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INCLUSIVE PION PRODUCTION IN RELATIVISTIC PROTON COLLISIONS WITH NUCLEI, A REEXAMINATION[*]

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ABSTRACT

Various data for the $pA \to \pi^{\pm}X$ reaction are examined with emphasis on viewing these data in a light most useful for understanding π production in heavy ion collisions. The 730 MeV(proton energy) results of Cochrane et al. are found to display a large amount of scaling - if plotted as a function of the Feynman variable x_R and if the $k_\perp$ behavior is removed. Viewed in this matter, the larger x_R behavior of the 730 MeV data agree well with the 1-5 GeV data of Papp et al. In the forward hemisphere, π production from nuclei appears simply related to nucleon-nucleon π production and is consistent with the limiting behavior of hard collision models. In the backward hemisphere, there is evidence for nuclear structure effects and clustering phenomena not included in hard collision models.

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[+] On leave from Oregon State University.

Key Words

Nuclear Reactions inclusive pion production, E=730 MeV- 5 GeV protons, Feynman variable.

Introduction

The production of pions in relativistic heavy ion collisions is currently being measured in part with the hope that pions may signal the formation of abnormal nuclear matter. These experiments(1,2), which provide inclusive pion spectra for both forward and backward hemispheres, reveal unexplained trends which may provide clues to the reaction mechanism or to some interesting new physics.(1-3) Unfortunately, there do not exist equally complete data on the inclusive π production by protons on nuclei(4) - except at one energy.(5) In this paper we reexamine these proton-nucleus π production data of Cochrane et al.(5) in an effort to provide a comparison and foundation for understanding π production in heavy ion collisions. Already the work of Refs. (1) and (2) have shown the high value of these elementary data.

A prior analysis of the 730 MeV data of Ref. (5) has been published by Sternheim and Silbar,(6) based on a semiclassical, quasi-geometrical approach in which the incoming proton and produced pion have straight line trajectories influenced by absorption, charge exchange and scattering.(7) Experimental pp pion production cross sections, supplemented by the isobar model, provided the elementary input. Within that model it is possible to obtain qualitative agreement with the data by fitting the magnitudes and energy dependences of the p and π absorption cross sections. Considering the approximations and uncertainties in a model of this sort, it appears to us that only a very general understanding of the reaction could be obtained, with no one aspect of the process being isolated.

A strikingly different way of viewing proton-nucleus inclusive π production, which may be particularly fruitful in examining the high momentum tail of the spectrum, is provided by Papp et al.$^{(8)}$ They find that the Lorentz invariant pion production cross section, $\frac{E}{k^2}\frac{d^2\sigma}{d\Omega dk}$, for 1-5 GeV incident proton energies all fall (approximately) on the same universal curve - when plotted as a function of the Feynman scaling variable $x_R = k_\pi^{cm}/(k_\pi^{cm})_{max}$. Although one would not expect scaling to hold at such low energies (based on its theoretical derivation$^{(9)}$ - that is), its empirical existence is welcome since this provides us with a simple tool to parameterize the p-nucleus data for use in nucleus-nucleus interactions.

Comparison of 730 MeV and 1-5 GeV Data

If scaling seems to work at 1 GeV, it is natural to query if the 730 MeV data also contain some simple behavior. To examine just the x_R dependence of the data, we have determined and then removed the $k_\perp$ ($k \sin\theta$) behavior with a method described in the next paragraph (this is important since the data of Ref. (5) cover large angles). A partial comparison of the 730 MeV $pC \to \pi^- X$ data of Cochrane et al.$^{(5)}$ with the 1.05 and 4.8 GeV data of Papp et al.$^{(8)}$ is shown in Fig. 1. For $x_R \gtrsim 0.4$ the 730 MeV data fall quite close to the 1-5 GeV data, with the 1 GeV and 730 MeV data within $\sim 20\%$ of each other. The higher energy data do not agree well with the 730 MeV data for smaller x values; this is reasonable since scaling is not expected to hold for small x.$^{(9)}$ In making this comparison we have used the radial scaling variable,

$$x_R = k_\pi^{cm}/(k_\pi^{cm})_{max} \qquad , \qquad (1)$$

with k_π^{cm} evaluated in the p-nucleus (A) c.m., and with $(k_\pi^{cm})_{max}$ occurring when the π recoils against $A+1$ nucleons. Note too that removal of the $k_\perp$ variation of the cross sections improves the scaling behavior.

Angular and $k_\perp$ Dependence

We separate off the x and $k_\perp$ dependence of the doubly differential cross sections by examining them with a two dimensional bicubic spline interpolation routine for either constant $k_\perp$ or constant x_R (or equivalently c.m. energy). Since to our knowledge these data have not been presented in this way before, the results of this interpolation are rather illuminating. For example, in Fig. 2A we present the interpolated (and slightly smoothed) invariant cross section $\frac{E}{k^2}\frac{d^2\sigma}{d\Omega dk}$ vs. $\theta_{cm}(pC)$ for the $pC \to \pi^- X$ reactions at several pion energies. The π^+ cross sections for production from C are almost identical in shape but a factor ~5 times larger. Viewed in the c.m. systems, very similar results (isotropy at low energies, forward peaking at high energies) are obtained for heavier nuclei; e.g. in Fig. 2B we display production from Pb.

The similarity in shape for inclusive π production from such different size nuclei indicates the absence of "diffractive" (but not necessarily multiple scattering) effects which would give additional structure for Pb. In fact, these angular dependences are so uniform in most cases that they can all be fit fairly well with a function of the form(10) $\exp[-r_2 k_\perp^2]$ or $\exp[-r_3 k_\perp^3]$, with $k_\perp = k_\pi^{cm} \sin\theta_{cm}$. The values of r_2 and r_3 for C and Pb are given in Table I and typical fits to interpolated points are given in Fig. 3. Again we see there is little effect in r_2 or r_3 due to nuclear size (the r_2 dependence reflects a nuclear fireball of ~110 MeV temperature).

Nagamiya et al.(1) have suggested that a clue to the reaction mechanism for the type of processes considered here is obtained by examining the cross sections in the proton-target nucleon c.m. (assuming "frozen" nucleons e.g.) and comparing these to the elementary proton-proton π production cross sections. To this end we display in Fig. 4 the actual $pp \rightarrow \pi^+X$ invariant cross section data of Cochrane et al.(5) at several pion energies, transformed to the pp c.m. For comparison, in Figs. 5A and B we show the $pC \rightarrow \pi^+ X$ and $pPb \rightarrow \pi^- X$ cross sections of Ref. (5) transformed to the pp c.m. We see in Fig. 4 that the actual pp data show only moderate angular dependence (compared to Figs. 2 and 5) with a maximum asymmetry of ~2 at $T_\pi \simeq 100$ MeV reflecting the P_{33} resonance. The p-nucleus data, on the other hand, are similar to the pp data for $\theta < 90°$, but develop a strong backward peak at $T_\pi \simeq 100$ MeV- when viewed in this pp reference frame.

Mathematically, we can understand the backward peaking at high energies as just a reflection of the large cross section for low energy pions at backward angles present in the p-A c.m. (Fig. 2) which get transformed to high energies when viewed in the pp c.m. Physically, a comparison of Figs. 4 and 5 indicates that the forward angle data can be simply represented as some type of convoluted $pN \rightarrow \pi X$ cross sections,(1) but that there is some different mechanism which produces high energy backward pions. A possibility would be proton scattering from a cluster, i.e. coherently from several nucleons.(11) As we discuss in the next paragraph, further examination of the scaling behavior of these data also implies a multi-nucleon effect. In making these deductions we are primarily concerned with the shapes of the cross sections; a more detailed understanding of the A dependences and of the magnitudes would require multiple scattering, absorption and charge exchange effects.(6)

x_R Dependence and Interpretation

In Fig. 1 we have seen that for $x_R \gtrsim 0.4$ the forward angle inclusive π production data scale. Further examination of the 730 MeV data also shows that the x_R dependence of these data can be parameterized as $(1-x_R)^H$, with different values of H for scattering into the forward and backward hemispheres. Fitted values of H for 730 MeV protons on C and Pb are given in Table I. The data points of Ref. (5) with the $k_\perp$ dependence removed are shown in Figs. 6A and B for pions with $\theta_{cm} < 90°$, and in Figs. 7A and B for pions with $\theta_{cm} > 90°$. The solid curves in Fig. 6 represent our average fit, which including the $k_\perp$ dependence is of the form:

$$\frac{E}{k^2}\,\frac{d^2\sigma}{d\Omega dk} = E(s)(1-x_R)^H \exp[-r_n k_\perp^n] \quad . \tag{2}$$

Schmidt and Blankenbecker(9) (SB) have taken the relativistic hard collision model which describes elementary particle reactions in terms of partons and extended it to describe the relativistic collisions of nuclei. In the high energy limit, this theory predicts cross sections of the form (2). Essentially, this theory is a single scattering, impulse approximation picture with neither initial nor final state interactions, but with a relativistic distribution function valid for very large internal nucleon momenta. In addition, the theory contains "counting rules" which simply relate the H in (2) to different models of the N-N force and to the number of nucleons in the nucleus. In particular, part of the power law in (2) follows from the very large momentum transfers q involved in high energy π production being shared equally amongst all the nucleons in the nucleus.(12)

In this simple picture of the $pA \rightarrow \pi X$ reaction, the forward angle pions come from proton "fragmentation" whereas the backward angle pions come from target fragmentation. In the former case the cross section should not depend upon the specific target distribution function and would therefore be the same for different NN forces and different nuclei. Indeed, in the Cochrane et al. data(5) for $\theta_{\pi}^{cm} < 90°$, we find the power H to be essentially the same for π^- production from C or Pb ($H \simeq 3.3$) or for π^+ production from C or Pb ($H \simeq 2.3$). Miraculously, these powers are in general agreement with the value "3" predicted by SB using a simple parametization of the $pp \rightarrow \pi X$ data.

Also evident in Figs. 6A and B is the higher degree of scaling present in π^- production than π^+ production; this was also noted by Papp et al.(8) for their higher energy data. Although both processes should occur through a similar isobar mechanism, it might well be that π^+ production is more sensitive to nuclear structure effects - as occurs in the (p,π) reaction.(4)

A remarkable result is found when we examine the scaling behavior for pions produced in the backward hemisphere. As we can see in Figs. 7A and B, and with the primed parameters in Table I, these data scale much better than those for forward production, but now with a power $H \gtrsim 12$. Since these back angle pions arise from target fragmentation, within the hard collision model(9) this power depends strongly on properties of the target. For an A = 12 system SB predict $23 \leq H \leq 67$ - depending on the theory of the nuclear force - whereas for an A = 207 system SB would predict $40 \leq H \leq 1200$.

It is thus somewhat of a puzzle that the forward angle data scale and have power law behavior in general agreement with SB, but that the back-angle data - which "scale" even better - do so with a power so different from the theory's prediction. If we assume that the theory is valid for this low an energy, the small power, ~13, indicates that the large momentum transferred to the nucleus is being absorbed by only one or a few nucleons and not equally distributed amongst "A" nucleons (as SB assume). In fact, since H = 6A-3 (for the most consistent model of the NN force) these data suggest that back angle pions are produced from clusters with $A \simeq 1$-3.

Stimulated by this intriguing possibility, Gyulassy and Landau(13) have carried this non-coherent production idea somewhat further and find that the shape of these spectra are consistent with production from a few nucleon cluster, or even from a single nucleon with Fermi motion. The solid curves in Fig. 7 are in fact Fermi-averaged, Lorentz-transformed $pp \rightarrow \pi X$ cross sections. We see that the production of pions from both C(7A) and Pb(7B), while showing different power law behavior (12 vs. 15), can still be simply related to the same elementary production process. The details of this calculation, plus a more complete examination of inclusive π production by protons and heavy ions at various energies, are found in Ref. (13).

In summary, we have found that a good amount of scaling behavior is present in proton-nucleus pion production at 730 MeV. Furthermore, the behavior of the invariant cross section can be described as $(1-x)^H$ for larger x, once the $k_\perp$ variation is removed. The forward angle (projectile fragmentation) production appears to be simply related to pp π-production via a hard collision model.(9) The backward angle (target fragmentation) production, however, does not agree with this model - although it and many other features of inclusive π production can be understood in an elementary impulse approximation model.

While we believe the above deduction of the x dependence of inclusive pion production data permits one to see the essential physics in a very large number of data,(13) a more detailed understanding of the magnitude and A dependence of the cross sections no doubt requires a more involved calculation. Unfortunately, that type of calculation requires many more parameters and is beset with many nuclear ambiguities.(6)

Acknowledgments

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11. Ref. 6's semiclassical model does indicate that the effective number of π^+ s should increase at back angles due to the decreased path length for absorption. However, since this model also indicates that the effective number of π^- s should decrease at back angles, this does not seem a viable explanation of the effect observed here.

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Figure Captions

Fig. 1 Invariant cross section $\frac{E}{k^2}\frac{d^2\sigma}{d\Omega dk}$ for π^- production from carbon versus the scaling variable $x_R = k_\pi^{cm}/(k_\pi^{cm})_{max}$: Data of Ref. (5) for 730 MeV protons at 15° (filled circles) and 30° (filled squares); data of Ref. (8) at 2.5° for 1.05 GeV protons (open circles) and 4.8 GeV protons (filled circles). The $k_\perp$ variation of Eq. (2) has been removed, but the overall normalization is unadjusted.

Fig. 2 Invariant cross sections for π^- production vs. pion emission angle in the proton-nucleus c.m. system for several pion kinetic energies in this system: (A) for production from carbon, (B) for production from lead. The curves are interpolated (and slightly smoothed) representations of the data of Ref. (5), each for a constant value of x_R (given in parenthesis). The π^+ curves have similar shapes.

Fig. 3 The $k_\perp$ variation of the invariant $\pi^\pm$ production cross sections from lead interpolated from the data of Ref. (5), and our exponential fits to these data. The interpolated points for different x_R values have been normalized to the $x_R = 0.40$ points to demonstrate the consistency of the $k_\perp$ behavior. Curves for other nuclei look similar.

Fig. 4 Invariant cross section for π^+ production from hydrogen versus pion emission angle in the pp c.m. for several pion c.m. energies (x_R's). The curves are interpolated from the 730 MeV proton data of Ref. (5).

Fig. 5 Invariant cross section for π^+ production from carbon (A) and π^- production from lead (B) versus the pion emission angle transformed to the "proton-proton" c.m. Each curve is for a constant pion energy as measured in the "pp" system.

Fig. 6 Invariant cross section for $\pi^{\pm}$ production by protons from a carbon target (A) and a lead target (B) versus the scaling variable x_R, for emission angles less than 90°. The points are those of Ref. (5) with the exponential $k_{\perp}$ variation of Eq. (2) removed. The curves are our fits to the large x_R points.

Fig. 7 Same as Fig. 6, except now for backward pions, $\theta_{cm} > 90°$. The curves here represent Fermi averaged, Lorentz-transformed $pp \rightarrow \pi X$ cross sections.

TABLE I Parameters Fit to Invariant Cross Section

$$(1 - x_R)^H \exp(- r_N k_1^N)$$

Reaction	H	H' ($\theta_{cm} > \frac{\pi}{2}$)	r_2 $[(GeV/c)^{-2}]$	r_2' $[(GeV/c)^{-2}]$	r_3 $[(GeV/c)^{-3}]$	r_3' $[(GeV/c)^{-3}]$
$p\ C \to \pi^- X$	3.3(1)	11.9(3)	18(4)	-16(4)	59(8)	-43(2)
$p\ C \to \pi^+ X$	2.2(.5)	11.1(1)	23(4)	-29(16)	53(6)	-59(15)
$p\ Pb \to \pi^- X$	3.3(.5)	15(4)	19(3)	-17(5)	58(10)	-46(18)
$p\ Pb \to \pi^+ X$	2.4(.5)	12(4)	24(1)	-28(10)	53(14)	-41(12)

The primed parameters are for pions with $\theta > \frac{\pi}{2}$ in the p-A c.m.

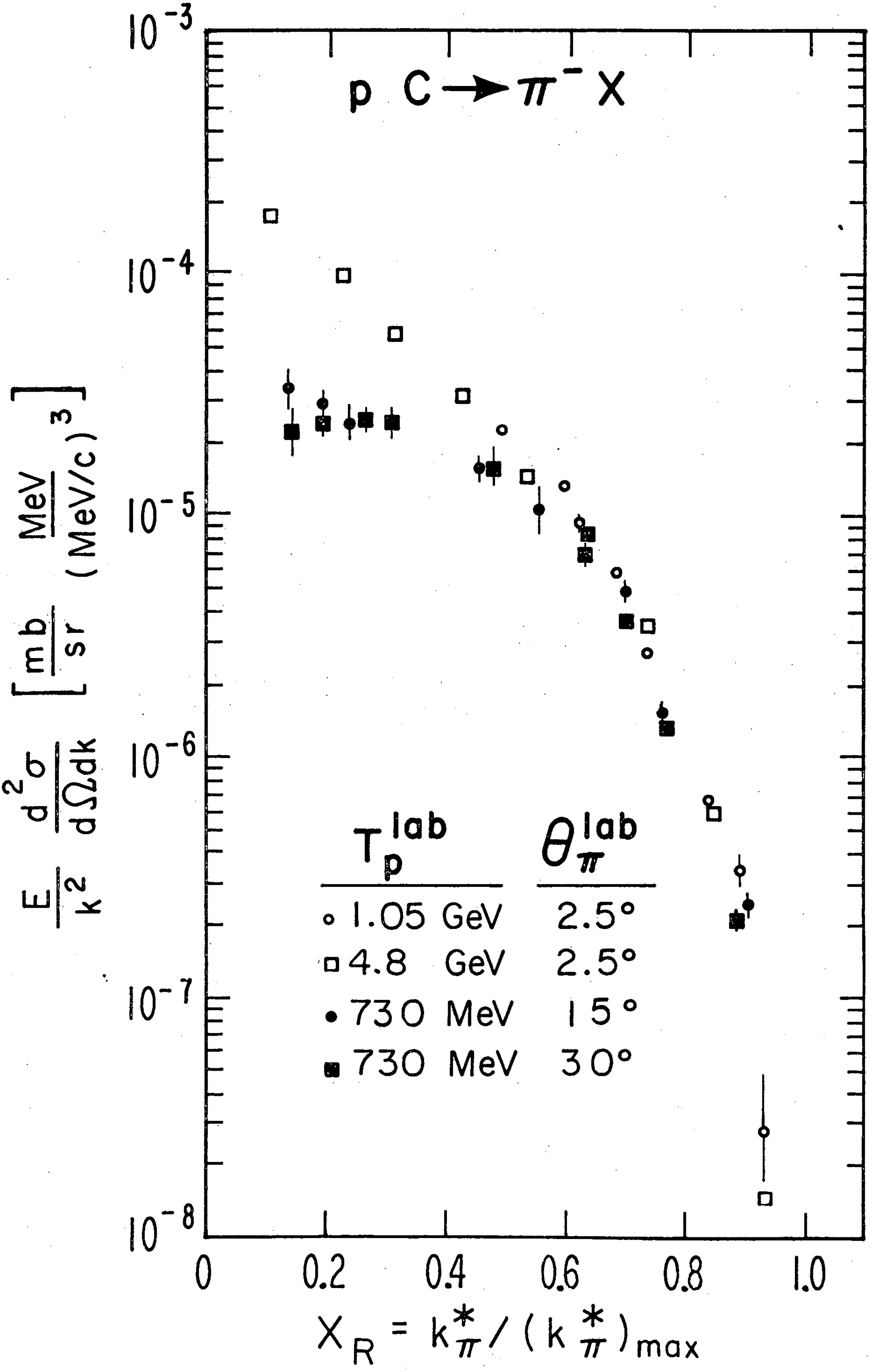

Fig. 1

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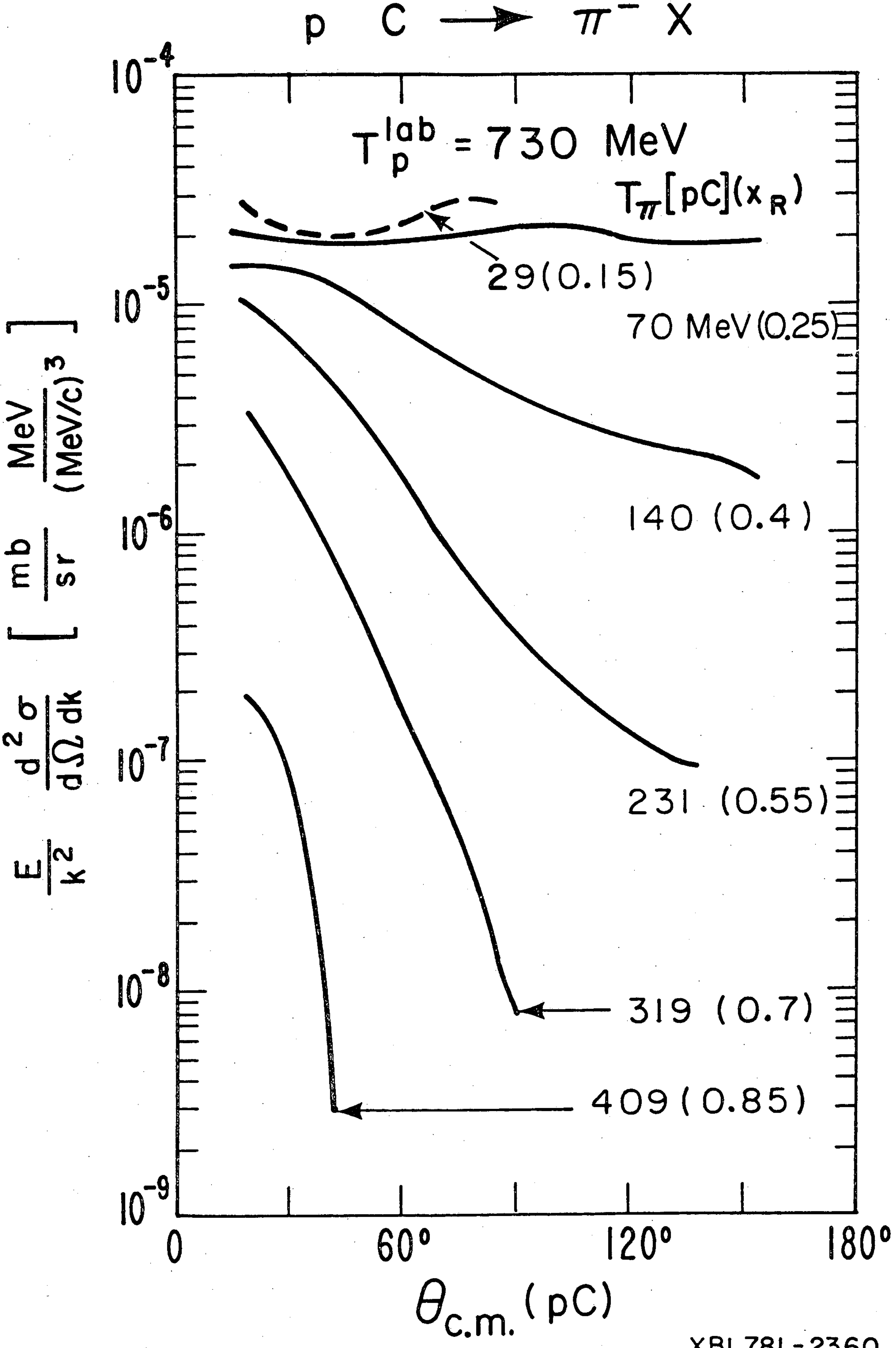

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Fig. 2A

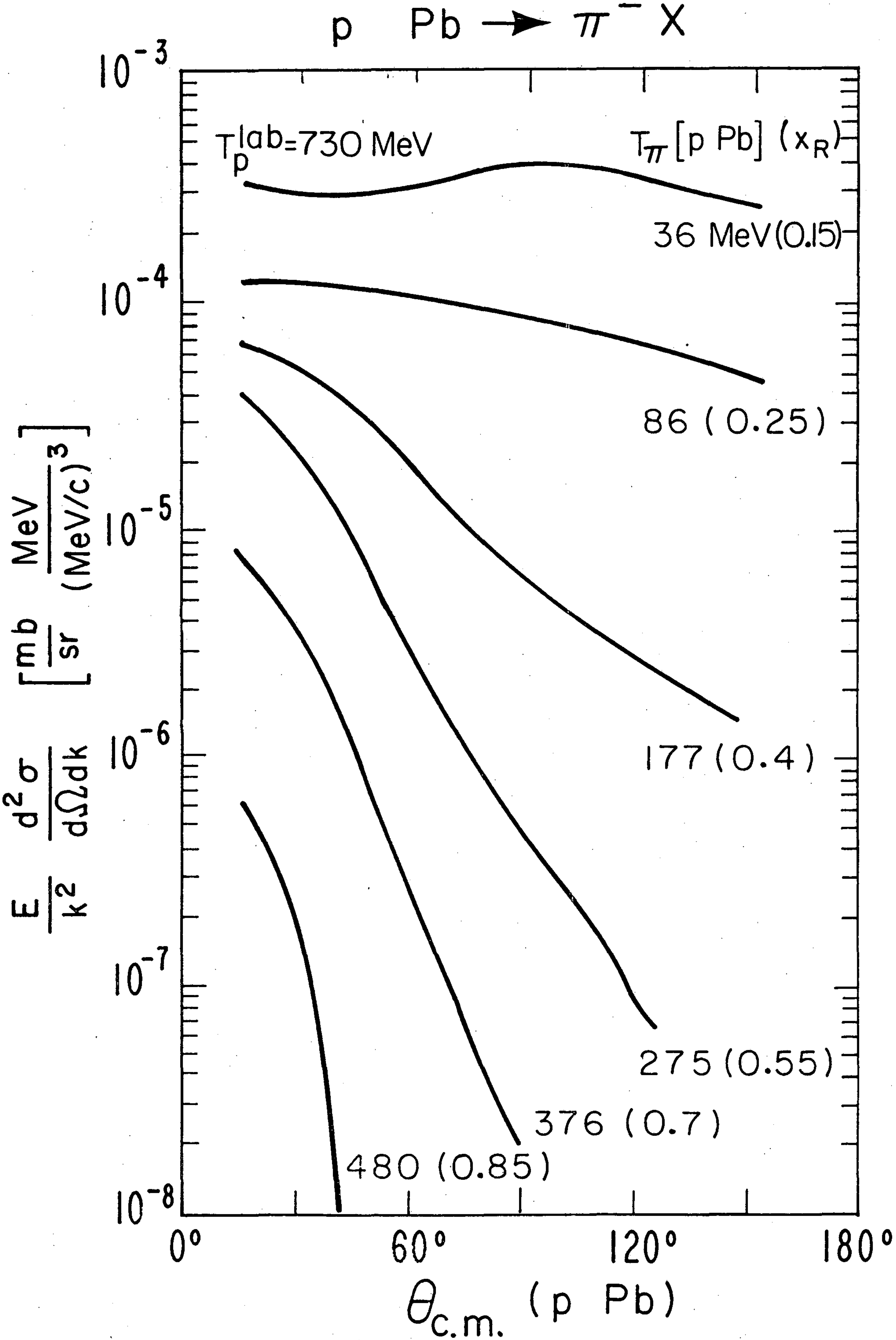

Fig. 2B

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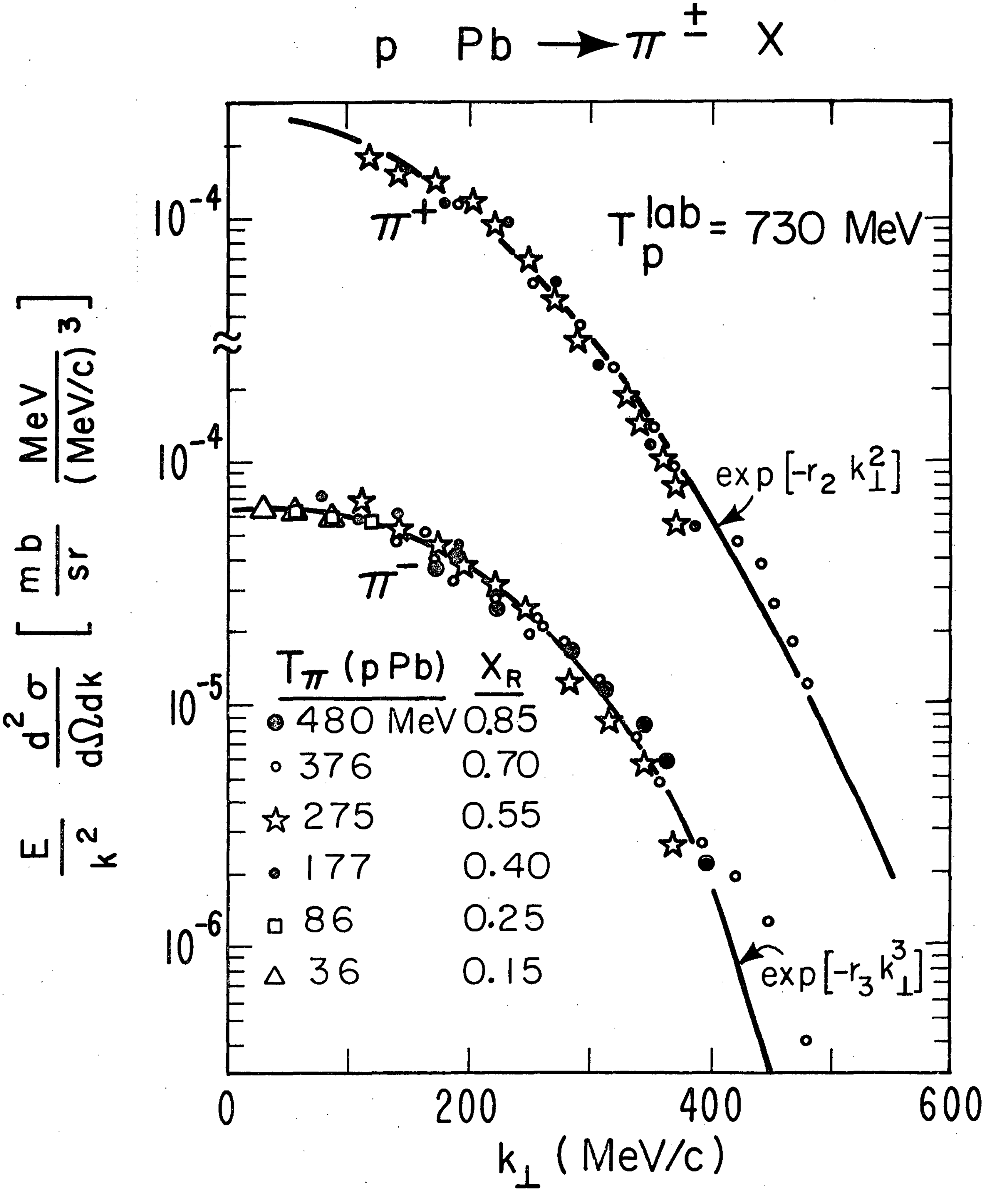

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Fig. 3

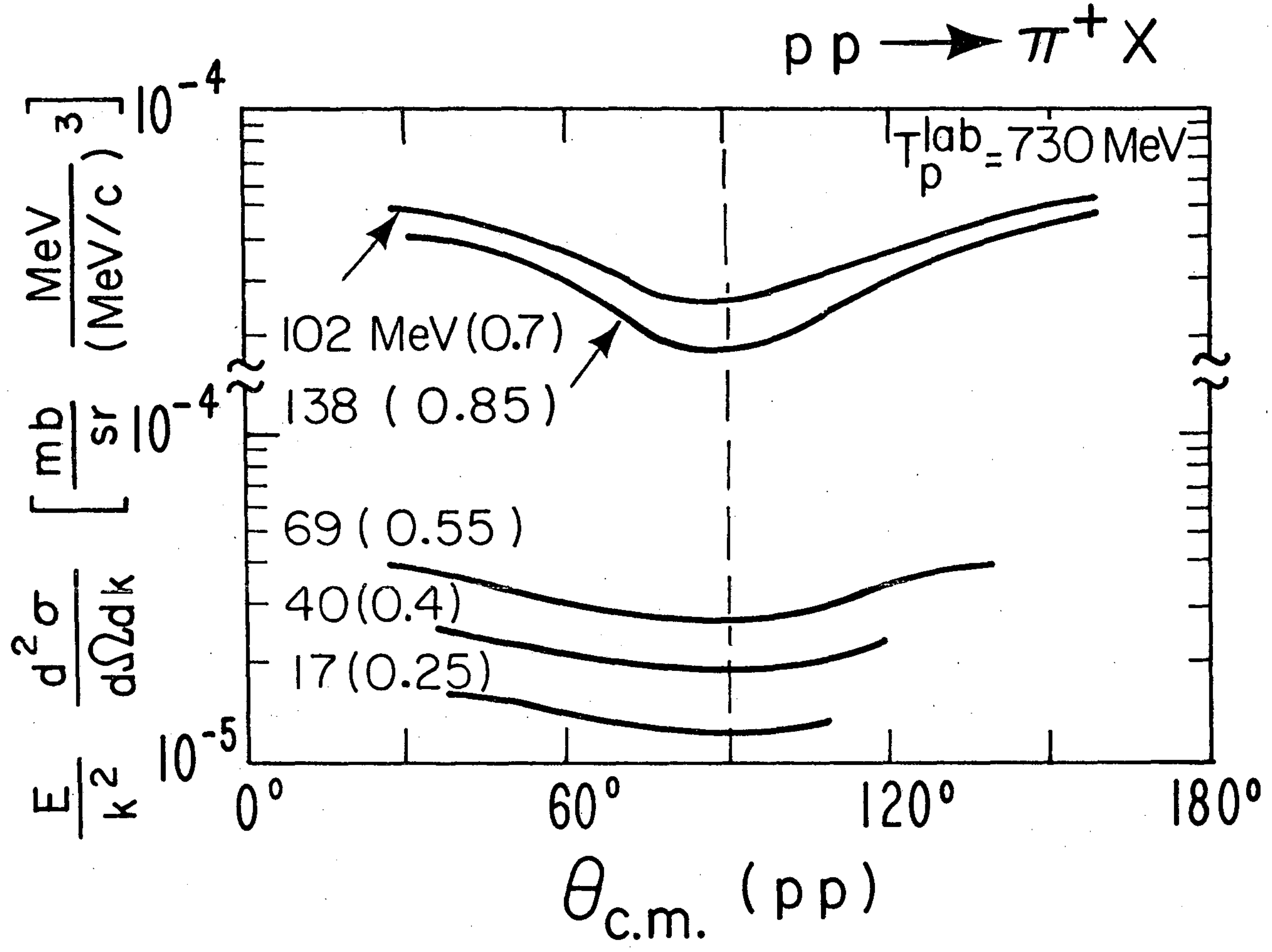

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Fig. 4

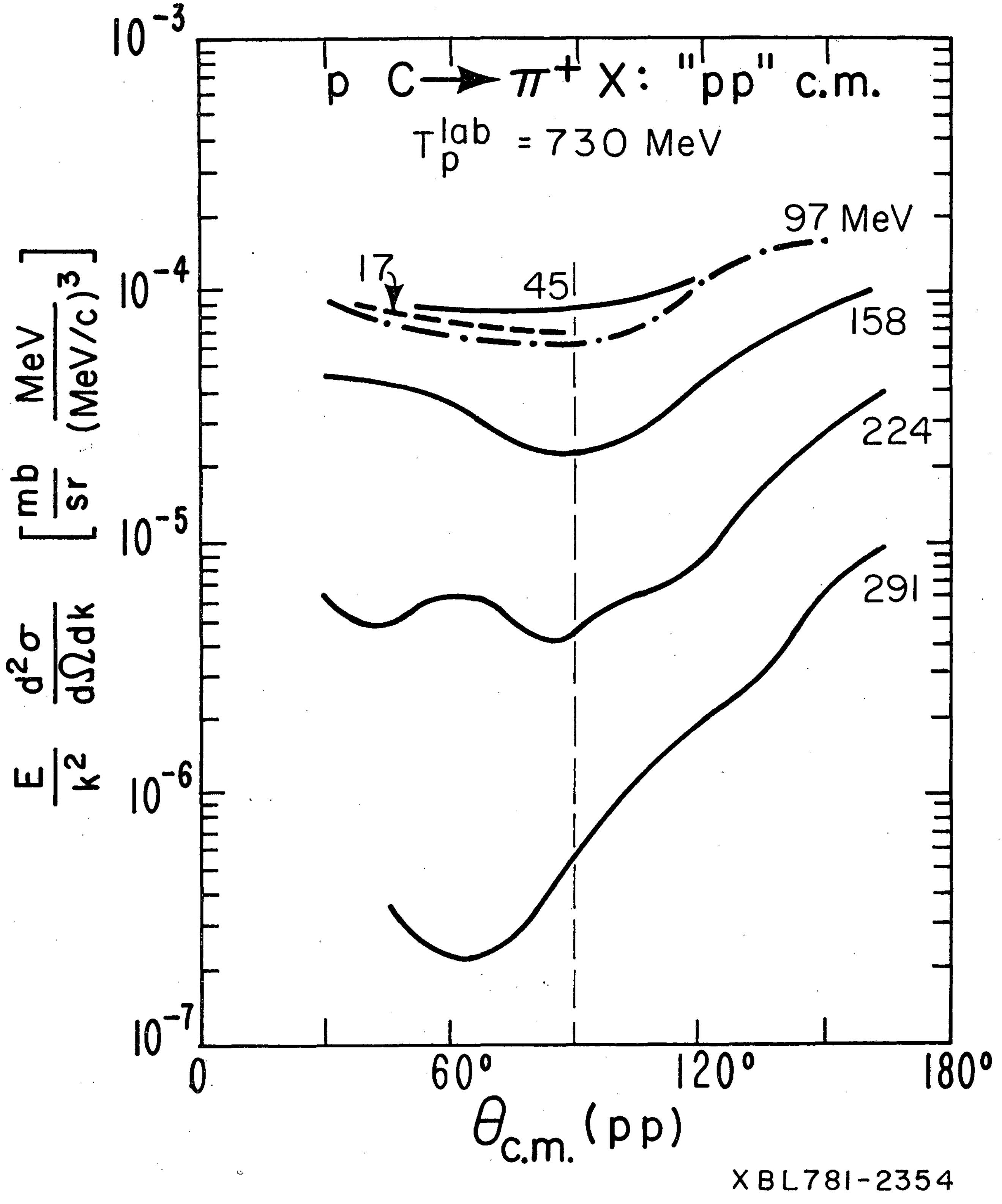
p C⟶ π⁺ X: "pp" c.m.
T_p^{lab} = 730 MeV
97 MeV
17
45
158
224
291
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$\frac{E}{k^2} \frac{d^2\sigma}{d\Omega dk} \left[\frac{mb}{sr} \frac{MeV}{(MeV/c)^3}\right]$
0
60°
120°
180°
$\theta_{c.m.}$(pp)
XBL781-2354

Fig. 5a.

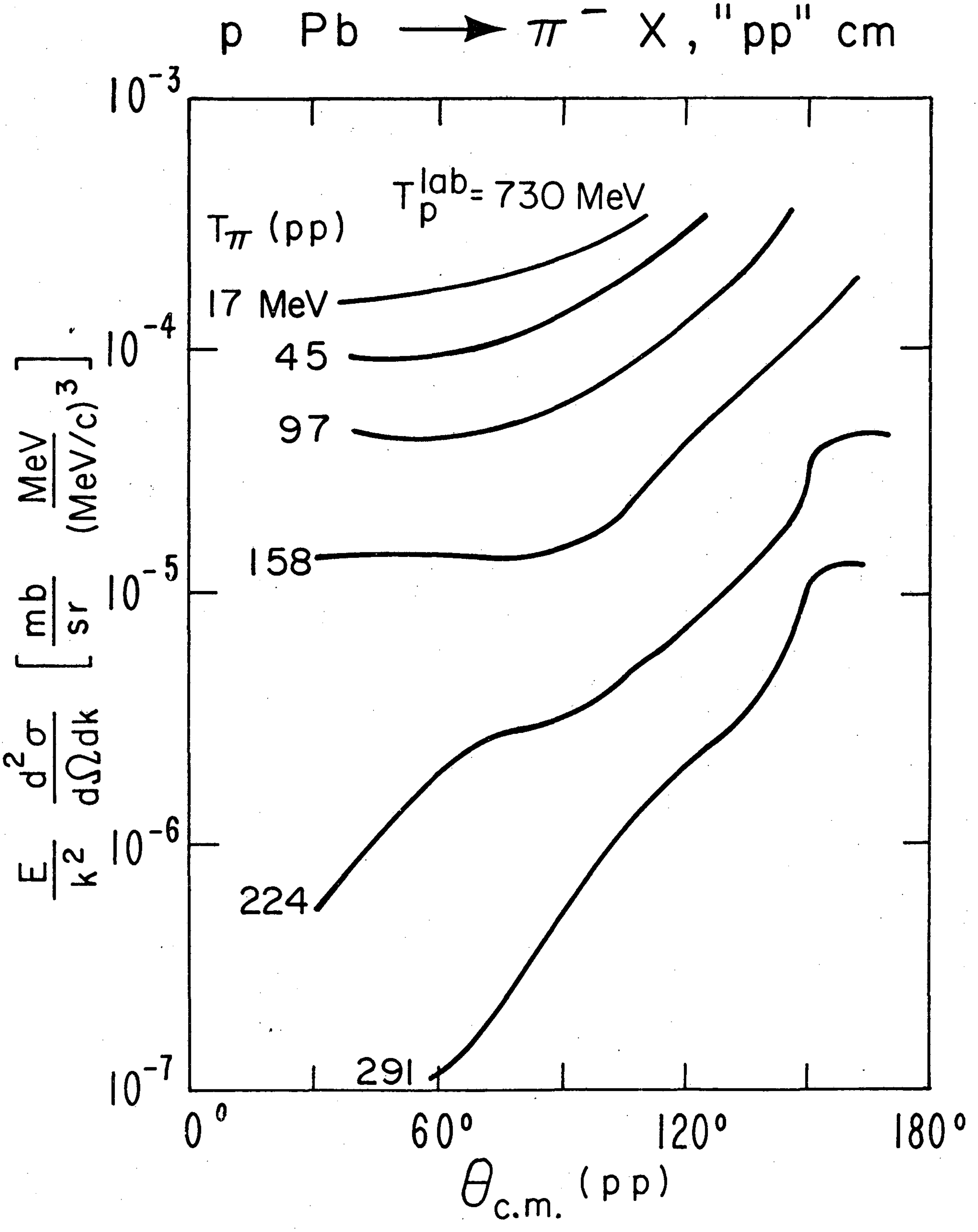

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Fig. 5b.

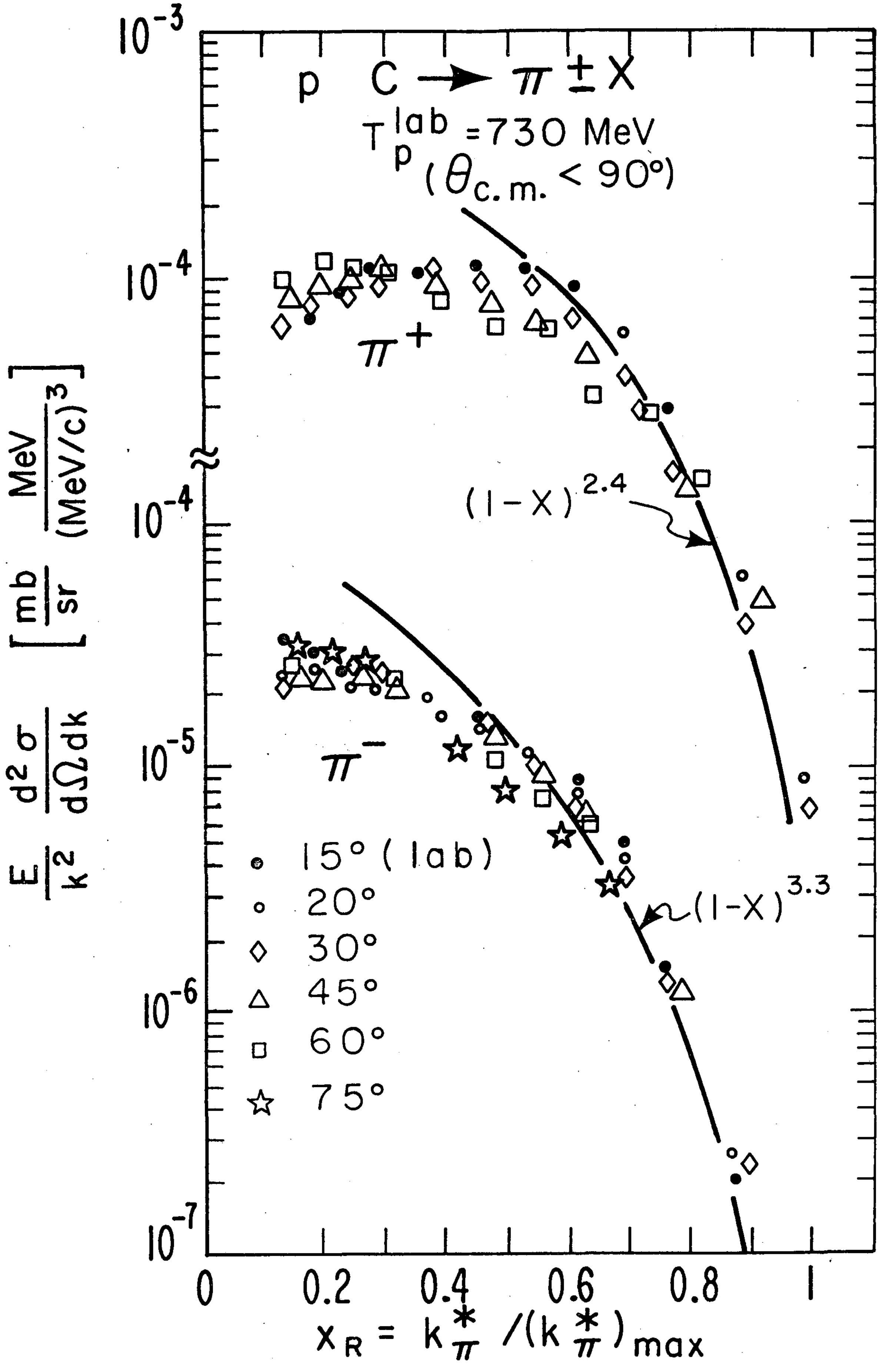

Fig.6a.

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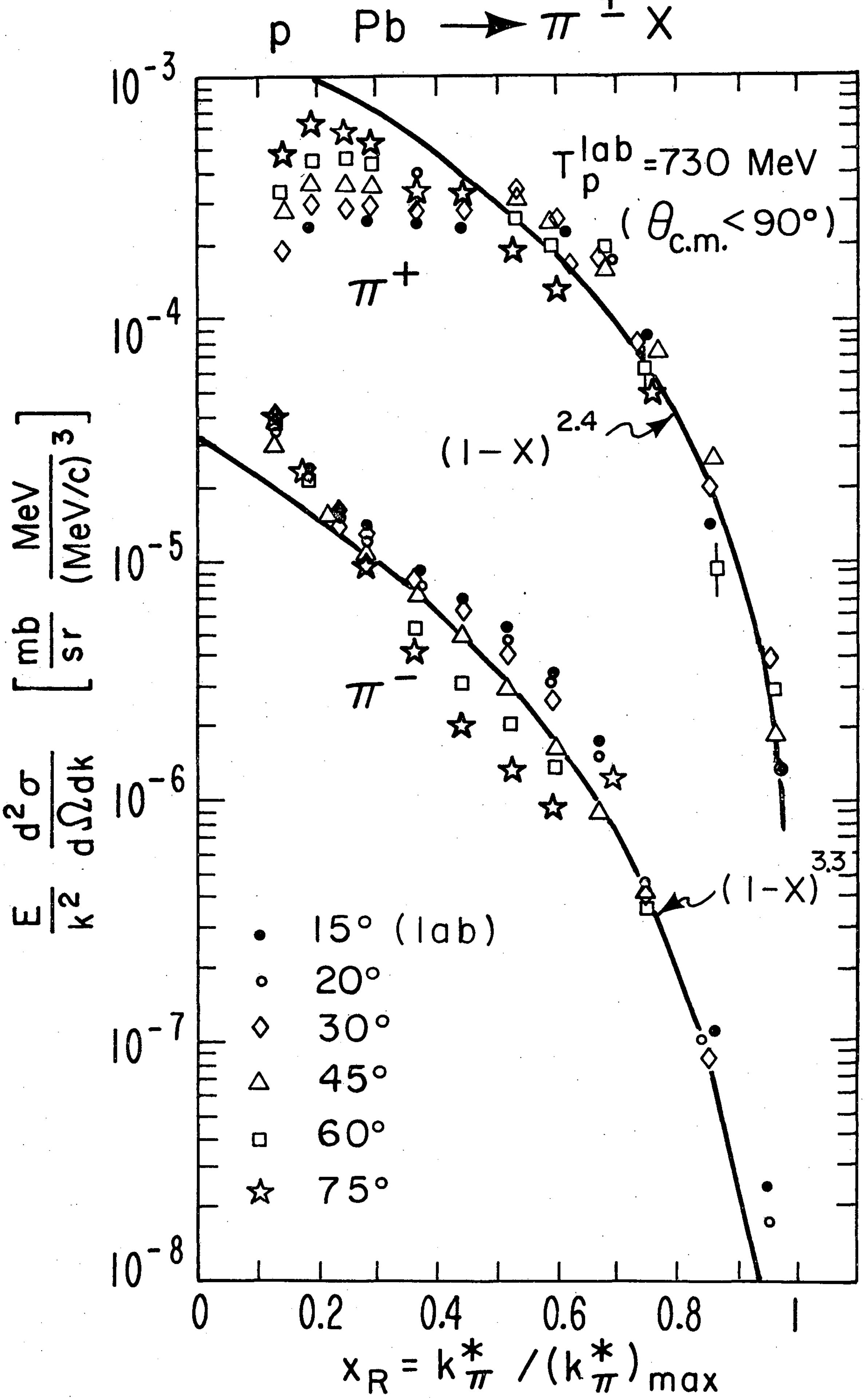

Fig. 6b.

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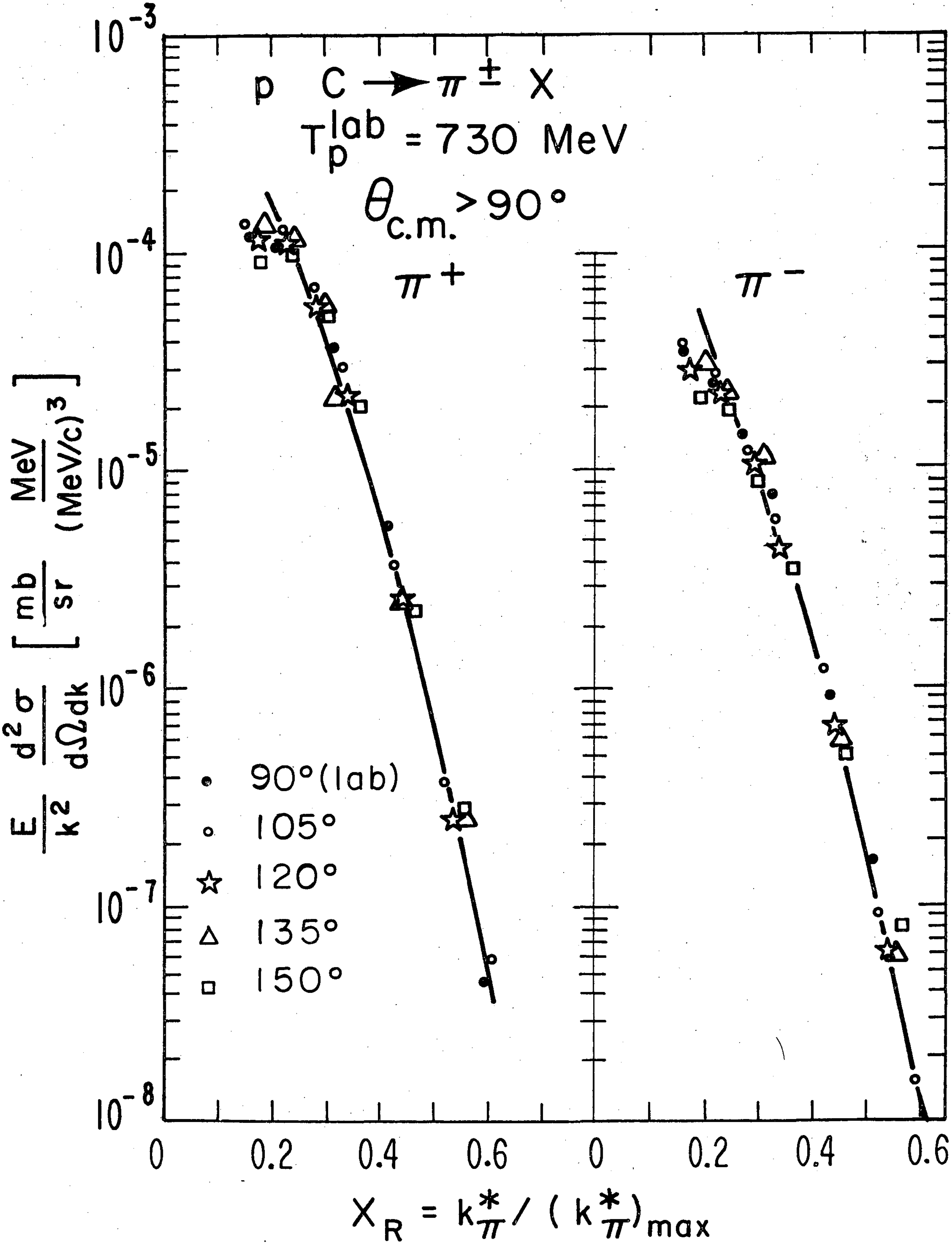

Fig. 7a

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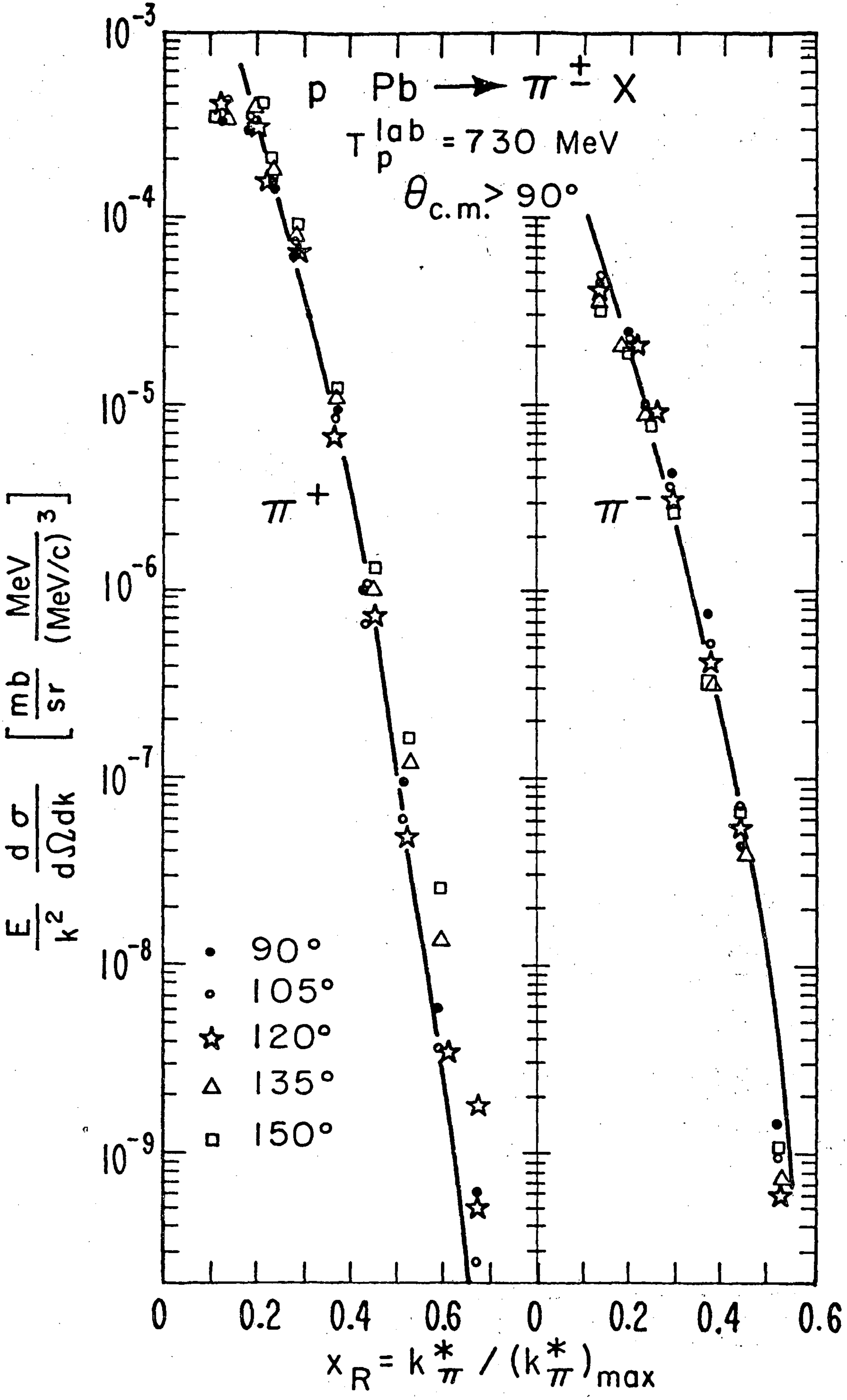

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Fig. 7b.

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