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Relativistic Di-quark Model of $p\overline{p} \to K^+K^-$ Reaction

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Abstract

The newly available experimental data (LEAP 92) on $K\bar{K}$ production is compared with a model calculation. We believe the simplicity of the model makes it a useful tool for studying charm and beauty baryon production, for which also experimental data will soon be profuse.

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1 Introduction

The importance of the gluon gauge field in QCD is obvious, but it is hard to incorporate in a simple model. Belavin et al.[1] found the instanton solution for the Yang-Mills-Maxwell fields, and subsequently in the works of 't Hooft[2] and Shifman et al.[3] an effective interaction for quarks was derived from this. This has been used very effectively to describe mesons and baryons, in a model as simple as the original constituent quark model [4].

The nucleon that emerges in the effective instanton interaction model of Shuryak and Rosner[4], for example, is three U quarks with constituent masses and a interaction between them for the spin singlet pairs. So in the Δ isobar the latter is absent and the constituent U mass should be just about one third of the isobar mass M_Δ, apart from a centre of mass correction. The form of the interaction that produces this is a short range $\delta(r)$ [3] that is about six times stronger than the conventional one-gluon-exchange (see for example Oka and Takeuchi [4]). So one can use this in the null plane formalism for three quarks, which behave like bosons after the colour antisymmetry is taken out, with a delta function force[5]. The ground state and the first excited state energies of the three particle system can now be given in terms of the constituent quark mass m_Q and the di-quark mass m_{Dq}, scaling out the strength of the delta function interaction. Now, given the quark mass and the nucleon mass, we can fit the diquark mass. This is given in Table 1 for a range of m_Q/m_{Dq}. The second excited state energy is close to $3m_Q$ and is thus omitted from the table.

One immediately gets interesting results (Table 1) in the sense that the two excited states of the nucleon can be predicted at 1300 MeV and 1480 MeV with the u-quark mass 493.7 MeV necessary to fit the nucleon. Further one can suggest that since there is practically no effect of the spin singlet interaction for the 2nd excited state, it should decay into $\Delta\ \pi$ and subsequently to $N\ \pi\ \pi$. Experimentally the first excited state of the nucleon is at 1440 MeV and decays most of the time to $N\ \pi$ whereas the second state at 1710 MeV decays mostly to $\Delta\ \pi$ and $N\ \pi\ \pi$ [6]. Thus the picture for the nucleon (anti-nucleon) that we

are going to use is the quark-diquark model, which has been very successful recently. See, for example, ref.[7].

We use this model to calculate the proton-antiproton going to $K\bar{K}$. Details may be found in [8]. The kaon wave-function in the null-plane has been recently parameterized [9] using the electromagnetic radius and weak decay constant. The beta parameter that goes into determining the size of the kaon has been taken to be 315.5 MeV and leads to $f_K = 113\ MeV$ and radius 0.514 fm.

An important point is the presence of the annihilation mechanism for the two kaon production, due to the strange quark[10]. The rearrangement mechanism does not contribute in this case. This allows a simplification in the model of the annihilation process, i.e., a pair of quarks is spectator in the kaon production. Thus, we describe the nucleon as one quark and a structureless diquark, for this first study of annihilation process in the context of the null-plane phenomenology.

The up-down spin-zero diquark concept has been recently probed in the study of the nucleon distribution amplitude with null-plane wave-functions[11] fitted to the results of QCD sum rules[12]. They found that the momentum scale of the wave-function of the scalar diquark is about eight times the corresponding scale for the relative wave-function of the third quark.

2 Details of the calculation

The purpose of this work is to make a first step in the study of the proton-antiproton annihilation process in the null-plane phenomenology. We obtain the matrix element of the transition operator of the proton-antiproton system into two charged kaons, using a schematic nucleon wave-function in terms of a quark and a scalar-diquark. The simplification provided by the quark-diquark wave-function allows to formulate the matrix element as a one-loop Feynman diagram. The next step is to integrate this diagram in the null-plane energy.

The null-plane proton, antiproton and kaon wave-functions are introduced in the amplitude according to the procedure of Ref.[13] . The initial-state interaction comes from a separable form of the Paris proton-antiproton potential [14]. No final-state interaction is accounted for the kaons.

We observe that the present approach, to the proton-antiproton annihilation process to two kaons, has the critical elements that will allow a more complete study in the context of the null-plane phenomenology.

We review the formulation of the nucleon one-loop diagram for the electromagnetic form-factor. The null-plane proton wave-function as a quark-diquark is introduced in the formulae after the integration over the null-plane energy. The normalization condition of the proton wave-function is also derived. Of course, a complete description of the nucleon wave-function is desirable, but this is beyond the scope of the present study.

The normalization of the quark-diquark null-plane wave function is obtained from the triangle diagram of the electromagnetic nucleon current. We use a constant vertex for the coupling of the proton to the quark-diquark fields. After the evaluation of the nucleon current, the coupling constants are properly substituted by the wave-functions, in analogy to the procedure discussed in [13].

The coupling of the nucleon to the quark and scalar-diquark fields is given by the effective Lagrangean:

$$\mathcal{L}_{N,q,D} = \Gamma_S \overline{N} q D^S + h.c., \tag{1}$$

where Γ_S is the coupling of the nucleon(N) to the quark(q) and scalar-diquark (D^S) fields.

The + component of the electromagnetic current ($J^+ = J^0 + J^3$) of the proton at momentum transfer, q^2, is given by triangle Feynman diagrams:

$$\begin{aligned} J_N^+(q^2) = & \, i\frac{2}{3} e\Gamma_S^2 N_C \int \frac{d^4k}{(2\pi)^4} \frac{1}{\not k + \not k_p - m_Q + i\epsilon} \gamma^+ \frac{1}{\not k + \not k'_p - m_Q + i\epsilon} \frac{1}{k^2 - m_S^2 + i\epsilon} \\ & + i\frac{1}{3} e\Gamma_S^2 N_C \int \frac{d^4k}{(2\pi)^4} \frac{1}{(k-k_p)^2 - m_S^2 + i\epsilon} \frac{2(k^+ + k_p^+)}{\not k - m_Q + i\epsilon} \frac{1}{(k+k'_p)^2 - m_S^2 + i\epsilon} , \end{aligned} \tag{2}$$

where m_Q and m_{Dq} are the masses of the quark and scalar-diquark, respectively. $N_C = 3$ is the number of quark colors. k_p^μ and $k_p'^\mu$ are the proton initial and final four-momentum; $k^+ = k^0 + k^3$ and $\gamma^+ = \gamma^0 + \gamma^3$. e is the proton charge.

The charge form factor is obtained when the Dirac-algebra and k^- integration are performed. We choose the Breit-frame, where $q^+ = q^0 + q^3 = 0$, $q^- = q^0 - q^3 = 0$ and only transversal momentum transfer $\vec{q}_\perp$ is non-zero. The result is

$$f_1(q^2) = \frac{\Gamma_S^2 m_N m_Q N_C}{4\pi^3} \int \frac{d^2K_\perp dx}{x(1-x)} \frac{1}{\left(m_N^2 - M_{0,N}^2\right)} \frac{1}{\left(m_N^2 - M_{0,N}'^2\right)}, \tag{3}$$

where m_N is the nucleon mass, $0 < x < 1$.

$$M_{0,N}^2 = \frac{K_\perp^2 + m_q^2}{x} + \frac{K_\perp^2 + m_S^2}{1-x} \tag{4}$$

is the square-mass of the free quark-diquark system, with relative transversal momentum $\vec{K}_\perp$, and the + component of the quark momentum has fraction x. $M_{0,N}'$ is free quark-diquark mass for the final proton, with the relative transversal momentum

$$\vec{K}_\perp' = \vec{K}_\perp + (1-x)\vec{q}_\perp. \tag{5}$$

The quark-diquark null-plane wave-function of the proton is introduced from the inspection of the result of the triangle diagram for the charge form-factor. We identify the nucleon bound-state wave function as

$$\Phi_N(M_{0,N}^2) = \frac{\Gamma_S}{m_N^2 - M_{0,N}^2} \left[\frac{m_N m_Q N_C}{4\pi^3}\right]^{\frac{1}{2}}. \tag{6}$$

The identification of the quark-diquark wave-function through Eq.6, above, is essential for the construction of the amplitude for the proton-antiproton annihilation in two charged kaons, as will be clear in the next section. In practical calculations a normalizable model wave-function is used instead Eq. 6, and the form-factor is free of divergence with the use of Eq. 7 below.

The charge form-factor, after the substitution of the proton bound-state wave-function in Eq.3, is

$$f_1(q^2) = \int \frac{d^2K_\perp dx}{x(1-x)} \Phi_N(M_{0,N}^2)\Phi_N(M_{0,N}'^2)\ , \tag{7}$$

with the normalization condition, $f_1(q^2=0)=1$.

3 The box diagram: $p\overline{p} \to K^+K^-$

The kaon couples to the constituent up and strange quarks via the pseudo-scalar coupling, which can be expressed in the following effective interaction Lagrangean

$$\mathcal{L}_{K,q} = -i\frac{m_Q}{f_K}K^+\overline{u}\gamma^5 s \; - i\frac{m_Q}{f_K}K^-\overline{s}\gamma^5 u \; , \tag{8}$$

where u and s are the up and strange quarks fields, respectively. The constituent up and strange quark masses were supposed equal. This assumption simplifies the algebra.

The transition amplitude for the annihilation process $p\,\overline{p} \to K^+\;K^-$ is diagrammatically represented by a box in which the diquarks are contracted with each other and a $s\bar{s}$ pair is created to couple with the other quark-antiquark pair to produce the K^+K^-.

We construct the transition amplitude using the effective Lagrangeans Eqs. 1 and 8, and obtain

$$\begin{aligned}\mathcal{T}_{p\overline{p}\to K^+K^-} = -\frac{m_q^2}{f_K^2}\Gamma_S^2 N_C \int \frac{d^4k}{(2\pi)^4}\mathcal{M}\left[(k+k_{\overline{p}})^2 - m_Q^2 + i\epsilon\right]^{-1} \\ \times\left[(k_K - k - k_{\overline{p}})^2 - m_q^2 + i\epsilon\right]^{-1} \\ \times\left[(k_p - k)^2 - m_Q^2 + i\epsilon\right]^{-1}\left[k^2 - m_{Dq}^2 + i\epsilon\right]^{-1} \; ,\end{aligned} \tag{9}$$

where the Dirac operator is given by

$$\mathcal{M} = (-\not{k} - \not{k}_{\overline{p}} + m_Q)\gamma^5(-\not{k} + \not{k}_K - \not{k}_{\overline{p}} + m_Q)\gamma^5(-\not{k} + \not{k}_p + m_Q) \; , \tag{10}$$

k_p^μ, $k_{\overline{p}}^\mu$ and k_K^μ being the four-momentum of the proton, antiproton and K^-, respectively.

We choose the center of mass frame (CM), and the z-direction is perpendicular to the scattering plane. This choice is the simplest to work with light-cone coordinates. The

momentum transfer of the proton-antiproton pair to the kaon pair is purely transversal. Such condition simplifies the integration over k^-. Recently a careful analysis[15] of the form-factor of a bound state of two bosons for longitudinal and transversal momentum transfer has shown that the integration over k^- gives the same answer in both cases. The + components of momentum of proton, antiproton and K^- are related according to

$$E = k_p^+ = k_{\bar{p}}^+ = k_K^+ , \tag{11}$$

where E is the CM proton energy.

The integration over k^- is straightforward and shown in ref.[8]. The result is

$$\mathcal{T}_{p\bar{p}\to K^+K^-} = -\frac{i}{(2\pi)^3}\frac{m_q^2}{f_K^2}\Gamma_S^2 N_C \int \frac{dx d^2k_\perp}{(1+x)(1-x)x^2}$$

$$\times \mathcal{M}\left[-2E^2 + \frac{(k_p-k)_\perp^2 + m_q^2}{1-x} + \frac{(k_{\bar{p}}+k)_\perp^2 + m_q^2}{1+x} - i\epsilon\right]^{-1}$$

$$\times\left[k_K^+ k_K^- - \frac{(k_p-k)_\perp^2 + m_q^2}{1-x} - \frac{(k_{\bar{p}}+k-k_K)_\perp^2 + m_q^2}{x}\right]^{-1}$$

$$\times\left[k_p^+ k_p^- - \frac{(k_p-k)_\perp^2 + m_q^2}{1-x} - \frac{k_\perp^2 + m_S^2}{x}\right]^{-1} , \tag{12}$$

where $x = k^+/E$, $0 < x < 1$ and

$$k^- = (E^2 - \frac{(k_p-k)_\perp^2 + m_q^2}{1-x})E^{-1} . \tag{13}$$

The next step is to evaluate the matrix element of $\mathcal{M}$,

$$< K^+K^- \mid \mathcal{M} \mid \bar{p}\, p >=< M_{\bar{p}} \mid i\sigma_2\vec{\sigma} \mid M_p > \cdot\vec{\mathcal{V}} . \tag{14}$$

The kaon state is determined by the final momentum in CM. The initial state is characterized by the initial proton CM momentum and the spin projections along z-direction, M_p and $M_{\bar{p}}$. σ_i are the Pauli-matrices.

$$\vec{\mathcal{V}} = 2\vec{k}_K E\left[(m_N+m_Q)^2 - \bar{m}_K^2\right] + 2\vec{k}E\left[m_q^2 - m_N^2 - \bar{m}_K^2 - 2\vec{k}\cdot(\vec{k}_K+\vec{k}_p)\right]$$

$$+2\vec{k}_p\ [\ (m_Q+m_N)(m_N^2 - m_q^2 + \bar{m}_K^2 + 2\vec{k}\cdot(\vec{k}_K+\vec{k}_p)) + \vec{k}_K\cdot\vec{k}_p\frac{\bar{m}_K^2-(m_N+m_Q)^2}{E+m_N}$$

$$+\ \vec{k}\cdot\vec{k}_p\frac{m_N^2 - m_q^2 + \bar{m}_K^2 + 2\vec{k}\cdot(\vec{k}_K+\vec{k}_p)}{E+m_N}\ ]\ , \tag{15}$$

where

$$\bar{m}_K^2 \ = \ x\ \left[E^2 - \frac{(k_p-k)_\perp^2 + m_q^2}{1-x}\right] - (\vec{k}_\perp)^2.$$

The vector $\vec{\mathcal{V}}$ has components in the x, y-plane; the component in z-direction vanishes because of the symmetry in the integrand in Eq. 10. The matrix element of $< K^+K^- \mid \mathcal{M} \mid \bar{p}\ p >$ is a pseudo-scalar as follows from the transformation properties under rotation and spatial reflexion of the transition amplitude, in agreement with the general structure presented in Eq. 9.

We insert the null-plane wave-functions of the proton, antiproton and kaons into Eq.12 . The coupling constants are substituted by

$$\Gamma_S = (m_n^2 - M_{0,N}^2)\Phi_N(M_{0,N}^2)\left[\frac{4\pi^3}{m_N m_Q N_C}\right]^{\frac{1}{2}}\ , \tag{16}$$

from Eq.6 for the nucleon and by

$$\frac{m_Q}{f_K} = (m_K^2 - M_{0,K}^2)\Phi_K(M_{0,K}^2)\left[\frac{\pi^3}{M_{0,K}N_c}\right]^{\frac{1}{2}}\ , \tag{17}$$

for the kaon.

The free square-mass operators for the quark-diquark system in the proton and antiproton wave-functions are assumed to be the same,

$$M_{0,N}^2 = \frac{(k_p-k)_\perp^2 + m_q^2}{1-x} + \frac{k_\perp^2 + m_S^2}{x} - (k_p)_\perp^2\ . \tag{18}$$

The free square-mass for the virtual constituent-quarks in the kaons is

$$M_{0,K}^2 = \frac{(k_p - k)_\perp^2 + m_q^2}{1-x} + \frac{(k_{\bar{p}} + k - k_K)_\perp^2 + m_q^2}{x} - (k_K)_\perp^2 \ . \tag{19}$$

The last two factors in Eq. 12 are functions of $(m_K^2 - M_{0,K}^2)$ and $(m_N^2 - M_{0,N}^2)$, once the substitutions

$$k_K^+ k_K^- = m_K^2 - (k_K)_\perp^2 \ , \tag{20}$$

and

$$k_p^+ k_p^- = m_p^2 - (k_p)_\perp^2 \ ,$$

are made.

The transition amplitude for the annihilation in two charged kaons, is obtained by the insertion of Eqs. 16 and 17 in Eq. 12. The result is

$$< K^+K^- \mid \mathcal{T}_{p\bar{p}\to K^+K^-} \mid \bar{p}p >=< M_{\bar{p}} \mid i\sigma_2\vec{\sigma} \mid M_p > \cdot \vec{\mathcal{I}} \tag{21}$$

where,

$$\vec{\mathcal{I}} = -i\frac{\pi^3/2}{m_Q m_N N_C}\int \frac{dx d^2k_\perp}{(1+x)(1-x)x^2}\vec{\mathcal{V}}\Phi_K^2(M_{0,K}^2)\Phi_N^2(M_{0,N}^2)\frac{(m_K^2 - M_{0,K}^2)(m_N^2 - M_{0,N}^2)}{M_{0,K}}$$

$$\times\left[-2E^2 + \frac{(k_p - k)_\perp^2 + m_q^2}{1-x} + \frac{(k_{\bar{p}} + k)_\perp^2 + m_q^2}{1+x} - i\epsilon\right]^{-1} . \tag{22}$$

We call the attention of the reader to the energy denominator in Eq. 22 . It is the free propagator for the quark-antiquark system carrying the total mass of the system, as the result of the proton-antiproton annihilation.

The normalization of the cross-section is as follows

$$\frac{d\sigma}{d\Omega} = \frac{k_K m_N}{64(2\pi)^2 E^3 k_p} \ |< K^+K^- \mid \mathcal{T}_{\bar{p}p\to K^+K^-} \mid \bar{p}p >|^2 \ , \tag{23}$$

where $E = \sqrt{k_p^2 + m_N^2}$.

4 Numerical results

Our numerical calculations of the K^+K^- production cross-sections take into account the initial state-interaction between the proton and antiproton. The great importance of the proton-antiproton initial interaction for the two-meson production channel, has been shown in Ref. 16 in a quark model. The calculations of meson production in the framework of effective Lagrangeans for the meson-baryon system[17] contain the nucleon-antinucleon initial state-interaction. For this purpose, we use the separable expansion of the G-parity transformed Paris N-N potential, with a coupled-channel two particle decay channel per isospin state, developed in ref.[14]. Their model reproduces the total, elastic and charge-exchange cross-sections up to 530 MeV/c of antiproton laboratory momentum. The proton and antiproton are supposed to be on-mass-shell in the elementary amplitude for the kaon production in the evaluation of the initial-state distorted matrix elements.

The kaon and proton null-plane wave-functions are of Gaussian-form

$$\Phi(M_0^2) = e^{-M_0^2/8\beta^2} \ , \tag{24}$$

where M_0^2 is the square free-mass for the quark-antiquark and quark-diquark systems, for the kaon and nucleon wave-functions, respectively. The null-plane model of ref.[9] with Gaussian wave-function for the pion and kaon, used constituents masses of 330MeV for the u and d quarks and 450MeV for s quark. We supposed equal constituent masses for up and strange quarks with value of 493.7MeV. We fit the decay constant of the kaon with $\beta_K = 315.5$MeV which gives a mean-square kaon charge radius of 0.26 fm^2 compared to the experimental value of (0.34±0.05) fm^2[25]. Our value of β_K is comparable to the average value of 320MeV for the neutral and charged kaons quoted in ref.[9] .

The value of β_p for the proton wave-function is chosen to be 863 MeV. The proton charge radius is 0.32 fm. For the consistency of our arguments the calculated proton charge radius must be smaller than the experimental value of (0.81±0.04) fm [26] by considering that part of the nucleon size is given by the diquark. The total production cross-section of K^+K^-

for the antiproton laboratory momentum of 390MeV/c is $\sigma_{K^+K^-} = 0.21$ mb compared to a experimental value of about 0.2 mb (see fig. 1). In fig. 1, the cross-section for the production of two charged kaons is shown together with the available data for laboratory momentum below 900MeV/c. Data below 300MeV/c are desirable to verify the model prediction.

To summarize : our results show that the null-plane approach [9,13,18], well succeeded in the electromagnetic and weak processes, can be still pursued in reactions with strongly interacting hadrons and can be easily formulated for other processes.

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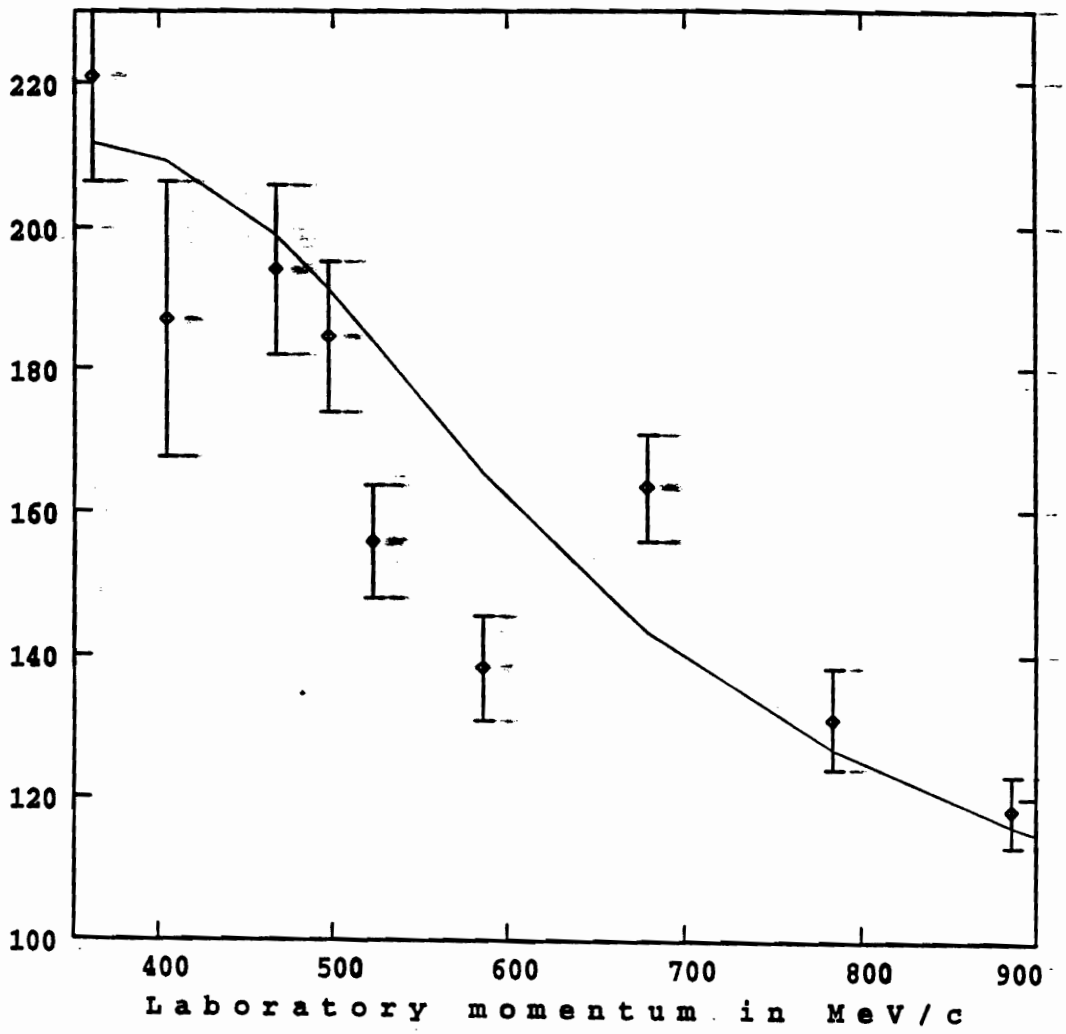
Table 1: Three body ground state and excited state energies, in units of quark mass, as a function of ratio of diquark/quark masses

m_{Dq}/m_Q	M_{ground}	$M_{excited}$
1	1.568	1.825
1.20	1.620	1.970
1.40	1.680	2.147
1.60	1.771	2.360
1.80	1.900	2.640
1.90	2.020	2.785
1.95	2.100	2.887

Figure Captions

Fig. 1 Total K^+K^- production cross-section as a function of laboratory momentum. Experimental data are from [19]. Our results are shown by the solid line.


220
200
180
160
140
120
100
400
500
600
700
800
900
Laboratory momentum in MeV/c