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TRANSVERSE-MOMENTUM PROPERTIES OF MULTI-PION SYSTEMS PRODUCED IN HIGH-ENERGY COLLISIONS*

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The results of an investigation of the correlation between the mass (M) and the transverse-momentum (p_T) of multi-pion systems produced in pp collisions at 102 GeV/c and 400 GeV/c indicate that, for fixed M, p_T distributions are only weakly dependent on the incident energy, as well as on the charge and multiplicity of the produced system. The dependence of $\langle p_T \rangle$ on M is much stronger and is similar to that measured for discrete hadronic states.

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This paper presents the results of a study of the transverse-momentum (p_T) distributions characterizing multi-pion systems produced in pp collisions at high energies.[1] The data are from previous exposures of the Fermilab 30-inch liquid hydrogen bubble chamber to protons of 102 GeV/c and 400 GeV/c.[2]

In the analysis to follow, we assign a pion-mass hypothesis to all tracks which have momenta in excess of 1.2 GeV/c in the laboratory frame. Below that momentum, bubble density provides an estimate of ionization which may be used to distinguish a proton from a pion. The arbitrary assignment of a pion-mass to charged tracks of higher momentum causes an estimated proton contamination of the π^+ spectra at about the 10% level.[2] It has been previously estimated that an additional 1% e^+ and 10% K^+ contamination exists in the π^+ tracks, and a 1% e^-, 7% K^- and 2% $\bar{p}$ contamination in the π^- tracks.[2] To further minimize fast-proton contamination of the π^+ sample, we have rejected from consideration all positively charged tracks with momenta in excess of 60 GeV/c and 240 GeV/c for 102 GeV/c and 400 GeV/c incident momenta, respectively. In addition, to reduce the effect of track-measurement and curvature errors, we have imposed the requirement that all individual tracks have $p_T < 1.5$ GeV/c.

In this analysis we studied the properties of all possible charge (Q) combinations of two, three, four, five and six-pion systems. Specifically, we have examined the following multi-pion production reactions:

$$pp \to \pi^+\pi^- + \text{Anything} \quad (Q = 0)$$
$$pp \to \pi^\pm\pi^\pm + \text{Anything} \quad (Q = \pm 2) \qquad (1)$$

$$pp \to 2\pi^\pm\pi^\mp + \text{Anything} \quad (Q = \pm 1)$$
$$pp \to 3\pi^\pm + \text{Anything} \quad (Q = \pm 3) \qquad (2)$$

$pp \to 2\pi^+2\pi^-$ + Anything	$(Q = 0)$		
$pp \to 3\pi^{\pm}\pi^{\mp}$ + Anything	$(Q = \pm 2)$	(3)	
$pp \to 4\pi^{\pm}$ + Anything	$(Q = \pm 4)$		

$pp \to 3\pi^{\pm}2\pi^{\mp}$ + Anything	$(Q = \pm 1)$	
$pp \to 4\pi^{\pm}\pi^{\mp}$ + Anything	$(Q = \pm 3)$	(4)
$pp \to 5\pi^{\pm}$ + Anything	$(Q = \pm 5)$	

$pp \to 3\pi^{\pm}3\pi^{\mp}$ + Anything	$(Q = 0)$	
$pp \to 4\pi^{\pm}2\pi^{\mp}$ + Anything	$(Q = \pm 2)$	
$pp \to 5\pi^{\pm}\pi^{\mp}$ + Anything	$(Q = \pm 4)$	(5)
$pp \to 6\pi^{\pm}$ + Anything	$(Q = \pm 6)$	

The mass spectra characterizing the multi-pion state for Reactions (1) through (5) at 400 GeV/c are displayed in Figs. 1 through 5, respectively.[3] For each multiplicity, the distributions have been normalized to the same area. Typical statistical error bars are shown on several data points to help evaluate trends in the data. The data, in general, peak at small values of M, but do not exhibit significant narrow structure. There is a clear dependence on the charge of the produced multi-pion system, in that distributions for large $|Q|$ are shifted to lower values of M relative to data for small $|Q|$.[4] (The spectra at 102 GeV/c are similar to those displayed in Figs. 1-5, except that the mean values of M are about 25% smaller and the distributions are not as wide as at 400 GeV/c.) The smooth curves in the figures, labeled Monte Carlo, will be discussed shortly.

The shapes of p_T spectra for multi-pion states produced in Reactions (1)-(5) at 400 GeV/c are displayed in Figs. 6-9.[3] All distributions

appear to drop at small p_T values and fall off exponentially for $p_T \gtrsim 1$ GeV/c. Figures 6 and 7 display the dependence of p_T spectra on the charge of produced multi-pion systems; the data are for the representative fixed mass intervals 1.0 GeV to 1.3 GeV for Reactions (2), and 2.9 GeV to 3.3 GeV for Reactions (5). The distributions do not exhibit any significant dependence on the charge of the multi-pion system.

Figure 8 presents the dependence of the p_T distributions on the multiplicity (n) of the produced multi-pion systems. The data are all for the mass interval between 1.2 GeV and 1.6 GeV, for 2π, 4π and 6π doubly charged states ($|Q|=2$). The p_T spectra appear to have a very weak but systematic variation with multiplicity. This will be displayed more clearly later in this paper.

Thus far we have noted that, at fixed mass, p_T spectra are only weakly dependent on the charge and multiplicity of produced multi-pion states. In Fig. 9 we display the variation of p_T spectra with mass in Reactions (1)-(5). The data have been summed over charge states and displayed for 0.2 GeV-wide mass intervals centered at the peaks of the M-distributions given in Figs. 1-5. We see from Fig. 9 that, although the peak of the p_T spectrum shifts with increasing mass, the fall-off at large p_T can be characterized by an universal dependence of the form $\exp(-3p_T)$. (Our experimentally motivated cut off at p_T=1.5 GeV/c on individual tracks is expected to affect the fall off only in the lowest-multiplicity data, particularly for $p_T \gtrsim 2$ GeV/c.) As an aside, it is interesting to note that the peak-values of the M distributions increase linearly with the charge multiplicity n.

It is well known that transverse momentum distributions of particles produced in high-energy collisions change very slowly with increasing energy.[5] It is therefore not surprising that the p_T spectra for

Reactions (1)-(5) do not change markedly between 102 GeV/c and 400 GeV/c. The kind of differences observed are typified by the results presented in Fig. 10. Here we provide a comparison between 102 GeV/c and 400 GeV/c data. The distributions are for 1.2 GeV<M<1.6 GeV, Q=0 2π data, and for 2.9 GeV < M < 3.3 GeV, Q= 0 6π data, in (a) and (b), respectively. The shapes of distributions at the two energies agree for $p_T \lesssim 1.2$ GeV/c. Above 1.2 GeV/c the p_T spectra at 400 GeV/c, particularly for the 6π events, do not fall off as rapidly as the 102 GeV/c data. This difference may be attributed to the known increase, with incident energy, of the inclusive pion cross section at large p_T.[5]

Figure 11 summarizes the variation of the average value of the transverse momentum ($\langle p_T \rangle$), for multi-pion systems produced at 400 GeV/c, with multiplicity and mass of the systems. (The data have been summed over charge.) The substantial increase of $\langle p_T \rangle$ with increasing mass reflects the results given previously in Fig. 9.[6] There is very little difference observed in $\langle p_T \rangle$ for different multiplicities at $M \leq 2$ GeV; it appears, however, that at these small mass values $\langle p_T \rangle$ decreases somewhat with increasing n. For M>2 GeV the variation of $\langle p_T \rangle$ with mass is weak, but the dependence on multiplicity far more pronounced. Several of the data points, especially for large n and large M, depart from a smooth trend in the dependence of $\langle p_T \rangle$ on M. This may be due to the fact that the error bars for large n are not realistic because we have ignored combinational correlations among tracks in assigning statistical errors to the individual points.

We have also studied, for fixed M, the variation of $\langle p_T \rangle$ with the Feynman x of the multi-pion system. There is a weak dependence of $\langle p_T \rangle$ on x, not unlike the kind observed for inclusive single-pion production data.[2] Figure 12 displays the typical variation of $\langle p_T \rangle$ with x for Reactions (2) and (3). For comparison we present the data

on π^- production at 400 GeV/c.[2]

Table I summarizes the results of a calculation of $\langle p_T \rangle$ values as a function of multiplicity using a Monte Carlo model. This model, which has been discussed previously in the literature[7], contains the single-particle inclusive and semi-inclusive distributions and charge multiplicities observed in the 400 GeV/c pp data, but no explicit correlations among kinematic variables or among produced particles. Mass distributions for Reactions (1)-(5) using the Monte Carlo calculation are indicated by the smooth curves shown in Figs. (1)-(5). The model provides a weak dependence of $\langle p_T \rangle$ on M (essentially no dependence on Q); this is displayed in the smooth curves shown in Fig. 11. Also, as can be seen from the entries in Table I, the $\langle p_T \rangle$ values, integrated over mass, scale with multiplicity approximately in the manner of a random walk, namely as $\sqrt{n}$. As mentioned before, the data in Fig. 11 for $M \lesssim 2$ GeV display essentially no dependence on multiplicity, and this implies that dynamic correlations among particles are so strong as to completely mask this kind of random behavior. At large values of M, however, there is some evidence of a growth of $\langle p_T \rangle$ with increasing n similar to that expected for a random addition of n independent p_T values. In fact, it appears that the mass regime in which random behavior dominates is a strong function of multiplicity. For two-pion data the region of dominantly random correlation appears to be M > 1.5 GeV, while for four-pion data this cut off is at $M \sim 2.5$ GeV.

Finally, in Fig. 11 we have included measured $\langle p_T \rangle$ values for elementary particles produced in pp collisions.[8] We note that the $\langle p_T \rangle$ values of elementary particles coincide with the data for $M \lesssim 1$ GeV (this is the region where dynamic correlations appear to be important). The recently measured $\langle p_T \rangle$ value for J/ψ production is ∿25% higher than expected, for example, from Reaction (2) at M ≈ 3 GeV.[9]

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References

1. Preliminary findings from this study and from an investigation of the variation of the x-distribution with mass have been reported by T. Ferbel, in Hadron Physics at Fermilab (UR-521), to appear in Proc. of the International School of Subnuclear Physics, Erice-1976, A. Zichichi ed. For related work see U. Becker, Phys. Rev. Letters 38, 140 (1977).

2. C. Bromberg et al., Nucl. Phys. B107, 82 (1976).

3. The mass spectra having charge +Q differ somewhat from spectra having charge −Q; however, the dependence of p_T on M (to be discussed later) is the same to several percent accuracy for the +Q and −Q data. Consequently, in this paper we will not distinguish between data of opposite charge, unless such differences are significant. We attribute the small discrepancies which depend on the sign of Q, partially, to proton contamination of the positively charged tracks.

4. This is similar to the Bose-Einstein-like effects observed in $\bar{p}p$ annihilations. See, for example, N-H. Xuong, UCLA-10129 (1962).

5. See, for example, T. Ferbel in Proc. of International Symposium on High Energy Physics, Tokyo 1973, Y. Hara et al. eds.; also see A. M. Rossi et al., Nucl. Phys. B84, 269 (1975). For the variation of the pion cross section with energy at large p_T see, for example, J. Cronin, Proc. Int. School of Subnuclear Physics, Erice, 1975, ed. A. Zichichi.

6. We speculate that this phenomenon is related to the observed properties of unstable multi-particle systems which are produced coherently in nuclear material. It is known that the extracted absorption cross sections which reflect the production p_T distribution, decrease as the masses of the produced systems become large.

This effect appears to be independent of multiplicity. Compare, for example, R. M. Edelstein et al., Phys. Rev. Letts. 38, 185 (1977) with W. Mollet et al., Bull. Am. Phys. Soc. 22-1, 22 (1977). We also suggest that the difference found between 3π and 5π coherent production in π-nuclear data is due to the mass difference rather than the multiplicity per se of the produced system. See C. Bemporad et al., Nucl. Phys. B33, 397 (1971) and P. Mühlemann et al., Nucl. Phys. B59, 109 (1973). See also G. Kane, Acta Phys. Pol. B3, 845 (1972) for theoretical ramification of the correlation between M and p_T.

7. C. Bromberg et al., Phys. Rev. D10, 3100 (1974).

8. See ref. 5 and J. Chapman et al., Physics Letters 47B, 465 (1973), and K. Böckman, BONN-HE-76-25 (1976).

9. K. J. Anderson et al., Phys. Rev. Letts. 37, 799 (1976); A. J.S. Smith, Proc. of International School of Subnuclear Physics, Etore Majorana-1976, A. Zichichi ed. The fact that the value of $\langle p_T \rangle$ for J/ψ appears to lie above the 6π data leads us to speculate that the $\langle p_T \rangle$ values for elementary particles follow the upper-most set of points when all multiplicities (including those greater than six) are included in Fig. 11. The data in this upper-most set of points consist of multiparticle systems having relatively low mass, and therefore of events with particles located within a narrow rapidity gap; such events would be expected to exhibit strong dynamic correlations among the produced particles. The $\langle p_T \rangle$ for elementary particles can be approximated by $\langle p_T \rangle = \frac{2}{9} M + \frac{1}{3}$.

Figure Captions.

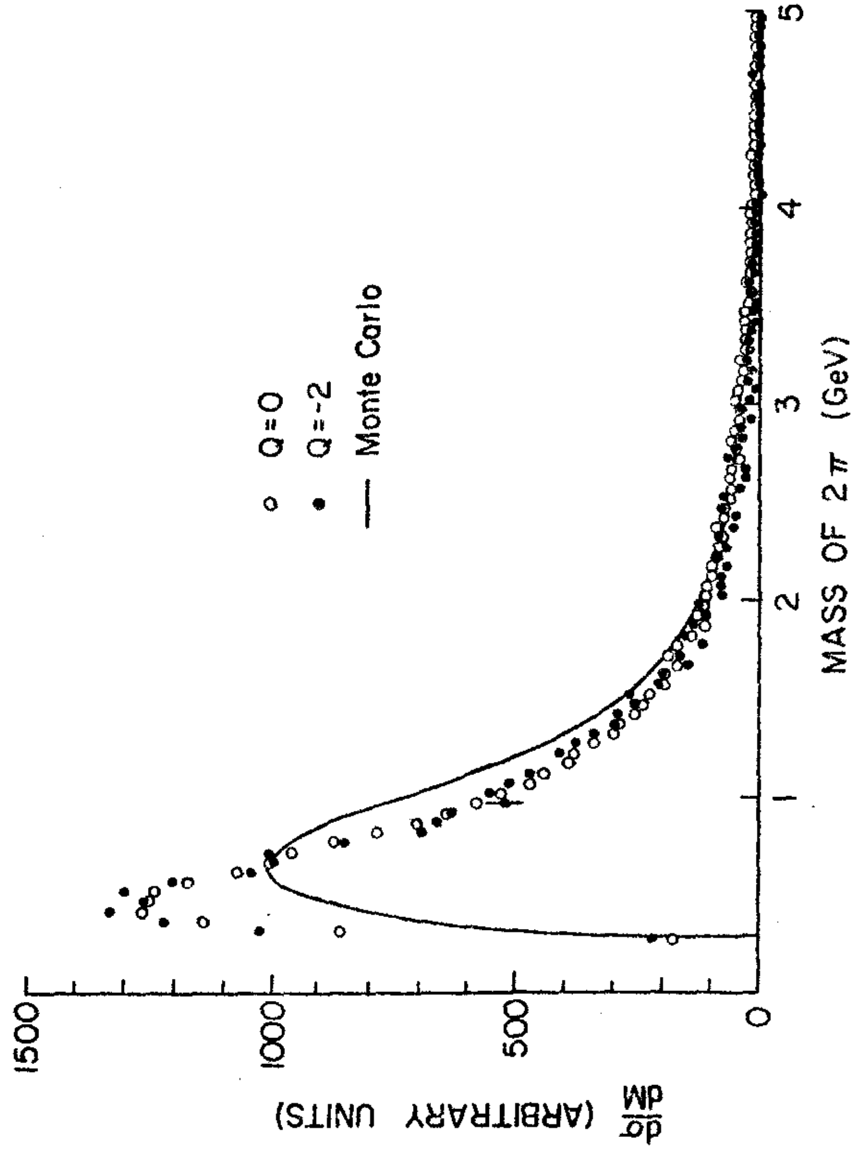
1. Mass distributions for two pions having charge Q=0 and Q=-2. The smooth curve is a Monte Carlo prediction for the mass spectra of Reactions (1).
2. Mass distributions for three pions having charge Q=-1 and Q=-3. The smooth curve is a Monte Carlo prediction for the mass spectra of Reactions (2).
3. Mass distributions for four pions having charge Q=0, Q=-2 and Q=-4. The smooth curve is a Monte Carlo prediction for the mass spectra of Reactions (3).
4. Mass distributions for five pions having charge Q=-1, Q=-3 and Q=-4. The smooth curve is a Monte Carlo prediction for the mass spectra of Reactions (4).
5. Mass distributions for six pions having charge Q=0, Q=-2, Q=-4 and Q=-6. The smooth curve is a Monte Carlo prediction for the mass spectra of Reactions (5).
6. Transverse-momentum distributions of three-pion systems having mass between 1.0 GeV and 1.3 GeV separated according to $|Q|$.
7. Transverse-momentum distributions of six-pion systems having mass between 2.9 GeV and 3.3 GeV separated according to $|Q|$.
8. Transverse-momentum distributions of doubly charged multi-pion systems of mass between 1.2 GeV and 1.6 GeV.
9. Transverse-momentum distributions of multi-pion systems in Reactions (1) through (5) for events with masses at the peaks of the distributions in Figs. (1) through (5).
10. Comparison of Q=0 102 GeV/c data with 400 GeV/c data. The distributions in (a) are for two-pion systems in the mass interval between 1.2 GeV and 1.6 GeV, and in (b) for six-pion systems having mass between 2.9 GeV and 3.3 GeV.

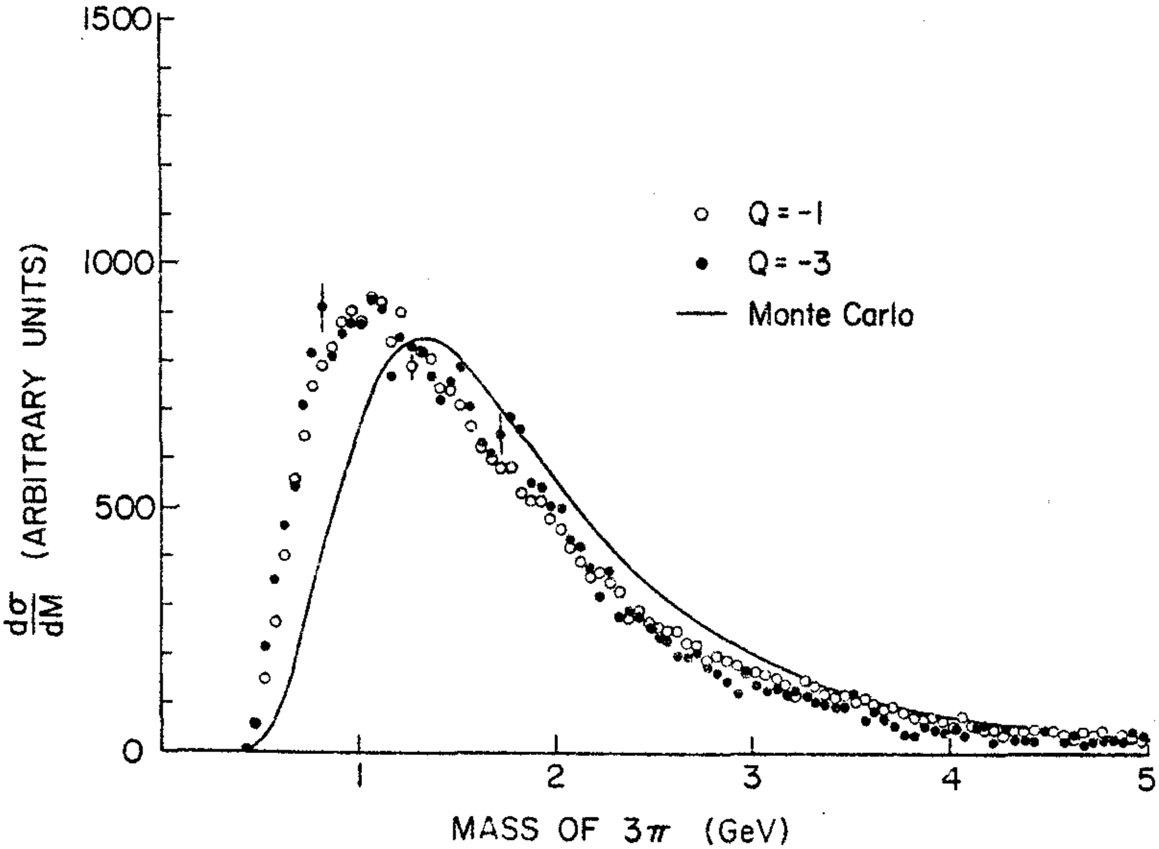
11. The values of $\langle p_T \rangle$ as a function of mass and multiplicity of the produced multi-pion systems. Smooth curves are results of a Monte Carlo calculation for inclusive two-pion and six-pion production. Values of $\langle p_T \rangle$ for known hadrons are indicated on the graph. The size of the letters representing the hadrons reflects the estimated errors on $\langle p_T \rangle$ for these particles.
12. The dependence of $\langle p_T \rangle$ on x.

Table I

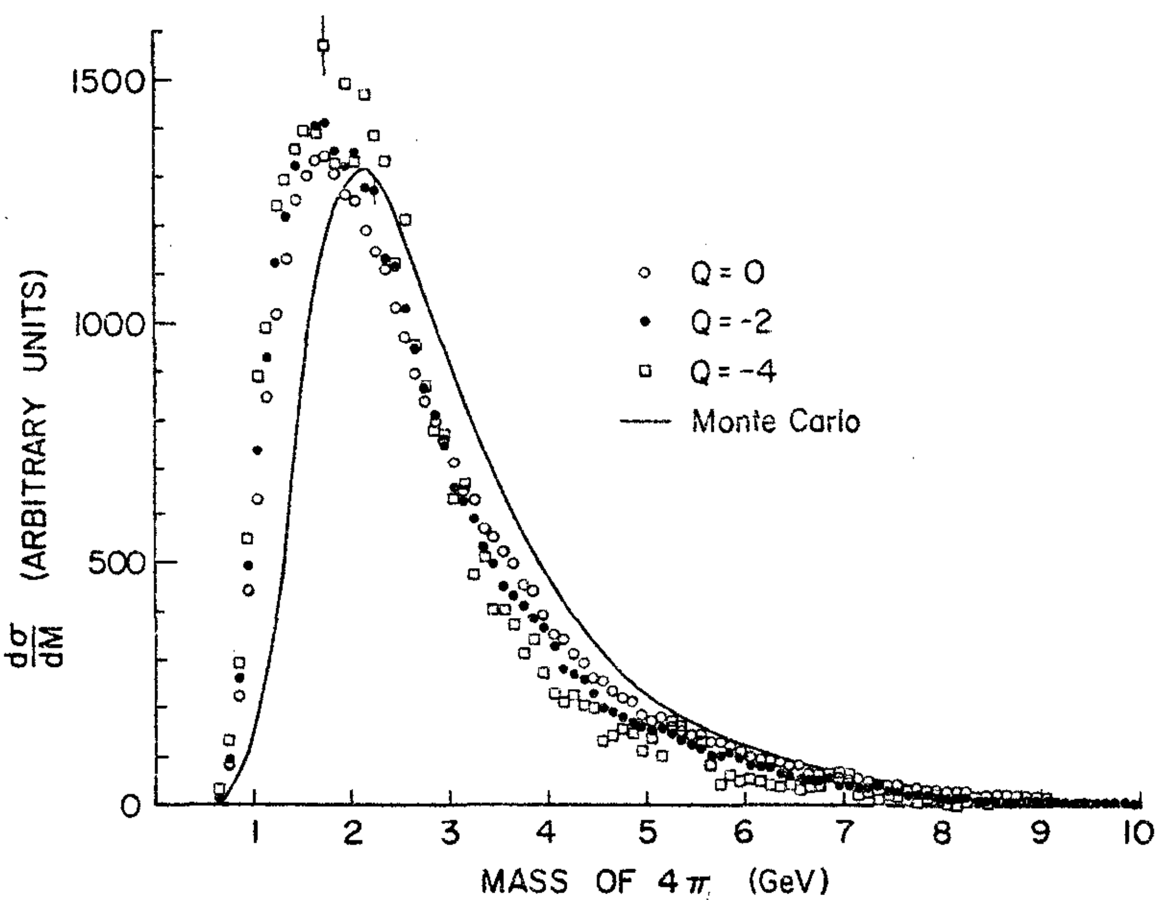
Monte-Carlo calculation of $\langle p_T \rangle$ as a function of inclusive multiplicity for multi-pion systems produced at 400 GeV/c.

Reaction	$\langle p_T \rangle$ (GeV/c)
1	0.58
2	0.70
3	0.79
4	0.87
5	0.91

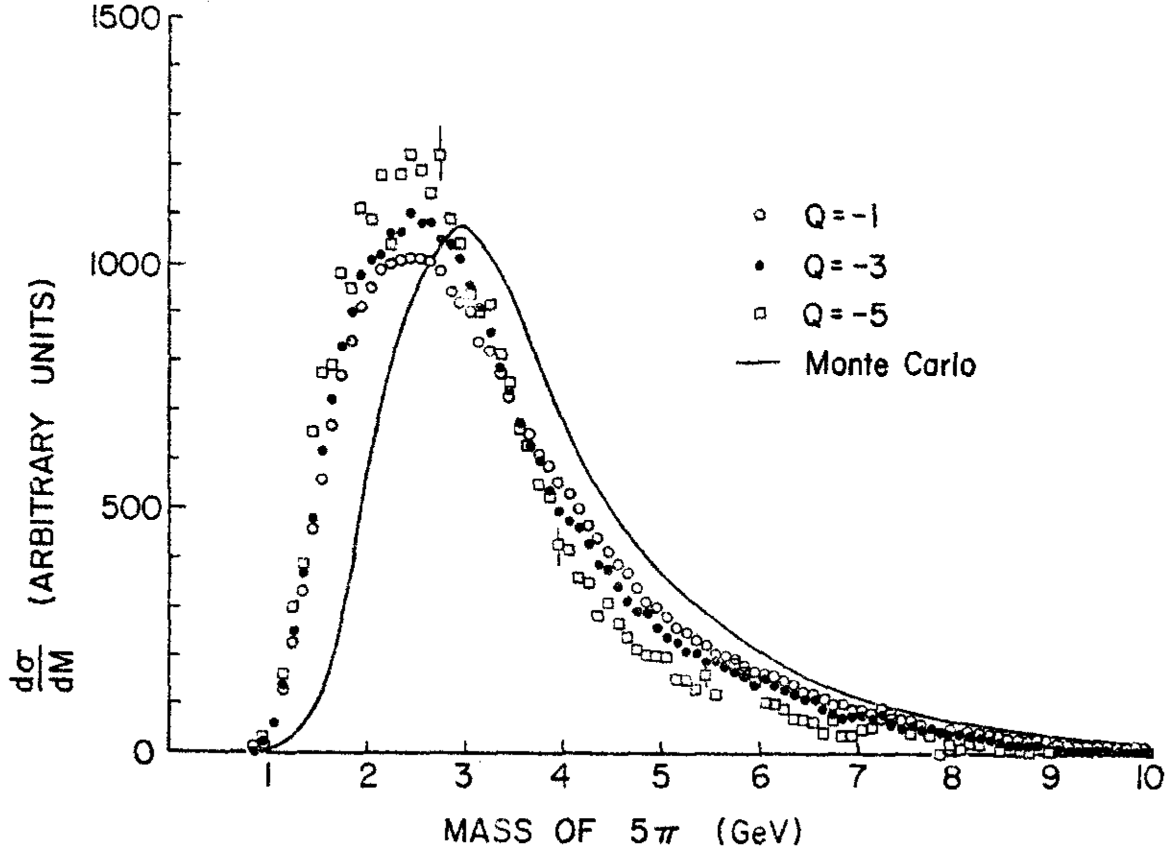



1500
1000
500
0
dσ/dM (ARBITRARY UNITS)
Q = -1
Q = -3
Monte Carlo
1
2
3
4
5
MASS OF 3π (GeV)

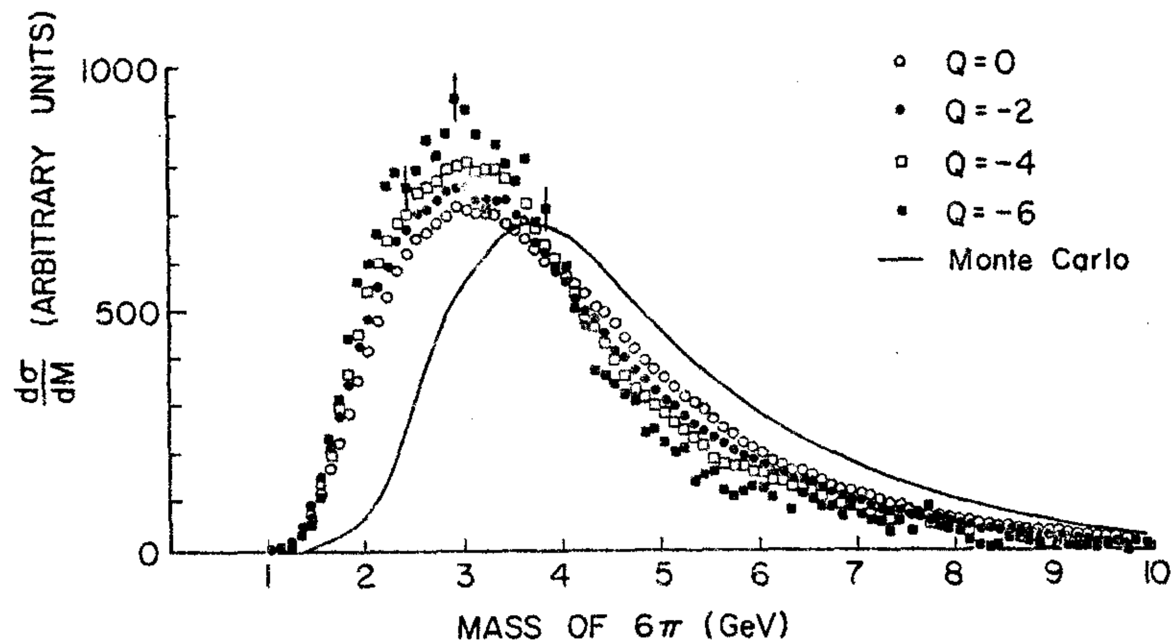
2


1500
1000
500
0
dσ/dM (ARBITRARY UNITS)
Q = 0
Q = -2
Q = -4
Monte Carlo
1
2
3
4
5
6
7
8
9
10
MASS OF 4π (GeV)

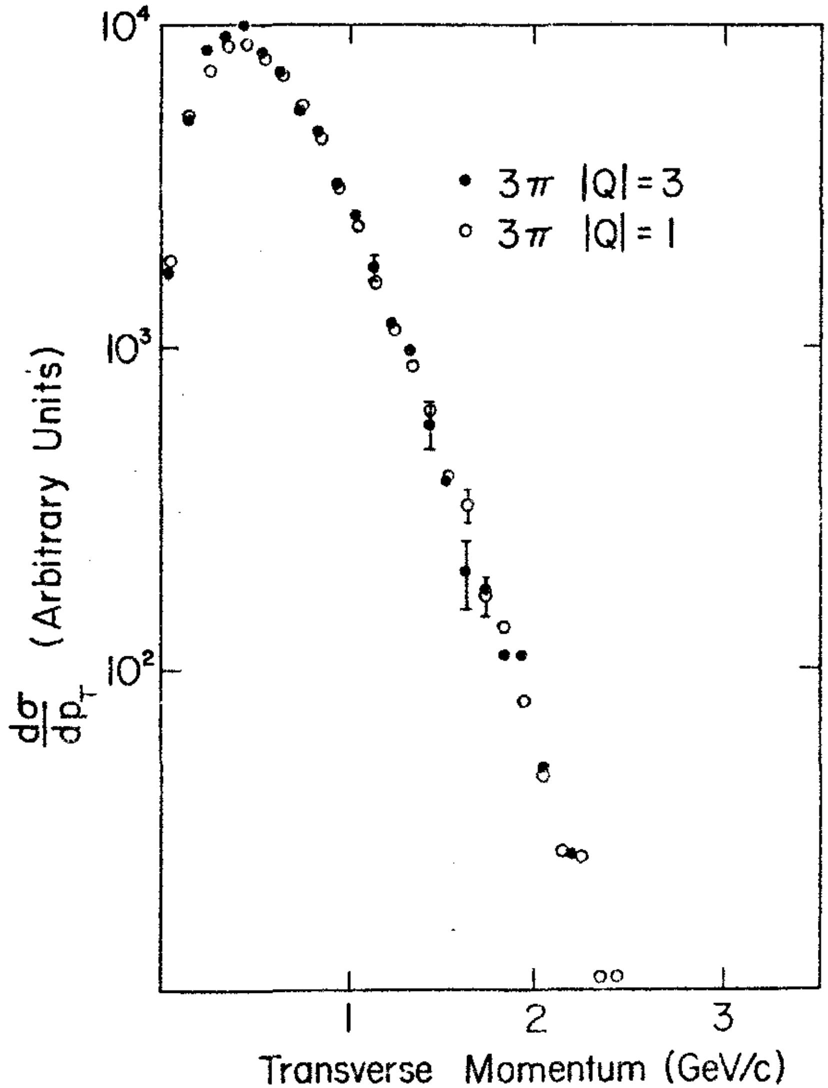
3


1500
1000
500
0
1
2
3
4
5
6
7
8
9
10
$\frac{d\sigma}{dM}$ (ARBITRARY UNITS)
MASS OF 5π (GeV)
Q = -1
Q = -3
Q = -5
Monte Carlo

4

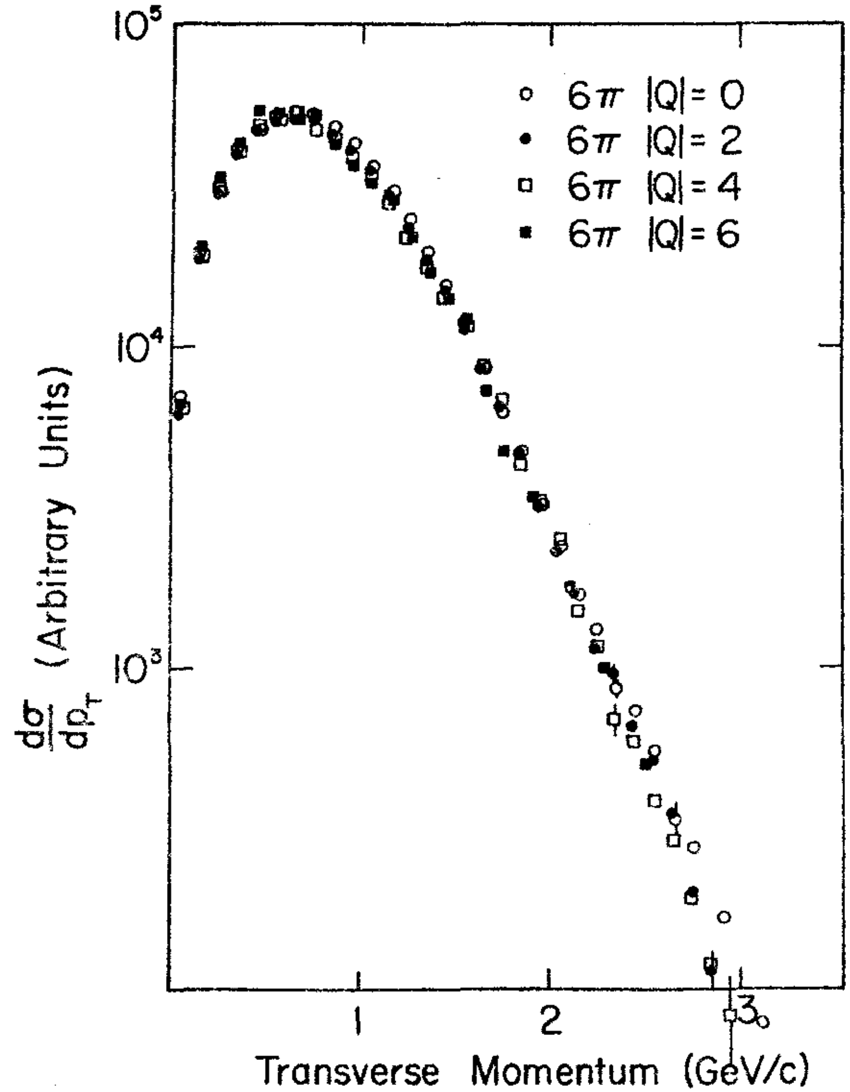

1000
500
0
1
2
3
4
5
6
7
8
9
10
$\frac{d\sigma}{dM}$ (ARBITRARY UNITS)
MASS OF 6π (GeV)
Q = 0
Q = -2
Q = -4
Q = -6
Monte Carlo

5



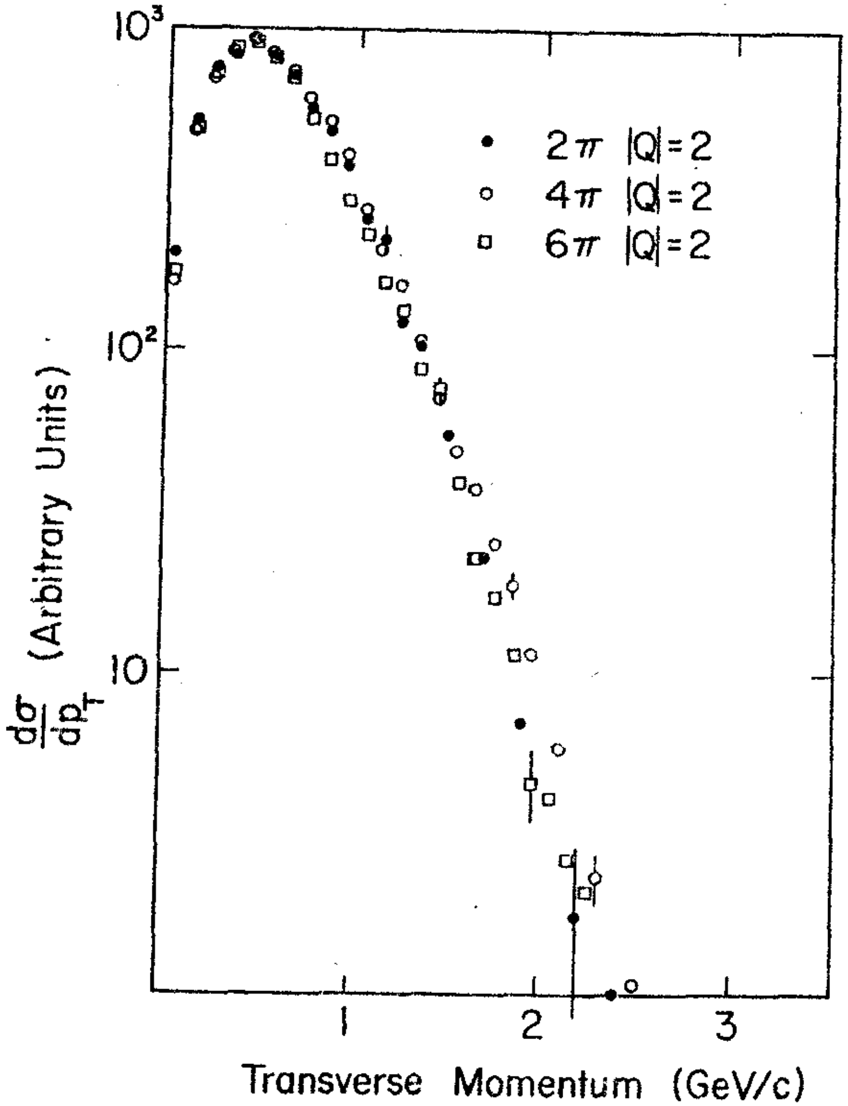
10^4
10^3
10^2
$\frac{d\sigma}{dp_T}$ (Arbitrary Units)
• 3π $|Q|=3$
○ 3π $|Q|=1$
1
2
3
Transverse Momentum (GeV/c)

6



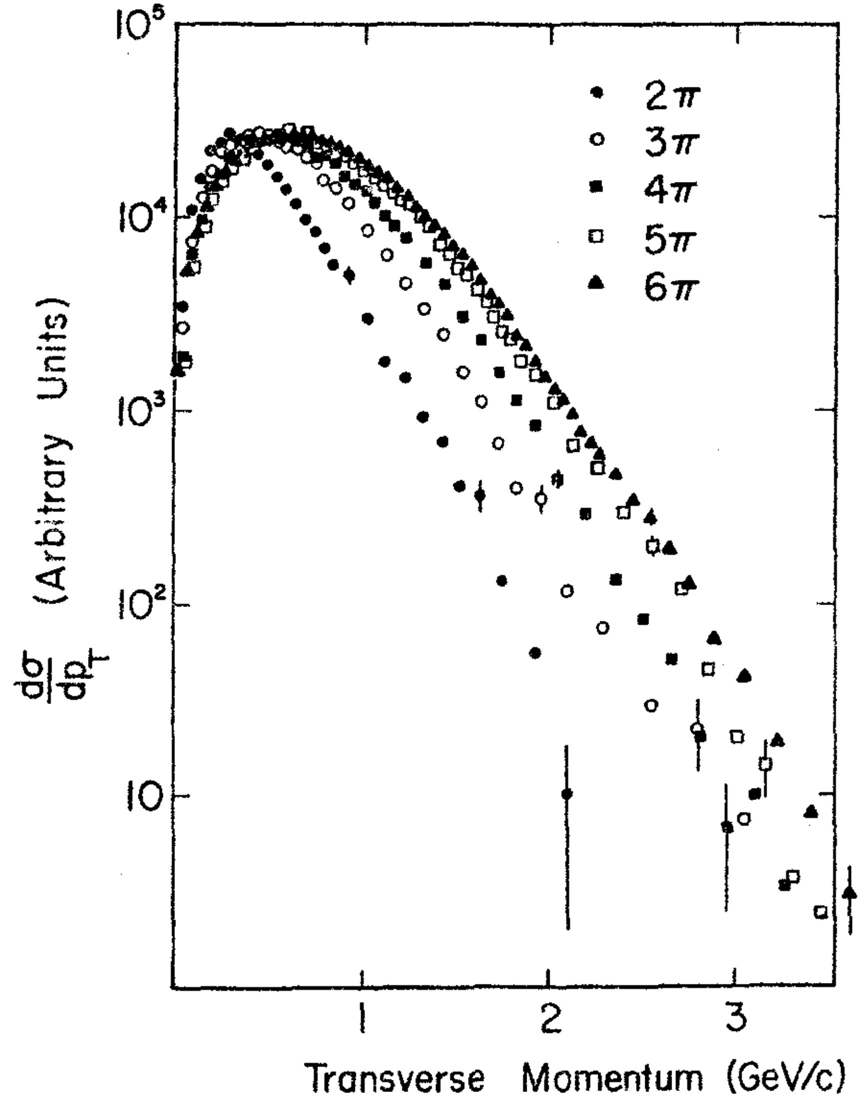
10^5
10^4
10^3
$\frac{d\sigma}{dp_T}$ (Arbitrary Units)
○ 6π $|Q|=0$
• 6π $|Q|=2$
□ 6π $|Q|=4$
■ 6π $|Q|=6$
1
2
3
Transverse Momentum (GeV/c)

7



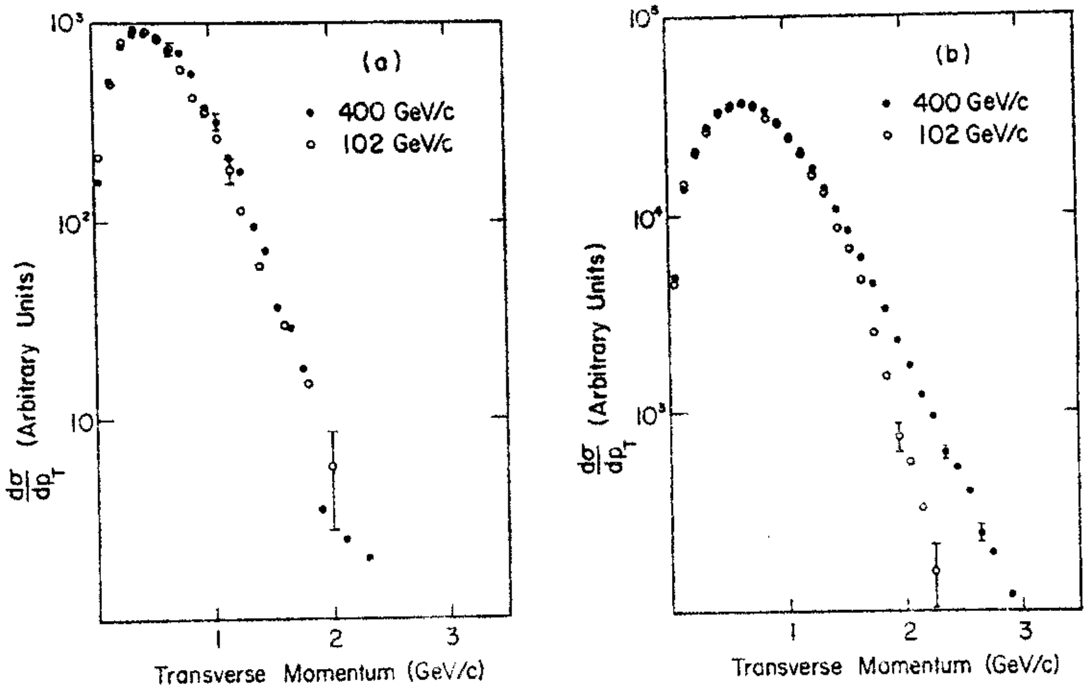
10³
10²
10
dσ/dp_T (Arbitrary Units)
2π |Q|=2
4π |Q|=2
6π |Q|=2
1
2
3
Transverse Momentum (GeV/c)

8



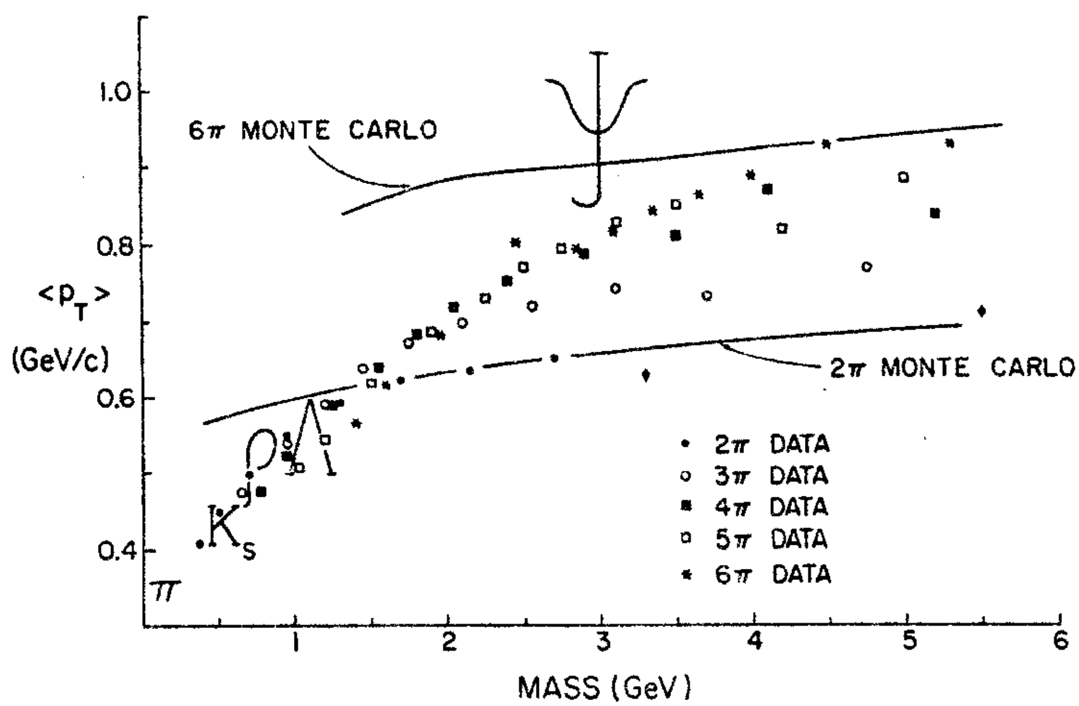
10⁵
10⁴
10³
10²
10
dσ/dp_T (Arbitrary Units)
2π
3π
4π
5π
6π
1
2
3
Transverse Momentum (GeV/c)

9



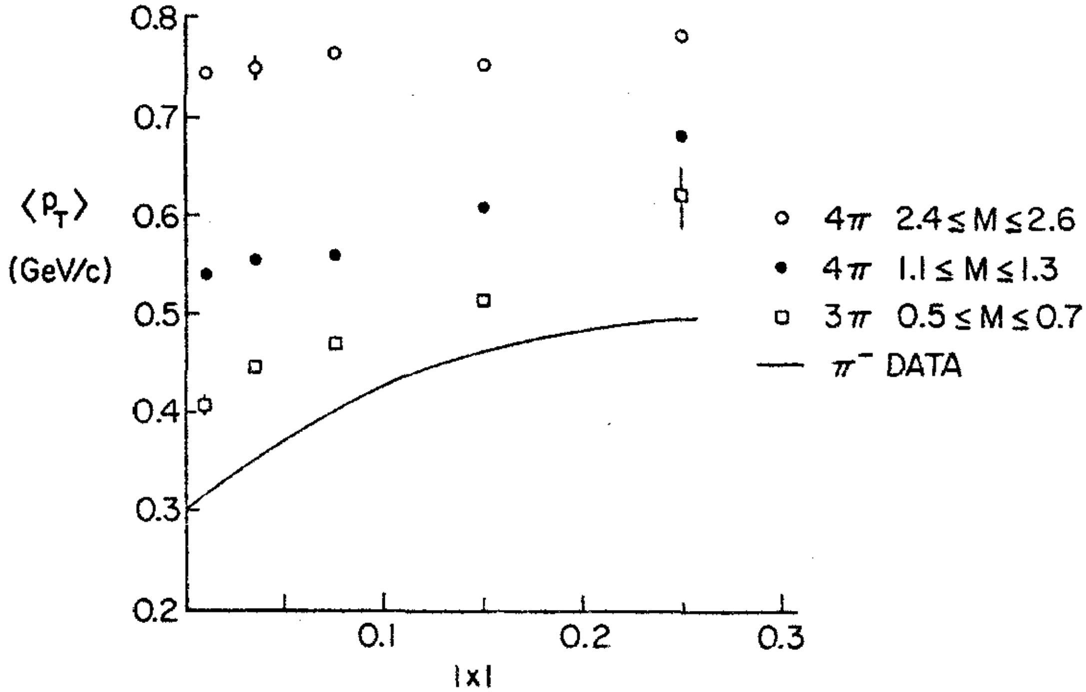
(a)
400 GeV/c
102 GeV/c
dσ/dp_T (Arbitrary Units)
Transverse Momentum (GeV/c)
(b)
400 GeV/c
102 GeV/c
dσ/dp_T (Arbitrary Units)
Transverse Momentum (GeV/c)

10



6π MONTE CARLO
2π MONTE CARLO
<p_T>
(GeV/c)
2π DATA
3π DATA
4π DATA
5π DATA
6π DATA
MASS (GeV)

11


0.8
0.7
0.6
0.5
0.4
0.3
0.2
⟨p_T⟩
(GeV/c)
0.1
0.2
0.3
|x|
4π 2.4 ≤ M ≤ 2.6
4π 1.1 ≤ M ≤ 1.3
3π 0.5 ≤ M ≤ 0.7
π^- DATA