Branching Fractions and *CP* Asymmetries in $B_{d,s} \to h^{\pm}h'^{\mp}$ at CDF

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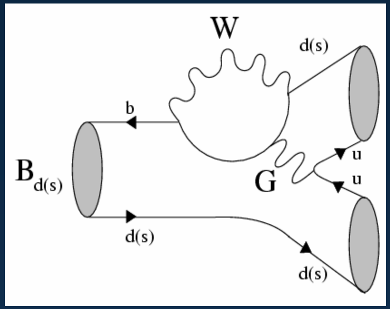
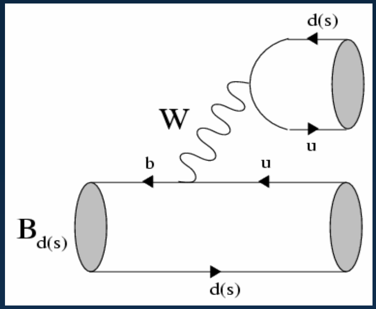
Outline

- Motivation
- CDF II and Charmless Two-Body Sample Selection
- Separation of the Decay Modes and Backgrounds
- Fit Results
- Systematic Uncertainties
- Preliminary Branching Fractions and A_{CP}
- Preliminary Charmless Λ_b Decay Studies
- Prospects and Summary



Motivation



CLEO: Penguins ($B_d \to K\pi$) dominate over Trees ($B_d \to \pi\pi$) by factor ~4

Penguin-Tree interference depends on
- CKM triangle angle γ (φ_3)
- hadronic amplitudes and phases (θ)
- New Physics?

BaBar [4.2σ] (hep-ex/0407057) & Belle [3.9σ] (hep-ex/0408100): evidence for direct CPV in $B_d \to K^+\pi^-$!

$$A_{\text{CP}} = \frac{N(\overline{B}^0_d \to K^-\pi^+) - N(B^0_d \to K^+\pi^-)}{N(\overline{B}^0_d \to K^-\pi^+) + N(B^0_d \to K^+\pi^-)}$$

Strategy:
- study several modes related by isospin and SU(3) flavour
- combine observables

Hadron colliders offer high yields and additional access to B_s mesons and b baryons with hh′ final states (This talk: h = $K^\pm$ or $\pi^\mp$)

CDF II is the first experiment with sensitivity to $B_s \to hh'$

Branching-Fraction Ratios involving $B_d \to \pi\pi, K\pi$ and $B_s \to KK$

$$H = \left(\frac{1-\lambda^2}{\lambda^2}\right)\left(\frac{f_K}{f_\pi}\right)^2 \left[\frac{Br(B_d \to \pi^+\pi^-)}{Br(B_d \to K^\pm\pi^\mp)}\right] = \frac{1 - 2d\cos\vartheta\cos\gamma + d^2}{\left(\frac{\lambda^2}{1-\lambda^2}\right)^2 + 2\left(\frac{\lambda^2}{1-\lambda^2}\right)d\cos\vartheta\cos\gamma + d^2}$$

$$R_d^s = \left[\frac{Br(B_s \to K^+K^-)}{Br(B_d \to \pi^+\pi^-)}\right] = \left(\frac{1-\lambda^2}{\lambda^2}\right)\left|\frac{C'}{C}\right|^2 \frac{\left(\frac{\lambda^2}{1-\lambda^2}\right)^2 + 2\left(\frac{\lambda^2}{1-\lambda^2}\right)d\cos\vartheta\cos\gamma + d^2}{1 - 2d\cos\vartheta\cos\gamma + d^2} F_{ps}$$

Tying Observables to Theory Parameters

Time-Dependent *CP* Asymmetries

$$A_{CP}(t) = A_{CP}^{dir} \times \cos\Delta m t + A_{CP}^{mix} \times \sin\Delta m t$$

$$A_{CP}^{dir}(\pi^+\pi^-) = -\frac{2d\sin\theta\sin\gamma}{1 - 2d\cos\theta\cos\gamma + d^2}$$

$$A_{CP}^{dir}(K^+K^-) = \frac{2d\frac{1-\lambda^2}{\lambda^2}\sin\theta\sin\gamma}{1 + 2d\frac{1-\lambda^2}{\lambda^2}\cos\theta\cos\gamma + \left(\frac{1-\lambda^2}{\lambda^2}\right)^2 d^2}$$

$$A_{CP}^{mix}(K^+K^-) = \frac{\sin 2\gamma + 2d\frac{1-\lambda^2}{\lambda^2}\cos\theta\sin\gamma}{1 + 2d\frac{1-\lambda^2}{\lambda^2}\cos\theta\cos\gamma + d^2\left(\frac{1-\lambda^2}{\lambda^2}\right)^2}$$

$$A_{CP}^{mix}(\pi^+\pi^-) = \frac{\sin 2(\beta+\gamma) - 2d\cos\theta\sin(2\beta+\gamma) + d^2\sin 2\beta}{1 - 2d\cos\theta\cos\gamma + d^2}$$

$$A_{CP}^{mix}(J/\psi K_S) = \sin 2\beta$$

Longer Term Goal for Run II:

- Time-Dependent Asymmetry Measurements
- B-Flavour Tagging, Greater Statistics

d : Function of penguin, tree amplitudes

F_{ps} : Phase-space factor (~0.92)

$\left|\frac{C'}{C}\right|$: Strong *CP*-conserving amplitudes
[~1.76 from QCD Sum Rules, Khodjamirian *et al.*, PRD **68**, 114007 (2003)]

D. London, J. Matias, hep-ph/0404009
R. Fleischer, hep-ph/0405091

CDF II: Detecting $B \to hh'$ in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.96 TeV

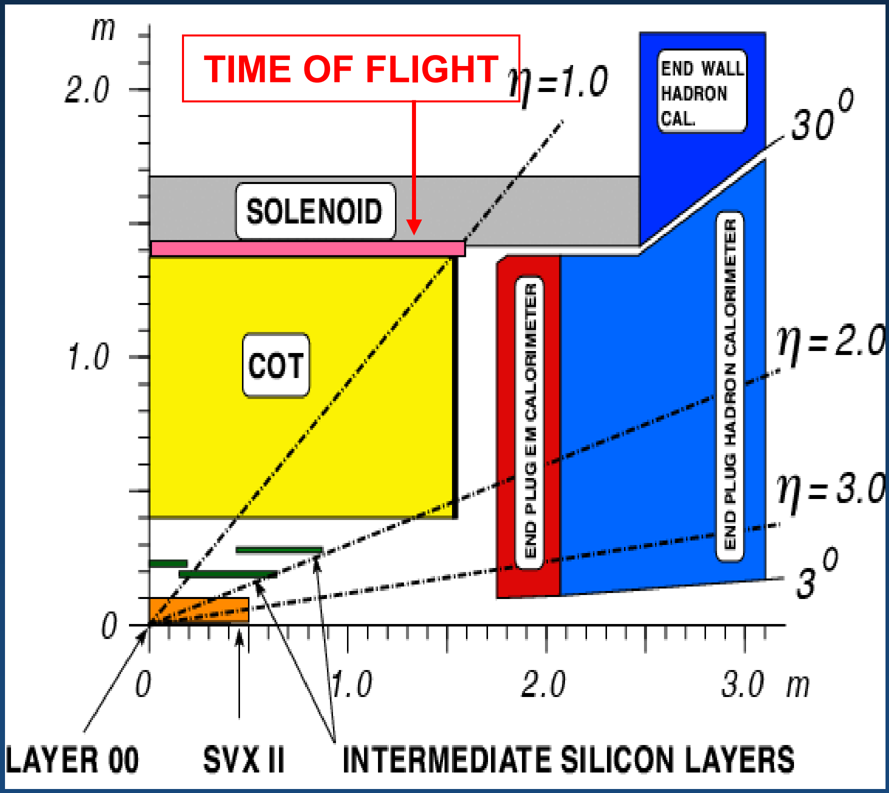
Trigger: **(Designed, in part, for $B \to hh'$)**
L1 eXtremely Fast Tracker (XFT)
L2 Silicon Vertex Trigger (SVT)

Tracking:
Drift Chamber (COT), 96 layers,
$\sigma(P_T)/P_T^{\,2} \sim 0.1\%\ \mathrm{GeV}^{-1}$
Silicon Vertex Detectors, 1 + 5 + 2 layers,
I.P. resolution 35μm @ 2 GeV

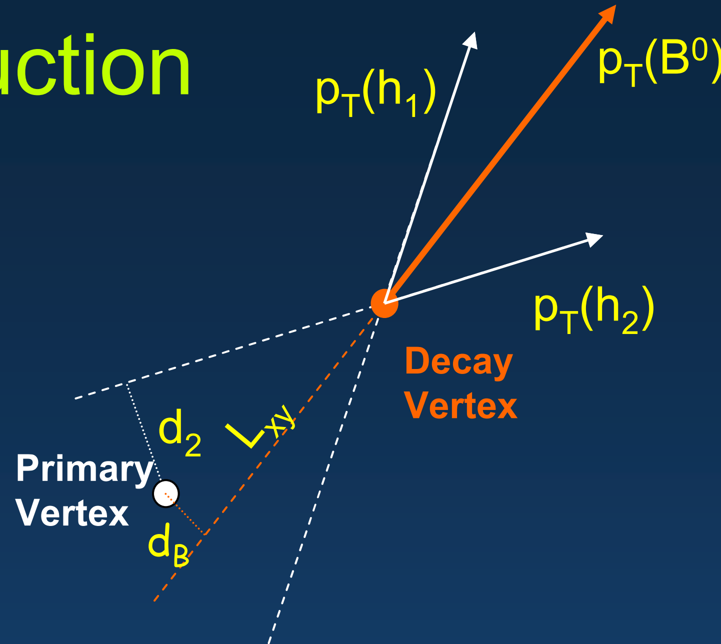
Particle ID (PID):
dE/dx provides >1.3σ K/π separation
for tracks >2 GeV
Time of Flight (ToF), 100 ps resolution,
2σ K/π separation for tracks <1.6 GeV

Data Sample:
$180 \pm 11\ \mathrm{pb}^{-1}$ of $p\bar{p}$ collisions at 1.96 TeV
(first results shown at Lepton-Photon 2003 using $65\ \mathrm{pb}^{-1}$)

Quadrant of CDF II



$B \to hh'$ Candidate Reconstruction

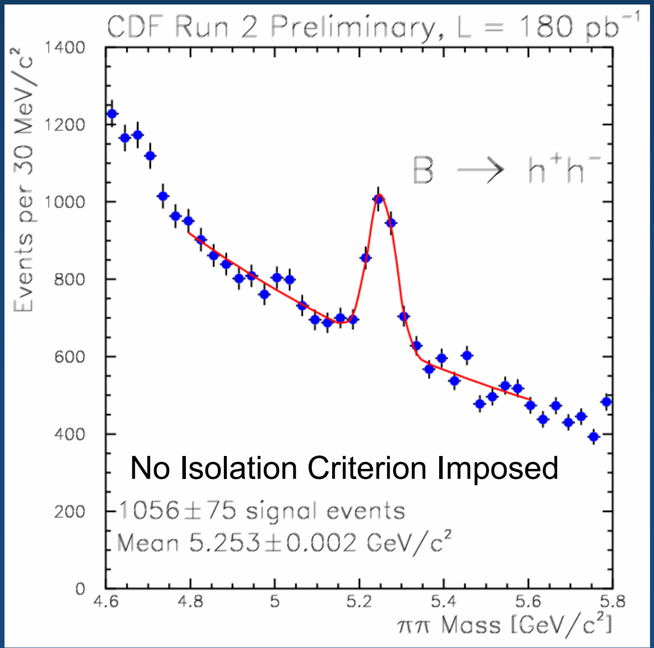


SVT trigger selects pairs of oppositely charged tracks with large impact parameters

Track pairs considered:

- $p_T(h_1)$ and $p_T(h_2) \geq 2$ GeV
- $p_T(h_1) + p_T(h_2) \geq 5.5$ GeV
- $20^o \leq \Delta\varphi \leq 135^o$
- $\min(|d_1|,|d_2|) \geq 150$ μm
- $L_{xy}(B) \geq 300$ μm
- $|d_B| \leq 80$ μm
- $d_1 \cdot d_2 < 0$

All kinematic cuts simultaneously optimized to maximize $S^2/(S+B)$:
S: signal Monte Carlo calculations
B: background from data sidebands



Signal Candidates

Isolation Criterion:

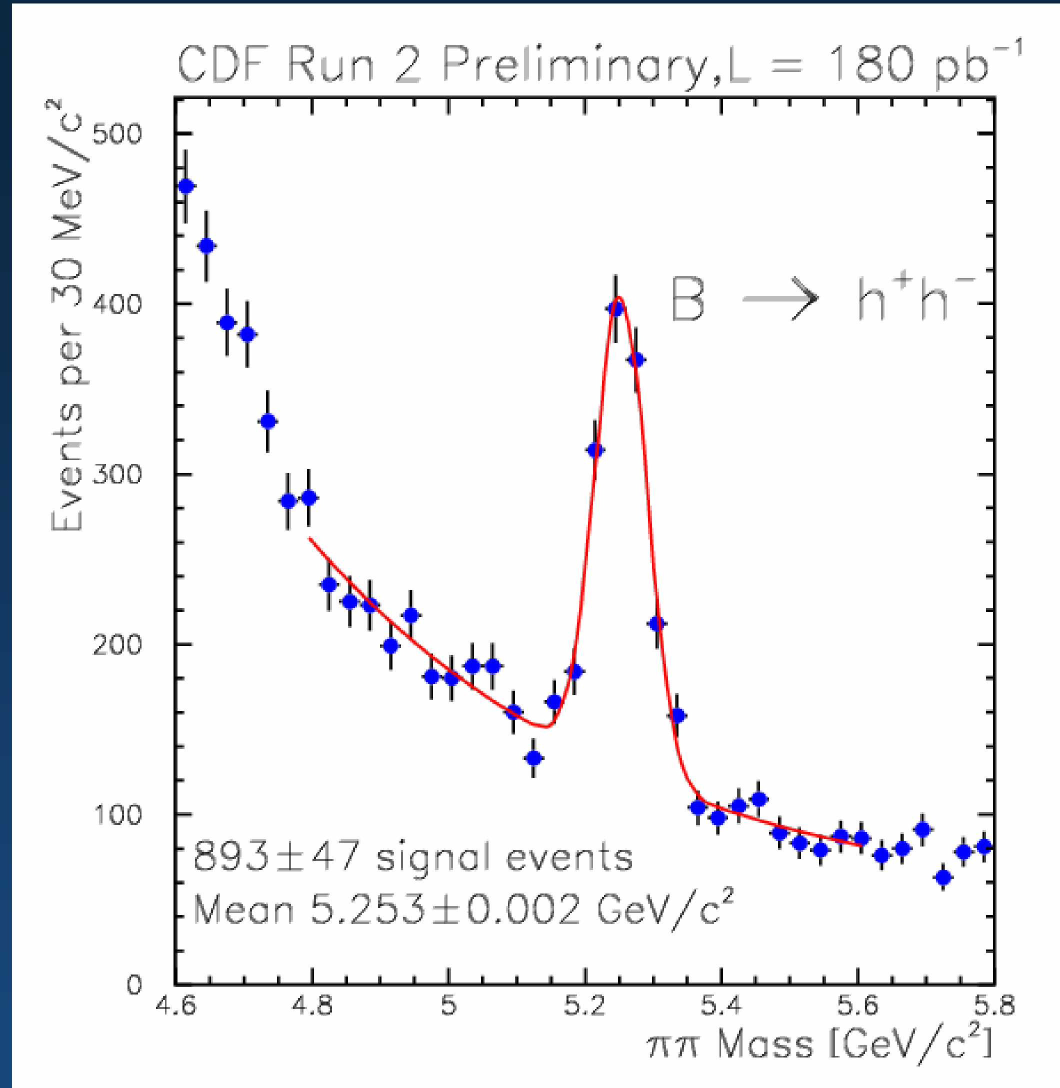
$I(B) \geq 0.5$

to reject light-quark backgrounds

$$I(B) \equiv \frac{p_T(B)}{p_T(B) + \sum_i p_T(\text{track}^i)}$$

Where the sum is over all non-B charged tracks within a cone of radius R = 1 around the candidate B-meson direction

85% signal efficiency
4x background rejection factor



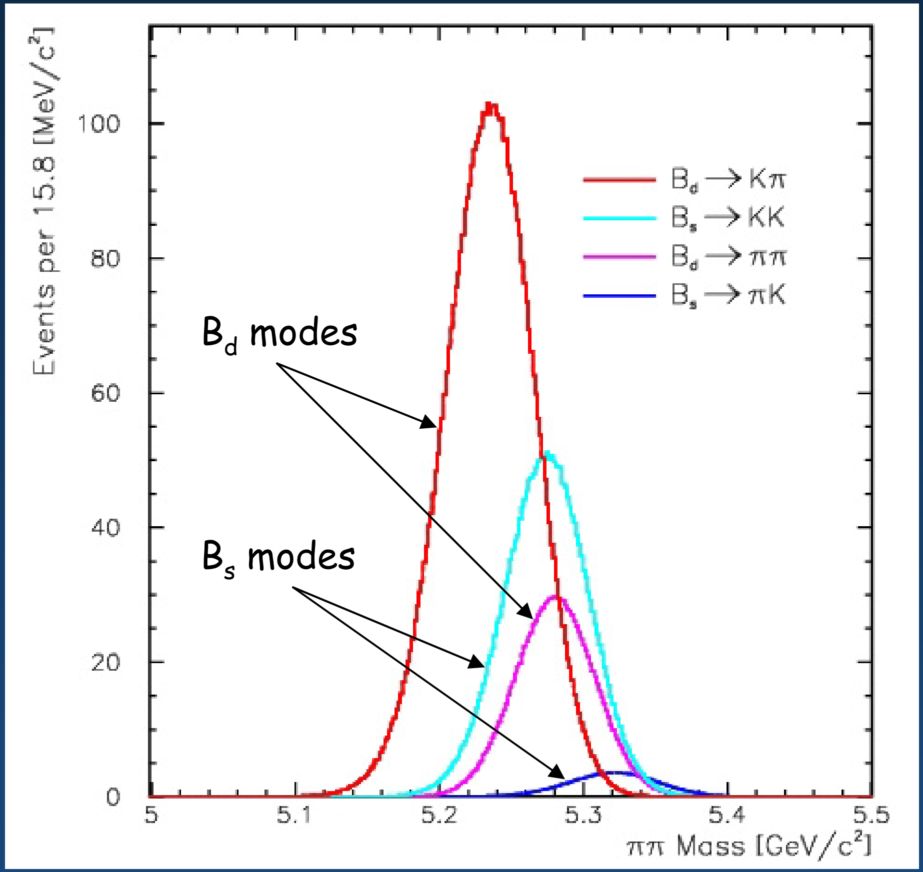
$B \to hh'$ Candidates: 893 ± 47, S/B > 1
cf. S/B at production: $\sim 10^{-8}$

Separation of Individual Modes

Disentangle 4 main modes;

Use unbinned maximum likelihood fit to separate channels statistically:

- Kinematics: invariant mass, signed momentum imbalance
- PID: dE/dx of tracks in the drift chamber (COT) and their correlations
- Signal channels: summed
- Backgrounds:
  - Kinematic bkg included in Likelihood as exponential + constant term;
  - PID bkgs assume all K and π, account for correlations in dE/dx between two tracks in same event



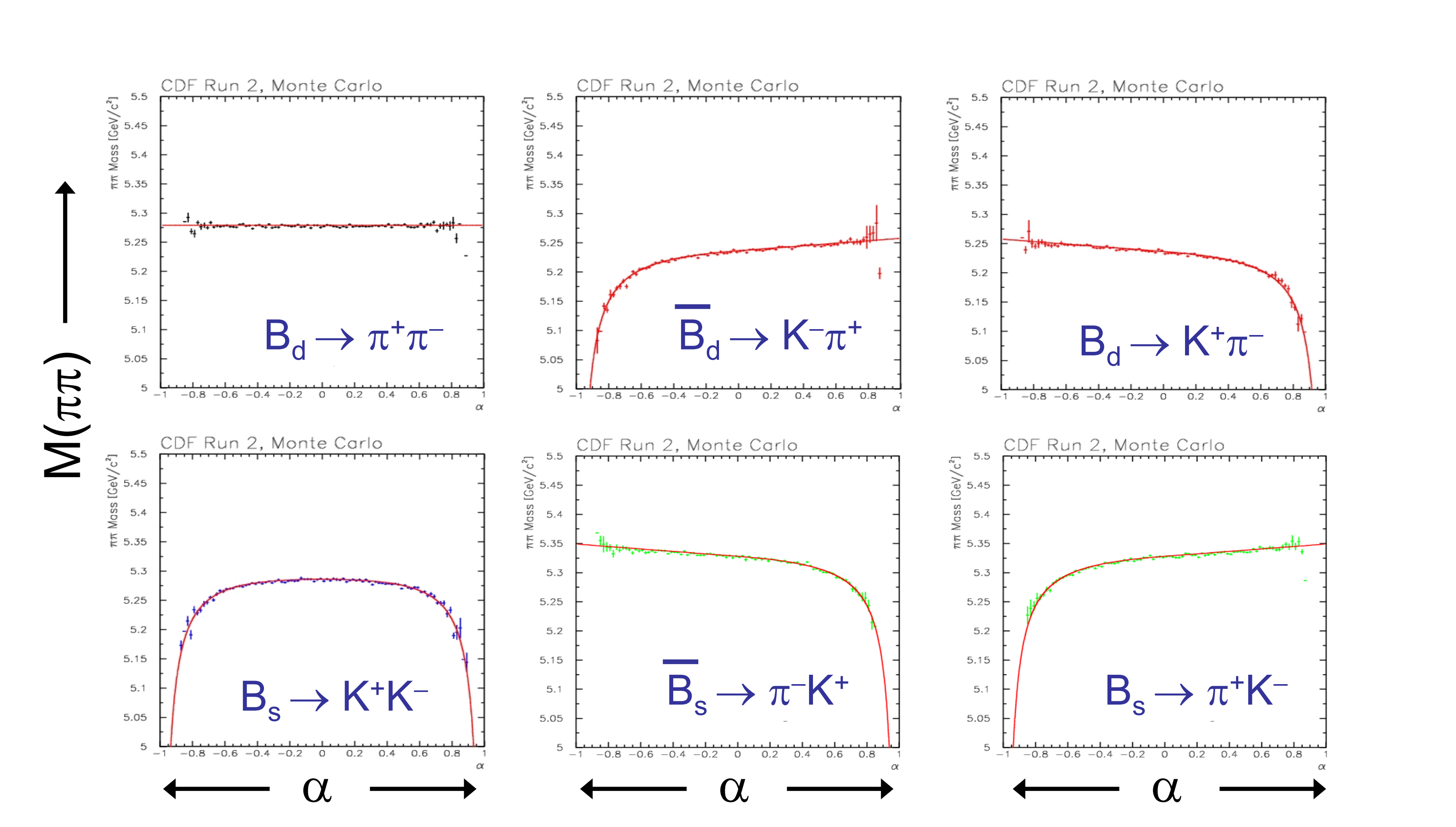
Kinematic Discrimination

$\boxed{M(\pi\pi) \text{ vs. } \alpha \equiv Q_1(1-p_1/p_2)}$

$p_1 \equiv \min(\ |p(h_1)|,\ |p(h_2)|\ )$

$Q_1 \equiv p_1$ track's charge

Discriminates amongst signals and between flavours for self-tagging modes



PID Discrimination

K/π separation: >**1.3**σ (p_T > 2 GeV/c)

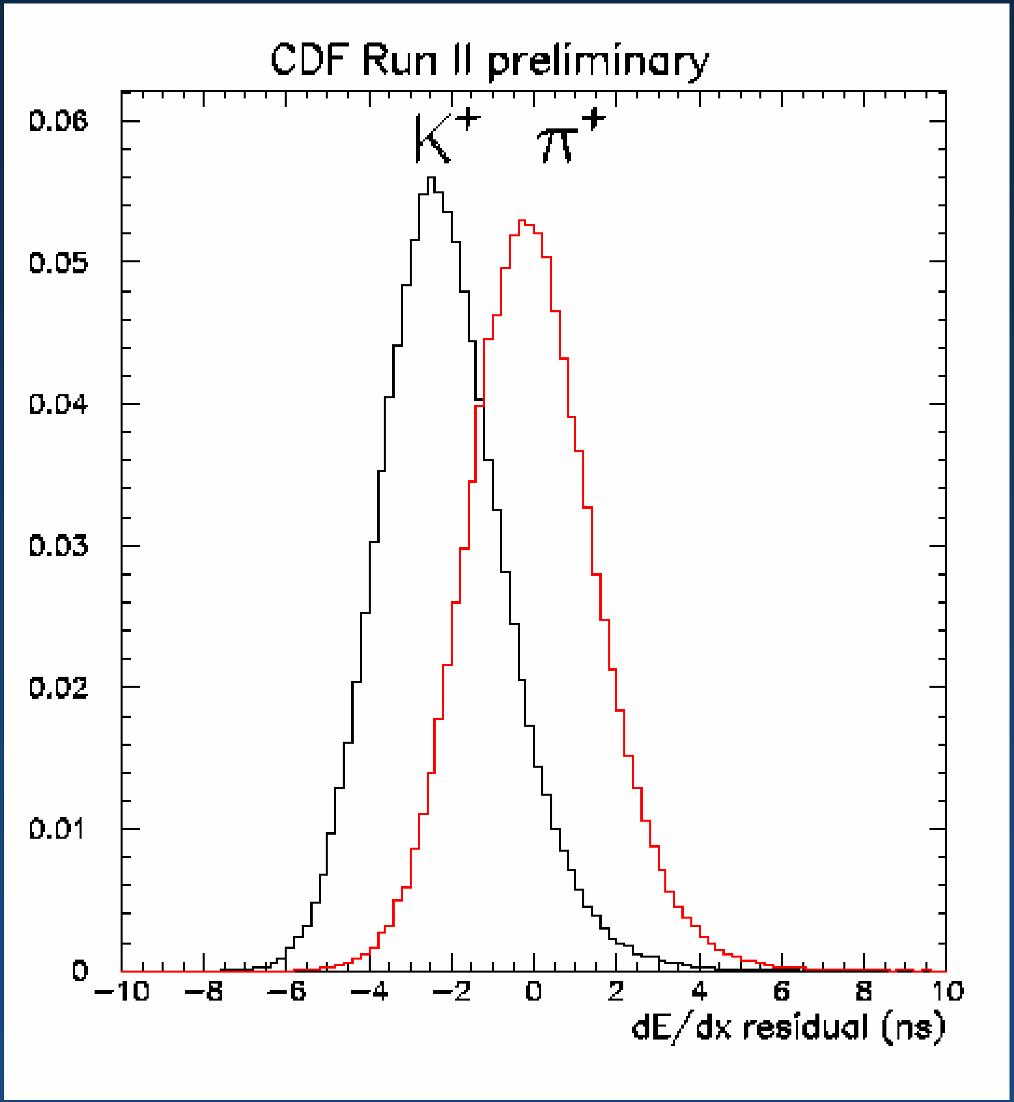
Improved since LP03 due to new time-dependent calibrations on CDF's large $D^{*+} \rightarrow D^0\pi^+$ sample.

This PID performance implies statistical separation of K-π with resolution 60% that of "perfect" PID.

Control of systematics:

Residual gain/baseline fluctuations cause correlated fluctuations of tracks in same event.

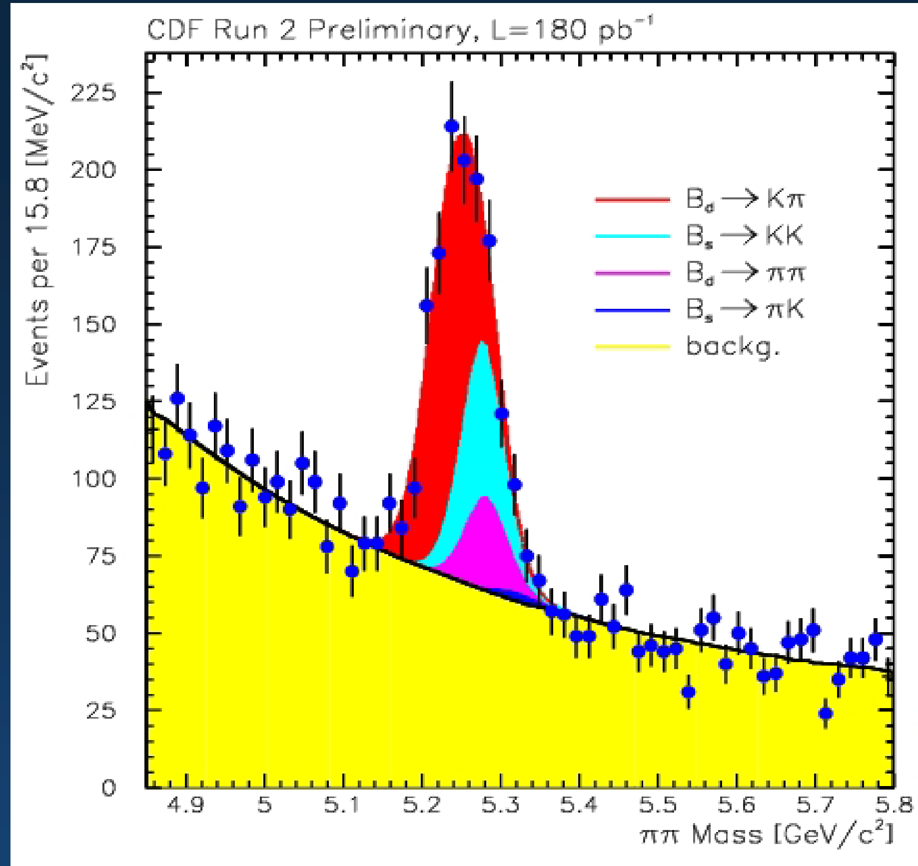
These have been measured and explicitly included in the fit.



Raw Fit Results

~ 10% corrections for efficiency differences between channels

parameter	value
$f(B_d \to \pi\pi)$	0.15±0.03
$f(B_d \to K^{\pm}\pi^{\mp})$	0.57±0.03
$A_{\mathrm{CP}}(B_d \to K^{\pm}\pi^{\mp})$	-0.05±0.08
$f(B_s \to K^{\pm}\pi^{\mp})$	0.02±0.03
$f(B_s \to KK)$	0.26±0.03
$\frac{N(B_s \to KK)}{N(B_d \to K\pi)}$	0.47±0.08
$\frac{N(B_d \to \pi\pi)}{N(B_d \to K\pi)}$	0.26±0.06
$\frac{N(B_d \to \pi\pi)}{N(B_s \to KK)}$	0.55±0.14
$f_\pi\ (4.85 < M_{\pi\pi} < 5.125)$	0.53±0.01
$f_\pi\ (5.125 < M_{\pi\pi} < 5.4)$	0.45±0.02
$f_\pi\ (5.4 < M_{\pi\pi} < 5.8)$	0.46±0.02
background fraction	0.82±0.01
signal fraction	0.18±0.01
c_0	14.0±6.2
c_1	-2.1±0.4
c_2	8.7±57.5



Decay	Raw Yields
$B_d \to K^+\pi^-$	500 ± 38
$B_d \to \pi^+\pi^-$	129 ± 26
$B_s \to K^+K^-$	234 ± 31
$B_s \to K^-\pi^+$	17 ± 31

Largest single sample of fully reconstructed B_s candidates

Systematic Uncertainties: Overview

Dominant systematics:

- dE/dx calibration (correlations, tails) 3~11% on Br/Br results
- Isolation cut efficiency, measured in CDF samples of $B_d \to J/\psi K^{*0}$, $B_s \to J/\psi \phi$, $B_s \to D_s\pi$, and $B_u \to J/\psi K$ ~10% on Br/Br results

GeV/c	$\epsilon_{Iso}(B_d)$	$\epsilon_{Iso}(B_s)$	$\epsilon_{Iso}(B_u)$	$\epsilon_{Iso}(B_d)/\epsilon_{Iso}(B_s)$
$p_T(B) < 6$	57.5±9.7	70.1±14.6	67.7±7.2	0.82±0.22
$6 < p_T(B) < 10$	84.6±2.4	84.8±5.7	85.1±1.2	1.00±0.08
$p_T(B) > 10$	93.8±1.2	90.4±2.8	93.6±0.8	1.04±0.03

Both the above systematics are *statistical* in origin, and expected to decrease with sample size (already observed going from 65 to 180 pb^{-1})

Other sources:

- Mass resolution
- Background model
- Input masses
- B lifetimes
- Charge asymmetry
- $p_T(B)$ distribution
- $\Delta\Gamma_s / \Gamma_s$ Standard Model
- MC statistics

Results for the B_d sector

	CDFII / 180 pb^{-1}	BaBar / 200 fb^{-1}	Belle / 253 fb^{-1}
$N(B_d \rightarrow K^+\pi^-)$	500 ± 38	1606 ± 51	2140 ± 53
$\frac{Br(B_d \rightarrow \pi^+\pi^-)}{Br(B_d \rightarrow K^+\pi^-)}$	0.24 ± 0.06 ± 0.05	0.26 ± 0.036 ± 0.015 *	0.24 ± 0.035 ± 0.018 *
$A_{CP}(B_d \rightarrow K^+\pi^-)$	-0.04 ± 0.08 ± 0.01	-0.133 ± 0.030 ± 0.009	-0.101 ± 0.025 ± 0.005

- Ratio of B_d branching fractions consistent with other experiments
- Valuable cross check, comparing hadron collider to e^+e^- collider data
- A_{CP} result compatible with BaBar/Belle observations
- CDF presently has ~3x more events on tape
- Latest tracking improvements and inclusion of ToF in PID still to be invoked
- Expect A_{CP} measurement at ~4.5% level from data now on tape

* Calculated from HFAG2004 info

Results for the B_s sector

	CDFII preliminary **180 pb^{-1}**	Beneke & Neubert Nucl. Phys. **B** 675, 333 (2003)
$N(B_s \to K^+ K^-)$	234 ± 31	
$Br(B_s \to K^+ K^-)$	$(0.50 \pm 0.08 \pm 0.09) * Br(B_d \to K\pi) * (f_s/f_d)$ $= (34.3 \pm 5.5 \pm 5.9) \times 10^{-6}$ *	$[23 - 36] \times 10^{-6}$
$Br(B_s \to K^+ \pi^-)$	$< 0.11 * [Br(B_d \to K\pi) * (f_s/f_d)]$ $\Rightarrow < 7.55 \times 10^{-6}$ (90% CL) *	$[7 - 10] \times 10^{-6}$

- $Br(B_s \to K^+ K^-)$ measured with resolution 15%(stat) + 15%(syst) – A First
- Value at high end of expected range, compatible with prediction by Beneke & Neubert [Nucl. Phys. B 675, 333 (2003)]
- No evidence for $B_s \to K^+ \pi^-$, 90% CL limit close to lowest expectation
- Eventually plan to measure A_{CP} in this channel (expect ±10%)

* Based on $Br(B_d \to K^+ \pi^-)$ and f_s / f_d from PDG2004
Assume $\Delta\Gamma_s / \Gamma_s$ Standard Model = 0.12 ± 0.06

New Limits on Rare B_d, B_s modes

	CDFII preliminary 180 pb^{-1} (90% CL)	PDG 2004 (90% CL)	Theoretical Predictions
$Br(B_d \to K^+K^-)$	$< 0.17 * Br(B_d \to K^+\pi^-)$ $\Rightarrow < 3.1 \times 10^{-6}$ *	$< 0.6 \times 10^{-6}$	$[0.01 - 0.2] \times 10^{-6}$ [Beneke & Neubert]
$Br(B_s \to \pi^+\pi^-)$	$< 0.10 * Br(B_s \to K^+K^-)$ ** $\Rightarrow < 3.4 \times 10^{-6}$ *	$< 170 \times 10^{-6}$	$0.42 \pm 0.06 \times 10^{-6}$ [Li *et al*. hep-ph/0404028] $[0.03 - 0.16] \times 10^{-6}$ [Beneke & Neubert]

- Decays dominated by annihilation/exchange diagrams; hard to evaluate using QCDF or LCSR - experimental data important to reduce theory uncertainties
- Current CDF limit for $Br(B_d \to KK)$ not very informative. Note: expected limit with current statistics is ~2x lower than observed
- Greatly improved limit on $B_s \to \pi\pi$, now just a factor x8 above pQCD expectation. Constrains the size of annihilation diagrams also contributing to $B_s \to KK$
- A targeted analysis could improve these limits beyond simple statistical gains

*** Based on $Br(B_d \to K^+\pi^-)$ from PDG2004**

*** * Assume equal lifetimes for KK and $\pi\pi$ modes**

Looking beyond mesons: Charmless Λ_b Decays

Use the same data to look for evidence of charmless Λ_b decays to ph^-

- Large direct CP asymmetries expected

Predictions:

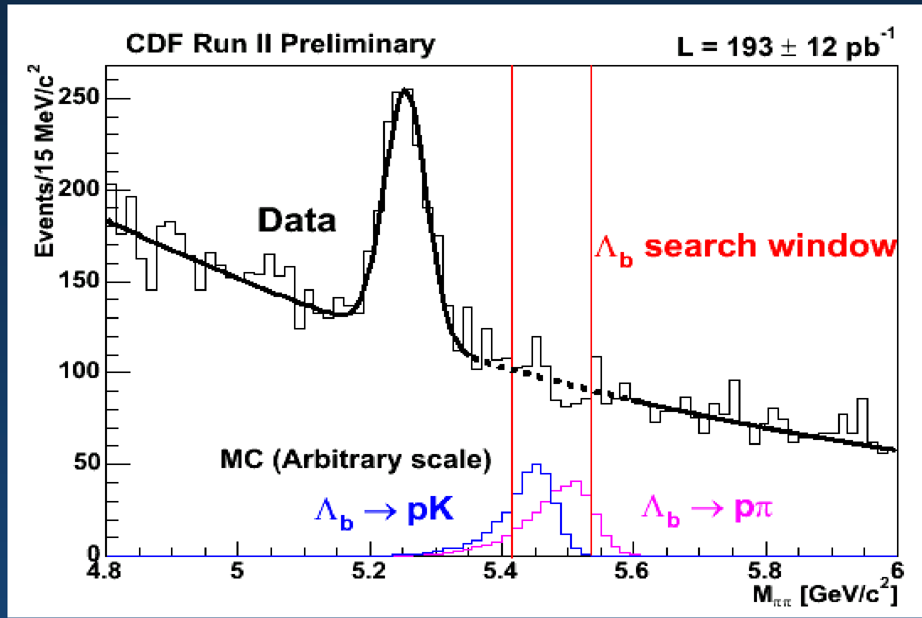
- $Br(\Lambda_b \rightarrow pK)$, $Br(\Lambda_b \rightarrow p\pi) \sim [1 - 2] \times 10^{-6}$
  [Mohanta, Phys. Rev. D 63, 074001 (2001)]

Current limits (PDG2004):

- $Br(\Lambda_b \rightarrow pK) < 50 \times 10^{-6}$ (90% CL)
- $Br(\Lambda_b \rightarrow p\pi) < 50 \times 10^{-6}$ (90% CL)

Blinded optimization to reduce background in Λ_b mass region, including from $B \rightarrow hh'$

Normalize to $Br(B_d \rightarrow K\pi)$



CDFII Preliminary

$Br(\Lambda_b \rightarrow p\pi) + Br(\Lambda_b \rightarrow pK) < 22 \times 10^{-6}$ (90% CL)

Using $f_\Lambda / f_d = 0.25 \pm 0.04$ and $Br(B^0 \rightarrow K\pi) = (17.4 \pm 1.5) \times 10^{-6}$

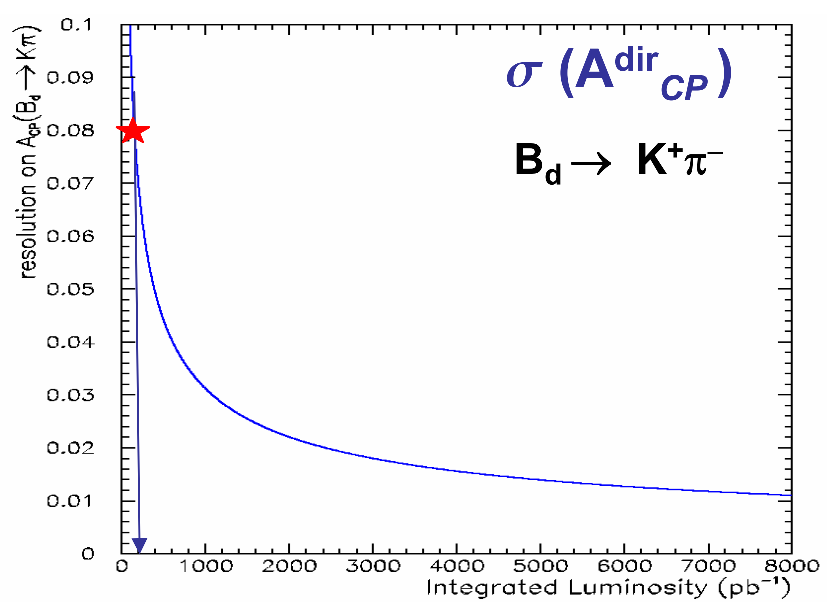
Expect improved sensitivity in the future with proton PID from ToF + dE/dx

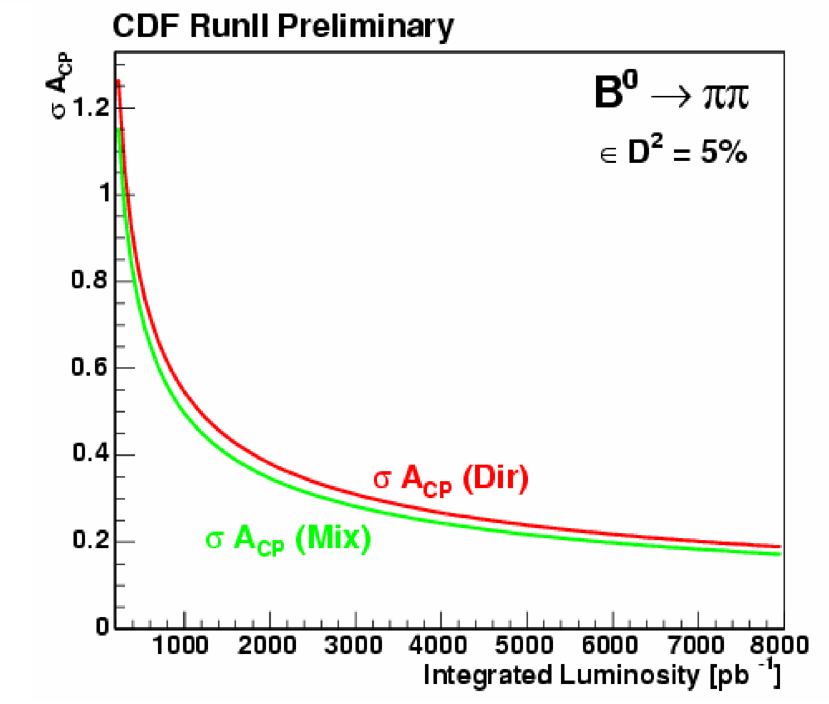
Prospects for the Future

- Higher precision Br(B_s→KK)
- B_s→KK lifetime → $\Delta\Gamma_s$
- B_s → Kπ branching fraction and direct A_{CP}
- Λ_b→ ph⁻ branching fraction and direct A_{CP}
- Precision A_{CP}(B_d→Kπ) [eventually few %]

Further ahead, tagged time-dependent measurements:

A_{CP} parameters for B_d → ππ
B_s → KK





Conclusion

New Preliminary CDFII Results:

$$A_{\mathrm{CP}} = -0.04 \pm 0.08\ (stat.) \pm 0.01\ (syst.)$$

$$\frac{f_d \cdot BR(B_d \to \pi^\pm \pi^\mp)}{f_s \cdot BR(B_s \to K^\pm K^\mp)} = 0.48 \pm 0.12\ (stat.) \pm 0.07\ (syst.)$$

$$\frac{f_s \cdot BR(B_s \to K^\pm K^\mp)}{f_d \cdot BR(B_d \to K^\pm \pi^\mp)} = 0.50 \pm 0.08\ (stat.) \pm 0.09\ (syst.)$$

- No evidence for $B_s \to K\pi$ seen yet
- No large annihilation observed in $B_s \to \pi\pi$
- Other charmless modes are being sought with available data; expect more new results with increasing data size and improved offline quality
- Stay tuned for valuable CKM information from CDF

Backup Slides

- Systematics Summary Table
- Detector Intrinsic Charge Asymmetry Systematic
- Production P_T Distribution
- Effect of $\Delta\Gamma_s$

Summary of Systematics

source	$\frac{f_s}{f_d} \cdot \frac{BR(B_s \to KK)}{BR(B_d \to K\pi)}$	$A_{CP}(B_d \to K\pi)$	$\frac{BR(B_d \to \pi\pi)}{BR(B_d \to K\pi)}$	$\frac{f_d}{f_s} \cdot \frac{BR(B_d \to \pi\pi)}{BR(B_s \to KK)}$
mass resolution	$^{+0.001}_{-0.004}$	$^{+0.001}_{-0.001}$	$^{+0.001}_{-0.002}$	$^{+0.001}_{-0.001}$
dE/dx **correlation: RMS(s)**	$^{+0.043}_{-0.031}$	$^{+0.002}_{-0.002}$	$^{+0.034}_{-0.025}$	$^{+0.029}_{-0.017}$
dE/dx **correlation:** *pdf* **(s)**	$^{+0.002}_{-0.002}$	$^{+0.002}_{-0.002}$	$^{+0.000}_{-0.000}$	$^{+0.002}_{-0.002}$
dE/dx **tail**	$^{+0.056}_{-0.056}$	$^{+0.003}_{-0.003}$	$^{+0.020}_{-0.020}$	$^{+0.017}_{-0.017}$
dE/dx **shift**	$^{+0.001}_{-0.002}$	$^{+0.001}_{-0.001}$	$^{+0.001}_{-0.003}$	$^{+0.017}_{-0.005}$
input masses	$^{+0.027}_{-0.028}$	$^{+0.003}_{-0.003}$	$^{+0.009}_{-0.010}$	$^{+0.009}_{-0.010}$
background model	$^{+0.005}_{-0.005}$	$^{+0.002}_{-0.002}$	$^{+0.003}_{-0.003}$	$^{+0.000}_{-0.000}$
lifetime	$^{+0.004}_{-0.004}$	-	-	$^{+0.004}_{-0.004}$
isolation efficiency	$^{+0.051}_{-0.051}$	-	-	$^{+0.050}_{-0.050}$
MC statistics	$^{+0.004}_{-0.004}$	$^{+0.001}_{-0.001}(*)$	$^{+0.003}_{-0.003}$	$^{+0.006}_{-0.006}$
charge asymmetry	-	$^{+0.002}_{-0.002}$	-	-
XFT-bias correction	$^{+0.010}_{-0.007}$	-	$^{+0.004}_{-0.004}$	$^{+0.015}_{-0.010}$
$p_T(B)$ **spectrum**	$^{+0.007}_{-0.007}$	-	-	$^{+0.007}_{-0.007}$
$\Delta\Gamma_s/\Gamma_s$ **Standard Model**	$^{+0.007}_{-0.006}$	-	-	$^{+0.006}_{-0.006}$
TOTAL	± 0.09	± 0.01	± 0.04	± 0.07

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Detector Intrinsic Charge Asymmetry Systematic

- Well measured in $D^0 \to K^-\pi^+$ meson samples tagged using $D^{*+} \to D^0\pi^+$ reconstruction (and C.C.)
  - Obtained using same two-track trigger as $B \to hh'$ sample
  - SM assumption of no *CP* violation in these modes is exercised
  - Measure residual asymmetry
  - Use realistic detector simulation to estimate nuclear interaction rate effects
- Cross-check using $K^{*+} \to K_S\pi^+ \to (\pi^+\pi^-)\pi^+$ decays
  - Insensitive to disparities in $K^\pm$ nuclear interaction rates
- These methods (and others) are limited only by data and MC statistics; will diminish further in future
- Refer to speaker Paul Karchin's talk in this conference

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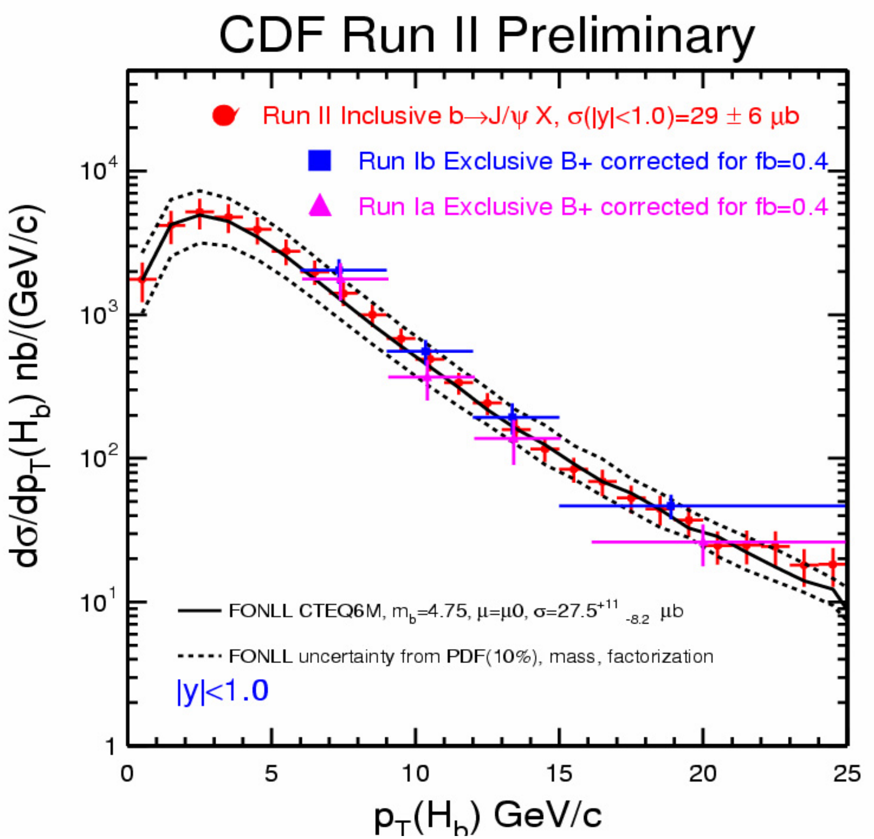
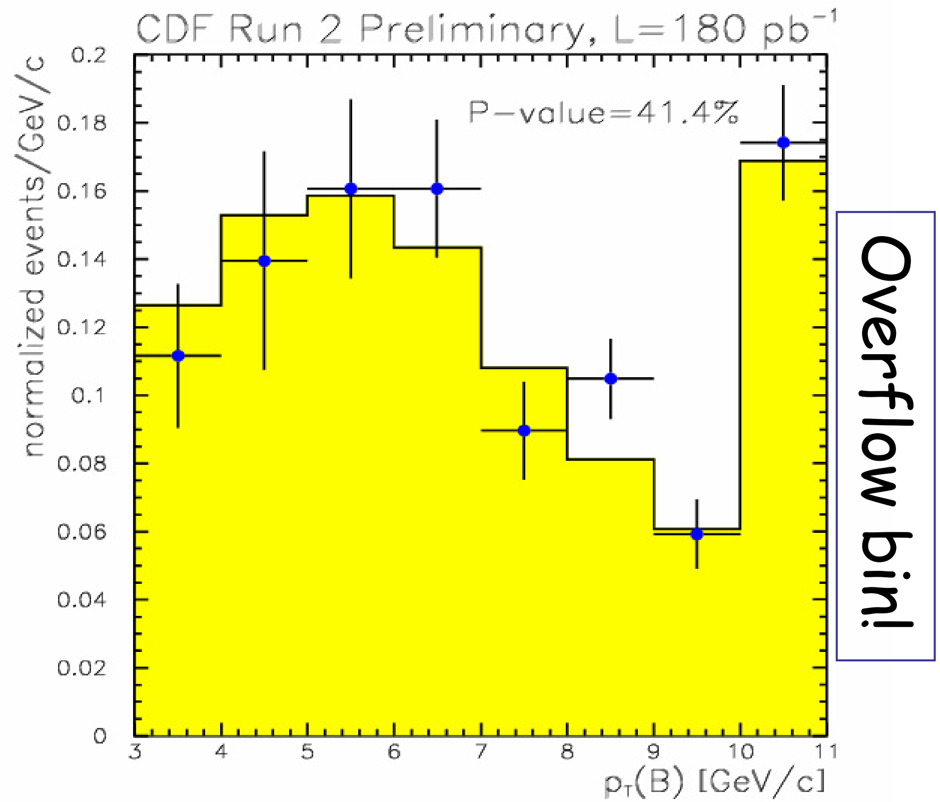
Production P_T Distributions





B→ hh trigger accepts very soft B candidates; large samples available!

Measurement of production P_T spectrum from inclusive b→J/ψX in this region is important for reliable MC simulation

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Sensitivity to a possible large value of $\Delta\Gamma_s$

$$\frac{f_s \cdot BR(B_s \rightarrow K^{\pm} K^{\mp})}{f_d \cdot BR(B_d \rightarrow K^{\pm} \pi^{\mp})} = 0.50 \pm 0.08 \pm 0.09$$

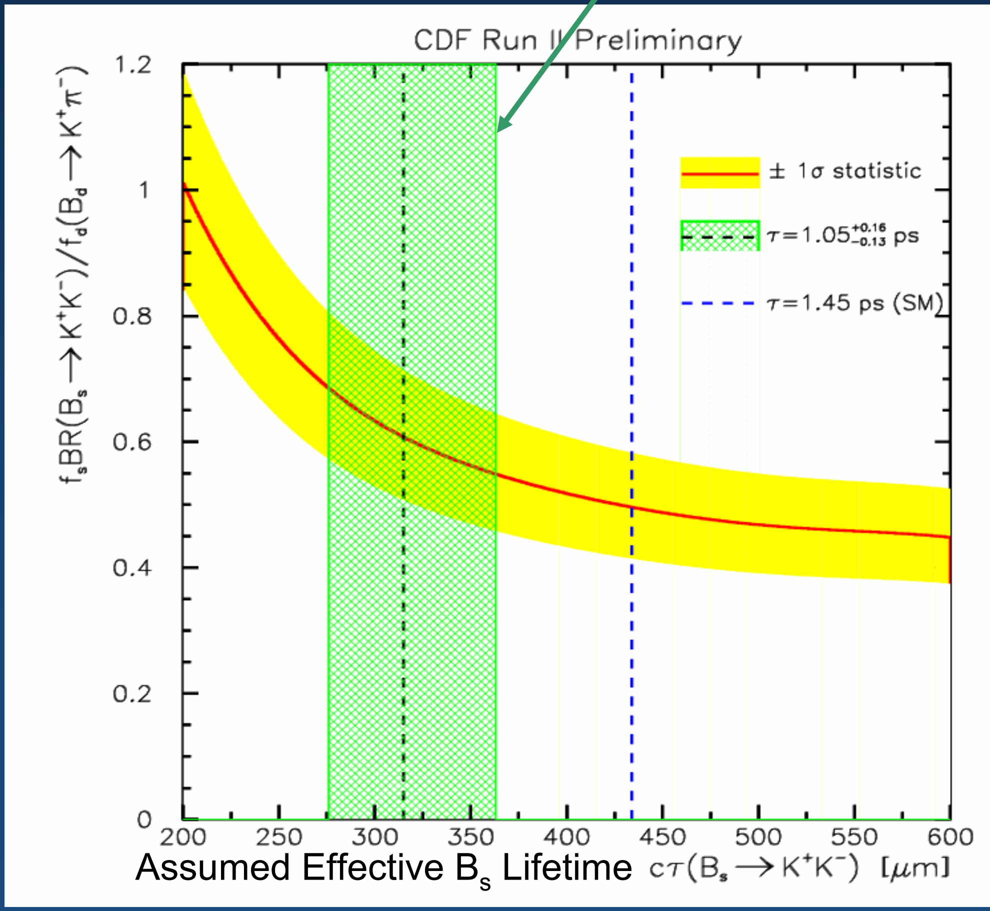
Preliminary CDF II measurement from $B_s \rightarrow J/\psi\ \phi$

Contains some assumptions on lifetimes:

$dN(B_s \rightarrow KK)/dt \propto R_L \exp(-t_L) + R_H \exp(-t_H)$

- $R_H = 0$ (no Heavy B_s decay to KK or, equivalently, no tree contribution)
- $t_L = 1/(\Gamma_s + \Delta\Gamma_s/2) = 1.45$ ps

(SM: $\Delta\Gamma_s/\Gamma_s = 0.12 \pm 0.06$ and $\Gamma_s = \Gamma_d$)



Refer to speaker James Russ' talk in this conference