Joel Heinrich
Kirk McDonald
Princeton U.
February 1, 1990

Mini-BCD: Geometric Acceptances

Using the ISAJET/GEANT package we have estimated the geometric acceptances for several possible B-decay modes in a mini-BCD detector that could be built in the existing C0 intersect.

The geometry of the detector is shown on the two figures and includes:

1. A 75-ton C-magnet, with nominal field volume of $30'' \times 30'' \times 80''$.
2. A silicon vertex detector extending over $\pm 40''$, assumed to be like that discussed for the full BCD at Fermilab.
3. Straw-tube tracking in a volume $30'' \times 60'' \times 80''$. The $60''$ is transverse to the beam horizontally. We suppose below that any particle that exits the sides of this volume has a momentum measurment and could be assumed to be a pion.
4. Particle identification in two forward arms. The arms have a square cross section perpedicular to the beam, and cover from 2° to 20° from the beams, measuring on an inscribed circle. We suppose that both electron identification and K/π separation are possible (although this may not be the case in a practical scenario).
5. Particle identification in a wide-angle arm, designed to fill the aperture of the existing hall off to the side. This permits coverage of $40^\circ < \theta < 110^\circ$ and $\Delta\phi = 45^\circ$. Again we suppose that both electron ID and K/π separation are available in this region.

For the present study, all events are taken to occur at a single point in the exact center of the intersect; the true longitudinal extent of the luminous regions is not simulated.

All accepted charged particles must have a minimum transverse momentum of 0.3 GeV/c, and electrons must have a minimum transverse momentum of 1 GeV/c.

All $K_S^0 \to \pi^+\pi^-$ decays must occur inside the silicon vertex detector.

We considered B-decays relevant to three physics topics:

1. Studies of individual decay modes $\Rightarrow$ differential cross sections for B production, and measurment of branching fractions.
2. Studies of B_s-$\bar{B}_s$ mixing. If this could be observed in a hadron collider before an e^+e^- collider, it would be complete vindication of the use of a hadron collider. But, as we will see, it is very difficult.
3. Studies of CP violation. We will conclude that the mini-BCD is not a CP-violation experiment.

1. Individual B-Decay Modes

We first list some branching ratios of various daughters of B mesons to all-charged final states:

Decay Mode	Branching Ratio
$K^0_S \to \pi^+\pi^-$	0.69
$\rho^0 \to \pi^+\pi^-$	1.0
$\phi \to K^+K^-$	0.5
$D^+ \to K^-\pi^+\pi^+$	0.08
$D^+ \to K^0_S\pi^+$	0.014
$D^+ \to K^0_S\pi^+\pi^+\pi^-$	0.035
$D^+ \to \phi\pi^+$	0.005
$D^{\star +} \to D^0\pi^+$	0.5
$D^0 \to K^-\pi^+$	0.04
$D^0 \to K^-\pi^+\pi^+\pi^-$	0.08
$D^0 \to K^0_S\pi^+\pi^-$	0.03
$D^+_s \to \phi\pi^+$	0.02
$D^+_s \to \phi\pi^+\pi^+\pi^-$	0.04
$D^+_s \to K^+K^-\pi^+$	0.02
$D^{\star +}_s \to D^+_s\gamma$	1.0
$J/\psi \to e^+e^-$	0.07

$D^{\star 0} \to D^-\pi+$ and $D^{\star +}_s \to D^+_s\pi^0$ are forbidden by conservation of energy!

The branching fractions we used for various B decays are:

Decay Mode	Branching Fraction
$B^+ \to \bar{D}^0\pi^+$	0.003
$B^+ \to \bar{D}^0\pi^+\pi^-\pi^-$	0.006
$B_d^0 \to D^-\pi^+$	0.003
$B_d^0 \to D^-\pi^+\pi^+\pi^-$	0.006
$B_d^0 \to D^{\star-}\pi^+$	0.003
$B_d^0 \to D^{\star-}\pi^+\pi^+\pi^-$	0.015
$B_d^0 \to D^0\pi^+\pi^-$	0.01
$B_d^0 \to D^-D_s^+$	0.01
$B_d^0 \to J/\psi K_S^0$	5×10^{-4}
$B_d^0 \to \pi^+\pi^-$	10^{-5}
$B_s^0 \to D_s^-\pi^+$	0.003
$B_s^0 \to D_s^-\pi^+\pi^+\pi^-$	0.006
$B_s^0 \to D_s^{\star-}\pi^+$	0.006
$B_s^0 \to D_s^{\star-}\pi^+\pi^+\pi^-$	0.01
$B_s^0 \to D_d^0K^-\pi^+$	0.003
$B_s^0 \to D^-K_S^0\pi^+$	0.003
$B_s^0 \to D^{\star-}K_S^0\pi^+$	0.006
$B_s^0 \to \rho^0K_S^0$	10^{-5}

We then calculated the following B-decays. The acceptance is almost entirely in the two forward arms. Just divide by 2 to get the acceptance in a single forward arm.

Decay Mode	Branching Fraction	Daughters	Total Branching Fraction	Geometric Acceptance
$B^+ \to \bar{D}^0\pi^+$	0.003	$K^+\pi^+\pi^-$	1.2×10^{-4}	0.23
$\bar{D}^0 \to K^+\pi^-$	0.04			
$B^+ \to \bar{D}^0\pi^+\pi+\pi^-$	0.006	$K^+\pi^+\pi^+\pi^-\pi^-$	2.4×10^{-4}	0.12
$\bar{D}^0 \to K^+\pi^-$	0.04			
$B^+ \to \bar{D}^0\pi^+\pi^+\pi^-$	0.006	$K^+\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$	4.8×10^{-4}	0.03
$\bar{D}^0 \to K^+\pi^-\pi^+\pi^-$	0.08			
$B_d^0 \to D^-\pi^+$	0.003	$K^+\pi^+\pi^-\pi^-$	2.4×10^{-4}	0.14
$D^- \to K^+\pi^-\pi^-$	0.08			
$B_d^0 \to J/\psi K_S^0$	5×10^{-4}	$e^+e^-\pi^+\pi^-$	2.5×10^{-5}	0.06
$J/\psi \to e^+e^-$	0.07			
$K_S^0 \to \pi^+\pi^-$	0.69			
$B_s^0 \to D_s^-\pi^+$	0.003	$K^+K^-\pi^+\pi^-$	3×10^{-5}	0.19
$D_s^- \to \phi\pi^-$	0.02			
$\phi \to K^+K^-$	0.5			
$B_s^0 \to D_s^-\pi^+\pi^+\pi^-$	0.006	$K^+K^-\pi^+\pi^+\pi^-\pi^-$	6×10^{-5}	0.09
$D_s^- \to \phi\pi^-$	0.02			
$\phi \to K^+K^-$	0.5			
$B_s^0 \to D_s^-\pi^+\pi^+\pi^-$	0.006	$K^+K^-\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$	1.2×10^{-4}	0.02
$D_s^- \to \phi\pi^+\pi^-\pi^-$	0.04			
$\phi \to K^+K^-$	0.5			
$B_s^0 \to D_s^{\star -}\pi^+$	0.006	$K^+K^-\pi^+\pi^-\gamma$	6×10^{-5}	0.07
$D_s^{\star -} \to D_s^-\gamma$	1.0			
$D_s^- \to \phi\pi^-$	0.02			
$\phi \to K^+K^-$	0.5			
$B_s^0 \to D_s^{\star -}\pi^+$	0.006	$K^+K^-\pi^+\pi^-(\gamma)$	6×10^{-5}	0.19
$D_s^{\star -} \to D_s^-\gamma$	1.0			
$D_s^- \to \phi\pi^-$	0.02			
$\phi \to K^+K^-$	0.5			

Rate Estimate for $B^{\pm} \to D^0\pi^{\pm}$

This is a typical B-decay to an all-charged final state that has a large branching fraction. Such decays would be used for cross-section studies.

- Luminosity . . . . 10^{31} cm^{2}sec^{-1}.
- Standard running year of 10^7 sec $\Rightarrow$ . . . . 100 pb^{-1}/year.
- $\sigma_{B\bar{B}} = 45$ μb at TEV I $\Rightarrow$ . . . . 4.5×10^9 B-$\bar{B}$ pairs/year.
- 3/4 B^+ or $\bar{B}^-$ per B-$\bar{B}$ pair $\Rightarrow$ . . . . 3.4×10^9 B^0/year.
- B.R. for $B^+ \to D^0\pi^+$; $D^0 \to K^+\pi^-$:
  $(0.003)(0.04) = 1.2 \times 10^{-4}$ $\Rightarrow$ . . . . 4×10^5 $B^+ \to K^+\pi^+\pi^-$/year.
- Geometric acceptance for $B^{\pm} \to K^{\pm}\pi^+\pi^-$ is 0.23;
  Vertex and tracking efficiency ~ 0.33
  $\Rightarrow$ . . . . 31,000 reconstructed $B^{\pm} \to K^{\pm}\pi^+\pi^-$/year.

This estimate assumes that the trigger efficiency is 100%!

2. Trigger

Even if we don't need to tag the reconstructed B, we still need a trigger for the event. We have often discussed using an electron trigger, based on decays such as $B^0 \to D^{\star -} e^+ \nu$. We optimistically suppose that the electron can be used if its transverse momentum is greater than 1 GeV/c.

The charged tracks that might be detected are then $K^+ \pi^- \pi^- e^+$. The π^- from the $D^\star$ decay is extremely soft and hard to detect. Hence we may want to use a trigger that requires only 0, 1, or 2 charged tracks along with the e. For the present example we found the following acceptances:

$e+$ all 3 other charged tracks	0.02
$e+$ 2 other charged tracks	0.14
$e + 1$ other charge track	0.24
e only	0.28

There is a correlation between the two B's in an event such that the acceptance for both B's together is about 1.5 times the product of the acceptance for each B alone.

But when we note that only about 10% of the B's decay (directly) to an electron, and that the vertexing efficiency will be at best about 50%, the electron trigger efficiency is only about 1.5% (for the case of $e + 1$ other).

This has led many to consider a possible secondary-vertex trigger. For this the luminosity would be kept to about 10^{30} so that every event could be fed to a processor farm to make the vertex calculation. Peter Schlein estimates that a vertex trigger is good for about a factor of 50 in rejection of minimum-bias events.

We reconsidered most of the B-decay chains in the table above, supposing that if we found all but one of the charged tracks matching to a secondary vertex, this would be sufficient for a trigger. The geometric acceptance was then about 50% for many modes. If the vertexing efficiency were also 50%, then a vertex trigger might have about 25% efficiency. As this is more than 10 times the efficiency of the electron trigger, it might pay to run at a lower luminosity where the vertex trigger could operate.

3. Rate Estimate for B_s^0-$\bar{B}_s^0$ Mixing Study

We identify the B_s^0 via the decay chains $B_s^0 \to D_s^- \pi^+(\pi^+\pi^-)$; $D_s^- \to \phi\pi^-(\pi^+\pi^-)$; $\phi \to K^+K^-$. A tag on the second B is required to determine whether the first B was initially a B^0 or a $\bar{B}^0$.

- Luminosity .... 10^{31} cm^{2}sec^{-1}.
- Standard running year of 10^7 sec $\Rightarrow$ .... 100 pb^{-1}/year.
- $\sigma_{B\bar{B}} = 45$ μb at TEV I $\Rightarrow$ .... 4.5×10^9 B-$\bar{B}$ pairs/year.
- 1/2 B_s^0 or $\bar{B}_s^0$ per B-$\bar{B}$ pair $\Rightarrow$ .... 2.25×10^9 B^0/year.
- B.R. for $B_s^0 \to D_s^- \pi^+(\pi^+\pi^-)$; $D_s^- \to \phi\pi^-(\pi^+\pi^-)$; $\phi \to K^+K^-$:
  $\sim (0.01)(0.05)(0.5) = 2.4 \times 10^{-4}$
  $\Rightarrow$ .... 5.6×10^5 $B_s^0 \to K^+K^-\pi^+\pi^-(\pi^+\pi^-)(\pi^+\pi^-)$/year.
- Geometric acceptance for $B_s^0 \to K^+K^-\pi^+\pi^-(\pi^+\pi^-)(\pi^+\pi^-)$ is 0.1;
  Vertex and tracking efficiency ~ 0.33
  $\Rightarrow$ .... 18,500 reconstructed $B_s^0 \to K^+K^-\pi^+\pi^-(\pi^+\pi^-)(\pi^+\pi^-)$/year.
- For the mixing analysis analysis we need a tag on the second B.
  Use the decays $B \to e\nu X$.
  The overall tagging efficiency is
  (0.25 geometric acceptance)
  $\cdot$(0.1 branching fraction)
  $\cdot$(0.5 vertex and tracking efficiency)
  $\cdot$(0.33 dilution factor for mixing of the neutral B's in the tagging sample)
  $= 0.004$
  $\Rightarrow$ .... 74 tagged, reconstructed $B_s^0 \to K^+K^-\pi^+\pi^-(\pi^+\pi^-)(\pi^+\pi^-)$/year.

4. Rate Estimate for CP-Violation Study of $B_d^0 \to J/\psi K_S^0$

The decay $B_d^0 \to J/\psi K_S^0$ is the typical example of one in which the final state is a CP-eigenstate and has a very clear experimental signature. The rate asymmetry for this decay from B^0 compared to $\bar{B}^0$ is expected in the range 0.05-0.3. A tag on the second B is required to determine whether the first B was a B^0 or a $\bar{B}^0$.

- Luminosity . . . . 10^{31} cm^{2}sec^{-1}.
- Standard running year of 10^7 sec $\Rightarrow$ . . . . 100 pb^{-1}/year.
- $\sigma_{B\bar{B}} = 45$ μb at TEV I $\Rightarrow$ . . . . 4.5×10^9 B-$\bar{B}$ pairs/year.
- 3/4 B_d^0 or $\bar{B}_d^0$ per B-$\bar{B}$ pair $\Rightarrow$ . . . . 3.4×10^9 B^0/year.
- B.R. for $B^0 \to J/\psi K_S^0$; $J/\psi \to e^+e^-$; $K_S^0 \to \pi^+\pi^-$:
  $(5 \times 10^{-4})(0.07)(0.69) = 2.4 \times 10^{-5} \Rightarrow$ . . . . 8×10^4 $B^0 \to e^+e^-\pi^+\pi^-$/year.
- Geometric acceptance for $B^0 \to e^+e^-\pi^+\pi^-$ is 0.06;
  Vertex and tracking efficiency ~ 0.33
  $\Rightarrow$ . . . . 1600 reconstructed $B^0 \to e^+e^-\pi^+\pi^-$/year.
- For a CP-violation analysis we need a tag on the second B.
  Use the decays $B \to e\nu X$.
  The overall tagging efficiency is
  (0.25 geometric acceptance)
  $\cdot$(0.1 branching fraction)
  $\cdot$(0.5 vertex and tracking efficiency)
  $\cdot$(0.33 dilution factor for mixing of the neutral B's in the tagging sample)
  $= 0.004$
  $\Rightarrow$ . . . . 6 tagged, reconstructed $B^0 \to e^+e^-\pi^+\pi^-$/year.

Possible improvement factors:

- Main Ring Upgrade $\Rightarrow$ . . . . $\times 5$ in luminosity.
- Full BCD (new collision hall) $\Rightarrow$ . . . . $\times 10$ in acceptance.

Mini-BCD: Channel Count and Cost Estimates

1. **C-Magnet** $0.5M
   - 75 tons of steel @ $2k per ton = $150k
   - Coils (wound at Fermilab) $350k
2. **Silicon Vertex Detector** $5M
   - Detector extends over ± 1 and follows the full BCD design $\Rightarrow \sim 10^6$ strips @ $5 per strip.
3. **Straw-Tube Tracker** $3M
   - The straws are vertical and extend over an area 2m $\times$ 1.5m in the horizontal plane.
   - Assuming each straw occupies 0.5 cm^2 and they are dense packed, there are 60k straws.
   - We estimate $50 per straw.
4. **Forward TRD** $4.5M
   - 4 layers per detector $\times$ 2 arms $\times \sim 1$ m^2 per layer = 8 m^2.
   - Need detector pads of about 1.5 cm^2 to keep occupancy low.
   - 60k pads; $75 per channel.
5. **Forward EM Calorimeter** $3M
   - 2 arms $\times$ 2.25 m^2 = 4.5 m^2
   - Cells 1 $\times$ 1 cm^2 at 2°; 3 $\times$ 3 cm^2 at 20°; on average we need about 3 cm^2 per cell; 15k cells in all.
   - Use a lead/scintilling-fiber technology; no longitudinal segmentation; $200 per cell.
6. **Central Liquid RICH** $1M
   - The central detector coverage is limited: $\Delta\eta = 1.4$, $\Delta\phi = 0.1$. There is only 1/2 charged particle per event in this solid angle. We choose 1000 cells per layer in all central detectors.
   - We estimate $1k per cell in a liquid RICH counter, including UV-windows.
7. **Central Gas RICH** $1.5M
   - We estimate $1.5k per cell in the gas RICH, which has bigger UV-windows.
8. **Central TRD** $0.5M
   - There are 5 layers; $100 per cell.

9. **Central EM Calorimeter** $0.5M
   - We estimate $500 per cell in this large device.

10. **Event-Builder Switch** $3.5M
    - A 512 × 512 barrel-switch event builder is estimated by Mark Bowden to cost about $3.5M including $1.5M of engineering support.

11. **On-line Computer Farm** $5M
    - 1000 processors; $5k each.

Total **$28M**