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M. Basile et al. : A STUDY OF POSSIBLE NEW HEAVY-FLAVOUR PRODUCTION AT THE CERN ($p\bar{p}$) COLLIDER

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A Study of Possible New Heavy-Flavour Production at the CERN ($p\bar{p}$) Collider.

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PCAS. 13.90. – Other topics in specific reactions and phenomenology of elementary particles.

Summary. – In this paper, we review briefly the main hypotheses and extrapolations used to predict the observability of new heavy flavours at the CERN ($p\bar{p}$) collider. Some results from this study are compared with the first experimental data on the production of high-p_T electrons accompained by hadronic «jets» at the ($p\bar{p}$) collider, as observed by the UA1 collaboration. These events could, in fact, be the signature of the semi-leptonic decay of a very massive new heavy-flavoured state. Its «downlike» or «uplike» nature cannot be established in a direct and unambiguous way. More sophisticated measurements are needed as discussed in detail in a previous paper.

Introduction. We have already emphasized the important role that the CERN ($p\bar{p}$) Collider might have as a machine to produce very heavy flavours (¹). So far, in the ($p\bar{p}$) Collider exploitation, the emphasis has been concentrated in the search for the intermediate vector bosons $W^{\pm}$ and Z^0. However, the discovery of these theoretically expected particles sheds no light on either of the two crucial and totally unresolved problems of subnuclear physics: the family and the hyerarchy.

This is why more attention should be devoted to the problem of what the ($p\bar{p}$)

(¹) M. Basile, J. Berbiers, G. Bonvicini, G. Cara Romeo, L. Cifarelli, A. Contin, M. Curatolo, G. D'Alí, C. Del Papa, B. Esposito, P. Giusti, T. Massam, R. Nania, F. Palmonari, G. Sartorelli, G. Susinno, L. Votano and A. Zichichi: *New flavours: experiment vs. theory. From charm to the 4th family*, in *III Topical Workshop on Proton-Antiproton Collider Physics, Rome, January 12-14, 1983* (to be published).

collider could do in the heavy-flavour domain. In fact, the search for new flavours compares very well with the physics of the electroweak gauge bosons.

We have already discussed in detail (1) a method to detect new heavy flavours with a direct and unambiguous identification of their «uplike» or «downlike» nature, via the (e^+/e^-) asymmetry measurement.

Here, we propose an approach to the heavy flavours at the $(p\bar{p})$ collider which shows the importance of the asymmetry method. This approach is based on known facts and on few simple hypotheses. Facts and hypotheses are then extrapolated to $(p\bar{p})$ collider energies.

Our estimates are compared with the UA1 data (2), *i.e.* their eleven events showing an isolated $(e^\pm)$ accompained by a hadronic jet.

The facts. The facts are that

1) the heavy flavours Λ_c^+ and Λ_b^0 are produced at ISR energies in a «leading» way (3), *i.e.*

$$\mathrm{d}\sigma/\mathrm{d}x \propto (1-x)^\alpha \,, \tag{1}$$

with $\alpha \sim 1$;

2) the «heavy»-quark masses are in the following ratios (4):

$$m_c/m_s \simeq 3.5 \,, \tag{2a}$$

$$m_b/m_s \simeq 11 \,; \tag{3a}$$

3) there are good reasons to believe (4) that the «strange»-quark mass, m_s, is heavy enough to behave like a heavy flavour, such as «charm» and «beauty»;

4) the cross-sections for the heavy flavours «strange» (s), «charm» (c) and «beauty» (b) are measured up to the ISR energies, even if with large uncertainties (c and b);

5) all generalized Cabibbo angles, measured so far, are either small or compatible with being small.

The hypotheses. The hypotheses are

1)

$$\frac{m_c}{m_s} = \frac{m(\text{uplike})}{m(\text{downlike})} \,; \tag{2b}$$

2)

$$\frac{m_b}{m_s} = \frac{m(\text{family } N+1)}{m(\text{family } N)} \,; \tag{3b}$$

3*a*) the cross-sections for production of heavy flavours are mainly dictated by dimensionality and scaling:

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(2) G. ARNISON *et al.* (UA1 COLLABORATION): preprint CERN-EP/83-13 (1983).

(3) 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); *Nuovo Cimento A*, **65**, 421 (1981).

(4) A. MARTIN: preprint CERN TH-3314 (1982).

dimensionality says

$$\sigma \propto (1/m_t)^2 ,$$

scaling says

$$\sigma \propto f(\sqrt{s}/m_t) ;$$

therefore

$$\sigma \propto (1/m_t)^2 f(\sqrt{s}/m_t) , \tag{4}$$

which means that the knowledge of the cross-section for the production of a heavy flavour having mass m_i at energy $(\sqrt{s})_i$ allows us to know the cross-section of a heavier flavour having mass m_j at the scaled energy $(\sqrt{s})_j$, according to

$$\sigma_j[(\sqrt{s})_j = (m_j/m_i)\times(\sqrt{s})_i] = \sigma_i[(\sqrt{s})_i]\times(m_i/m_j)^2 ; \tag{5}$$

3*b*) the cross-sections for heavy-flavour production can be predicted by QCD (⁵);

4) the generalized Cabibbo angles, even those coming from the existence of the 4th family, are small, and the «flavour changing» neutral currents are forbidden to any order of family. The amplitude for a transition from family N to family $(N\pm\alpha)$ has a coefficient

$$\prod_{i=1,\alpha} \sin\theta_i ;$$

this implies that the dominant transitions are those between neighbouring families.

The extrapolations. The extrapolations are

1*a*) the «leading» phenomenon holds for the production of heavy flavours at the collider energies;

1*b*) the «leading» phenomenon is also present in the decay of the heavy-flavoured states;

2) $\dfrac{m_c}{m_s} \simeq 3.5 \simeq \dfrac{m(\text{uplike})}{m(\text{downlike})} = 4$;

3) $\dfrac{m_b}{m_s} \simeq 11 \simeq \dfrac{m(\text{family } N+1)}{m(\text{family } N)} = 11$;

4*a*) the cross-sections measured for «s» and «c» at lower energies can be extrapolated to the $(p\bar{p})$ collider energy, by using formula (5);

4*b*) the cross-sections calculated by using QCD (⁵) can be extrapolated, by using formula (5), to very heavy masses at the $(p\bar{p})$ collider energies.

The consequences. The consequences are the following:

1*a*) The «leading» phenomenon in the production of heavy-flavoured states at the $(p\bar{p})$ collider, produces an (e^+/e^-) asymmetry which changes sign from the proton

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(⁵) R. ODORICO: preprint IFUB 82/3 (1982).

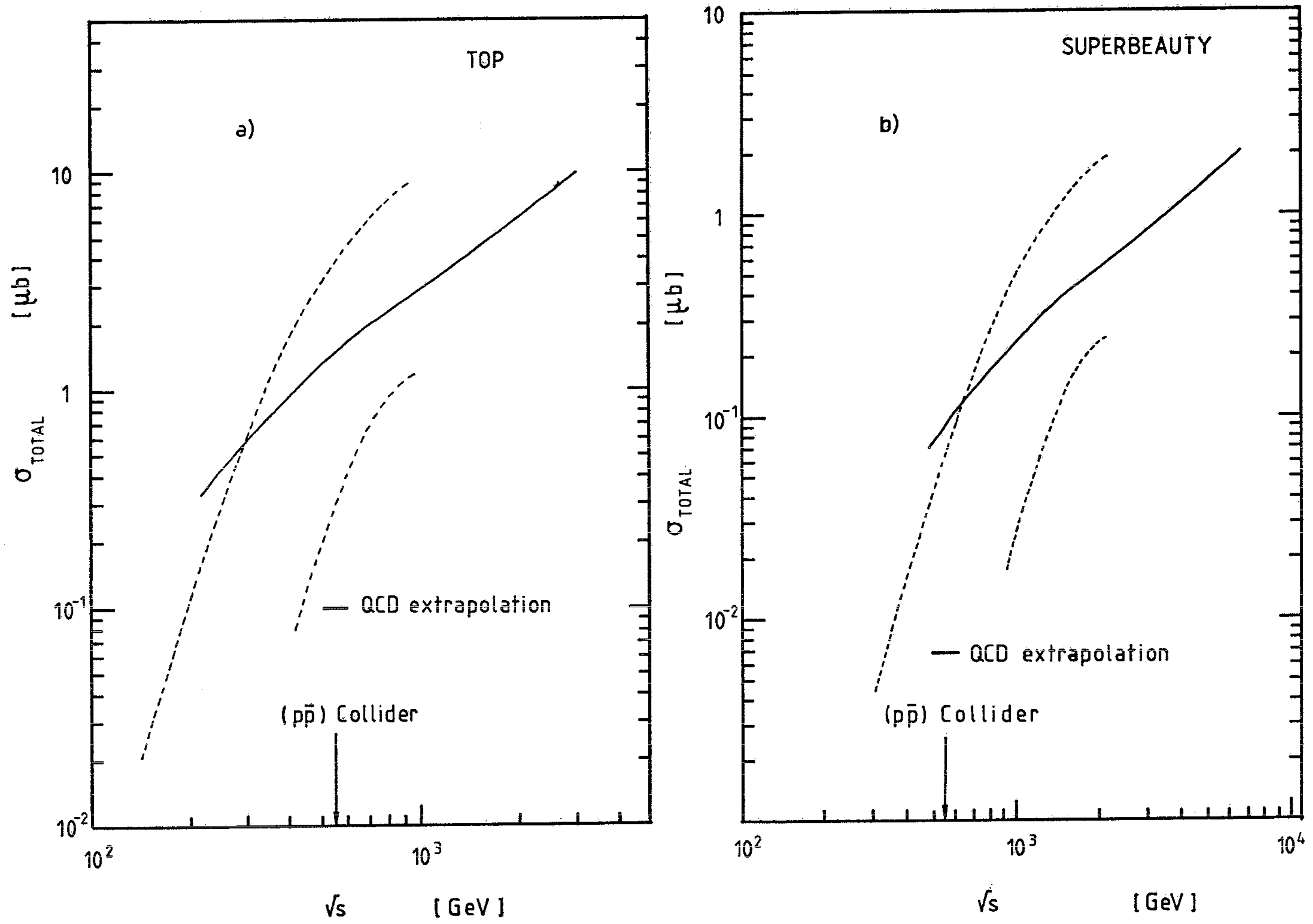

Fig. 1. – « Top » (*a*)) and « superbeauty » (*b*)) cross-sections derived from « strange » (full line) and « charm » cross-sections (dashed lines—notice the width due to the experimental uncertainties) following formula (5).

to the antiproton hemisphere and is (e^+/e^-) energy dependent. Notice that the asymmetry method allows the « uplike » or « downlike » nature of the new heavy flavours to be distinguished in a direct way.

This effect has already been discussed in detail elsewhere (1).

1*b*) The « leading » phenomenon in the semi-leptonic decay of a heavy-flavoured state, produces a very specific pattern: the heavy-quark side of the decay state has a depressed « hadronization » and it recoils against the weak intermediate boson, *i.e.* against the ($e\nu$) pair.

2) The mass of the « top » quark is expected to be in the 25 GeV/c^2 range. This mass value is important because it determines the energy available in the decay from a heavier quark.

3) The mass of the first member of the 4th family, « downlike », (called « superbeauty ») (1) is in the 55 GeV/c^2 range. We will, therefore, take $\Delta m \simeq 30$ GeV/c^2 as the typical mass difference in the decay of « superbeauty » into « top ».

4) The values of the cross-sections for « top » and « superbeauty » are given, respectively, in fig. 1*a*) and *b*) as extrapolations from « s » and from « c ». It is interesting to note that these two ways of getting cross-section information in the ($p\bar{p}$) collider range are not in violent disagreement. Furthermore, the QCD expectation is within the « charm » extrapolated range of uncertainty in the « superbeauty » case.

Comparison with preliminary data from the CERN ($p\bar{p}$) *collider.* As a first step in the study of the heavy-quark physics using the ($p\bar{p}$) collider, we propose to compare our predictions with the data already available from the ($p\bar{p}$) collider.

In their search for electron candidates, the UA1 collaboration finds 16 events with an isolated electron (2). Five of these events are attributed to $W^\pm$ decay, while the remaining 11 are characterized by a « jet activity » in the azimuthal region opposite to the isolated electron. The events correspond to a total integrated luminosity of $L = 20\ \text{nb}^{-1}$.

According to the Monte Carlo program discussed in detail in a previous paper (1), the acceptance for electrons originated by « superbeauty » decays in the phase-space region defined by the UA1 data ($p_T > 15$ GeV/c and, for the polar angle, $25° < \theta < 155°$) is, for baryon and antibaryon decays,

$$\varepsilon_B(e^\pm) = 0.08$$

and, for meson and antimeson decays,

$$\varepsilon_M(e^\pm) = 0.12\ .$$

We can, therefore, use the approximation

$$\varepsilon(e^\pm) = \varepsilon_B(e^\pm) = \varepsilon_M(e^\pm) = 0.1\ .$$

Since the heavy flavours are produced in pairs, the total efficiency to see at least one electron from the semi-leptonic decay of « superbeauty » is

$$\varepsilon_T(e^\pm) = 2 \times \varepsilon(e^\pm) = 0.2\ ,$$

where we have assumed equal semi-leptonic branching ratios for baryon and meson decays.

The request of « jet activity » opposite in azimuth to the electron, gives rise to another acceptance factor, $\varepsilon_{\text{T}}(\text{jet})$, which we can derive by analysing the hadronic pattern of the « superbeauty » semi-leptonic decays predicted by our Monte Carlo simulation, according to the « jet » definition outlined by the UA1 collaboration, *i.e.*

i) all particles with $p_{\text{T}} > 2.5$ GeV/c are associated to a jet, if their separation in phase space is

$$\Delta R = \sqrt{(\Delta\varphi)^2 + (\Delta\eta)^2} < 1$$

with $\Delta\varphi$ in radians and $\eta(=\text{pseudorapidity}) = -\ln(\text{tg}\,\theta/2)$;

ii) all other particles are associated to the jet defined as in point i), if they satisfy the conditions

$$p_{\text{T}}\ \text{relative to the jet} < 1\ \text{GeV/c}\,,$$

$$\theta\ \text{relative to the jet} < 45°;$$

iii) the total transverse energy of the jet must be greater than 10 GeV.

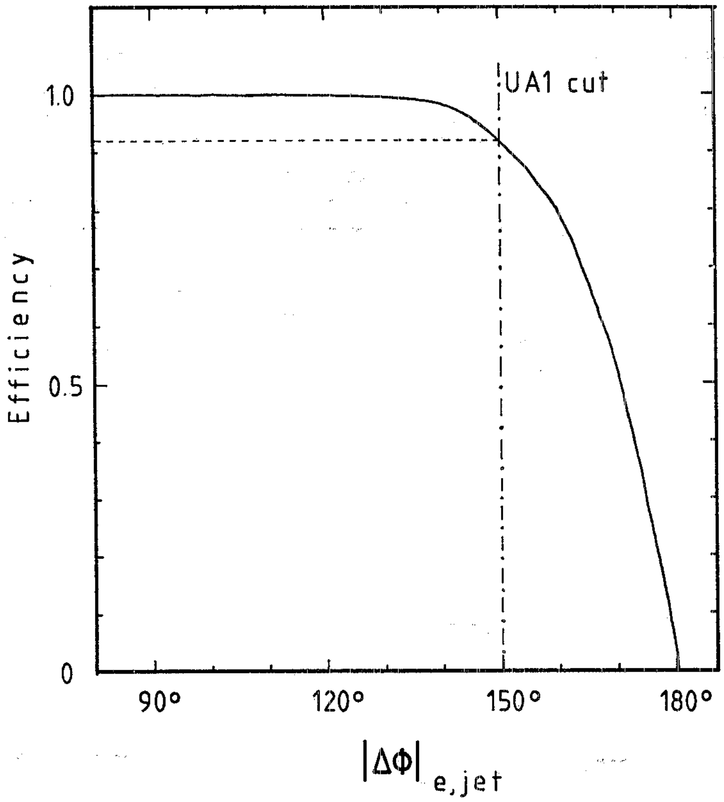

Fig. 2. – Efficiency *vs.* the cut value in the difference of azimuth $|\Delta\varphi|$ between the electron and the hadronic jet in « superbeauty » decay, as derived from the Monte Carlo simulation.

The result is

$$\varepsilon_T(\text{jet}) \simeq 70\% .$$

On the other hand, as shown in fig. 2, the condition that the jet is opposite in azimuth to the electron within $\Delta\varphi = 30°$, is nearly always satisfied.

The number of electrons from « superbeauty » semi-leptonic decays in the UA1 electron sample is, therefore, given by

$$N(e^\pm) = \sigma_{sb} \times \text{BR} \times L \times \varepsilon_T(e^\pm) \times \varepsilon_T(\text{jet}) , \tag{6}$$

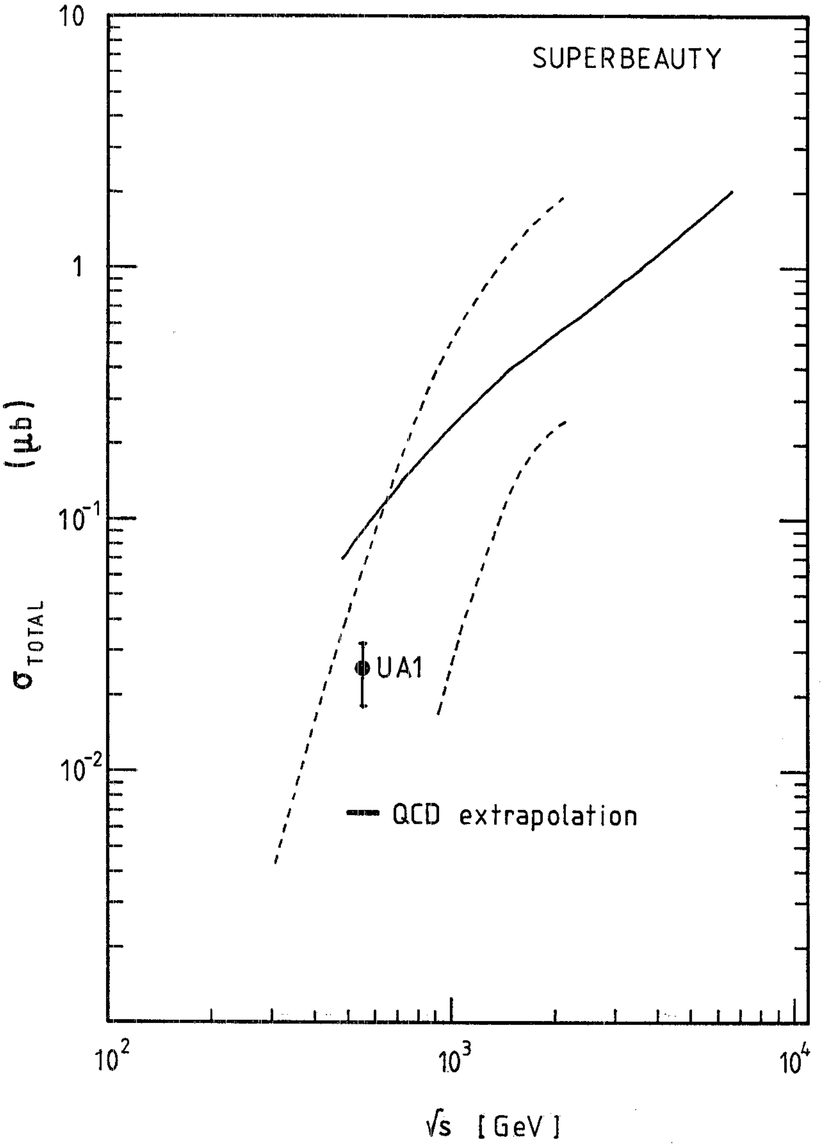

Fig. 3. – Where the cross-section evaluated from the UA1 data falls.

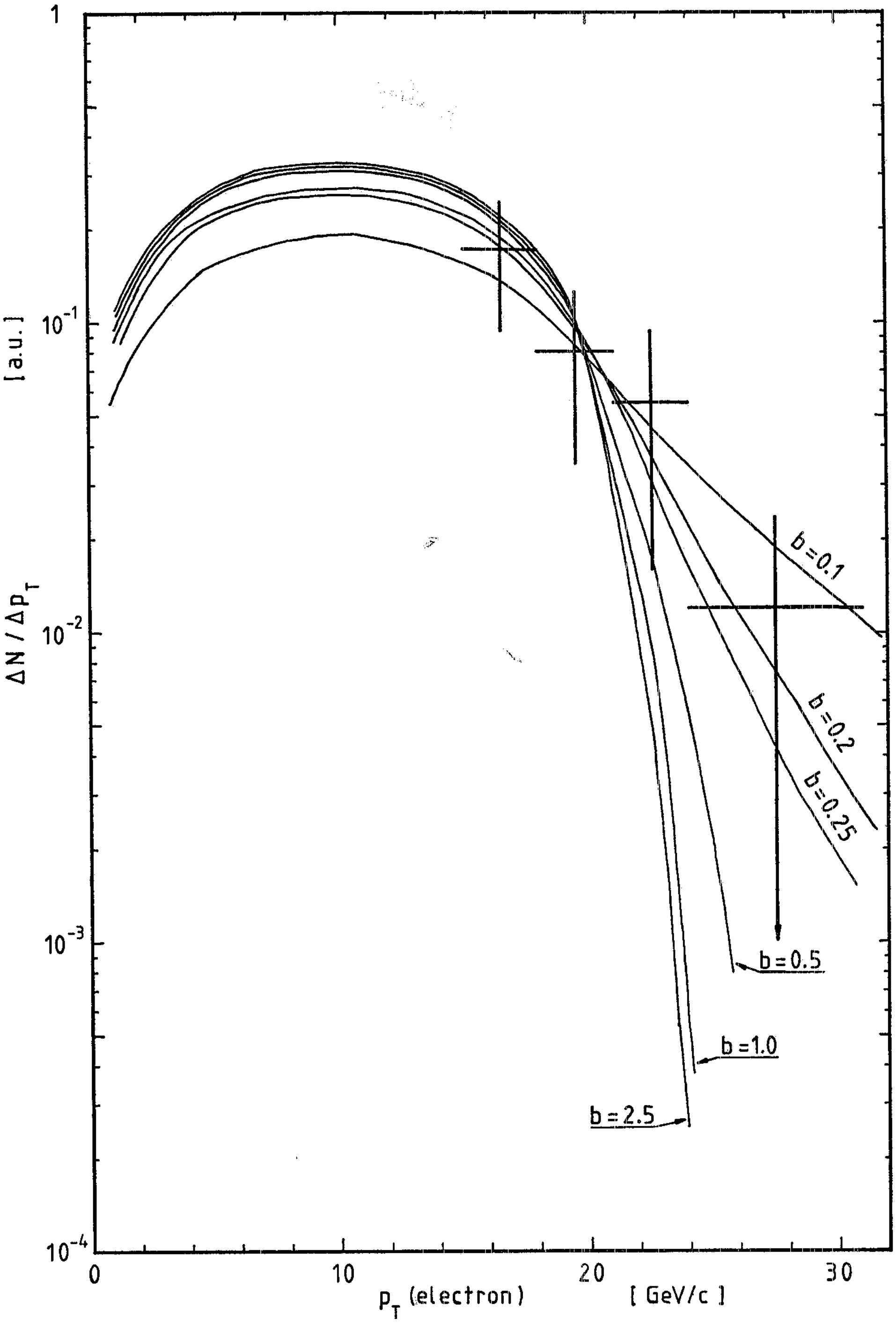

Fig. 4. - p_T spectra of the electrons produced in the decay (sb) → teν, for different $(d\sigma/dp_T) \propto \propto p_T \exp[-bp_T]$ production distributions of the parent (sb) particle, and comparison with UA1 data. The normalization is for $p_T > 15$ GeV/c.

where BR is the semi-leptonic branching ratio of the « superbeauty » state (¹), taken to be BR $\simeq 0.15$, σ_{sb} is the cross-section for the production of « superbeauty » particle states at the $(p\bar{p})$ collider, and the other symbols have already been defined.

From the UA1 it results: $N(e^{\pm}) = 11 \pm 3$.

Note that, in (6), the efficiencies for the electron trigger have not been taken into account. They are as follows:

i) The efficiency for detecting « isolated » electrons, *i.e.* with no other particles with $p_T > 2$ GeV/c in a 20° cone around the electron direction. Here the risk is in the random vetoing, otherwise the efficiency for genuine events is very high. From UA1 data (²) it is possible to deduce the upper limit for random vetoing: it must be below 75%, and it could be, in fact, pratically zero.

ii) The efficiency of the energy cut $E_T > 15$ GeV/c, due to the finite resolution of the EMSDs. This efficiency can be evaluated to be $> 95\%$, by using the quoted EMSD energy resolution $(\Delta E/E = 0.15/\sqrt{E})$.

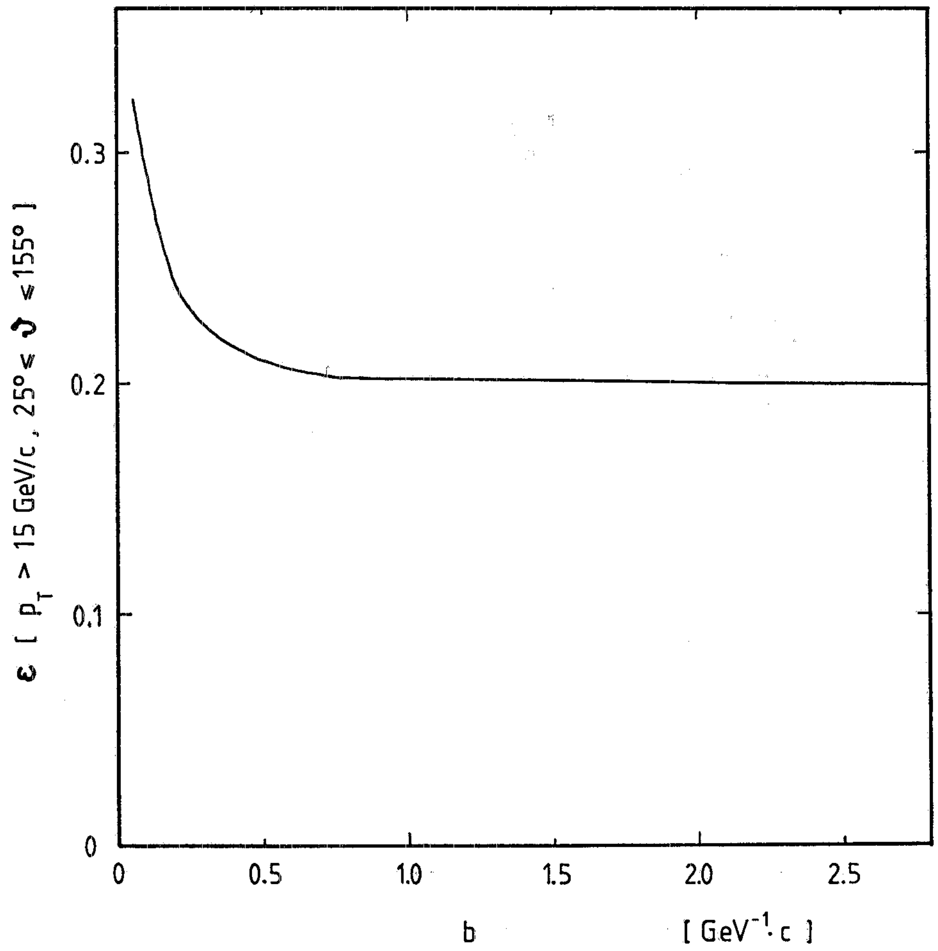

Fig. 5. – Efficiency of the Monte Carlo simulation for the UA1 electron selection, as a function of the exponent parameter b in the parent (sb) p_T production distribution.

Figure 3 shows the cross-section corresponding to the (11 ± 3) events observed. Notice that the « experimental » finding of UA1 falls in a remarkable range of agreement with the crude extrapolations from « charm » and QCD.

Going further, we have compared the p_T distributions of the $(e^{\pm})$ from UA1 with that from our Monte Carlo simulation. This is shown in fig. 4, where the Monte Carlo expectations are obtained using different values for the parameter b in the « superbeauty » production process:

$$d\sigma/dp_T \propto p_T \exp[-bp_T] .$$

Data and Monte Carlo distributions are normalized to the total number of events $p_T \geqslant 15$ GeV/c.

A value of $b \simeq 0.20\ (\text{GeV})^{-1}/c$, *i.e.* a mean value for the production average transverse momentum, $\langle p_T \rangle$, of the order of 10 GeV/c, fits the UA1 data quite well. This value for b is much smaller than the value $(b = 2.5)$ which we found in our study of « charm » production at the ISR (⁶). However, it should be noticed that we are dealing here with the production of a flavour much heavier than « charm ». The value $b = 0.2$ is in good agreement with the prescription $\langle p_T^2 \rangle \simeq m^2/4$ (m is the quark mass) used by ODORICO (⁵) to compute the « charm » production properties from flavour excitation.

The efficiency for detecting electrons with $p_T > 15$ GeV/c in the Monte Carlo simulation does not change very much for $b > 0.2$, as shown in fig. 5. Thus the total « superbeauty » cross-section, derived by formula (6), holds, within $\pm 30\%$, even with this very low, but expected, value of b.

As mentioned above the « downlike » nature of the observed (11 ± 3) events cannot be established in a direct way. It is based on a chain of self-consistent arguments. Let us give up the ratio (2*b*) which binds the « top » flavour to be in the 25 GeV range. If we repeat the analysis without this constraint the (11 ± 3) events can be reinterpreted as the « uplike » signature, with the « top » flavour mass 30 GeV above the « beauty » flavour. The value of the cross-section would in this case be as shown in fig. 6.

Conclusions. A sequence of arguments based on known facts, and on simple hypotheses, extrapolated to the CERN $(p\bar{p})$ Collider energies, allow us to conclude that the (11 ± 3) events observed by the UA1 collaboration and consisting each of a single $(e^{\pm})$ accompained by a jet activity in the opposite hemisphere, correspond to a value of the cross-section expected for the production of a very-heavy-flavoured state, in the 55 GeV/c² mass range. Moreover, the observed p_T spectrum of the $(e^{\pm})$ follows the expectations for the semi-leptonic decay of a very massive state, again in the 55 GeV/c² mass range.

It should, however, be noticed that the identification of the « downlike » nature of the heavy-flavoured state is based on a series of hypotheses which produce the

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(⁶) 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**, 481 (1981); M. BASILE, 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*, **33**, 17 (1982).

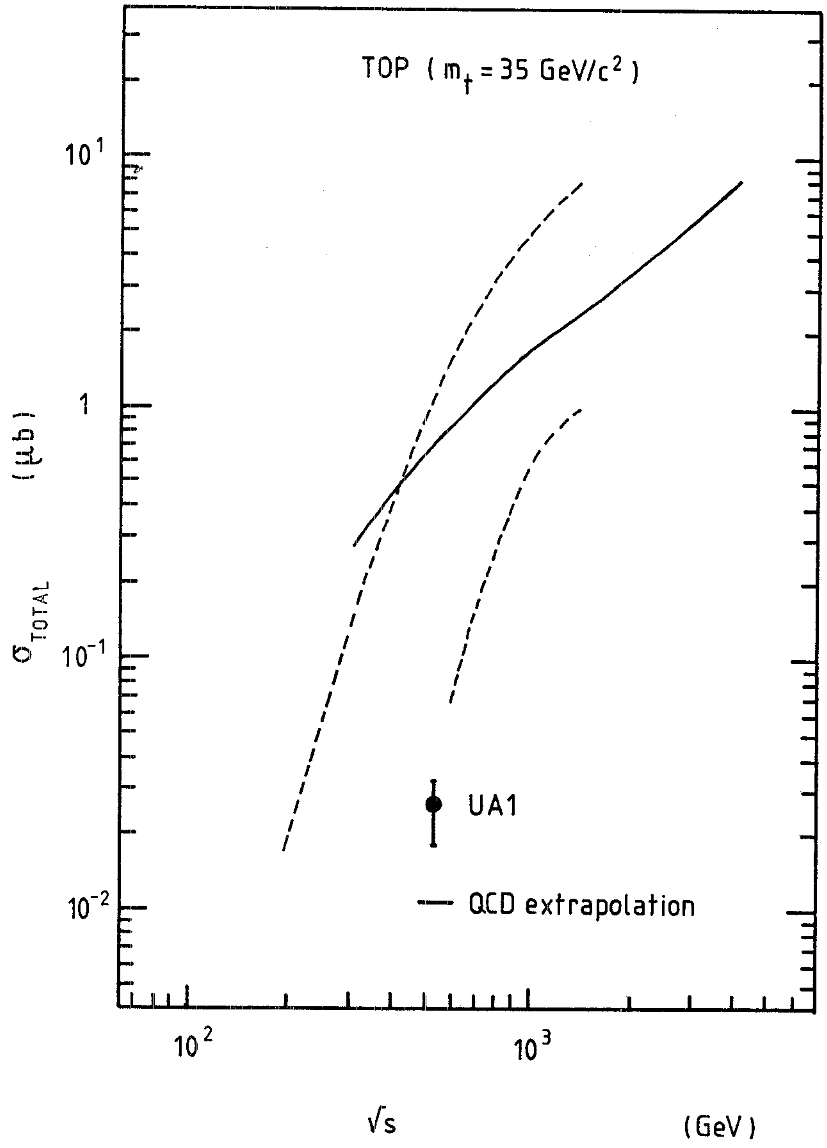

Fig. 6. – Comparison between the cross-section evaluated from the UA1 data, and the cross-sections derived from « strange » (full line) and « charm » (dashed lines) following formula (5) and using for « top » the mass value $m_t = 35$ GeV/c^2.

correct $\Delta m \simeq 30$ GeV/c^2 for the (e$^\pm$) transverse-momentum spectrum observed, and the correct magnitude for the cross-section. If we were to ignore the cross-section and the quark mass ratios which allows us to predict the masses of the 4th family, the only parameter left to fit the observed (e$^\pm$) transverse-momentum spectrum, would be the value $\Delta m \simeq 30$ GeV/c^2. In this case the conservative interpretation of the UA1 results would be a « top » with a mass 30 GeV/c^2 above the « beauty ».

This shows the importance of our proposal (1) to study in detail the production of new heavy flavours at the CERN ($p\bar{p}$) collider, by measuring the (e^+/e^-) asymmetry. In fact, the sign of the asymmetry allows the identification of the « uplike » or « downlike » nature of the heavy-flvoured state in a direct and unambiguous way. Moreover, the (e^+/e^-) energy dependence of the asymmetry allows us to establish the correct sequence of

« downlike » ↔ « uplike »

decay chains for the new heavy flavours, and their mass difference.

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