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Beauty Physics at Fermilab Fixed Target Energies*

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Abstract

The very high luminosities ($>>10^{32}$ $cm^{-2}sec^{-1}$) available in the Fermilab fixed target experimental areas offer immediate opportunities for producing large samples ($>10^{8}$) of B hadrons in individual experiments. The possibilities of accumulating large samples of B decays are limited by experimental techniques and trigger strategies and not by available luminosity. At the present time one experiment, E771, is approved to begin B physics experimentation and several other experimental possibilities are being discussed. Some of the problems and the potential of B experiments at fixed target energies as B factories are discussed.

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I. Introduction

The weak decays of B hadrons offer perhaps the one remaining experimental opportunity to study CP violation. To date CP violation effects have been observed only in the decays of K mesons. Since the observation of CP effects will require substantial statistics, a great deal of attention has been devoted recently to evaluating the possibilities of accumulating large samples of B decays at the SSC[1,2,3] and at the TEV I collider[4,5]. The possibilities for various types of e^+e^- B factories[6] have also been extensively discussed. All of these possibilities must be considered to be relatively far in the future. A much more immediate possibility for attaining large samples of B hadrons is available using the hadron beams in the Fermilab TEV II fixed target experimental areas[7,8]. Indeed, the experimental configurations necessary to perform such experiments at TEV II bear a striking resemblance those necessary for SSC experiments. This similarity adds extra impetus to the investigation of the TEV II possibilities. It is the purpose of this paper to investigate the potential and discuss some of the problems of fixed target B experiments.

II. Comparison Yields of $B\bar{B}$ for Various Experimental Options

The comparison of fixed target options for B physics and various hadron and e^+e^- collider options is a complex enterprise. There may be no clear cut global choice based solely on experimental feasibility and physics if we ignore cost comparisons and possible schedules for implementation. We show below Table I extracted from Ref. 7 which gives the $B\bar{B}$ event yields for 10^7 seconds of operation of experiments at TEV II (Fermilab fixed target), TEV I (Fermilab collider) and the SSC. In a similar spirit, Table II extracted from Ref. 6 compares the yields of B's for 200 days of operation of various e^+e^- experimental options to E771[8] (the only TEV II fixed target B experiment approved thus far) and to future possible Fermilab collider experiments. Several general conclusions can be drawn from these tables, ignoring for the time being all the complex differences and relative feasibilities of the various experiments that must be mounted to take advantage of these yields.

First, it is clear that the ultimate B hadron yields of the present and the various future e^+e^- options lie considerably below the potential yields of all the hadroproduction experiments because of the luminosities of electron-positron colliders and the much lower cross sections for electroproduction of B's. The most promising e^+e^- options in Table II (which are far in the future) are at least an order of magnitude lower in yield of B's than the yield that is expected for the fixed target hadroproduction experiment, E771. In addition, while one might think that e^+e^- production of B's would be a somewhat cleaner process than hadroproduction thereby allowing a greater percentage of the B's decays to be detected and reconstructed (especially since operation at the Υ(4S) resonance produces events with only a B and $\overline{B}$), there are formitable problems in this type of experiment in reconstructing B's. The fact that the B and $\overline{B}$ are produced at rest with respect to one another in e^+e^- interactions at the 4S leads to great difficulties in untangling their decay products since the secondary vertices cannot be distinguished. This combinatorial difficulty has resulted in only a couple of hundred B's reconstructed out of the quarter of a million produced during the lifetimes of the ARGUS and CLEO experiments at DESY and at Cornell[9]. In addition, no B hadron has been reconstructed thus far at the higher energy e^+e^- machines, PEP and PETRA. This is partially because of the much smaller cross sections for electroproduction of B's at energies other than that of the Υ(4S) resonance but mainly because secondary vertices are not observed.

The development of microstrip detectors, fast on-line trigger processors, fast data acquisition systems and sufficient computing power to compute 10^8-10^9 trigger experiments together with the unique features of the B decays (especially the long lifetime[10] of 1.42×10^{-12} seconds) have given rise to the possibility that hadroproduction of B's may be the optimal way of obtaining large sample of B decays. The fixed target photoproduction experiment, E691 has demonstrated the power of microvertex detectors in detecting and reconstructing charm decays through detection of the charm secondary vertices. However, the low yield of high energy photons (due to the tertiary nature of Fermilab fixed target photon beams) and the small cross sections for B photoproduction does not point us toward photoproduction as the optimal place to accumulate large numbers of B's.

Instead, attention has slowly been focussed on hadroproduction both at the CERN SPS and Fermilab TEV II fixed target experiments and at the TEV I and CERN colliders as the most promising possibilities for producing large B samples. The presence of a resolvable secondary vertex coupled with clever trigger strategies can help overcome the small size of the B hadroproduction cross section relative to the large hadronic total cross section. The ratio of these cross sections, as shown in Table I, varies between 10^{-6} at the Fermilab fixed target hadroproduction energies and and 10^{-3} at the SSC. Therefore, the hadroproduction experiment which seeks to study a particular exclusive mode (typically having a 10^{-4} branching ratio) must be able to select one in ten billion interactions at TEV II. Therefore, there is a premium on good triggers to select the appropriate interactions and striking features of desired exclusive decays to allow offline separation of signal from backgrounds. While the ratio of cross sections (approximately 10^{-4}) is more favorable at present collider energies, the relative low momentum of the large majority of the B's produced at TEV I and the CERN collider and the presence of the huge multiplicities in the high energy interactions present daunting experimental obstacles to both online triggering and separation of the B's from backgrounds offline. Not until one reaches SSC energies (as shown in Table I) does the average momentum of the B's approach the momentum of the Lorentz boosted TEV II B mesons and does the decay product momenta become appreciable.

While formidable, the difficulties of selecting the B production from the large hadronic total cross section in fixed target experiments are not insurmountable. Strategies, involving single lepton and lepton pair triggers[8,11,12] have already been discussed (and in the case of E771, the J/Ψ trigger strategy has been approved for experimentation). Such trigger strategies have the potential of rejecting the total cross section at the level of 10^{-6} while preserving a substantial fraction of interesting B decays. We concentrate on fixed target options for B experiments in this paper.

In the following discussions we will briefly weigh the various fixed target hadroproduction options . Much more detailed work will have to be done by the advocates of any approach to B physics experimentation (including e^+e^- experiments) to completely evaluate the different techniques by the correct meter stick, the number of fully reconstructed B decays. Indeed, an even more stringent meter stick must be applied in the search for CP violating effects in B decay, i.e.the number of fully reconstructed B decays in a particular exclusive modes that can be both fully reconstructed and tagged as being a B or $\overline{B}$ at t=0 (at production).

III. Features of Hadroproduction of Beauty Hadrons

There is only a small amount of data available on hadroproduction of beauty at fixed target energies at the present time. The WA78 experiment at CERN has inferred[13,14] the cross section for B production in 320 GeV/c π^-U interactions from a measurement of the di- and tri-muon yields. They quote a result of (2.0±0.3±0.9) nb per nucleon assuming a linear A dependence of the B hadroproduction cross section. The QCD cross section calculated by E. Berger[15] agrees roughly with this result (using a K factor of 2). In Fig. 1 we show the B hadroproduction cross sections for π^-N and pN interactions calculated by E. Berger together with the WA78 data point. We will use these calculated cross sections later to estimate the B hadron yields of π^-N and pN interactions for fixed target B experiments.

The general features of B hadroproduction have been reported in several places[1,2]. The dominance of gluon fusion mechanism at collider energies leads to several salient features. This mechanism produces strong correlations between the b and $\overline{b}$ quark directions such that both quark and antiquark are produced in the same direction strongly peaked along one or the other beam. In addition, the momentum of the b quarks is appreciable only in the forward direction. Thus, the b quarks in the very high energy collisions at the SSC mimic the Lorentz boosted TEV II fixed target b quarks and make the spectrometers required for B physics at the SSC and TEV II quite similar in configuration. This is discussed more fully in Ref. 1, 2 and 3.

The hadronization of the b quark into one of the various species of B meson or baryon proceeds by gluon radiation and in the process softens the spectrum of B hadrons. The decay of the B hadrons into the various exclusive final states further degrades the energy of the particles that must be detected. As an example of the effect that this multistage process can have, we have calculated the momentum spectra of the leptons from the semileptonic and the J/Ψ decays of the B's using the PYTHIA Monte Carlo[18]. Both of these modes figure prominently in trigger strategies which have been proposed for B's. In Fig. 2a, b and c we show the momentum spectra of the electrons from the semileptonic decay of the $B \to De\nu$ for the B's produced at the SSC, TEV I and TEV II respectively. In Fig. 3a,b and c we show the momentum spectra of the muons from the decay $B \to \Psi K\pi$ followed by the subsequent decay of the $\Psi \to \mu^+\mu^-$. In both cases the TEV II leptons have higher momentum than those produced at the SSC and very much higher momentum than those produced in TEV I collider energies. The higher momentum of the B decay products makes possible a clean lepton trigger for TEV II and SSC experiments as has been discussed in Ref. 2.

IV. Fixed Target B Physics Hadron Beam Options

Having rejected photoproduction as a possibility in our search for methods of accumulating large numbers of B decays, there still exist many different hadron beam options to choose from for experiments seeking to produce large numbers of B's. Among these are neutron and pion secondary beams. In addition, primary proton beams from the accelerator can be used.

We will not quantitatively evaluate the possibilities of using neutron beams for B hadroproduction experiments since such an evaluation is an intricate task which must take into consideration the backgrounds from beam halo which couple to particular experiments in a complex and experiment specific way. The neutron beam is unique in its neutral nature. It also has a relatively high energy spectrum. On the other hand it has all of the bad features of a secondary pion beam, ie large hadronic total cross sections, copious hadron and muon halos, and restricted yields. In addition, neutron beams have some particularly nasty features such as relatively uncontrollable beam spot size. We will leave it to others to argue that the neutral nature of neutron beams outweigh their negative aspects.

We will concentrate instead on comparing the use of secondary pion beams (and in particular negative pion beams) with the use of an extracted proton beam for B experiments. In Fig. 4a we give, as an example, the negative pion yield of a relatively high intensity pion beam, the Proton West High Intensity Laboratory transport. When combined with the $\pi^- N \rightarrow B$ production cross section of Fig. 1, the yield curve of B's shown in Fig. 4b results. The B yield curve resulting from the product of the production cross section and the pion beam yield curve is relatively flat. Choosing 500 GeV/c (in order to stay away from the region of rapid increase of the production curve for B's and to enhance the ratio of B cross section to total cross section as much as possible) as the beam momentum for π^- production of B's, we can calculate the yield of $B\overline{B}$'s per second as shown below.

The number of π^- available for a given experiment is dictated by the number of primary protons available for a given experiment. In general, proton "economics' at Fermilab has made it difficult to obtain more than 2×10^{12} protons per minute from the Tevatron. Using this number of protons as a limit, we could expect 2.6×10^7 pions per second of spill (assuming 900 GeV/c primary protons) leading to approximately 7.5×10^5 interactions per second for a optimized silicon tracker target such as that of E771 shown in Fig. 5 (2.9% of an interaction length for pions). Since the E771 spectrometer can already operate at rates above 10^6 interactions per second, this means that the available pion beams cannot saturate the spectrometer. The ratio of $B\overline{B}$ cross section per nucleon at 500 GeV/c (approximately 10 nb as calculated by Berger) to the total πN cross section of

22 mb per nucleon is approximately 0.5×10^{-6}. In correcting this ratio to allow for operation with a nuclear target, the relative A dependence of the total cross section and the B cross section is taken to be $A^{0.28}$. For the silicon foils used in E771, the allowance for the relative A dependence results in an increase in the ratio to 1.3×10^{-6}. So finally, 7.5×10^{5} interactions per second of spill results in 0.38 $B\overline{B}$/sec for operation with a pion beam.

In contrast, experiments using the extracted proton beam suffer no lack of available flux. For the case of the E771 target (4.5% of an interaction length for protons), 10^{7} interactions per second can be achieved with approximately 2×10^{8} protons per second. Using the calculation of Berger to get a pN->B cross section of approximately 8 nb at 900 GeV/c and using 32 mb for the pN total cross section per nucleon we calculate a ratio of $.25\times10^{-6}$. Correcting for the use of a heavy target (silicon), we get 0.63×10^{-6} for the ratio of B cross section to total cross section for pN interactions. If we can operate at 10^{7} interactions per second this will result in 6.3 $B\overline{B}$/sec or almost 10^{8} $B\overline{B}$'s per 10^{7} seconds of beam . Even if we can only operate at 10^{6} interactions per second, we will still produce 0.63 $B\overline{B}$/sec, still a factor of 2 higher than the rate that can be achieved with pions.

The potential of the extracted proton beam for higher B production rates than can be attained with a pion beam can only be realized if the maximum beam flux usable by an experiment is not limited by other factors. The radiation damage sustained when operating at 10^{7} interactions per second (with 2×10^{8} protons per second of spill distributed in a one cm radius spot) is at the level of a few x 10^{14} minimum ionizing particles per cm^{2}. This is the level where leakage current may begin to increase and the performance of the detector may begin to degrade but is probably still bearable. In addition, the average number of interactions per bucket, 0.2, is still tractable. The power of the trigger system, as discussed below, can be a limitation but at least for some trigger strategies 10^{7} interactions per seconds seems to be reasonable. Finally, the individual elements of a given spectrometer may suffer rate effects but, presuming that these can be handled in some way, it seems clear that the proton beam offers the most potential for a high rate experiment. Indeed, the relative cleanliness of the extracted proton beam which has very little halo in comparison to a pion beam is a very attractive feature especially when trigger rates are considered. When the cleanliness of the proton beam is coupled to higher rates of $B\overline{B}$ production which are attainable, the extracted proton beam seems to be the optimum choice for fixed target experimentation.

V. Fixed Target Experimental Techniques

At present there are several approaches to fixed target B physics under investigation. They range form a totally "open geometry" experiment such as that of experiment, E771[8] which might hope to observe both the B and $\overline{B}$ to a "semi-closed geometry" inclusive B experiment[20] of P789 which seeks to observe the inclusive B spectrum via two body decay modes. The interaction rates require for the various experimental techniques will depend on the techniques and acceptances of individual spectrometers. We will not attempt to evaluate all of these techniques. Rather, we will attempt instead to outline some general features of the fixed target experiments.

The most important aspect of these fixed target experiments are the trigger strategies. At present there are a number of triggers that are being discussed by the various experiments. These triggers can be characterized as "physics" triggers and as "generic" triggers in the manner of Ref. 8. The physics triggers prejudice the physics a priori while the generic trigger do not select a particular mode except through second order acceptance effects. We list below some of the more widely discussed triggers:

1. Di-muon or J/Ψ trigger strategy	Fermilab Experiment E771, Ref. 8
2. Single lepton trigger	Refs. 11,12
3. Secondary vertex triggers	
a. Multiplicity change trigger	Ref. 18
b. Impact parameter trigger	CERN Experiment WA82, Ref. 17
4. Intermediate p_t trigger	CERN Experiment WA84, Ref. 19

The boundary conditions for such trigger systems are 1) the interaction rate that is required to accumulate the desired statistics for the experiment and 2) the amount of data than can be written on tape. The trigger system must make these two rates compatable. In the case of E771, they expect to eventually operate at 10^7 interactions per second. Since the data acquisition system (limited by tape writing speeds) can operate continuously at approximately 1 megabyte per second which is equivalent to a few hundred events per second of spill, the trigger system must produce a reduction of interaction rate by a factor of 10^{-4} to 10^{-5} without losing signal.

These types of considerations are common to all the trigger systems. In the case of each of the triggers mentioned above, the problem of matching the suppression of the interaction rate to data handling capability must be addressed to determine the sensitivity of the experiment. Again, in the case of E771, the J/Ψ trigger strategy is powerful enough to contemplate operation at 10^7 interactions per second. The requirement that there be two or muons in an event will produce a few $\times 10^{-4}$ reduction by itself. The additional requirement that the two muons have an invariant mass greater than 2.4 GeV/c^2 should produce a factor of >10 further reduction in trigger rate producing a total suppression of the interaction rate in the range 10^{-4}-10^{-5}. This can be done while losing only a small fraction of the B->J/Ψ+x signal. The number of produced B-> J/Ψ+x events should be in the few tens of thousands per species of B per 10^7 seconds of operation if 10^7 interactions per second is , indeed, an achievable operating point.

Finally there have been discussions of experiments which might go considerably beyond 10^7 interactions per second into the regime where we will see several interactions overlap within a single bucket. They range from the suggestion that one might be able to distribute the beam over a much larger spot in order to separate decays in space rather than in time in order to work at 10^9 interactions per second (Sandweiss) to the proposition that a double arm focussing spectrometer might be able to select two body decay modes of the B's and operate at a rate of greater than 10^{12} interactions per second by detecting the presence of the B secondary vertex early in the trigger sequence (Bjorken). These ambitious speculations await further definition.

VI. Conclusions

We can draw several conclusions form this quick inspection of the possibilities for fixed target B physics experiments. First, given the low multiplicity of events at fixed target energies and the relatively high momentum of the B hadrons relative to the high multiplicities and quite low average momentum of the B's at TEV I, the fixed target experiments seem quite attractive in spite of the lower B cross sections at fixed target energies. It may well be that fixed target hadroproduction is the optimum place to do B physics until the era of the SSC. Of the possible methods advanced for executing hadroproduction experiments at TEV II, the hadroproduction experiments which use the primary proton beams offer the promise of the highest yield of B's if the spectrometers can be made to operate at high rates and the trigger systems powerful enough to suppress the total cross section interaction rate and to preserve the B events.

Second, the experiments at TEV II because of the similarity of B event configuration (ignoring the much higher multiplicity at the SSC), the similarity of RF bucket structure (15ns at the SSC vs 18.7 ns at TEV II), and the similarity of rates at which the experiments are intended to operate (10^7 interactions per second and above at TEV I which is equivalent to luminosities of greater than 10^{32} $cm^{-2}sec^{-1}$ at the SSC), provide a excellent school for learning to do the comparable experiments at the SSC. The similarity of spectrometers proposed for the SSC for B physics attest to this.

Finally, there is relatively unlimited luminosity available for B experimentation at TEV II. The facility exists here and now and not in some future era. The limitations are the spectrometers and the cleverness of the experiments.

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Table I*
Comparison of Beauty Hadroproduction at Different Machines
(from Ref. 7)

	TEV II	TEV I	SSC
$\sqrt{s}$ (TeV)	.041	1.8	40
$\sigma(b\bar{b})$ (cm^2)	$\approx 2.4\times10^{-32}$	$\approx 1.5\times10^{-29}$	$\approx 1.0\times10^{-28}$
$\sigma(b\bar{b})/\sigma_T(pN)$	$\approx 0.75\times10^{-6}$	$\approx 1.5\times10^{-4}$	$\approx 10^{-3}$
$\#b\bar{b}/10^7$ sec	$\approx 0.75\times10^{8}$	$\approx 1.5\times10^{9}$	$\approx 10^{11}$
Int. $/10^7$ sec	$\approx 10^{14}$	$\approx 10^{13}$	$\approx 10^{14}$
$\langle p_b \rangle_{<45^0}$	145 GeV/c	38 GeV/c	130 GeV/c
$\langle p_B \rangle_{\text{into det.}}$	118 GeV/c	32 GeV/c	60 GeV/c
$\langle n \rangle_{\text{into det.}}$	≈ 8	≈ 100	≈ 35
$\gamma\beta c\tau$	$\approx .7$ cm	$\approx .2$ cm	$\approx .3$ cm

* For purposes of estimating the detector dependent entries in this table,the detectors for TEV II (Fermilab Experiment E771[8] is taken as a model) and the SSC[1,2,3] have been taken to be relatively forward along a given beam direction. Because of the low momentum and wide angular distribution of the B hadrons at TEV I, the TEV I detector has been assumed to be a 4π detector. The calculation of the average momentum of the b quark has been done for b's in an angular cone of 45^0 around the beam direction for all three experimental configurations.

Table II
Various Future (Mid 1990's) B Sources
(from Ref. 6)

Sources	E_{cm}(GeV)	σ_T(nb)	$Frac_{B's}$	Luminosity/day	BB/200 day
TEV II (Fixed Target)	40	5×10^{7}	5×10^{-7}	2.8 pb^{-1} (E771)	1.6×10^{7} ** (E771)
TEV I (Collider)	2000	1×10^{8}	5×10^{-5}	0.03 pb^{-1}	3×10^{7}
SIN New CESR	10.6 (4S)	3.9	0.26	15 pb^{-1}	3×10^{8}
SBF-Multi Bunch PEP	26	0.5	0.09	175 pb^{-1}	1.5×10^{8}
SLC (SLD)	92	40	0.13	0.2 pb^{-1}*	2×10^{5}
LEP	92	40	0.13	0.6 pb^{-1}	6×10^{5}

* For SLC $\langle L\rangle = L_{peak}/2$, for storage rings $\langle L\rangle = L_{peak}/3$

**As an example of fixed target experiments, this number is appropriate to the updated E771 experiment objectives assuming operation at 10^{6} int/sec with 23 seconds of spill every 60 seconds. The intention of the experiment, however, is to attempt to move toward operation at 10^{7} int/sec.

Figures

Fig. 1 B hadroproduction cross sections for $\pi^{-}N$ and pN interactions at fixed target experiment energies.

Fig. 2a Momentum spectrum of electrons from the semileptonic decay, B->Deν for B production at the SSC.

Fig. 2b Momentum spectrum of electrons from the semileptonic decay, B->Deν for B production at the TEV I.

Fig. 2c Momentum spectrum of electrons from the semileptonic decay, B->Deν for B production at the TEV II.

Fig. 3a Momentum spectrum of muons from the decay, B->$\Psi K\pi$->$\mu\mu K\pi$ for B production at the SSC.

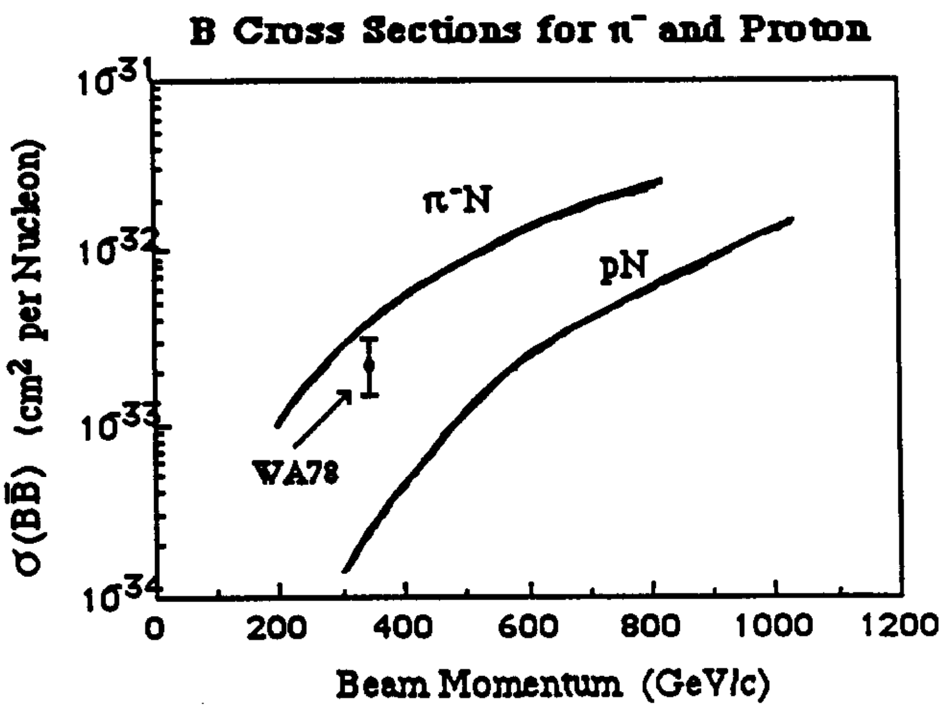
Fig. 3a Momentum spectrum of muons from the decay, B->$\Psi K\pi$->$\mu\mu K\pi$ for B production at the TEV I.

Fig. 3a Momentum spectrum of muons from the decay, B->$\Psi K\pi$->$\mu\mu K\pi$ for B production at the TEV II.

Fig. 4a Negative pion yield per incident proton for the Fermilab High Intensity Laboratory beam transport as a function of beam momentum.

Fig. 4b $B\bar{B}$ yield as a function of secondary negative pion beam momentum for the Fermilab HIL secondary pion beam transport.

Fig. 1



B Cross Sections for π⁻ and Proton
10⁻³¹
10⁻³²
10⁻³³
10⁻³⁴
σ(BB̄) (cm² per Nucleon)
π⁻N
pN
WA78
0
200
400
600
800
1000
1200
Beam Momentum (GeV/c)

Fig. 2a

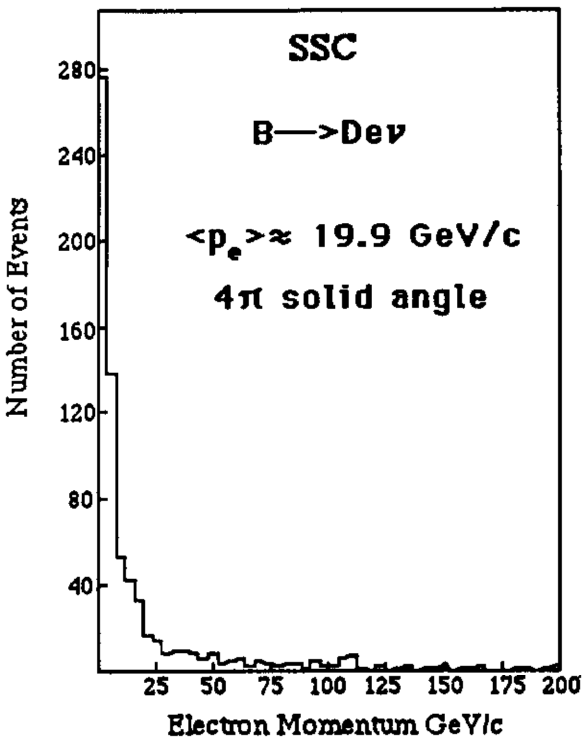


Fig. 2b

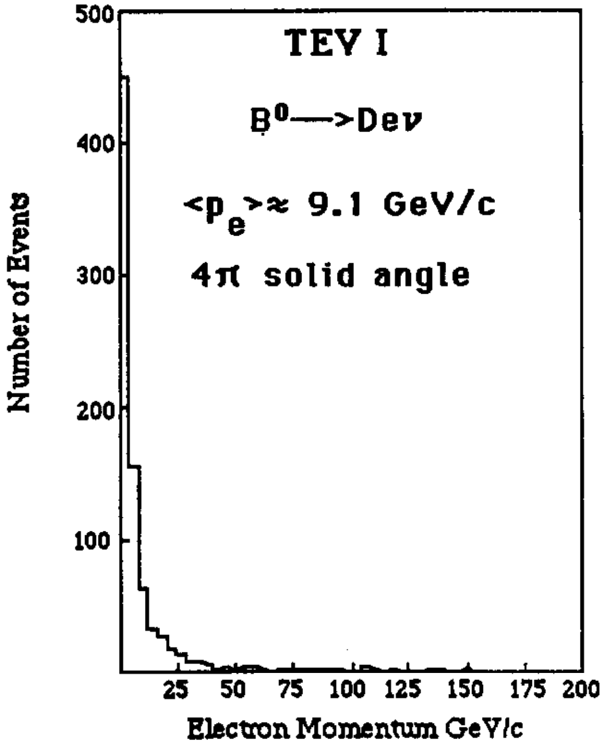


Fig. 2c

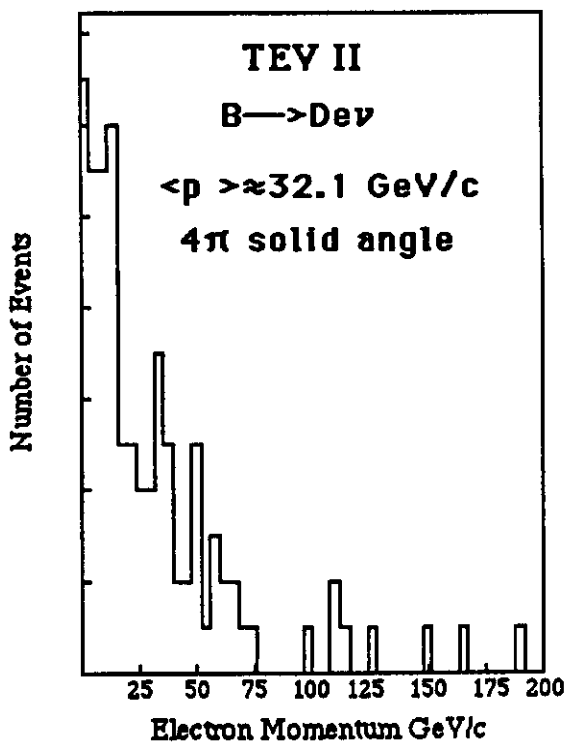


Fig. 3a

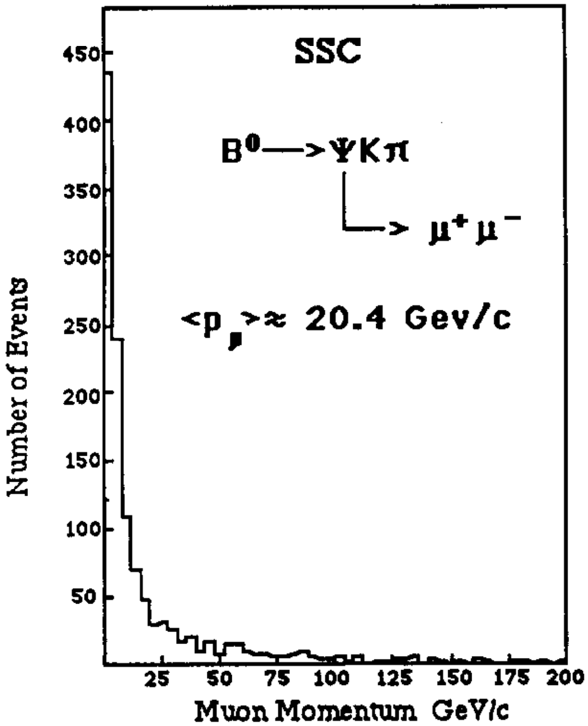


Fig. 3b

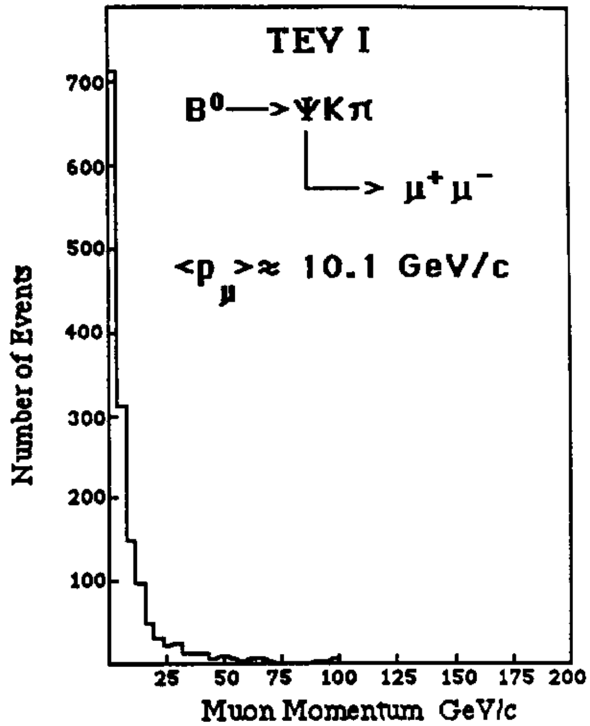


Fig. 3c

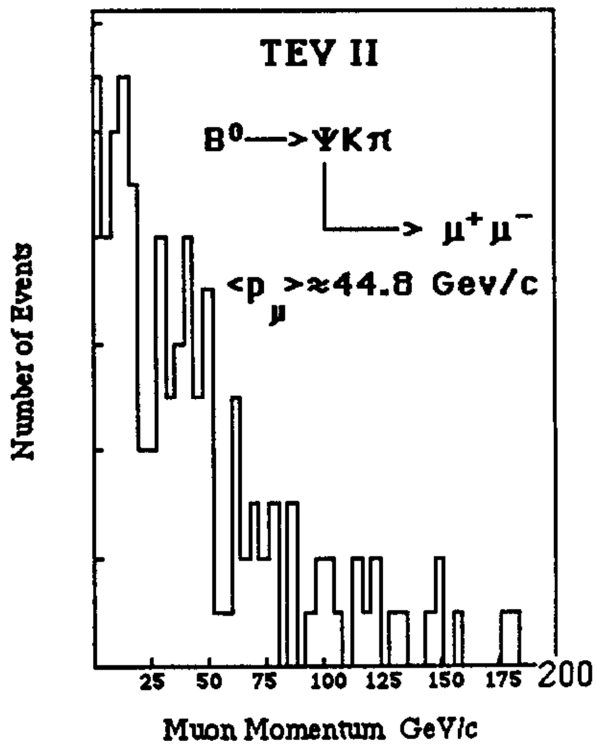


Fig. 4a

HIL Negative Pion Yield

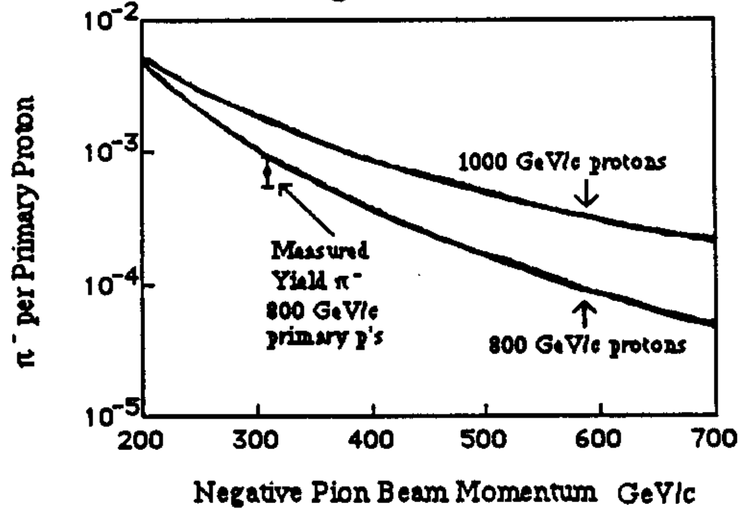


Fig. 4b

B Yields from Negative Pion Beams

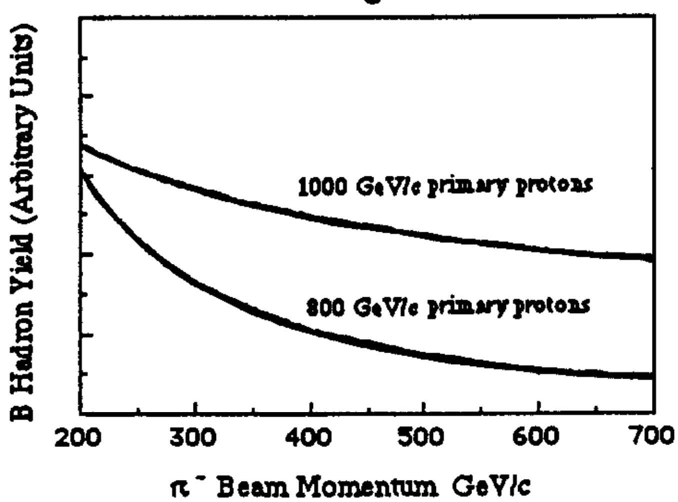
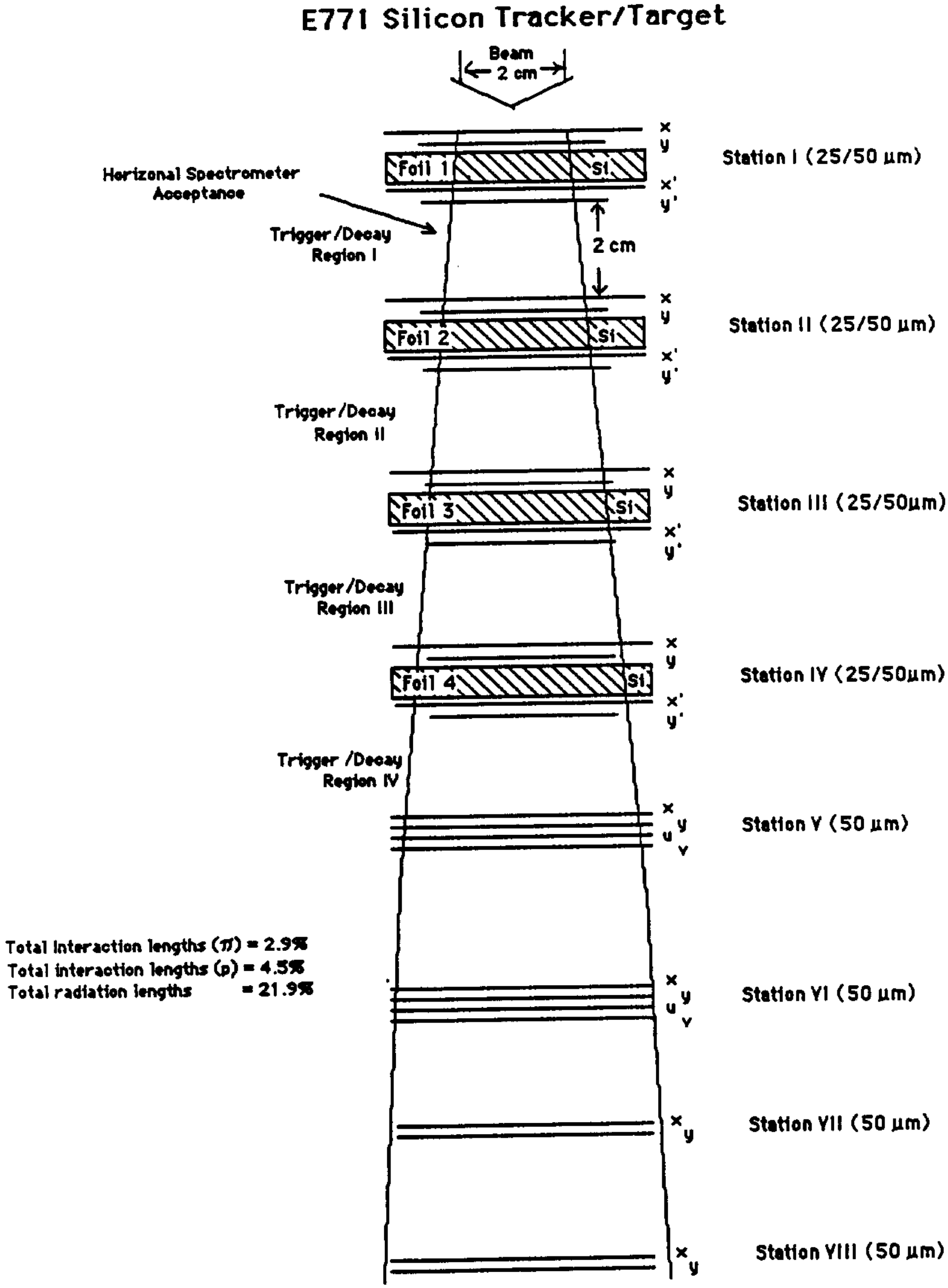


Fig. 5


E771 Silicon Tracker/Target
Beam
2 cm
Horizonal Spectrometer Acceptance
Foil 1
Si
Station I (25/50 µm)
Trigger/Decay Region I
2 cm
Foil 2
Si
Station II (25/50 µm)
Trigger/Decay Region II
Foil 3
Si
Station III (25/50µm)
Trigger/Decay Region III
Foil 4
Si
Station IV (25/50µm)
Trigger /Decay Region IV
Station V (50 µm)
Total interaction lengths (π) = 2.9%
Total interaction lengths (p) = 4.5%
Total radiation lengths = 21.9%
Station VI (50 µm)
Station VII (50 µm)
Station VIII (50 µm)
x
y
x'
y'
u
v