$B_{s(d)} \rightarrow \mu^+\mu^-$ with 7 fb^{-1} of CDF Data

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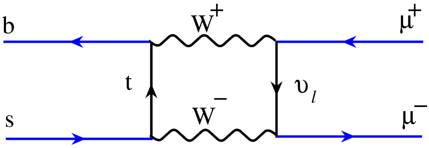
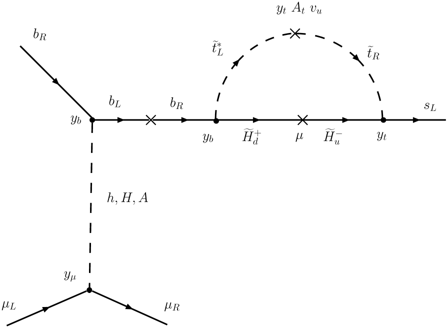
Motivation

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

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

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

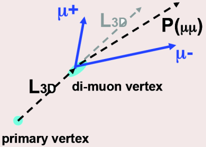
Analysis Flow Chart

- 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

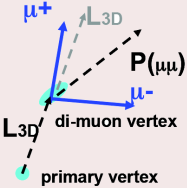
Signal Properties

- 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



Data Sample and Signal Selection

Central-Central (CMU) and Central-Forward (CMX) Di-muon Trigger

- **Central**: p_T >2.0 GeV and $|\eta|$ <0.6 – **Forward**: p_T >2.2 GeV and 0.6< $|\eta|$ <1.0
- p_T cuts restrict us to well understood trigger regions

Basic Quality Cuts

- Tracker tracks with hits in 3 silicon layers
- Likelihood and dE/dx based muon Id
- Vertex Quality
- Various Baseline Cuts
  - $p_T(\mu^+\mu-) > 4.0$ GeV;
  - Loose Isolation and opening angle (pointing) cuts

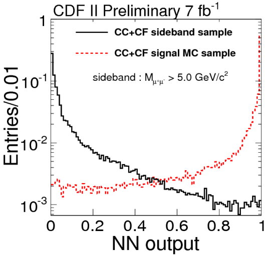
Still background dominated after a reduction of events of 4 orders of magnitude

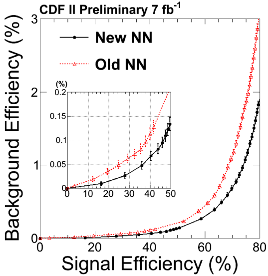
Neural Network

- 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

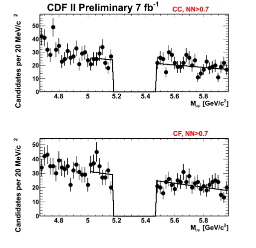




Background Estimates

Combinatorial Background

- Use sideband to estimate combinatorial background in signal window
- Assign systematic errors on background estimates based on slope variation
- Highest 3 NN bins have additional systematic from uncertainty of background shape



Peaking Background

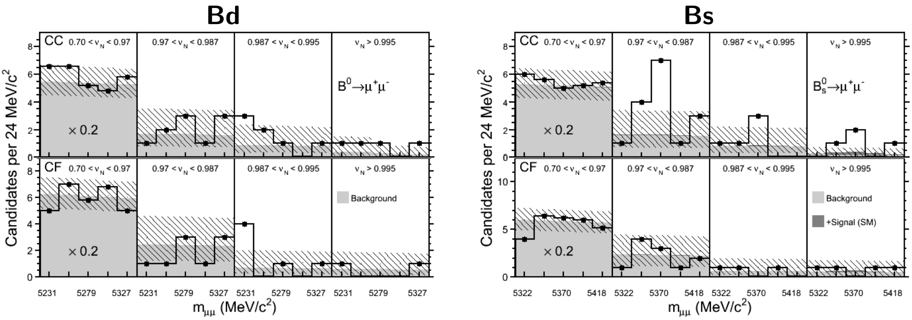
- $B \to hh$ processes where both hadrons (either kaons or pions) are misidentified as muons
- Estimate fake rate dataset rich in kaons and pions ($D*$-tagged $D^0 \to K^+\pi^-$
- Use MC to similulate kinematics of processes

Control Samples: Background Estimate Cross Checks

- 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

Checked background with 64 samples ⇒ good agreement between predicted and observed

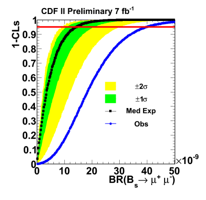
Results: Unblinded Mass Plots



Results: Limits and P-Values

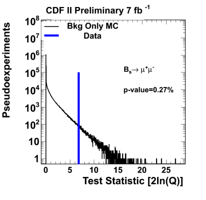
Limits

- Set limits using CLs methodology
- No excess in B_d, limit:
  $\mathcal{B}(B_d \rightarrow \mu^+\mu^-) < 6.0 \times 10^{-9}$ at 95% C.L.
- Significant excess in B_s, limit:
  $\mathcal{B}(B_s \rightarrow \mu^+\mu^-) < 4.0 \times 10^{-8}$ at 95% C.L.



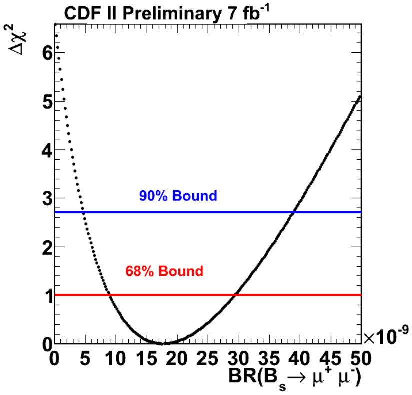
P-Values

- Generate background only MC
- Compare observed LLR ($\frac{P(s+b|data)}{P(b|data)}$) value with LLR distribution of MC
- P-value for bkg only hypothesis: 0.27%
- P-value for SM+bkg hypothesis: 1.9%



Results: Central Value

- Estimate central value for B_s case using χ^2 fit
- Measured central value: $\mathcal{B}(B_s \to \mu^+\mu^-) = 1.8^{+1.1}_{-0.9} \times 10^{-8}$
- 90% bounds: $4.6 \times 10^{-9} < \mathcal{B}(B_s \to \mu^+\mu^-) 3.9 \times 10^{-8}$



Summary

- First two sided limit from CDF using 7 fb^{-1} of data
- Compatible with limits set by CMS and LHCb
- Plan to update the analysis with full CDF dataset ($\sim$10 fb^{-1})