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Vertex Detection at the Tevatron

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ABSTRACT

Addition of vertex detectors to CDF and D0 will facilitate a rich program of beauty physics at the Tevatron, and may enable tags of B and τ which facilitate searches for top and other heavy objects. We also address the operational considerations of triggering and radiation protection, and speculate on possible directions for upgrades.

1. INTRODUCTION

The profound potential for high luminosity at the Tevatron Collider will place great demand on detector sensitivity and power. As an example, consider the size of the recent celebrated B signals at CDF in comparison to the potential B yield at the Tevatron. One signal is observed in the reconstructable modes $B^{\pm} \rightarrow \Psi K^{\pm}$ and $B^0 \rightarrow \Psi K^{0*}$ as shown in Fig 1. The signal is of the order of 20 events. To understand the size of the possible yield, consider the limited kinematical regime of 2 B jets with $P_t \geq 10 GeV/c$ and $|\eta| \leq 1.0$, which is well matched to the triggering and tracking capabilities of the CDF detector. The cross section for this sample is approximately 1 μB, or 1 million such B pairs for every 1pb^{-1} of exposure. While the signal is obviously exciting, the yield, compared to the 40 million B pairs created within CDF in the last data run, reveals a discomforting signal to noise ratio of 10^{-6}!

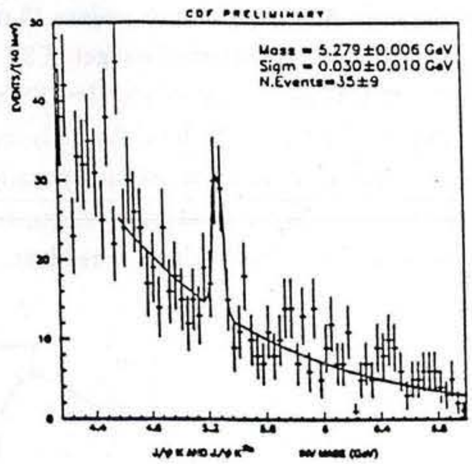

Fig. 1 $B \rightarrow \Psi$ K and Ψ K*

The small signal size is due to the pernicious backgrounds in hadronic collisions. At the trigger level, the total inelastic cross section of 75 mB swamps everything but isolated leptons. At the reconstruction level, the large charge multiplicity produces a huge combinatoric background (see Fig. 1, for example) which can only be handled by severe selections with correspondingly compromised efficiency. High sensitivity B physics awaits a detection scheme that can beat down the noise.

The solution is vertex detection. Resolution of the rich information near the event vertex, where the long lived B states appear as secondary vertices, will add profound background rejection in reconstruction and triggering, with a concomittant increase in sensitivity in a wide variety of physics

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topics.

2. THE CDF SILICON VERTEX DETECTOR

The CDF Collaboration is building a silicon vertex detector to be used in the 1991 Tevatron Collider run. [1] The device, shown in Fig. 2, employs 4 layers of silicon microstrip detectors at radii between 3 and 8 cm from the beamline. Two 25 cm long barrel arrays assure reasonable acceptance for the long Tevatron intersection diamond. Mechanical support uses a stiff lightweight array of plastic foam, carbon fiber, and beryllium to achieve 15 micron precision with a total material budget of 3% of a radiation length at normal incidence. The SVXD readout chip, developed at LBL by Haber, Ely, and Kleinfelder [2] is a 128 channel device incorporating sample and hold, leakage current subtraction, test over threshold, and sparse, multiplexed readout.

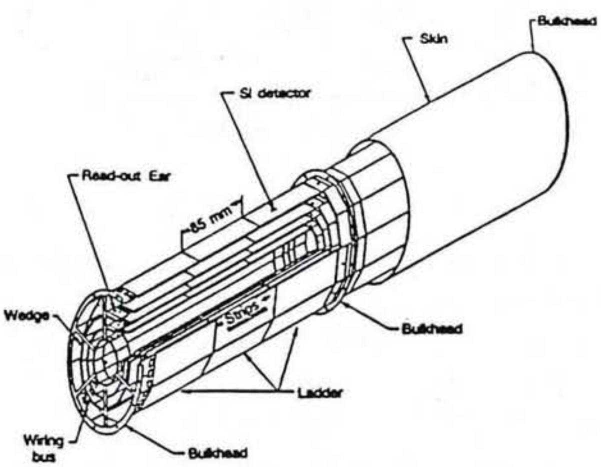

Fig. 2. The CDF SVX Detector

Operation of a 4 layer SVX telescope in a Fermilab test beam in summer '90 verified the achievability of design goals for efficiency, signal- to-noise, and resolution. Construction of the barrel modules for the 1991 Collider run is well under way.

The expected impact parameter resolution for this detector is shown in Fig. 3; for high momentum tracks, the expected resolution is 15 microns. Rough estimates of the vertex tagging capability of the SVX have been derived in the context of beauty decays using Monte Carlo simulation. A tagging strategy is based on counting the number of tracks which significantly miss the primary vertex. We require at least 3 tracks with impact parameter to the beam line greater than 3 times the error of the measurement. The efficiency of this tag as a function of b parton P_t is shown in Fig. 4, and is seen to vary from 20% to 35% over the b parton P_t range of 10 to 30 GeV/c. The background from direct charm production is suppressed by the lower mean multiplicity and transverse momentum; the accidental tag rate is estimated to be of order a few percent.

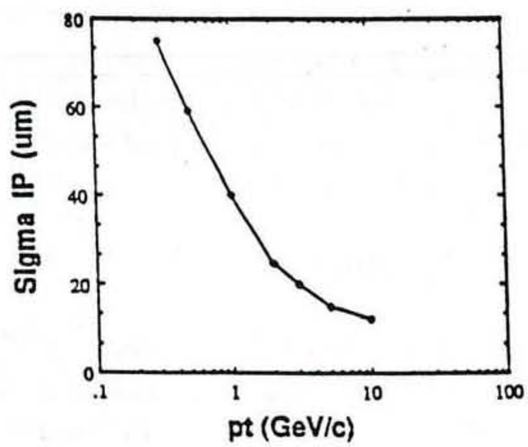

Fig. 3. SVX impact parameter resolution

This estimate used only those tracks which were already reconstructed in the large Central Tracking Chamber (CTC), and thus reflects the intrinsic efficiency of the SVX alone. The effective CTC acceptance ($P_t \geq 400 MeV/c$, $|\eta| \leq 1.0$) will reduce the tagging rate by an additional factor which depends on the B production kinematics and the length of the Tevatron bunch. For inclusive B production in the above momentum range, with present bunch length, this factor is approximately 60%.

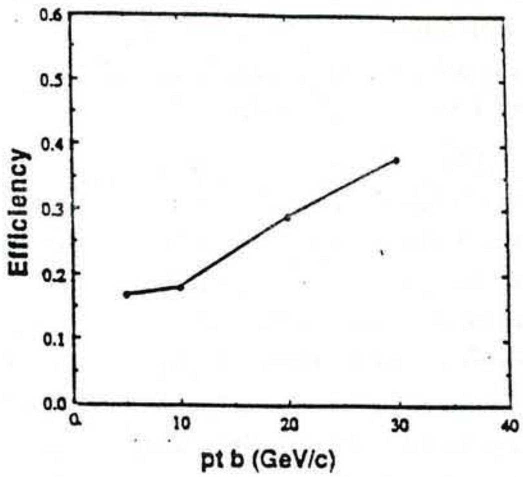

Fig. 4 SVX B tag efficiency

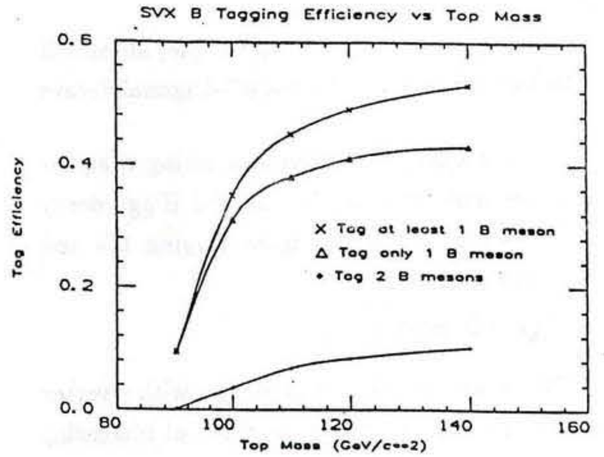

Fig. 5. SVX top → B tag efficiency

3. TOP PHYSICS

As an example of a specific physics application, we briefly discuss the use of the SVX to tag beauty jets from the decay of massive top quarks, which we have studied using the ISAJET Monte Carlo. Consider the decay of 120 GeV top pairs. Here, 65% of the B jets have $|\eta| \leq 1.0$, giving good acceptance into the tracking volume. The mean P_t of the B jets is 30 GeV/c, which guarantees a finite B flight path, containment of most B secondaries in the tracking volume, and minimal tracking errors from multiple Coulomb scattering. The complete CTC+SVX efficiency of the 3 track tag is 29%. The probability of tagging at least 1 B jet in an event is a respecatble 40%. A similar study for the case of the D0 detector has been done by J. Ellison with similar conclusion [3].

The top tagging efficiencies for the accessible range of M_{top} in next run are shown in Fig. 5. For M_{top} greater than about 100 GeV, the SVX tagging rate is substantial. Note, also, that with more experience in a specific application, more efficient tags are possible. For instance, a Z+jets data set could be used as a control sample in order to develop tags that efficiently isolate the top signal from the similar W+jets background.

Observation of top production at CDF, and successful tags of its decay to beauty opens a spectrum of applications:

1. In an unequivocal top sample $(ee, e\mu, \mu\mu)$ add further verification by the tag itself.

2. In a dubious sample $(e, \mu + jets)$, tagging $t \rightarrow B$ is expected to enhance the signal to noise ratio by a factor of 4, and may be instrumental in making a convincing observation.

3. In an ideal world:

a. Find top in a pure 6 jet sample by kinematic requirements on the jets and the constraint that B mesons are present. The branching ratio for these modes is a whopping $4/9 = 44\%$, but this technique will require a clever trigger (ΣE_t) and extensive Monte Carlo work.

b. Add to the top sample by tagging tau modes $e\tau, \mu\tau, \tau\tau$, and $\tau + jets$. These account for $17/81 = 21\%$ of the top branching ratio. Events without an e or a μ will require a τ or missing Et trigger. In τ + jets events, the vertex detector could conceivably be used to tag both the tau and the B's!

4. If a large top sample shows up, the B tag can be used to study further aspects of the physics:

a. Discrimination of the B jet will sharpen up the mass determination via correct combinatorics in $M((W \rightarrow jj) + b)$.

b. The P_t spectrum of the b measures the top mass, and may provide some information on couplings.

c. In a sufficiently solid top sample, an anti-B tag can be used to search for the off-diagonal decays $t \rightarrow s/d$.

5. If the Universe is more interesting than expected, we may uncover the charged Higgs decay mode $t \rightarrow bH^{\pm} \rightarrow bt^{\pm}\nu$, again tagging B's and tau's in the same event.

4. BEAUTY PHYSICS

Various possibilities for B physics with a vertex detector are outlined below, in order of increasing sophistication and difficulty.

1. B production mechanism and cross-section: The B tag provides a powerful alternative to the usual techniques of working backwards from the lepton spectra. By tagging Ψ's with non-zero flight path, it will be possible to separate B decay from direct charm production. The ability to tag, and possibly reconstruct, the "other B" in inclusive lepton or Ψ events gives a large increase in the statistics for studying the relative contributions of the higher order processes of flavor excitation and gluon splitting.

2. Exclusive B decays: The reconstructed $B \rightarrow \Psi$ K decays decays alluded to earlier are telling examples of the power of the CDF magnetic momentum analysis. Upgrades to the CDF muon system, and trigger as well as to the Tevatron luminosity, suggest that the following samples could be accumulated in the next run:

$B_d \rightarrow \Psi K^{*0}$	1000
$B_u \rightarrow \Psi K^{\pm}$	1000
$B_s \rightarrow \Psi \phi$	1000
$\Lambda_b \rightarrow \Psi \Lambda$	50
$B_c \rightarrow \Psi \pi$	?

Note that discovery of the B_s meson is assumed! By tagging tracks with significant impact parameter, a vertex detector will significantly reduce combinatorial backgrounds to these samples. An efficient tag with combinatoric rejection power may also enable observation of the "other B" in events with lepton triggers. This will provide an essentially unbiassed sample for the study of B decay, with albeit reduced efficiency.

3. B Lifetimes: Lifetime measurements are the bread and butter of vertex detection. The lifetime differences between B species provide information on decay dynamics. B lifetime measurements to date have been hampered by inadequate statistics and resolution, and have averaged over species. As indicated above, large samples of various individual B species should be forthcoming. Trigger requirements on these samples will ordain a mean track P_t of approximately 2 GeV. Even if the extrapolated impact parameter resolution is twice as bad as that of the SVX, as shown in Fig 3, say 50 microns at 2 GeV, the benchmark comparison of $c\tau/\sigma$ is still 7 per event, yielding final results which will be only systematic limited.

4. B oscillations: Time integrated mixing measurements like the Argus and UA1 results [4] unable to measure values of x_s greater than about 2. Since the resolution of silicon detectors is much less than the B decay length, the vertex detector can be used to directly observe the time structure of B^0 oscillations, enabling measurement of x_d and x_s, and thus the ratio V_{td}/V_{ts}. Note that measurement of the time structure in B^0 oscillation is one of the only practical methods to access V_{ts}.

5. Rare decays: As experience is gained experience the study of exclusive decays can evolve into the study of rare decays. One interesting possibility is $B \rightarrow \pi\pi$, which measures V_{ub}, but requires a secondary vertex trigger.

5. OPERATIONAL ISSUES AT THE TEVATRON

Besides the usual challenges associated with getting a new piece of hardware up and running, the Tevatron environment places special demands on a vertex detector program.

a. Triggers.

The problem with beauty production at the Tevatron is that the rate is almost too large to use, and the luminosity is going to go up! Accumulation of a high statistics sample will require either.

i. A super data acquisition system OR
i. An acquiescence to large deadtimes OR
iii. Very selective triggers.

The mutual interplay of these requirements can be illustrated in the context of the CDF data acquisition system. A concerted effort there has succeeded in reducing the CDF scan time to about 2 ms per event. If we demand a maximum of 5% deadtime, the standard queuing theory result $t_{live} = (1 + Rate * t_{scan})^{-1}$ implies that the maximum trigger rate be less than 26 Hz. The kinematically limited subset of B production described in the introduction has a cross section of 1 μB, or 10Hz at L = 10^{31}, so a perfectly selective B trigger could have it all. Unfortunately, the perfect B trigger does not exist; in the absence of vertex information, B trigger schemes at the Collider must rely on lepton identification, with comcomittant loss in signal to noise ratio and efficiency. As the noise rate goes up, so does the fraction of livetime consumed, with implications for final sample size, AND for the livetime available for other processes of interest to general purpose experiments.

Based on rates and efficiencies measured at CDF, we can propose the following strawman solution to the multifaceted problem of B triggers at the Collider. Rates are for L = 10^{31}, and yields are for 100 pb-1.

i.) $B \rightarrow \psi X$ via $\psi \rightarrow \mu\mu$: Requiring 2 muons with $P_t \geq$ 2GeV/c within the acceptance of the CDF muon Upgrade will give a very pure signal. Rate = 1 Hz. Yield = 4000 in each $B \rightarrow \Psi$ decay mode.

ii.) $B \rightarrow \mu\nu X$: Requiring a single muon with $P_t \geq$ 9 GeV/c in the thick central region of the CDF muon upgrade will have S/N ratio for B's of approximately 1/8. Rate = 2 Hz. Yield = 2 million.

iii.) $B \rightarrow e\nu X$: Requiring a good central electron with $P_t \geq$ 12 Gev/c via the standard CDF electron selection will have a S/N ratio for B's of about 1/10. Rate = 5 Hz. Yield = 4 million.

These triggers will give a total rate of approximately 8 Hz, a reasonable request out of the total 26 Hz available. It will be interesting to see how the better muon and calorimeter systems at D0 can improve on these numbers.

Although the yields above are respectable, they are a pale reflection of the 4 billion B's that will be produced. The limiting factors are the lepton branching fraction, and the difficulty of picking the leptons out of the hadronic debris. The most powerful B selection criteria would use fast information from the vertex detectors to tag the secondary decay vertices at the trigger level of general B decays. Some preliminary work on the architecture of such a trigger has been studied by L. Ristori at INFN and the University of Catania [5]. Ristori has simulated the performance of a massively parallel system of content addressable memories searching for track patterns in an ideal SVX detector. Pattern matches in the memories are organized into track roads, and the information in found roads is passed to Digital Signal Processors for linearized track fits. The process is claimed to take 25 msec, fast enough for a Level 2 trigger, and have impact parameter resolution of order 35 microns. With this level of accuracy, it may be possible to simply flag the large impact parameter of tracks from B decays, and thus avoid the additional complication of vertex recognition. Simulation of this simple tag shows reduction of the overall jet rate by a factor of 35, with a B tag efficiency of 25%

b. Radiation Hardness of the Detector

The high luminosity of the collider both for the coming run and after the upgrade to 200/400 ns bunch spacing poses a serious challenge to vertex detectors with respect to the radiation hardness of both the silicon detectors and the associated readout electronics. The principle problems are increases in the leakage currents of the individual detector strips and increases in the noise of the front end analog electronics used to amplify the detector signals.

Measurements during the last CDF run indicate that the level of ionizing radiation in rads per pb^{-1} of integrated luminosity due to charged particles as a function of the radial distance from the colliding beams is well described by the relationship Dose (rads/pb^{-1}) $= 380R^{-1.5}$ where R is measured in inches.[6] This estimate is probably uncertain by a factor of two due to the effects of machine tuning on beam loss and other "accidents". Neutron estimates are even more uncertain at least in part because the pin diodes used for the measurements are sensitive to bulk damage from both neutrons as well as charged hadrons. The overall effect of neutrons both on the silicon detectors and the electronics can be expected to be significantly less than that of the charged hadrons primarily because their flux is smaller, but further work is required.

John Matthews has recently evaluated the available data and studied the implications for the CDF SVX [7]. This work indicates that a delivered luminosity of 40 pb^{-1} will result in an ionizing dose of approximately 14 kRads at SVX Layer 1, and a probable increase in leakage current, from all sources, in the range 30 - 90 nA per strip at Layer 1.

Radiation damage studies of the radiation soft version of the SVXC readout chip indicate that for source capacitances of 30 pf the equivalent noise charge of the chip operated in the quad sampling mode doubles from 2650 electrons to 5300 electrons with an exposure of about 20 Krads of ionizing radiation from Cobalt 60. In the quiter double correlated sampling mode, the noise doubled with an exposure of about 12 Krads, although it was still a modest 2200 electrons. [8] In any case, with the radiation dose from charged particles at 14 kRads/40pb^{-1} at Layer 1, as above, it is clear that the use of radiation soft electronics for high luminosity running in areas close to the beam is unacceptable.

Concurrent with these studies, a radiation hardened version of the SVX chip produced by UTMC has been measured to have a noise versus radiation dose slope which is flat. The initial equivalent noise charge of this radiation hardened chip was 14% higher than the non hardened version, but this may be an acceptable penalty for a stable signal to noise ratio in a high radiation environment. [10]

6. SVX DETECTOR UPGRADE

The upgrade of the Tevatron prior to the beginning of the collider run presently scheduled for the middle of 1994 will increase the luninosity and decrease the time between bunch crossings from 3.5 μs to 395 ns or possibly 200 ns. There are several significant challenges posed by these machine changes.

a) Electronics

The readout electronics will need to be redesigned to provide a signal to noise ratio (S/N) as good or better than the present double correlated sample of the current SVX chip, at significantly shorter shaping times. Pipelining will need to be added to accommodate the delay required for the level 1 trigger. A radiation hardened technology will be needed for the electronics chip. A techinique will be required to produce the necessary DC stabilization for amplifiers connected to detector strips which can be expected to produce hundreds of nanoamps of leakage current as the result of bulk radiation damage. Finally the speed of the readout must be increased to accomodate the 5 microseconds scan times required for operation of an appropriate level 2 trigger based on the SVX information.

The interplay of S/N, input capacitance, and shaping time is concisely expressed as

$$Q_{enc}^2 = \epsilon^2(\tfrac{1}{4} e i_{leak}\tau_s + \tfrac{1}{2}kTC_{in}^2(g_m\tau_s)^{-1} + \tfrac{1}{2}A_f C_{in}^2)$$

where Q_{enc} is the noise in equivalent electrons, g_m is the transconductance of the front end transistor, τ_s is the shaping time, and ϵ is approximately 2.7 for RC-CR shaping. The first term is the parallel or "shot" noise, the second term is the series or thermal noise in the amplifier, and the third term is 1/f noise, which is negligable. We have estimated the increase in leakage current in a single strip 26 cm long by 50 microns wide for 300 micron thick detector at a distance of one inch from the beam. For integrated luminosities of 100 pb-1 and 400 pb-1, the results discussed in Sec 5b suggest leakage currents of 175 nA and 700 nA, respectively, with an uncertainty of about a factor of two.

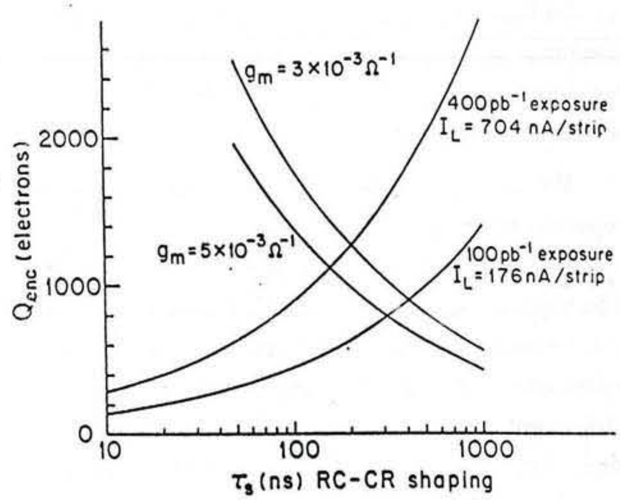

Fig. 6 Input noise vs. shaping time

In Fig. 6, we plot the Q_{enc} for the parallel noise as a function of τ_s for the two i_{leak} values given above. The other two curves shown in Fig. 6 correspond to the series noise contribuiton for two different values of g_m, and are discussed below. The shorter shaping times required for the Tevatron upgrade help to reduce the parallel noise contribution. One sees that even with a leakage current of 700 nA/strip, Q_{enc} is $\approx$ 800 electrons for $\tau_s \approx$ 100 ns. Thus, the series noise will dominate under most conditions. The only way to reduce this contribution once C_{in} is fixed is to increase the product $g_m\tau_s$ which appears in the denominator. For purposes of this discussion let C_{in} = 40 pf (actually the detector is 30 pf but there is a contribution from the amplifier plus some conservatism on our part). Then specifying an allowable Q_{enc} determines the value of the product.

In Fig. 7, which is a graph of shaping time τs versus g_m we plot lines of constant $g_m\tau_s$ corresponding to fixed Q_{enc} at constant C_{in}. By comparison, the present SVXD chip with a 30 pf detector capacitance has a Q_{enc} of $\approx$ 1500 electrons for the case of double correlated sampling and $\approx$ 2100 electrons for quadruple correlated sampling. Fig. 7 suggests that a g_m of 3 x $10^{-3}\Omega^{-1}$ is marginal and that a gm of 5 x $10^{-3}\Omega^{-1}$ is adequate. In Fig. 6 we plot the Q_{enc} from the series noise as function of the shaping time τ_s for values of g_m equal to 3 x 10-3 Ω^{-1} and 5 x $10^{-3}\Omega^{-1}$. For g_m = 5 x $10^{-3}\Omega^{-1}$ and a shaping time of $\approx$ 100 ns, the series Q_{enc} is $\approx$ 1400 electrons corresponding to S/N $\geq$ 17. This can be expected to degrade to a S/N of about 14 for the case where i_{leak} has risen to a value of $\approx$ 700 nA due to radiation damage to the detectors.

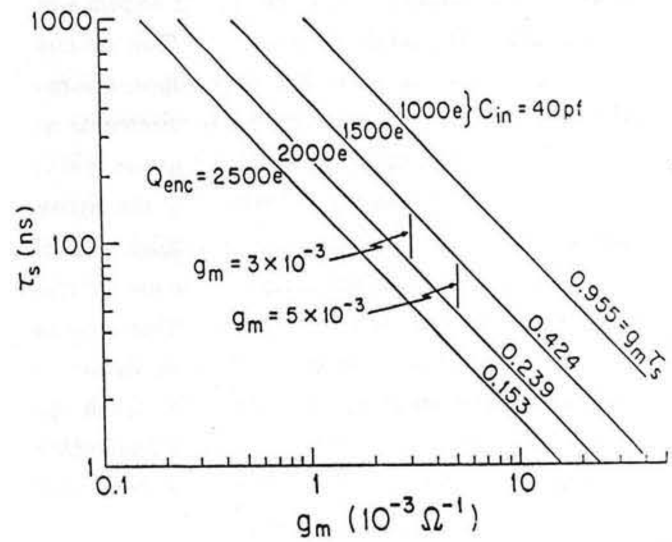

Fig. 7 Shaping time vs. transconductance

b) Detectors geometry and strategy

There are at least three upgrade scenarios under discussion. The first is to keep the present arrangement of long ladders with their 30 pf input capacitance, but use AC coupled detectors to solve the DC stabilization problem, and redesign the readout chip with the necessary pipelining, S/N and shaping time in a radiation hardened technology. The analysis above suggests that acceptable S/N are achievable, even with this large C_{in}. This scenario requires the least mechanical redesign of the SVX detector and it will not add any additional material to the detector presently under construction. It does have the disadvantage that a redesigned chip will require some additional power, but the present SVX cooling scheme may be adequate. As with the SVX under construction, only $r - \phi$ information will be available.

The second scenario would be to disperse the electronics throughout the detector to reduce the input capacitance to the analog electronics. As shown above, by reducing the input capacitance, the transconductance g_m required by the input transistor in order to achieve a particular S/N at a particular shaping time is reduced. This means a smaller transistor and generally less power. However, this advantage is secured at the expense of a redesign of the mechanical system. The ladders would now have to serve not only support functions but also cooling and cabling requirements as well. The electronics introduce dead spaces which can only be eliminated by overlapping the active areas of the detectors with the electronics. All of this inevitably adds complication to the mechanical design and material to the detector. Other options within this scenario such as double sided detectors and very short strips are also possible. Such options would give z information and may have other advantages as well, but they all have the draw back of adding material and complexity.

A third scenario would be to replace layer one or possibly two layers with pixels (see below). This would certainly give more pattern recognition power to the detector, but again the challenge would be in avoiding large increase in the amount of material in the detector.

It is worth noting that all the possible upgrade scenarios are going to require radiation hardened electronics. In this regard a possible implementation of the first scenario outlined has been started by the University of Pennsylvania along the lines of the AMPLEX chip using continuous feedback in a radiation hard technology available at UTMC.

7. NEW TECHNOLOGIES

It is clear that an extended plan for vertex detection at the Tevatron will be driven by the experience drawn from the coming run in 1991, and the physics program of the collider experiments. The planned accelerator upgrade program, which shortens the bunch spacing and increases the luminosity also provides the possibility of using a Tevatron vertex detector as an R&D platform for SSC related silicon detector studies.

We briefly discuss some future detector concepts in which silicon detectors and front end readout are integrated on the same silicon substratum. The main advantages of monolithic silicon detectors are enhanced electronics performance due to minimized capacitance between the detector and preamplifier and simplified mechanical design. Such designs also reduce the number of connections leading outside a detector. They require a high performance design of front end electronics and high quality detectors.

A "short strips" monolithic detector discussed by H. Spieler is one of the first prototypes of this type of devices. A detector - fully depleted p-i-n junction and a low noise premaplifier are fabricated on a high resistivity silicon crystal. The preamplifier was designed in a conventional MOS process with several additional steps made, e.g. application of a backside gettering layer. The fabrication process used to make this working prototype in a simple technology opens a way to integrate detectors and readout electronics using more advanced technologies, e.g. CMOS.

The "smart pixels" concept was developed at LBL by Dave Nygren's group with the main goal being the sparsification of data in a high background environment. Each pixel conatins a premaplifier, a shaper, a discriminator, an analog storage and various communication functions. In a 2 micron process the electronics requires an area of about $10^4 \mu m^2$. Pattern registers on a pixel chip record the x-y position and correlated time information. The analog information remains on the pixel until it is read out or reset. Power dissipation and noise generation are kept at minimal values. A small value of the input capacitance, 100fF, allows the amplifier noise to be reduced down to about 200 electrons, leading to a S/N ratio exceeding 100. The small pixel detector volume provides inherent radiation hardness. The Shot Noise from the detector dark current stays small even after many years of operation in the SSC environment. The ultimate goal of the smart pixel detector is a monolithic structure with readout integrated with a detector. A collaboration between the LBL and Hughes Aircraft together with many other institutions has been established to develop first prototypes. Beam tests with a telescope of pixel and strip detectors are planned for 1991.

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