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CENTAURO EVENTS AND MULTIPLE PRODUCTION PHENOMENA AT $10^{14} - 10^{16}$ eV ENERGY

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The main characteristics of the exotic events like *Centauro* and *Mini-Centauro* have been studied within a scheme of multiparticle production phenomena at high energy where $\langle n_\pi \rangle \sim S^{1/3}$ (S in GeV^2) and $F_{N\pi} = 1.062 \exp [- 2.38 \langle n_\pi \rangle x]$. Here the two different processes: i) the production of baryon-antibaryon pairs from secondary real pions and ii) the direct baryon and antibaryon production in pp scattering have been suggested to explain these events. The observed $\langle P_T \rangle$ in these two processes have been found to be in nice agreement with experiments.

1. Introduction

The exotic events like *Centauro* and *Mini-Centauro* events, first reported by Brazil-Japan collaboration (Denver Conference, 1973) in Mt. Chacaltaya emulsion exposures[1] have drawn much attention regarding their rational interpretations. Later on also two other famous experimental groups[2] reported the same type of events together with some more new types of interesting exotic events. Three classes of explanation for *Centauro* events have been proposed so far in a broad way: (1) Those involving a new kind of interactions[3,4,5,12] of ordinary hadrons beyond some threshold energy.

(2) Those may be due to fluctuations effects in the development of cascade air showers[6].

(3) Those may be due to heavy primaries at that energy range[7].

Among these interpretations, many authors[8] considered the high $\langle P_T \rangle$ of these events as an important clue to the nature of the process involved in these events. A value of $\langle P_T \rangle = 1.7 \pm 0.7$ GeV/c for hadrons produced in *Centauro* interactions is claimed. But it is still a difficult task to explain all the structures reported[8] until now in a consistent way.

In this note, we shall try to understand these events in the framework of a multiparticle production mechanism which can explain all the features of *Centauro* and *Mini-Centauro* events in a consistent way. To start with, we shall recapitulate very briefly this new framework of multiparticle production mechanism depending upon which an attempt to the main characteristics of *Centauro* and *Mini-Centauro* events will follow.

According to this new framework of hadronic interactions and the multiparticle production phenomena as proposed and developed by Bandyopadhyay et al.[10], FEYNMAN scaling is not exact but may be taken to be approximately valid in ISR range. The inclusive distributions as well as $x \left(\frac{\mathrm{d}\sigma}{\mathrm{d}x}\right)$ [x for FEYNMAN variable] for $pp \to \pi^\pm X$, $pp \to p\bar{p}$, $p\bar{p} \to K^\pm X$ have been evaluated explicitly so that the average multiplicity comes out as $\langle n_\pi \rangle \sim S^{1/3}$ where $S = 2\,E_{lab}$ and is expressed in GeV^2. Though almost all the workers identified the observed charged hadrons as baryons, Bellandi Filho et al.[11] and also others suggested nucleons and antinucleons as most suitable and probable candidate for the experimentally observed hadrons in *Centauro* and *Mini-Centauro* events. So let us concentrate to study two different processes by which nucleons and antinucleons can be produced in this framework[10]. For this, we have to consider the following two processes:

(1) Processes produced from high energetic real pions.

(2) Processes which arise due to direct baryon-antibaryon production in pp scattering.

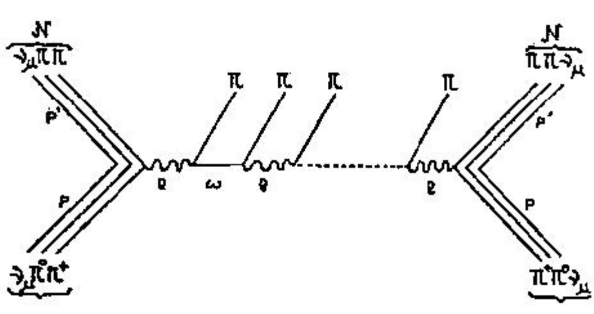

Fig. 1. Multiple pion production in pp scattering.

Process 1: The following diagram (Fig. 1) shows the inclusive pp scattering with the production of secondary pions according to this scheme. Here the pions are produced through the production of ϱ, ω π chain and thus the energy of incoming interaction protons decreases. (Details are in Ref. 10.)

The inclusive cross section for $pp \to pX$ process becomes

$$E \frac{d\sigma}{d^3 p}\bigg|_{pp \to \pi^- X} = 88.87 \exp\left[-\frac{26.88}{\langle n_{\pi^-}\rangle} \cdot \frac{P_T^2}{1-x}\right] \exp\left[-2.38 \langle n_{\pi^-}\rangle x\right] \tag{1}$$

where x = FEYNMAN-variable and $a_{in} = 35\ \mathrm{fm}^{-2}$ at $S = 1000\ \mathrm{GeV}^2$. For total pion production $\langle n_{\pi^-}\rangle = \frac{1}{3} \langle n\rangle_\pi$, where

$$\langle n\rangle_\pi = 1.05\, S^{1/3} = 1.05\,(2\, E_{lab})^{1/3} \text{ (Details in Ref. 10).} \tag{2}$$

Now the inclusive cross sections when integrated over transverse momentum and normalized to pair inelastic cross section (in case of air-shower cascade) are the production cross section through which high energy multiparticle production phenomena enter onto the cascade equations. The relevant coupled equations for the hadronic cascade in its simplified form can be written as

$$\frac{dN(E,y)}{dy} = -\frac{N(E,y)}{\lambda_N(E)} + \int_E^\infty \frac{N(E',y)\, F_{NN}(E,E')}{\lambda_N(N')} \cdot \frac{dE'}{E} \tag{3}$$

and

$$\frac{d\pi(E,y)}{dy} = -\frac{\pi(E,Y)}{\lambda_\pi(E)} - \frac{\varepsilon_\pi\, \pi(E,y)}{Ey\cos\Theta} + \int_E^\infty \frac{\pi(E',y)\, F_{\pi\pi}(E,E')}{\lambda_\pi(E')} \cdot \frac{dE}{E} +$$

$$+ \int_E^\infty \frac{N(E',y)\, F_{N\pi}(E,E')}{\lambda_N(E')} \cdot \frac{dE'}{E} \tag{4}$$

where N stands for nucleon and π for charged pion, $F_{ab}(E,E')\frac{dE}{E}$ is the number of particles for type b in the energy between E and $E + dE$ product on average in the collision with particle a of energy $E' > E$. High energy physics enters equations only through the inelastic hadron-air cross sections

$$\sigma^{inel}_{P-air} \sim \frac{1}{\sigma_{P-air}} \text{ and } \sigma^{inel}_{\pi-air} \sim \frac{1}{\sigma_{\pi-air}}$$

and through the production cross section $F_{NN}, F_{N\pi}, F_{\pi\pi}$ for $pp \to pX, pp \to \pi^\pm X$ and $\pi\pi \to \pi X$, respectively. Here,

$$F_{ab}(E,E') = \frac{\pi}{\sigma_{inel}} \int E \frac{d\sigma_{ab}}{d^3 p}\, dp_T^2\, E_b \frac{dN_b(E,E')}{dE_b} \tag{5}$$

where $E\left(\frac{d\sigma}{d^3p}\right)$ is the Lorentz invariant inclusive cross section for the process $a+air$ (nucleus) $\rightarrow b +$ *anything* and $dN_b(E, E')$ is the number of the particles p oduced with lab. energy between E and $E + dE$ in the collision of a particle of lab. energy E' with air nucleus (mass number $A = 14.5$).

So from (1) and (2) we obtain

$$F_N = 1.062\, e^{-2.38 \langle n_{\pi^-} \rangle x}$$

$$F_{\pi\pi} = 1.062\, e^{-2.38 \times 5/9 \langle n_{\pi^-} \rangle x}. \qquad (6)$$

Now it is quite evident from the nature of impression for $F_{N\pi}$ and $\langle n \rangle_\pi$ that when multiplicity of pion production increases with energy rapidly, $F_{N\pi}$ decreases sharply as shown in Fig. 2 and so the secondary pions produced in this process will have

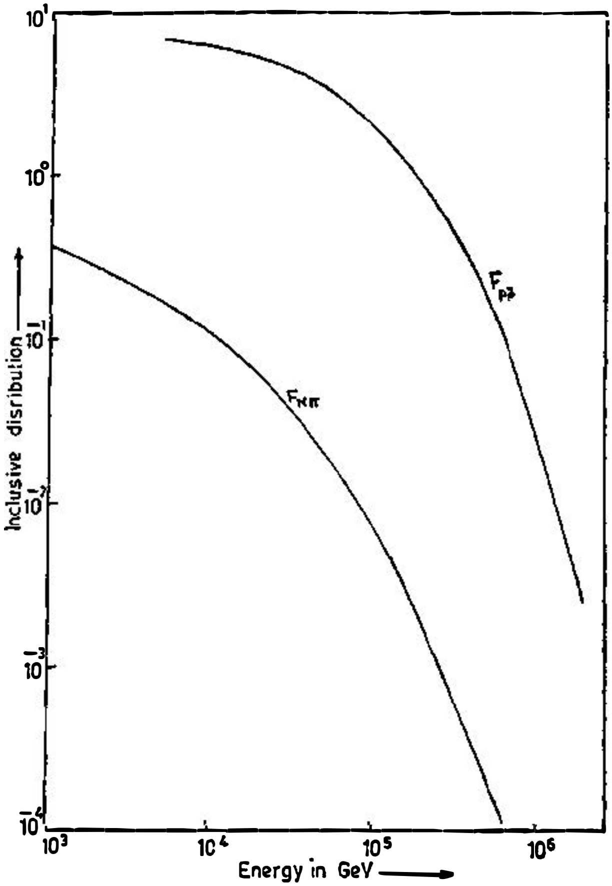

Fig. 2. Inclusive distribution $F_{N\pi}$ for multiple pion production in pp scattering and inclusive distribution F_{pp} in multiple production of baryon/antibaryon in pp scattering, respectively.

more than sufficient energy to be involved in secondary production of nucleons and antinucleons i. e.,

$$\pi^+ \to p\bar{n}$$

$$\pi^- \to \bar{p}n$$

and

$$\pi^0 \to \bar{N}N$$

due to hard scattering.

To illustrate the phenomena, let us consider $E_{lab} \approx 10^6$ GeV around which most of the events (*Centauro* and *Mini-Centauro*) have been observed.

Thus we have

$$\langle n \rangle_\pi = [\langle n_{\pi^0} \rangle + \langle n_{\pi^+}^+ \rangle + \langle n_{\pi^-} \rangle]$$

where

$$\langle n_{\pi^+} \rangle = \langle n_{\pi^-} \rangle = \langle n_{\pi^0} \rangle$$

and

$$\langle n \rangle_\pi = 1.05\,(2E_{lab})^{1/3} \approx 130 \text{ for } E = 10^6 \text{ GeV}.$$

The nucleons and antinucleons produced in this process will transverse a path H i. e., the interaction height above the counter to be observed at the chamber. According to Tamada[8])

$$N_H = N \exp\left[\frac{H}{\lambda}\right]$$

where N_H = total multiplicity of nuclear active particles (*n. a. p.*) produced in the parent interaction, i. e., 130 (approx.) in our case

N = total number of *n. a. p.* arrived at the chamber = interaction mean free path 86 g/cm^2.

So if we choose the value of N as estimated by Tamada[8]), the interaction height H will be ≈ 500 which comes as around (520 ± 150), as observed by experimental groups. Now the average transverse momentum $\langle P_T \rangle$ of *n. a.* particles can be obtained in a straightforward way from our dynamical model without the necessity of any experimental bias. The average P_T of any type of produced secondaries (charged) is defined by

$$\langle P_T \rangle_C = \frac{\int F(X, P_T, S)\, P_T \, \mathrm{d}\, p_{T^2}}{\int F(X, P_T, S)\, \mathrm{d}P_T^2}$$

where $F(X, P_T, S)$ is easily deducable from Eqs. (1) and (3). Thus $\langle P_T \rangle$ for the produced pion in the process $pp \to \pi X$

$$\langle P_T \rangle = 2.26 \text{ GeV/c}.$$

If we assume that this value of P_T is distributed equally among two baryons since $\pi^+ \to p\bar{n}$, $\pi^- \to \bar{p}n$, $\langle P_T \rangle$ for baryons/antibaryons will be 1.12 GeV/c, which is very close to the value suggested by Gaisser[7], instead of 1.7 ± 0.7 GeV/c as found by others[8].

Process II: Direct production of baryons-antibaryons pair:

The diagram (Fig. 3) gives the schematic explanation of the production of baryons (details in Ref. 10) of which $\overline{P}$ is a member.

Thus for $p\,\overline{p}$ production the average multiplicity comes out as

$$\langle n_{\bar{p}} \rangle = 1.03 \times 10^{-2} \times S^{2/5} \tag{7}$$

where S is expressed in GeV^2 and

$$E \frac{d^3\sigma}{dp^3}\bigg|_{pp \to \bar{p}X} = \frac{9}{\langle n_{\bar{p}} \rangle} \times \frac{25}{4} \times 0.154 \left(\frac{S}{1000}\right)^{1/5} \times$$

$$\times \exp\left[-\frac{0.66}{\langle n_{\bar{p}} \rangle^{3/2}} \frac{P_T^2 + \mu^2_{\bar{p}}}{1-x}\right] \times \exp\left[-25.4 \langle n_{\bar{p}} \rangle x\right]. \tag{8}$$

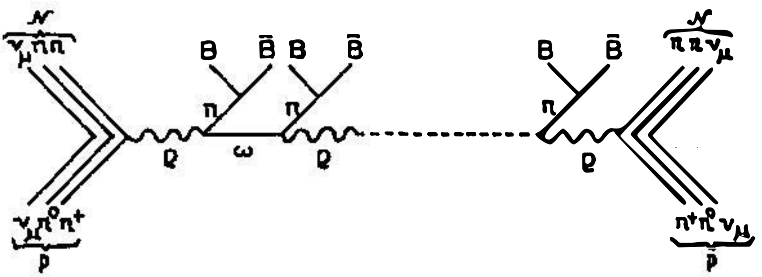

Fig. 3. Multiple production of baryon/antibaryon in pp scattering.

Following Eq. (5)

$$F_{p\bar{p}} \simeq \frac{9}{\langle n_{\bar{p}} \rangle} \times \frac{25}{4} \times 0.152 \left(\frac{S}{1000}\right)^{1/5} \frac{\langle n_{\bar{p}} \rangle^{3/2}}{0.66} \times$$

$$\times \exp\left[-25.4 \langle n_{\bar{p}} \rangle x\right] = 0.482\, S^{2/5}\, e^{-0.026\, S^{2/5}} \tag{9}$$

where S is expressed in GeV^2.

In this process also, $F_{p\bar{p}}$ decreases whereas $\langle n_{\bar{p}} \rangle$ increases as energy increases, but in much slower pace becaus energy dependence of multiplicity differes in $pp \to \pi^{\pm} X$ ($\langle n_\pi \rangle \sim S^{1/3}$) from $pp \to \overline{p}X$ ($\langle n_{\bar{p}} \rangle \sim S^{2/5}$). This has been illustrated in Fig. 4. So we can emphasize that the $pp \to \pi^{\pm} X$ will dominate in the lower energy whereas $pp \to \overline{p}X$ process will be more and more prominent in the higher side of the energy range (in which *Centauro* and *Mini-Centauro* have been observed).

Thus taking the same energy $E_{lab} = 10^6$ GeV we obtain $\langle n_{p\bar{p}} \rangle \approx 13.6$ from Eq. (5), whereas in case of *Mini-Centauro* events it has been found around 15[8]. Hence we can associate the $pp \to \bar{p}X$ with the direct baryon production mechanism in *Mini-Centauro* events. Similar to our main *Centauro* events $\langle P_T \rangle = 1.91$ GeV/c in this case also.

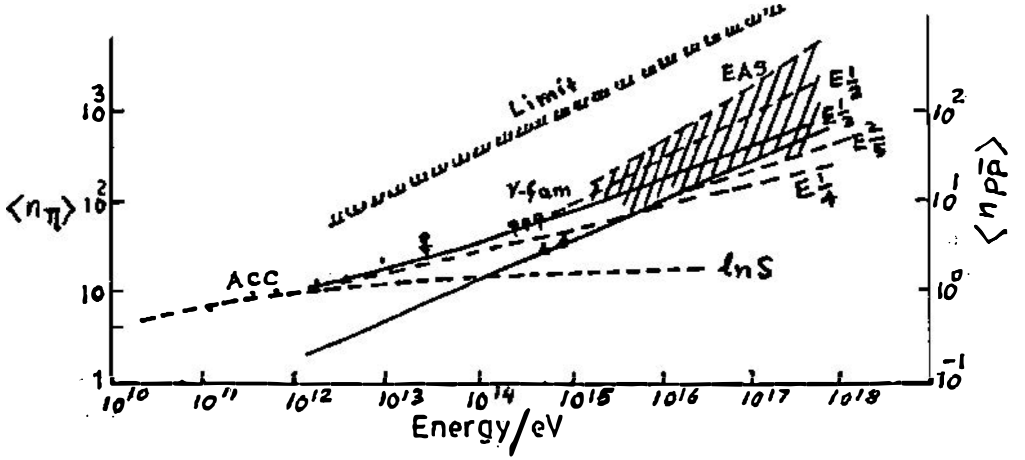

Fig. 4. Average pion multiplicity $\langle n_\pi \rangle \sim S^{1/3}$ (S in GeV^2) and average baryon/antibaryon multiplicity $\langle n_{p\bar{p}} \rangle \sim S^{2/5}$ are shown together with the prediction from other models and compared with experimental values (Ref. 12).

The indirect experimental indication about the $\langle P_T \rangle$ of *Mini-Centauro* events gives rise to the same order as that of *Centauro* events. This is in well agreement with those obtained from the point of view of our model. The other main characteristics of *Centauro* and *Mini-Centauro* events that the baryons and antibaryons are the only products without π production also comes true from our theoretical framework.

2. *Discussions*

It is evident from the above discussion that the main characteristics i. e., the high $\langle P_T \rangle$ for hadrons produced as well as around 120 baryons (approx.) for *Centauro* and 15 baryons for *Mini-Centauro* events can be explained consistently within our scheme of multiparticle production mechanism. However, two processes are considered to be responsible for these exotic events:

i) Pions are directly produced as $pp \to \pi_0^\pm X$, but eventually giving nucleons and antinucleons due to very high energy of pions produced. It is to be noted that an unusual characteristics of *Centauro* is the multiple production of more than fifty nucleon active particles without noticeable emission of neutral π-mesons. In our case, these high energy pions will produce nucleons and antinucleons and possibly statistically insignificant γ-rays due to hard scattering.

ii) Directly into baryons only as $pp \to pX$ and $pp \to \bar{p}X$. In the first process the fact that pions will produce nucleons and antinucleons as $\langle n \rangle_\pi$ increases whereas the structure function starts falling very steeply is evident from Fig. 2, indicating a threshold for the scattering processes. But the second process starting at a low pace compared to first one makes it felt after a certain threshold (10^6 GeV) though with a very low probability due to very small effective cross section.

It is worth mentioning that recently Ammiraju et al.[13] have analysed data on multiparticle production of hadrons from very high energy interactions, both of cosmic rays and at accelerator energies and suggested that the fire balls seem to posses two different decay modes either

i) to pion decay only or

ii) directly into baryons only. They have tried to correlate these to *Centauro* and *Mini-Centauro* events which agree from our point of view. Here we like to emphasize that we neither need nor require the appreciable presence of heavy primaries or any completely new type of high energy interactions at least in explaining these phenomena.

Lastly it is worth mentioning that at flattening or knee region of primary spectrum from 10^{14} eV to 10^{16} eV energy range, apart from usual cascading processes, the production of baryons and antibaryons thus produced may have some additive effect to the primary spectrum. This provides support to the suggestion of Hillas[14] in explaining the problem of primary cosmic ray spectrum at around $(10^{14} - 10^{16})$ eV. Miyake[12] also indicated the presence of some superimposed component (though different origin considered) in this range. Again the direct production of such high energy baryons and antibaryons pairs from $pp \to \to pX$, $pp \to \bar{p}X$ as well as from $pp \to \pi^{\pm} X$ may support to decreasing tendency of charged to neutral particles ratio (C/N) with increasing energy and size specially at primary energy around 10^6 GeV, which facts have been observed by many experimental groups[15,16,17]. These however should be dealt with more details. All the other supposed characteristics and exotic events will be studied in subsequent papers.

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References

1) Japan-Brazil Collaboration: Conference Papers, Denver Conference on Cosmic Rays **3** (Denver, Colo., 1973) 2227; **4** (Denver, Colo., 1973) 2671;

2) Pamir Collaboration: Conference papers, Sixteenth International Cosmic Ray Conference, Kyoto 1979 (Institute of Cosmic Ray Research, University of Tokyo, 1979), **7**, 75 and **7**, 241;

3) J. D. Bjorken and L. D. Mc. Lerran, Phys Rev **D20** (1979), 2533, in *Cosmic Rays and Particle Physics* 1978, proceedings of the Bartol Conference edited by T. K. Gaisser (AIP, New York, 1978) 334;

4) D. G. Sutherland, in *Cosmic Rays and Particle Physics* 1978 edited by T. K. Gaisser, (AIP, New York, 1978) **49** (1978) 49;

5) J. Dias and W. A. Rodrigues, Jr., Nuovo Cim. **55A** (1980) 34;

6) B. S. Acharya, M. V. S. Rao, K. Sivaprasad and Srikantha Rao, Nuovo Cimento Letters **31** (1981) 149;
B. S. Acharya, M. V. S. Rao, K. Sivaprasad and Srikantha Rao in proceedings of the 16 th International Cosmic Ray Conf. Kyoto, Japan, 1979 (Science Council of Japan and Physical Society of Japan, Kyoto, (1979) **6**, 289; B. S. Acharya, M. V. S. Rao, K. Sivaprasad and Srikantha Rao, Phys. Rev. **D24** (1981) 2437;

7) R. W. Ellsworth, J. Goodman and G. B. Yodh, Phys. Rev. **D23** (1981) 771;
T. K. Gaisser and G. B. Yodh, Ann. Rev. Nucl. Part. Sci. **30** (1980) 475;

8) M. Tamada, Nuovo Cim. **41B** (1977) 245;
Y. Fujimoto and S. Hasegawa, in *Cosmic Ray and Particle Physics* 1978, proceedings of the Bartol Conference edited by T. K. Gaisser (AIP. New York, 1978) 317;
C. M. G. Latters, Y. Fujimoto and S. Hasegawa, Physics Reports **65** (1980) 151;

9) Malabika Sinha, submitted for publication:

10) P. Bandyopadhyay. R. K. Roychoudhury, S. Bhattacharya and D. P. Bhattacharya, Nuovo Cim. **59A** (1979) 133;
P. Bandyopadhyay and S. Bhattacharya, Lett. Nuovo Cimento **17** (1976) 339; Nuovo Cim. **43A** (1978) 305;

11) Brazil-Japan Emulsion Chamber Collaboration in *Cosmic Ray and Particle Physics* 1978, Proceedings of the Bartol Conference editted by T. K. Gaisser (AIP, New York, 1978) 317;

12) S. Miyake in *Cosmic Ray and Particle Physics* 1978, Proc. of the Bartol Conference edited by T. K. Gaisser (AIP, New York, 1978) 352;

13) P. Ammiraju, E. Recami and W. A. Rodrigues Jr., Nuovo Cim. **78A** (1983) 172;

14) A. M. Hillas, in *Cosmic Ray and Particle Physics* 1978, Proceedings of Bartol Conference edited by T. K. Gaisser (AIP, New York, 1978) 373;

15) R. H. Vatcha and B. V. Sreekanton, J. Phys. A. Math. Nucl. Gen. **6** (July 1973) 1050, 1067;

16) K. Dobrzynski, T. Firkowski, J. Glowacki, J. Wdowczyk, A. Wlodarek and G. B. Christiansen, Proc. 17th ICRC EA 4—6 (Paris, 1981);

17) T. Kameda, T. Maeda, H. Oda and T. Sugihara, Proc. 9th Int. Cosm. Ray Conf. **2**, 681 (London, 1965).

CENTAURO DOGAĐAJI I FENOMENI VIŠESTRUKE PRODUKCIJE KOD ENERGIJA OD 10^{14}—10^{16} eV

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Glavne karakteristike egzotičnih događaja *Centauro* i *Mini-Centauro* studirane su u okviru sheme višečestičnih produkcija sa $\langle n_\pi \rangle \sim S^{1/3}$ (S je u GeV^2) i $F_{N\pi} = 1{,}062 \exp [- 2{,}38 \langle n_\pi \rangle x]$. Za objašnjenje događaja predložena su dva različita procesa: i) produkcija barion-antibarion parova sa sekundarnih piona i ii) direktna produkcija barion-antibarion parova u pp raspršenju. Opažene distribucije $\langle P_T \rangle$ u tim procesima dobro se slažu s eksperimentima.