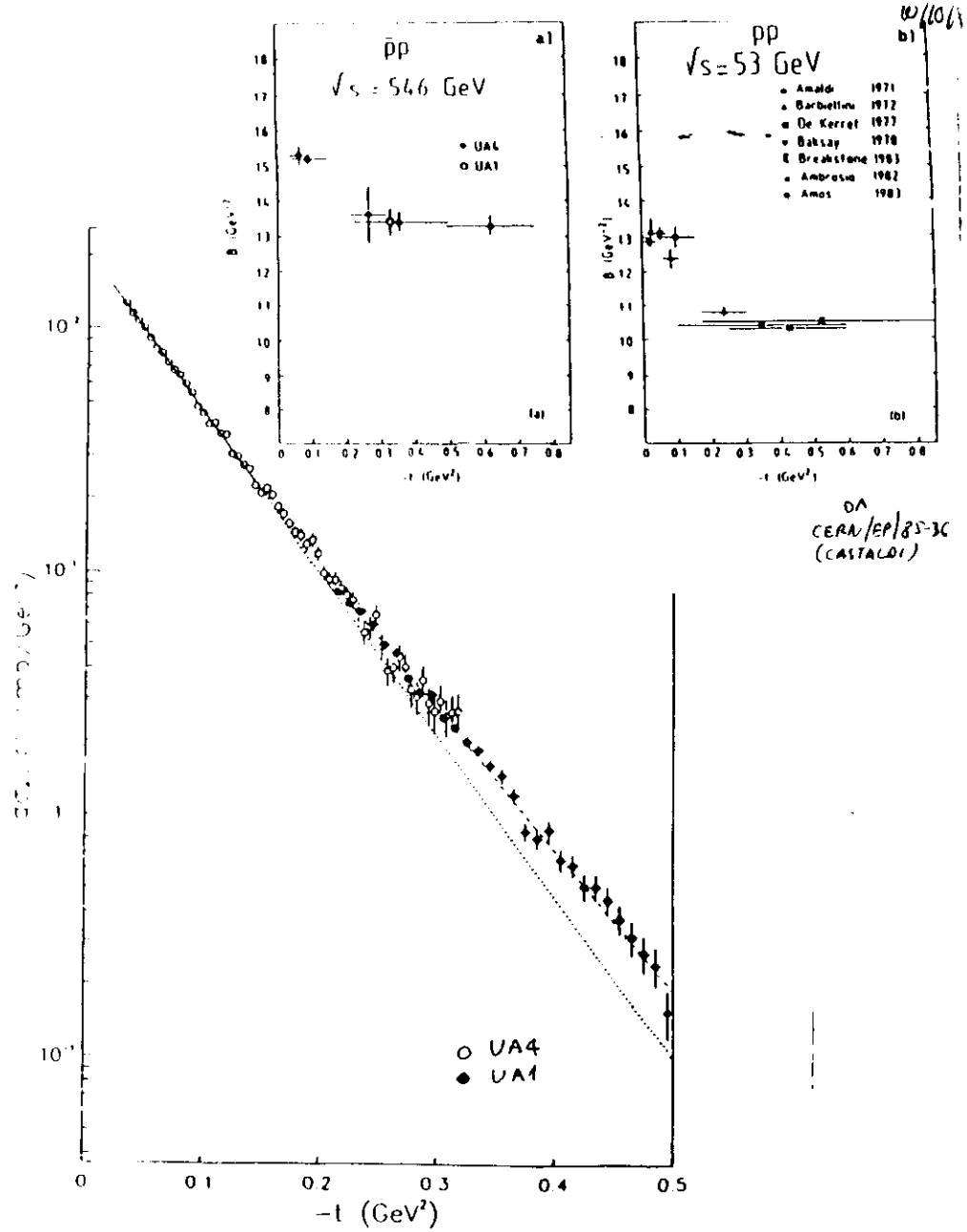
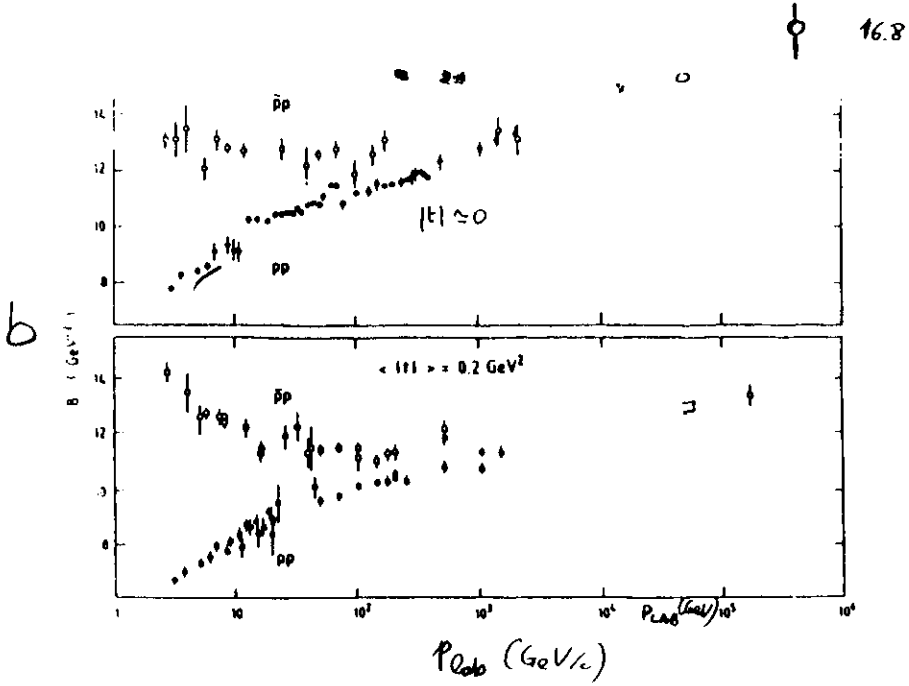


Fig. 18. Compilation of results on the pp and pp total cross sections. The solid lines correspond to the fit to the data discussed in the text. The compilation comprises low energy data [48] and SPS collider data.





ure 6. Elastic differential cross-section for p̄p at √s = 546 GeV; the s are single-exponential fits below and above -t = 0.15 GeV² [from


16.8
b
p̄p
pp
|t| ≃ 0
< |t| > = 0.2 GeV²
p̄p
pp
P_{Lab} (GeV/c)
P_{Lab} (GeV/c)

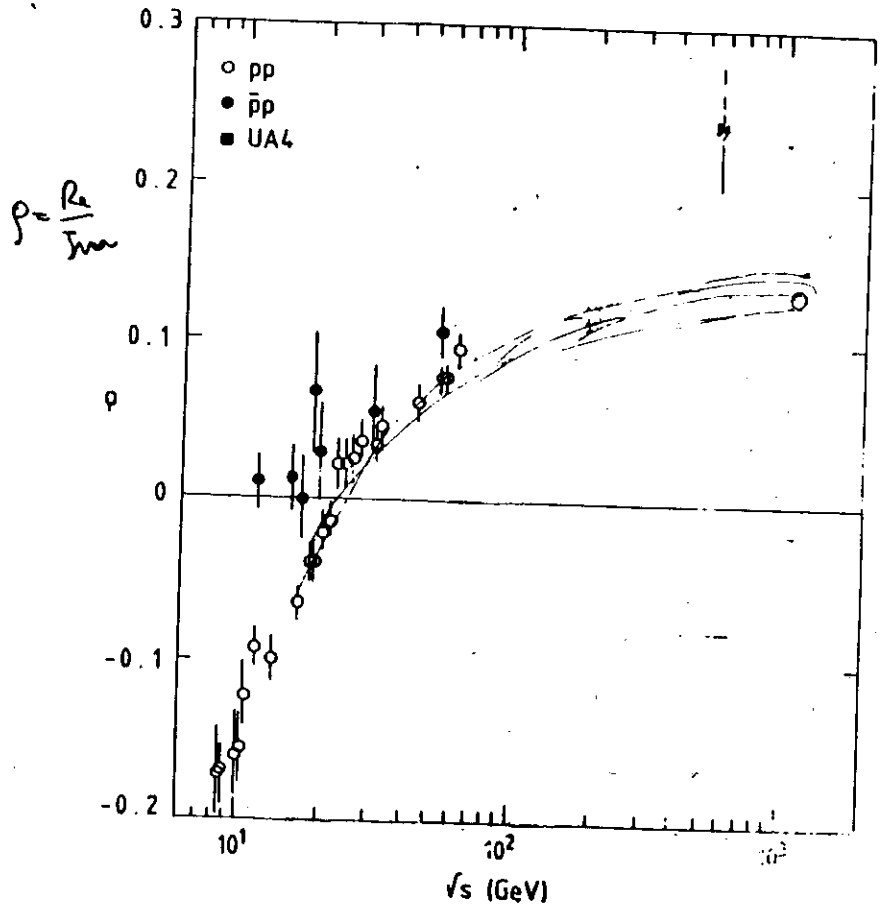

0.3
0.2
0.1
0
-0.1
-0.2
ρ
pp
p̄p
UA4
$\rho = \frac{R_e}{I_{mm}}$
10^1
10^2
√s (GeV)

Fig. 4

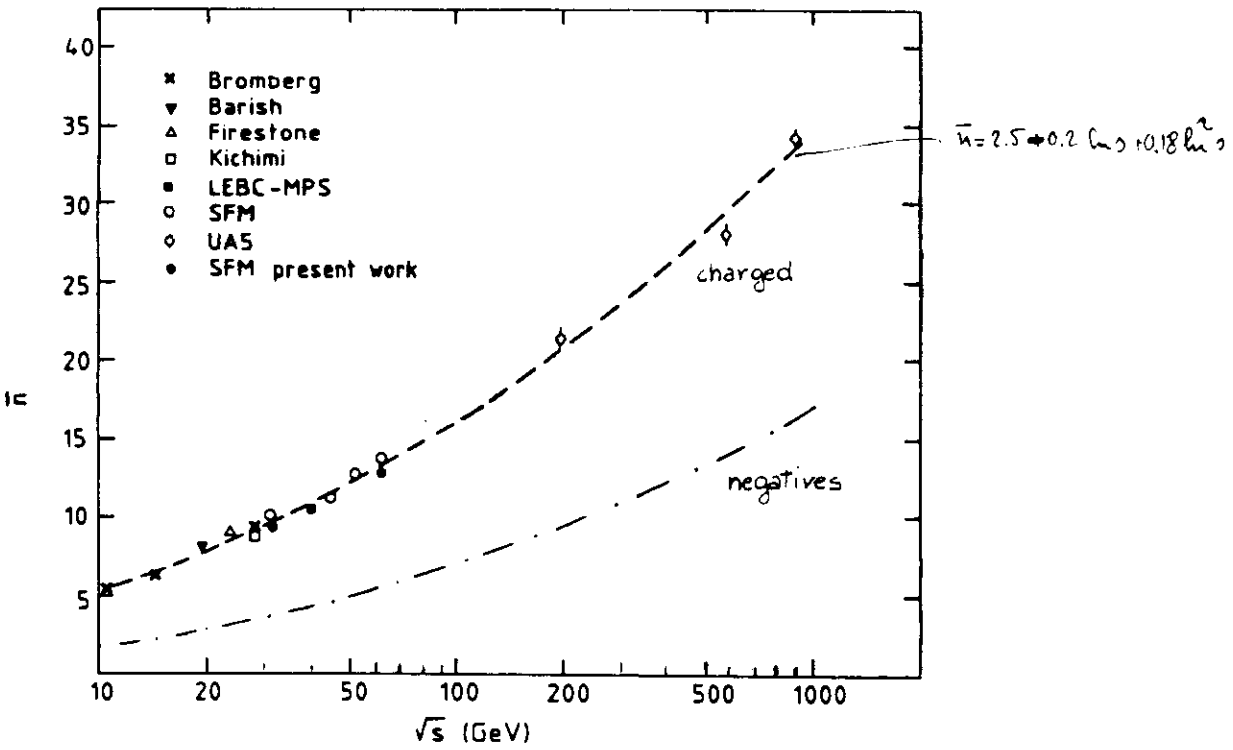
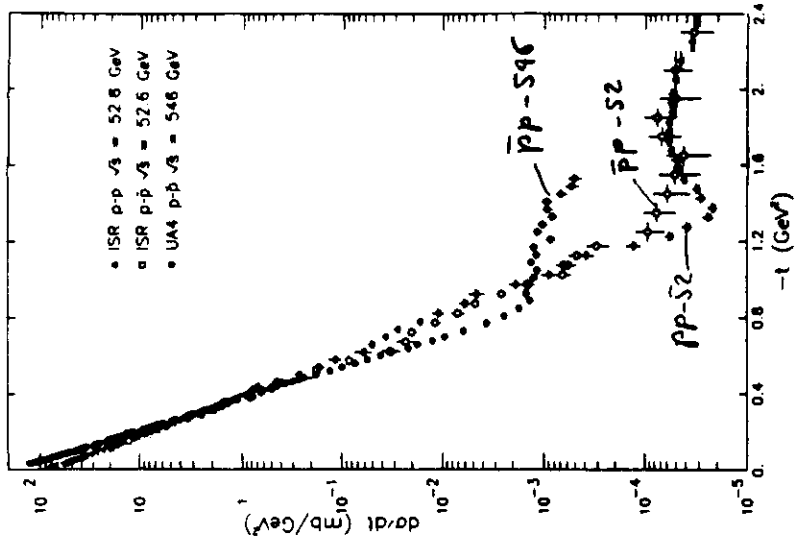

Bromberg
Barish
Firestone
Kichimi
LEBC-MPS
SFM
UA5
SFM present work
charged
negatives
$\bar{n} = 2.5 \rightarrow 0.2 \ln s + 0.18 \ln^2 s$
$\sqrt{s}$ (GeV)

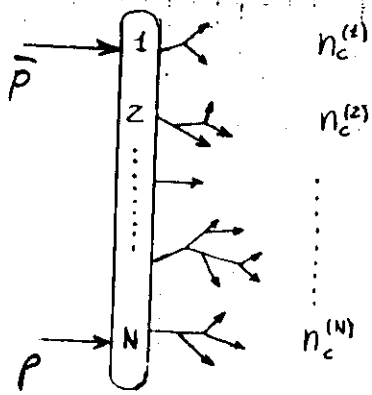
FIG. 6


ISR p-p $\sqrt{s}$ = 52.8 GeV
ISR p-$\bar{p}$ $\sqrt{s}$ = 52.6 GeV
UA4 p-$\bar{p}$ $\sqrt{s}$ = 546 GeV
$\bar{p}p$ - 546
$\bar{p}p$ - 52
pp-52
$d\sigma/dt$ (mb/GeV^2)
$-t$ (GeV^2)

Negative binomial distribution

$$P(n) = \frac{K(K+1)\cdots\cdots(K+n-1)}{n!} \frac{(\langle n\rangle/K)^n}{(1+\langle n\rangle/K)^n} \frac{1}{(1+\langle n\rangle/K)^K}$$

Cascading mechanism of particle production



$$n = n_c^{(1)} + \cdots\cdots + n_c^{(N)}$$

$$P(N) = e^{-\langle N\rangle} \cdot \langle N\rangle^N / N!$$

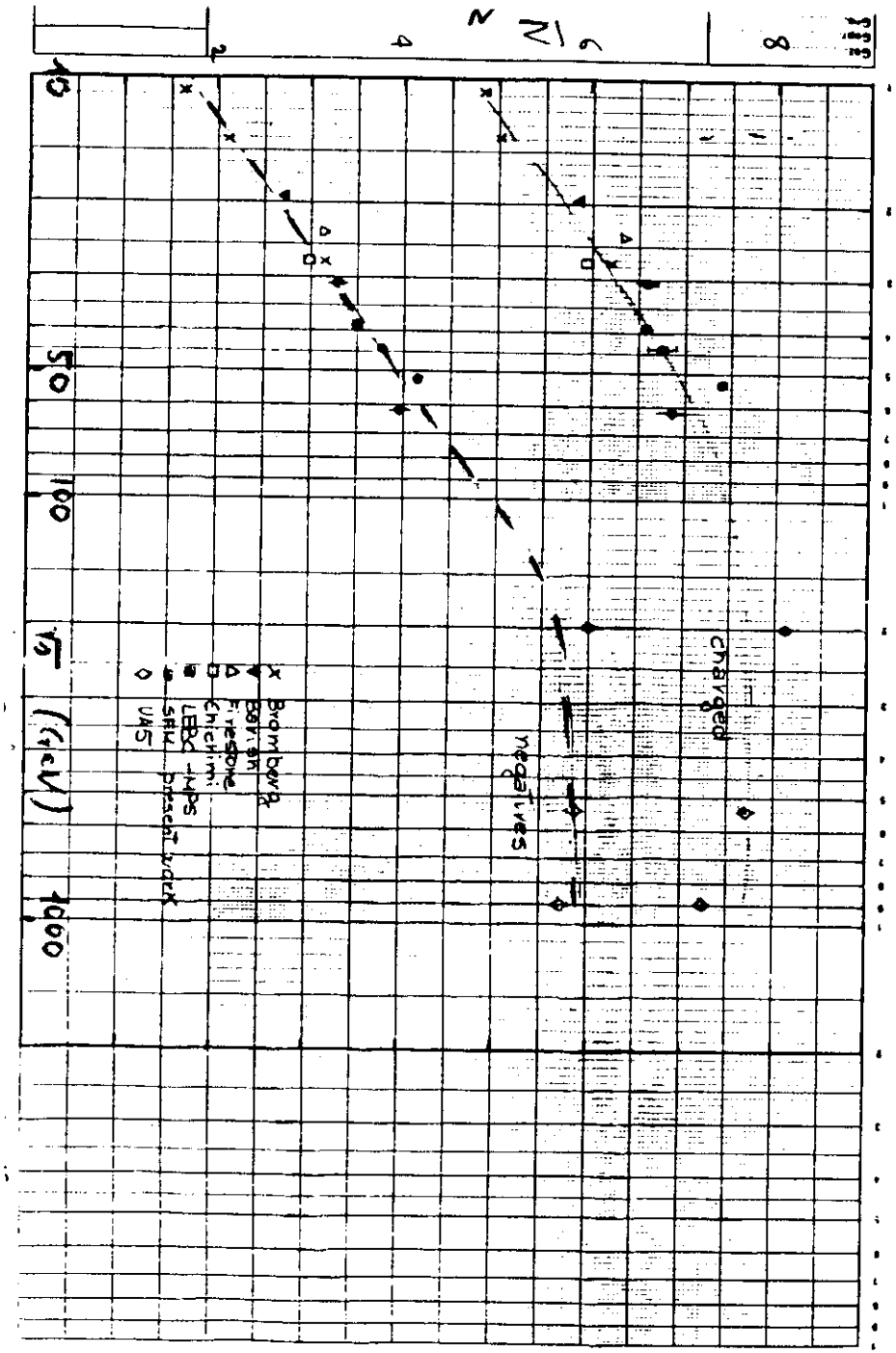
Poisson distribution

$$\langle n_c\rangle = \frac{\langle n\rangle}{K} \Big/ \ln(1+\langle n\rangle/K)$$

average multiplicity per clan

$$\langle N\rangle = \frac{\langle n\rangle}{\langle n_c\rangle} = K \ln(1+\langle n\rangle/K)$$

average number of clans



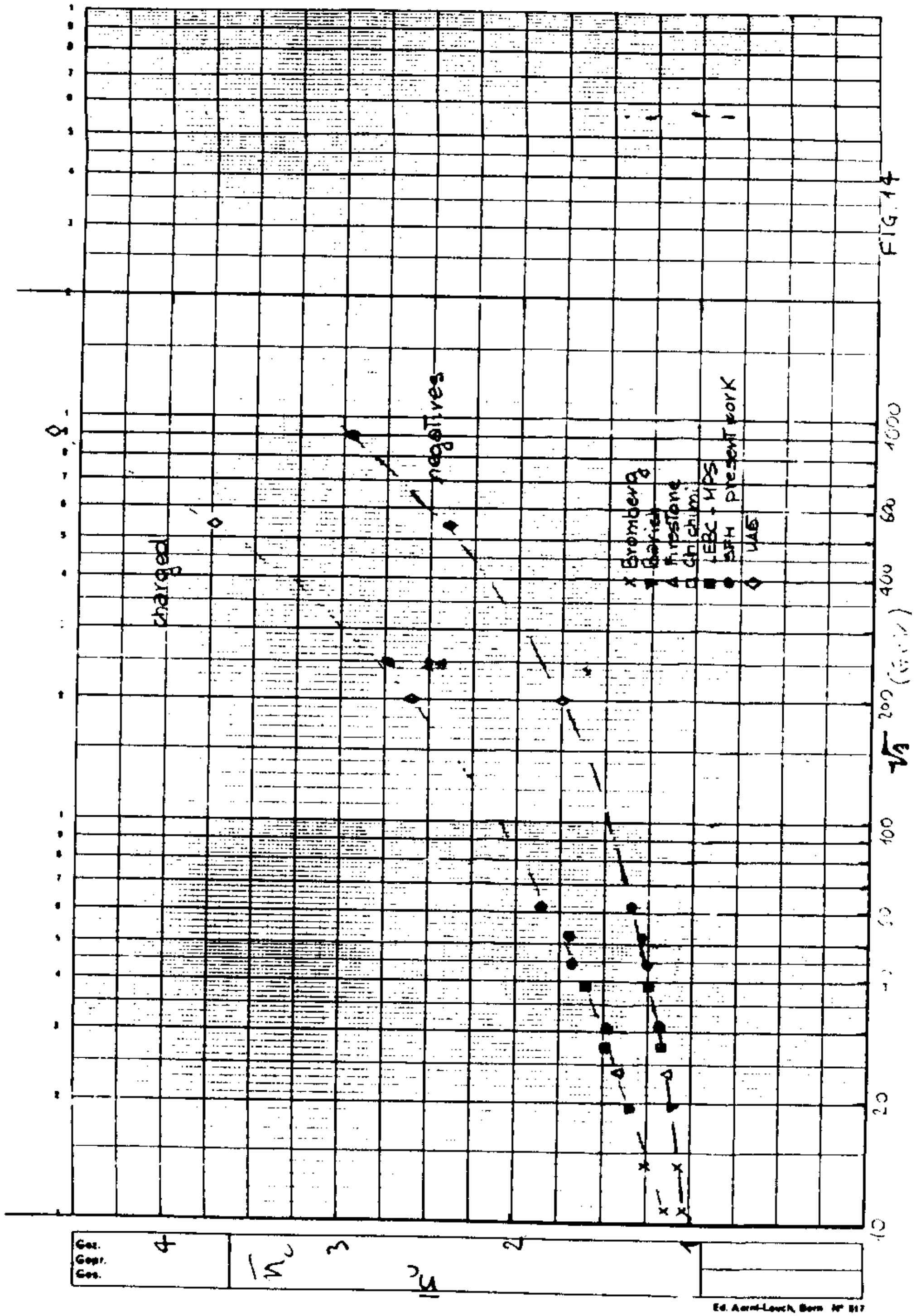
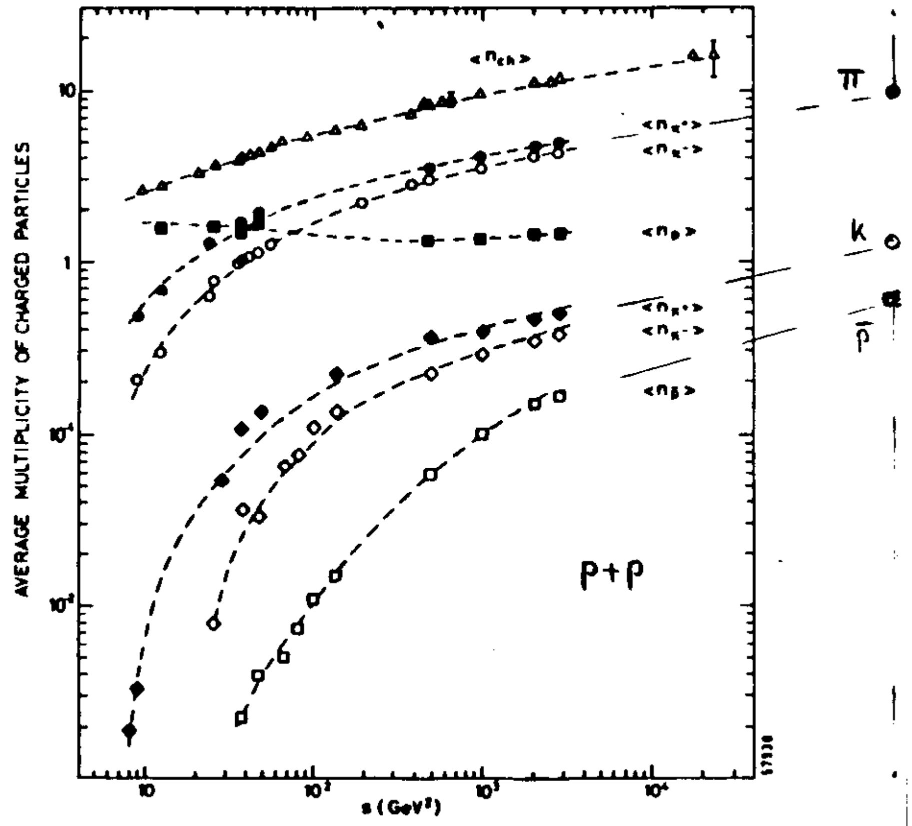
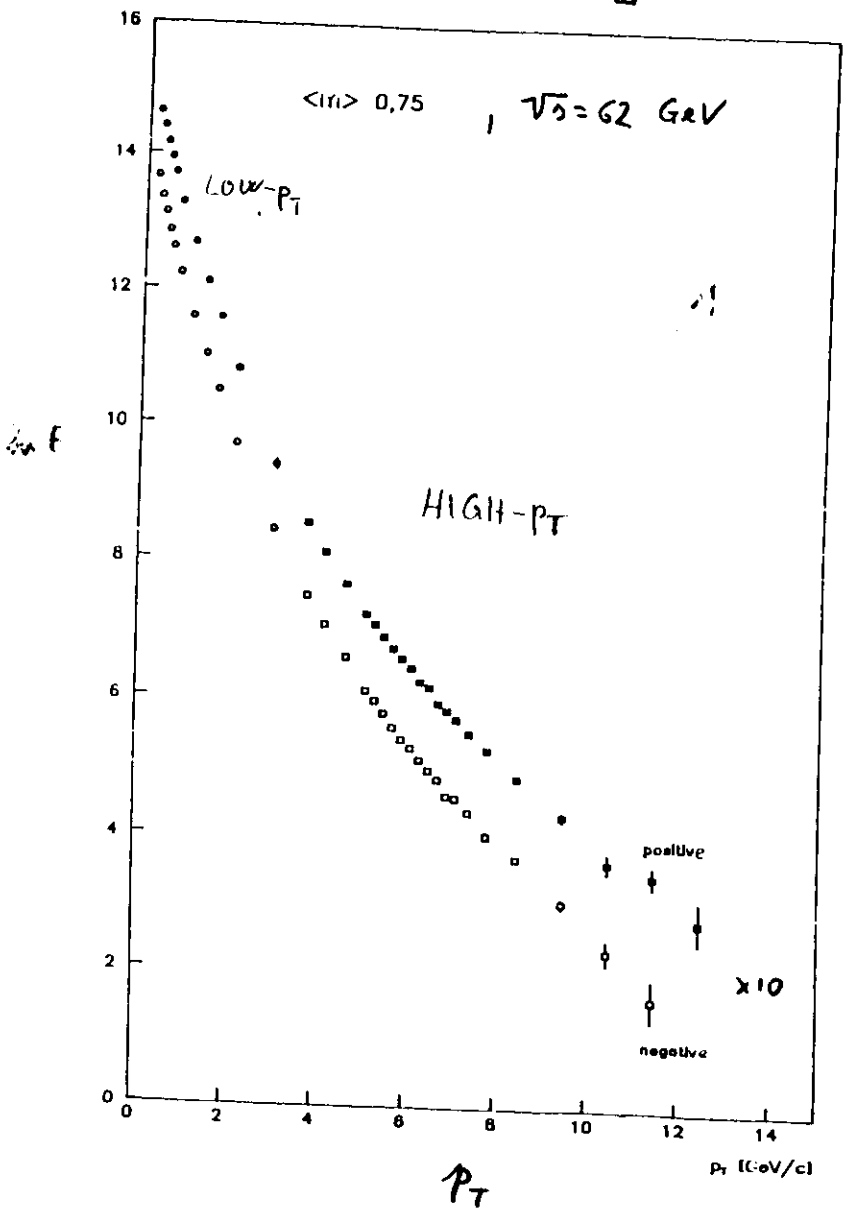


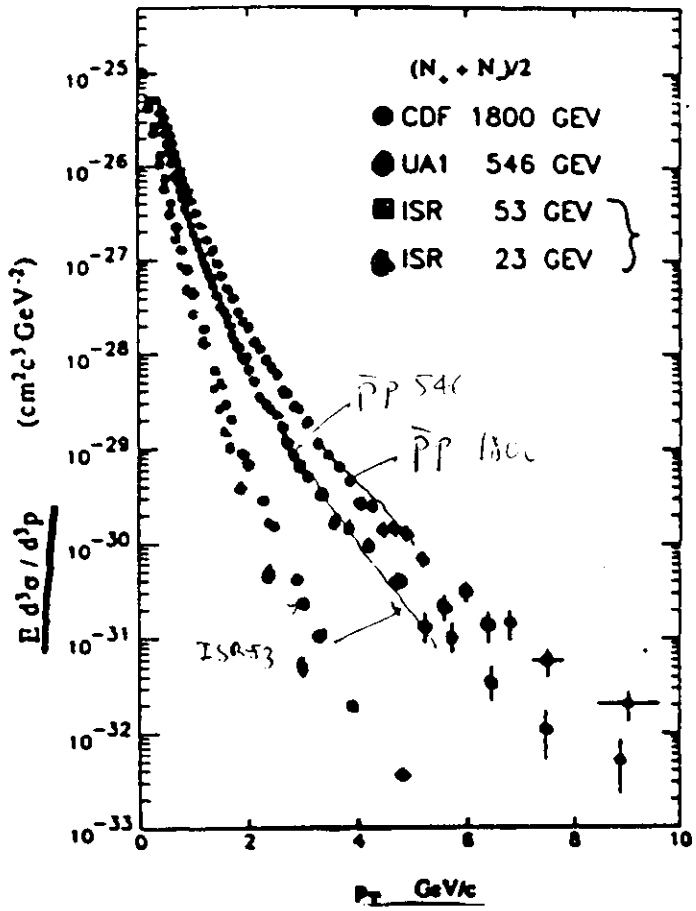
FIG. 14
charged
negatives
x Bromberg
LEBC - MPS
present work
UA5
√s (GeV)
Ed. Aerni-Leuch, Bern

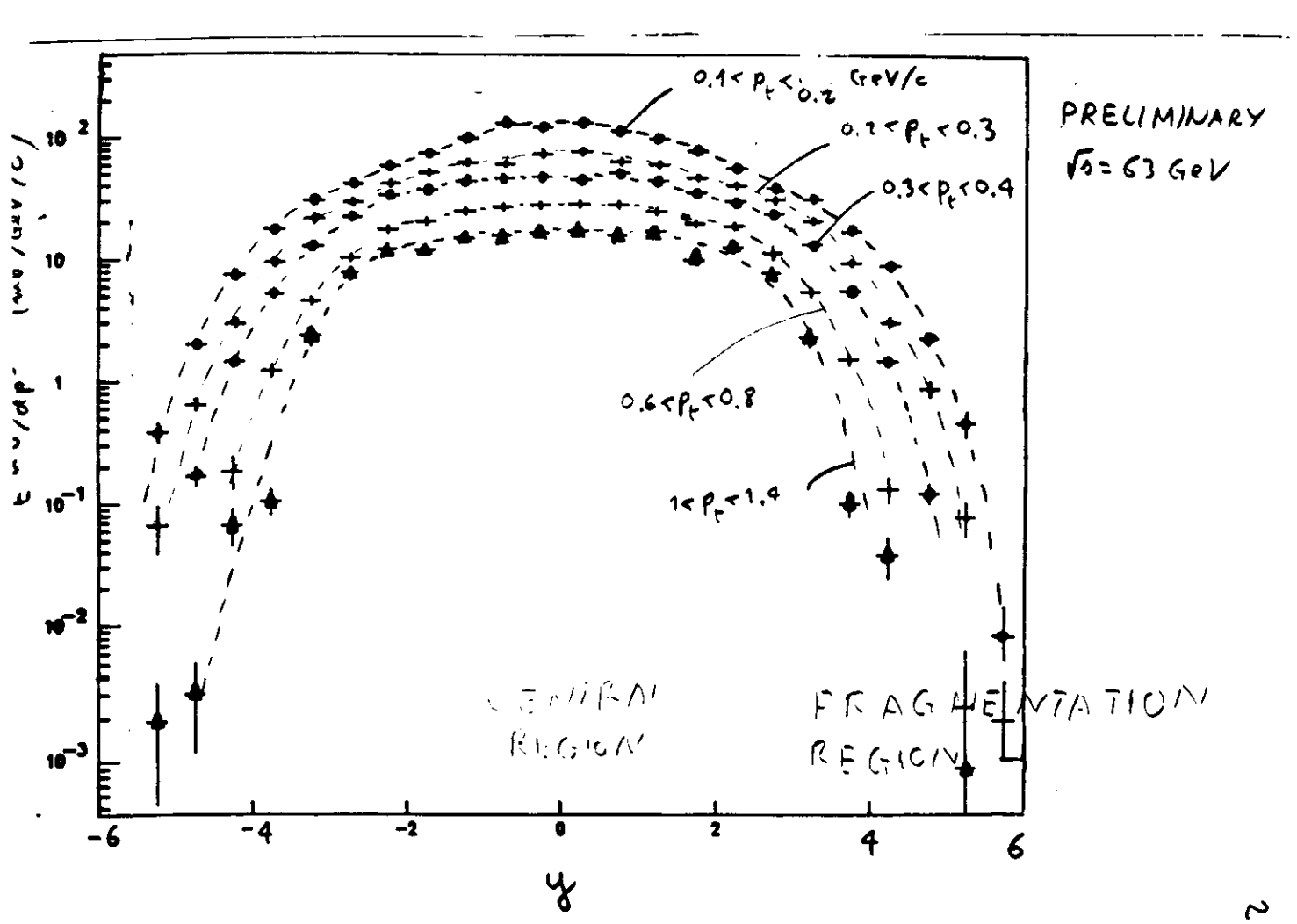


AVERAGE MULTIPLICITY OF CHARGED PARTICLES
s (GeV²)
<n_ch>
<n_p>
p+p
π
K
p̄

Fig. 2


pp → +
→ −
10/10/86
<|η|> 0,75
√s = 62 GeV
LOW-p_T
HIGH-p_T
positive
negative
x10
p_T [GeV/c]
p_T


$(N_+ + N_-)/2$
CDF 1800 GEV
UA1 546 GEV
ISR 53 GEV
ISR 23 GEV
$\bar{p}p$ 546
$\bar{p}p$ 1800
ISR 53
$E\, d^3\sigma/d^3p$ $(cm^2 c^3 GeV^{-2})$
p_T GeV/c


PRELIMINARY
$\sqrt{s}$ = 63 GeV
$0.1 < p_t < 0.2$ GeV/c
$0.2 < p_t < 0.3$
$0.3 < p_t < 0.4$
$0.6 < p_t < 0.8$
$1 < p_t < 1.4$
CENTRAL REGION
FRAGMENTATION REGION
y

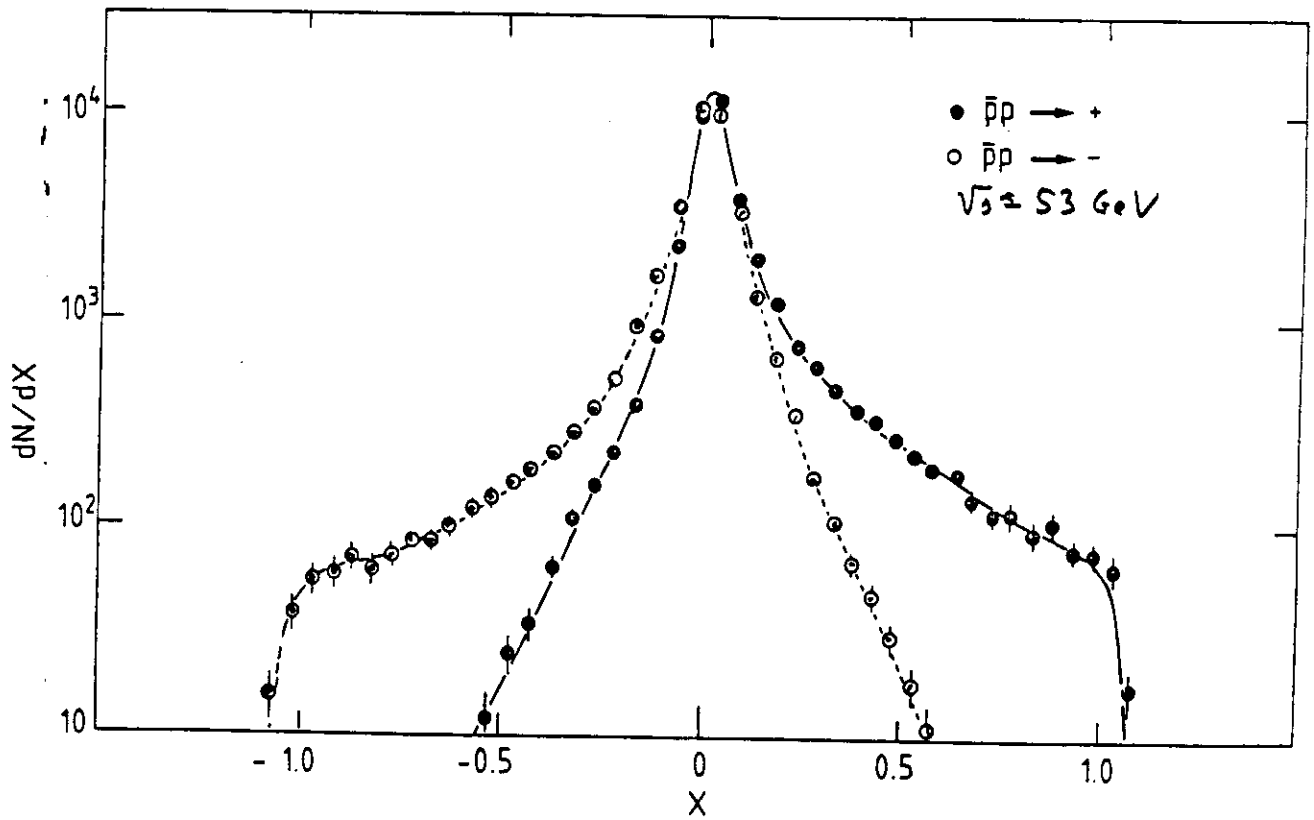
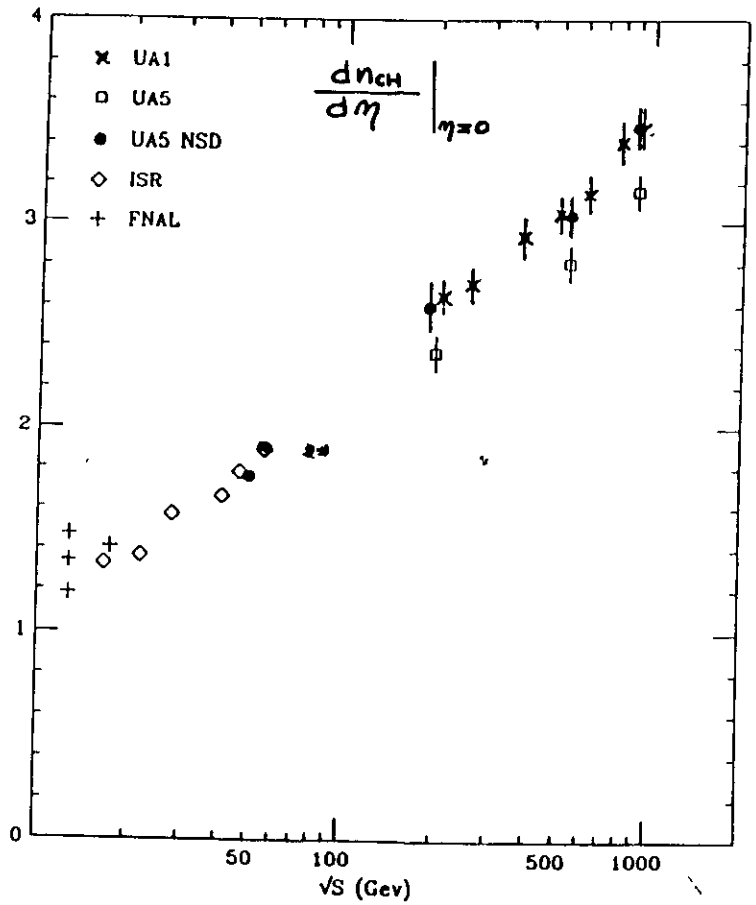

$\bar{p}p \rightarrow +$
$\bar{p}p \rightarrow -$
$\sqrt{s} \simeq 53$ GeV
dN/dX
X

Fig. 3

CHARGED MULTIPLICITY / ETA ETA=0



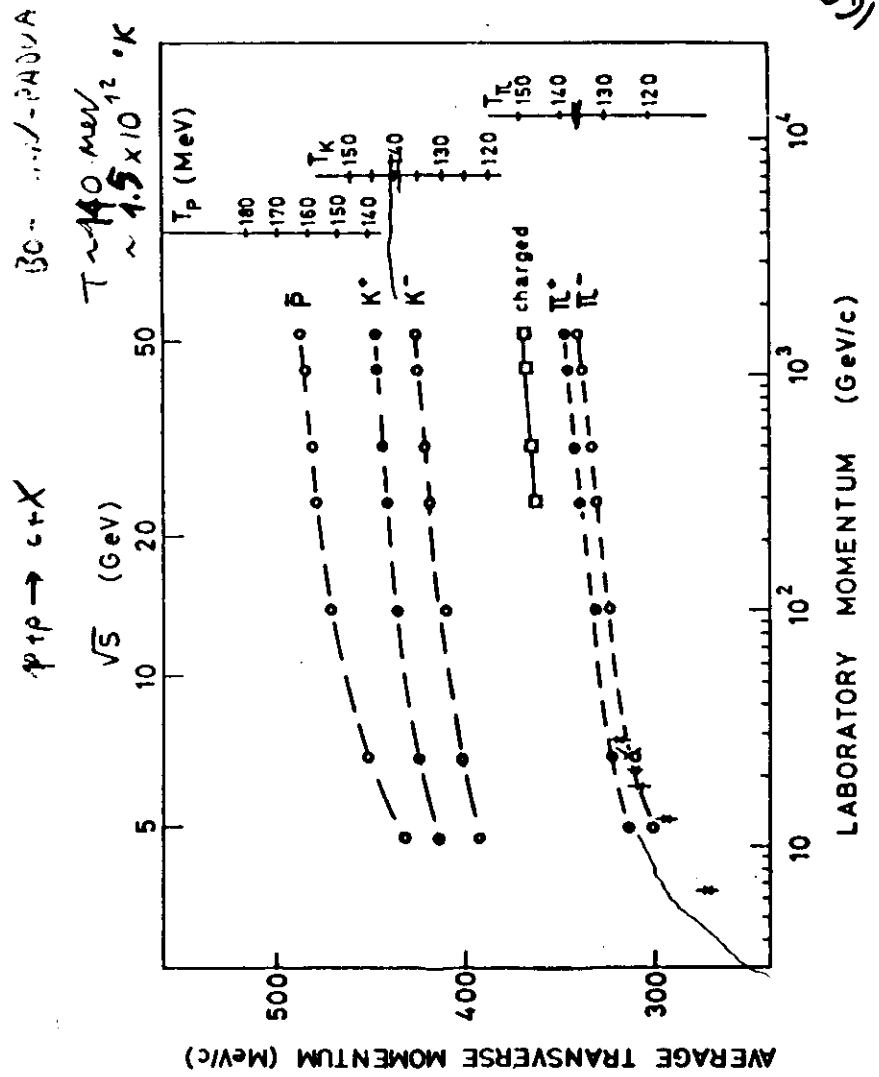
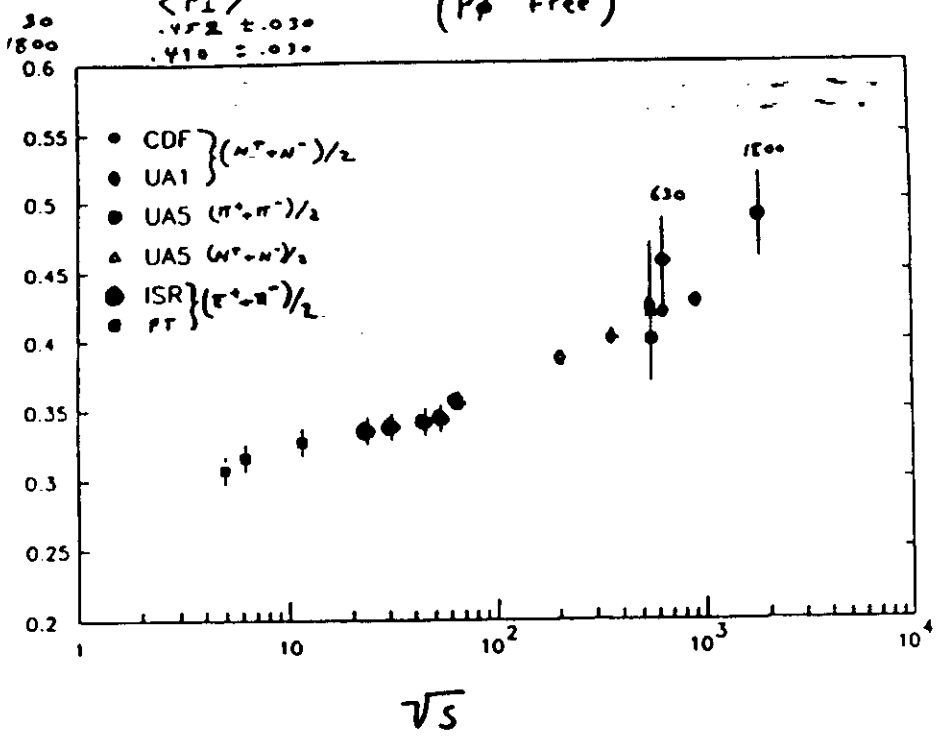
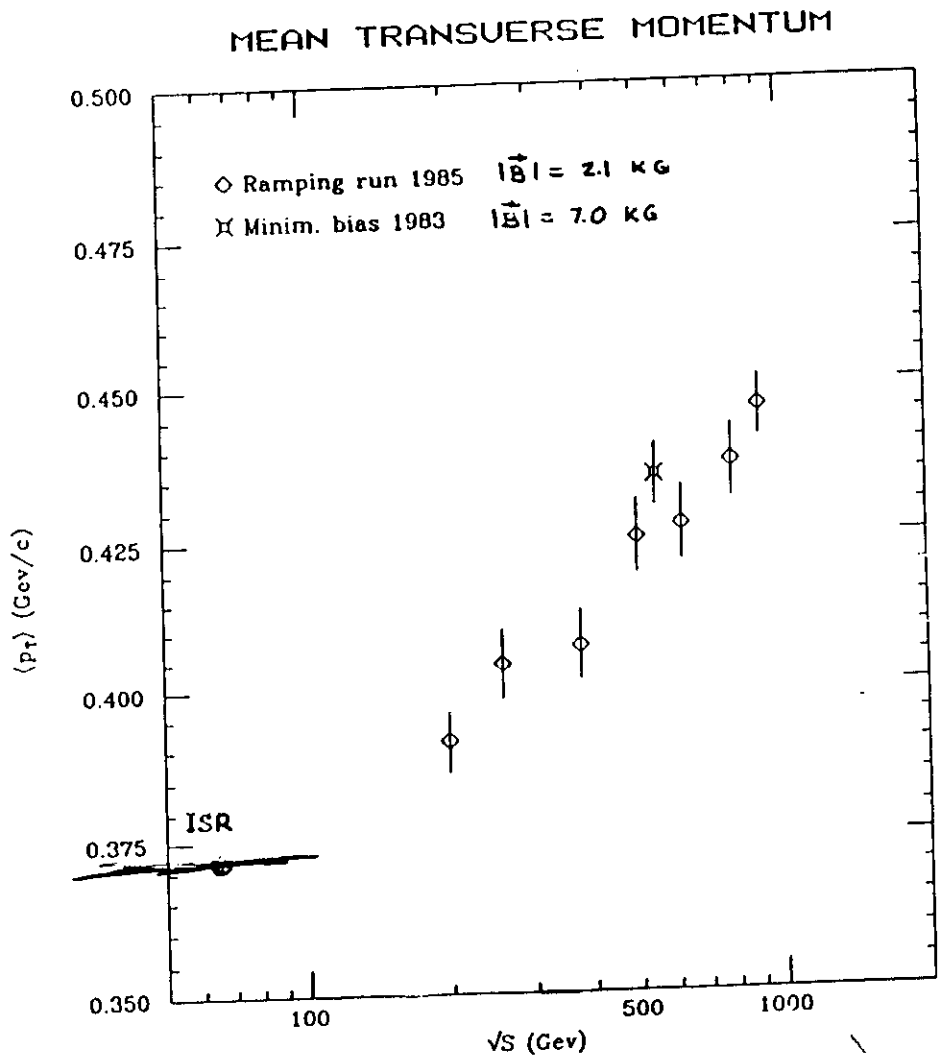


Fig 20

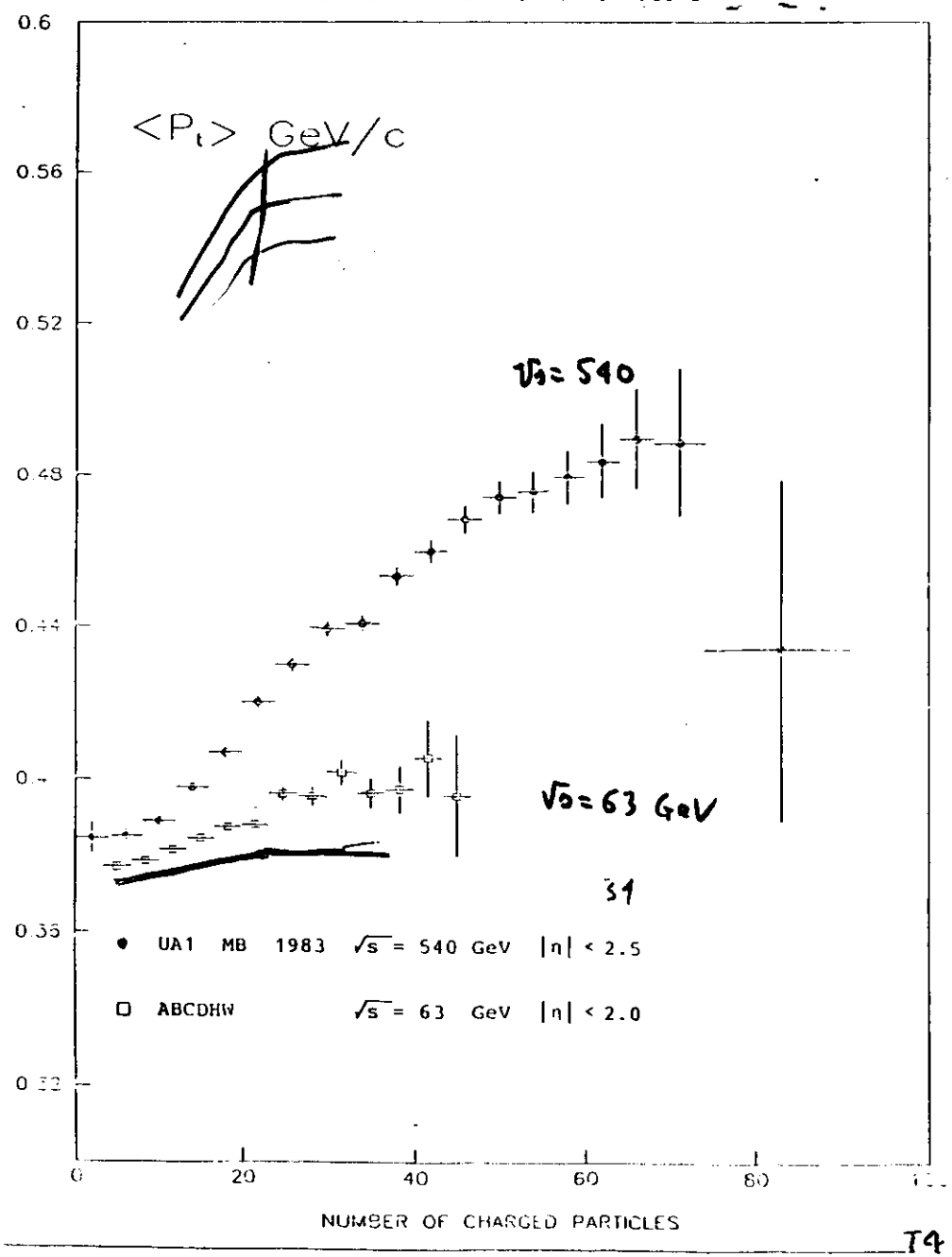


$\langle p_\perp \rangle$ Determined from Fit To inclusive $p_\perp$ spectra for $p_\perp > 0.4$ GeV/c ⇒ 55% of spectrum is "unseen". We Use $dN/d\eta$ constraint To check low $p_\perp$ Parameterization. Error estimated by varying low $p_\perp$ shape To change $dN/d\eta \pm 10\%$. ... Still working ON error ESTIMATES

al, Nucl Phys B84 (1975) 269



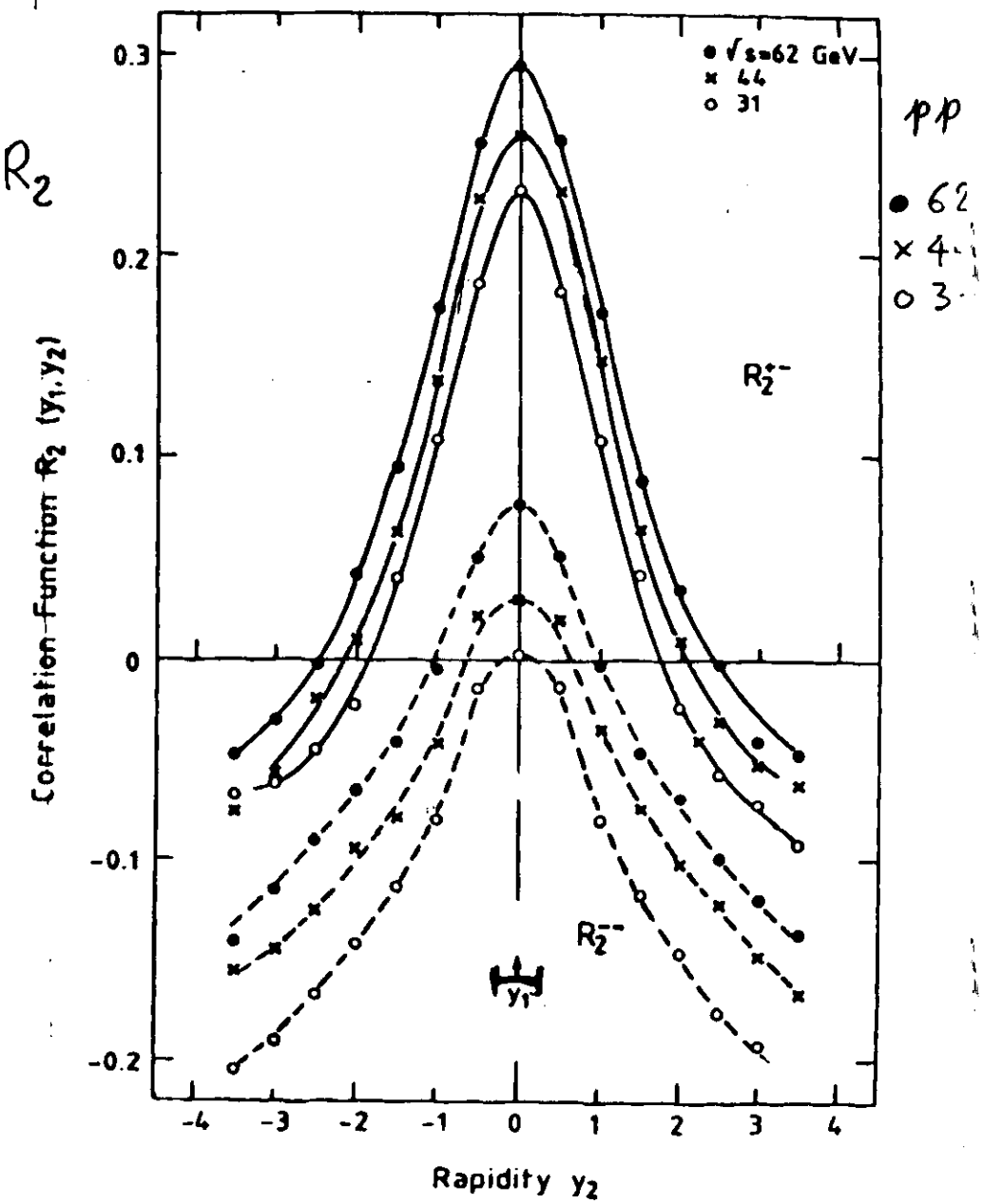
PT AVERAGE VS MULT. TOT. EVTS 1983 DATA



T4

PRELIMINARY

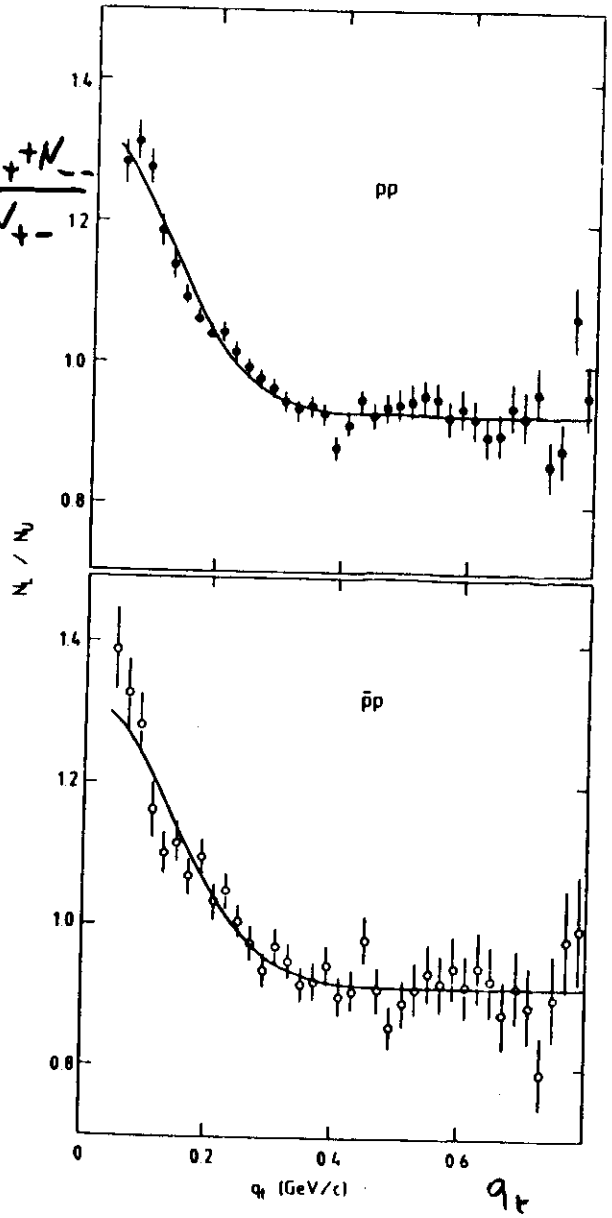
$\bar{p}p \to 1 + 2 + X$



$$I = \frac{N_L}{N_U} = \gamma\left(1 + \alpha\, e^{-\beta q_t^2}\right)$$

$\gamma = .928 \pm .005$
$\alpha = .432 \pm .021$
$R = .197\sqrt{\beta}$
$= 1.13 \pm .07$ fm

$$\frac{N_L}{N_U} = \frac{N_{++}+N_{--}}{N_{+-}}$$



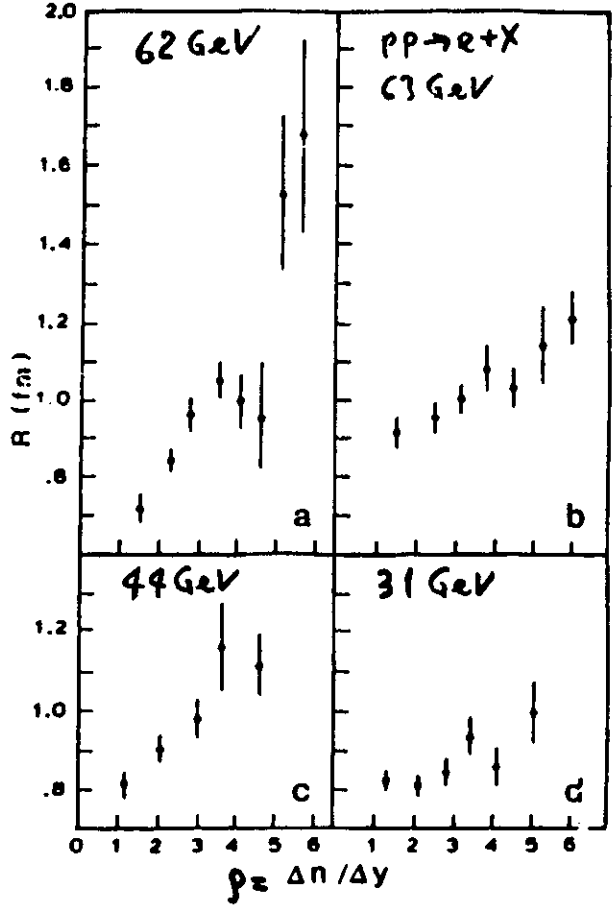
$\sqrt{s} = 53$ GeV

$R = 1.03 \pm .07$ fm

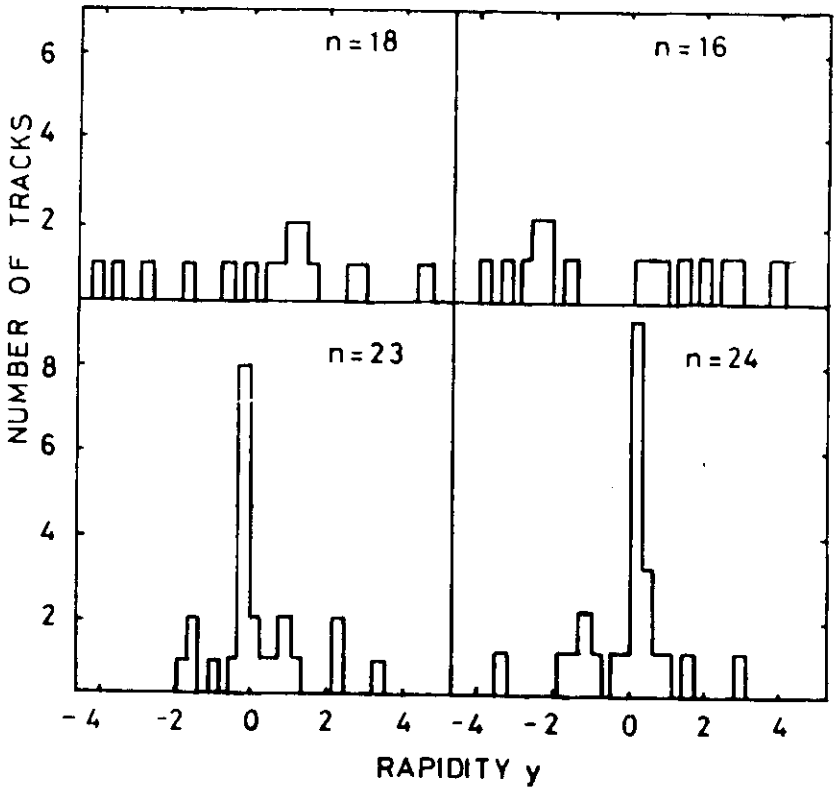
$n_{ch} \geq 6$
$|x_F| < 0.5$
$\Delta p < 0.1$ GeV/c
$P_T > 0.1$
$\cos\theta_{\pi\pi} \geq 0$
$m < 1.2$ GeV

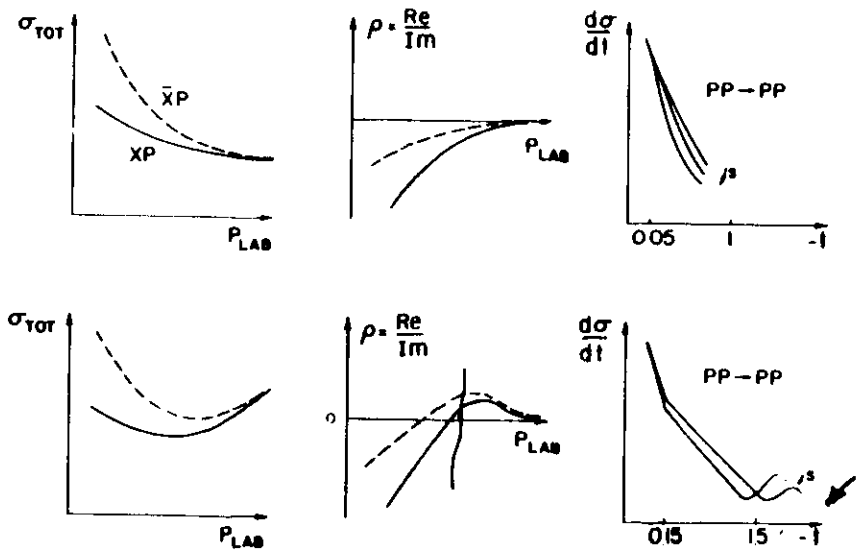
FIG. 1

BOSE-EINSTEIN CORRELATIONS



7/9/87





1968

1975