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A Comparison between « Beauty » and « Charm » Production in pp Interactions.

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Summary. — A comparison between « beauty » ($pp \to \Lambda_b^0 + M_{\bar{b}}^- +$ anything) and « charm » ($pp \to \Lambda_c^+ + \bar{D} +$ anything) production cross-sections is presented. It is shown that our results are consistent with expectations on the ratio of « beauty » to « charm » cross-sections and on the branching ratio $B[(\Lambda_b^0 \to pD^0\pi^-)/(\Lambda_b^0 \to \text{all})]$.

1. – Introduction.

We have recently reported [1] the first proof of the associated production of the « beauty »-flavoured baryon, Λ_b^0, in the reaction

(1) $pp \to \Lambda_b^0$ + « antibeauty »-flavoured state + anything

- $\Lambda_b^0 \to pD^0\pi^-$, with $D^0 \to K^-\pi^+$
- « antibeauty »-flavoured state $\to e^+ +$ anything
- anything $\to \geqslant 4$ charged particles

at $\sqrt{s} = 62$ GeV (pp) c.m. energy.

[1] M. BASILE, G. BONVICINI, G. CARA ROMEO, L. CIFARELLI, A. CONTIN, G. D'ALÍ, P. DI CESARE, B. ESPOSITO, P. GIUSTI, T. MASSAM, R. NANIA, F. PALMONARI, G. SARTORELLI, G. VALENTI and A. ZICHICHI: *Lett. Nuovo Cimento*, **31**, 97 (1981).

The partial cross-section for the observation of the final state (1), as specified in the same paper [1], has also been given to be

$$\Delta\sigma_1 = (3.8 \pm 1.2)\cdot 10^{-35}\ \text{cm}^2\ .$$

The main purpose of the present paper is to find how this result compares with expectations on the « beauty » to « charm » cross-section σ_b/σ_c, and with the branching ratio $B[(\Lambda_b^0 \to pD^0\pi^-)/(\Lambda_b^0 \to \text{all})]$.

In order to do this, we first need to elaborate on different possibilities for estimating the « beauty » cross-section σ_b, *i.e.* the cross-section for the process

$$(2)\qquad pp \to \Lambda_b^0 + M_{\bar{b}} + \text{anything}\ ,$$

where $M_{\bar{b}}$ is the « antibeauty »-flavoured meson, produced in association with the Λ_b^0.

The next step is to repeat analogous calculations for the « charm » cross-section σ_c, *i.e.* the cross-section for the process

$$(3)\qquad pp \to \Lambda_c^+ + \overline{D} + \text{anything}\ ,$$

which was in fact observed via the study of the reaction

$$(4)\qquad pp \to \underset{\hookrightarrow\, pK^-\pi^+}{\Lambda_c^+} + \underbrace{\text{« anticharm »-flavoured state}}_{\hookrightarrow\, e^- + \text{anything}} + \text{anything}\ .$$

The experimental set-up used for the observation of reactions (1) and (4) was the same. For details we refer the reader to previously published papers [1,2].

2. – Estimate of the Λ_b^0 production cross-section.

In order to proceed further, from our value of $\Delta\sigma_1$, it is necessary to know the source of the positive electron. In fact the e^+ is coming from the semileptonic decay of an «antibeauty»-flavoured state which can be either an antibaryon or an antimeson. However, the following points must be emphasized: i) an antibaryon needs three antiquarks, while an antimeson needs an antiquark-quark pair to be made; ii) the experimental results on associated production of flavour-antiflavour states in pp interactions favour the baryon-antimeson with respect to the baryon-antibaryon–flavoured pairs. This is why, in order

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(2) M. BASILE, G. CARA ROMEO, L. CIFARELLI, A. CONTIN, G. D'ALI, P. DI CESARE, B. ESPOSITO, P. GIUSTI, T. MASSAM, F. PALMONARI, G. SARTORELLI, G. VALENTI and A. ZICHICHI: *Nuovo Cimento A*, **63**, 230 (1981).

to estimate the associated production cross-section (2), we have chosen the antimeson as the associated state produced with the Λ_b^0.

In order to derive, from our measurement of $\Delta\sigma_1$, the production cross-section for the process (2), it is necessary to know the production and decay distributions for Λ_b^0 and $M_{\bar{b}}$, and the following branching ratios:

$$B_1(D^0 \to K^-\pi^+) = \frac{D^0 \to K^-\pi^+}{D^0 \to \text{all}},$$

$$B_2(M_{\bar{b}} \to e^+ + \text{anything}) = \frac{M_{\bar{b}} \to e^+ + \text{anything}}{M_{\bar{b}} \to \text{all}},$$

$$B_3(\Lambda_b^0 \to pD^0\pi^-) = \frac{\Lambda_b^0 \to pD^0\pi^-}{\Lambda_b^0 \to \text{all}}.$$

Two are measured, B_1 and B_2; B_3 is obviously unknown.

To distinguish, in the successive steps, the relevance of the different information needed from other sources outside our experiment, we will first assume that all the branching ratios (B_1, B_2, and B_3) are equal to one. In this case, to go from reaction (1) to reaction (2) it is necessary to know the production and decay distributions of the Λ_b^0 and the $M_{\bar{b}}$.

For the « antibeauty »-flavoured meson $M_{\bar{b}}$, the production distributions were taken to be

$$\left(E\frac{d\sigma}{dx}\right)_{M_{\bar{b}}} \propto (1-|x|)^3,$$

$$\left(\frac{d\sigma}{dp_T}\right)_{M_{\bar{b}}} \propto p_T \cdot \exp[-2.5p_T],$$

in analogy with our previous study of associated charm production (2). As usual, x is the fractional momentum $x = 2p_L/\sqrt{s}$, where p_L and p_T are the longitudinal and transverse components of the momentum of the produced particle.

For the decay process of $M_{\bar{b}} \to \bar{D}e^+\nu_e$, a K_{l3} matrix element has been used. For the Λ_b^0, three models have been taken. However, in all three models the transverse-momentum production distribution has been taken to be

$$\left(\frac{d\sigma}{dp_T}\right)_{\Lambda_b^0} \propto p_T \cdot \exp[-2.5p_T],$$

as suggested by the heavy-flavour (charm) baryon production Λ_c^+, measured under the same experimental conditions (3).

(3) M. BASILE, G. CARA ROMEO, L. CIFARELLI, A. CONTIN, G. D'ALÍ, P. DI CESARE,

Model I: *The « leading » baryon conditions.* The x production distribution has been chosen according to the « leading » baryon effect, *i.e.*

$$\left(\frac{d\sigma}{dx}\right)_{\Lambda_b^0} = \text{const}\,,$$

as observed in the Λ_c^+ production studies ([2,4]), and working out the apparatus acceptance under the same conditions, $x > 0.32$ and $|y_{pK^-\pi^+\pi^-}| > 1.4$, which allow us to see the Λ_b^0. The result will not be the «total» cross-section for reaction (2); rather, it will be the partial cross-section according to the experimental cuts used for the experimental observations. This procedure is justified for two reasons:

i) Because it is important to evaluate a cross-section (even if only a partial one) without extrapolations, where it is not possible to see anything.

ii) Because the same procedure will be adopted for the Λ_c^+ case; the ratio of the two cross-sections minimizes systematic effects and is free from extrapolation uncertainties, thus allowing a straightforward comparison between the Λ_b^0 and the Λ_c^+ production cross-section. For completeness, other models will be adopted in which extrapolations will be allowed.

For the Λ_b^0 decay process, Lorentz-invariant phase space, with, as mentioned above, the « leading » proton condition $x \geqslant 0.32$ in the laboratory system has been assumed.

The result is (*)

$$\sigma_2(\text{model I})_{(\text{assuming all branching ratios}=1)} = (13.0^{+4.1}_{-3.4})\cdot 10^{-33}\ \text{cm}^2\,.$$

Model II: *Minimum leading conditions.* The x production distribution ([4]) for the Λ_b^0 is taken to be

$$\left(\frac{d\sigma}{dx}\right)_{\Lambda_b^0} = \text{const}$$

without any further « leading » baryon conditions.

B. ESPOSITO, P. GIUSTI, T. MASSAM, F. PALMONARI, G. SARTORELLI, G. VALENTI and A. ZICHICHI: *Lett. Nuovo Cimento*, **30**, 481 (1981).
([4]) M. BASILE, G. CARA ROMEO, L. CIFARELLI, A. CONTIN, G. D'ALÍ, P. DI CESARE, B. ESPOSITO, P. GIUSTI, T. MASSAM, F. PALMONARI, G. SARTORELLI, G. VALENTI and A. ZICHICHI: *Lett. Nuovo Cimento*, **30**, 487 (1981).

(*) The central value and the quoted errors on cross-sections with various models and on B_3 are derived via Monte Carlo calculations in order to account for the fact that the law of propagation of errors for ratios does not apply when the errors on the denominators are large ($\geqslant 20\%$).

For the Λ_b^0 decay, we have again taken Lorentz-invariant phase space and less stringent « leading » proton conditions: $p_p > p_{D^0}$, $p_p > p_{\pi^-}$.

The result is

$$\sigma_2(\text{model II})_{(\text{assuming all branching ratios}=1)} = (43.9^{+13.7}_{-12.2})\cdot 10^{-33}\ \text{cm}^2 .$$

Model III: Isotropic, no « leading » proton conditions. Here the x production has been taken according to phase space, *i.e.* isotropic. Therefore, in this model there is no « leading » proton condition.

The result is

$$\sigma_2(\text{model III})_{(\text{assuming all branching ratios}=1)} = (130^{+41}_{-34})\cdot 10^{-33}\ \text{cm}^2 .$$

So far we have taken the branching ratios B_1, B_2 and B_3 all equal to one. As already mentioned, two of them are known, even if with large uncertainties

$$B_1(D^0 \to K^-\pi^+) = (3.0 \pm 0.6)\% \qquad \text{(ref. (5))}$$

$$B_2(M_{\bar{b}} \to e^+ + \text{anything}) = (13 \pm 6)\% \qquad \text{(ref. (6))} .$$

The use of these branching ratios allows the estimation of σ_2, under the hypothesis specified in the three models described above.

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(5) R. H. SCHINDLER, M. S. ALAM, A. M. BOYARSKI, M. BREIDENBACH, D. L. BURKE, J. DORENBOSCH, J. M. DORFAN, G. J. FELDMAN, M. E. B. FRANKLIN, G. HANSON, K. G. HAYES, T. HIMEL, D. G. HITLIN, R. J. HOLLEBEEK, W. R. INNES, J. A. JAROS, P. JENNI, R. R. LARSEN, V. LÜTH, M. L. PERL, B. RICHTER, A. ROUSSARIE, D. L. SCHARRE, R. F. SCHWITTERS, J. L. SIEGRIST, H. TAUREG, M. TONUTTI, R. A. VIDAL, J. M. WEISS, H. ZACCONE, G. ABRAMS, C. A. BLOCKER, A. BLONDEL, W. C. CARITHERS, W. CHINOWSKY, M. W. COLES, S. COOPER, W. E. DIETERLE, J. B. DILLON, M. W. EATON, G. GIDAL, G. GOLDHABER, A. D. JOHNSON, J. A. KADYK, A. J. LANKFORD, R. E. MILLIKAN, M. E. NELSON, C. Y. PANG, J. F. PATRICK, J. STRAIT, G. H. TRILLING, E. N. VELLA and I. VIDEAU: SLAC-PUB-2507; LBL-10905, May 1980 (T/E), submitted to *Phys. Rev. D*.

(6) C. BEBEK, J. HAGGERTY, J. M. IZEN, W. A. LOOMIS, F. M. PIPKIN, J. ROHLF, W. TANENBAUM, R. WILSON, A. J. SADOFF, D. L. BRIDGES, K. CHADWICK, P. GANCI, H. KAGAN, R. KASS, F. LOBKOWICZ, A. MELISSINOS, S. L. OLSEN, P. POLING, C. ROSENFELD, C. RUCINSKI, E. H. THORNDIKE, G. WARREN, D. BECHIS, J. J. MUELLER, D. POTTER, F. SANNES, P. SKUBIC, R. STONE, A. BRODY, A. CHEN, M. GOLDBERG, N. HORWITZ, J. KANDASWAMY, H. KOOY, P. LARICCIA, G. C. MONETI, M. S. ALAM, S. E. CSORNA, R. S. PANVINI, J. S. POUCHER, D. ANDREWS, K. BERKELMAN, R. CABENDA, D. G. CASSEL, J. W. DEWIRE, R. EHRLICH, T. FERGUSON, T. GENTILE, M. G. D. GILCHRIESE, B. GITTELMAN, D. L. HARTILL, D. HERRUP, M. HERZLINGER, D. L. KREINICK, N. B. MISTRY, E. NORDBERG, R. PERCHONOK, R. PLUNKETT, K. A. SHINSKY, R. H. SIEMANN, A. SILVERMAN, P. C. STEIN, S. STONE, R. TALMAN, H. G. THONEMANN and D. WEBER: preprint CLNS-80/4/5 (1980).

As $B_3(\Lambda_b^0 \to pD^0\pi^-)$ is unknown, the result will be σ_2 times this branching raio, *i.e.*

$$\sigma_2 \cdot B_3(\Lambda_b^0 \to pD^0\pi^-) .$$

The three models provide the following values:

$$A) \qquad \begin{cases} \sigma_2(\text{model I}) \cdot B_3(\Lambda_b^0 \to pD^0\pi^-) = (2.7^{+1.8}_{-1.1}) \cdot 10^{-30}\ \text{cm}^2, \\ \sigma_2(\text{model II}) \cdot B_3(\Lambda_b^0 \to pD^0\pi^-) = (8.2^{+6.0}_{-2.8}) \cdot 10^{-30}\ \text{cm}^2, \\ \sigma_2(\text{model III}) \cdot B_3(\Lambda_b^0 \to pD^0\pi^-) = (27\ ^{+17}_{-11}) \cdot 10^{-30}\ \text{cm}^2. \end{cases}$$

The large uncertainty of these estimates and their model dependence does not allow these results to be used as « absolute » measurements. However, they can provide a useful tool for the comparison with analogous estimates for « charm » production.

3. – Estimates of the Λ_c^+ production cross-section.

The above models have been used to compute the Λ_c^+ production cross-section, under conditions identical to those for the Λ_b^0. As mentioned above, for the Λ_c^+ the reaction studied was (4)

$$(4) \qquad \begin{aligned} pp \to \Lambda_c^+ + &\overline{D} \qquad\qquad + \text{anything} \\ &\hookrightarrow e^- + \text{anything} \\ \Lambda_c^+ &\hookrightarrow pK^-\pi^+ \end{aligned}$$

at the same (pp) c.m. energy and using the same set-up.

In order to calculate the cross-section for the « charm » reaction (3)

$$(3) \qquad pp \to \Lambda_c^+ + \overline{D} + \text{anything},$$

the knowledge of two more branching ratios is needed:

$$B_4(\overline{D} \to e^- + \text{anything}) = \frac{\overline{D} \to e^- + \text{anything}}{\overline{D} \to \text{all}} = 0.08 \pm 0.01 \qquad (\text{ref. } (^7)),$$

$$B_5(\Lambda_c^+ \to pK^-\pi^+) = \frac{\Lambda_c^+ \to pK^-\pi^+}{\Lambda_c^+ \to \text{all}} = 0.022 \pm 0.01 \qquad (\text{ref. } (^8)).$$

(7) G. GOLDHABER and J. E. WISS: preprint LBL/10652 (March 1980).

(8) G. S. ABRAMS, M. S. ALAM, C. A. BLOCKER, A. M. BOYARSKI, M. BREIDENBACH, D. L. BURKE, W. C. CARITHERS, W. CHINOWSKI, M. W. COLES, S. COOPER, W. E. DIETERLE, J. B. DILLON, J. DORENBOSCH, J. M. DORFAN, M. W. EATON, G. J. FELDMAN,

The results are

$$B)\qquad \begin{cases} \sigma_3(\text{model I}) = (\ 77.5^{+57}_{-28})\cdot 10^{-30}\ \text{cm}^2\,, \\ \sigma_3(\text{model II}) = (100\ \ ^{+68}_{-36})\cdot 10^{-30}\ \text{cm}^2\,, \\ \sigma_3(\text{model III}) = (190\ \ ^{+140}_{-68})\cdot 10^{-30}\ \text{cm}^2\,. \end{cases}$$

4. – Comparison between « beauty » and « charm » cross-sections.

We are now in a position to compare the results *A*) and *B*). The interest is twofold. Firstly, because in this comparison the systematic effects are minimized. In fact, the two heavy-flavour production processes, « charm » and « beauty », are measured with the same set-up. Secondly, this comparison allows

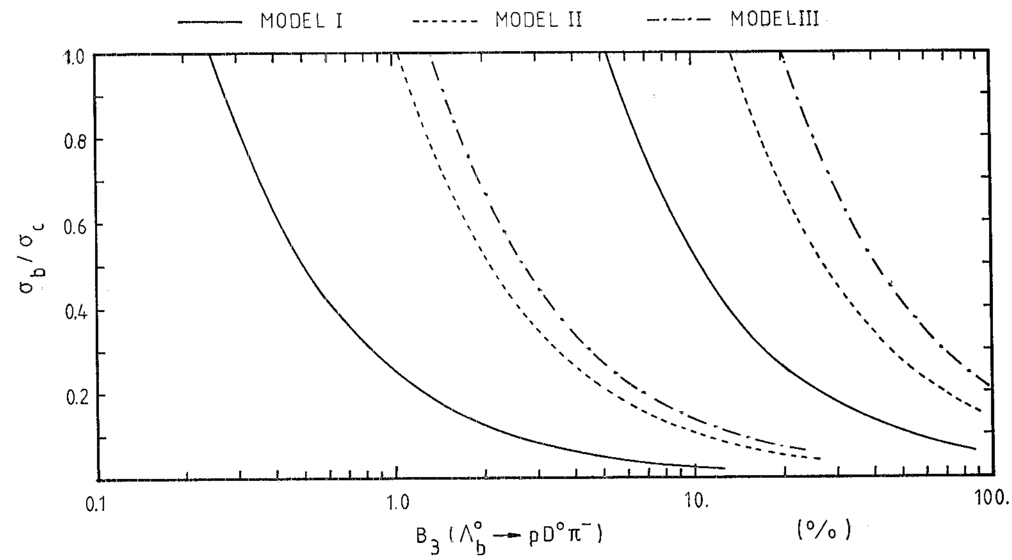

Fig. 1. – The correlations between σ_b/σ_c and B_3 are reported for the three models (I, II, III) described in the text. The various curves indicate the 1.5 standard-deviation bands for model I (full lines), for model II (dotted lines) and for model III (dash-dotted lines).

M. E. B. Franklin, G. Gidal, G. Goldhaber, G. Hanson, K. G. Hayes, T. Himel, D. G. Hitlin, R. J. Hollebeek, W. R. Innes, J. A. Jaros, P. Jenni, A. D. Johnson, J. A. Kadyk, A. J. Lankford, R. R. Larsen, M. J. Longo, V. Lüth, R. E. Millikan, M. E. Nelson, C. Y. Pang, J. F. Patrick, M. L. Perl, B. Richter, A. Roussarie, J. J. Russell, D. L. Scharre, R. H. Schindler, R. F. Schwitters, J. L. Siegrist, J. Strait, H. Taureg, M. Tonutti, G. H. Trilling, E. N. Vella, R. A. Vidal, I. Videau, J. M. Weiss and H. Zaccone: *Phys. Rev. Lett.*, **44**, 10 (1980).

(9) G. Gustafson and C. Peterson: *Phys. Rev. Lett. B*, **67**, 81 (1977).

(10) A. Martin: preprint CERN Th. 2980 (1980), and private communication.

a direct check on the flavour dependence of the pp production processes. Some theoretical estimates ([9,10]) on quasi-diffractive production predict a ratio between heavy-flavour cross-sections of the order of the ratio of the produced flavour masses squared, *i.e.*

$$\frac{\sigma_b}{\sigma_c} \simeq \frac{1}{8}\,. \tag{5}$$

The direct comparison of *A*) and *B*) has, as the unique unknown, the branching ratio $B_3(\Lambda_b^0 \to pD^0\pi^-)$. However, in order to study the influence of the ratio

$$\frac{\sigma_b}{\sigma_c} = \frac{\sigma(pp \to \Lambda_b^0 + M_{\bar b} + \text{anything})}{\sigma(pp \to \Lambda_c^+ + \bar{D} + \text{anything})}$$

on the branching ratio $B_3(\Lambda_b^0 \to pD^0\pi^-)$, we have considered how B_3 varies with σ_b/σ_c. The purpose of this study was to see if a value σ_b/σ_c of the order of the inverse mass squared of the produced flavours was compatible with a « reasonable » value for B_3. The results are shown in fig. 1, where the correlation

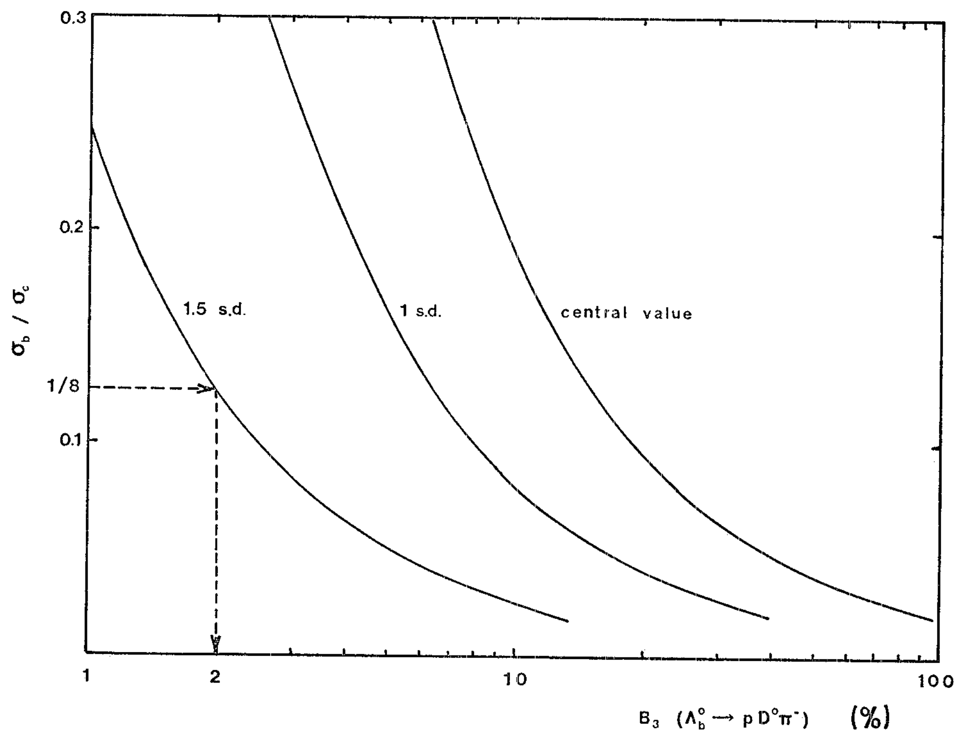

Fig. 2. – The correlation between σ_b/σ_c and B_3 as given by model I. The main point of this graph is to show that, for $\sigma_b/\sigma_c \simeq \frac{1}{8}$, which is the value expected from the inverse-mass-squared relation, the partial branching ratio $B_3(\Lambda_b^0 \to pD^0\pi^-)$ is compatible, within 1.5 standard deviation, with the 2% level.

between σ_b/σ_c and B_3 is shown for the three models. The 1.5 standard-deviation limits are indicated. The main point of these results is their large uncertainty, which is coming from the errors in the various branching ratios and from the limited knowledge of the apparatus acceptances. To these sources of uncertainties one should add those coming from the various hypotheses concerning the production and decay distributions. This is especially true for those models, such as models II and III, which need wide extrapolations. Moreover, it should be noticed that models II and III are just two examples out of many possible other ones.

The most reliable comparison, as already emphasized, is the one based on the first model.

5. – Conclusions.

We will, therefore, base our main conclusion on model I. The results are reported in fig. 2. Here it is shown that, if we choose for σ_b/σ_c the value (5) given by the inverse masses squared, *i.e.* $\sim 1/8$, the value of B_3 is, within 1.5 standard deviations, compatible with a 2% level.

● RIASSUNTO

Si presenta un confronto tra le sezioni d'urto di produzione di « beauty » ($pp \to \Lambda_b^0 + M_{\bar{b}} +$ + anything) e « charm » ($pp \to \Lambda_c^+ + \bar{D} +$ anything). I risultati sono compatibili con le previsioni sul rapporto tra le sezioni d'urto di produzione di « beauty » e « charm » e sul « branching ratio » $B[(\Lambda_b^0 \to pD^0\pi^-)/(\Lambda_b^0 \to \text{all})]$.

Резюме не получено.