Rare B Meson Decays at Tevatron

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CDF and DØ Collaborations

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Topics

Outline

- Motivation
- Analysis Method
  - Signal and Background discrimination
- Results
- Update

$b \to s\mu^+\mu^-$

- CDF: 4.4 fb^{-1} (Phys. Rev. Lett. 106, 161801 (2011))

$B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$

- CDF: 3.7 fb^{-1} (CDF Public Note 9892)
- DØ: 6.1 fb^{-1} (PLB 693, 539 (2010))
- CDF Update: 7 fb^{-1}

$b \to s\mu^+\mu^-$

CDF, 4.4 fb^{-1}, Phys. Rev. Lett. 106, 161801 (2011)

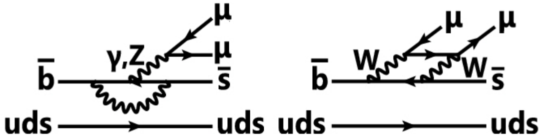
Motivation

Theory

- $b \to s\mu^+\mu^-$ can only occur through higher order FCNC diagrams in Standard Model (SM)
- SM predicts $\mathcal{BR}(b \to s\mu^+\mu^-) = 10^{-6} - 10^{-7}$
- New Physics Search: A_{FB}

Experimental Status

- $B^+ \to \mu^+\mu^- K^+$: BaBar, Belle, CDF
- $B^0 \to \mu^+\mu^- K^*$: BaBar, Belle (2.7σ deviation for A_{FB}), CDF
- $B_s \to \mu^+\mu^-\phi$: **CDF, DØ**



Analysis Flow

Concept

- Measure non-resonant modes w.r.t. corresponding resonant modes

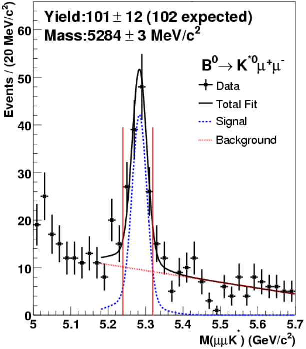
Signal Mode	Control Mode
$B^0 \to \mu^+\mu^- K^*$	$B^0 \to J/\Psi K^*$
$B^+ \to \mu^+\mu^- K^+$	$B^+ \to J/\Psi K^+$
$B_s \to \mu^+\mu^- \phi$	$B_s \to J/\Psi \phi$

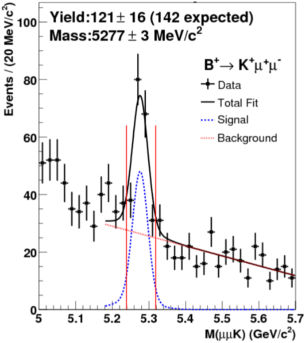
Reconstruction

- Online selection: two muons with $p_T > 1.5$
- Offline: loose preselection + NN (optimized for best sensitivity)
- Remove resonant regions ($J/\Psi, \Psi'$)
- Remove backgrounds such as B→charm and B→charmless by kinematics and muon likelihood cuts.
- Apply acceptance/efficiency corrections (from MC validated on control modes)

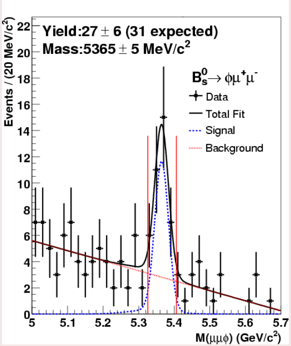
The Decays

- Collected on dimuon trigger
- Employed Neural Network to optimize event selection





First Obs: $\sim 6\sigma$



$$\mathcal{BR}(B_s \to \mu^+\mu^-\phi) = (1.44 \pm 0.33[\text{stat}] \pm 0.46[\text{syst}]) \times 10^{-6}$$

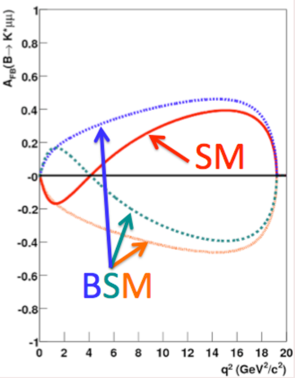
Consistent with theory: 1.61×10^{-6}

Forward-Backward Asymmetry (A_{FB})

- Sensitive to non-SM physics
- For $B^0 \rightarrow \mu^+\mu^- K^*$ there are many prediction from several new physics models

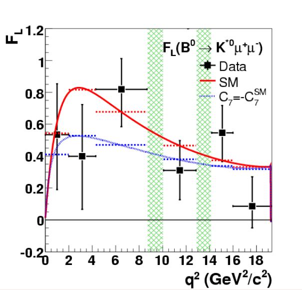
Wilson Coefficients

- $b \rightarrow s\mu^+\mu^-$ described by Wilson coefficients: C_7, C_9, C_{10}
- BSM Wilson Coefficients
  - A_{FB} flip
  - C_9 or C_{10} has flipped sign relative to SM
  - $C_7 = -C_7(SM)$

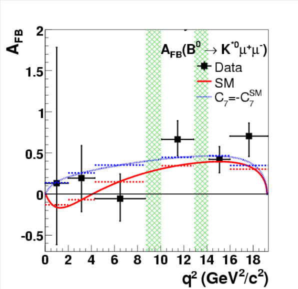


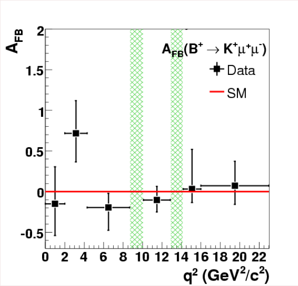
$b \to s\mu^+\mu^-$ A_{FB} Results

K^* Polarization



A_{FB}: Forward-Backward Asymmetry





Unable to clearly distinguish between NP and SM with current resolution

Compatible and Competitive with B-factories

- $A_{FB} = 0.43 \pm 0.37 \pm 0.06$ for $(1 < q^2 < 6\ \mathrm{GeV/c^2})$
- BaBar 384M BB, PRD79,031102(R) (2009)
- Belle 657M BB, PRL103,171801(2009)

$b \rightarrow s\mu^+\mu^-$ Conclusion

- CDF competitive on $b \rightarrow s\mu^+\mu^-$ modes with B factories
- Significant impact on world averages
- CDF competitive with B factories in NP searches through $b \rightarrow s\mu^+\mu^-$ modes
- Will update the analysis with full run II statistics

$B_s \to \mu^- \mu^+$

and

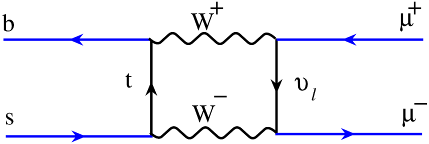
$B_d \to \mu^- \mu^+$

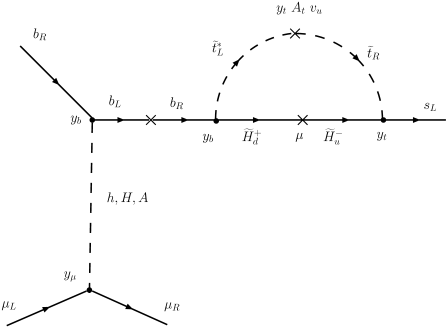
CDF, 3.7 fb^{-1}**, CDF Public Note 9892**

DØ: 6.1 fb^{-1} **(PLB 693, 539 (2010))**

CDF Update: 7 fb^{-1}

- $B_s \to \mu^+\mu^-$ can only occur through higher order FCNC diagrams in Standard Model (SM)
- This decay is not only suppressed by the GIM Mechanism but also by helicity
- SM predicts very low rate with little SM background ($\mathcal{BR}(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$, Andrzej J. Buras et al, JHEP 1009 (2010) 106
- BSM models predict enhancement
- Ratio of $\mathcal{BR}(B_s \to \mu^+\mu^-)$ and $\mathcal{BR}(B_d \to \mu^+\mu^-)$ is important to discriminate amongst BSM models
- Clean experimental signature $\to$ τ's would have stronger coupling but experimentally difficult





The Measurement

- Measure rate of $B_s \to \mu^+\mu^-$ relative to $B^+ \to J/\Psi K^+$, $J/\Psi \to \mu^+\mu^-$
- Apply same selection to find $B^+ \to J/\Psi K^+$
- Systematic uncertainties will cancel in ratio $\Rightarrow$ e.g. dimuon trigger efficiency is the same for both modes

$$\mathcal{BR}(B_s \to \mu^+\mu^-) = \boxed{\frac{N_{B_s}}{N_{B^+}} \frac{\epsilon^{trig}_{B^+}}{\epsilon^{trig}_{B_s}}} \boxed{\frac{\epsilon^{reco}_{B^+}}{\epsilon^{reco}_{B_s}} \frac{\alpha_{B^+}}{\alpha_{B_s}} \frac{1}{\epsilon^{NN}_{B_s}}} \boxed{\frac{f_u}{f_s} \cdot \mathcal{BR}(B^+ \to J/\Psi K^+ \to \mu^+\mu^- K^+)}$$

From Data, From MC, From PDG

$$\boxed{N_{B^+} \sim 2 \times 10^4,\ \frac{\epsilon^{trig}_{B^+}}{\epsilon^{trig}_{B_s}} \sim 1} \boxed{\frac{\epsilon^{reco}_{B^+}}{\epsilon^{reco}_{B_s}} \sim 1,\ \frac{\alpha_{B^+}}{\alpha_{B_s}} \sim 0.5,\ \frac{1}{\epsilon^{NN}_{B_s}} \sim 1}$$

$$\boxed{\frac{f_u}{f_s} \sim 3,\ \mathcal{BR}(B^+ \to J/\Psi K^+ \to \mu^+\mu^- K^+) \sim 5 \times 10^{-5}}$$

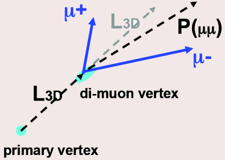
Analysis Flow Chart

- Estimate acceptances and efficiencies
- Identify variables that discriminate signal and background
- Make multivariate discriminant, for background rejection
    - Optimized with Pythia signal MC and data mass sideband
    - Validate in B^+ sample
- Estimate Background
    - Combinatoric background
    - Peaking background: B$\rightarrow$hh
- Unblind

Signal vs. Background

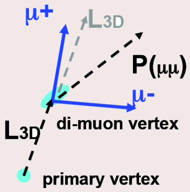
Signal Properties

- Final state fully reconstructed
- B_s is long lived ($c\tau =\sim 450\mu$m)
- B fragmentation is hard: few additional tracks



Background contributions & characteristics

- Sequential semi-leptonic decay: $b \rightarrow c\mu^- X \rightarrow \mu^+\mu^- X$
- Double semi-leptonic decay: $bb \rightarrow \mu^-\mu^+ X$
- Continuum $\mu^-\mu^+$
- μ + fake and fake+fake
  - Partially reconstructed
  - Softer
  - Short lived
  - Has more tracks
- $B \rightarrow hh$: peaking in signal region



Combinatoric Background and Control (CDF)

Control Samples

- Signal contains two opposite signed muons with positive lifetime ($\vec{p}_{B_{s(d)}}$ aligned with primary to secondary vertex vector)
- Checked background estimates with 4 control samples
  - Opposite sign muons with negative lifetime ($\vec{p}_{B_{s(d)}}$ anti-aligned with primary to secondary vertex vector)
  - Same sign muons with positive lifetime
  - Same sign muons with negative lifetime
  - Fake muons with positive lifetime (Fake muons = muon that failed muon ID requirements)
- Followed our procedure for background estimation in each control sample for all mass and NN bins
- Compared estimate with observed events in blinded region

Combinatoric Background and Control (CDF)

sample	*NN* cut	CMU-CMU pred	CMU-CMU obsv	CMU-CMU prob(%)	CMU-CMX pred	CMU-CMX obsv	CMU-CMX prob(%)
OS-	$0.80 < \nu_{NN} < 0.95$	$275 \pm (9)$	287	26	$310 \pm (10)$	304	39
	$0.95 < \nu_{NN} < 0.995$	$122 \pm (6)$	121	46	$124 \pm (6)$	148	3.2
	$0.995 < \nu_{NN} < 1.0$	$44 \pm (4)$	41	36	$31 \pm (3)$	50	0.4
SS+	$0.80 < \nu_{NN} < 0.95$	$2.7 \pm (0.9)$	1	29	$2.7 \pm (0.9)$	0	10
	$0.95 < \nu_{NN} < 0.995$	$1.2 \pm (0.6)$	0	34	$1.2 \pm (0.6)$	1	66
	$0.995 < \nu_{NN} < 1.0$	$0.6 \pm (0.4)$	0	55	$0.0 \pm (0.0)$	0	-
SS-	$0.80 < \nu_{NN} < 0.95$	$8.7 \pm (1.6)$	9	49	$5.7 \pm (1.6)$	2	11
	$0.95 < \nu_{NN} < 0.995$	$3.0 \pm (1.0)$	4	36	$3.6 \pm (1.0)$	2	34
	$0.995 < \nu_{NN} < 1.0$	$0.9 \pm (0.5)$	0	43	$0.3 \pm (0.3)$	0	70
FM+	$0.80 < \nu_{NN} < 0.95$	$169 \pm (7)$	169	50	$73 \pm (5)$	64	19
	$0.95 < \nu_{NN} < 0.995$	$55 \pm (4)$	43	9	$19 \pm (2)$	18	49
	$0.995 < \nu_{NN} < 1.0$	$20 \pm (2)$	20	48	$3.6 \pm (1.0)$	3	53

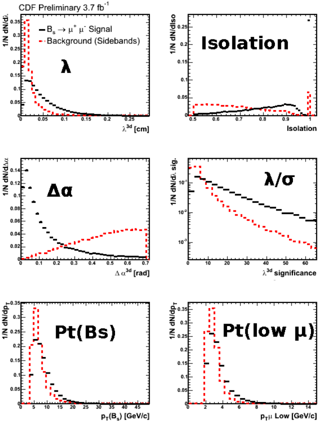
Table: The values given in the parentheses are the uncertainties on the mean of the background prediction. The Poisson probability for making an observation at least as large (or fewer than observed when observed is less than predicted) given the predicted background is also shown in the table.

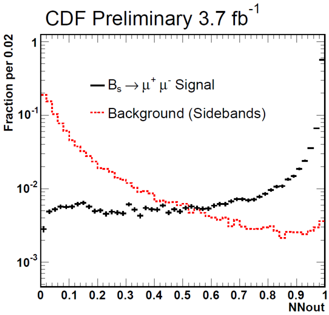
Conclusion

- Checked combinatoric background estimates with control samples
- Good agreement between predicted observed

Signal Discrimination (CDF)

- Invariant mass of muons with 2.5σ window, σ=24 MeV
- 3 Secondary vtx variables
  - $\lambda = c\tau$, proper decay time
  - $\frac{\lambda}{\sigma_\lambda}$
  - $\Delta\alpha = |\phi_B - \phi_{vtx}|$
- Isolation: $\frac{p_T(B)}{\Sigma p_T(trks)+p_T(B)}$
- p_T of B and lower momentum muon

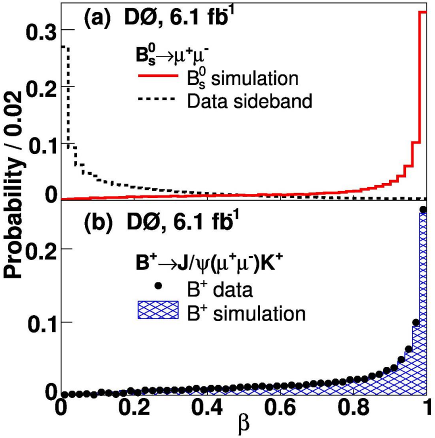


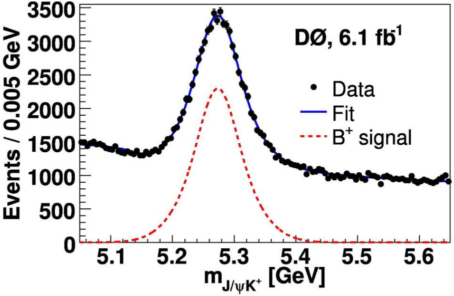


- Combined in NN, optimized with signal MC and data mass sideband
- NN extensively tested for mass bias
- Set limit with 3 NN and 5 mass bins

Signal Discrimination (DØ)

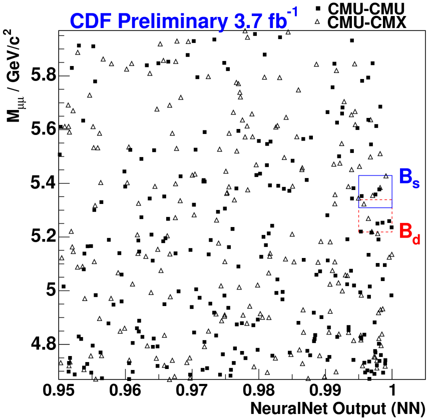
Used Bayesian Neural Network





Expect 3 signal events after all cuts

Results (CDF)



Events in Unblinded Region

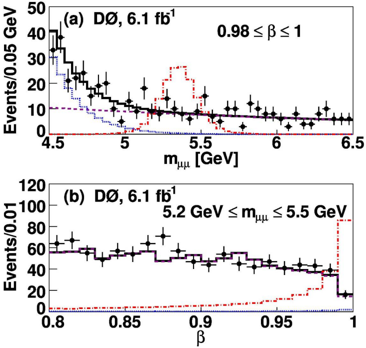
Channel	Expected	Observed
B_s Central	4.0±1.0	3
B_s Extended	2.1±0.8	4
B_d Central	5.3±1.0	5
B_d Extended	2.8±0.8	3

Limits

	90% CL	95% CL
B_s	3.6×10^{-8}	4.3×10^{-8}
B_d	6.0×10^{-9}	7.6×10^{-9}

CDF Public Note 9892

Used Bayesian Neural Network



- Dots with Error = data
- Solid Black = Exp Bkg
- Dotted-dashed = SM Signal $\times 100$
- Dashed = $B(D) \to \mu^+ \nu X$, $\bar{B}(\bar{D}) \to \mu^- \bar{\nu} X'$
- Dotted = $B \to \mu^+ \nu \bar{D}$, $\bar{D} \to \mu^- \bar{\nu} X$

- In highest sensitivity region: 51 ± 4 expected bkg events
- 55 observed
- Expected B_s limit: 3.8×10^{-8} at 95% CL

Limits

	90% CL	95% CL
B_s	4.2×10^{-8}	5.1×10^{-8}

PLB 693, 539 (2010)

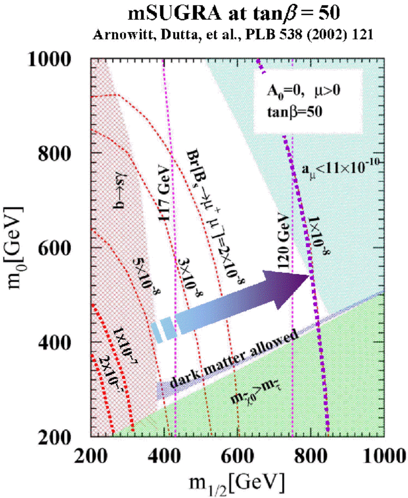
Summary of Limits

$B_s \rightarrow \mu^-\mu^+$ at 95% CL

Exeriment	Data	Limit
CDF	3.7fb^{-1}	4.3×10^{-8}
D0	6.1fb^{-1}	5.1×10^{-8}
LHCb	36pb^{-1}	5.6×10^{-8}

$B_d \rightarrow \mu^-\mu^+$ at 95% CL

Exeriment	Data	Limit
CDF	3.7fb^{-1}	0.76×10^{-8}
D0	6.1fb^{-1}	-
LHCb	36pb^{-1}	1.5×10^{-8}



CDF still has world's best limit

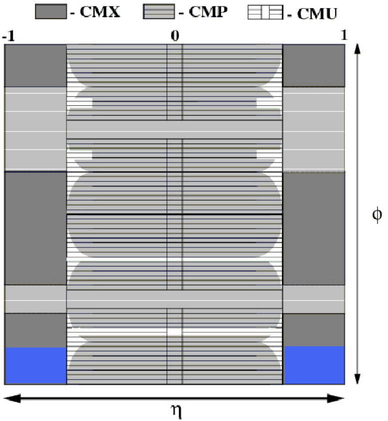
CDF Improvements since 2009

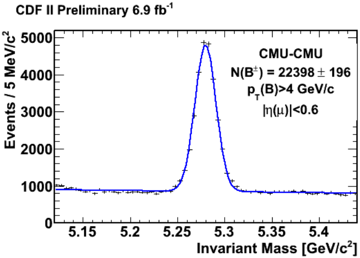
Improvements

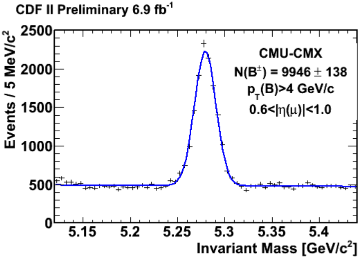
- 2x more data$\Rightarrow \sim$7fb^{-1}
- Increased muon acceptance
- New Neural Network with better signal efficiency
- Improved background predictions

Acceptance Increase

Measure rate of $B_s \to \mu^+\mu^-$ relative to $B^+ \to J/\Psi K^+$, $J/\Psi \to \mu^+\mu^-$







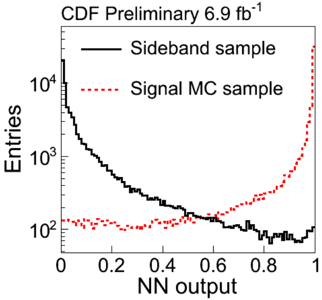
- $\sim$50% increase is due to new data
- $\sim$15% increase of CMU-CMX stats $\Rightarrow$ 7% total due new muon acceptance

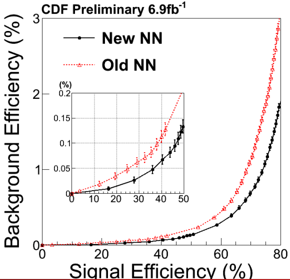
New Neural Network

- New 14-variable NN to increase S/B
- Carefully chose input variables to avoid bias in $M_{\mu\mu}$

NN Input Variables

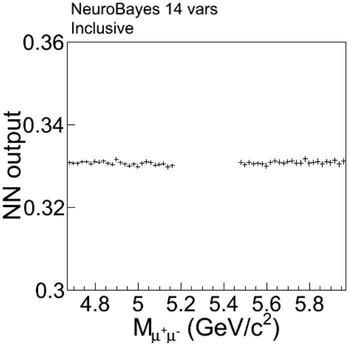
- λ (proper decay length)
- Isolation
- Pointing angle
- λ/σ_λ
- lower $p_T(\mu)$
- Secondary vertex χ^2
- Decay length (L_{3D})
- Transverse Decay length significance ($L_{xy}/\sigma_{L_{xy}}$)
- 2D Pointing angle
- Smaller impact parameter
- Larger impact parameter
- Smaller impact parameter significance
- Larger impact parameter significance
- $B_{s(d)}$ impact parameter



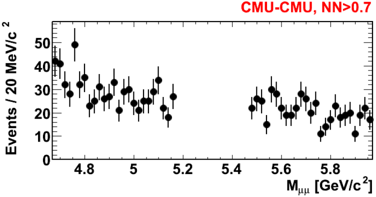


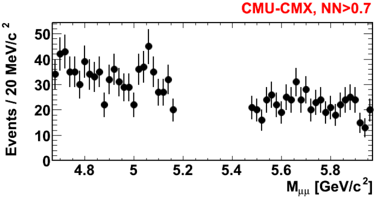
Dimuon Mass and NN Mass Bias Check

Mass bias checked with mass sideband regions



No mass bias

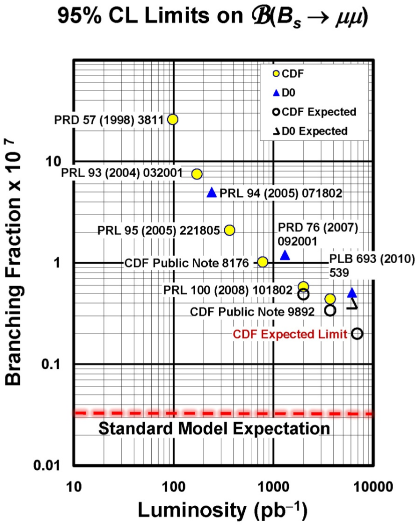




Expected Limits ($B_s \to \mu^- \mu^+$)

Limits at 95% CL (CDF)

	Expected	Observed
2fb^{-1}	4.9×10^{-8}	5.8×10^{-8}
3.7fb^{-1}	3.3×10^{-8}	4.3×10^{-8}
6.9fb^{-1}	$\sim 2\times10^{-8}$	-



Summary

- FCNC decays provide powerful probe to New Physics
- CDF and DØ experiment lead rare decay searches in B sector
- CDF on its way to provide most sensitive information on $B_s \to \mu^- \mu^+$ and $B_d \to \mu^- \mu^+$ rate with 2x data and improved analysis

Backup Slides

NN Input Variables and B^+ sample