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Scaling particle-antiparticle production in Cosmic Rays

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Abstract

The momentum distributions of Cosmic Ray particles are analyzed using the partition temperature T_p model of Chou, Yang and Yen. It is found that the scaling of $< P >$ holds for electrons, positrons and protons of the AMS experiment: $< P >_{e^+} \approx < P >_{e^-} \approx \frac{1}{4} < P >_p$ indicating that e^+ and e^- are pair production from $\pi^0 \to \gamma + \gamma$, with $\gamma \to e^+ + e^-$ and that T_p determined by $< P >$ for π^0's is the same for protons, comparable to that of $Z^0(91) \to \pi^+\pi^- + ...$ of the CERN-LEP experiments. For solar $\bar{\text{p}}$ and p of the BESS experiment, the proton spectrum resembles that of AMS, its $< P >$ is about the same as that of $\bar{\text{p}}$ within $\sim$ 2 s.d., just like particle-antiparticle production. The scaling property revealed by these Cosmic Ray particles suggests their origin from Z^0's emitted during the star evolution.

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1 Introduction

Among Cosmic Ray particles of various kinds, electrons and protons are a great majority. Their antiparticles exist also, but in different proportions: $e^+/e^- \approx 4$, due to deflections by Earth's magnetic field, whereas $\bar{p}/p \simeq 10^{-5}$ due to annihilations of $\bar{p}$ by cosmic dusts. There remains this question: Is the CP invariance valid for Cosmic Ray particle production? We recall that in the case of pair-production in high energy interactions, the c.m. momentum is the same for the particle and the antiparticle but in the opposite direction, according to the CP invariance. Therefore the average momentum should be the same for both particle and antiparticle. It is imperative to investigate this fundamental property for Cosmic Rays electrons and positrons on the one hand, and protons and antiprotons, on the other hand.

Experimentally, the momentum measurements of Cosmic Ray particles cover only a portion of the kinematic range for the particle under consideration. Therefore, an exact form to describe its spectrum is needed in order to make a reliable estimate of the average momentum, which determines the partition temperature for particle production of the Chou, Yang and Yen model [1]. For this purpose we assume the production process to be stochastic and use the lognormal distribution in terms of Log P, to describe the single-particle momentum spectrum and estimate the average momentum according to the fit (Sect. 2).

We present in this paper results of analysis of recent data of high altitude Cosmic Ray experiments. For electrons, positrons and protons of the AMS Collaboration [2], the average momentum, $< P >$, for e^+ and e^- is found to be the same, despite of the positive excess, so that they are from $\pi^0 \to \gamma + \gamma$ with $\gamma \to e^+ + e^-$ through their passage in the stellar space. This $< P >$ of $e^\pm$ amounts to $\simeq 1/4$ of that of proton, indicating that the π^0's which decay into $\gamma's$ giving rise to $e^\pm$, therefore the π's themselves, have the same partition temperature as the protons, (Sect. 3). For solar antiprotons and protons of the latest balloon flight experiment of the BESS Collaboration [3], we find the width of their distributions about the same within ~ 1 standard deviation and $< P >_{\bar{p}} \simeq < P >_p$ within ~ 2 standard deviations, indicating pair-production of proton-antiproton from the Sun (Sect. 4).

A comparison of the proton momentum spectrum from the AMS and the BEES experiments indicates that they are similar, the former has its $< P >$ consistent with that of π's from the $Z^0(91) \to \pi^+\pi^- + ...$ of the ALEPH Collaboration [4] (Sect. 2). This gives strong feeling that the Cosmic Ray protons are from the decays of some gauge bosons emitted by stars in their evolution (Sect. 5).

2 The scaling of momentum spectrum

We discuss the scaling property for the single-particle momentum distribution of non-diffractive high energy interactions and present an adequate statistical distribution to describe its structure. Consider, v.e., $e^+ + e^- \to \pi^+\pi^- + ...$ at $\sqrt{s} = 91$ GeV of a CERN-LEP experiment by the ALEPH Collaboration [4], their normalized $z = 2P/\sqrt{s}$ distribution is shown in Fig. 1. Following the partition temperature model of Chou, Yang and Yen [1], we assume the process to be stochastic and describe the momentum spectrum with a lognormal distribution in terms of the scaling variable

$$\zeta = \mathrm{Log} P, \tag{1}$$

which represents the invariant phase-space of the particle under consideration,

$$\frac{dn}{NdP} = Ae^{-(\zeta+\zeta^*)^2/L} \tag{2}$$

where ζ^* denotes the position of the maximum, L is the width of the distribution and A is the normalization coefficient.

The parameters determined by the least-squares fit are

$$\zeta^* = 0.547 \pm 0.015, \;\; L = 0.247 \pm 0.010, \;\; A = 502.2 \pm 4.5.$$

The fit as shown by the curve is very satisfactory, especially in the very small P region near the origin (see the insert) up to $\sim$ 8 GeV/c, covering about 85 percent of the data.

The average momentum according to the fit is:

$$< P >= 2.337 \pm 0.088 \; GeV/c,$$

which determines the partition temperature T_p of single-particle production [5].

Clearly, the estimation of $< P >$ depends on the range covered by P. If we cut off the data at P_{cut}, the corresponding average $< P >_{cut}$ for $P \leq P_{cut}$ will be less than the average for the entire range without cut-off. The behavior of $< P >_{cut}$ as a function of P_{cut} is shown in Fig. 2. We see that it increases monotonically with the cut-off and reaches a plateau at $P \simeq 15$ Gev/c, in the vicinity of the inflection point of the spectrum, which takes place at

$$\zeta_{inf} = \sqrt{2L} + \zeta^* \tag{3}$$

corresponding to

$$P_{inf} = 17.78 \pm 1.05 \; GeV/c.$$

in Fig. 1. Assuming an exponential behavior, we may write

$$< P >_{cut}= C(1 - e^{aP_{cut}}), \tag{4}$$

and obtain by least-squares fit

$$a_\pi = 0.249 \pm 0.025 \; (GeV/c)^{-1}, \;\; C_\pi = 2.144 \pm 0.074 \; GeV/c,$$

the fit is shown by the solid curve. The end points are slightly above the plateau, probably due to diffractive production of pions.

It is interesting to note that the coefficient a of P_{cut} in the exponent of Eq. (4), characteristic of the scaling of the momentum distribution, turns out to be the same as that for the average multiplicity of hadrons from the inclusive pp collisions as well as $\bar{p}$p annihilations, as reported elsewhere [6]. Indeed, $< n > \sim < P >$ by definition and in view of

$$\int_0^{P_{cut}} e^{-ax}dx = \frac{1}{a}(1 - e^{aP_{cut}}), \qquad (5)$$

the relationship (4) implies a Poisson-type distribution for the average multiplicity of π production by high energy interactions, as has been known experimentally.

3 Electrons, positrons and protons of Cosmic Rays

We now analyze the momentum distributions of electrons, positrons and protons at the top of the atmosphere (altitude about 300 km, residual atmospheric matter $1.5 g/cm^2$) of the AMS Collaboration [2]. Their flux measurements (in particles/$(m^2 sr sec GeV/c)$ are shown in Fig. 3(a) and (b). The curves represent the least-squares fits with the lognormal distribution, Eq. (2). The parameters are summarized in Table I, together with the estimates of average momentum according to the fits.

Table I - Parameters of lognormal distributions, Eq. (2), for electrons, positrons and protons of the AMS Collaboration [2] and the estimate of the average momentum $< P >$ (in GeV/c), A in particles/$(m^2 sr sec GeV/c)$.

	electrons	positrons	protons
ζ^*	0.665 ± 0.044	0.593 ± 0.015	0.350 ± 0.246
L	0.144 ± 0.013	0.121 ± 0.004	0.240 ± 0.060
A	208.1 ± 13.9	913.0 ± 19.1	0.136 ± 0.057
$< P >$	0 .626 ± 0.004	0.623 ± 0.007	2.911 ± 0.456

A comparison of the parameters for electrons and positrons indicates that the estimates of ζ^* and L are practically the same. However, the normalization coefficients, therefore their intensities, are quite different, due to the geomagnetic field in the stellar space, the positive excess being

$$\frac{e^+}{e^-} \simeq \frac{A_{e^+}}{A_{e^-}} = 4.39 \pm 0.07.$$

On the other hand, the average momentum $< P >$ computed from the fits is the same for both e^+ and e^-, to the point that their normalized spectra may be superposed into one pattern, as can be seen from the plots of $< P >_{cut}$ against the cut-off on P as shown in Fig. 4(a). The curve is an overall fit to both e^+ and e^- according to Eq. (4) with

$$a_e = 1.107 \pm 0.016\ (GeV/c)^{-1},\ \ C_e = 0.658 \pm 0.004\ GeV/c.$$

We therefore conclude

$$< P >_{e^-} = < P >_{e^+},$$

namely, these electrons and positrons of the AMS experiment are particles and antiparticles from the decays of $\pi^0 \to \gamma + \gamma$, with $\gamma \to e^+ + e^-$ during their traversal in the stellar space.

$$< P >_e = \frac{1}{2} < P >_\gamma = \frac{1}{4} < P >_\pi . \qquad (6)$$

Turn next to the protons, the distribution as shown in Fig. 3(b) is much broader than those of e^+ and e^-. The curve is a fit with Eq. (2), the parameters are listed in Table I.

The ratio of average momentum of p and $e^\pm$ is about 4:

$$\frac{< P >_p}{< P >_e} = 4.658 \pm 0.730.$$

The behavior of $< P >_{cut}$ for the protons as shown in Fig. 4(b) is also different from the electrons, as can be seen in Fig. 4(b); the parameters of the exponential fit with (4) are:

$$a_p = 0.249 \pm 0.016\ (GeV/c)^{-1},\ \ C_p = 2.760 \pm 0.064\ GeV/c.$$

Here, $C_p/C_e = 4.195 \pm 0.670$ is consistent with 4, therefore $< P >_e = < P >_p /4$ so that

$$< P >_\pi = < P >_p , \qquad (7)$$

thus π^0's which decay into γ's then lead to e^+ and e^- have the same $< P >$ as the protons, in other words, the same partition temperature, therefore they are from the same interaction.

Furthermore, $< P >_\pi$ here found is comparable to that of $Z^0(91) \to \pi^+\pi^- + ...$ as mentioned in the previous section. Thus, the particles measured by the AMS experiment may originate from a source like Z^0.

Now, it is remarkable that the coefficient a_p here found is exactly the same as a_π we have got for pions from the $Z(91)$ decay in the previous section. As the partition temperature governs the particle production by equipartition, it remains the same, i.e. independent of the mass of the particle, as predicted by the model of Chou, Yang and Yen [1] for inclusive $e^+ + e^- \to$ hadrons.

To sum up, the scaling properties of momentum distributions of electrons, positrons and protons of Cosmic Rays of the AMS experiment [2] give strong indication that the electrons and the positrons are pair-production by γ rays from the decays of π^0's, these π^0's together with the charged ones i.e., $\pi^{\pm}$, being produced with the protons; probably there are other hadrons as well, but not observed in the experiment. That the partition temperature of these Cosmic Ray particles, pions and protons, is comparable to that of $\pi^{\pm}$ of the decay of Z^0, suggests their origin from the fragmentation of a particle like the gauge boson Z^0 emitted by the explosion of a star.

4 Protons and antiprotons from the Sun

We now analyze protons and antiprotons of the latest balloon flight experiment (altitude $\sim$ 5 km, residual atmospheric matter $\sim 5g/cm^2$) of the BEES Collaboration during the maximum solar activity in 2000 [3]. Their data are shown in Fig. 5. The curves represent fits with the lognormal distributions, Eq. (2), the parameters and the averages $< P >$ are listed in Table II.

Table II - Parameters of lognormal distributions, Eq. (2), for antiprotons and protons of the BEES Collaboration [3] and the estimate of the average momentum $< P >$ (in GeV/c).

	antiprotons	protons
ζ^*	0.496 ± 0.062	-0.218 ± 0.007
L	0.110 ± 0.041	0.098 ± 0.006
A	(2.845 ± 0.013)/100	(2.29 ± 0.04).100
$< P >$	2.885 ± 0.213	2.488 ±0.198

The statistical errors for antiprotons are rather large. Nonetheless, their average momentum is approximately the same

$$< P >_{\bar{p}} \simeq < P >_p . \tag{8}$$

within about 2 standard deviations.

Note that the estimates of $< P >$ are rather biased by the statistics, as the data cover only a limited momentum range for an interval from 0.695 GeV/c to 4.726 GeV/c.

The baryon-antibaryon asymmetry computed by integrating the spectra leads to

$$\frac{\bar{p}}{p} = \frac{(1.129 \pm 0.119).10^{-2}}{(2.487 \pm 0.198).10^2} = (4.540 \pm 0.528).10^{-5}. \tag{9}$$

The dependence of the average momentum on the cut-off is shown in Fig. 6. The curves represent exponential fits according to Eq. (4). The parameters for antiprotons are

$$a_{\bar{p}} = 0.157 \pm 0.104 \ (GeV/c)^{-1}, \ \ C_{\bar{p}} = 5.43 \pm 2.75 \ GeV/c,$$

and for protons

$$a_p = 0.020 \pm 0.043 \ (GeV/c)^{-1}, \ \ C_e = 3.92 \pm 0.54 \ GeV/c.$$

We find

$$a_{\bar{p}} \simeq a_p \tag{10}$$

within ~ 1.5 standard errors. Therefore, the antiprotons and the protons in the BESS experiment are pair-production of particles and antiparticles from the Sun, a majority of $\bar{p}$'s being annihilated by collisions with the stellar dust during their traversal to reach the Earth.

Finally, we note that the shape of this proton spectrum is similar to that of the AMS experiment in Fig. 3(b). Indeed, if we compute the average momentum for AMS data with $P < 4.726$ GeV/c as in the BEES case, we get 2.017 ± 0.017 GeV/c in agreement with the value in Table II. This similarity of the proton spectrum for the AMS and the BEES experiments indicates their origin from similar interactions.

5 Conclusion

We have used the scaling property for the average momentum $< P >$ of single-particle production according to the partition temperature model of Chou, Yang and Yen [1] to test particle-antiparticle production in Cosmic Rays. The momentum distributions are analyzed using lognormal distributions in terms of the scaling variable Log P.

For electrons, positrons and protons of the satellite experiment of the AMS Collaboration [2], we find $e^+/e^- \sim 5$, $< P >_{e^+} = < P >_{e^-} \simeq < P >_p$, indicating that the electrons and the positrons are from the decays of $\pi^0 \to \gamma + \gamma$ with $\gamma \to e^+ + e^-$. As the average momentum of π^0 is the same as that of the proton, they have the same partition temperature and originate from the same interaction. This $< P >$ turns out to be comparable to that of $Z^0(91) \to \pi^+ + \pi^- + ...$ of the CERN-LEP experiment [4]. Thus the energy of the source of e^-, e^+, and p of the AMS experiment is $\sim Z^0$ mass.

For protons and antiprotons of the balloon flight experiment of the BEES Collaboration [2], we find $< P >_p \simeq < P >_{\bar{p}}$ within ~ 2 standard deviations, indicating that they are produced as pairs of particle-antiparticle. The extremely large asymmetry $\bar{p}/p \sim 10^{-5}$ is due to annihilations of antiprotons by the stellar dust during their traversal in space from the Sun to the setup for measurement.

The range of the proton momentum is rather limited in the BEES data. Nonetheless, its shape is found to be similar to that of the AMS experiment, indicating the same partition temperature for both experiments.As $< P >_p$ of AMS is consistent with $< P >_\pi$ of $Z^0 \to \pi^+ + \pi^- + ...$, therefore the origin of the Cosmic Ray particles observed in the AMS and the BEES experiments may be some Z^0 bosons emitted by stars during their evolution.

Acknowledgements

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References and Footnotes

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[6] T, F. Hoang, Phys. Rev. D 24, 1409 (1981) and Zeit. fur Phys. C 57, 655 (1993). For inclusive $p/\bar{p} \to h + ...$, at c.m. energy $\sqrt{s} = 2m_p\gamma_{cm}$, the average multiplicity for particles of mass m is given by $n = c.(m/m_\pi)^2(E^* - \Delta\, m)$, where $E^* = \sqrt{s}/\gamma^* - 2m_{p},$, $\gamma^* = \gamma_{cm}/2\sqrt{\gamma_{cm} - 1}$ being the Lorentz factor of the fire-ball and $\Delta\, m$ is the threshold energy: $\Delta m = 2.m$ for pair production of particle-antiparticle, whereas $\Delta m = m$ for self-charge-conjugate particle production. The coefficient c depends on the flavor of the particle, $c(m) = 2Exp(-\mu/\Theta)$, μ being the chemical potential and Θ the temperature: $\Theta = 0.140$ GeV for flavorless particles and 0.240 Gev for charm particles.

Figure Captions

[1] The momentum spectrum of inclusive $e^+ + e^- \rightarrow \pi^+\pi^- + ... at \sqrt{s} = 91$ GeV, ALEPH Collaboration, Ref. [2]. The curve represents a least-squares fit with a lognormal distribution in terms of the invariant phase space Log P(GeV/c). The partition temperature is given by $< P > = 2.337 \pm 0.188$ GeV/c.

[2] Plot of $< P >_{cut}$as a function of the cutoff on the momentum P_{cut}(in GeV/c). The curve is an exponential fit: $C(1 - e^{-aPcut})$ with $a = 0.299 \pm 0.025 (GeV/c^{-1})$ and C = 1.144 ± 0.074 GeV/c.

[3] Momentum distributions of electrons, positrons and protons of the AMS Collaboration [2]. The curves are fits using the lognormal distribution, Eq. (2). The parameters are listed in Table I.

[4] Dependence of the average momentum on the cut-off on the spectrum, $P < P_{ct}$ for e^+, e^- and p of the AMS Collaboration [2]. The curves are exponential fits with Eq. (4), see text.

[5] Momentum distributions of solar antiprotons and protons of the BEES Collaboration [2]. The curves are fits using the lognormal distribution, Eq. (2). The parameters are listed in Table II.

[6] Dependence of the average momentum on the cut-off on the spectrum, $P < P_{ct}$ for $\bar{p}$ and p of the BEES Collaboration [3]. The curves are exponential fits with Eq. (4), see text.

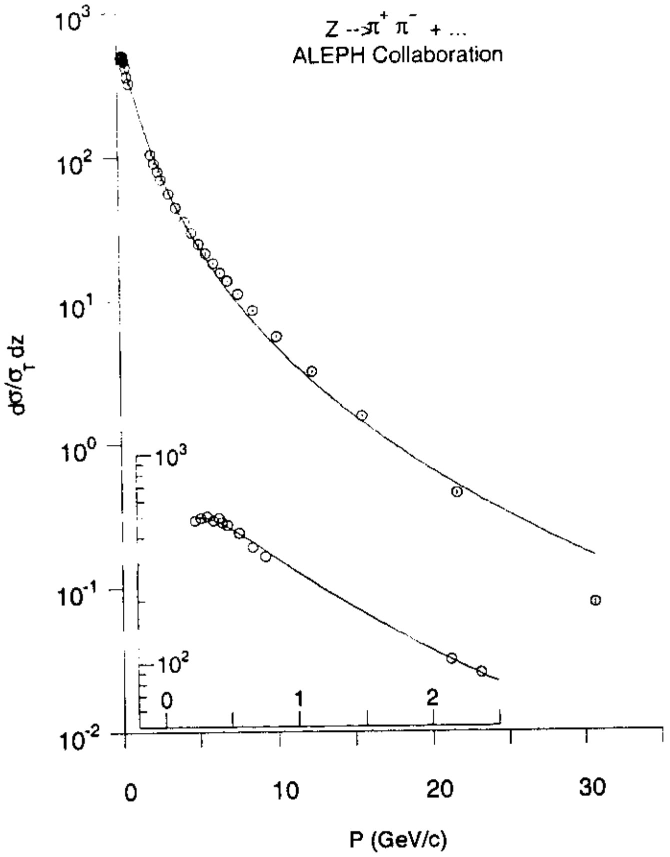
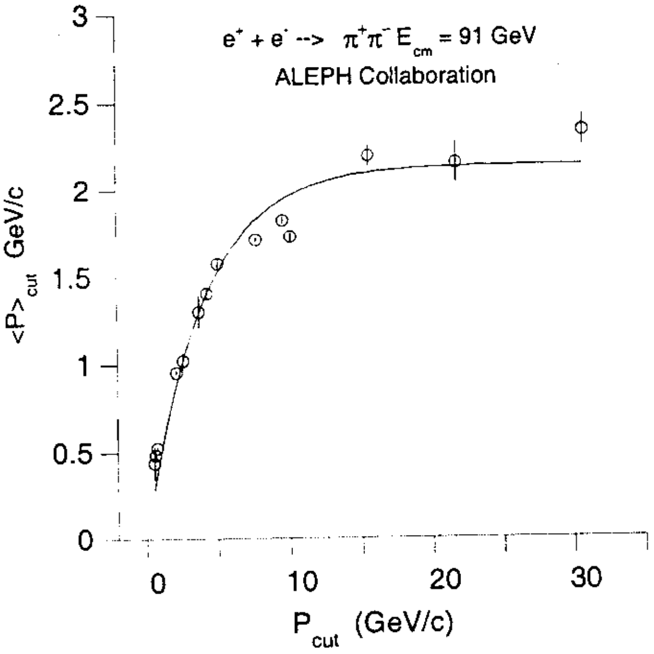

$Z \to \pi^+\pi^- + \ldots$
ALEPH Collaboration
$d\sigma/\sigma_T dz$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^3
10^2
0
1
2
0
10
20
30
P (GeV/c)

Fig. 1


$e^+ + e^- \to \pi^+\pi^-$ E_{cm} = 91 GeV
ALEPH Collaboration
$\langle P\rangle_{cut}$ GeV/c
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2.5
2
1.5
1
0.5
0
0
10
20
30
P_{cut} (GeV/c)

Fig. 2

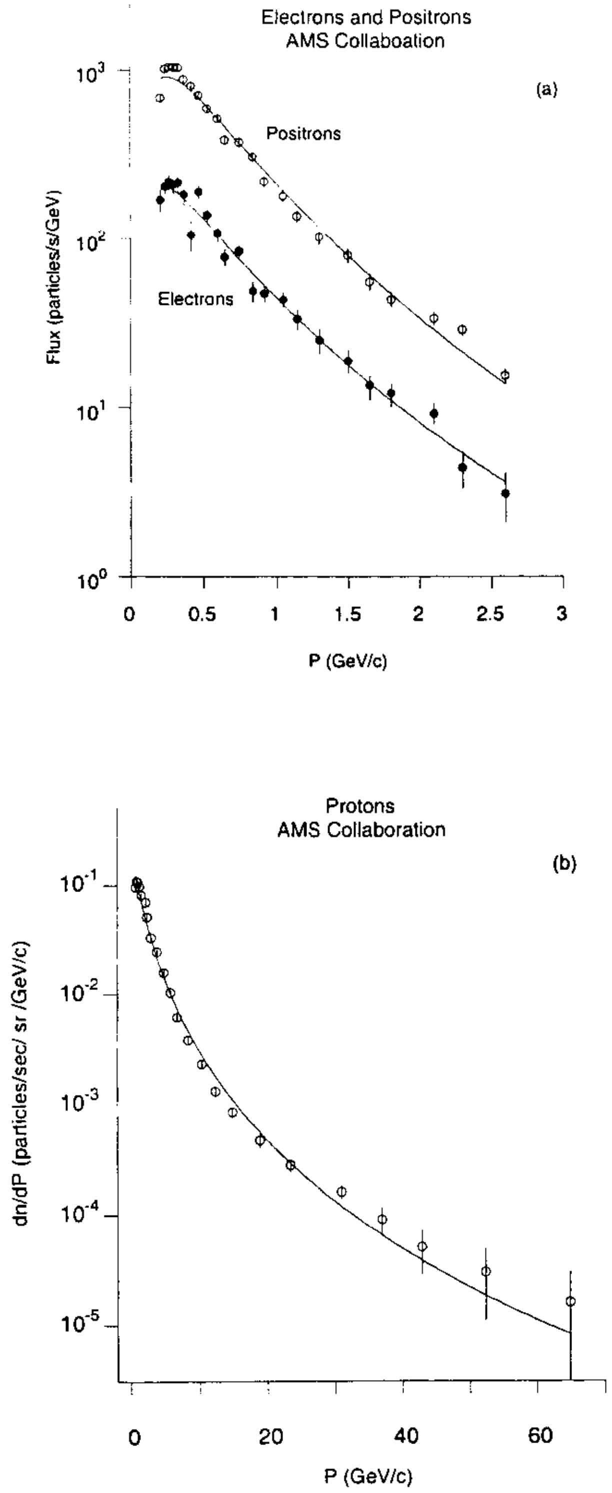
Electrons and Positrons
AMS Collaboation
(a)
Positrons
Electrons
Flux (particles/s/s/GeV)
10^0
10^1
10^2
10^3
0
0.5
1
1.5
2
2.5
3
P (GeV/c)
Protons
AMS Collaboration
(b)
dn/dP (particles/sec/ sr /GeV/c)
10^-1
10^-2
10^-3
10^-4
10^-5
0
20
40
60
P (GeV/c)

Fig.3

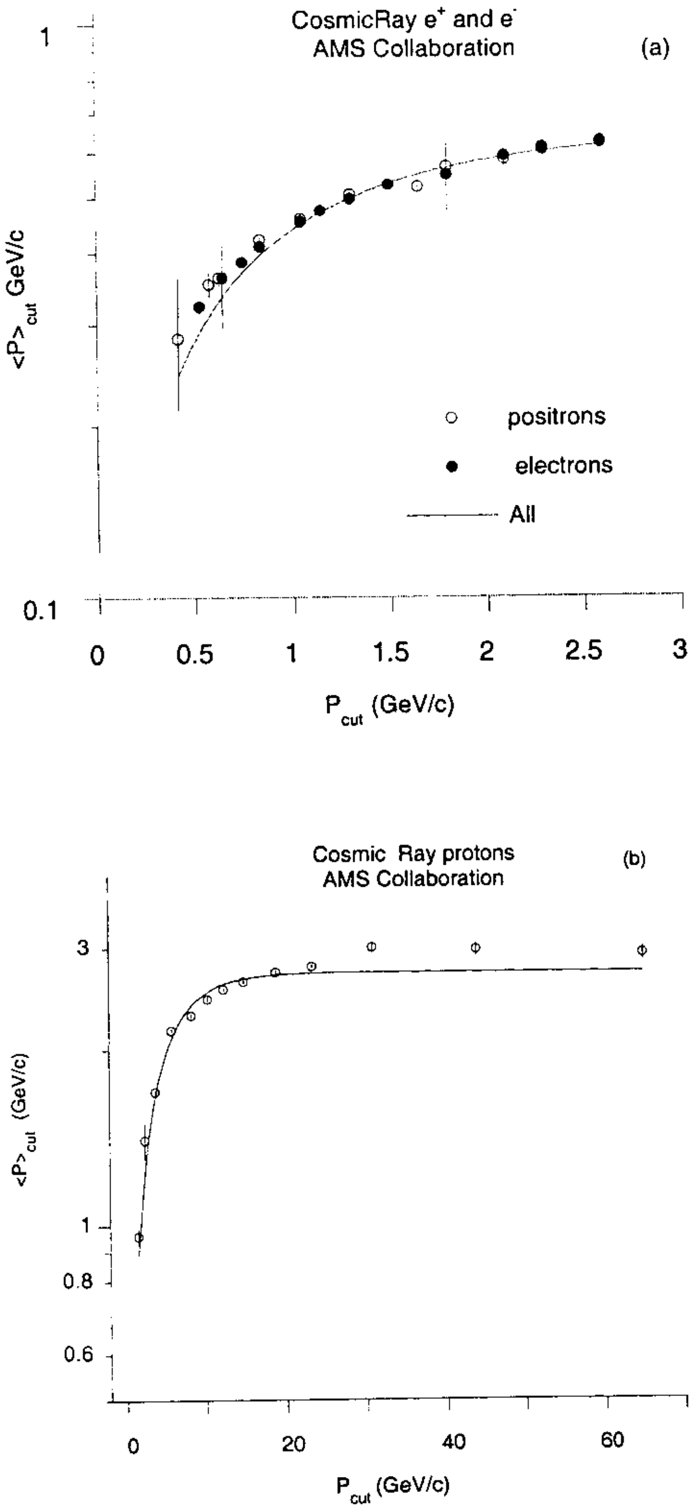
CosmicRay e^+ and e^-
AMS Collaboration
(a)
$\langle P \rangle_{cut}$ GeV/c
1
0.1
0
0.5
1
1.5
2
2.5
3
P_{cut} (GeV/c)
○ positrons
● electrons
All
Cosmic Ray protons
AMS Collaboration
(b)
$\langle P \rangle_{cut}$ (GeV/c)
3
1
0.8
0.6
0
20
40
60
P_{cut} (GeV/c)

Fig.4

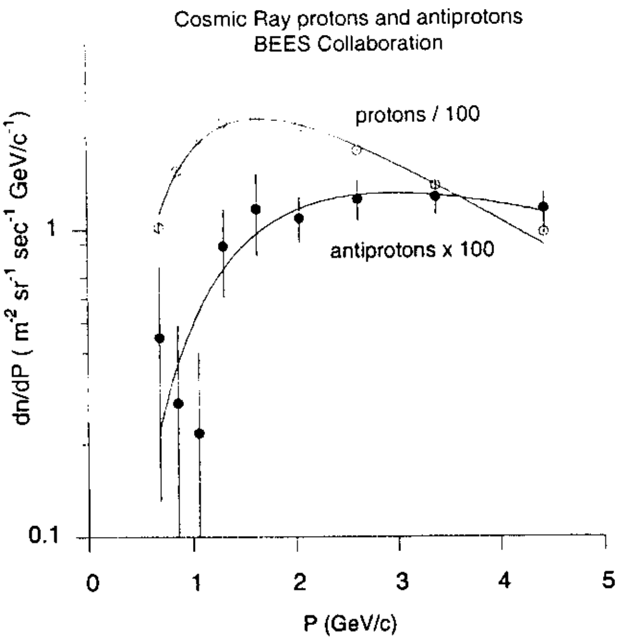
Cosmic Ray protons and antiprotons
BEES Collaboration
protons / 100
antiprotons x 100
dn/dP (m^2 sr^{-1} sec^{-1} GeV/c^{-1})
1
0.1
0
1
2
3
4
5
P (GeV/c)

Fig. 5

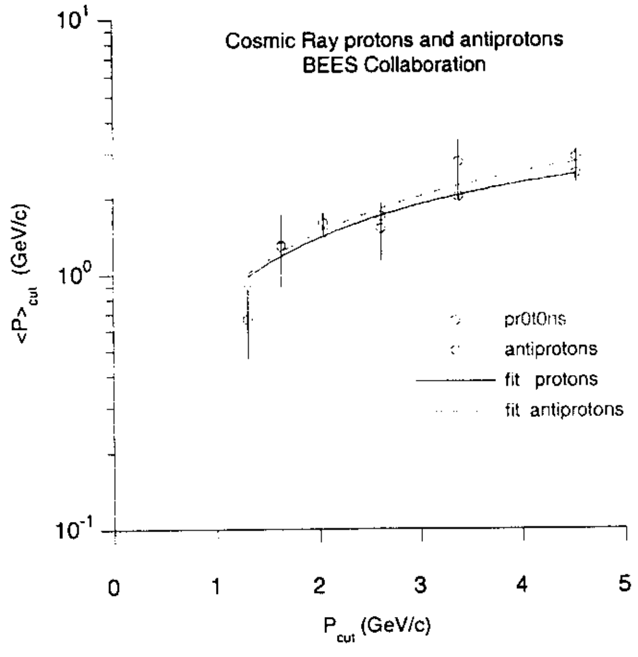
Cosmic Ray protons and antiprotons
BEES Collaboration
10^1
10^0
10^{-1}
$<P>_{cut}$ (GeV/c)
protons
antiprotons
fit protons
fit antiprotons
0
1
2
3
4
5
P_{cut} (GeV/c)

Fig. 6