Rare B Meson Decays at Tevatron

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for the CDF Collaboration

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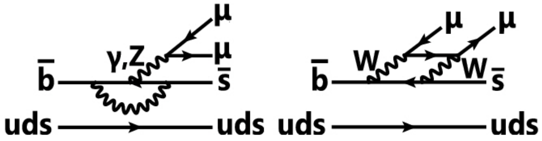
$b \to s\mu^+\mu^-$

CDF, 6.8 fb^{-1}, arXiv:1108.0695, Phys. Rev. Lett. 107, 201802 (2011)

Motivation



Theory

- $b \rightarrow s\mu^+\mu^-$ can only occur through higher order FCNC diagrams in Standard Model (SM)
- New Physics Search: Angular Measurements

Experimental Status

- $B^+ \rightarrow \mu^+\mu^- K^+$: BaBar, Belle, CDF
- $B^0 \rightarrow \mu^+\mu^- K^*$: BaBar, Belle (2.7$\sigma$ deviation for A_{FB}), CDF
- $B_s \rightarrow \mu^+\mu^- \phi$: **CDF, DØ**
- $B^+ \rightarrow \mu^+\mu^- K^{*+}$: BaBar, Belle, CDF
- $B^0 \rightarrow \mu^+\mu^- K_s$: BaBar, Belle, CDF
- $\Lambda_b \rightarrow \mu^+\mu^- \Lambda$: **CDF**

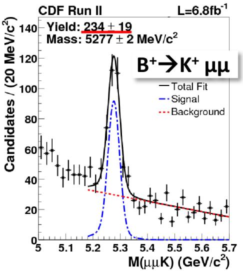
Analysis Flow

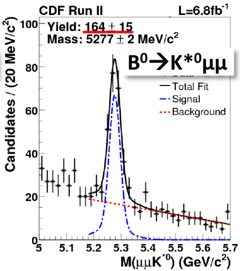
- Measure non-resonant modes w.r.t. corresponding resonant modes ($J/\Psi \rightarrow \mu^+\mu^-$)
- Use dimuon trigger
- Reconstruct $H_b \rightarrow h\mu^+\mu^-$
- Optimize selection with multivariate discriminant
- Measure $\mathcal{B}$
- Angular measurements

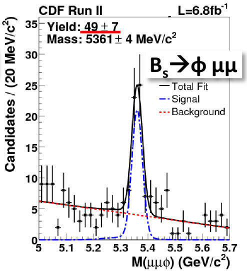
Signal and Control

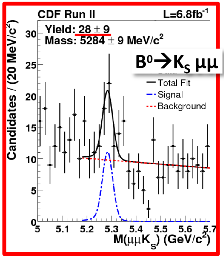
Signal Mode	Hadron Decay
$B^+ \rightarrow \mu^+\mu^- K^+$	-
$B^0 \rightarrow \mu^+\mu^- K^{*0}$	$K^{*0} \rightarrow K^+\pi^-$
$B_s \rightarrow \mu^+\mu^- \phi$	$\phi \rightarrow K^+K^-$
$B^+ \rightarrow \mu^+\mu^- K^{*+}$	$K^{*+} \rightarrow K_s\pi^+$
$B^0 \rightarrow \mu^+\mu^- K_s$	$K_s \rightarrow \pi^+\pi^-$
$\Lambda_b \rightarrow \mu^+\mu^- \Lambda$	$\Lambda \rightarrow p\pi^-$

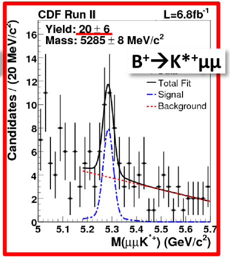
Meson Decays







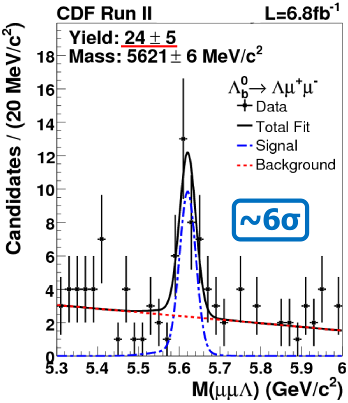




First reconstruction at hadron collider

Λ_b Decay

- Theory expectation: $(4.0 \pm 1.2) \times 10^{-6}$ Phys.Rev.D81, 056006 (2010)
- Rarest Λ_b to date

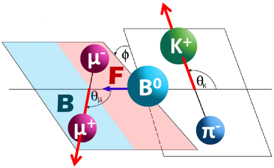


$$\mathcal{B}(\Lambda_b \to \mu^+\mu^-\Lambda) = (1.73 \pm 0.42[\text{stat}] \pm 0.55[\text{syst}]) \times 10^{-6}$$

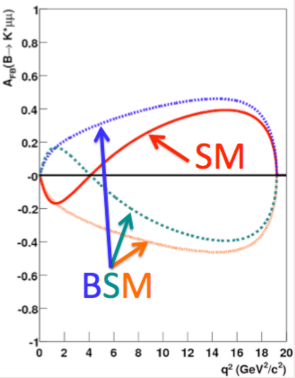
First Observation

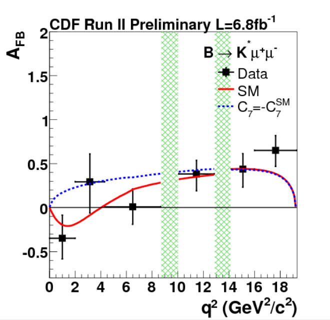
Angular Observables

- Sensitive to non-SM physics
- For $B^0 \to \mu^+\mu^- K^*$ there are many prediction from several new physics models
- Measure $A_T^{(2)}$, A_{Im}, A_{FB}, and F_L



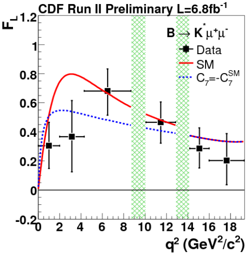
Expectations and Observations

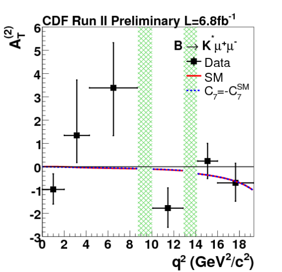


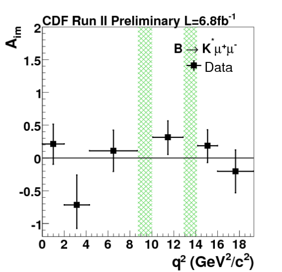


$$A_{FB}(1 < q^2 < 6) = 0.29^{+0.20}_{0.23}\ (\text{stat}) \pm 0.07\ (\text{syst})$$

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







First measurements of right handed currents $A_T^{(2)}$ and A_{im}

No significant deviation from SM with current statistics

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

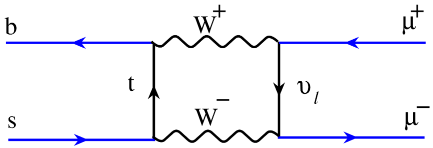
and

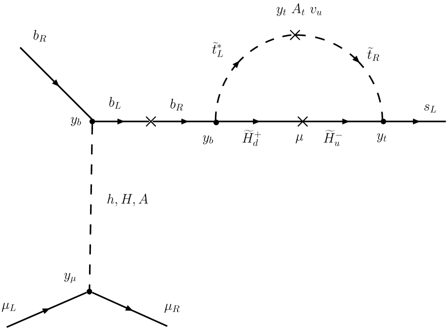
$$B_d \to \mu^- \mu^+$$

CDF, 7 fb^{-1}, Phys. Rev. Lett. 107, 191801 (2011)

Motivation

- $B_s \to \mu^+\mu^-$ can only occur through higher order FCNC diagrams in Standard Model (SM)
- Suppressed by the GIM Mechanism and helicity
- SM predicts very low rate with little SM background ($\mathcal{BR}(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$, $\mathcal{BR}(B_d \to \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$, E.Gamiz et al. (HPQCD Collaboration), A.J. Buras et al.
- 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





Analysis Description

Simple Analysis

- 2 Muons
- Identify methods of suppressing background and keep signal
- Look for bump in di-muon mass distribution

Analysis Strategy

- Blind ourselves to di-muon signal mass region
- Use mass sidebands to estimate dominant background in signal region
- Optimize selection criteria a priori
- Build confidence in background estimates by employing same methods on control regions

What do we measure?

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

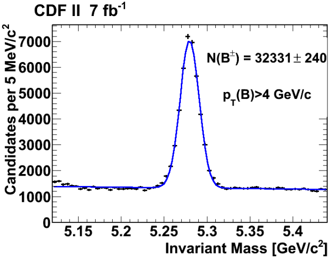
From Data, From MC, From PDG

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

$\frac{\epsilon^{reco}_{B^+}}{\epsilon^{reco}_{B_s}} \sim 1$, $\frac{\alpha_{B^+}}{\alpha_{B_s}} \sim 0.5$, $\frac{1}{\epsilon^{NN}_{B_s}} \sim 1$

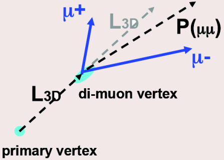
$\frac{f_u}{f_s} \sim 3$, $\mathcal{B}(B^+ \to J/\Psi K^+ \to \mu^+\mu^- K^+) \sim 5 \times 10^{-5}$

- 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, e.g. dimuon trigger efficiency is the same for both modes



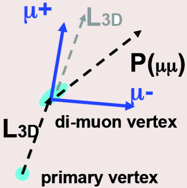
Signal Properties

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



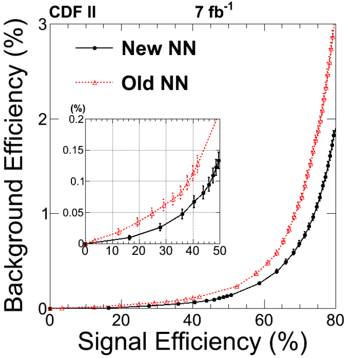
Background contributions & characteristics

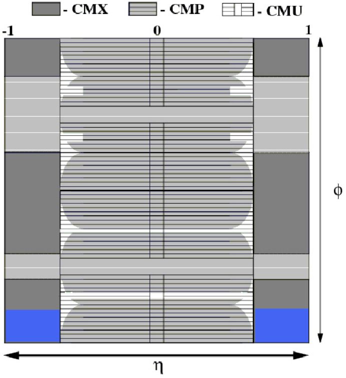
- Sequential semi-leptonic decay: $b \to c\mu^- X \to \mu^+\mu^- X$
- Double semi-leptonic decay: $bb \to \mu^-\mu^+ X$
- Continuum $\mu^-\mu^+$
- μ + fake and fake+fake
  - Partially reconstructed
  - Softer
  - Short lived
  - Has more tracks
- $B \to hh$: peaking in signal region



Analysis Improvements

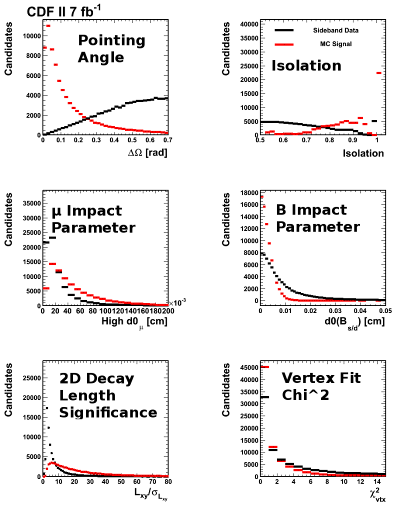
- $\sim$50% more data
- 20% Increase in acceptance from CMX miniskirts and COT spacer regions
- New dE/dx calibration for better μ ID
- Improved fake rates for peaking background est.
- New NN with 2x better background rejection

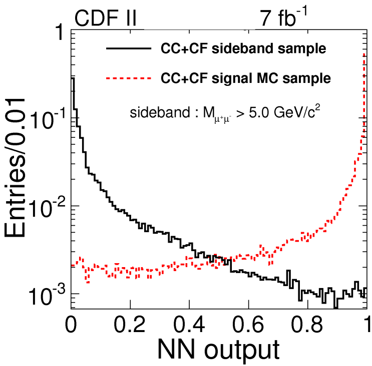




Signal Discrimination

- 14 Discriminating variables
- Invariant mass of muons with 2.5σ window, σ=24 MeV





- Combined in NN, optimized with signal MC and data mass sideband
- Optimize NN a priori with data mass sideband and signal MC
- Validated NN with normalization mode and control region

Background Estimates

Combinatorial Background

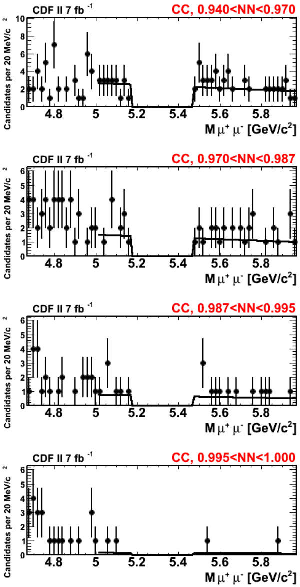
- Fit common slope to all sidebands of NN bins
- Estimate systematics due to shape uncertainty

Peaking background

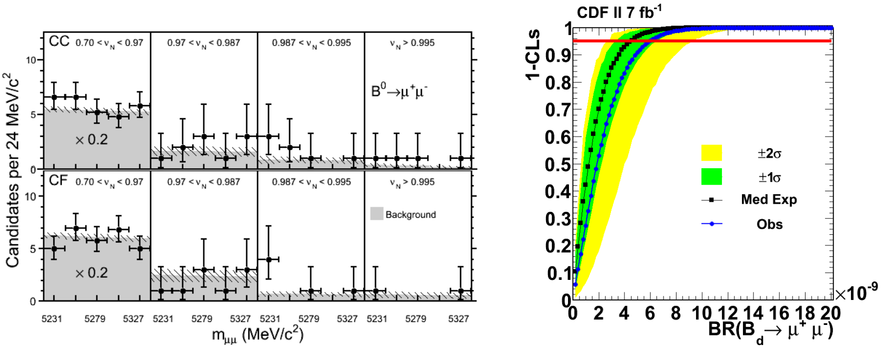
- Only peaking background is $B \to hh$
- Estimated using MC and D^*-tagged $D^0 \to \pi^+ K^-$ data
- Only 10% of combinatorial background in B_s
- 10x larger in B_d

Background Cross Checks

- Use background enhanced samples to check background procedure
- Good agreement



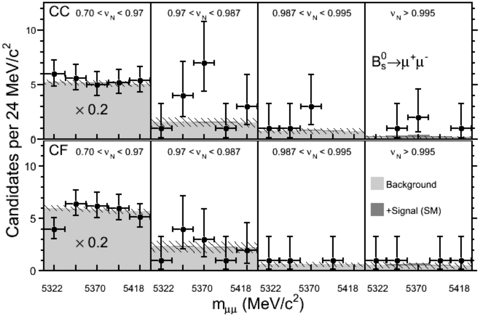
Results: B_d

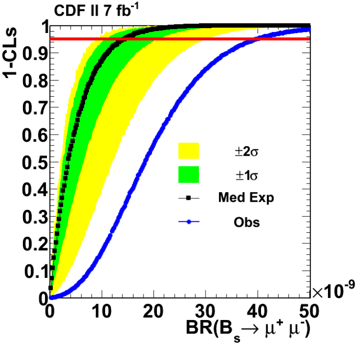


- Five mass bins
- Five lowest NN bins combined
- Light gray: Background estimates, Hashed: Systematic errors on background
- Error bars on points: Poisson error on mean
- Expected limit: $\mathcal{B}(B_d \to \mu^+\mu^-) < 4.6 \times 10^{-9}$ @ 95% C.L.
- **No excess in B_d mass region (p-value=23%)**

B_d limit: $\mathcal{B}(B_d \to \mu^+\mu^-) < 6.0 \times 10^{-9}$ @ 95% C.L.

Results: B_s



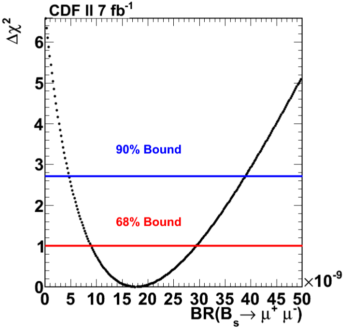


- Dark gray: Expected SM signal
- Expected limit: $\mathcal{B}(B_s \to \mu^+\mu^-)<1.5 \times 10^{-8}$ @ 95% C.L.
- **Excess over background-only in central region (the most sensitive)**
  - p-value for background only hypothesis: 0.27%
  - p-value for SM+background hypothesis: 1.92%

B_s **limit:** $\mathcal{B}(B_s \to \mu^+\mu^-)<4.0 \times 10^{-8}$ **@ 95% C.L. (**$> 2\sigma$ **from expected)**

B_s: Central Values, Bounds and P-Values

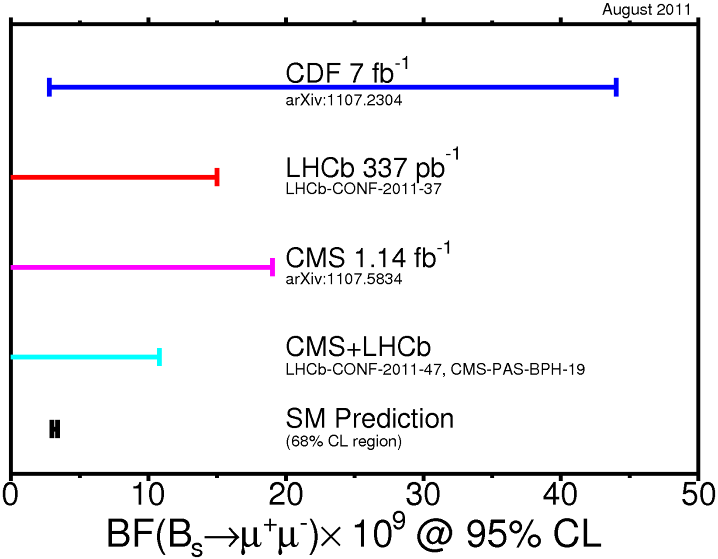
- Includes all systematics
- 90% Bound:
  $4.6 \times 10^{-9} < \mathcal{B}(B_s \to \mu^+\mu^-) < 3.9 \times 10^{-8}$
- Stable: No large deviation when only using subset of bins



Summary of p-values and limits

	All Bins	2 Highest NN Bins
Best Fit ($\times 10^{-8}$)	$1.8^{+1.1}_{-0.9}$	$1.4^{+1.0}_{-0.8}$
90% Bounds ($\times 10^{-8}$)	$0.46 < \mathcal{B} < 3.9$	$0.33 < \mathcal{B} < 3.3$
Bkg Only p-value	0.27%	0.66%
SM+Bkg p-value	1.92%	4.14%

Current Experimental Status



Summary

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

- Updated CDF analysis with more data and analysis improvements
- First observation or $\Lambda_b \to \mu^+\mu^-\Lambda$
- First measurement of $A_T^{(2)}$ and A_{im}
- World's best or comparable results for A_{FB}
- Agreement with SM

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

- CDF updated the $B_s \to \mu^+\mu^-$ search with doubled dataset (7fb^{-1}) and improved analysis technique
- CDF has excess of $B_s \to \mu^+\mu^-$ events at the level of 2.7σ relative to background only hypothesis
- Set the first two-sided bound on the rate: $4.6 \times 10^{-9} < \mathcal{B}(B_s \to \mu^+\mu^-) < 3.9 \times 10^{-8}$ at the 90% CL, compatible with SM and other experiments
- Set upper bound on $B_d \to \mu^+\mu^-$ of $\mathcal{B}(B_d \to \mu^+\mu^-) < 6.0 \times 10^{-9}$
- Update analysis with full CDF dataset is ongoing

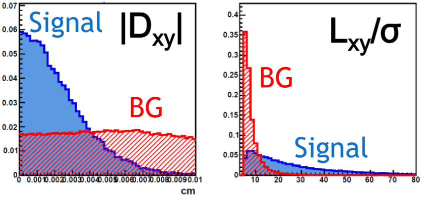
Backup Slides

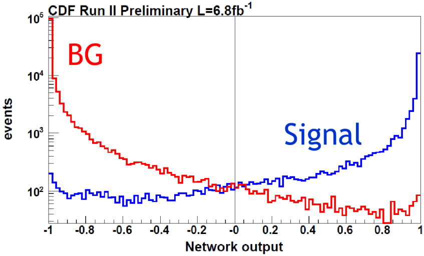
Event Selection

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

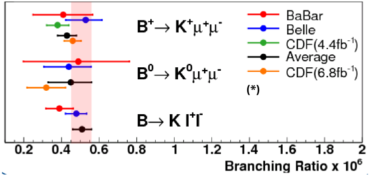
Kinematical variables

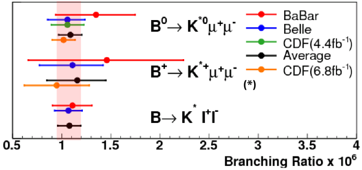


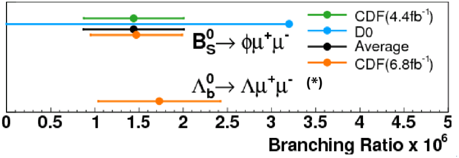


$p_T(H_b)$, $p_T(h)$, $p_T(\mu)$, h mass, D_{xy}, L_{xy}/σ, muon likelihood...

Summary of $\mathcal{B}$ Measurements







World's most precise $\mathcal{B}(b \to s\mu^+\mu^-)$ measurements

Background Estimate Check

- Check background estimates with background dominated control samples
  - Signal has two opposite sign muons with positive lifetime
  - Control samples have opposite sign negative lifetime, same-sign positive/negative lifetime, and reverse muon ID
  - Total of 64 samples
- Apply same background methods on control sample that we can unblind

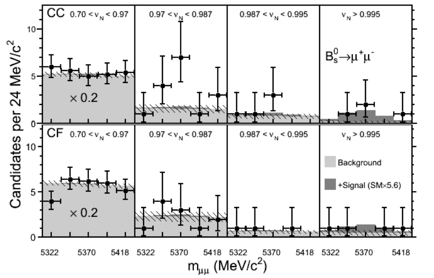
	CC		
NN cut	pred	obsv	prob(%)
0.700<NN<0.760	217.4±(12.5)	203	77.7
0.760<NN<0.850	262.0±(14.1)	213	99.1
0.850<NN<0.900	117.9±(8.6)	120	44.7
0.900<NN<0.940	112.1±(8.4)	116	39.4
0.940<NN<0.970	112.7±(8.4)	108	64.2
0.970<NN<0.987	80.2±(6.9)	75	68.3
0.987<NN<0.995	67.6±(6.3)	41	99.8
0.995<NN<1.000	32.5±(4.2)	35	37.5

Good agreement between observed and expected background

Third NN Bin Excess

Background Estimate Problem

- Combinatorial Background Problem
  - B_d Uses same sideband as $B_s \Rightarrow$ No excess in B_d
- Peaking Backgound Problem
  - Only peaking background is $B \to hh$
  - 10x larger in B_d region
  - No excess in $B_d \Rightarrow$ good fake rates

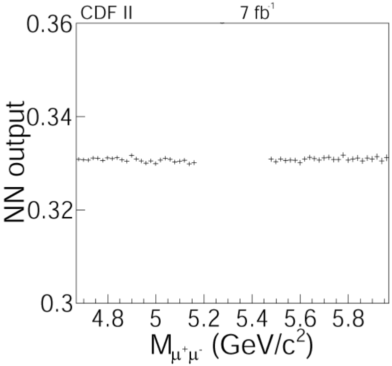


Neural Network Problem

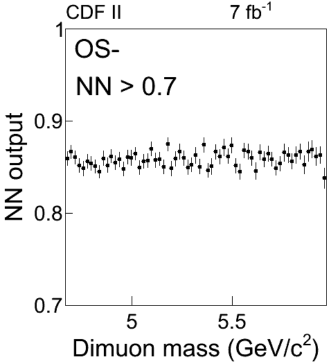
- Mass bias?
- Overtrained?
- Mismodels data?

NN Studies: Mass bias

NN Output vs Dimuon Mass for Signal Sample (blinded)



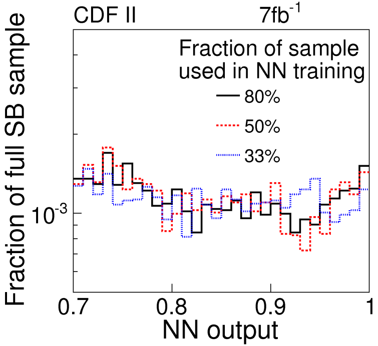
NN Output vs Dimuon Mass for Control Sample



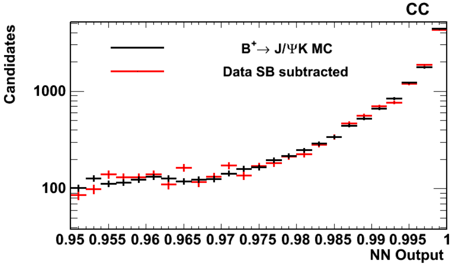
Unlikely to be cause of excess in 3rd NN bin of CC

NN Studies: Overtraining and Mismodeling

NN SB background eff for NN's trained on different fractions of SB



$B^+ \to J/\psi K^+$ MC and Data Signal NN Output Distribution



Unlikely to be cause of excess in 3rd NN bin of CC

MC models data well

Conclusion on 3rd NN bin

- Not due to any NN mismodeling
- Not due to background mismodeling
- **Only explanation left: Not unlikely statistical fluctuation in 80 bins**

From PRL:

In short, there is no evidence that the excess in this bin is caused by a mistake or systematic error in our background estimates or our modeling of the ν_{NN} performance and distribution. The most plausible remaining explanation is that this is a statistical fluctuation.