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PHYSICS

HIGH-ENERGY PARTICLE DATA

By

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Charles V. Stableford

November 1956

Radiation Laboratory
University of California
Berkeley, California

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Berkeley, California

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HIGH-ENERGY PARTICLE DATA
Volume I

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Printed for the U. S. Atomic Energy Commission

HIGH-ENERGY PARTICLE DATA Volume I

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HIGH-ENERGY PARTICLE DATA

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INTRODUCTION

In planning and in interpreting experiments in high-energy physics, one often requires data of the kind given in this document. Studies of meson production require many rather tedious calculations to interconvert laboratory-system and center-of-mass results. The availability of graphs such as these should reduce the labor involved in making relativistic calculations.

The number of graphs was kept finite by imposing a lower kinetic-energy limit of 100 kev for all particles except electrons, for which the lower limit is 1 kev. The upper energy limit corresponds in all cases to a gamma of between 20 and 100, beyond which the extreme relativistic equations can be used with no appreciable errors. This revision of High-Energy Particle Data is separated into two volumes; Volume I contains graphs of particle kinematics and dynamics only, and Volume II contains graphs of range-energy and range-momentum relations for the same particles.

As an aid to those who wish to construct similar graphs for other particles (e. g., tritons or some as yet undiscovered heavy mesons), a set of master sheets is included.

The curves showing dynamical variables as functions of kinetic energy were all traced directly from the set of master curves. The masters show β , $\beta\gamma = p/m_0c$, and $\gamma - 1 = \text{kinetic energy}/\text{rest energy} = K/R$ as functions of $\gamma - 1$. To construct curves for a new particle, one merely traces from the master to a new sheet of similar paper which has been shifted properly with respect to the master. To trace curves of β and $\gamma - 1$, one shifts the new paper horizontally until the master abscissa labeled $(\gamma - 1) = 10^n$ is directly under the abscissa labeled $K.E. = 10^n R$, where R is the rest energy of the particle in the same energy units. To trace the momentum curves, one shifts the overlying paper vertically by the same distance as it has already been shifted horizontally (along the direction of the $\gamma - 1$ lines). Because H_p is proportional to p/Z , the H_p curves are always the same distance above the p curves for a singly charged particle. This vertical shift is a factor of 1.31×10^3 gauss inches per Mev/c. For a particle with charge Z , the vertical shift is $1.31 \times 10^3/Z$.

The curves have been reproduced in their original size, so that standard K & E graph paper may be used as described above.

In this revised edition several additions and changes have been made. Sets of graphs for the K meson and for Λ^0 , Σ , and Ξ hyperons have been added; the mass assumed for each particle is indicated at the top of each graph so that the user may make appropriate corrections as mass values are determined with greater accuracy. The mass value is also useful in obtaining $\beta\gamma$, since we have the relation

$$\beta\gamma \equiv pc \text{ (in Mev)} / \text{rest mass (in Mev)}.$$

Furthermore, the addition of the quantity $p\beta$ (which did not appear in the original edition) increases the usefulness of the graphs.

Graphs for the dynamics of proton interactions have been added to aid in the transformation of the momentum and energy to the center-of-mass system for $\pi^\pm$ mesons, $K^\pm$ mesons, protons, electrons, and photons, all incident on protons.

This collection of new graphs makes possible a graphical method of solving relativistic "two-body to two-body" problems. The method is essentially that of J. Blaton.¹ His notation has been changed to conform more closely to that normally used in the high-energy physics literature. A few graphical procedures have been added to his method that allow finding the laboratory-system kinetic energy without reference to graphs or tables in the kinematics section.

Throughout this work, masses, energies, and momenta are measured in energy units--normally Mev or Bev. (In other words, the mass M is an abbreviation for mc^2 , and the momentum p is an abbreviation for pc .) E is the total energy, equal to a kinetic energy T plus a rest energy M . Unstarred energies and momenta are those measured in the laboratory system; starred energies and momenta, E^* and p^* , are those measured in the center-of-mass (c.m.) system. The barred quantities $\bar{\beta}$, $\bar{\gamma}$, and $\bar{\beta}\bar{\gamma}$ refer to the motion of the center of mass of the system relative to the laboratory system. Subscripts 1 through 4 refer to the four particles involved in the reaction.

Figure 1 is a typical diagram for a reaction of the type

where M_1 is the bombarding particle with kinetic energy T_1 . M_3 and M_4 differ from M_1 and M_2 , except in an elastic scattering event (in which they do not differ).

The use of the graphical system for solving relativistic two-body problems may be illustrated as follows. One may wish to know, for a given T_1 , the laboratory-system kinetic energies T_3 and T_4 , and momenta p_3

¹ J. Blaton, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 1950.

Fig. 1. A typical diagram for a reaction of the type $\pi^- + p \rightarrow K^+ + \Sigma^-$. M_1 is the bombarding particle with kinetic energy T_1 . M_3 and M_4 are the rest masses of the resulting particles.

and p_4 corresponding to various center-of-mass angles θ_3^* and θ_4^* (where $\theta_3^* = \pi - \theta_4^*$), and the related laboratory-system angles θ_3 and θ_4 at which the particles No. 3 and No. 4 emerge.

The procedure for the general case in which particle No. 2 is at rest in the laboratory system, is as follows:

1. Find the total energy in the center-of-mass system,

$$E^* = \sqrt{(M_1 + M_2)^2 + 2T_1 M_2}.$$

2. Obtain $\bar{\gamma} = (T_1 + M_1 + M_2) / E^*$.

3. Obtain $\bar{\eta} = \frac{p_1}{E^*} = \frac{\sqrt{T_1(T_1 + 2M_1)}}{E^*}$.

where $\bar{\eta} \equiv \bar{\beta} \bar{\gamma}$. Note that the quantities $\bar{\gamma}$ and $\bar{\eta}$ are obtained from the graphs on pages 73 through 87.

4. Calculate the center-of-mass energies of particles No. 3 and No. 4:

$$E_3^* = (E^{*2} + M_3^2 - M_4^2) / 2E^*,$$

$$E_4^* = E^* - E_3^*.$$

5. Calculate the center-of-mass momentum

$$p^* \equiv p_3^* = p_4^* ;$$

$$p^* = \sqrt{E_3^{*2} - M_3^2} \quad (= \sqrt{E_4^{*2} - M_4^2}).$$

6. Compute $\bar{\eta} E_3^*$, $\bar{\eta} E_4^*$, and $\bar{\gamma} p^*$.

These steps yield all the necessary information to finish the problem by a graphical method.

The quantities $\bar{\gamma}$, $\bar{\eta}$, and E^* necessary for the following construction are presented in graphical form on pages 73 through 87.

The procedure now is as follows:

1. Draw a circle of radius p^* .
2. Mark off the circle at the c.m. angle desired (e.g., 0° , 30° , 60° , etc.).
3. Draw a horizontal line through the mark-off point on the p^* circle.
4. Lengthen these semichords of the circle by the factor $\bar{\gamma}$ to give points on an ellipse with semiminor axis = p^* and semimajor axis = $\bar{\gamma} p^*$.
5. Locate point No. 3 at the distance $\bar{\eta} E_3^*$ to the left of the center of the circle, and point No. 4 at the distance $\bar{\eta} E_4^*$ to the right of the center. (The distance between these points is equal to the original laboratory-system momentum p_1 of the bombarding particle. That is, it must be the vector sum of the laboratory-system momenta of M_3 and M_4 .)
6. Draw verticals through points No. 3 and No. 4, and locate points No. 3' and No. 4' at distances M_3 and M_4 above points No. 3 and No. 4, respectively.
7. Draw momentum vectors p_3 and p_4 , as shown, from points No. 3 and No. 4 to the plotted points on the ellipse (i.e., for predetermined c.m. angles).
8. Measure laboratory-system angles θ_3 and θ_4 .
- 9a. Measure p_3 and p_4 , and convert to T_3 and T_4 by reference to graphs, or
- 9b. Alternatively, find T_3 and T_4 graphically by using the general relation $p^2 + M^2 = (T + M)^2$ and applying Pythagoras's Theorem; the procedure is as follows:

Place one tip of a pair of dividers on point No. 3, and the other tip of the dividers at a distance of p_3 on the ellipse. Pivot the dividers about point No. 3 until the other tip is on the major axis of the ellipse at Point a. Next pivot the dividers about Point a, and open the dividers so that the other tip is on Point 3'. The dividers now show a separation $E_3 = \sqrt{p_3^2 + M_3^2}$. Now pivot the dividers about point No. 3' until the other leg is vertically below Points 3' and 3 at Point b. This Point b lies at a distance T_3 below point No. 3, since we have $T_3 = E_3 - M_3$. An energy scale plotted downward from point No. 3 permits direct reading of T_3 .

This procedure, seemingly complicated to describe, is very simple to perform, and has been shown separately on Fig. 1 for clarity.

It may be helpful to recall that the properties of the ellipse are simply consequences of the Lorentz transformation for the energy-momentum vector; only the longitudinal component of the momentum is transformed. Thus we can write (for particle No. 3, say)

$$\begin{pmatrix} p_3 \cos \theta_3 \\ E_3 \end{pmatrix} = \begin{pmatrix} \bar{\gamma} & \bar{\eta} \\ \bar{\eta} & \bar{\gamma} \end{pmatrix} \begin{pmatrix} p_3^* \cos \theta_3^* \\ E_3^* \end{pmatrix}; \quad \bar{\eta} = \bar{\beta} \bar{\gamma}.$$

The major axis of the ellipse is the difference between the momentum vector for $\theta_3^* = 0$ and $\theta_3^* = \pi$, i.e.,

$$(\bar{\gamma} p_3^* + \bar{\eta} E_3^*) - (-\bar{\gamma} p_3^* + \bar{\eta} E_3^*) = 2\bar{\gamma} p_3^*.$$

The origin for the ellipse is given by the particle going at 90° in the c.m. system, i.e.,

$$\theta_3^* = \pi/2, \text{ hence } p_3 \cos \theta_3 = \bar{\eta} E_3^*.$$

One can easily show that in the extreme relativistic limit a particle going backward in the c.m. system (i.e., $\theta_3^* = \pi$) approaches a constant momentum in the laboratory system, namely

$$(M_3^2 - M_2^2) / 2 M_2.$$

ACKNOWLEDGMENTS

We gratefully acknowledge the assistance of Mrs. Marjory Simmons, who shared the burden of constructing all the new range-vs-momentum graphs in Vol. II, as well as most of the new graphs in Vol. I. We are deeply appreciative of the ever-willing helpfulness of Mrs. Mary McLeod.

Our thanks are due to Drs. M. Lynn Stevenson, Arthur Rosenfeld, and Frank Solmitz for their many helpful suggestions on the presentation of this report. And finally, we wish to thank Dr. Luis Alvarez for his suggestions concerning this collection of graphs.

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Information Division
1/11/57 db

MASTER SHEET 1

MASTER SHEET 2

MASTER SHEET 3

8-1

MASTER SHEET 4

ELECTRONS

1 kev to 10 kev

p in kev/c
H ρ in gauss inches
M = 0.51097 Mev
= m

β , $(\gamma-1)$, p, $p\beta$, and H ρ

ELECTRONS

10 kev to 100 kev

p in kev/c
H_p in gauss inches
M = 0.51097 Mev
= m

β , $(\gamma-1)$, p, $p\beta$, and H_p

ELECTRONS

100 kev to 1 Mev

p in Mev/c
H_p in gauss inches
M = 0.51097 Mev
= m

β , $(\gamma-1)$, p, $p\beta$, and H_p

ELECTRONS

1 Mev to 10 Mev

p in Mev/c
H_p in gauss inches
M = 0.51097 Mev
= m

β , $(\gamma-1)$, p, $p\beta$, and H_p

100 kev to 1 Mev

$$\beta, (\gamma-1), p, p\beta, \text{ and } H\rho$$

$\mu^\pm$ MESONS

1 Mev to 10 Mev

p in Mev/c
H_p in gauss inches
M = 105.72 Mev
= 206.9 m

β , $(\gamma-1)$, p, $p\beta$, and H_p

$\mu^\pm$ MESONS

10 Mev to 100 Mev

p in Mev/c
H ρ in gauss inches
M = 105.72 Mev
= 206.9 m

β , $(\gamma - 1)$, p, $p\beta$, and H ρ

$\mu^\pm$ MESONS

100 Mev to 1 Bev

p in Mev/c
H_p in gauss inches
M = 105.72 Mev
= 206.9 m

β , $(\gamma - 1)$, p, p β , and H_p

$\mu^\pm$ MESONS

1 Bev to 10 Bev

p in Mev/c
H ρ in gauss inches
M = 105.72 Mev
= 206.9 m

β , $(\gamma-1)$, p, $p\beta$, and H ρ

π^0 MESONS

100 kev to 1 Mev

p in Mev/c
M = 135.15 Mev
= 264.5 m

β , $(\gamma-1)$, p, and $p\beta$

π^0 MESONS

1 Mev to 10 Mev

p in Mev/c
M = 135.15 Mev
= 264.5 m

β , $(\gamma-1)$, p, and $p\beta$

π^0 MESONS

10 Mev to 100 Mev

p in Mev/c
M = 135.15 Mev
= 264.5 m

β , $(\gamma-1)$, p, and $p\beta$

π^0 MESONS

100 Mev to 1 Bev

p in Mev/c
M = 135.15 Mev
= 264.5 m

β , $(\gamma-1)$, p, and $p\beta$

π^0 MESONS

1 Bev to 10 Bev

p in Mev/c
M = 135.15 Mev
= 264.5 m

β , $(\gamma-1)$, p, and $p\beta$

$\pi^\pm$ MESONS

100 kev to 1 Mev

p in Mev/c
H_p in gauss inches
M = 139.65 Mev
= 273.3 m

β , $(\gamma-1)$, p, $p\beta$, and H_p

$\pi^\pm$ MESONS

1 Mev to 10 Mev

p in Mev/c
H_p in gauss inches
M = 139.65 Mev
= 273.3 m

β , $(\gamma-1)$, p, $p\beta$, and H_p

$\pi^\pm$ MESONS

10 Mev to 100 Mev

p in Mev/c
H ρ in gauss inches
M = 139.65 Mev
= 273.3 m

β , $(\gamma-1)$, p, $p\beta$, and H ρ

$\pi^\pm$ MESONS

100 Mev to 1 Bev

p in Mev/c
H ρ in gauss inches
M = 139.65 Mev
= 273.3 m

β , $(\gamma-1)$, p, $p\beta$, and H ρ

$\pi^\pm$ MESONS

1 Bev to 10 Bev

p in Mev/c
H ρ in gauss inches
M = 139.65 Mev
= 273.3 m

β , ($\gamma-1$), p, p β , and H ρ

$K^\pm$ MESONS

100 kev to 1 Mev

p in Mev/c
Hp in gauss inches
M = 493.96 Mev
= 966.71 m

β , $(\gamma-1)$, p, $p\beta$, and Hp

$K^\pm$ MESONS

1 Mev to 10 Mev

p in Mev/c
H ρ in gauss inches
M = 493.96 Mev
= 966.71 m

β , $(\gamma-1)$, p, $p\beta$, and H ρ

$K^\pm$ MESONS

10 Mev to 100 Mev

p in Mev/c
H_p in gauss inches
M = 493.96 Mev
= 966.71 m

β , $(\gamma-1)$, p, $p\beta$, and H_p

100 Mev to 1 Bev

 β , $(\gamma-1)$, p , $p\beta$, and $H\rho$

$K^\pm$ MESONS

1 Bev to 10 Bev

p in Mev/c
H_p in gauss inches
M = 493.96 Mev
= 966.71 m

β , $(\gamma-1)$, p, $p\beta$, and H_p

Λ^0 HYPERONS

100 kev to 1 Mev

p in Mev/c
M = 1114.86 Mev
= 2181.85 m

β , $(\gamma-1)$, p, and $p\beta$

1 Mev to 10 Mev

 $\beta, (\gamma-1), p,$ and $p\beta$

Λ^0 HYPERONS

10 Mev to 100 Mev

p in Mev/c
 $M = 1114.86 \text{ Mev}$
 $= 2181.85 \text{ m}$

β , $(\gamma-1)$, p, and $p\beta$

Λ^0 HYPERONS

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β , $(\gamma-1)$, p, and $p\beta$

100 kev to 1 Mev

 β , $(\gamma-1)$, p , $p\beta$, and $H\rho$

p in Mev/c
H_p in gauss inches
M = 1194.05 Mev
= 2336.83 m

$$\beta, (\gamma-1), p, p\beta, \text{ and } H\rho$$

10 Mev to 100 Mev

$$\beta, (\gamma-1), p, p\beta, \text{ and } H\rho$$

Σ_{av} HYPERONS

100 Mev to 1 Bev

p in Mev/c
H ρ in gauss inches
M = 1194.05 Mev
= 2336.83 m

β , $(\gamma-1)$, p, $p\beta$, and H ρ

Σ_{av} HYPERONS

1 Bev to 10 Bev

p in Mev/c
H ρ in gauss inches
M = 1194.05 Mev
= 2336.83 m

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Σ_{av} HYPERONS

10 Bev to 100 Bev

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Hp in gauss inches
M = 1194.05 Mev
= 2336.83 m

β , $(\gamma-1)$, p, $p\beta$, and Hp

100 kev to 1 Mev

 β , $(\gamma-1)$, p , $p\beta$, and $H\rho$

1 Mev to 10 Mev

 β , $(\gamma-1)$, p , $p\beta$, and $H\rho$

Ξ^- HYPERONS

10 Mev to 100 Mev

p in Mev/c
H_p in gauss inches
M = 1321 Mev
= 2585.28 m

β , $(\gamma-1)$, p, $p\beta$, and H_p

Ξ^- HYPERONS

100 Mev to 1 Bev

p in Mev/c
Hp in gauss inches
M = 1321 Mev
= 2585.28 m

β , $(\gamma-1)$, p, $p\beta$, and Hp

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1 Bev to 10 Bev

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= 2585.28 m

β , $(\gamma-1)$, p, $p\beta$, and Hp

PROTONS

100 kev to 1 Mev

p in Mev/c
H_p in gauss inches
M = 938.21 Mev
= 1836 .14 m

β , $(\gamma-1)$, p, p β , and H_p

PROTONS

1 Mev to 10 Mev

p in Mev/c
H_p in gauss inches
M = 938.21 Mev
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= 1836.14 m

β , $(\gamma-1)$, p, $p\beta$, and H_p

DEUTERONS

100 kev to 1 Mev

p in Mev/c
H_p in gauss inches
M = 1875.49 Mev
= 3670.45 m

β , $(\gamma-1)$, p, $p\beta$, and H_p

DEUTERONS

1 Mev to 10 Mev

p in Mev/c
H_p in gauss inches
M = 1875.49 Mev
= 3670.45 m

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β , $(\gamma-1)$, p, p β , and H_p

DEUTERONS

10 Bev to 100 Bev

p in Mev/c
H_p in gauss inches
M = 1875.49 Mev
= 3670.45 m

β , $(\gamma-1)$, p, $p\beta$, and H_p

ALPHA PARTICLES 100 kev to 1 Mev

p in Mev/c
 Hp in gauss inches
 M = 3727.23 Mev
 = 7294.47 m

β , $(\gamma-1)$, p, $p\beta$, and Hp

ALPHA PARTICLES 1 Mev to 10 Mev

p in Mev/c
H_p in gauss inches
M = 3727.23 Mev
= 7294.47 m

β , $(\gamma-1)$, p, p β , and H_p

ALPHA PARTICLES 10 Mev to 100 Mev

p in Mev/c
 Hp in gauss inches
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β , $(\gamma-1)$, p, $p\beta$, and Hp

ALPHA PARTICLES 100 Mev to 1 Bev

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H_p in gauss inches
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β , $(\gamma-1)$, p, $p\beta$, and H_p

ALPHA PARTICLES 10 Bev to 100 Bev

p in Mev/c
H_p in gauss inches
M = 3727.23 Mev
= 7294.47 m

β , $(\gamma-1)$, p, p β , and H_p

$\gamma + p$

10 Mev to 100 Mev

$$M_{\gamma} = 0$$

$$M_p = 938.21 \text{ Mev}$$

$\bar{\beta}$, $(\bar{\gamma}-1)$, $\bar{\eta}$, and E^*

$\gamma + p$

100 Mev to 1 Bev

$$M_{\gamma} = 0$$

$$M_p = 938.21 \text{ Mev}$$

$\bar{\beta}$, $(\bar{\gamma}-1)$, $\bar{\eta}$, and E^*

$\gamma + p$

1 Bev to 10 Bev

$$M_{\gamma} = 0$$

$$M_p = 938.21 \text{ Mev}$$

$\bar{\beta}$, $(\bar{\gamma}-1)$, $\bar{\eta}$, and E^*

e + p

10 Mev to 100 Mev

$M_e = 0.51 \text{ Mev}$
 $M_p = 938.21 \text{ Mev}$

$\bar{\beta}$, $(\bar{\gamma}-1)$, $\bar{\eta}$, and E^*

e + p

100 Mev to 1 Bev

$M_e = 0.51 \text{ Mev}$
 $M_p = 938.21 \text{ Mev}$

$\bar{\beta}$, $(\bar{\gamma}-1)$, $\bar{\eta}$, and E^*

e + p

1 Bev to 10 Bev

$$M_e = 0.51 \text{ Mev}$$

$$M_p = 938.21 \text{ Mev}$$

$\bar{\beta}$, $(\bar{\gamma}-1)$, $\bar{\eta}$, and E^*

$\pi + p$

10 Mev to 100 Mev

$M_{\pi} = 139.65 \text{ Mev}$

$M_p = 938.21 \text{ Mev}$

$\bar{\beta}$, $(\bar{\gamma}-1)$, $\bar{\eta}$, and E^*

$\pi + p$

100 Mev to 1 Bev

$$M_{\pi} = 139.65 \text{ Mev}$$

$$M_p = 938.21 \text{ Mev}$$

$\bar{\beta}$, $(\bar{\gamma}-1)$, $\bar{\eta}$, and E^*

$\pi + p$

1 Bev to 10 Bev

$$M_{\pi} = 139.65 \text{ Mev}$$

$$M_p = 938.21 \text{ Mev}$$

$\bar{\beta}$, $(\bar{\gamma}-1)$, $\bar{\eta}$, and E^*

K + p

10 Mev to 100 Mev

$$M_K = 493.96 \text{ Mev}$$

$$M_e = 938.21 \text{ Mev}$$

$\bar{\beta}$, $(\bar{\gamma}-1)$, $\bar{\eta}$, and E^*

K + p

100 Mev to 1 Bev

$$M_K = 493.96 \text{ Mev}$$

$$M_e = 938.21 \text{ Mev}$$

$\bar{\beta}$, $(\gamma-1)$, $\bar{\eta}$, and E^*

K + p

1 Bev to 10 Bev

$$M_K = 493.96 \text{ Mev}$$

$$M_e = 938.21 \text{ Mev}$$

$\bar{\beta}$, $(\bar{\gamma}-1)$, $\bar{\eta}$, and E^*

10 Mev to 100 Mev

$$\overline{\beta}, (\overline{\gamma}-1), \overline{\eta}, \text{ and } E^*$$

p + p

100 Mev to 1 Bev

$M_p = 938.21 \text{ Mev}$

$\bar{\beta}$, $(\bar{\gamma}-1)$, $\bar{\eta}$, and E^*

p + p

1 Bev to 10 Bev

$$M_p = 938.21 \text{ Mev}$$

$\bar{\beta}$, $(\bar{\gamma}-1)$, $\bar{\eta}$, and E^*