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# Angular Dependence of High-$p_T$ $\pi^0$ Production

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The $\pi^0$ inclusive cross section for c.m. production angles $\theta = 90°$ and $22° \geq \theta \geq 5°$ at c.m. energies of $\sqrt{s} = 23$ and 53 GeV has been measured. This cross section is strongly dependent on both $\theta$ and $\sqrt{s}$ at small angles. The hypothesis of radial scaling is shown to be incapable of incorporating both $\theta$ and $\sqrt{s}$ dependence of the cross section. A recent quantum-chromodynamics calculation is in qualitative agreement with our results.

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We have performed an experiment at the CERN intersecting storage rings (ISR) to determine the angular dependence of high-$p_T$ $\pi^0$ production in $p$-$p$ collisions at the widely separated energies, $\sqrt{s} = 23$ and 53 GeV. In the context of constituent scattering models,[1] these data furnish an experimental constraint on the distributions of constituents within the proton and their evolution into observable hadrons. They also provide a decisive test of the radial scaling hypothesis.[2,3]

The experimental apparatus consisted of a set of large-solid-angle scintillation-counter hodoscopes and a 4×4 array of lead-glass shower counters. The hodoscopes[4] provided the basic intersection trigger and timing information used to eliminate background events due to beam-gas collisions. The shower counters[5] measured the energy of the decay photons of the $\pi^0$ and thus determined the $\pi^0$'s transverse momentum. The shower-counter array was positioned at three locations corresponding to c.m. angles of 90°, 25°–15°, and 12°–5°.

The trigger[5] required at least one charged particle in both hemispheres of the hodoscopes. The high-$p_T$ photons were selected by demanding a mininum energy deposit in the shower counter together with a signal from a counter plane sandwiched between a 1-cm lead converter and the shower-counter array.

In the analysis of the data, the measured transverse momentum, $q_T$, was determined from the cell showing the largest signal, and those bordering it. The value of $q_T$ differs from the true transverse momentum, $p_T$, for several reasons, enumerated below. Our procedures for obtaining the true $p_T$ distribution was to convolute the observed $q_T$ distribution with a function, $f(q_T, p_T)$, determined from a Monte Carlo (MC) calculation. Incorporated in the MC calculation is a hypothesis for the true inclusive cross section and the various effects which cause $q_T$ to be different from $p_T$. The initial cross-section hypothesis was taken from existing data; the MC procedure was then iterated until the output and input cross sections agreed. The calculation included (i) the production of $\eta$'s as well as $\pi^0$'s (with the $\eta/\pi^0$ ratio = 0.55 at high $p_T$),[6] (ii) a detailed simulation of both the longitudinal[7] and the radial[8] development of electromagnetic showers, (iii) the extra energy deposited by associated hadrons in the detector (measured previously by this experiment[5]), (iv) the energy resolution of the shower counters (determined from test-beam studies), and (v) the loss of shower energy due to leakage out of the detector, spillover outside the cells used to define the cluster, and photons from $\pi^0$ (or $\eta$) decays that escaped detection.

We have studied the sensitivity of our results to these effects by allowing the MC parameters to vary within generous limits. We find, for example, at 90° the systematic errors due to effects (i)–(v) to be ± 5%, ± 3%, ± 10%, ± 3%, and ± 5%, respectively. The transformation matrix that was obtained with the MC procedure was sharply peaked along the line $p_T - q_T = 0.1$ GeV/$c$. At constant $p_T$, the tails of the peak fell to ≲10% with-

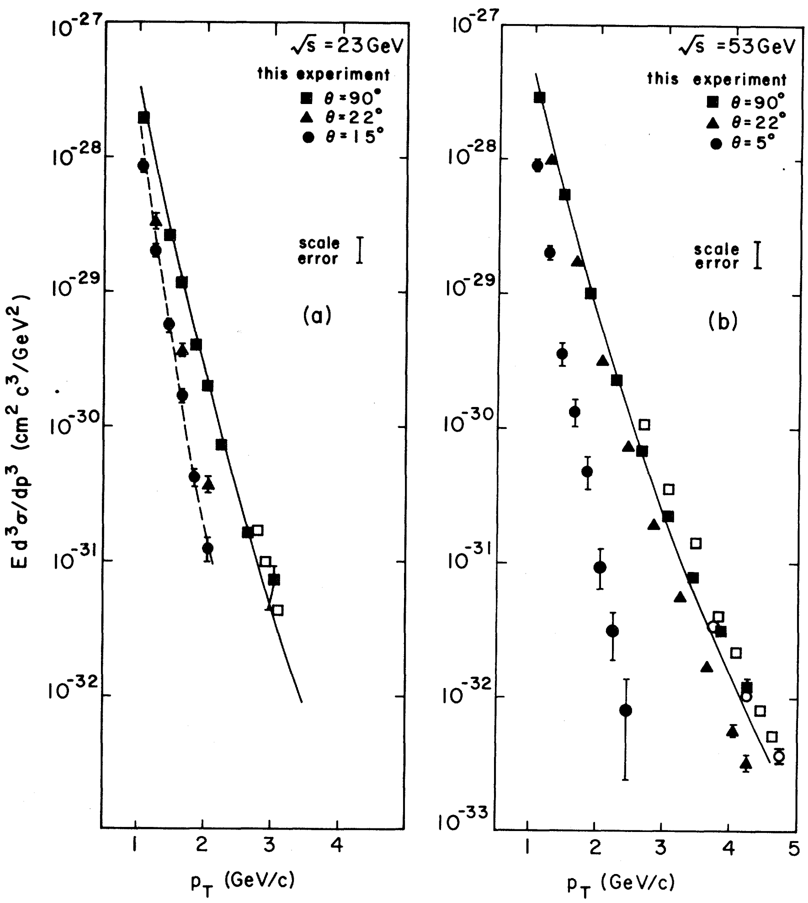


FIG. 1. Invariant cross section for inclusive $\pi^0$ production vs $p_T$. Solid symbols are for data from this experiment; open squares, data of Büsser *et al.* (Ref. 10) at 90°; open circles, data of Angelis *et al.* (Ref. 11) at 90°. The solid line is the fit to 90° production of Beier *et al.* (Ref. 12). (a) $\sqrt{s} = 23$ GeV. The broken line is the fit to the data of Donaldson *et al.* (Ref. 13) at $\theta = 15$. (b) $\sqrt{s} = 53$ GeV.

in ± 0.4 GeV/$c$ in $q_T$. The MC procedure was also used to determine the geometrical acceptance of the shower-counter array. The cross sections quoted are for inclusive $\pi^0$ production, with $\eta$ subtracted. There is a ± 5% error on the $p_T$ scale due to calibration uncertainty.

At 90°, where there is no cross-section variation over the aperture of the detector, we have compared the invariant cross sections measured in different cells of the shower-counter array. The agreement, to within ± 10%, of the cross sections for corner, edge, or interior cells verifies that our parametrization of the electromatic shower evolution was adequate.

In Figs. 1(a) and 1(b) we show a representative[9] sample of our data for $\sqrt{s} = 23$ and 53 GeV. Agreement between our data and other data[10-12] at 90° is good; we also agree with data at 15° from an experiment at the lower energy by Donaldson *et al.*[13] We observe that the cross sections at small angles deviate from the 90° values. At 53 GeV, the slope of the cross section steepens markedly in the vicinity of $\theta = 20°$; at 23 GeV, this transition occurs at $\theta \gtrsim 25°$.

The hypothesis of radial scaling[2] has been investigated by Carey *et al.*[3] for inclusive $\pi^0$ production. The hypothesis asserts that the inclusive cross section for $A + B \rightarrow C + X$ should be a function of just two variables, $x_R$ and $p_T$, instead of three (e.g., $s$, $x_R$, $p_T$) as the c.m. energy becomes large. Here $x_R \equiv E_c^*/E_{\max}^*$, where $E_{\max}^*$ is the maximum value of c.m. energy for particle $C$ consistent with conservation laws. In subsequent work, Carey *et al.* have examined their $\pi^0$ data[14] and the results of other experiments on high-$p_T$ inclusive production for evidence of radial scaling; the same group also reported[15] that radial scaling was indeed valid from $\sqrt{s} \simeq 10$ GeV up to 63 GeV (the highest, available energy at the CERN ISR) and have produced fits for the cross-section dependence on $x_R$ and $p_T$. Two other Fermilab experiments[13,16] have since found their results consistent with radial scaling. The data from our experiment provide a sensitive test of this hypothesis since they allow comparisons of cross sections at fixed $x_R$ and $p_T$ but widely different $\sqrt{s}$ and $\theta$. Figure 2 shows our data at fixed

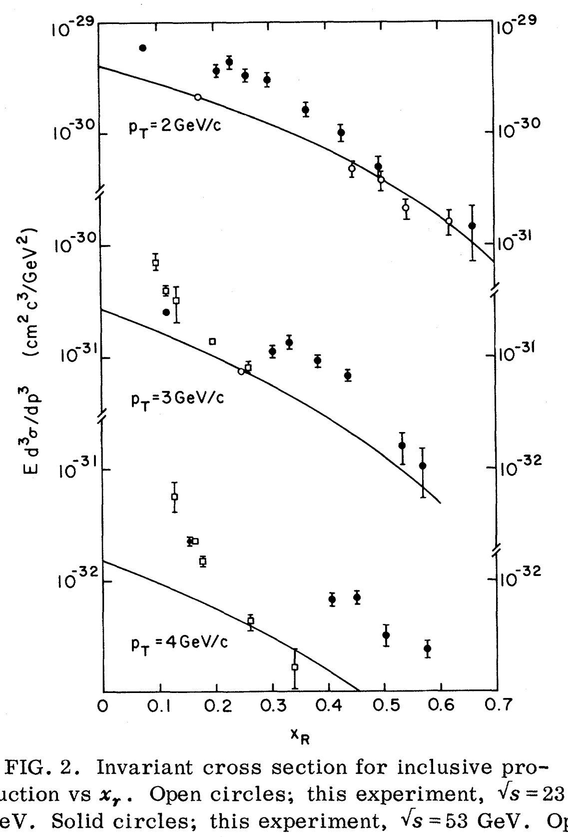


FIG. 2. Invariant cross section for inclusive production vs $x_r$. Open circles; this experiment, $\sqrt{s} = 23$ GeV. Solid circles; this experiment, $\sqrt{s} = 53$ GeV. Open squares; data from Büsser *et al.* (Ref. 10) at $\theta = 90°$ for five different $\sqrt{s}$. The solid lines are the fits for radial scaling in Taylor *et al.* (Ref. 15), normalized to our 90°, $\sqrt{s} = 23$ GeV datum point.

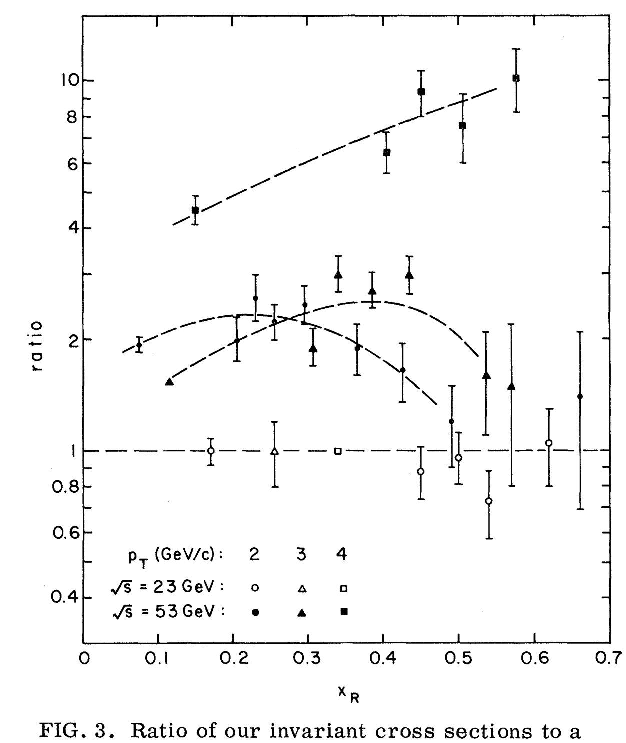


FIG. 3. Ratio of our invariant cross sections to a radial-scaling fit, normalized to the datum point at $\sqrt{s} = 23$ GeV and $\theta = 90°$. The lines are hand drawn to guide the eye for constant-$p_T$ data.

$p_T$ vs $x_R$. The lines are the fits of Taylor *et al.* (Ref. 15) normalized to our datum point at $\sqrt{s}=23$ GeV and $\theta=90°$, which agree well with the $x_R$ dependence of our data at $\sqrt{s}=23$ GeV and $p_T=2$ GeV/$c$. However, our data at $\sqrt{s}=53$ GeV are consistently higher than the radial-scaling prediction at all $p_T$. The ratio of our data to the normalized fits of Taylor *et al.* are shown in Fig. 3. We observe that the violation of radial scaling is large, particularly at large $x_R$ and $p_T$.

The violation of radial scaling observed here is not altogether inconsistent with earlier reports supporting its validity. Of the twenty experiments included in the fit of Taylor *et al.*, ten are at low energy ($\sqrt{s}<10$ GeV). Seven of the remainder give charged-hadron data at either $\theta\sim 90°$ or $\theta\sim 0°$. Two[10,17] of the three $\pi^0$ experiments are at $\theta\sim 90°$ at the CERN ISR; these agree with our 90° data and fail to conform to radial scaling at the higher energies. The remaining experiment[14] and two more recent experiments[13,16] span a large angular range but are limited in energy to $\sqrt{s}<27$ GeV; these agree with our data where overlap exists. Thus, our observation of radial-scaling violations at $\sqrt{s}=53$ GeV does not disagree with any particular experiment but does conflict with the central conclusion of Taylor *et al.*

Another test of radial scaling can be made without recourse to specific data fits. For fixed $p_T$, variation of $x_R$ can be achieved either by letting $\theta$ vary at fixed $\sqrt{s}$ or through $\sqrt{s}$ variation at fixed $\theta$. In Fig. 2 we have plotted the data of Rüsser *et al.* (Ref. 10), taken at $\theta=90°$ and several $\sqrt{s}$. For both $p_T=3$ and 4 GeV/$c$, we see that the $x_R$ dependence of these data is in marked disagreement with that from our own fixed-$\sqrt{s}$ data at several $\theta$.

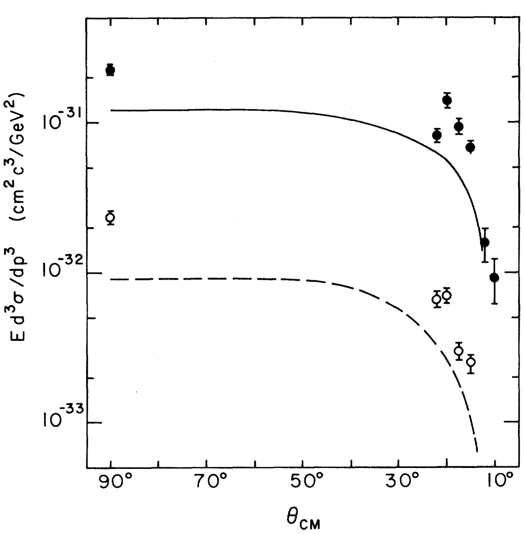


FIG. 4. Invariant cross section for inclusive $\pi^0$ production vs $\theta$; solid circles, data at $p_T=3$ GeV/$c$. Open circles, data at $p_T=4$ GeV/$c$. The curves are the prediction of the model discussed in Feynman *et al.* (Ref. 1).

Predictions for a large body of high-$p_T$ inclusive data have been made[1] in the framework of a model based on constituent scattering in quantum chromodynamics (QCD). These predictions reproduce existing data quite well, including results on the 90° production of $\pi^0$'s with $p_T\geq 5$ GeV/$c$. In Fig. 4 we compare the angular dependence of high-$p_T$ $\pi^0$ production found in this model to that measured by our experiment for $p_T=3$ and 4 GeV/$c$ at $\sqrt{s}=53$ GeV. The predicted shape of the angular distribution is in reasonable agreement with our data, but the normalization of the model is too low at all angles by a factor of about 2. The same normalization problem was encountered for 90° production at these moderate $p_T$. On the other hand, we note that the substantial violation of radial scaling predicted by this model is in agreement with the data shown in Fig. 3. For $0.3\leq x_R\leq 0.6$ at $p_T=4$ GeV/$c$ the model predicts that the ratio of the cross section at $\sqrt{s}=53$ GeV to that at $\sqrt{s}=23$ GeV should be about 5.

We conclude that over the presently available $s$ range, inclusive cross sections depend significantly on all three kinematic variables (e.g., $s$, $p_T$, and $\theta$) and that reduction of the number of variables through the introduction of the radial-scaling ratio, $x_R$, is untenable. The constituent scattering models based on QCD provide a reasonable qualitative representation of our data.

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# Neutron Oscillations and the Existence of Massive Neutral Leptons

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The neutron-antineutron transition which changes baryon number by two units is considered under some general assumptions. The resultant neutron oscillation time scale is found to vary as $M^4$, with $M$ the unification mass scale, if there exists a neutral, massive, Majorana lepton. In this case, the oscillation time scale is comparable to the proton lifetime. However, in the presence of matter or external magnetic fields, the detection of such oscillations, at the present time, seems improbable.

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Baryon number ($B$) nonconservation is a natural consequence of grand unified theories[1] of strong, weak, and electromagnetic interactions. The most spectacular process of this kind is the decay of the proton, which has been amply discussed in the literature.[2] Recently, Weinberg[3] and Wilczek and Zee[4] discussed a general method of dealing with $B$ nonconserving processes. They pointed out that such processes are governed by a local effective Lagrangian containing only ordinary particles. The Lagrangian is invariant under $\mathrm{SU}(3)_c \otimes \mathrm{SU}(2) \otimes \mathrm{U}(1)$, and has an effective coupling proportional to $M^{4-d}$, where $M$ is the unification mass and $d$ is the dimension of the operator Lagrangian. Thus they showed that the dominant $B$-nonconserving process varies as $(M^{-2})^2$ and satisfies the selection rules $\Delta B = 1$, $\Delta(B-L) = 0$, where $L$ is the lepton number.

It is straightforward to generalize their method and construct the next most important $B$-nonconserving effective Lagrangian involving only fermions, which necessarily takes the form[5]

$$\mathcal{L}_{\mathrm{eff}} \sim \epsilon_{\alpha\beta\gamma}\epsilon_{\xi\eta\sigma}[\bar{q}_\alpha{}^c q_\beta][\bar{q}_\gamma{}^c q_\xi][\bar{q}_\eta{}^c q_\sigma], \qquad (1)$$

so that $d = 9$. Thus, $\mathcal{L}_{\mathrm{eff}}$ describes a $\Delta B = 2$ process and has an effective coupling of $M^{-5}$. A particular example of such a process is the transition of a neutron ($N$) into an antineutron ($\bar{N}$). The mixing of $N$ and $\bar{N}$ arising from $\mathcal{L}_{\mathrm{eff}}(\Delta B = 2)$ can be treated in complete analogy to the $K^0$-$\bar{K}^0$ system, where the weak interaction produces a $\Delta S = 2$ effective Lagrangian which mixes $K^0$ and $\bar{K}^0$. Thus, just as the $K^0$-$\bar{K}^0$ transition generates "kaon (strangeness) oscillations", the $N$-$\bar{N}$ transition generates "neutron (baryon) oscillations". This oscillation is characterized by the period $2\pi\tau_{N\bar{N}}$, where

$$\tau_{N\bar{N}} = |(2\delta m)^{-1}|. \qquad (2)$$

Here $\delta m$ is the matrix element governing the $N\bar{N}$ mixing in the neutron mass matrix,

$$\delta m = \langle \bar{N} | -\int d^3x\, \mathcal{L}_{\mathrm{eff}}(x) | N \rangle. \qquad (3)$$

Unlike the proton decay, whose rate is second order in $\mathcal{L}_{\mathrm{eff}}(\Delta B = 1)$, the $N\bar{N}$ transition rate is linear in $\mathcal{L}_{\mathrm{eff}}(\Delta B = 2)$. It is thus conceivable that $\tau_{N\bar{N}}$ could be comparable to $\tau_p$, the proton lifetime. However, when $\mathcal{L}_{\mathrm{eff}}$ is given by an $\mathrm{SU}(3)_c \otimes \mathrm{SU}(2) \otimes \mathrm{U}(1)$-invariant six-quark local operator, dimensional arguments suggest that $\delta m \sim m_N{}^6/M^5$, where $m_N$ is the nucleon mass. This translates into $\tau_{N\bar{N}} \sim \tau_p (M/m_N)$. Such time scales are still