The Forward Arm of a Bottom Collider Detector

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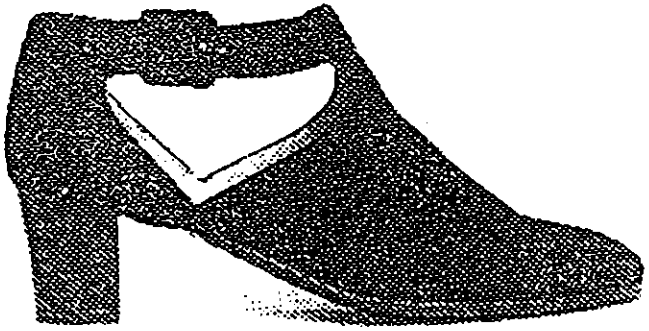
Having a
good idea is not
enough, he says.
You must be
the only one
to have it.



The Goal

Measurement of CP violation free from uncertainty due to strong interactions.

The Opportunity

This cannot be done even in principle in the K-meson system.

However, there are six ways to measure CP-violating phases in the B-meson system.

$\sigma_{b\bar{b}}/\sigma_{\text{total}}$ may be as high as 1/30 at the SSC (Collins and Ellis, 1991).

Six Ways to Measure CP Violation in B Decays

1. B decays to D^0X, $\bar{D}^0X$, and $D^0_{1,2}X$ where $X \neq \bar{X}$.

   Example:

   $B^+ \to DK^+$ and $B^0_d \to DK^{*0}$ measure ϕ_{ub}.

2. Neutral B-meson decays to f and $\bar{f}$ where $f \neq \bar{f}$.

   Example:

   $B^0_d \to D^\pm\pi^\mp$ measures $2\phi_{td} + \phi_{ub}$,

   $B^0_s \to D^\pm_s K^\mp$ measures ϕ_{ub};

3. Neutral B-meson decays to D^0X, $\bar{D}^0X$, and $D^0_{1,2}X$ where $X = \bar{X}$.

   Example:

   $B^0_d \to DK^0_S$ measures ϕ_{ub}, $2\phi_{ub}+\phi_{td}$ and $\phi_{ub}+\phi_{td}$,

   $B^0_s \to D\phi$ measures ϕ_{ub}.

Six Ways to Measure CP Violation

4. Neutral B-meson decays to CP eigenstates.

   Example:

   $B_d^0 \to J/\psi K_S^0$ measures ϕ_{td},

   $B_d^0 \to \pi^+\pi^-$ measures $\phi_{td} + \phi_{ub}$,

   $B_s^0 \to \rho^0 K_S^0$ measures ϕ_{ub}.

5. B decays to sets of final states related by isospin.

   Example:

   $B_d^0 \to \pi^+\pi^-$, $\pi^0\pi^0$ and $B^+ \to \pi^+\pi^0$ measure $\phi_{td} + \phi_{ub}$ free from uncertainty due to penguin contributions.

6. Angular analysis of B decays to mixtures of CP eigenstates.

   Example:

   $B_d^0 \to J/\psi K_S^0 \pi^0$ and $D^{*+}D^{*-}$ measure ϕ_{td},

   $B_d^0 \to \rho^+\rho^-$ and $\rho^0\rho^0$ measure $\phi_{td} + \phi_{ub}$.

Six Ways to Measure CP Violation

- All of these except Method 4 involve non-CP eigenstates.
- Methods 1-3 allow extraction of ϕ_{ub} from B_u and B_d, and will require greater emphasis on Kaon identification than methods 4-6.
- Methods 5 and 6 require photon detections in most cases.
- All except Method 1 require tagging of the particle/antiparticle character of the second B.
- Each Method requires 10^8-10^{10} B's.
- The mode $B_d^0 \to J/\psi K_S^0$ which measures ϕ_{td} via Method 4 is the most accessible of all those considered here.

Why Study B's at $\sqrt{s} = 40$ TeV?

- Good signal-to-noise: $\sigma_{b\bar{b}}/\sigma_{\text{total}} \gtrsim 1/50$.

  [Compare $\sigma_{b\bar{b}}/\sigma_{\text{total}} = 1/5$ at e^+e^- on $\Upsilon(4s)$.]

- High rates: Vertex detector at small radius can survive radiation damage due to $\approx 10^7$ events/sec ($\mathcal{L} = 10^{32}$).

  $\Rightarrow > 10^{12}$ $b\bar{b}$ produced per year.

  [Compare to 3×10^7 $b\bar{b}$/year at an e^+e^- 'B Factory' with $\mathcal{L} = 3 \times 10^{33}$.]

- Can trigger on $B \to J/\psi X,\ J/\psi \to l^+l^-$ for $\mathcal{L} > 10^{32}$.

- Can use high-rate data-acquisition system to record > 1000 events/sec,

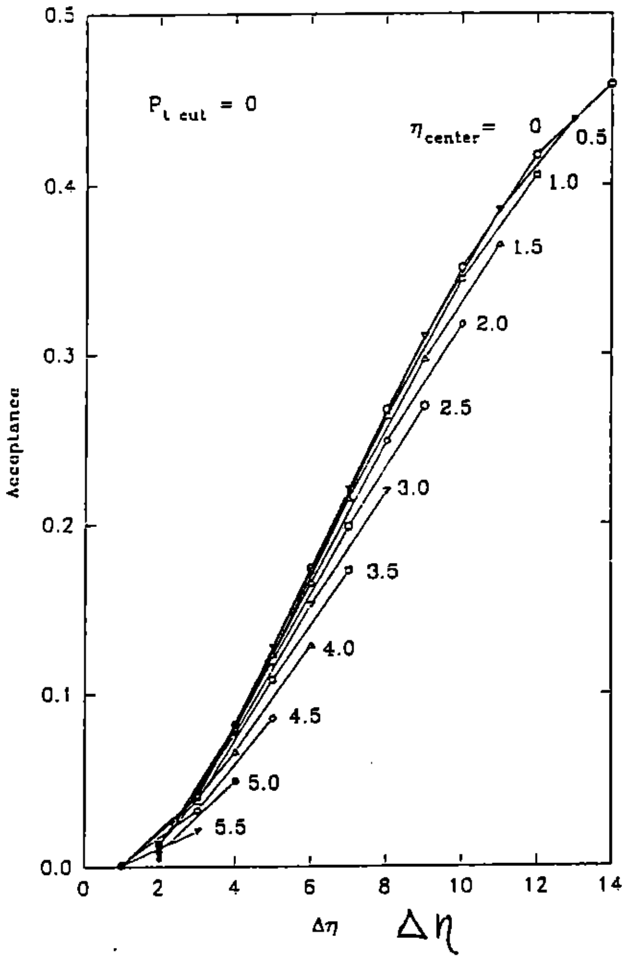
  $\Rightarrow \approx 10^8$ $b\bar{b}$/year with minimum-bias trigger.

  $\Rightarrow \approx 10^{10}$ $b\bar{b}$/year if achieve software trigger rejection of 100:1 in processor farm.

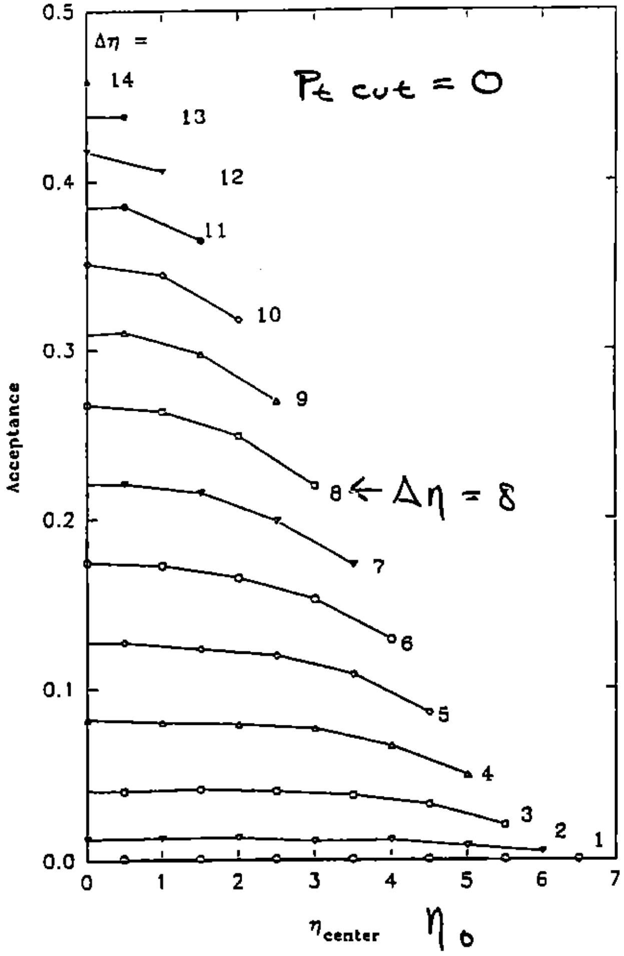
Table 5: B-$\bar{B}$ production at hadron accelerators. In this comparison we suppose that the experiments all operate at 10^7 interactions/sec, and that corresponding luminosity $\mathcal{L}$ can be achieved. We then consider $\sigma_{b\bar{b}}/\sigma_{\text{tot}}$, as the figure of merit of the various accelerator options.

Accelerator	$\sqrt{s}$ (TeV)	$\sigma_{b\bar{b}}$ (μb)	σ_{tot} (mb)	$\sigma_{b\bar{b}}/\sigma_{\text{tot}}$	$\mathcal{L}_{\text{ave}}$ (cm^{-2}sec^{-1})	$N_{b\bar{b}}/10^7$ sec	Figure of Merit
TEV II (p-W)	0.04	0.003	6	5×10^{-6}	1.7×10^{33}	1.7×10^7	1/10,000
SSC (p-Si)	0.2	3	15	1/5000	6.7×10^{32}	2×10^{10}	1/100
RHIC (p-p)	0.5	10	40	1/4000	2.5×10^{32}	2.5×10^{10}	1/80
TEV I (p-$\bar{p}$)	1.8	40	40	1/1000	2.5×10^{32}	10^{11}	1/20
LHC (p-p)	16	600	75	1/125	1.3×10^{32}	7.9×10^{11}	2/5
SSC (p-p)	40	2,000	100	1/50	10^{32}	2×10^{12}	1

ISAJET $\sqrt{s} = 40$ TeV



ISAJET $\sqrt{s} = 40$ TeV

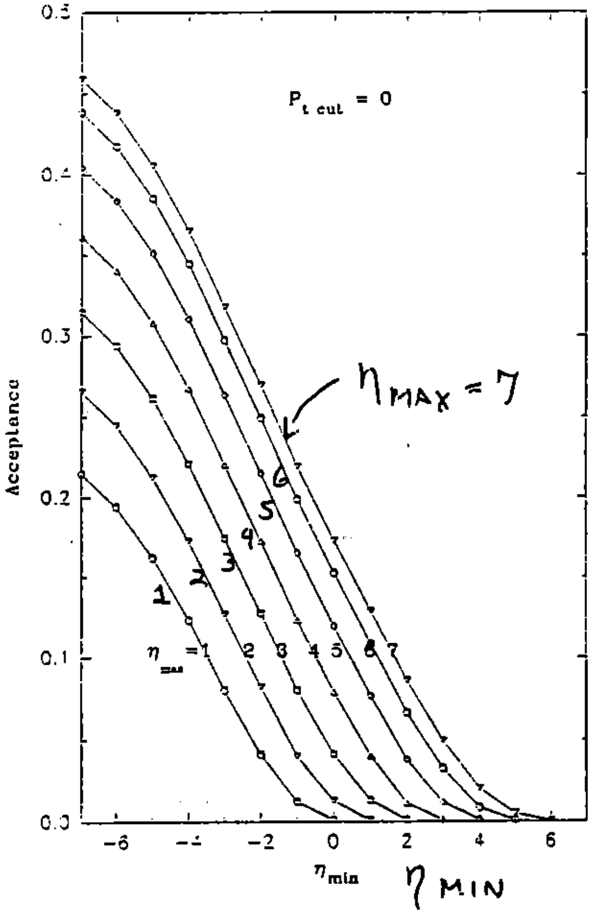


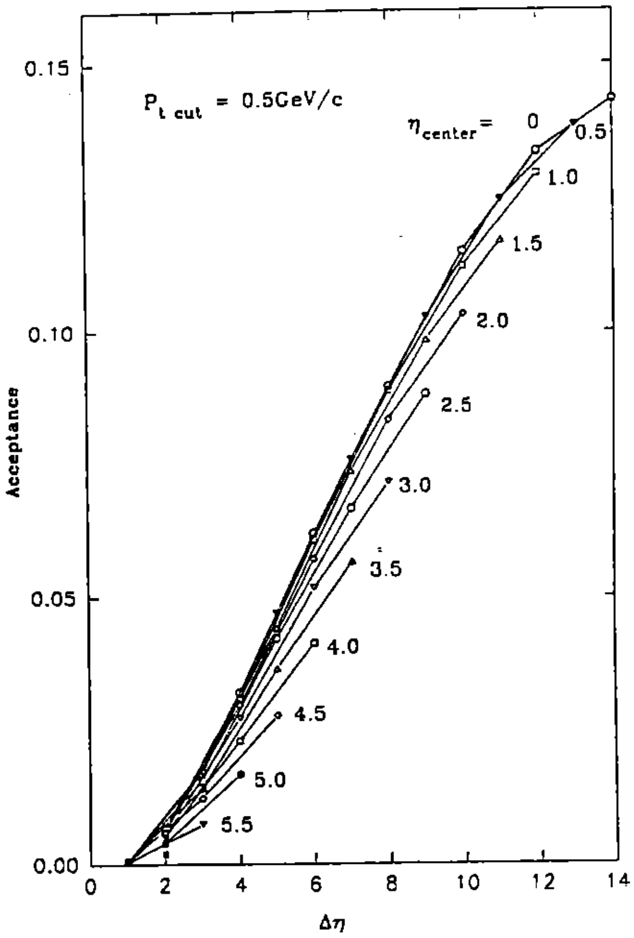
$B^0 \to J/\psi\ K_S^0$
$\quad \hookrightarrow \mu^+\mu^- \quad \hookrightarrow \pi^+\pi^-$

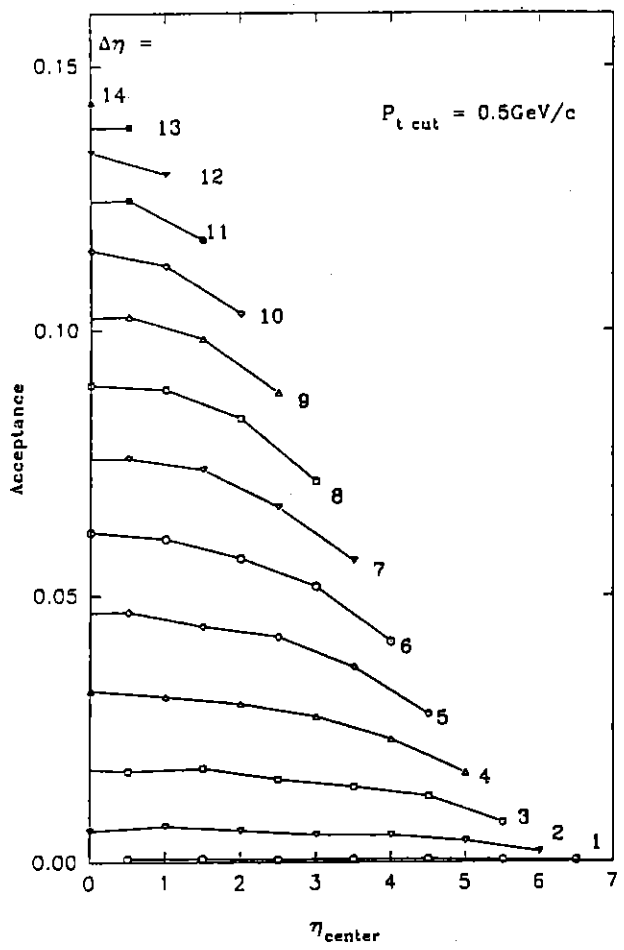
$\bar{B} \to K^+ X$ ← FOR TAGGING

} MUST ACCEPT ALL 5 PARTICLES:
$\mu^+, \mu^-, \pi^+, \pi^-, K^+$

ISAJET √s = 40 TeV



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P_t cut = 0.5GeV/c
Acceptance
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η_center
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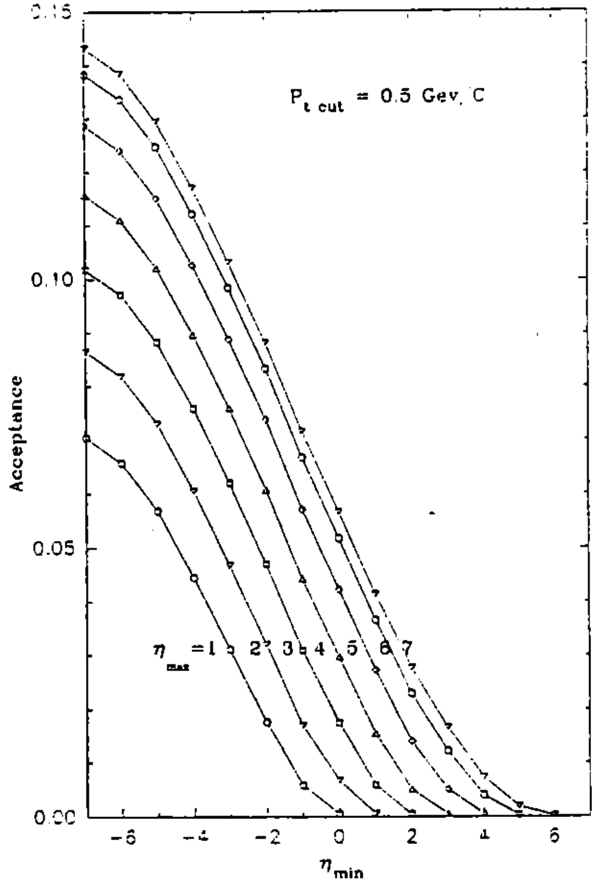
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η_max = 1 2 3 4 5 6 7
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η_min
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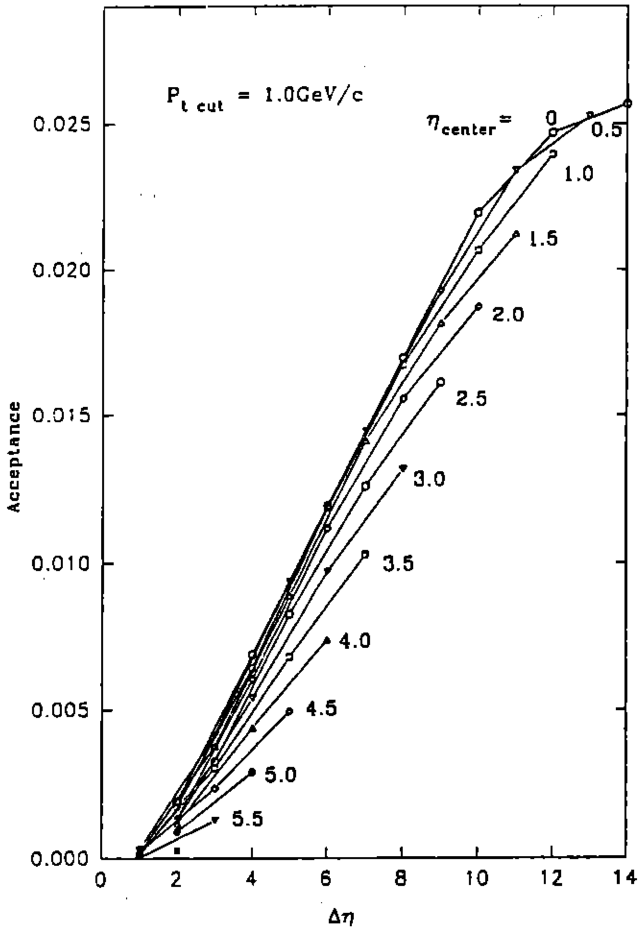
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η_{center} =
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0.5
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1.5
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Acceptance
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Δη
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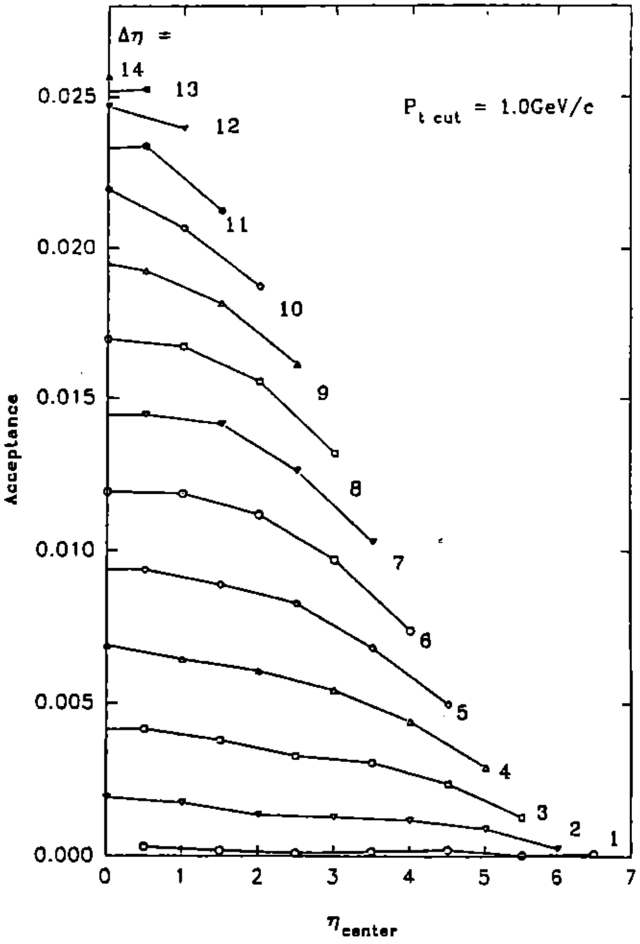
Δη =
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$P_{t\,cut}$ = 1.0GeV/c
Acceptance
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η_{center}
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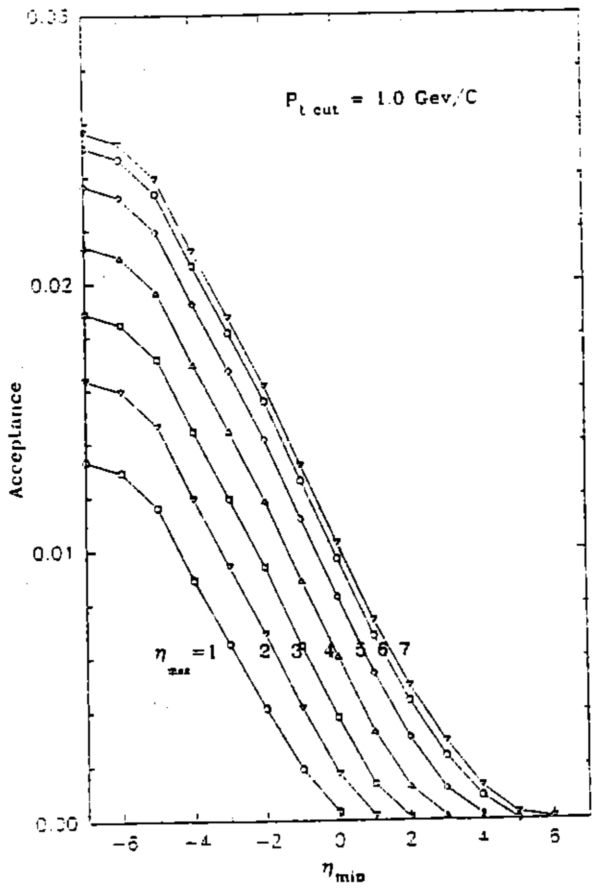


Ingredients of a B-physics Experiment

- $P_t \lesssim M_B = 5$ GeV/c.
- Wide angular range: $|\eta| \lesssim 6$ at $\sqrt{s} = 40$ Tev.
- A 3-D silicon vertex detector.
- Good momentum measurement:

  $\Rightarrow \sigma_M \approx 25$ MeV/c^2 for B's.
- Particle ID of π, K, e and μ.
- High-rate trigger and data acquisition for any mode but $B \rightarrow J/\psi X$.
- Hadron calorimetry not needed.

- A path for upgrades from a modest initial configuration.

Architecture

- The architecture of a collider experiment will likely remain fixed for 20-30 years, while detector elements will have 5-10 year cycle.
- The architecture should be compatible with a full acceptance detector.
- Should use thin, small radius beampipe for $\eta \lesssim 5$, and flared pipe for larger η.
- Dipole fields prior to flares are troublesome:

  A central dipole is somewhat incompatible with clean coverage for $\eta > 5$.
- Solenoids, quadrupoles (sextupoles...) may be preferable as have only weak or no transverse field near beams.
- All schemes have an awkward transition at $\eta \approx 1.3$ ($\theta \approx 30°$).

Magnetic Architecture

- The configuration of the central magnet is the key architectural feature.

  ⇒ Need clear plan for eventual central magnet even if choose to instrument only a forward arm initially.
- Central **dipole**:

  A central dipole magnet can provide sufficient momentum analysis for all tracks with $|\eta| < 5.5$ if use a silicon tracker for $|\eta| \gtrsim 3.5$.

  A central $2n$-pole magnet has regions of poor resolution given by $\sqrt{\cos^2 n\phi + \sin^2 n\phi \cos^2\theta} \lesssim 1/4$, covering about $1/2$ unit of (η, ϕ) space.

  Compensating dipoles ⇒ no net kick for $|\eta| > 5.5$.

- Central **solenoid**:

  Good momentum resolution only for $|\eta| \lesssim 2$.

  Cover $|\eta| > 2$ with forward dipoles or quadrupoles.

  Best configuration for fast P_t trigger.

- Central **Quadrupole**

  Good momentum resolution only for $|\eta| \lesssim 3$.

  Cover $|\eta| > 3$ with forward dipoles or quadrupoles.

  2-m diameter superconducting quadrupoles have never been built, but can be intrinsically more stable than solenoids.

Central or Forward?

- **Central**: $|\eta| < 1.2 - 1.5$

  Low $P \Rightarrow$ poorer secondary vertex resolution.

  Solenoid or dipole?

    Solenoid is poorer match to $\eta > 1.5$.

    Tracking, P_t trigger easier in solenoid.

    Solenoid more compatible with detectors at $\eta > 5$.

    20% loss of azimuth in central dipole.

- **Forward**: $1.2 < \eta < 5.5$

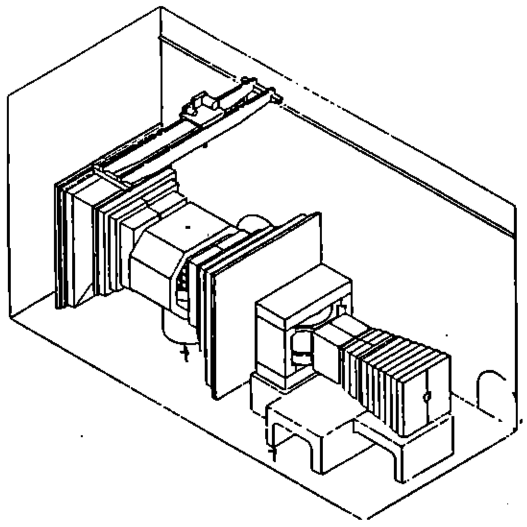
  Detectors more accessible, $\Rightarrow$ cheaper.

  Vertex detector can use disks only.

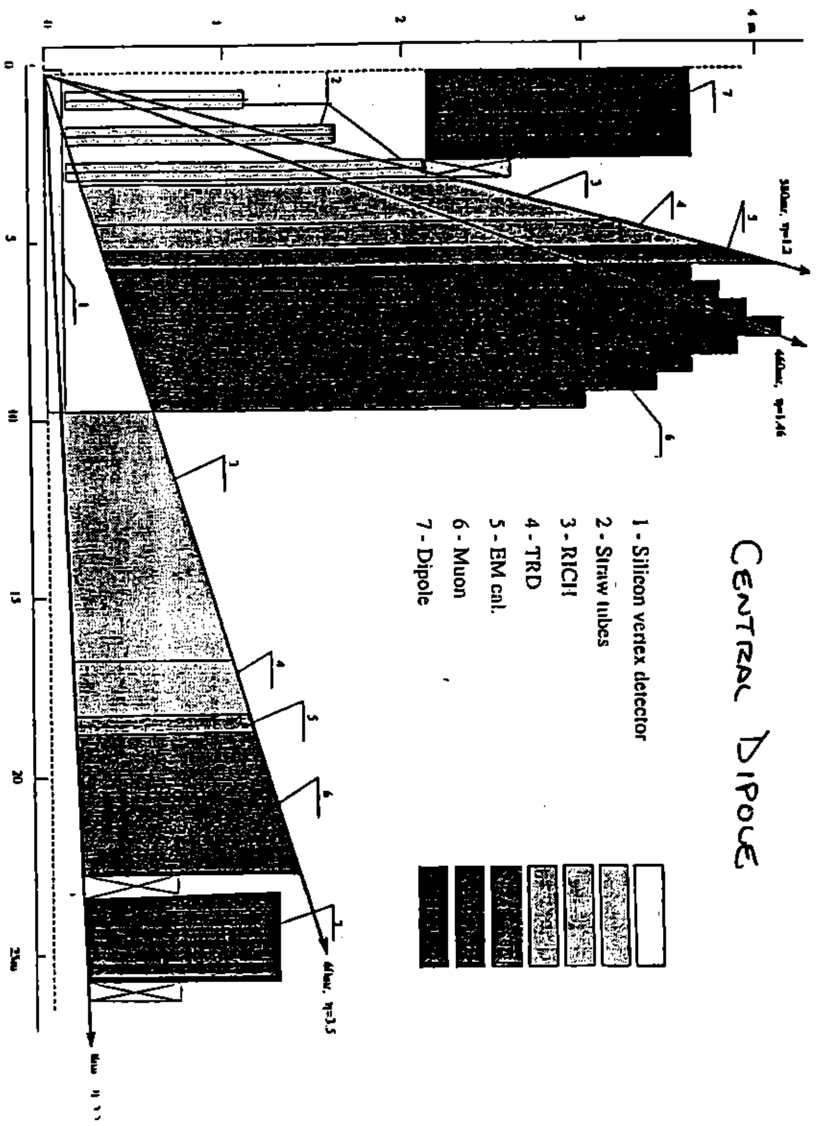
  Good momentum analysis via central dipole.

  Compensating dipoles $\Rightarrow$ no net kick for $|\eta| > 5.5$.

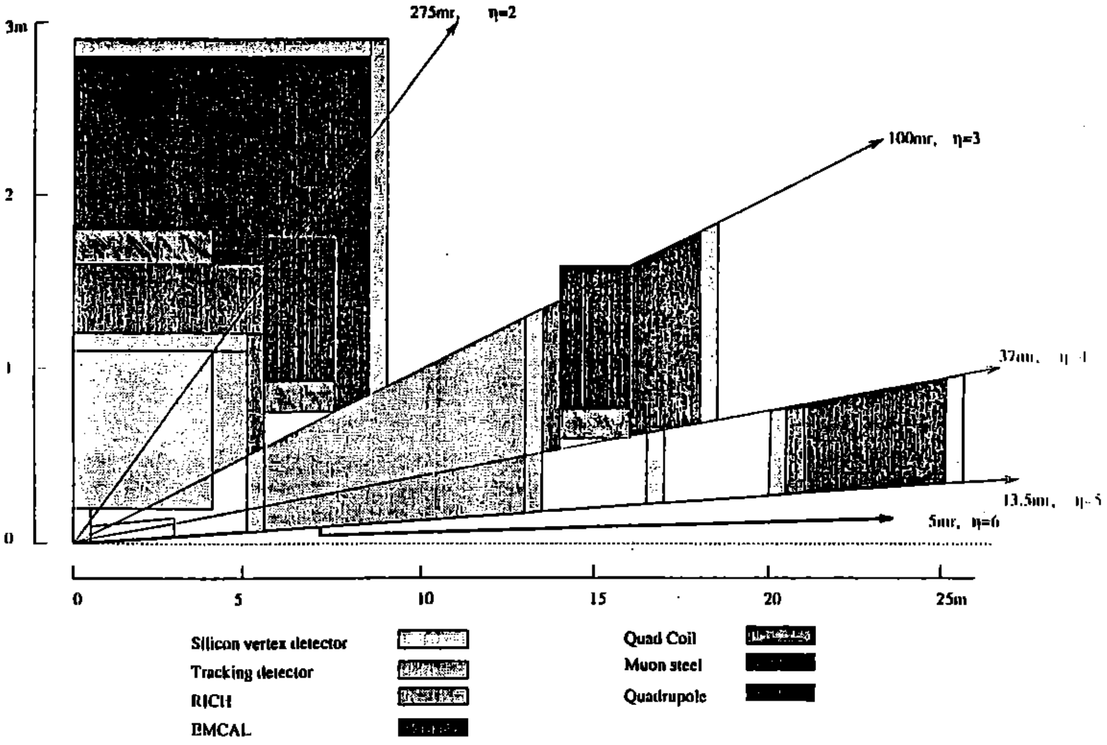
BCD (EOI0008)



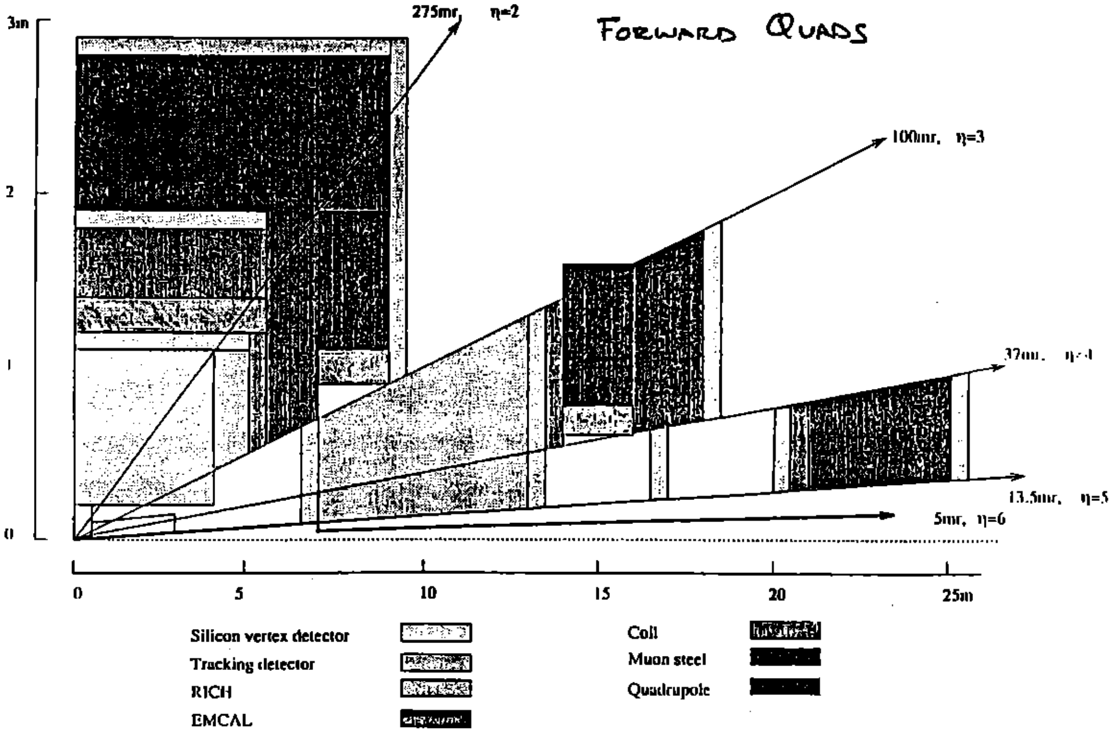
- Designed for maximal coverage of CP-violation physics at the SSC.
- Dipole geometry with Central, Intermediate, and Forward detectors.
- $|\eta| < 5.5$, $P_t \gtrsim 0.3$ for π, K, $P_t \gtrsim 1$ for e, μ.
- Cost ~ \$200M for the full detector.



CENTRAL + FORWARD QUADRUPOLES



CENTRAL SOLENOID / FORWARD QUADS



BCD Phase I: Single Forward Arm

$1.2 < \eta < 5.5$

1. Central dipole magnet, 1 T, gap height 4 m, pole tip radius 2 m, two small forward dipoles	$5M
2. Silicon vertex detector, 49 disks, 550k channels, $10/channel	$5M
3. Straw-tube tracking, 72 planes, 75k straws, $65/straw	$5M
4. RICH counter, 60k channels, $40/channel	$2.5M
5. Transition radiation detector ($\eta < 3.5$ only), 50k channels, $50/channel	$2.5M
6. EM calorimeter, 4k cells, 5 samples/cell, $250/channel	$5M
7. Muon detector ($\eta > 1.5$ only), 1800 tons, 12k channels	$5M
8. Data-acquisition, barrel-switch event builder, 1000-processor online computer farm	$10M
9. Contingency	$10M
10. **Total**	**$50M**

BCD (T-784) Ongoing R&D

- Silicon Vertex Detector
  - BVX readout chip: 1 ADC per channel.
  - Beam tests of double-sided DC-coupled detectors (Micron).
  - Mechanical studies of air-cooled detector with interleaved disks and barrels.
- Straw Tracker prototype: U. Penn bipolar preamp
  - 200-channel system test Fall 91.
- RICH Counter: solid CsI photocathode
  - 400-channel system test Fall 91.
- Barrel-Switch Event Builder
  - 600 event/sec demo in 1/4 crate, Summer 91.
- Processor Farm: high-bandwidth network
  - 1991: 512 *i860* cpu's on mesh network.

Table 2: The minimum values of $\sin 2\varphi_i$ resolvable to three standard deviations in 10^7 sec of running at luminosity of 10^{32} cm^{-2}sec^{-1}in an SSC experiment covering $1.2 < \eta < 5.5$.

Angle	Mode	Tag	Tagged Events	$1-2p$	b	x_q	D	$\sin 2\varphi_{\mathrm{min},3\sigma}$
φ_1	$B_d^0 \to J/\psi K_S^0$	$e^\pm$	9,600	0.60	0.1	0.7	0.47	0.11
φ_1	$B_d^0 \to J/\psi K_S^0$	$K^\pm$	73,000	0.40	0.1	0.7	0.47	0.066
φ_2	$B_d^0 \to \pi^+\pi^-$	$e^\pm$	40,000	0.60	1.0	0.7	0.47	0.076
φ_2	$B_d^0 \to \pi^+\pi^-$	$K^\pm$	307,000	0.40	1.0	0.7	0.47	0.041
φ_3	$B_s^0 \to \rho^0 K_S^0$	$e^\pm$	267	0.60	1.0	~ 10	0.64	0.68
φ_3	$B_s^0 \to \rho^0 K_S^0$	$K^\pm$	2,300	0.40	1.0	~ 10	0.64	0.34
φ_3	$B_s^0 \to K^+K^-$	$e^\pm$	1,000	0.60	~ 0.1	~ 10	0.64	0.27
φ_3	$B_s^0 \to K^+K^-$	$K^\pm$	9,200	0.40	~ 0.1	~ 10	0.64	0.12
φ_4	$B_s^0 \to J/\psi\phi$	$K^\pm$	107,000	0.40	~ 0.1	~ 10	0.64	0.039