B Physics at Hadron Accelerators with RHIC as an Example

K.T. McDonald
Princeton U.

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The Goal

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

The Opportunity

This cannot be done in the foreseeable future in the K-meson system.

However, there are six ways to measure CP-violating phases in the B-meson system (free from hadronic ambiguity).

$\sigma_{b\bar{b}}/\sigma_{\text{total}}$ may be as high as 1/30 at the SSC.

Initial studies of CP violation can be pursued at the TEVATRON and at RHIC.

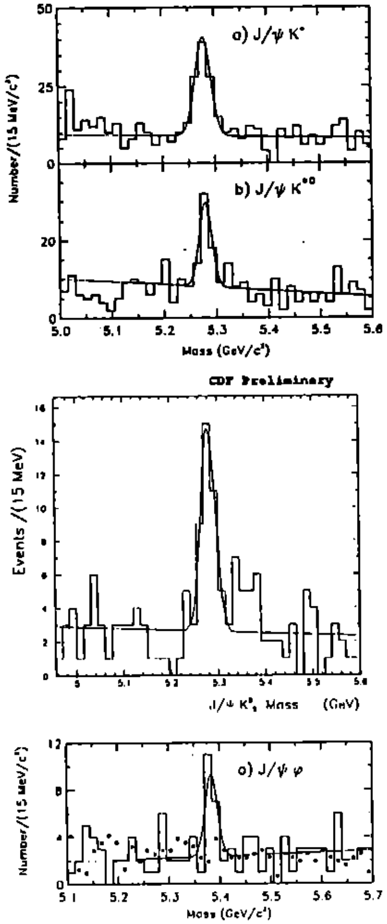
The Last Decade of B Physics

- CP violation is expected to be more dramatic in the B-meson system than with K's.
  (if B-$\overline{B}$ mixing is large; Carter and Sanda, 1980)
- The B-meson lifetime is much long than expected, longer than that of D mesons.
  (Fernandez *et al.*; Lockyer *et al.*, 1983)
- B_d-$\overline{B}_d$ mixing is much larger than expected.
  (Albrecht *et al.*, 1987)
- The B-pair cross section at the SSC should be 1-3% of the total, much larger than previously expected.
  (Collins and Ellis, 1991)

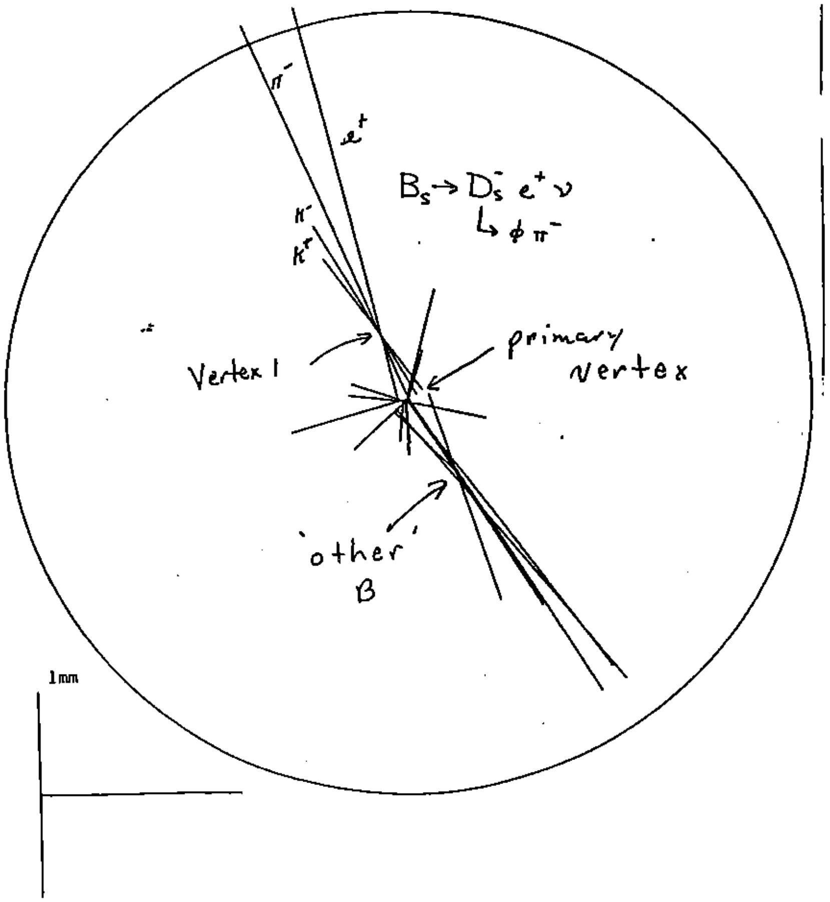
B Physics Initiatives at Hadron Accelerators

- 1977: $b\bar{b}$ bound states (Υ) discovered at Fermilab (Lederman *et al.*).
- 1984, Snowmass: B physics hard to do with high-P_t detector (Trilling *et al.*); needs new technology (Cronin).
- 1987: Two Letters of Intent to FNAL (Lockyer *et al.*, Reay *et al.*);
  Berkeley summer study, FNAL beauty workshop.
- 1989 onward: R&D for B detectors: T-784 at FNAL;
  various Generic and Subsystem R&D at SSC;
  P-238 at CERN.
- 1990: $B \to J/\psi K$ decays reconstructed at CDF;
  three EOI's at the SSC; two proposals at FNAL;
  one proposal at CERN.
- 1992: Workshops at FNAL and SSC.
- 1993: $B_s \to J/\psi\phi$ discovered at CDF;
  Snowmass workshop; Letters of Intent to HERA, LHC.

$B \to J/\psi X$ Decays Reconstructed at CDF



B Decays Cleanly Observed in CDF Vertex Detector



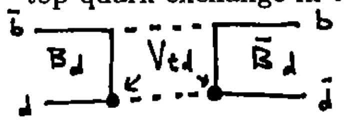
CP Violation in the B-Meson System

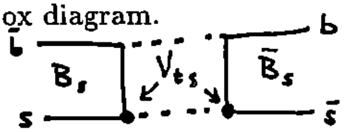
- CP violation in weak eigenstates is tiny.
- CP violation occurs via first-order phases in the CKM matrix.

  In the Wolfenstein representation:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} Re & Re & Im \\ Re & Re & Re \\ Im & Re & Re \end{pmatrix}.$$

- The phase of V_{td} enters in B_d (but not B_s) mixing due to top-quark exchange in the box diagram.





- The phase of V_{ub} enters in $b \to u$ (but not $b \to c$) decays.
- Hence there are 4 classes of CP violation in decays of neutral B's:
  1. B_d decay, $b \to c$ $(B_d \to J/\psi K_S)$ $\sim V_{td}$
  2. B_d decay, $b \to u$ $(B_d \to \pi^+\pi^-)$ $\sim V_{td}V_{ub}$
  3. B_s decay, $b \to u$ $(B_s \to \rho K_S)$ $\sim V_{ub}$
  4. B_s decay, $b \to c$ $(B_s \to J/\psi\phi)$ no effect

Interference in CP-Violating Processes

CP violation appears in a single graph only as a phase factor:

$A(B \to f) \equiv A_f = |A_f|\, e^{i\phi_W} e^{i\delta_S}$, W = weak, S = strong.

CP conjugation $\Rightarrow A(\overline{B} \to \overline{f}) \equiv \overline{A}_{\overline{f}} = |A_f|\, e^{-i\phi_W} e^{i\delta_S}$.

Hence cannot observe CP violation in only a single graph.

Total rate measurement when two graphs interfere:

$$A(B \to f) = |A_1|\, e^{i\phi_1} e^{i\delta_1} + |A_2|\, e^{i\phi_2} e^{i\delta_2},$$

$$A(\overline{B} \to \overline{f}) = |A_1|\, e^{-i\phi_1} e^{i\delta_1} + |A_2|\, e^{-i\phi_2} e^{i\delta_2}.$$

$$\Gamma(B \to f) = |A_1|^2 + |A_2|^2 + 2\,|A_1|\,|A_2| \cos(\phi + \delta),$$

$$\Gamma(\overline{B} \to \overline{f}) = |A_1|^2 + |A_2|^2 + 2\,|A_1|\,|A_2| \cos(\phi - \delta),$$

where $\phi = \phi_1 - \phi_2$ and $\delta = \delta_1 - \delta_2$.

Only if both ϕ and δ are nonvanishing can the interference term be determined from measurements of the two decay rates.

Neutral B-Meson Decays to CP Eigenstates

If both B^0 and $\overline{B}^0$ decay to the same final state f then CP violation can be revealed due to mixing (Carter and Sanda):

$$\begin{aligned} B^0(t) &= e^{-iMt}e^{-t/2}[\cos(xt/2)|B^0\rangle + ie^{2i\phi_M}\sin(xt/2)|\overline{B}^0\rangle], \\ \overline{B}^0(t) &= e^{-iMt}e^{-t/2}[ie^{-2i\phi_M}\sin(xt/2)|B^0\rangle + \cos(xt/2)|\overline{B}^0\rangle], \end{aligned}$$

where $x = \Delta M/\Gamma$ and

$$\phi_M = \begin{cases} \phi_{td}, & \text{for } B_d^0 \\ \phi_{ts} \approx 0, & \text{for } B_s^0 \end{cases}$$

The analysis is especially beautiful if f is a CP eigenstate;

$$|\overline{f}\rangle \equiv CP|f\rangle = \eta|f\rangle \qquad \text{where} \qquad \eta = \begin{cases} +1 & CP(\text{even}) \\ -1 & CP(\text{odd}) \end{cases}.$$

$$A(B^0 \to f) = |A|\,e^{-i\phi_D}e^{i\delta_S}, \qquad \phi_D = \begin{cases} \phi_{cb} = 0, & b \to c \\ \phi_{ub}, & b \to u \end{cases}.$$

$$A(\overline{B}^0 \to \overline{f}) = \eta A(\overline{B}^0 \to f) = |A|\,e^{i\phi_D}e^{i\delta_S},$$

and hence $A(\overline{B}^0 \to f) = \eta\,|A|\,e^{i\phi_D}e^{i\delta_S}$,

Then

$$\begin{aligned} \Gamma(B^0(t) \to f) &\propto |A|^2\,e^{-t}[1 - \eta\sin(xt)\sin 2(\phi_M + \phi_D)], \\ \Gamma(\overline{B}^0(t) \to f) &\propto |A|^2\,e^{-t}[1 + \eta\sin(xt)\sin 2(\phi_M + \phi_D)]. \end{aligned}$$

- **The strong-interaction phase δ_S does not appear.**
- **A CP violating phase ϕ_M appears in mixing of B_d.**
- **A CP violating phase ϕ_D appears in $b \to u$ decays (direct CP violation).**
- **Complications arise if a penguin graph contributes with different CP-violating phases.**

Other ways to isolate CP-violating phases (Gronau *et al.*):

1. If $B \to D^0X$ and $B \to \overline{D}^0X$ then useful interference arises via the D_1^0 and D_2^0 states.

   Examples: $B^+ \to DK^+$, $B_d^0 \to DK^{*0}$.

2. Neutral B-meson decays to f and $\overline{f}$ where $f \neq \overline{f}$ also have interference due to mixing.

   Examples: $B_d^0 \to a_1^{\pm}\pi^{\mp}$, $B_s^0 \to D_s^{\pm}K^{\mp}$.

CP-Violating Asymmetries

- For decays of neutral B's to CP eigenstates,

$$A(t) = \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})} = \sin 2\varphi \sin xt,$$

where φ = phase of the CKM matrix element,

and $x = \Delta M/\Gamma$ = mixing parameter.

- Three classes of nonzero asymmetries:

1. $B_d^0 \to J/\psi K_S^0$ depends on $\varphi_1 = 2\pi - \varphi_{td}$.
2. $B_d^0 \to \pi^+\pi^-$ depends on $\varphi_2 = -\pi + \varphi_{td} + \varphi_{ub}$.
3. $B_s^0 \to \rho^0 K_S^0$ depends on $\varphi_3 = -\varphi_{ub}$.

- Unitarity relation: $\varphi_1 + \varphi_2 + \varphi_3 = \pi$.

$\Rightarrow$ Three measurements of the two CKM phases.

$\Rightarrow$ Can overconstrain the Standard Model.

- But, must tag the particle/antiparticle character of the B by observation of the second B in the event.

Estimates of the CP-Violating Phases φ_i

From present measurements of τ_B and $|V_{ub}| / |V_{cb}|$, and estimates of M_t, we infer that $0.1 < \sin 2\varphi_1 < 0.9$.

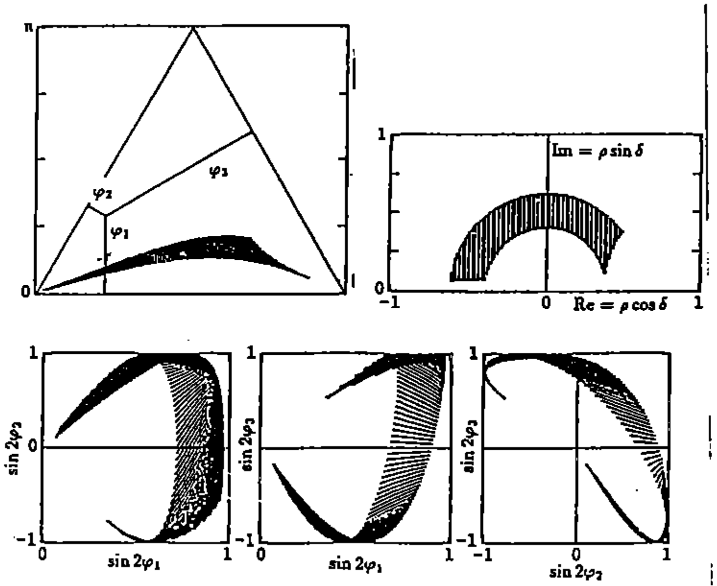


Figure 5: Allowed regions of the φ_i at 90% confidence, based on present knowledge of the CKM matrix. In the triangle plot, $\varphi_1 + \varphi_2 + \varphi_3 = \pi$. The top-quark mass was taken to be 150 GeV/c^2.

The Einstein-Rosen-Podolsky Effect

- If the B^0-$\overline{B}^0$ pair is produced in a C(odd) or C(even) combination, this quantum-mechanical correlation leads to the combined decay asymmetry

$$A(t_1, t_2) = \sin 2\varphi \sin x(t_1 \mp t_2).$$

- If we don't observe the decay times, the integrated asymmetry is

$$A = \begin{cases} 0 & C(\text{odd}) \\ \frac{2x}{(1+x^2)^2} \sin 2\varphi & C(\text{even}) \end{cases}$$

- For B^0-$\overline{B}^0$ produced at the $\Upsilon(4S)$ at an e^+e^- collider, we have only C(odd) states,

⇒ CP violation vanishes unless can observe the time evolution.

⇒ Need \$100-250M to build an asymmetric e^+e^- collider.

CP-Asymmetries at a Hadron Collider

- Here, the B^0-$\overline{B}^0$ pair is produced as an incoherent sum of C(odd) and C(even) states,

  ⇒ The combined decay asymmetry averages to

$$A(t_1, t_2) = \sin 2\varphi \sin xt_1 \sin xt_2,$$

and the time-integrated asymmetry is

$$A = \frac{x}{(1+x^2)^2} \sin 2\varphi.$$

- The asymmetry is 'diluted' by a factor $x/(1+x^2)$ from mixing of the first B, and by a factor $1/(1+x^2)$ from mixing of the 2nd B.
- With $x_d \approx 0.7$, we would have $A \approx (1/4) \sin 2\varphi$.

  ⇒ $A_{\text{min},3\sigma} = 12/\sqrt{N}$ for a sample of N events.

Example: $A_{\text{min},3\sigma} = 0.1$

⇒ $N = 14,400$ reconstructed, tagged decays

Branch $= 10^{-5}$, acceptance $= 0.01$

⇒ need $> 10^{11}$ B's produced.

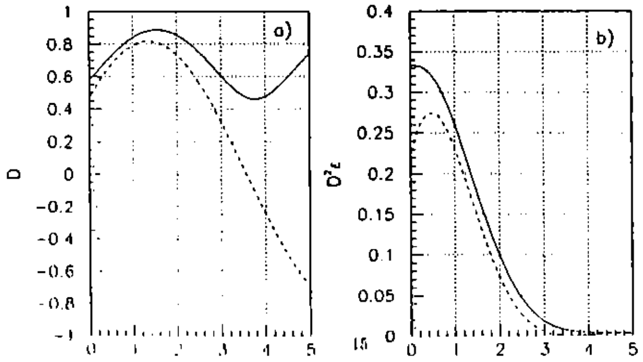
Dilution Due to Mixing of First B

- For time-resolved analysis, the dilution due to mixing is
$$D = \sqrt{\frac{1}{2} + \frac{2x\sin 2xt_0 - \cos 2xt_0}{2(1+4x^2)}} = 0.59 \text{ for } x = \frac{1}{\sqrt{2}},\ t_0 = 0,$$
if the analysis begins only a time $t_0 > 0$.

- Then the efficiency is reduced by $\epsilon = e^{-t_0}$.

- For time-integrated analysis:
$$D = \frac{x\cos xt + \sin xt}{1+x^2} = 0.47 \text{ for } x = \frac{1}{\sqrt{2}},\ t_0 = 0.$$

- The statistical power of a time-resolved analysis, $D^2(t_0)\epsilon(t_0)$, is reduced even if $D(t_0) > D(0)$.



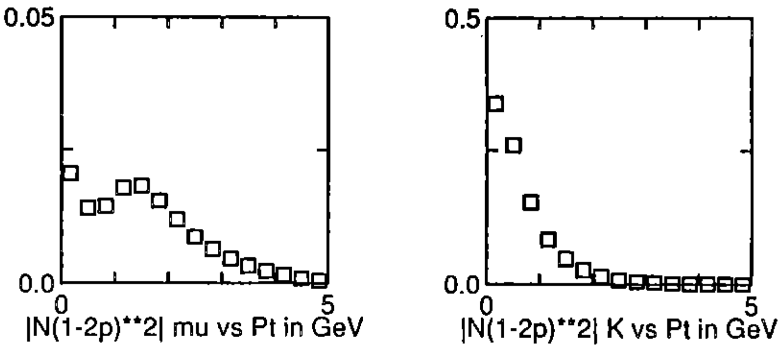
Tagging via Leptons and Kaons from the Other B

- The particle/antiparticle character of a neutral B can be tagged by the sign of the lepton or Kaon from the 2nd B.

- The statistical power of the tag is reduced by $(1-2P)^2$ where P = probability of wrong-sign tag.

- Wrong-sign leptons are copius for $P_t < 1.5$ GeV/c, so e or μ tag is never better than 3% (each).

- 65% of $\overset{*}{B}$'s decay to right-sign Kaons; 15% to wrong-sign
$\Rightarrow$ Kaon tag effective 35%, if can go to low P_t.



Tagging via Correlated Hadrons

- Ali and Barreiro (1986) noted that a B_s $(= \bar{b}s)$ is produced with a nearby $q\bar{s}$ $(= K^+)$, but usually not with a $\bar{q}s$ $(= K^-)$.
- Similarly, a B_d $(= \bar{b}d)$ is preferentially produced with a nearby π^+.
- Advantages:

  Kaon identification not needed to tag B_d;

  Acceptance for correlated hadron better than for 2nd B.
- Now being studied with 200 $B^\pm$ decays in CDF, but no clear signal yet...

Program to Study *CP* Violation

1. $B \rightarrow J/\psi X$ modes:
   - Good low-rate trigger on $J/\psi \rightarrow l^+ l^-$.
   - Branching fractions $\sim$ 3-6 $\times 10^{-5}$.
   - Study CP violation (ϕ_{td}) in $B_d \rightarrow J/\psi K_S^0$; expect no effect in $B_s \rightarrow J/\psi\phi$.
   - Study mixing in $B_{d,s} \rightarrow J/\psi K^{*0}$.
   - Tag second B with Kaons (and leptons).
2. Non-J/ψ modes:
   - Trigger not yet clear: try medium-P_t hadron or lepton, secondary vertex....
   - Need high-rate data acquisition.
   - Large backgrounds in $B_d \rightarrow \pi^+\pi^-$.
   - Low rates in $B_s \rightarrow \rho^0 K_S^0$, $D_s^\pm K^\mp, B_d \rightarrow DK^{*0}$, $a_1^\pm \pi^\mp$, $B^\pm \rightarrow DK^\pm$.

Need $\sim 10^4$ reconstructed, tagged decays per mode.

Need $\sim 10^{11}$ produced B's.

Will Even $B_d^0 \to J/\psi K_S^0$ Be Easy?

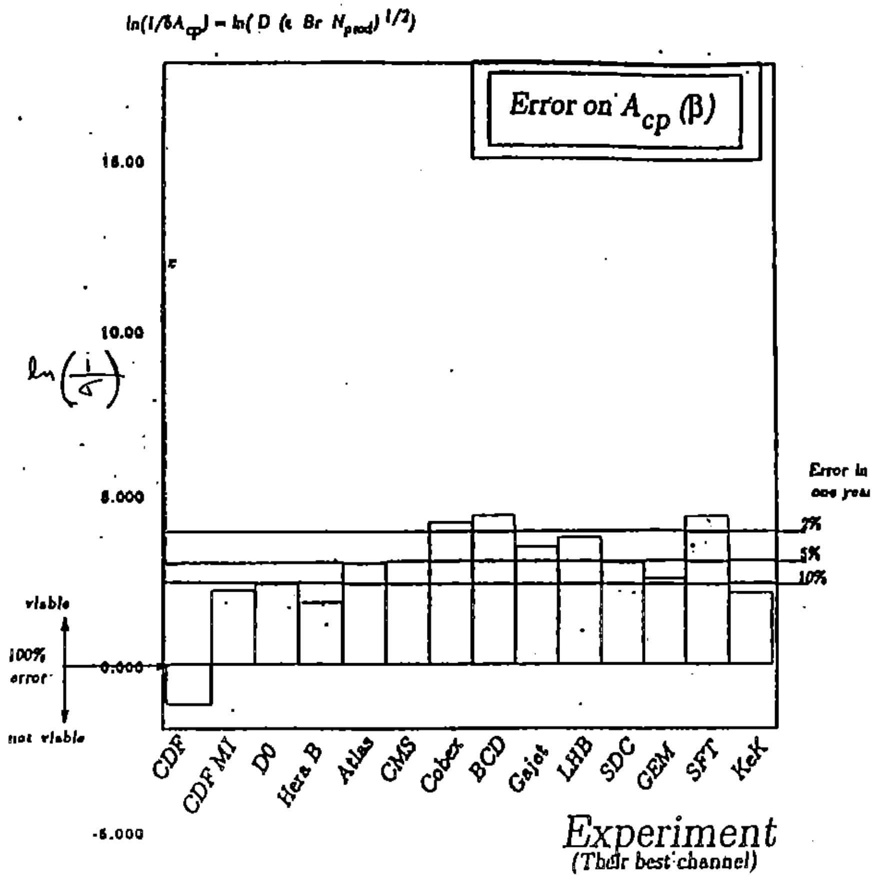
- In 1992-93 CDF reconstructed ~ 40 $B_d^0 \to J/\psi K_S^0$ decays.
- The efficiency of tagging the second B with e's and μ's is less than 2.5%.
- Need $\sim 10,000$ tagged, reconstructed $B_d^0 \to J/\psi K_S^0$.
- So if no changes, CDF would need $10,000/(40 \times 0.025) =$ 10,000 years!

How to find a factor of 10^4:

1. Claim only need 1,000 tagged, reconstructed decays.
2. Increase acceptance for $J/\psi K_S^0$ by 10.
3. Increase tagging efficiency by 10 (use Kaons).
4. Increase luminosity by 100.
5. Increase cross section by 10 (LHC or SSC).
6. Run for 10 years.

Comparing the Physics Reach of Detectors In Measuring CP Violating Angle β

W. Toki
Colorado State University, Fort Collins
J.F. Hassard
Imperial College, London



Comparison of B-$\overline{B}$ Production at Hadron Accelerators

We suppose that the experiments all operate at 10^7 interactions/sec, and that the corresponding luminosity $\mathcal{L}$ can be achieved.

We then consider $\sigma_{b\overline{b}}/\sigma_{\rm tot}$ as the figure of merit of the various accelerator options.

Accelerator	$\sqrt{s}$ (TeV)	$\sigma_{b\overline{b}}$ (μb)	$\sigma_{\rm tot}$ (mb)	$\sigma_{b\overline{b}}/\sigma_{\rm tot}$	$\mathcal{L}_{\rm ave}$ ($\rm cm^{-2}sec^{-1}$)	$N_{b\overline{b}}/10^7$ 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-$\overline{p}$)	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

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

- Good signal-to-noise: $\sigma_{b\overline{b}}/\sigma_{\rm total} \sim 1/30$.

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

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

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

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

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

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

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

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

The *p*-*p* Option at RHIC

(Mike Harrison, RHIC/AP/8, 8/13/93)

- Without major modification, RHIC could operate with 250-GeV proton beams.
- 3×10^{11} protons per bunch, head-on collisions.
- Geometric transverse emittance $(1\ \sigma) = 3 \times 10^{-8}$ m-rad.
- $\beta^* = 1$ m, so $\sigma_x = \sqrt{\epsilon\beta^*} = 170\ \mu$m.
- Vacuum pipe radius could be 1-2 cm (needs study).
- $\sigma_z = 15$ cm for luminous region.
- 114 bunches, 110 ns between crossings.
- Luminosity $\mathcal{L} = 5 \times 10^{32}$ cm^{-2}sec^{-1}.
- 2 interactions per crossing for $\sigma_{\text{inel}} \approx 40$ mb.
- This luminosity can only be delivered at two intersection regions!
- ±8 m free space at intersection region.

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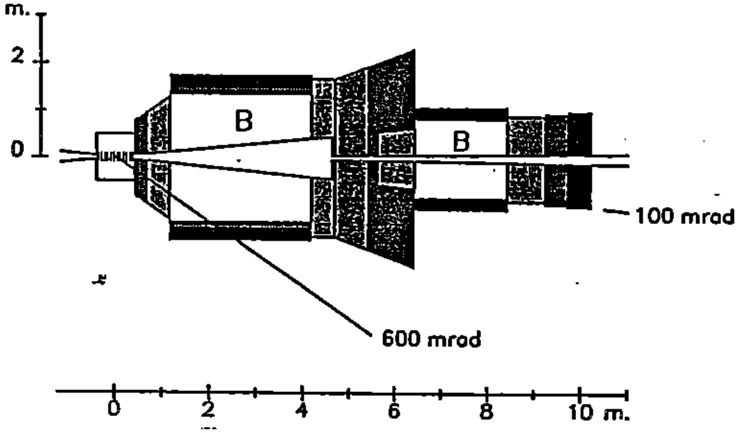
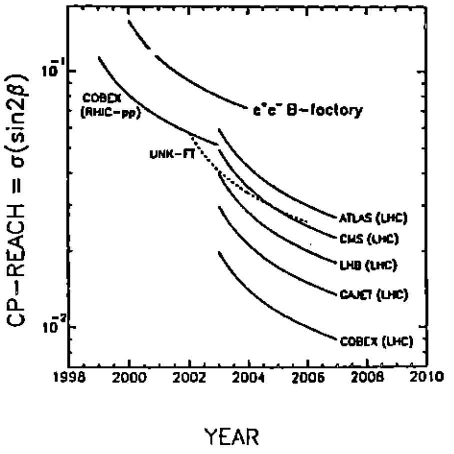
9 September, 1993

Proposal to Brookhaven National Lab.

COBEX,

A Collider B Experiment for RHIC





Pseudorapidity – A Logarithmic Angular Variable

Cosmic-ray data ⇒ $dN \propto d\theta/\theta$ in high-energy hadron interactions.

Castagnoli *et al.* [Nuovo Cim. **10** (1953) 1539] introduced the pseudorapidity:

$$\eta \equiv -\ln\tan\theta/2, \qquad d\eta = -\frac{d\theta}{\sin\theta} \approx -\frac{d\theta}{\theta}.$$

For low P_t, $$\eta \approx y = -\frac{1}{2}\ln\left(\frac{E-P_\parallel}{E+P_\parallel}\right) \equiv \text{rapidity}.$$

ISAJET simulation of B-decay products at the RHIC:

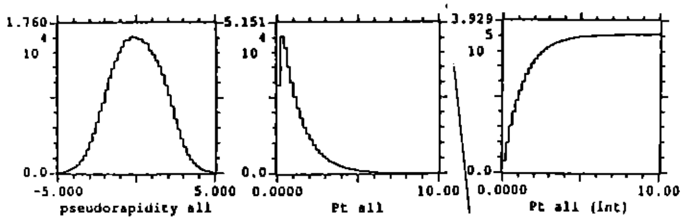


Figure 4: a) Distribution in pseudorapidity η, b) the P_t distribution , and c), the integral of the P_t distribution for B-decay products at RHIC, according to an ISAJET simulation that averages over the 12 decay modes in Table 5. 87% of all B-decay products have $P_t < 2.5$ GeV/c.

Acceptance for B Decays

Next two transparencies:

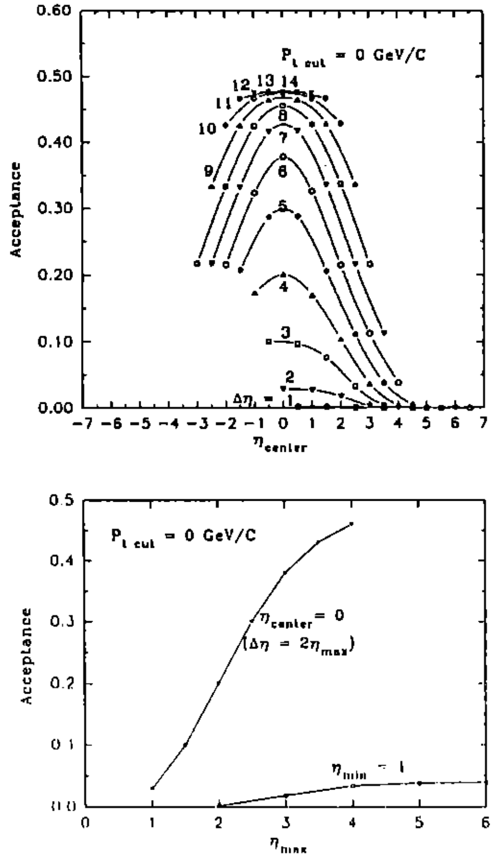
The acceptance of a detector at $\sqrt{s} = 0.5$ TeV and at 40 TeV for all four tracks from the decay chain

$$B_d^0 \to J/\psi K_S^0 \to \mu^+\mu^-\pi^+\pi^-$$

plus a charged Kaon from the decay of the second B
(for tagging particle/antiparticle character of the first B).

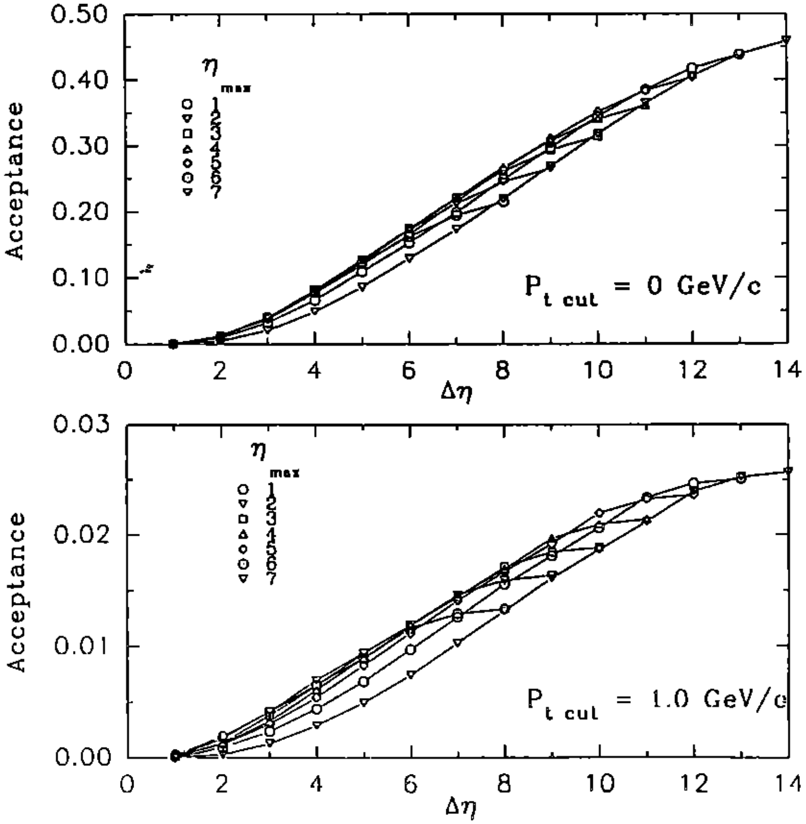
Acceptance for B Decays at RHIC

The detector extends from $\eta_{\min}$ to $\eta_{\max} = \eta_{\min} + \Delta\eta/2$.



Acceptance for B Decays at the SSC

The detector extends from $\eta_{\min}$ to $\eta_{\max} = \eta_{\min} + \Delta\eta/2$.



Central or Forward?

- At the SSC, it is debatable whether a central of a forward detector is more advantageous.
- At RHIC, production of B's is much more central, and a forward detector would have considerably less acceptance.
- Cost?

Cost $\propto$ No. of channels

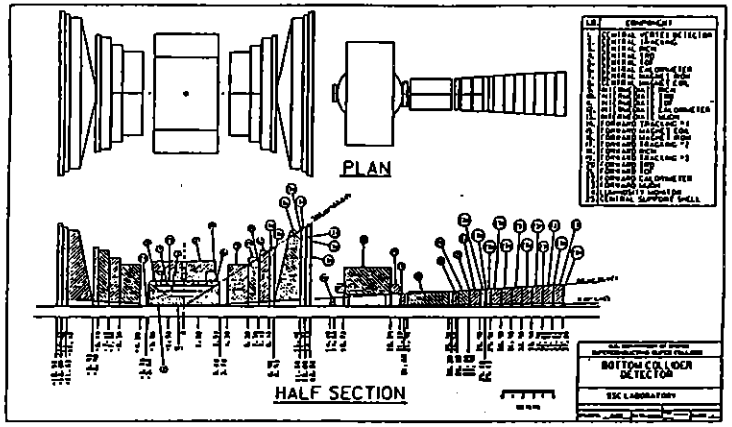
Acceptance $\propto$ No. of particles

Quality $\propto$ (No. of channels)/(No. of particles)

$\Rightarrow$ Cost $\propto$ Quality $\times$ Acceptance,
largely independent of whether forward or central.

Central Dipole

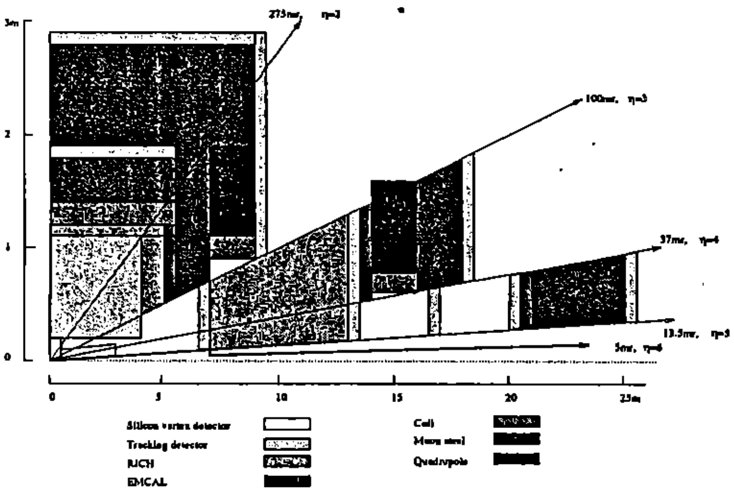
BCD (EOI0008):



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

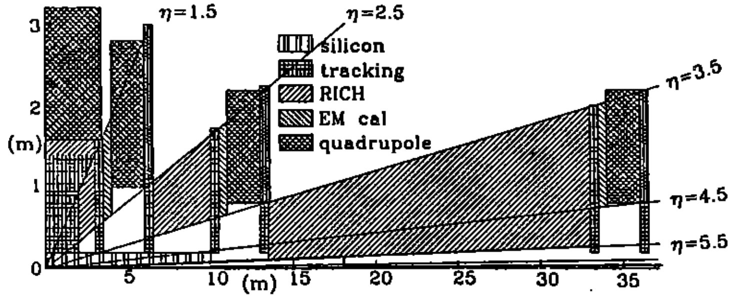
A central $2n$-pole magnet has regions of poor resolution given by $\sqrt{\cos^2 n\phi + \sin^2 n\phi \cos^2\theta} \lesssim 1/4$, covering about 1/2 unit of (η, ϕ) space.

Central Solenoid

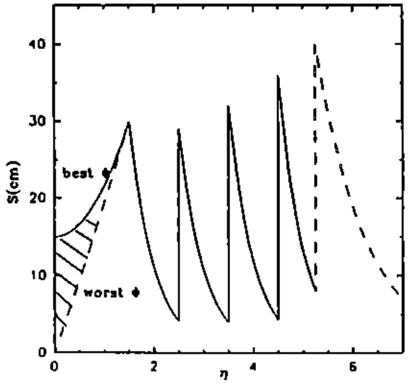


- Good momentum resolution only for $|\eta| \lesssim 2$.
- Best configuration for fast P_t trigger.
- Could cover $|\eta| > 3$ with forward dipoles or quadrupoles.

Central Quadrupole



- Good momentum resolution out to $|\eta| \lesssim 2.5$.

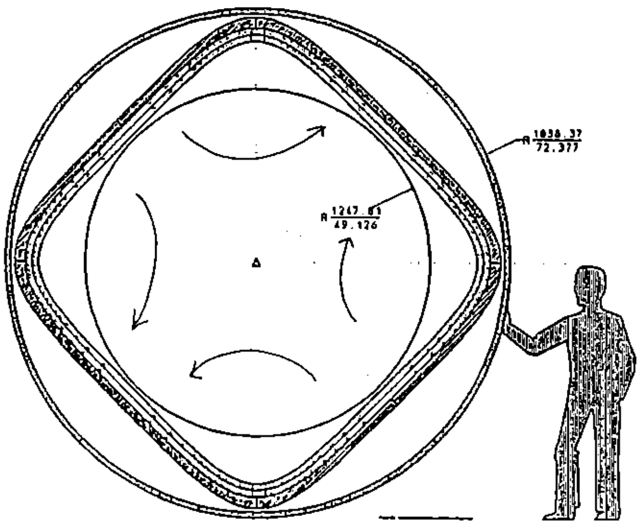


- Low field near beam ⇒ good for secondary-vertex trigger.
- Could cover $|\eta| > 2.5$ with forward dipoles or quadrupoles.

Bending-Free Quadrupoles

(D. Dell'Orco and C. Taylor, LBL, 7/15/93)

- A new concept for a thin superconducting quadrupole coil has been developed by the LBL Manget Group.
- The coil shape is chosen so that the magnetic forces are always perpendicular to the coil ⇒ no bending moment.
- The coil could be only 1-2 radiation lengths thick.



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 to isolate B's from primary vertex.
- Good momentum measurement:

  $\Rightarrow \sigma_M \underset{\sim}{\approx} 25$ MeV/c^2 for B's.
- Particle ID of π, K, e and μ.
- Large detector-channel count to survive high-multiplicity hadron interactions.
- High-rate trigger and data acquisition for any mode but $B \to J/\psi X$.
- Hadron calorimetry not needed.
- Upgrade path from modest initial configuration.

Sketch of a RHIC B Experiment

- Run at highest luminosity ($> 5 \times 10^{32}$) to compensate for lower cross section.
- Emphasize $B \rightarrow J/\psi X$ modes to simplify triggering.
- Use central detector to maximize acceptance.
- Use solenoid magnet if cautious; quadrupole if bold.
- Cover $|\eta| \gtrsim 1.5$.
- Identify e, μ, K.
- Trigger on non-J/ψ modes as funding permits.

One month of this experiment at RHIC would equal about 4 months of a B experiment at FNAL with $\mathcal{L} = 5 \times 10^{31}$.

B Factory at RHIC?[1]

N. S. Lockyer, R. Van Berg, F. M. Newcomer
University of Pennsylvania
K. Foley, W. Morse, F. Paige, V. Polychronakos,
S. Protopopescu, P. Rehak
Brookhaven National Laboratory
R. Sidwell
Ohio State University
E. Mannelli, M. Mannelli
Yale University

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Abstract

A dedicated B physics experiment located in the proposed Relativistic Heavy Ion Collider at Brookhaven (RHIC) is considered. The machine may operate in a p-p mode with a luminosity in excess of $10^{32} cm^{-2} sec^{-1}$ at 250 x 250 GeV. The estimated $B\bar{B}$ cross section at these energies is about 10 μbarns and a run of 10^7sec would produce roughly 10^{10} $B\bar{B}$ pairs. A comparison to similar ideas proposed for the Fermilab Tevatron Upgrade and the SSC are discussed. The most ambitious physics objective of such an experiment would be the study of CP nonconservation. Particular emphasis at this workshop was given to the self tagging mode $B \rightarrow K^+\pi^-$. Experimental techniques developed during this experiment would be extremely useful for more ambitious projects anticipated at the SSC.

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[1] B Physics Working Group Summary presented by N. S. Lockyer at the RHIC Workshop held at BNL July (1988)

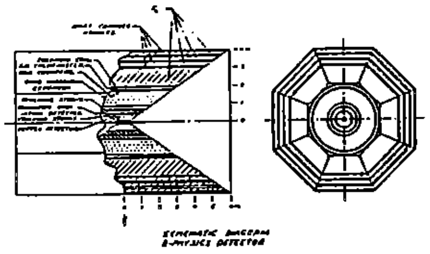

Figure 6: Schematic representation of a B Physics detector showing the various types of devices needed and their likely dimensions.