Rare and charmless decays at CDFII
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Michael J. Morello
(morello@fnal.gov)
Istituto Nazionale di Fisica Nucleare
Pisa

for the CDFII collaboration
This focus on rare and charmless B decays. Analysis of such modes provides CDF with a physics program competitive with ($B^0$ modes), and complementary ($B^0_s$ modes) to B-factories. Well suited to illustrate the methods used in flavor physics analyses at CDF.

- CDF at the Tevatron: HF physics at hadron colliders;
- triggering on displaced tracks;
- search for FCNC $B^0_{(s)} \rightarrow \mu^+\mu^-$ decays;
- BRs and DCPV in $B^0_{(s)} \rightarrow \pi\pi/K\pi/KK$ (PP) decays;
- $\Delta\Gamma_s/\Gamma_s$ in $B^0_s \rightarrow K^+K^-$ decays;
- BR in $B^0_s \rightarrow \phi\phi$ (VV);
- Recent measurement of $B_c$ mass and lifetime.
The Tevatron $p\bar{p}$ collider

36 (proton) × 36 (antiproton) bunches X-ing time 396 ns at $\sqrt{s} = 1.96$ TeV
record peak is $L=1.82 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
~ 18 pb$^{-1}$/week recorded on tape
# of interactions per bunch-crossing:
$< N >$poisson = 2 (at $10^{32}$ cm$^{-2}$s$^{-1}$)

Regularly exceeding $10^{32}$ cm$^{-2}$ s$^{-1}$ since ‘05

$L_{\text{int}} \sim 1400$ pb$^{-1}$ on tape
($\sim 1000$ pb$^{-1}$ for analysis)

Stable data taking efficiency: > 85%.
Results here use ~180-800 pb$^{-1}$
The CDF II detector

7 to 8 silicon layers
1.6 < r < 28 cm, |z|<45 cm
|\eta| \leq 2.0 \ \sigma(\text{hit}) \sim 15\ \mu m

96 layer drift chamber
|\eta| \leq 1.0
44 < r < 132 cm, |z|<155 cm
30k channels, \ \sigma(\text{hit}) \sim 140\ \mu m
dE/dx for p, K, \pi \text{ identification}

1.4 T magnetic field
Lever arm 132 cm

132 ns front end chamber tracks at L1
silicon tracks at L2
25000 / 300 / 100 Hz
with dead time < 5%

time-of-flight
110 ps at 150 cm
p, K, \pi \text{ identific.}
2\sigma \text{ at } p_T<1.6 \text{ GeV}

Some resolutions:
\ p_T \sim 0.15\% \ p_T \ c/\text{GeV}
J/\Psi \text{ mass } \sim 14 \text{ MeV}
EM E \sim 16\%/\sqrt{E}
Had E \sim 80\%/\sqrt{E}
d_0 \sim 40\ \mu m
(includes beam spot)

\mu \text{ coverage}
|\eta| \leq 1.5
84\% \text{ in } \phi

scintillator and tile/fiber
sampling calorimetry
|\eta| < 3.64
Heavy Flavor physics at the Tevatron

The Good

$bb$ production x-section $O(10^5)$ larger than $e^+e^-$ at $\gamma(4S)/Z^0$. Incoherent strong production of all $b$-hadrons: $B^+$, $B^0$, $B^0_s$, $B_c$, $\Lambda_b$, $\Xi_b$ …

The Bad

Total inelastic x-section $\times 10^3$ larger than $\sigma(bb)$. BRs’ for interesting processes $O(10^{-6})$.

…and The Ugly

Messy environments with large combinatorics.

Need highly selective trigger
B hadron signature

“Long” (~1.5 ps) lifetime of $b$-hadrons: a powerful signature against light-quark background.

Traditional $B$-trigger at hadronic collider: look for one ($B \rightarrow l\nu X$) or two leptons ($B \rightarrow J/\psi X$) exploiting easy signature and ~20% of total width.

For the first time, trigger HF without leptons: rare hadronic $B$ decays. Cut online (L2 trigger) on impact parameter $d_0$(track).

Very high-purity samples of hadronic $B$ (and $D$) decays. Price to pay: trigger-bias distorts proper-time distributions. Complexity in lifetime-based analyses.

$\sigma(d_0) = 48 \mu m = 35 [SVT] \oplus 33$ [beam-spot size]
Charmless

$B^0/B^0_s \rightarrow PP (\pi\pi/K\pi/KK)$

- Interpretation of B results often plagued by uncertainties from non-perturbative QCD uncertainties.
- Joint study of $B^0$ and $B^0_s$ decays into 2-body charm-less ($\pi\pi/K\pi/KK$) plays a key role, related by subgroup of SU(3) symmetry.
- Until the beginning of the planned Y(5S) at Belle only CDF has simultaneous access to both $B^0/B^0_s \rightarrow h^+h^-$ decays thus exploiting an original physics program complementary to the B-Factories.
Some specific motivations

- These modes include $B^0 \rightarrow K^+\pi^-$, where the direct CP asymmetry was observed for the first time in B sector (B-Factories).
- Large (~10%) effect established, but still many things to understand, i.e. asymmetry in $B^0$ not compatible with $B^+$ as expected. [Gronau and Rosner, Phys. Rev. D71:074019, 2005]
- Additional experimental input is helpful: copious yields at TeVatron make CDF a major player in the direct-CPV game.
- Compare rates and asymmetries of $B^0 \rightarrow K^+\pi^-$ and $B^0_s \rightarrow K^0\pi^+$ unique to CDF – to probe NP with no need for assumption, just SM. [Lipkin, Phys. Lett. B621:126, 2005]
- Currently accessible BR can constrain theory too: compare CDF measurements with allowed regions in spaces of $B^0 \rightarrow \pi^+\pi^-$ and $B^0_s \rightarrow K^+K^-$ observables: a probe for both $\gamma$ and NP [Fleischer and Matias PRD66: 054009, 2002 - London and Matias PRD70:031502, 2004]
- From lifetime of $B^0_s \rightarrow K^+K^-$ (unique to CDF), information on the relative width-difference $\Delta \Gamma_s/\Gamma_s$. Compare with $B^0_s$ mixing results to search for new, CP-violating physics. Can be strong affected by new, CP-violating physics.
Trigger confirmation

TRIGGER REQUIREMENTS

- Two oppositely-charged tracks (i.e. \( B \) candidate) from a **long-lived decay**:
  - track’s impact parameter >100 \( \mu \)m;
  - \( B \) transverse decay length > 200 \( \mu \)m;
- \( B \) candidate **pointing back to primary vertex**:
  - impact parameter of the \( B \) < 140 \( \mu \)m;
- **Reject light-quark background** from jets:
  - transverse opening angle \([20^\circ, 135^\circ]\);
  - \( p_T^1 \) and \( p_T^2 \) > 2 GeV;
  - \( p_T^1+p_T^2 \) > 5.5 GeV.

Signal (BR \( \sim 10^{-5} \)) visible with just offline trigger cuts confirmation:

a bump of \( \sim 3850 \) events with \( S/B \approx 0.2 \) (at peak) in \( \pi\pi \)-invariant mass
B^0/B^{0}_s \rightarrow PP DATA SAMPLE

Optimize cuts (IP, transverse decay length, 3D-vertex quality, isolation of B candidate and IP of both tracks) by minimizing the expected statistical resolution on A_{CP}. Its expression in terms of S and B is determined from actual resolutions observed in analysis of toy-MC samples.

Despite excellent mass resolution, modes overlap an unresolved peak, and PID resolution is insufficient for event-by-event separation. Hence, fit signal composition with a Likelihood that combines information from kinematics (M_{\pi\pi}, \alpha=(1-p_1/p_2)q_1 where p_1<p_2, p_{tot}=p_1+p_2) and particle ID (dE/dx).

Signal yield: ~2300 events
S/B \approx 6.5 (peak value)
Fit of composition

Un-binned ML fit that uses kinematic and PID information from 5 observables

$$\mathcal{L}(\vec{\theta}) = \prod_{i=1}^{N} \mathcal{L}_i(\vec{\theta})$$

$$\mathcal{L}_i(\vec{\theta}) = (1 - b) \sum f_j \mathcal{L}_j^{\text{sign}} + b \mathcal{L}_j^{\text{bckg}}$$

$$\mathcal{L} \sim \varphi^m(m_{\pi \pi} | \alpha) \times \varphi^p(\alpha, p_{\text{tot}}) \times \varphi^{\text{PID}}(dE/dx_1, dE/dx_2 | \alpha, p_{\text{tot}})$$

Signal shapes: from MC and analytic formula
Background shapes: from data sidebands

fraction of jth mode, to be determined by the fit

mass term
momentum term
PID term
Direct CP asymmetry $B^0 \rightarrow K^+ \pi^-$ (360 pb$^{-1}$)

**Uncorrected fractions**

<table>
<thead>
<tr>
<th>Decay</th>
<th>Fraction</th>
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<tbody>
<tr>
<td>$B_s^0 \rightarrow K^+ K^-$</td>
<td>22%</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow K^+ \pi^+$</td>
<td>3%</td>
</tr>
<tr>
<td>$B^0 \rightarrow \pi^+ \pi^-$</td>
<td>13%</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^+ \pi^-$</td>
<td>62%</td>
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<table>
<thead>
<tr>
<th>Decay</th>
<th>Number</th>
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<tr>
<td>$B^0 \rightarrow K^+ \pi^-$</td>
<td>787 ± 42</td>
</tr>
<tr>
<td>$\bar{B^0} \rightarrow K^- \pi^+$</td>
<td>689 ± 41</td>
</tr>
</tbody>
</table>

$$A_{\text{CP}}^{\text{CDF}}(B^0 \rightarrow K^+ \pi^-) = -0.058 \pm 0.039 \ (\text{stat.}) \pm 0.007 \ (\text{syst.})$$

$$A_{\text{CP}}^{\text{Babar}}(B^0 \rightarrow K^+ \pi^-) = -0.133 \pm 0.030 \ (\text{stat.}) \pm 0.009 \ (\text{syst.})$$

$$A_{\text{CP}}^{\text{Belle}}(B^0 \rightarrow K^+ \pi^-) = -0.113 \pm 0.022 \ (\text{stat.}) \pm 0.008 \ (\text{syst.})$$

Result is $\sim 1.5\sigma$ different from 0, and compatible with $B$-factories results. With data already available on disk (1fb$^{-1}$), we expect $\sim 2.5\%$ statistical uncertainty: CDF will be soon (summer) very competitive.

In same data, is likely first observation of $B_s^0 \rightarrow K^- \pi^+$ self-tagged decay: will measure its BR and CP asymmetry that is expected large. [Lipkin, Phys.Lett.B621:126, 2005].
Systematics $A_{\text{CP}}(B^0 \rightarrow K^+\pi^-)$ (360 pb$^{-1}$)

Total systematic uncertainty is 0.7%, much smaller than the 3.9% statistical uncertainty.

- $dE/dx$ model (partially reduces with statistics);
- Nominal $B$-meson masses input to the fit (reduces with statistics);
- Mass-resolution model;
- Global scale of masses;
- Charge-asymmetries in background;
- Combinatorial background model.
BRs: $B^0/B^0_s \rightarrow PP \ (180 \ pb^{-1})$

\[
\frac{f_s \cdot BR(B^0_s \rightarrow K^+K^-)}{f_d \cdot BR(B^0 \rightarrow K^+\pi^-)} = 0.46 \pm 0.08 \ (\text{stat.}) \pm 0.07 \ (\text{syst.})
\]

$B^0_s \rightarrow K^+K^-$ decay established. BR ratio may favor large SU(3) breaking as predicted from sum rules [Khodjamirian et al. PRD68:114007, 2003].

\[
\frac{f_s \cdot BR(B^0_s \rightarrow K^-\pi^+)}{f_d \cdot BR(B^0 \rightarrow K^+\pi^-)} < 0.08 \ @ \ 90\% \ C.L.
\]

No evidence for $B^0_s \rightarrow K^-\pi^+$, set a limit a factor $\sim 40$ better than PDG04.

\[
\frac{BR(B^0_s \rightarrow \pi^+\pi^-)}{BR(B^0_s \rightarrow K^+K^-)} < 0.05 \ @ \ 90\% \ C.L
\]

\[
\frac{BR(B^0 \rightarrow K^+K^-)}{BR(B^0 \rightarrow K^+\pi^-)} < 0.10 \ @ \ 90\% \ C.L.
\]

Upper limit on annihilation mode $B^0_s \rightarrow \pi^-\pi^+$ and $B^0 \rightarrow K^+K^-$ Great improvement on $B^0_s \rightarrow \pi^-\pi^+$: a factor $>100$ below PDG04 (time-evolutions of $B^0_s \rightarrow \pi^-\pi^+$ and $B^0_s \rightarrow K^-K^+$ assumed the same).
$B^0_s \rightarrow K^+K^-$ lifetime (360 pb$^{-1}$)

Add lifetime information to the fit of composition:

$$L \sim \phi^m(m_{\pi\pi}|\alpha)\phi^p(\alpha, p_{\text{tot}})\phi^\text{PID}(dE/dx_1, dE/dx_2|\alpha, p_{\text{tot}})\phi^\text{life}(ct).$$

$$\phi^\text{life}(ct) = \exp(ct) \times \text{Gauss}(ct) \times \varepsilon(ct)$$

decay detector smearing trigger bias

Trigger bias for signal is extracted from detailed simulation.

Procedure validated in unbiased $B \rightarrow J/\psi X$ decays from dimuon trigger.

Check that lifetime fits of samples with/without applying track-trigger cuts yield consistent results.

Lifetime p.d.f for background is extracted from higher mass data sideband.
$B^0_s \rightarrow K^+K^-$ lifetime results (360 pb$^{-1}$)

<table>
<thead>
<tr>
<th></th>
<th>$ct(B^0)$ [μm]</th>
<th>$ct(B^0 \rightarrow K^+K^-)$ [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>both free</td>
<td>452 ± 24</td>
<td>463 ± 56</td>
</tr>
<tr>
<td>$ct(B^0)$ constrained to PDG</td>
<td>–</td>
<td>458 ± 53</td>
</tr>
</tbody>
</table>

$B^0_s \rightarrow K^+K^-$ predicted ~95% CP-even: has the lifetime of “light $B^0_s$”:

$$\tau_L = 1.53 \pm 0.18 \text{ (stat.)} \pm 0.02 \text{ (syst.)} \text{ps}$$

Combine with HFAG average $(\tau_L^2 + \tau_H^2)/(\tau_L + \tau_H)$:

$$\frac{\Delta\Gamma^\text{CP}}{\Gamma^\text{CP}} = -0.08 \pm 0.23 \text{ (stat.)} \pm 0.03 \text{ (syst.)}$$

Dominant systematics:
- detector alignment;
- dE/dx model;
- input $p_T(B)$ in simulation;
- trigger-bias;
- lifetime model of background;

$\Delta \Gamma_s/\Gamma_s$ compatible with direct measurement from $B^0_s \rightarrow J/\psi\phi$ [PRL 94:101803(2005)]
Behind the corner: $\Lambda^0_b \to p\pi/pK$ (190 pb$^{-1}$)

- In the same data of charmless $B^0_{(s)} \to PP$ decays to look for evidence of charmless $\Lambda_b \to pK/p\pi$ decays.
- Theoretical expectations for BRs:
  \[
  \text{BR}(\Lambda_b \to p\pi) = [0.9 - 1.2] \cdot 10^{-6} \\
  \text{BR}(\Lambda_b \to pK) = [1.4 - 1.9] \cdot 10^{-6}
  \]
- Large direct CP asymmetries expected.
- Analysis on 190 pb$^{-1}$ without PID.
- Normalize to BR($B^0 \to K\pi$).

Our current limit on 190 pb$^{-1}$ is already the world best
\[
\text{BR}(\Lambda_b \to pK) + \text{BR}(\Lambda_b \to p\pi) < 2.3 \cdot 10^{-5} @ 90\% \text{ C.L}
\]

[Phys. Rev. D72, 051104 (2005)]

Assuming theoretical values for BRs, expect in 1 fb$^{-1}$ $\sigma(\text{BRs})_{\text{TOY}} \approx [0.3-0.2] \cdot 10^{-6}$, data already under analysis using the complete framework for $B^0_{(s)} \to PP$. Likely observation and measurement of BRs and “direct CPV”.
Charmless

$B^0/B^0_s \rightarrow VV$
Motivations

- CDF can access to $B^0_s \to VV$ decays into self-conjugate final states, like $B^0_s \to \phi\phi$.
- Angular correlations (polarization) between the final state particles allow the statistical separation of the CP-even and CP-odd components of the decay amplitude.
- With sufficient statistics, this decomposition allows of the $B^0_s$ decay width difference $\Delta\Gamma_s$, CKM studies and the tests of decay polarization.
- The BR measurement gives insight into the size of penguin amplitude.
- $B^0_s \to \phi\phi$ proceeds through a pure $b \to sss$ transition $\Rightarrow$ probe for NP [hep-ph/0510245].
- Hints of NP in $B^0 \to \phi K^0_s$, $B^0 \to \eta' K^0_s$ from B-factories suggest to investigate in other pure $b \to sss$ transitions like $B^0_s \to \phi\phi$ and $B^+ \to \phi K^+$. 
Bs → φφ (VV)

Normalize to another Bs → VV: Bs → J/ψφ

Using the same hadronic trigger

On the first 180 pb⁻¹ data CDF established the Bs → φφ decay and measure its BR:

\[
\text{BR}(B^0_s \rightarrow \phi \phi) = (14^{+6}_{-5} \text{ (stat.)} \pm 6 \text{ (syst.)}) \times 10^{-6}
\]

Soon update with the completely angular analysis using the full data sample (1fb⁻¹)!!!!
Search for FCNC current

$$B^0/B^0_s \rightarrow \mu^+ \mu^-$$
Motivation: $B^0/B^0_s \rightarrow \mu^+\mu^-$

In the SM, FCNC decays are highly suppressed. Expectations:

$\text{BR}(B^0_s \rightarrow \mu\mu) \propto |V_{ts}|^2 \equiv (3.42 \pm 0.54) \cdot 10^{-9}$

$\text{BR}(B^0 \rightarrow \mu\mu) \propto |V_{td}/V_{ts}|^2 \equiv (1.00 \pm 0.14) \cdot 10^{-10}$


The BRs predicted from SM are about two orders of magnitude smaller than the current experimental sensitivity. However NP (SUSY) can significantly enhance (up to x100) these BRs $\implies$ simultaneous observation of $B^0/B^0_s \rightarrow \mu^+\mu^-$ is important in determining structure of NP otherwise significant constraints to many SUSY models.
Analysis strategy: $B^0/B^0_s \rightarrow \mu^+\mu^-$

Search the sample from rare di-muon trigger (tracking + $\mu$-system):
- **CMU**(drift chambers)
  $|\eta|<0.6$ muons with $p_T>1.4$ GeV
- **CMX**(drift tubes)
  $0.6<|\eta|<1$ muons with $p_T>2$ GeV

Offline reconstruction:
- Confirmation trigger requirements
- Discriminate using multivariate LR (decay length, 3D-pointing of the B to PV, isolation)

Significant backgrounds from:
(a) Sequential semileptonic: $b \rightarrow c\mu^-\nu$, $c \rightarrow s\mu^+\bar{\nu}$
(b) Double semileptonic decays: $b \rightarrow c\mu^-\nu$, $b \rightarrow \bar{c}\mu^+\bar{\nu}$
(c) Drell-Yan $pp \rightarrow \mu^+\mu^-$
(d) Fake leptons
Upper limit (780 pb\(^{-1}\)): \(B^0/B^0_s \rightarrow \mu^+\mu^-\)

CDF (not D0) has good mass resolution (~24 MeV) allows separation of \(B^0_s \rightarrow \mu^+\mu^-\) and \(B^0 \rightarrow \mu^+\mu^-\):

Measure of BR (or set limit) with respect to normalization decay \(B^+ \rightarrow J/\psi K^+\).

Number of events observed in either mass window compatible with background, set upper limit for both decays (world best):

NEW 780 pb\(^{-1}\)

\[
\text{BR}(B^0_s \rightarrow \mu^+\mu^-) < 8 \times 10^{-8} \text{ @ 90\% CL}
\]

\[
\text{BR}(B^0 \rightarrow \mu^+\mu^-) < 2.3 \times 10^{-8} \text{ @ 90\% CL}
\]

Previous results:
PRL 95, 221805(2005)
PRL 93, 032001(2004)
Future prospects for $B^0_s \rightarrow \mu^+ \mu^-$

- Assuming unchanged analysis techniques and reconstruction and trigger efficiencies are unaffected with increasing luminosity
- for 8 fb$^{-1}$/experiment an exclusion at 90% C.L. down to $2 \times 10^{-8}$ is possible
- both experiments (CDF + D0) pursue further improvements in their analysis.
$B_c$ properties
Motivations

• Bound state of two heavy quarks (bc).
• Good lab for potential models, lattice QCD (only meson with different heavy flavors).
• Experimental challenge
  – $B^0:B^+:B^0_s:\Lambda^0_b\approx40:40:10:10$, $B^-_c\approx0.5\%$
  – Short lifetime $\implies$ difficult selection
• First observation by CDF (1998) in semi-leptonic decays
  – properties not well measured.
• Today in Run II
  – higher statistics
  – more precise lifetime
  – access to exclusive modes $\implies$ mass measurement.
$B_c$ observation and mass (800 pb$^{-1}$)

$B_c$ is not produced at B factories
Full reconstruction allows for precise mass measurement.

Signal yield ≈ 38.9 events
Background yield ≈ 26.1
between 6.24 and 6.3 GeV/c$^2$
Significance > 6$\sigma$ over search area

Lattice calculations [PRL 94:1720001]
show moderately good agreement with the CDF measurement:
$$m_{B_c} = 6304 \pm 4 \pm 11^{+18}_{-10} \text{ MeV}$$

Mass($B_c^-)$ = 6275.2 ± 4.3 ± 2.3 MeV/c$^2$
World best
$B^-_c$ lifetime (360 pb$^{-1}$)

$B_c$ lifetime extracted from semi-leptonic decay modes $\implies$ more statistics than hadronic mode but also more background too

![Diagram of $B_c$ decay process]

Theoretical prediction [V. Kiselev hep/ph 0308214]:

$\tau(B_c) \cong 0.55 \pm 0.15$ ps.
Conclusions

As data keep flowing, CDF impact on FP becomes more and more crucial: Charm-less two-body B decays, a case-study to show how CDF is competitive with (B^0) and complementary to (B^0_s) B-factories.

- direct CPV in B^0 \rightarrow K^+\pi^-, small systematics, and as yet available statistics places CDF among the best by this summer;
- unique opportunity to combine A_{CP}(B^0 \rightarrow K^+\pi^-) with A_{CP}(B^0_s \rightarrow K^-\pi^+);
- precise and unique measurement of BR(B^0_s \rightarrow K^+K^-): SU(3) breaking issue and \gamma angle useful information;
- B^0_s \rightarrow K^+K^-: the statistics(1fb-1) may be sufficient to look at measurement time-dependent A_{CP}(t) (from mixing analysis: \epsilon D^2 \approx 5\% and \Delta m_s);
- world best upper-limit on annihilation mode B^0_s \rightarrow \pi^+\pi^-;
- world best upper-limit on mode \Lambda_b \rightarrow pK/\rho\pi and big probability to observe this decay in the next step of the analysis.
- unique extraction of \Delta \Gamma_s/\Gamma_s in B^0_s \rightarrow K^+K^- (already one of world best results);
- first establishment of B^0_s \rightarrow \phi\phi (VV) and measurement its BR with the possibility to perform very soon a full angular analysis;
- Unique simultaneous sensitivity to B^0 /B^0_s \rightarrow \mu^+\mu^- (already world best results);
- study of B_c properties in a fully reconstructed and semi-leptonic mode.
backup
Luminosity

~ 1400 pb\(^{-1}\) on tape (~ 1000 with silicon)

Stable data taking efficiency: > 85%. Results here use ~180-800 pb\(^{-1}\)

- Apr 2001
- Feb 2002
- Jul 2002

1 fb\(^{-1}\) milestone!

first data for analyses

data for physics

detector commiss.
Heavy flavor signature

“Long” (~1.5 ps) lifetime of $b$-hadrons: a powerful signature against light-quark background. Before decaying, sufficiently boosted $b$-hadrons fly a distance resolvable with vertex detectors.

In Run I, CDF exploited this in offline analyses. In Run II, we exploit it at trigger level. An experimental challenge that requires:

1. **High resolution** vertex detector (silicon)
2. Read out silicon $r$-$\varphi$ side (212,000 channels); within 25 $\mu$s,
3. Do pattern recognition and track fitting in silicon.
Displaced track trigger: pros and cons

Very high-purity samples of hadronic $B$ (and $D$) decays.

“golden” modes for $B^0_s$ mixing

price to pay: trigger-bias distorts proper-time distributions. Introduce complexity in lifetime-based analyses, ....more later...
**Triggering heavy flavors**

Traditional $B$-trigger at hadronic collider: look for one ($B \to l\nu X$) or two leptons ($B \to J/\psi X$) exploiting easy signature and $\sim 20\%$ of total width.

For the first time, trigger HF without leptons: rare hadronic $B$ decays.

<table>
<thead>
<tr>
<th>conventional</th>
<th>partially new approach</th>
<th>new approach</th>
</tr>
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<tbody>
<tr>
<td><strong>di-muon</strong></td>
<td><strong>electron or $\mu$ and displaced track</strong></td>
<td><strong>two displaced tracks</strong></td>
</tr>
<tr>
<td>$B \to \text{charmonium}$</td>
<td>$B \to \ell\nu X$</td>
<td>$B \to hh$</td>
</tr>
<tr>
<td>$B \to \mu\mu$</td>
<td>electron (or $\mu$) with:</td>
<td>two tracks with:</td>
</tr>
<tr>
<td>two muons with:</td>
<td>$p_T &gt; 4$ (or 1.5) GeV</td>
<td>$p_T &gt; 2.0$ GeV</td>
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<tr>
<td>$p_T &gt; 1.5$ GeV</td>
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<td>$</td>
<td>\eta</td>
<td>&lt; 1$</td>
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</table>
Motivation: $B^0/B^0_s \rightarrow \mu^+\mu^-$

**Standard Model**

In the SM, FCNC decays are highly suppressed. Expectations:

- $\text{BR}(B^0_s \rightarrow \mu \mu) \propto |V_{ts}|^2 \approx (3.42 \pm 0.54) \cdot 10^{-9}$
- $\text{BR}(B^0 \rightarrow \mu \mu) \propto |V_{td}/V_{ts}|^2 \approx (1.00 \pm 0.14) \cdot 10^{-10}$

[Books and Papers]

**SUSY (MSSM)**

However NP can significantly enhance these BRs: $\text{BR}(B^0_s \rightarrow \mu \mu) \propto (\tan \beta)^6$ where $\beta$ is the ratio of vacuum expectation values of the neutral CP-even Higgs fields. Large $\tan \beta$ enhance the decay rate (up to $\times 100$) to a level observable by the TeVatron.
Cuts optimization

Optimize cuts by minimizing the expected statistical resolution on $A_{CP}$. Its expression in terms of $S$ and $B$ is determined from actual resolutions observed in analysis of toy-MC samples.

Gain $\sim 10\%$ improvement in the resolution versus standard $S/\sqrt{(S+B)}$.

Unbiased cut optimization where: for any combination cuts, evaluate the above score function; optimal cuts are found when the functions reach the maximum.

Signal yield $S$ is derived from MC simulation.

Background $B$ is estimated from mass sidebands on data.
Despite excellent mass resolution, modes overlap an unresolved peak, and PID resolution is insufficient for event-by-event separation. Hence, fit signal composition with a Likelihood that combines information from kinematics (masses and momenta) and particle ID (dE/dx).

Optimize cuts by minimizing the expected statistical resolution on $A_{CP}$. Its expression in terms of $S$ and $B$ is determined from actual resolutions observed in analysis of toy-MC samples.

Crucial isolation: fraction of $p_T$ carried by the $B$ after fragmentation. Rejects 18% of sig. and $\sim4x$ of background.

$\eta - \phi$ space

Signal yield: $\sim2300$ events

$S/B \approx 6.5$ (peak value)
Peak composition handle 1: Kinematic

Invariant $\pi\pi$-mass vs signed momentum imbalance: $(1-p_{\text{min}}/p_{\text{max}})q_{\text{min}}$

Discriminates among modes (and among self-tagging modes $K^+\pi^- / K^-\pi^+$)
Peak composition handle 2: dE/dx

~95% pure K and π samples from ~700K decays:

\[ D^{*+} \rightarrow D^{0} \pi^{+} \rightarrow [K^{-}\pi^{+}] \pi^{+} \]

Strong D*+ decay tags the D0 flavor. dE/dx accurately calibrated over tracking volume and time.

1.4σ K/π separation at p>2GeV (60% of “perfect” separation)
~11% residual correlation form gain/baseline fluctuations included int the fit of composition
Uncorrected fit results

<table>
<thead>
<tr>
<th>mode</th>
<th>fraction [%]</th>
<th>yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow \pi^+\pi^- + \bar{B}^0 \rightarrow \pi^+\pi^-$</td>
<td>13.2 ± 1.4</td>
<td>313 ± 34</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow K^-\pi^+ + \bar{B}_s^0 \rightarrow K^+\pi^-$</td>
<td>2.7 ± 1.3</td>
<td>64 ± 30</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow K^+K^- + \bar{B}_s^0 \rightarrow K^+K^-$</td>
<td>22.0 ± 1.6</td>
<td>523 ± 41</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^+\pi^- + \bar{B}^0 \rightarrow K^-\pi^+$</td>
<td>62.1 ± 1.7</td>
<td>1475 ± 60</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^+\pi^-$</td>
<td>–</td>
<td>787 ± 42</td>
</tr>
<tr>
<td>$\bar{B}^0 \rightarrow K^-\pi^+$</td>
<td>–</td>
<td>689 ± 41</td>
</tr>
</tbody>
</table>

$$A_{CP}^{\text{RAW}} = \frac{N_{\text{raw}}(\bar{B}^0 \rightarrow K^-\pi^+) - N_{\text{raw}}(B^0 \rightarrow K^+\pi^-)}{N_{\text{raw}}(\bar{B}^0 \rightarrow K^-\pi^+) + N_{\text{raw}}(B^0 \rightarrow K^+\pi^-)} = -0.066 \pm 0.039$$

Small (~1%) correction of fit result for trigger, acceptance, and selection efficiency to convert it into a measurement.
Extraction of asymmetry

\[ A_{\text{CP}} = \frac{N(B^0 \to K^-\pi^+)}{N(B^0 \to K^-\pi^+)} \frac{\varepsilon_{\text{kin}}(B^0 \to K^+\pi^-)}{\varepsilon_{\text{kin}}(B^0 \to K^-\pi^+)} - \frac{N(B^0 \to K^+\pi^-)}{N(B^0 \to K^+\pi^-)} \frac{\varepsilon_{\text{kin}}(B^0 \to K^+\pi^-)}{\varepsilon_{\text{kin}}(B^0 \to K^-\pi^+)} \]

A < 2% charge asymmetry affects the CDF II detector and tracking code. Only the different \( K^+/K^- \) interaction rate with material matters. Effect under control down to 0.5% in CDF \( A_{\text{CP}}(D^0 \to h^+h^-) \) measurement (Phys.Rev.Lett.94:122001, 2005). Used unbiased kaons to extract the ~ 1% correction.
Asymmetry Result (360 pb⁻¹)

\[ A_{CP}^{CDF}(B^0 \rightarrow K^+\pi^-) = -0.058 \pm 0.039 \ (stat.) \pm 0.007 \ (syst.) \]

Result is \(~1.5\sigma\) different from 0, and compatible with \(B\)-factories results:

\[ A_{CP}^{Belle}(B^0 \rightarrow K^+\pi^-) = -0.113 \pm 0.022 \ (stat.) \pm 0.008 \ (syst.) \]

\[ A_{CP}^{Babar}(B^0 \rightarrow K^+\pi^-) = -0.133 \pm 0.030 \ (stat.) \pm 0.009 \ (syst.) \]

Systematic uncertainties from CDF and \(B\)-factories are comparable.

With data already available on disk, we expect \(\sim2.5\%\) statistical uncertainty: CDF will be soon (summer) very competitive.

In same data, is likely first observation of \(B^0_s \rightarrow K\pi^+\) decay: will measure its BR and CP asymmetry that is expected large. Model-independent NP-probe proposed by Lipkin (Lipkin, Phys.Lett.B621:126, 2005).
$\text{BR}(B_{s}^{0} \rightarrow K^{+}K^{-})$ (180 pb$^{-1}$)

$$\frac{f_s \cdot \text{BR}(B_{s}^{0} \rightarrow K^{+}K^{-})}{f_d \cdot \text{BR}(B^{0} \rightarrow K^{+}\pi^{-})} = 0.46 \pm 0.08 \, \text{(stat.)} \pm 0.07 \, \text{(syst.)}$$

The $B_{s}^{0} \rightarrow K^{+}K^{-}$ decay has been established.

$\text{BR}(B_{s}^{0} \rightarrow K^{+}K^{-})$ consistent with QCD-factorization predictions [M. Beneke et al., Nucl.Phys.B675:333-415, 2003]

This BR ratio is crucial to check assumptions on U-spin symmetry. Exact U-spin symmetry would predict this BR ratio to be 1. Our result may favor large SU(3) breaking as predicted from QCD sum-rules [Khodjamirian et al. PRD68:114007, 2003].

For the summer update of this measurement with data already available on tape (1fb$^{-1}$). Expected resolution from TOY $\sigma \approx 0.02$.

The statistics(1fb$^{-1}$) may be sufficient to look at measurement time-dependent $A_{\text{CP}}(t)$ (from mixing analysis: $\epsilon D^{2} \approx 5\%$ and $\Delta m_{s}$).
\[ f_s \cdot BR(B_s^0 \rightarrow K^-\pi^+) < 0.08 \text{ @ 90\% C.L.} \]

\[ f_d \cdot BR(B^0 \rightarrow K^+\pi^-) \]

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\[ BR(B_s^0 \rightarrow K^-\pi^+) < 5.4 \cdot 10^{-6} \text{ @ 90\% C.L.} \]

On 180 pb\(^{-1}\) no evidence for \(B_s^0 \rightarrow K^-\pi^+\), set a limit a factor \(~40\) better than PDG04. Our current upper-limit constrains already

Expected BR(\(B_s^0 \rightarrow K^-\pi^+)\):

Beneke\&Neubert \([\text{NP B675, 333(2003)}]\): \(\approx [7-10] \cdot 10^{-6}\)

PQCD \([\text{Yu, Li, Yu, Phys.Rev. D71: 074026} (2005)]\): \(\approx [6-10] \cdot 10^{-6}\)

SCET \([\text{Williamson, Zupan. Jan 2006. hep-ph/0601214} ]\): \(\approx 4.9 \cdot 10^{-6}\)

Assuming \(BR \approx 4.9 \cdot 10^{-6}\) \([\text{hep-ph/0601214}]\) \(\implies\) expect in 1fb\(^{-1}\) \(\sigma(BR)_{\text{TOY}} \approx 0.8 \cdot 10^{-6}\) corresponding to observe this decay with significance \(\approx 6\sigma\). This is a self-tagging mode \(\implies\) DCPV measurement to compare with \(A_{\text{CP}}(B^0 \rightarrow K^+\pi^-)\).
Upper limits on annihilation mode (180 pb$^{-1}$)

Both $B^0_s \rightarrow \pi^+\pi^-$ and $B^0 \rightarrow K^+K^-$ are annihilation-dominated decays and no observed yet them – they are hard to predict exactly.

It will be very interesting to be able to measure one because these unknown amplitudes contribute to many relevant process as $B^0_s \rightarrow K^+K^-$ decay.

$$\frac{BR(B^0_s \rightarrow \pi^+\pi^-)}{BR(B^0_s \rightarrow K^+K^-)} < 0.05 \text{ @ 90\% C.L.}$$

Great improvement on annihilation mode $B^0_s \rightarrow \pi^-\pi^+$. A factor $>100$ below PDG04 (time-evolutions of $B^0_s \rightarrow \pi^-\pi^+$ and $B^0_s \rightarrow K^-K^+$ assumed the same).

$$\frac{BR(B^0 \rightarrow K^+K^-)}{BR(B^0 \rightarrow K^+\pi^-)} < 0.10 \text{ @ 90\% C.L.}$$

Limit on pure annihilation/exchange mode $B^0 \rightarrow K^+K^-$. A factor $\sim3$ above B-factories, expect much better performance on current sample(1fb$^{-1}$).
Incertezze sistematiche dominanti

\[
\begin{align*}
\frac{f_s \cdot BR(B^0_s \rightarrow K^+K^-)}{f_d \cdot BR(B^0 \rightarrow K^+\pi^-)} & \quad (\text{stat. } \sim 17\%) \\
\frac{BR(B^0 \rightarrow \pi^+\pi^-)}{BR(B^0 \rightarrow K^+\pi^-)} & \quad (\text{stat. } \sim 24\%) \\
\frac{f_s \cdot BR(B^0 \rightarrow \pi^+\pi^-)}{f_d \cdot BR(B^0_s \rightarrow K^+K^-)} & \quad (\text{stat. } \sim 29\%)
\end{align*}
\]

Si riduce con la statistica:

- dE/dx correlazione track-to-track
- Masse dei mesoni B in input al fit
- Efficienza relativa Isolamento tra $B^0_s$ e $B^0$
- Code radiative FSR
- Trigger bias sull’efficienza
- Dipend. della carica del dE/dx
- Background shape
- Asimmetria di carica nel background
- Altro.
$B_s \rightarrow \phi \phi (VV)$ sample selection

TRIGGER: very similar requirement to $B \rightarrow PP$, based just on impact parameter

Blind analysis (expected a small yield)

**Optimized cuts:** lifetime, Vertex quality, impact parameter of $B_s$, transverse momentum of $\phi$, impact parameter of $\phi$ daughter tracks

Signal search and BR measurement $\rightarrow$ maximize:

$$\frac{1}{S_{\text{min}}} \propto \frac{\epsilon(t)}{a/2 + \sqrt{B(t)}} ; \ a=3.$$  

$t$=set of cuts

Where $\epsilon(t)$ is the signal efficiency from MC and $B(t)$ is the expected background from sidebands extrapolation for the set $t$ of selection cuts. For $a=3$ maximize the sensitivity region for a 3 sigma discovery with 99% C.L. [G.Punzi, hep-ph/0308063]

Nice feature: optimization independent of MC normalization

For the control sample $B_s \rightarrow J/\psi \phi$ maximize usual significance:

$$\text{Sig} = \frac{S(t)}{\sqrt{S(t) + B(t)}}$$
$B^\pm \rightarrow \phi K^\pm (180 \text{ pb}^{-1})$

- Extended unbinned ML fit to:
  - $M_{KKK}$
  - $M_\phi$
  - Cosine of $\phi$ meson Helicity angle
  - $dE/dx$ deviation from the expected value (pion hypothesis) for the lowest momentum trigger track.

- Background sources:
  - $B^\pm \rightarrow f^0 K^\pm$
  - $B^\pm \rightarrow K^{*0} \pi$
  - $B_{u,d} \rightarrow \phi X$
  - combinatorial background

Normalize yield to $B^\pm \rightarrow J/\psi \ K^\pm$ to measure

$$BR(B^\pm \rightarrow \phi K^\pm) = (7.6 \pm 1.3(stat.) \pm 0.7(syst.)) \cdot 10^{-6}$$

$$A_{CP}(B^\pm \rightarrow \phi K^\pm) = \frac{\Gamma(B^- \rightarrow \phi K^-) - \Gamma(B^+ \rightarrow \phi K^+)}{\Gamma(B^- \rightarrow \phi K^-) + \Gamma(B^+ \rightarrow \phi K^+)} = -0.07 \pm 0.17(stat.)^{+0.03}_{-0.02}(syst.)$$
Systematics $A_{CP}(B^0 \rightarrow K^+\pi^-)$

<table>
<thead>
<tr>
<th>source</th>
<th>shift wrt central fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass scale</td>
<td>0.0022</td>
</tr>
<tr>
<td>mass resolution</td>
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</tr>
<tr>
<td>asymmetric momentum-p.d.f</td>
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<tr>
<td>dE/dx</td>
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<tr>
<td>input masses</td>
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<tr>
<td>combinatorial background model</td>
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<tr>
<td>$p$ spectra of background</td>
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</tr>
<tr>
<td>MC statistics</td>
<td>0.0010</td>
</tr>
<tr>
<td>charge asymmetry</td>
<td>0.0022</td>
</tr>
<tr>
<td>$m_{\pi\pi} - p_{tot}$ non-factorizability</td>
<td>0.0018</td>
</tr>
<tr>
<td><strong>TOTAL (sum in quadrature)</strong></td>
<td><strong>0.0074</strong></td>
</tr>
</tbody>
</table>
B_c observation and mass (800 pb^{-1})

B_c is not produced at B factories
Full reconstruction allows for precise mass measurement.

\[ \bar{u}d \quad \pi \quad B_c \quad \bar{c}b \quad J/\psi \quad c/\bar{c} \]

Signal yield \( \approx 38.9 \) events
Background yield \( \approx 26.1 \)
between 6.24 and 6.3 GeV/c^2
Significance > 6\( \sigma \) over search area

Mass(\( B_c \)) = 6275.2 \pm 4.3 \pm 2.3 \text{ MeV/c}^2