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ABSTRACT

Various approaches to the hadronic productions of the double heavy meson B_c are investigated in this paper. The resultant cross sections obtained by the approaches are compared with in several aspects. One may see that the differences are quite substantial. The advantages and shortcomings of the approaches are discussed.

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The B_c meson, being an important sample of double heavy flavor mesons, is gaining general interest recently. One reason is due to its nature: it, similar to η_c, J/ψ, and η_b, Υ etc., is a double heavy quark-antiquark bound state, so the QCD inspired potential model will work well for describing the binding effects of it[1,2]; but it, different from those, carries flavors explicitly, so it may decay by weak interaction only, and as a result, it has a much longer lifetime (a typical weak decay one) and plentiful decay channels with a sizeable branching ratio. Some of its decays may be calculated quite reliably and will be measurable experimentally in the near future [3,4]. Thus we may use it, in addition to the J/ψ and Υ families, to test the QCD inspired potential models further and test the acting weak decay mechanisms for relevant heavy flavors, i.e. we may achieve very useful and comprehensible information and experiences for understanding the potential models and clarifying some obscurity on the acting weak decay mechanisms, especially those responsible for heavy flavors, through investigating the theoretical predictions and experimental data when the data about the spectrum, the decays and productions of the B_c meson are accumulated sufficiently.

Another important reason to make the B_c physics interesting recently, is the experimental B_c study being accessible soon, as pointed by several independent theoretical estimates[2-12]. Namely, according to the estimates, the cross sections of its production at certain existent colliders are sizeable and some typical signals may project over the background.

Having all the possible mechanisms for producing a double heavy flavored meson reviewed, the authors of refs.[5,6] have pointed out that the most suitable ones of high energy processes to produce sufficient events of the B_c meson at the existent and planned facilities, are of Z^0 boson decay and energetic hadronic collisions. In ref.[5], besides a complete calculation on the B_c meson production at the level of the lowest order of perturbative QCD, the fragmentation functions for $\bar{b} \to B_c$ and $\bar{b} \to B_c^*(S-wave)$ were also worked out correctly, while those for $\bar{b} \to \chi_{\bar{b}c}(P-wave)$ in ref.[7]. It is the first time that the calculations on the fragmentation functions have involved all the terms which should be concerned, i.e. none of them could be ignored due to being the same order, as pointed in ref.[5]. The fragmentation functions obtained in ref.[5] were confirmed by others soon[8,11] (in ref.[5] there are some misprints in the formulas but the numerical curves are correct). The authors of refs.[8,11] recalculated the fragmentation functions in an axial gauge, a different gauge from that adopted in ref.[5], so as to manipulate the factorization of the fragmentation functions manifestly. Moreover they also worked out the evolution of the fragmentation functions with changing of the fragmentation energy scale by means of solving the corresponding Alteralli-Parisi equation.

In fact, besides those of pure phenomenological ones with Monte Carlo simulation such as done in ref.[10], of all the proposed theoretical estimates[5-12], the adopted approaches may be divided into two categories, although all are based on the perturbative QCD. The first category is to concern the production just as if a fragmentation of a heavy flavor jet (here $\bar{b}$ jet mainly). It is similar to that of the light-quark hadronization, but different from that on the fragmentation energy scale. As the produced relevant quark pair in the fragmentation is so heavy that the fragmentation happens already above the region where the perturbative QCD (pQCD) works well, so the specific fragmentation functions are calculable in the sense of pQCD. The production mechanism, as pointed out by the authors of refs.[8], may be applied further to the productions of heavy quarkonia, if possible gluon fragmentations are added into as well. In this approach, the fragmentation

functions may be extended straightforwardly to an accuracy up to the leading logarithm approximation (LLA) level as done in ref.[8, 11]. The second category is to apply the factorization theorem of pQCD only once to the calculation i.e. only to factorize out the structure functions of the colliding hadrons from the 'rest parts' of the production, but not as the first category to factorize the 'rest parts' into two factors: the 'jet production' and the 'fragmentation' of the B_c meson from the jet. Here the 'rest parts' treated as a whole, are computed in the framework of pQCD. Although the computations are of the lowest order at the moment, in principle, it may be extended to a higher order of pQCD with lengthy and boring calculations. In short, the difference of the first category from the second one is that the first will factorize the 'rest parts' of the second further into two steps: to produce jets first and then to fragment. For convenience, we will call the 'rest parts' as 'the subprocess' and denote the first category as Approach-I, whereas the second one as Approach-II throughout the paper.

The presice differences between the two categories in the production of the double heavy meson B_c in Z^0 decay, may be found in ref.[5], although there the LLA corrections were not considered. Since the relevant $\bar{b}$-jet produced in the Z^0 decay is very energetic ($E_b = m_{Z^0}/2$ at C.M.S.), the difference in the partial width between the two categories is not very great, less than 20%. However, for the hadronic productions of the B_c meson and its excited states at Tevatron, even at LHC, the colliding energies of the subprocess are various in a wide region and may not be very high. The energies of the subprocess just are of the colliding partons inside the hadrons, and they are measurable experimentally in fact. At the peak 'luminosity' of the coming gluons, according to the structure functions of the colliding hadrons of Tevantron (even LHC), the energy is smaller than the corresponding one in Z^0

decay; one will see this point more precisely later on. Thanks to the heavy masses of the quarks in the B_c meson production play an essential role here, the perturbative QCD calculations are always applicable no matter how the P_T as long as the energy of the colliding partons is above the threshold, thus the contribution from low P_T components should be calculated out and to see how substantial the low P_T contribution is, in the concerned case where a double heavy flavored meson B_c, and two heavy quark jets: b and $\bar{c}$ are produced at least. Especially, in the case, a great momentum, so a high P_T for the B_c meson cannot always be available, when the energy of the colliding partons is not very high above the threshold. The low P_T components of the production should not be ignored, also because the experimental ability may cover them. For comparison, we note here that for a light flavor production, in contrary, such low P_T components are neither calculable in perturbative QCD nor measurable experimentally at the moment.

In hadronic collisions, if the high P_T components of a double heavy flavor production were dominant everywhere, Approach-I would be equivalent to Approach-II always according to the general provement of the factorizaton theorem of pQCD, however realistically, comparative 'low' energy collisions for the relevant subprocess are involved, so the low P_T components should be examined carefully, the former probably will be so good as the latter. In Approach-I, to factorize the subprocess further i.e. to produce heavy quark jets first and then to fragment a meson B_c from one of the jets is taken. If the jet, responsible for the fragmentation of a B_c meson, carries a comparative low P_T, the further factorization is doubtable. It is because that it has to ignore the terms which are much smaller than the kept ones only at large P_T. Therefore the shortcoming for Approach-I is conspicuous, especially when considering the measurable observable to which the low P_T components contribute substantially. Whereas in respect to Approach-II, a full complete calculation of perturbative QCD on the subprocess in whole, not as Approach-I to factorize the subprocess further, is carried out so the Approach-II should be better than Approach-I in the cases when the contribution from the low P_T components is important. The shortcoming of Approach-II is that so far only the lowest order calculations is available, and even so, the computations are still very complicated (more diagrams should be considered) and the results may be presented numerically only. Theoretically it would be able to be extended to a higher order with skills.[13]

Besides the above theoretical consideration, experimentally quite low P_T productions of the B_c mesons may be accessible by improving the existent and newly designing detectors, thus the low P_T components of hadronic productions become measurable experimentally. Thus in the sense to see the precise differences of Approach-I and -II is interesting and even useful for experimental searching for, and/or studying the double heavy flavor meson B_c.

As matter of fact, it is not straightforward to see the differences quantitatively and to say which of the two kinds of approaches is better definitely, although we have argued some advantages and shortcomings of them. Therefore a thorough investigation quantitatively even numerically, is very interesting for understanding the mechanism of the hadronic production of the double heavy flavor mesons, such as the B_c meson. We will devote this paper to the investigation, i.e. to compare the two categories of the approaches in various features.

In hadronic production, since the B_c meson is flavored explicitly, only heavy quark fragmentation contributes to the B_c meson production, whereas as pointed out in ref.[8], for a hidden flavored quarkonium, not only heavy quark fragmentation but also gluon one contribute, thus to see the differences of the two approaches, at the first stage is suitable not to start with a complicated case, i.e. not to start with that of the hidden flavored quarkonium, although the hidden flavored case is also very interesting. Therefore in the paper, besides the interest of the problem itself, we choose the B_c meson as an sample to do the investigation. Moreover we are to make the comparison in such a way by plotting each of the numerical results obtained by the two approaches into one figure together, and different figures show different aspects of the approaches for the hadronic productions.

First of all, we compare the total cross sections of the B_c and B_c^* productions obtained by the two approaches at various hadronic colliders i.e. for various C.M.S's energies of the colliding hadrons. We put the numerical results in Tab.1. We should note here that when calculating the productions of $p-p$ and $p-\bar{p}$ collisions, only gluon-gluon fusion mechanism is considered due to its domination over those of quark-antiquark[6]; the SET II of the EHLQ structure functions[14] with an energy scale $Q^2 = \hat{s}/4$ ($\hat{s}$ is the c.m. energy squared of the subprocess) are adopted; while the masses $m_c = 1.5GeV$, $m_b = 4.9GeV$ and $M_{B_c} = 6.4GeV$[2] are taken. One may see the resultant total cross sections for B_c and B_c^* productions are different only within a factor two.

TABLE I. The total cross sections for the productions of the B_c meson and its excited state B_c^* obtained by the two approaches (in unit pb).

Collision	Approach-I		Approach-II	
	$B_c\ (1^1S_0)$	$B_c^*\ (1^3S_1)$	$B_c\ (1^1S_0)$	$B_c^*\ (1^3S_1)$
$p\bar{p}(\sqrt{S}=1.8TeV)$	0.98	1.60	0.96	2.57
$pp(\sqrt{S}=16TeV)$	9.8	15.6	11.3	29.8
$gg(\sqrt{S}=20GeV)$	$0.70\cdot10^{-2}$	$0.118\cdot10^{-1}$	$0.49\cdot10^{-2}$	$0.144\cdot10^{-1}$
$gg(\sqrt{S}=30GeV)$	$0.68\cdot10^{-2}$	$0.103\cdot10^{-1}$	$0.85\cdot10^{-2}$	$0.235\cdot10^{-1}$
$gg(\sqrt{S}=60GeV)$	$0.32\cdot10^{-2}$	$0.46\cdot10^{-2}$	$0.79\cdot10^{-2}$	$0.200\cdot10^{-1}$

Note here that i). The authors of refs.[10-12] obtained

$$\frac{\sigma(pp(\bar{p})\to b\bar{b}\, c\bar{c}\, X)}{\sigma(pp(\bar{p})\to b\bar{b}\, X)} \sim 10^{-2}$$

with $\alpha_s(4m_c^2)$, however our result is

$$\frac{\sigma(pp(\bar{p})\to b\bar{b}\, c\bar{c}\, X)}{\sigma(pp(\bar{p})\to b\bar{b}\, X)} \sim 10^{-3},$$

with $\alpha_s(\hat{s})$ and consistent with that obtained by ref.[15]. The ratio is in the region about 10^{-2} – 10^{-3} generally, and the uncertainty depends on the adopted value of α_s mainly. ii). All estimates agree with that the ratio

$$\frac{\sigma(pp(\bar{p})\to B_c\, b\, \bar{c}\, X)}{\sigma(pp(\bar{p})\to b\bar{b}\, c\bar{c}\, X)} \sim 10^{-1},$$

the uncertainty comes from the choice of the value of f_{B_c}, whereas the decay constant is fixed by potential model through the wave function at origin essencially. Concerning with the effects of the wave function at origin of the produced meson and the colour matching (from two coloured quarks to a colourless meson) as well as the above four heavy quark production, the results presented in Table I are reasonable.

According to the factorization theorem of perturbative QCD, all the resultant cross sections of the hadronic productions are achieved by a convolution of the subprocess and a common factor: the structure functions of the incoming hadrons. Highlighting the differences of the two approaches, we have calculated the subprocess as if an independent one, i.e. the gluon-gluon fusion at various precise energies of it, and put the results in Tab.1 too. In fact, the cross sections may be measured experimentally merely to have an exclusive measurement on all products of the subprocess.

In order to have an outline about the gluon-gluon fusion, in Fig.1 we present the production cross sections at Tevatron and LHC versus the collision energy $\hat{s}$

of the active gluons inside the collision hadrons. From the figure, one may see the cross sections decrease as $\bar{s}$ is increasing clearly. We should note here that the cross sections in Fig.1 are not merely of gluon-gluon fusion, but the structure functions of the collision hadrons are convoluted into, so that they are different from those of the gluon-gluon fusion in Tab.1. In Fig.1 a quite complex feature about the cross sections is presented, but all the cross sections have a common tendency: after a peak around $\hat{s} = 20GeV$ all drop in a logarithm scale versus $\bar{s}$ increasing. When $\bar{s}$ reaches at $80GeV$, the cross sections drop down three orders of the magnitude almost. Thus one may conclude that in the hadronic collisions the dominant contribution to the B_c and B_c^* meson productions is not from very high energy gluon fusion but from relatively low energy $\bar{s} \sim 20\ GeV$. The cross sections obtained by Approach-II are greater than those by Approach-I at most energies ($\bar{s} \geq 20\ GeV$) within a factor 5 due to the contribution from low P_T components at various $\bar{s}$, and the difference of the two approaches for $B_c(1^1S_0)$ production is less than that for $B_c^*(1^3S_1)$ production.

Highlighting the differences further and the other aspects, we present the distributions of the transverse momentum P_T and the rapidity Y for the process of the gluon fusion at various C.M.S's energies in Fig.2 for $\bar{s} = 20\ GeV$, Fig.3 for $\bar{s} = 30\ GeV$ and Fig.4 for $\bar{s} = 60\ GeV$ respectively. One may see the fact very clearly that, as expected, the values obtained by Approach-II at small P_T and small Y are always greater than those obtained by Approach-I, whereas the values are approaching close when P_T or Y increases.

In summary, the two approaches have some substantial differences, especially, at low P_T and low Y. In fact, the differences may be understood some in the framework of the Approach-II formalism. According to it, there are 36 diagrams responsable

for the subprocess in total, and they may be split into five independent and gauge invariant subgroups[6]. In general, all terms contribute, but at very high energies and for high P_T components, only some terms keep contributing substantially without cancellation, and they are just those considered by Approach-I; whereas the rest terms are decreasing very quickly as the P_T is increasing, and they are ignored by Approach-I. Thus the two approaches happen to be consistent for high P_T components at high energy as shown by Figs.2,3,4, due to the fact that both of them have kept the same substantial terms; whereas the differences come from the fact that some terms are ignored in Approach-I.

Recently the authors of ref.[16] also recognized that certain higher order gluon fragmentation besides that of heavy quark may contribute substantially. According to the experiences of heavy quark productions in hadronic collisions and the theoretical loop calculations, we know that full perturbative QCD calculations up to one loop level achieved quite high accuracy[17], thus it is sure that a higher order full perturbative QCD calculation on the hadronic production of the double heavy flavor meson B_c under Approach-II will be very interesting[13].

Acknowledgments

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Figure Captions

1. The differential Cross Sectons of the B_c and B_c^* Productions versus the C.M. Energies of the Colliding Gluon-Gluon at the Colliders for Approach-I and Approach-II.
   (a) The differential Cross Sections of the B_c Production versus the C.M. Energies of the Colliding Gluon-Gluon at Tevatron. The solid line $A\ V$ and the dashed line $C\ V$ are those of the B_c^* productions obtained by Approach-I and Approach-II respectively; the dashed-dotted line $A\ P$ and the dotted line $C\ P$ are those of the B_c productions obtained by Approach-I and Approach-II respectively.
   (b) The differential Cross Sections of the B_c Production versus the C.M. Energies of the Colliding Gluon-Gluon at LHC. The lines have the same meaning as those of Fig.1(a).
2. The differential Cross Sections of the B_c and B_c^* Productions versus the Produced Transverse Momentum P_T and the Rapidity Y respectively at $\sqrt{s} = 20GeV$.
   (a) The differential Cross Sections of the B_c and B_c^* Productions versus the Produced Transverse Momentum P_T at $\sqrt{s} = 20GeV$. The lines have the same meaning as those of Fig.1(a).
   (b) The differential Cross Sections of the B_c and B_c^* Productions versus the Rapidity Y at $\sqrt{s} = 20GeV$. The lines have the same meaning as those of Fig.1(a).

3. The differential Cross Sections of the B_c and B_c^* Productions versus the Produced Transverse Momentum P_T and the Rapidity Y respectively at $\sqrt{s} = 30GeV$.
   (a) The differential Cross Sections of the B_c and B_c^* Productions versus the Produced Transverse Momentum P_T at $\sqrt{s} = 30GeV$. The lines have the same meaning as those of Fig.1(a).
   (b) The differential Cross Sections of the B_c and B_c^* Productions versus the Rapidity Y at $\sqrt{s} = 30GeV$. The lines have the same meaning as those of Fig.1(a).
4. The differential Cross Sections of the B_c and B_c^* Productions versus the Produced Transverse Momentum P_T and the Rapidity Y respectively at $\sqrt{s} = 60GeV$.
   (a) The differential Cross Sections of the B_c and B_c^* Productions versus the Produced Transverse Momentum P_T at $\sqrt{s} = 60GeV$. The lines have the same meaning as those of Fig.1(a).
   (b) The differential Cross Sections of the B_c and B_c^* Productions versus the Rapidity Y at $\sqrt{s} = 60GeV$. The lines have the same meaning as those of Fig.1(a).

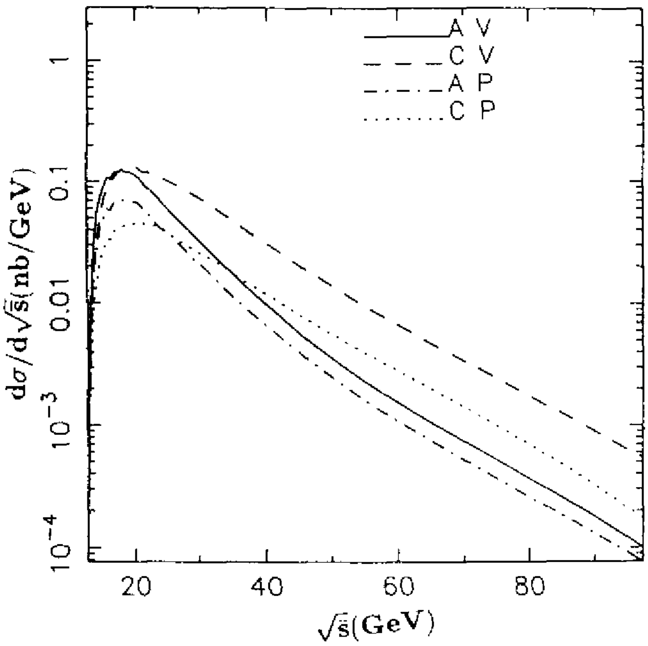

Fig1a

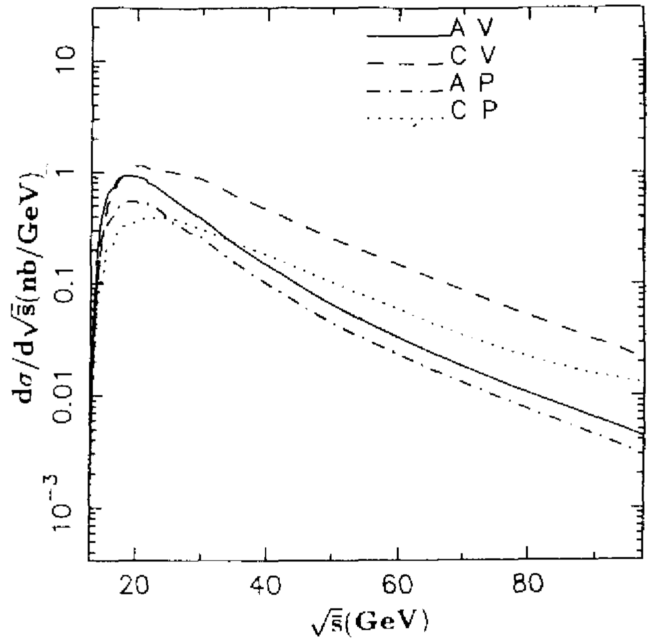

Fig1b

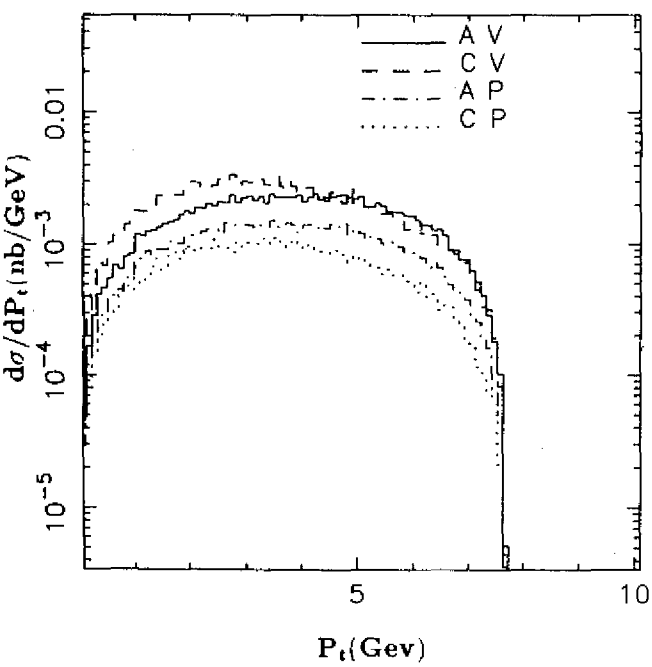

Fig2a

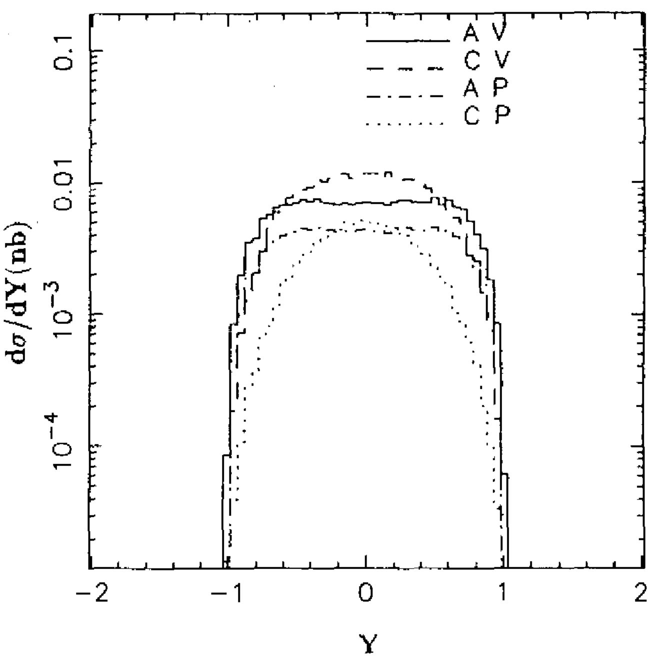

Fig2b

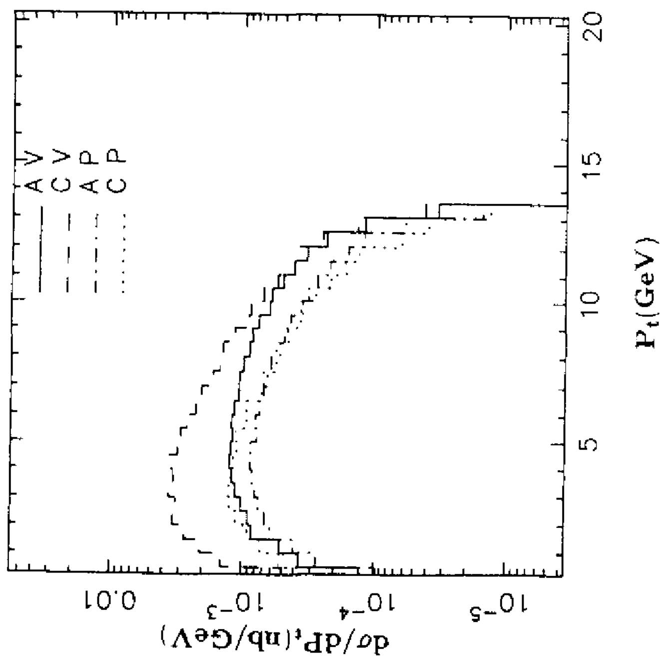

Fig3a

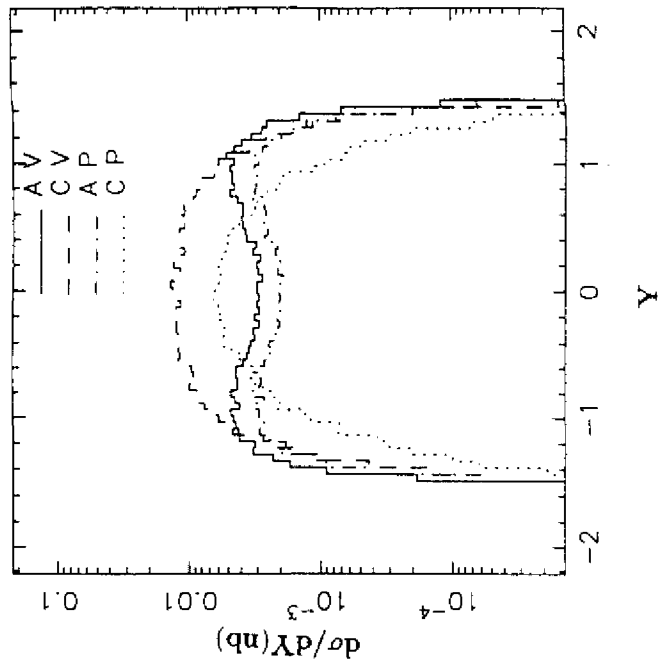

Fig3b

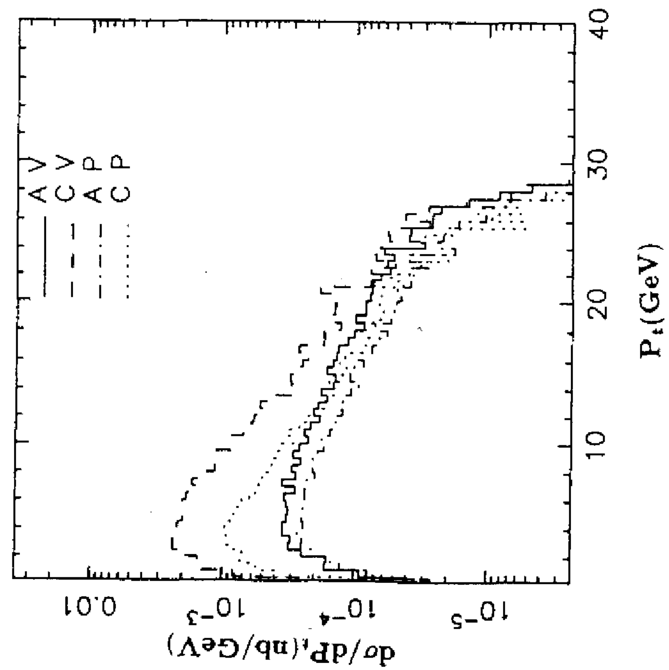

Fig4a

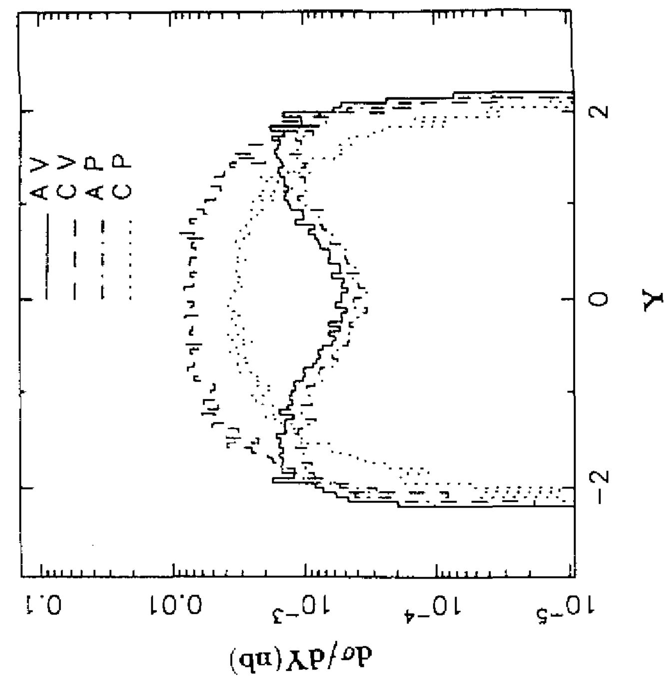

Fig4b