NEUTRAL PION PRODUCTION AT THE ISR

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At the CERN Intersecting Storage Rings (ISR) we have measured angular and energy distributions of single photons produced in proton-proton collisions at $\sqrt{s}$ = 30 to 53 GeV. The experimental technique using a lead glass total absorption Čerenkov counter and two large area trigger counters has been described in two papers by Neuhofer et al.[1,2]. In this report we reproduce in Fig. 1 the summary of all data obtained, and then we want to concentrate on the conclusions which may be drawn for π^0 production and on the comparison with the data on $\pi^\pm$ production obtained by other groups.

Figure 1 shows the invariant differential cross-section $F_\gamma = E_\gamma\, d^3\sigma_\gamma/d^3p_\gamma$ as a function of $x = 2E_\gamma \cos\theta_\gamma/\sqrt{s}$ for different values of the transverse momentum $p_t = E_\gamma \sin\theta_\gamma$ and for three primary energies $\sqrt{s}$. To obtain these cross-sections, the measured energy spectra at four fixed angles have been divided by the calculated efficiency of the γ telescope, corrected for γ conversion in the ISR vacuum tube, transformed into the proper centre-of-mass system and absolutely normalized.

There are two basically different normalization procedures for particle production data at the ISR; therefore we want to discuss again our procedure in some detail. Single-arm telescopes, requiring the production of one particle c and no other information on the event, measure $dN_c/dpd\Omega = L\, d\sigma_c/dpd\Omega$. Having measured the ISR luminosity L, one can deduce production cross-sections, independent of the total pp cross-section.

The drawbacks of this method are contaminations due to beam-gas events and the precision limitations given by the measurement of L (actually ±10%). The second procedure, adopted for our data, uses a "three-arm" set-up with one telescope in coincidence with two large area trigger counters about 3 m downstream from the interaction centre around each ISR beam tube. This method determines the ratio

$$\frac{d(N_\gamma \cdot H1 \cdot H2)/dpd\Omega}{H1 \cdot H2} = \frac{dN_\gamma/dpd\Omega}{N_{interaction}} , \qquad (1)$$

where H1·H2 are the coincidence counts from the two trigger counters H1 and H2 with the correct time of flight to accept beam-beam events and to reject beam-gas events. If one subtracts the elastic pp counts from H1·H2 and if the remaining events form a random sample of all inelastic pp events, the ratio in Eq. (1) is equal to $(d\sigma_\gamma/dpd\Omega)/\sigma_{inel}$, the <u>production rate per inelastic interaction</u>. This ratio is independent of the knowledge of L and σ_{inel}.

Do our detected H1·H2 events form a random sample of all inelastic events? Using[3] σ_{inel} = (32 ± 2) mb and calculating L with an effective beam height[4] h_{eff} = (6 ± 1) mm, we can estimate the observed fraction R of detected events. With the trigger conditions in which most of the data have been taken, we find R = 0.54 ± 0.09 at $\sqrt{s}$ = 30 GeV, R = 0.63 ± 0.11 at $\sqrt{s}$ = 45 GeV and R = 0.66 ± 0.11 at $\sqrt{s}$ = 53 GeV. Taking data with a fraction R varying from 0.09 ± 0.02 to 0.79 ± 0.15 we find that the production rates and spectrum slopes are independent of R within ±5%. A further support for the randomness assumption is given by the ISR experiment of Breidenbach et al.[5], where the angular distribution of all charged particles has been measured. The shapes of this angular distribution, obtained with the "three-arm" method using our trigger counters and obtained with the single-arm method, agree within ±3%.

With these justifications we have quoted our results as F_γ/σ_{inel}. The errors in Fig. 1 are the quadratic sum of the statistical errors and the normalization errors due to our method which we have estimated to be ±10%.

The conjecture of limiting distributions[6,7] predicts that F_γ/σ_{inel} reaches an s-independent limit if $s \to \infty$. Within the experimental errors, our data in the range $\sqrt{s}$ = 30 to 53 GeV are in agreement with this prediction, even at x = 0. The photon production data of Fidecaro et al.[8], obtained with a similar technique at the CERN-PS, indicate that at $\sqrt{s}$ = 6.8 GeV the limit of F_γ/σ_{inel} has not yet been reached. At small values of p_t and x their data are below the limit (at x = 0 a factor of about 1.6). For $p_t > 0.1$ GeV and $x > 0.05$ the scaling prediction seems to be already fulfilled at $\sqrt{s}$ = 6.8 GeV. This observation is in agreement with the data on $\pi^\pm$ production[9,10] at the ISR.

The solid lines in Fig. 1 represent the function

$$\frac{1}{\sigma_{inel}} F_\gamma(p_t,x) = \frac{1.48}{\text{GeV}} \frac{1}{p_t} \exp\left(\frac{-Pt}{162 \text{ MeV}} - \frac{x}{0.083}\right) , \qquad (2)$$

which is a satisfactory and very useful interpolation formula for our data points. With the restriction $p_\gamma > m_\pi/2$, it will be used in this report to derive π^0 spectra and a π^0 angular distribution.

The main source of photon production is π^0 decay. The next source is probably the decay $K_S^0 \to \pi^0\pi^0 \to 4\gamma$, which is estimated*) to contribute 7%; thus $N(\gamma) \approx 2.14\ N(\pi^0)$.

A rigorous deduction of π^0 spectra from the measured γ spectra has not yet been made. The amount of Monte Carlo calculation work necessary has led us to look for approximative ways to solve this question. A first-order approximation[1] is given by the method of Sternheimer[11]; with $p_\pi = p$ and $p_\gamma = k$:

$$\frac{dN_\pi(p,\theta)}{dpd\Omega} = -\frac{1}{2}\, p \frac{d}{dp} \frac{dN_\gamma}{dkd\Omega} (p = k,\ \theta) \ . \qquad (3)$$

This is valid for $p >> m_\pi/2$. The second approximation, also already discussed by Sternheimer, is a strict relation in the case of isotropic π^0 production in the centre-of-mass system[12]:

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*) The assumptions are: $\pi^0/(\pi^+ + \pi^-) = 0.5$, $(K^+ + K^-)/(\pi^+ + \pi^-) = 0.1$, $(K^0 + \bar{K}^0)/(K^+ + K^-) = 1$, all K_S^0 decay (the branching ratio into $\pi^0\pi^0$ is 0.33).

$$\frac{dN_\gamma(k)}{dkd\Omega} = 2 \int_{|k-m_\pi^2/4k|} \frac{1}{p}\frac{dN_\pi(p)}{dpd\Omega}\, dp \ , \qquad (4)$$

$$\frac{dN_\pi(p)}{dpd\Omega} = -\frac{1}{2}\, p\, \frac{d}{dp}\frac{dN_\gamma}{dkd\Omega}\left(p = k - \frac{m_\pi^2}{4k}\right), \quad p \geq \frac{m_\pi}{2} \ . \qquad (4')$$

According to Eq. (4), a spectrum of photons produced by the decay of isotropic neutral pions must have the following two properties: a) $n_\gamma = dN_\gamma/dk$ has a maximum at $k = m_\pi/2$; b) the spectrum part with $k < m_\pi/2$ is rigorously related to the part with $k > m_\pi/2$, $n_\gamma(k) = n_\gamma(m_\pi^2/4k$

The assumption of isotropic π^0 production is best fulfilled for $\theta_{cm} = 90°$, i.e. x = 0; therefore, we want to start with some conclusions for these data. According to Eq. (4), the γ spectra at fixed angle cannot be purely exponential. Because we found exponential behavior[1] for $k \gtrsim 150$ MeV, we have refitted the 90° photon spectra under the assumption of isotropic π^0 spectra of "Cocconi shape":

$$\frac{dN_\pi(90°)}{dpd\Omega} = \frac{A}{p_0^2}\, p \exp\left(-\frac{p}{p_0}\right), \qquad \frac{dN_\pi(90°)}{d\Omega} = A \ , \qquad (5)$$

$$\frac{dN_\gamma(90°)}{dkd\Omega} = \frac{2A}{p_0} \exp\left(-\frac{|k - m_\pi^2/4k|}{p_0}\right), \qquad \frac{dN_\gamma(90°)}{d\Omega} = 2\,A \ . \qquad (5')$$

Figure 2 shows the 90° photon data for $\sqrt{s} = 52.7$ GeV together with the best two-parameter fit in A and p_0. Table 1 shows the obtained fit values for all $\sqrt{s}$ including those from the PS. The errors include the estimated systematics due to normalization and absolute energy calibration. [The values and errors obtained are in very good agreement with the results of our first analysis[1].] The average π^0 transverse momentum is $\langle p_t(\pi^0)\rangle = 2\,p_0$, the average γ transverse momentum approximately $\langle p_t(\gamma)\rangle \approx \sqrt{p_0^2 + (m_\pi/2)^2}$.

Table 1

Results of the fits for the 90° data

$\sqrt{s}$ (GeV)	$2A = \frac{d\sigma_\gamma/d\Omega}{\sigma_{inel}}$	p_0 (MeV)	$\langle p_{t\pi} \rangle$ (MeV)
6.8[a]	0.15 ± 0.02	152 ± 10	304 ± 20
30.2	0.205 ± 0.021	162 ± 8	324 ± 12
44.7	0.213 ± 0.021	156 ± 10	312 ± 20
52.7	0.209 ± 0.021	157 ± 8	314 ± 12

a) Reference 8.

The obtained values of $[d\sigma_\gamma(90°)/d\Omega]/\sigma_{inel}$ agree well with the data on charged particles obtained at the ISR by Breidenbach et al.[5] and Barbiellini et al.[13]. Thus $N_\gamma = N_{all\ charged} \pm 15\%$ in the x = 0 region.

At forward angles the assumption of isotropic π^0 production is certainly not valid. Nevertheless we prefer Eq. (4) to Eq. (3) for estimating the π^0 production rates, because it takes the π^0 mass into account. We have applied it with $\theta_\pi = \theta_\gamma$ to the interpolation formula in Eq. (2) and multiplied[3] the results with σ_{inel} = 32 mb in order to get absolute π^0 cross-sections. They are shown in Fig. 3 for p_t = 0.2 and 0.4 GeV, together with the medium angle π^+ data obtained by Ratner et al.[9] and the π^- data of Bertin et al.[10]. For the small p_t value, $N(\pi^+) = N(\pi^-) = N(\pi^0)$ is well fulfilled. For the bigger p_t value, where $N(\pi^+) > N(\pi^-)$, the π^0 rates are more on the side of the negative pions.

The invariant differential cross-section $E_\pi\ d^3\sigma_\pi/d^3p$, as obtained in the way described, may be integrated over all momenta for fixed centre-of-mass angle θ_{cm} to get an angular distribution $d\sigma_\gamma/d\Omega$. The result of this integration is shown in Fig. 4.

Because of the good agreement between $2\sigma(\pi^0)$ and $\sigma(\pi^+) + \sigma(\pi^-)$, we may integrate our results one step further and give an estimation for the average charged multiplicity in proton-proton collisions. As many authors have shown:

$$\langle n_c \rangle = \frac{2\pi}{\sigma_{inel}} \int_0^{\pi} \frac{d\sigma_c}{d\Omega} \sin\theta \, d\theta \quad . \tag{6}$$

We set $\langle n_c \rangle = \langle n_{all\ charged} \rangle = 2\langle n_{\pi^0} \rangle + 1.5$, where n_{π^0} contains the already mentioned $K_S^0 \to \pi^0\pi^0$ decays and therefore takes into account $K^{\pm}$ production, and 1.5 is the average charge of the two leading baryons. The results are given in Table 2 and shown in Fig. 5, together with directly obtained values for $\langle n_c \rangle$ in bubble chamber and cosmic-ray experiments. Unfortunately, the estimated errors of ±15% are too big to be able to reach some definite conclusions on the logarithmic or power law increase of $\langle n_c \rangle$.

Table 2

Deduced average charged multiplicities

$\sqrt{s}$	30.2 GeV	44.7 GeV	52.7 GeV
$\langle n_c \rangle$	9.3 ± 1.4	10.5 ± 1.6	10.9 ± 1.7

Because of the present special interest in particle production at x = 0, we summarize in Fig. 6 all pertinent ISR results obtained so far. The experiments of Refs. 5 and 13 do not determine momenta of the particles produced; thus the only comparable quantity is $d\sigma/d\Omega$. The scaling conjecture of s-independent invariant cross-sections leads to a constant $d\sigma/d\Omega$:

$$\frac{d\sigma(90°)}{d\Omega} = \int p^2 dp \, \frac{d^3\sigma}{d^3p} = \int p_t^2 \, dp_t \, \frac{F(x = 0, p_t)}{\sqrt{p_t^2 + m^2}} = \text{const.} \tag{7}$$

Also shown in Fig. 6 are the PS results on γ production[8] and those on $(\pi^{\pm} + K^{\pm})$ production obtained in the CERN 2 m bubble chamber by Mück et al.[14] at p_{lab} = 12 GeV/c, $\sqrt{s}$ = 4.9 GeV and p_{lab} = 24 GeV/c, $\sqrt{s}$ = 6.9 Ge

Our conclusions are the following: a) The γ data agree well with the charged particle data. b) The one-arm measurement of Ref. 5 agrees well with the three-arm measurements[1,13]. c) In contrast to data in the fragmentation region there is a pronounced increase of rate between PS energies and ISR energies. d) A Mueller-Regge ansatz of the form $d\sigma/d\Omega = A + B\ s^{-1/4}$ gives a good fit to all data, though B is negative and rather large compared to A.

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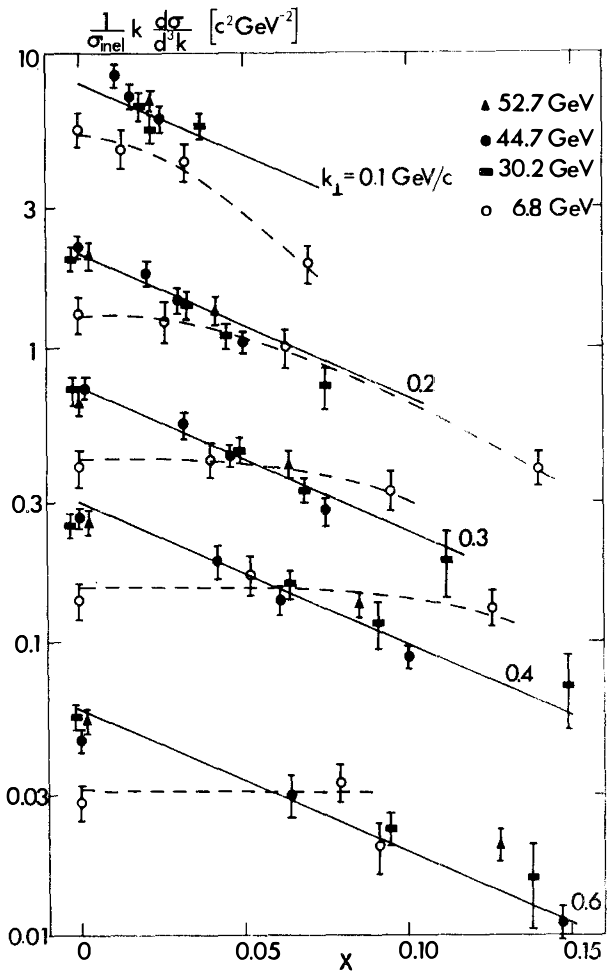

Fig.1 The (normalized) single photon distribution function [2] as function of $x = 2\ k \cos\theta / \sqrt{s}$ for various values of the transverse momentum $k_\perp = k \sin\theta$ and of the centre-of-mass energy $\sqrt{s}$. The solid lines represent the interpolation formula of eq.2. The dashed lines connect the data [8] at $\sqrt{s}$ = 6.8 GeV to guide the eye.

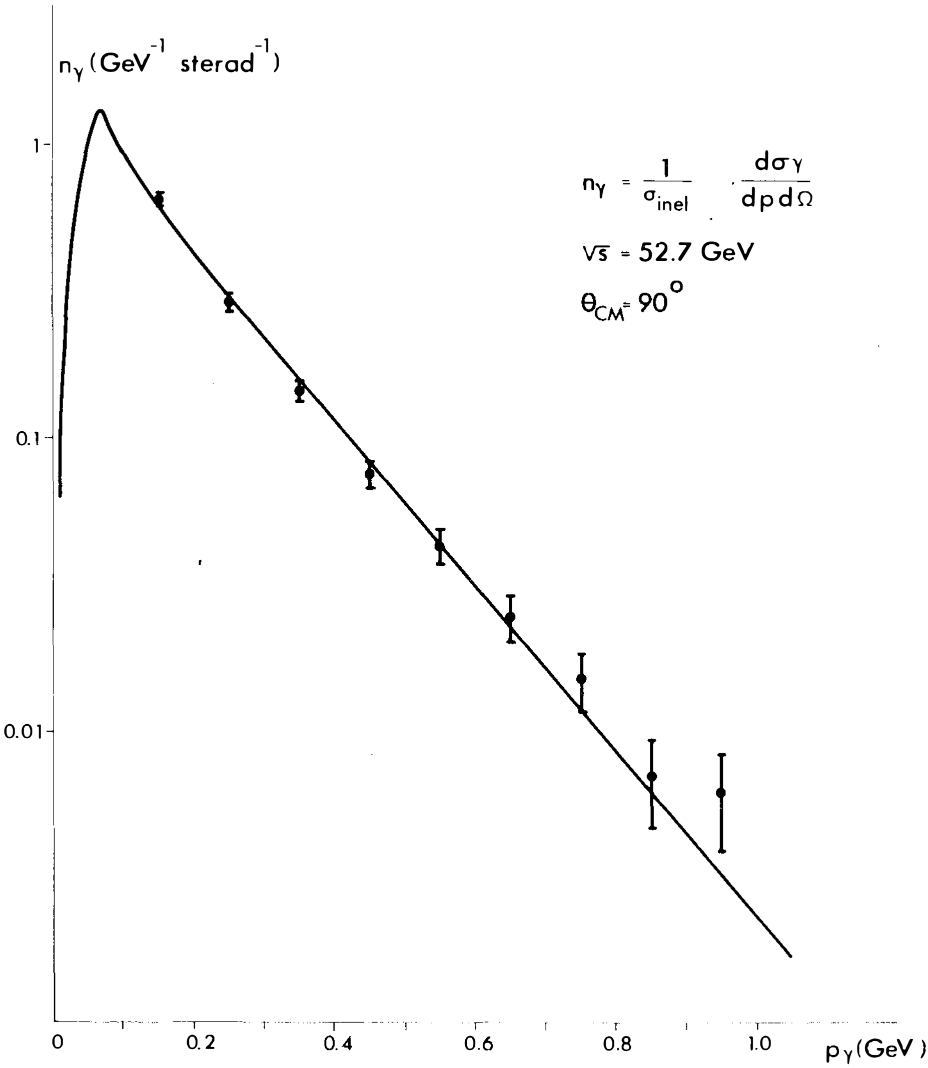

Fig.2 The 90° single photon spectrum at $\sqrt{s}$ = 52.7 GeV. The solid line represents the best two parameter fit of the photon spectrum originating from the decay of isotropically produced π^0 of a "Cocconi type" spectrum, eqs.5.

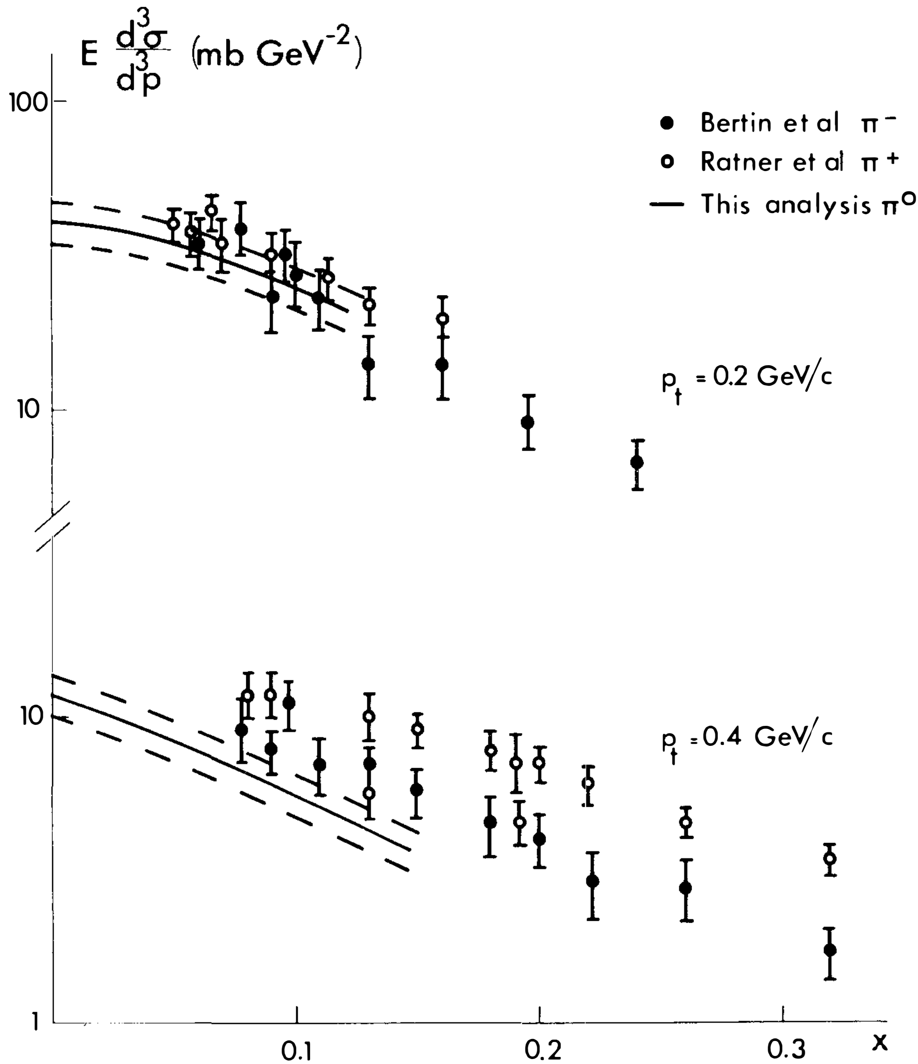

Fig.3 The neutral pion distribution function $E_\pi d^3\sigma_\pi/d^3p_\pi$ in the $\sqrt{s}$ range from 30 to 53 GeV for transverse momenta of 0.2 and 0.4 GeV/c. To compare it with the π^+ and π^- data of refs. 9 and 10 in the same $\sqrt{s}$ range, σ_{inel} = 32 mbarn has been assumed.

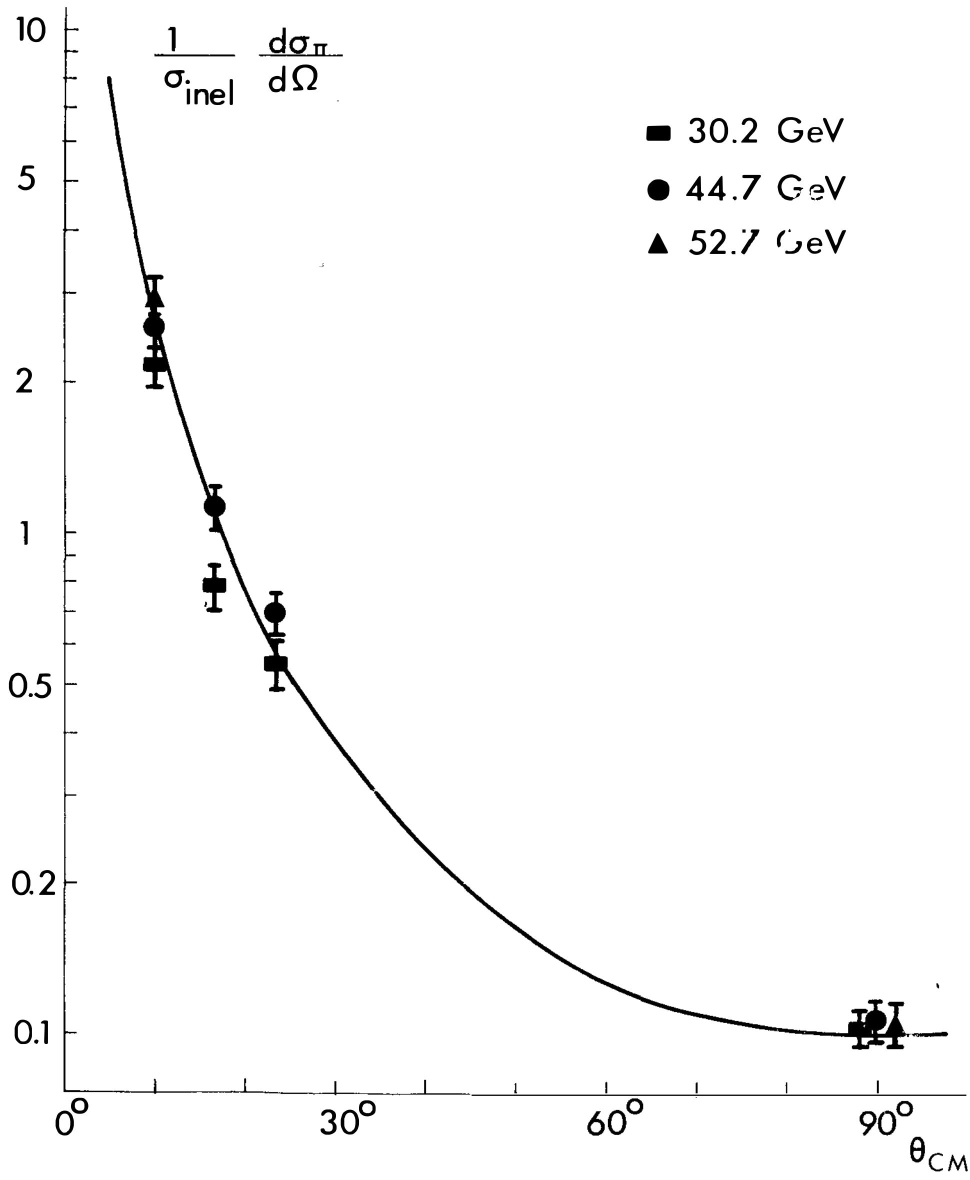

Fig.4 The neutral pion angular distributions. The data points at 90° are the results of the reanalysis as given in table 1; the points at 10° to 24° are the values of ref. 2 with $d\sigma_\pi(\theta)/d\Omega = 1/2\ d\sigma_\gamma(\theta)/d\Omega$. The solid line represents the distribution obtained by applying eq. 4' to eq. 2, integrated over all momenta, at $\sqrt{s}$ = 44.7 GeV.

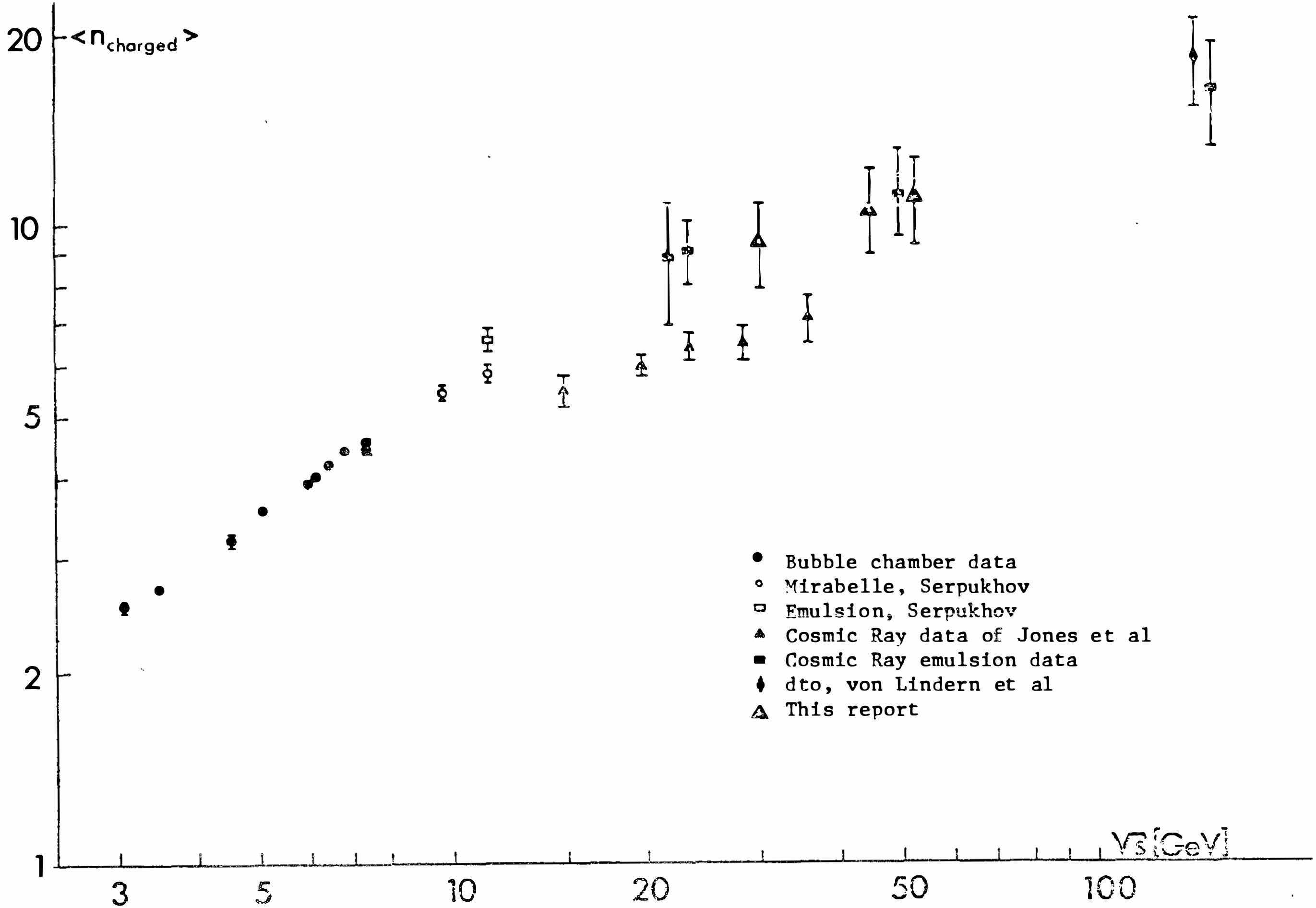

Fig.5 The deduced values for the average charged multiplicity in pp collisions, together with older results.

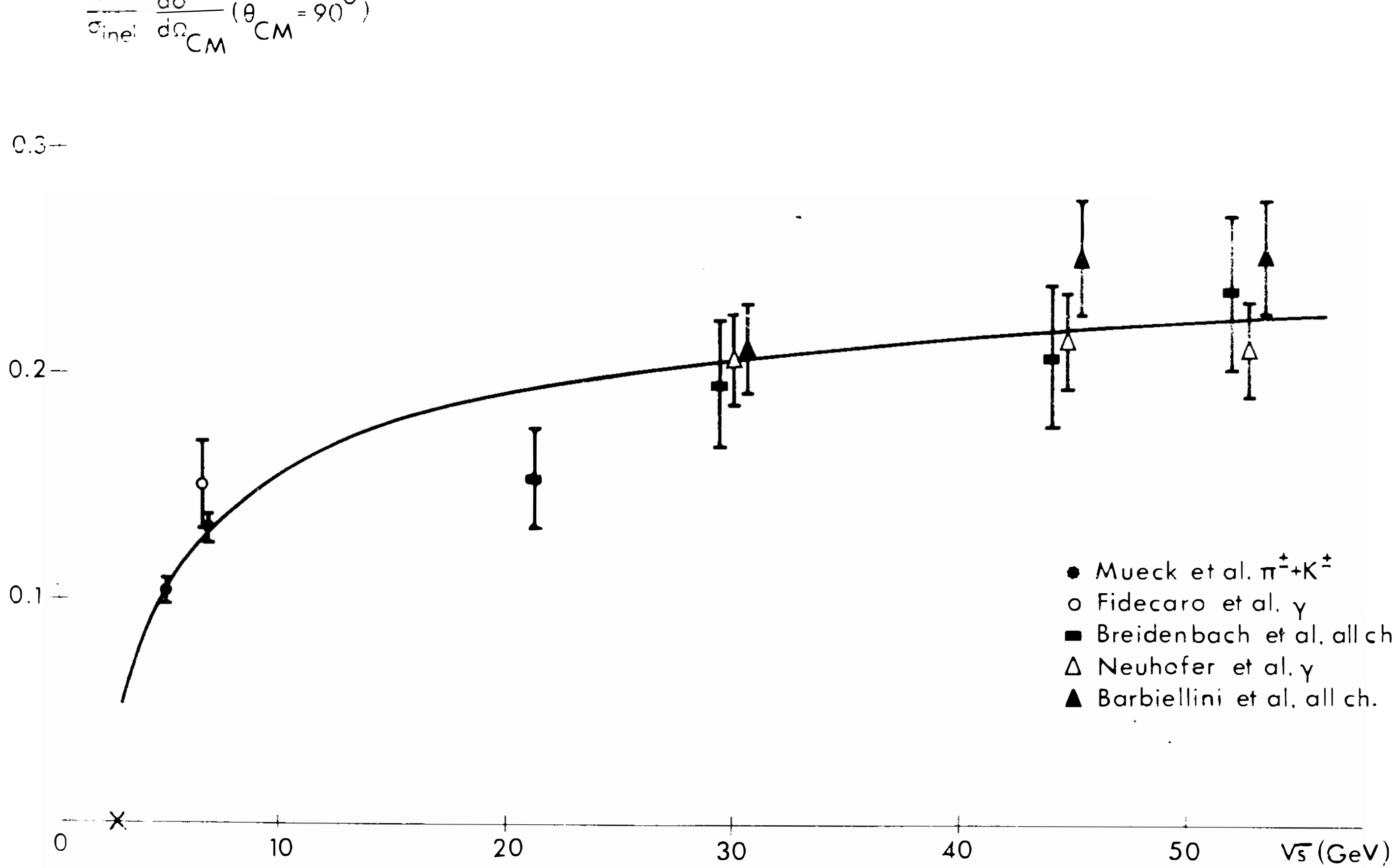

Fig.6 The summary of particle production data [π+K, γ and all charged] at x = 0. The solid line represents an A + B $s^{-1/4}$ least square fit to the data. The results are A = 0.274 ± 0.012, B = -0.377 ± 0.031.