Flavor Physics at CDF

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for the CDF Collaboration

SUSY 2012

Topics

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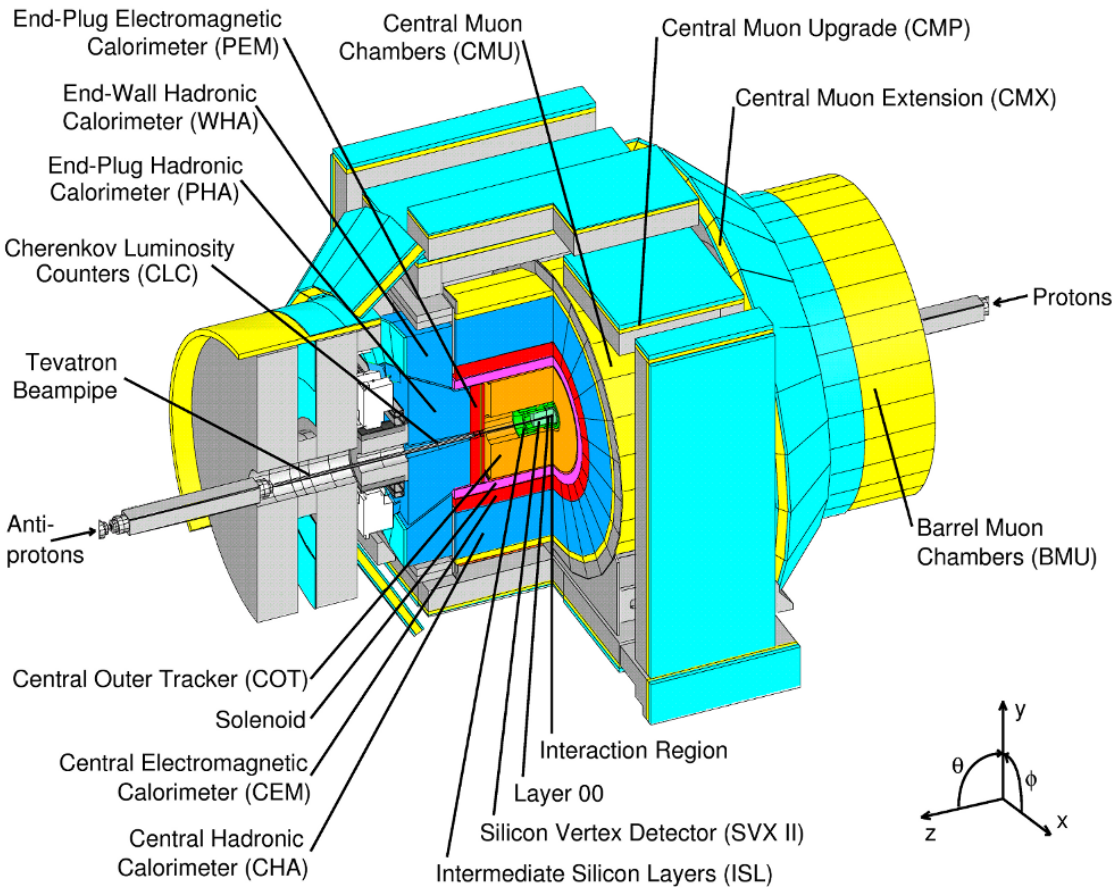
- CP Violation in Heavy Flavor
  - $B_s^0 \to J/\psi\phi$
  - $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$
  - $H_b \to h^+ h'^-$ ($h = \pi^\pm$, $h = K^\pm$, $h = p$)
  - $D \to h^+ h^-$ ($h = \pi^\pm$, or $h = K^\pm$)
- Rare Heavy Flavor Decays
  - $b \to s\mu^+\mu^-$
  - $B_{s,d} \to \mu^+\mu^-$

Outline

- Motivation
- Analysis Method
- Results

CDF II Detector

- Multi-purpose detector
- Silicon vertex detector close to beam line ⇒ secondary vertex identification
- Central Outer Tracker (COT) ⇒ multi-wire drift chamber
  - Measure track trajectory
  - Measure deposited ionization energy (dE/dx)
- Good Muon drift chambers: Central (C) and some Forward (F) (yellow and cyan)



Heavy Flavor Reconstruction at CDF

- B and D mesons have long lifetimes ($\sim 450\mu$m and $\sim 120\mu$m)
  - Signature: displaced vertex

Two triggers used

- Dimuon: requires two tracks matched to muon chambers
  - $B_s^0 \to J/\psi\phi \to \mu^+\mu^- K^+K^-$
  - $b \to s\mu^+\mu^-$
  - $B_{s,d} \to \mu^+\mu^-$
- Displaced vertex trigger: require two tracks with displaced vertex
  - $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$
  - $H_b \to h^+h'^-$
  - $D \to h^+h^-$

CP Violation in Heavy Flavor

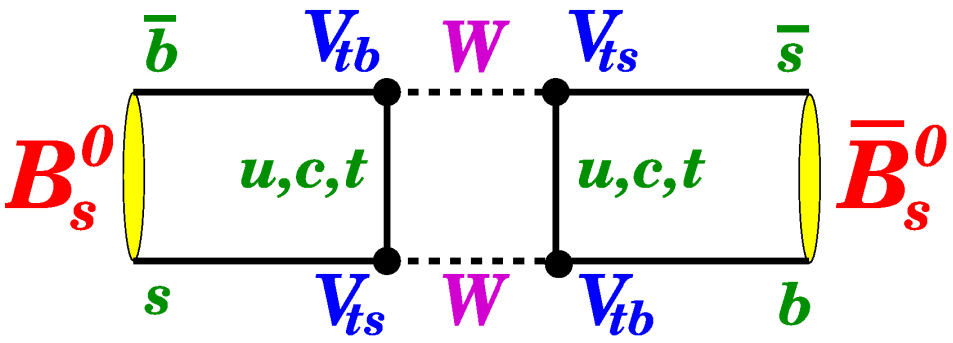
$$B_s^0 \to J/\psi\phi$$

Using 10 fb^{-1}

CDF Public Note 10784

Motivation

- B mesons mix with $\overline{B}$ mesons
- Light (B_L) and heavy (B_H) eigenstate $\rightarrow$ different decay rates for light and heavy states
- CP violation in $B_s^0 \rightarrow J/\psi\phi$ decay from mixing
- Relative phase between decay rates with and without mixing
  $\phi_s = 2 \cdot arg[-(V_{ts}V_{tb})/(V_{cs}V_{cb})] + \phi_s^{NP}$
- SM CP violation small, theoretically well understood
- Several NP scenarios predict enhancements $\rightarrow$ new contributions in loop?



Measurements

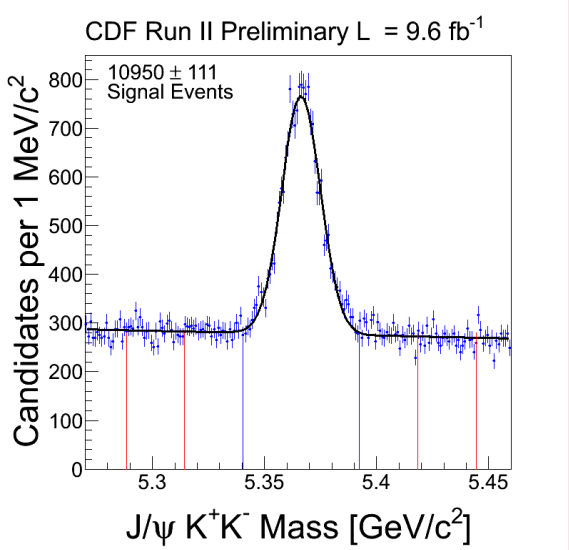
- CP violating mixing phase in $B_s^0 \rightarrow J/\psi\phi$
- Decay rate difference, $\Delta\Gamma_s = \Gamma_L - \Gamma_H$

Analysis Flow

Reconstruction

- Reconstruct J/ψ with dimuons and ϕ with dikaons
- Data collected with dimuon trigger
- Offline requirements using multivariate discrimant with kinematic variables

Final Yield $\sim$ 11K events



Complex unbinned likelihood fit

- Mass for signal and background separation
- Transversity angles (since we have pseudo-scalar $\rightarrow$ 2 vectors)
- Decay time for time evolution
- Flavor tagging: separate $\overline{B}$ and B
  - Look at lepton from B meson from other b quark produced
  - Look at $K^{\pm}$ produced with B meson

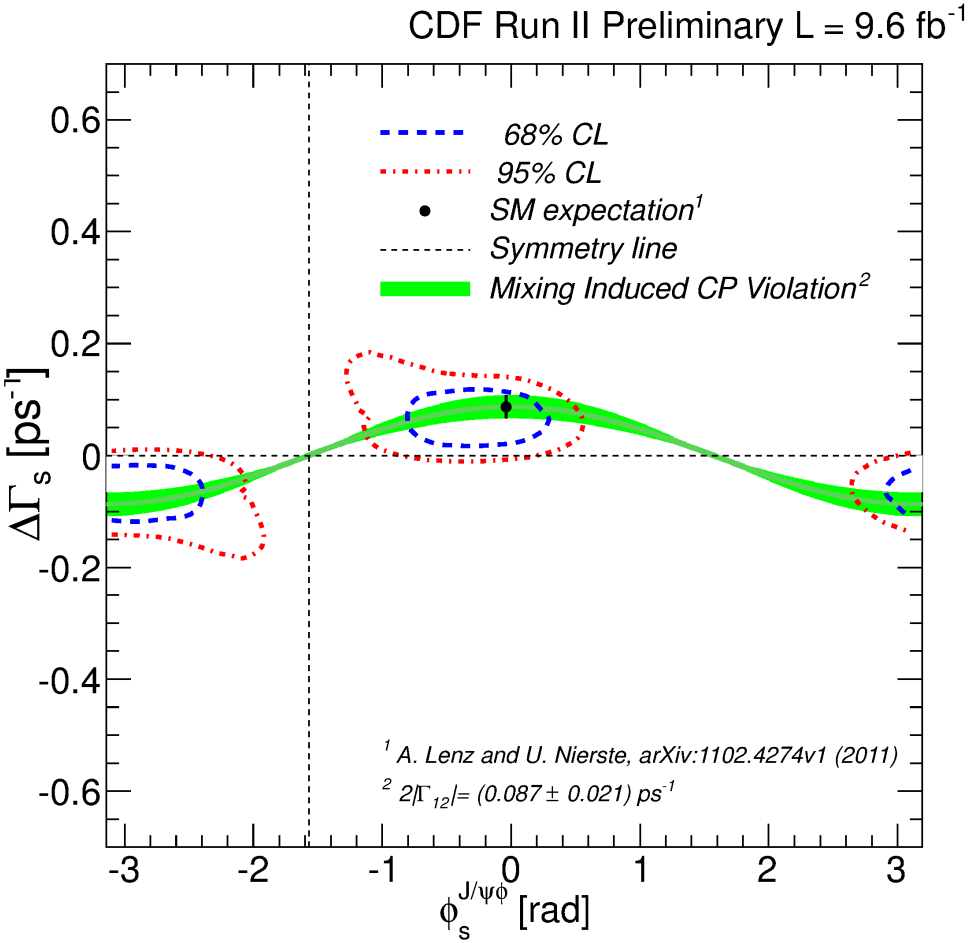
Decay Rate Result

$$\mathbf{\Delta\Gamma_s = 0.068 \pm 0.026\ (stat) \pm 0.007\ (syst)\ ps^{-1}}$$
$$\mathbf{\tau_s = 1.528 \pm 0.019\ (stat) \pm 0.009\ (syst)\ ps}$$

- Assumed SM like $\phi_s \sim 0$
- Consistent with SM and other experiments
- Important constraints on NP models and D0 a_{SL} result
- Among world's best result

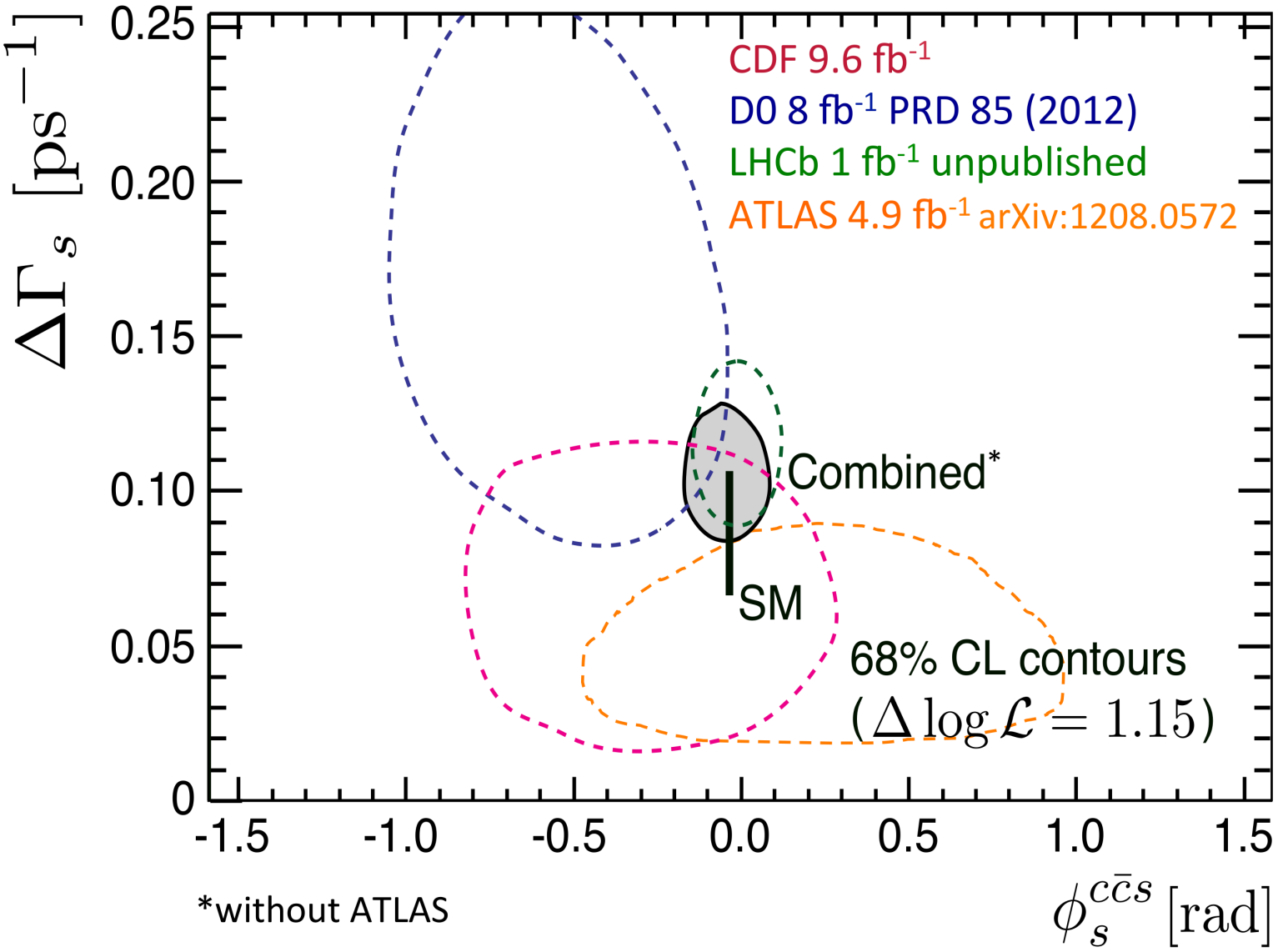
Mixing Phase Result

- p-value=54%
- 40% decrease in errors since 5fb^{-1} analysis



CDF Public Note 10784

Experimental Status



*without ATLAS

$$B_s^0 \to D_s^{(*)+} D_s^{(*)-}$$

Using 6.8 fb^{-1}

Phys. Rev. Lett. 108, 201801 (2012)

Motivation

- Light and heavy states, B_L and B_H, with different decay rates
- Mainly CP even $\rightarrow$ could give insight to Γ_L
- Under certain theoretical assumptions: $\frac{\Delta\Gamma_s}{\Gamma_s} \sim \frac{2\mathcal{B}}{1-\mathcal{B}}$ for $B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-}$
  - Could yield $\Delta\Gamma_s$ test

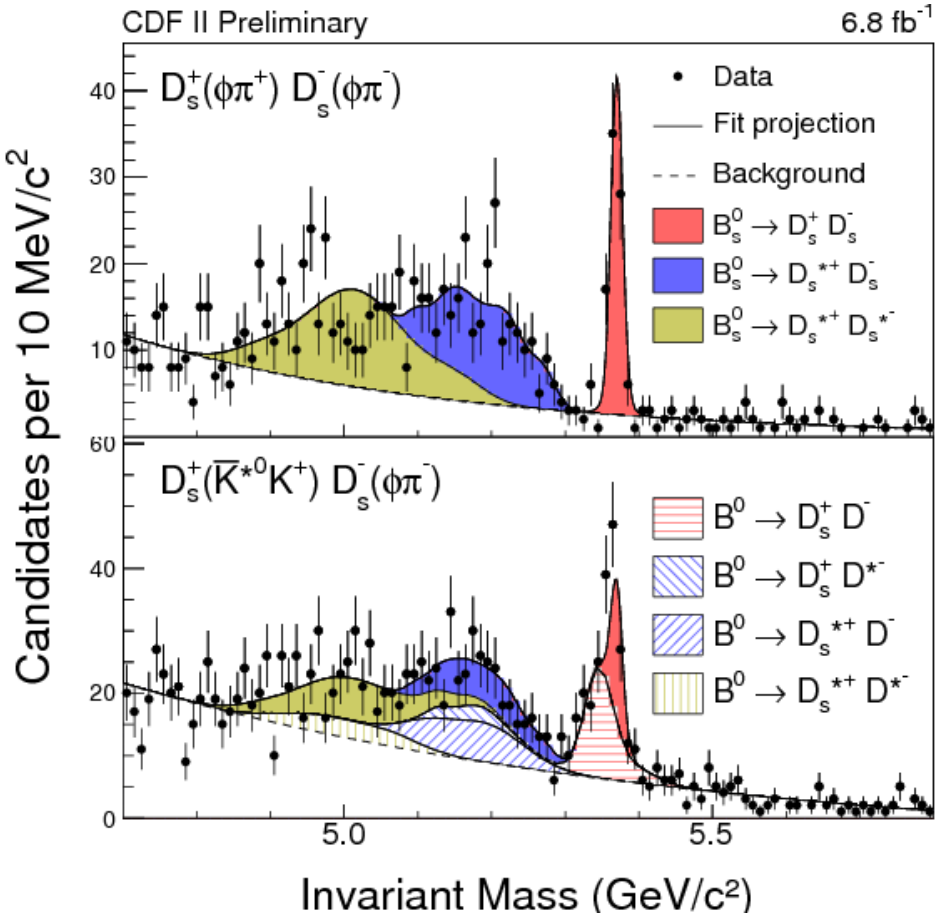
Analysis Flow

- Displaced Vertex Trigger
- Measure $\mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-})$ relative to $\mathcal{B}(B_d^0 \to D_s^+ D^-)$
- Offline requirements using multivariate discrimant with kinematic and vertex variables as input
- Use of Dalitz structure for precise efficiency/acceptance estimate
- Perform unbinned max likelihood fit simultaniously to normalization and signal mode

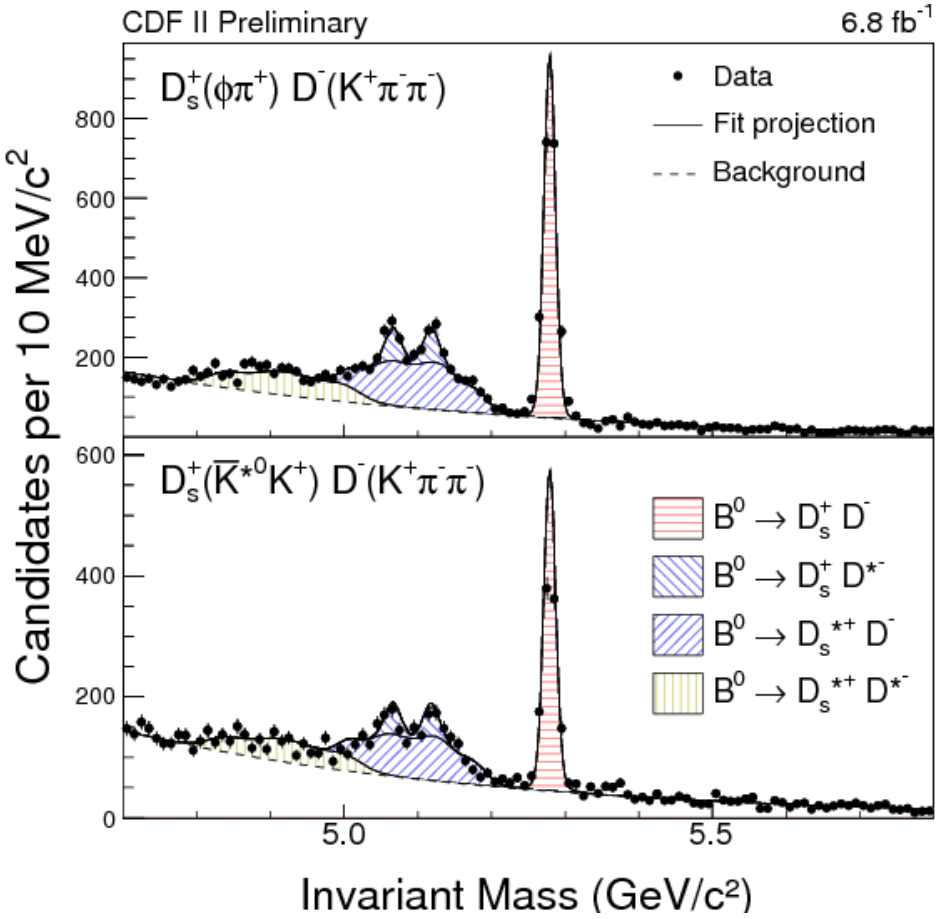
Final Yield $\sim$ 750 events

Results

$D_s^+ D_s^-$



$D_s^+ D^-$



Results

Branching Ratio

Mode	Result (stat) (syst) (norm)
$\mathcal{B}(B_s^0 \to D_s^+ D_s^-)$	$(0.49 \pm 0.06 \pm 0.05 \pm 0.08)\%$
$\mathcal{B}(B_s^0 \to D_s^{*\pm} D_s^{\mp})$	$(1.13 \pm 0.12 \pm 0.09 \pm 0.19)\%$
$\mathcal{B}(B_s^0 \to D_s^{*+} D_s^{*-})$	$(1.75 \pm 0.19 \pm 0.17 \pm 0.29)\%$
$\mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-})$	$(3.38 \pm 0.25 \pm 0.30 \pm 0.56)\%$

- PDG values for B_d^0 BR and f_u/f_s
- One of world's best measurements
- $\Delta\Gamma_s/\Gamma_s \sim (6.99 \pm 0.54\ (\text{stat}) \pm 0.64\ (\text{syst}) \pm 1.20\ (\text{norm}))\%$

Phys. Rev. Lett. 108, 201801 (2012)

$$H_b \to h^+ h'^-$$

Using 10 fb^{-1}

CDF Public Note 10726

Motivation

- Tevatron is in a CP symmetric state: $p\overline{p}$
  - Same production rate for b and $\overline{b}$ quarks
- Search for CP violation in decay: Is $N(B \to F) = N(\overline{B} \to \overline{F})$?
- Recent unexpected result (BaBar) shows that CP violation in $B_d^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ very different
  - Relationship between $B_d^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$ well known, B_s^0 could be a good test

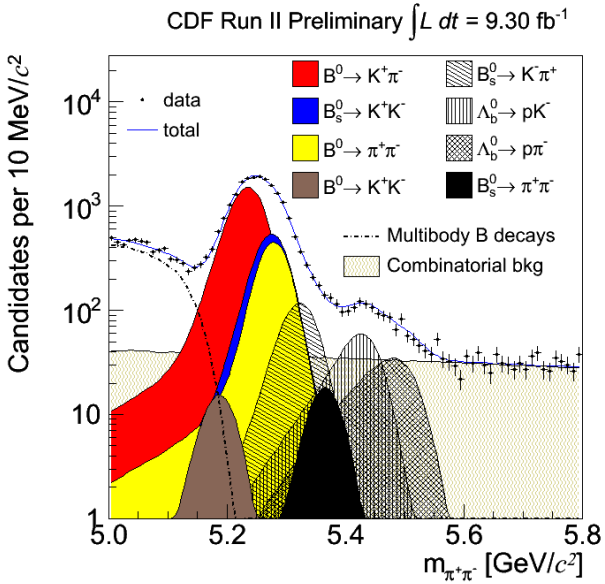
Measurements

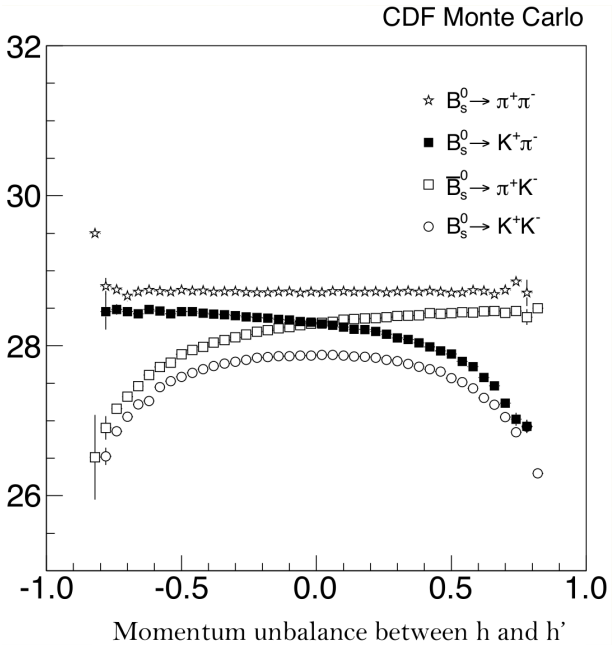
$$A_{CP} = \frac{N(B \to F) - N(\overline{B} \to \overline{F})}{N(B \to F) + N(\overline{B} \to \overline{F})}$$

- $B_d^0 \to K^+\pi^-$
- $B_s^0 \to K^-\pi^+$
- $\Lambda_b \to p\pi^-$
- $\Lambda_b \to pK^-$

Analysis Flow

- b-hadron decaying to combination of π, K, or protons
- Data collected with displaced vertex trigger
- Use likelihood fit
  - Mass and Momentum
  - PID: dE/dx, 1.4σ separation between K and π
- Extract $A_{CP} = \frac{N_{b\to f} - N_{\bar{b}\to\bar{f}}}{N_{b\to f} + N_{\bar{b}\to\bar{f}}}$
  - Account for detector asymmetries using D^*-tagged $D^0 \to K^-\pi^+$ and $\Lambda \to p\pi^-$: $\sim 1-2\%$





Results

Quantity	Result (stat) (syst)
$A_{CP}(B_d^0 \to K^+\pi^-)$	$-0.083 \pm 0.013 \pm 0.003$
$A_{CP}(B_s^0 \to K^-\pi^+)$	$+0.22 \pm 0.07 \pm 0.02$
$A_{CP}(\Lambda_b^0 \to p\pi^-)$	$+0.07 \pm 0.07 \pm 0.03$
$A_{CP}(\Lambda_b^0 \to pK^-)$	$-0.09 \pm 0.08 \pm 0.04$

- Compatible with B factories and LHCb
- Comparable precision to B factories and LHCb
- Confirms 3σ from CPV=0 in $B_s^0 \to K^+\pi^-$ result from LHCb
- $A_{CP}(B_s^0 \to K^+\pi^-)$ within 2σ of SM
- Not enough statistical power to separate Λ_b^0 SM prediction from NP.

CDF Public Note 10726

$$D \to h^+ h^-$$

Using 10 fb^{-1}

arxiv:1207.2158

Motivation

- No large SM higher order diagram contribution, could come from NP
- Theory predictions difficult but would expect little CP violation from SM
- LHCb found CP violation $D^0 \to h^+h^-$
  - Indicated direct CP violation (in decay and not mixing)
  - Need independent confirmation

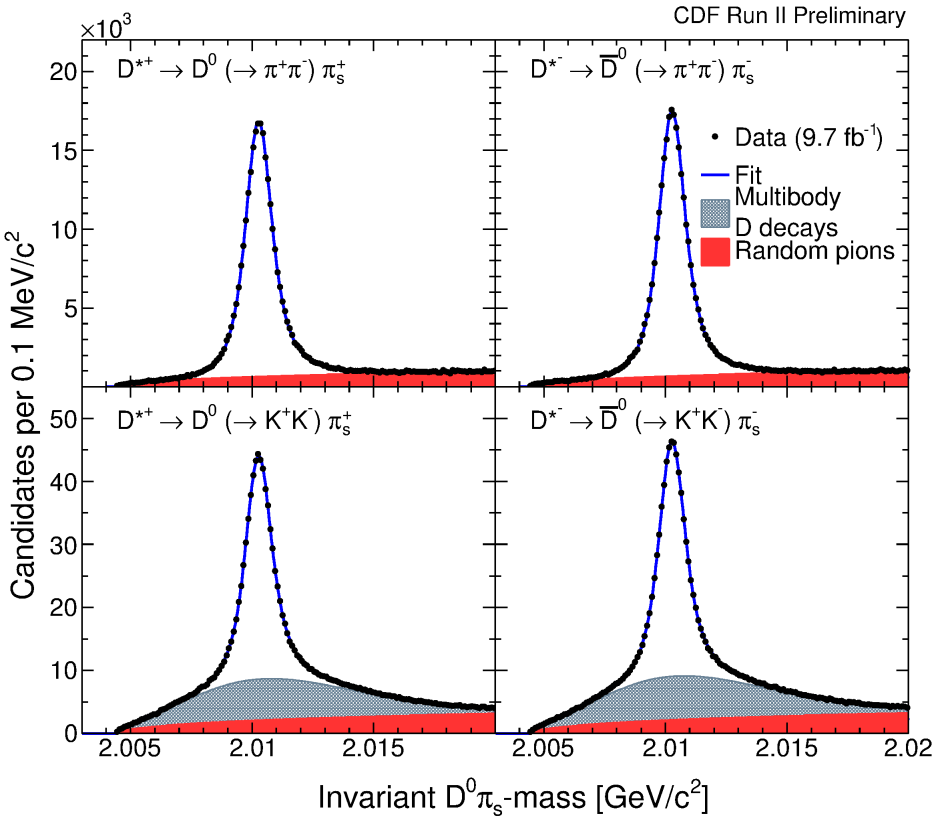
Measurements

$$A_{CP}(h^+h^-) = \frac{N(D^0 \to h^+h^-) - N(\overline{D}^0 \to h^+h^-)}{N(D^0 \to h^+h^-) + N(\overline{D}^0 \to h^+h^-)}$$

- $h^+h^- = \pi^+\pi^-$ or $h^+h^- = K^+K^-$
- Expect opposite sign for $\pi^+\pi^-$ and K^+K^-
- Difference in asymmetry: $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$

Analysis Flow

- New: Measure ΔA_{CP}, remove detector asymmetries
- Use displaced vertex trigger and offline kinematic and vertex requirements
- Use D^* tagged D^0 decays $\rightarrow$ know flavor of D^0 using soft pion charge
- Looser (than direct measurement) requirements needed for ΔA_{CP} $\rightarrow$ significant increase in statistics
- Perform fit to $D^0\pi$ mass to get yield



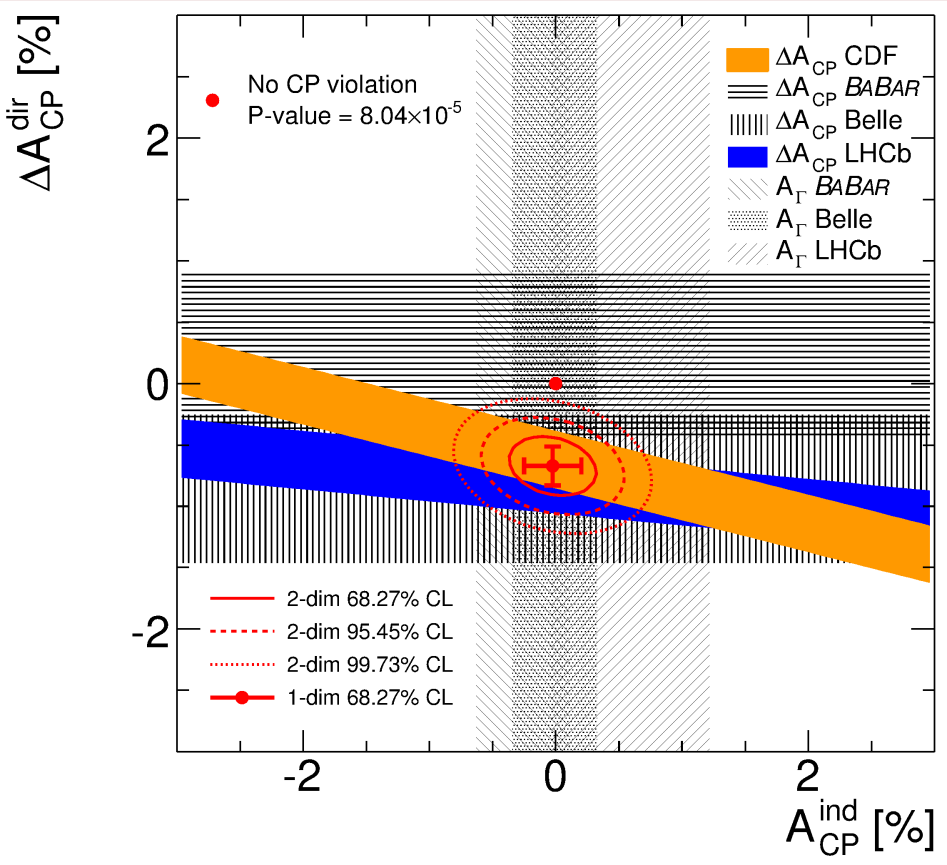
Yields

- 550K D^*-tagged $D^0 \rightarrow \pi^+\pi^-$
- 1.21M D^*-tagged $D^0 \rightarrow K^+K^-$

Results ΔA_{CP}

- D mesons oscillate $\Rightarrow$ indirect and direct A_{CP}
- A_{CP} can be divided into direct and indirect parts
  - $\Delta A_{CP} = \Delta A_{CP}^{dir} + \frac{\Delta t}{\tau} A_{CP}^{ind}$

- $\Delta A_{CP} = (-0.62 \pm 0.21 \pm 0.10)\%$
- Result is 2.7σ from CPV=0
- Within 1σ of LHCb central value



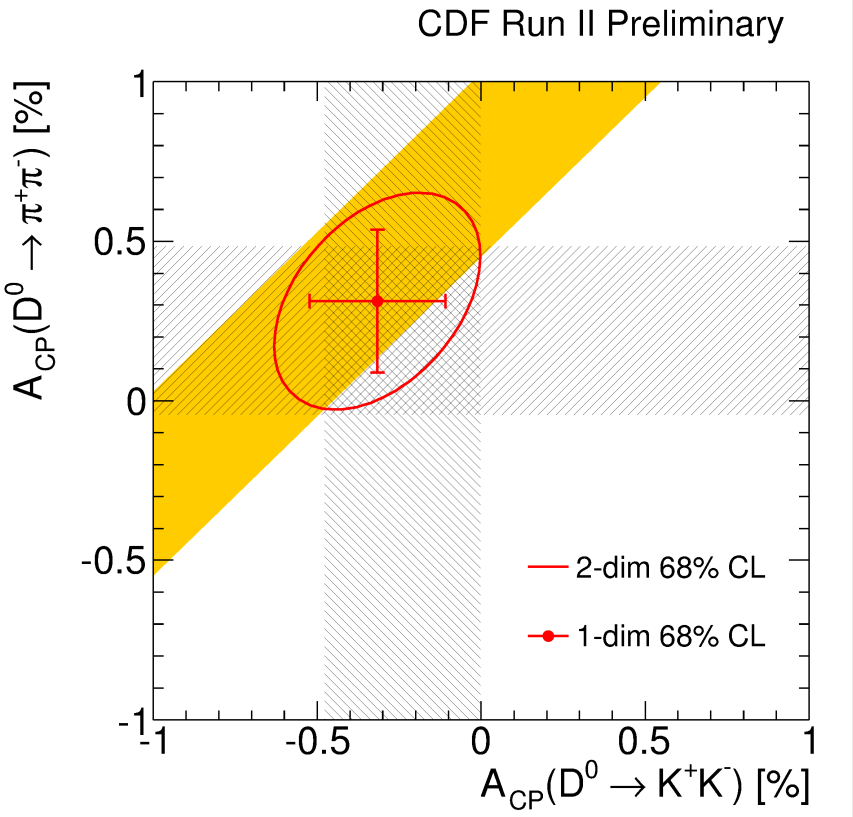
arxiv:1207.2158

Results for Separate A_{CP}

- Used D^*-tagged $D^0 \to K^-\pi^+$ decays to quantify detector asymmetries
- Combined ΔA_{CP} result for new data with separate A_{CP} from previous analysis

Results

$$A_{CP}(\pi^+\pi^-) = [0.31 \pm 0.22]\%$$
$$A_{CP}(K^+K^-) = [-0.32 \pm 0.21]\%$$



World's best measurement

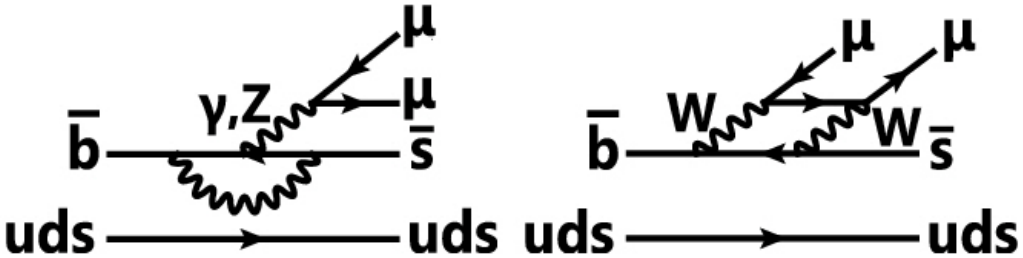
Rare B-meson decays

Rare B-meson decays

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

using 10 fb^{-1}

Motivation



- $b \to s\mu^+\mu^-$ can only occur through higher order FCNC diagrams in SM
- Possible enhancements from NP (new charged scalars, squarks, etc)

Measurements

- $\mathcal{B}(b \to s\mu^+\mu^-)$, SM predicts $10^{-6} - 10^{-7}$
- $\mathcal{B}(b \to s\mu^+\mu^-)$ as a function of $q^2 = M^2_{\mu^+\mu^-}$
- Angular Measurements in $B \to K^*\mu^+\mu^-$
  - A_{FB}: muon forward-backward asymmetry
  - F_L: K^* longitudinal polarization fraction

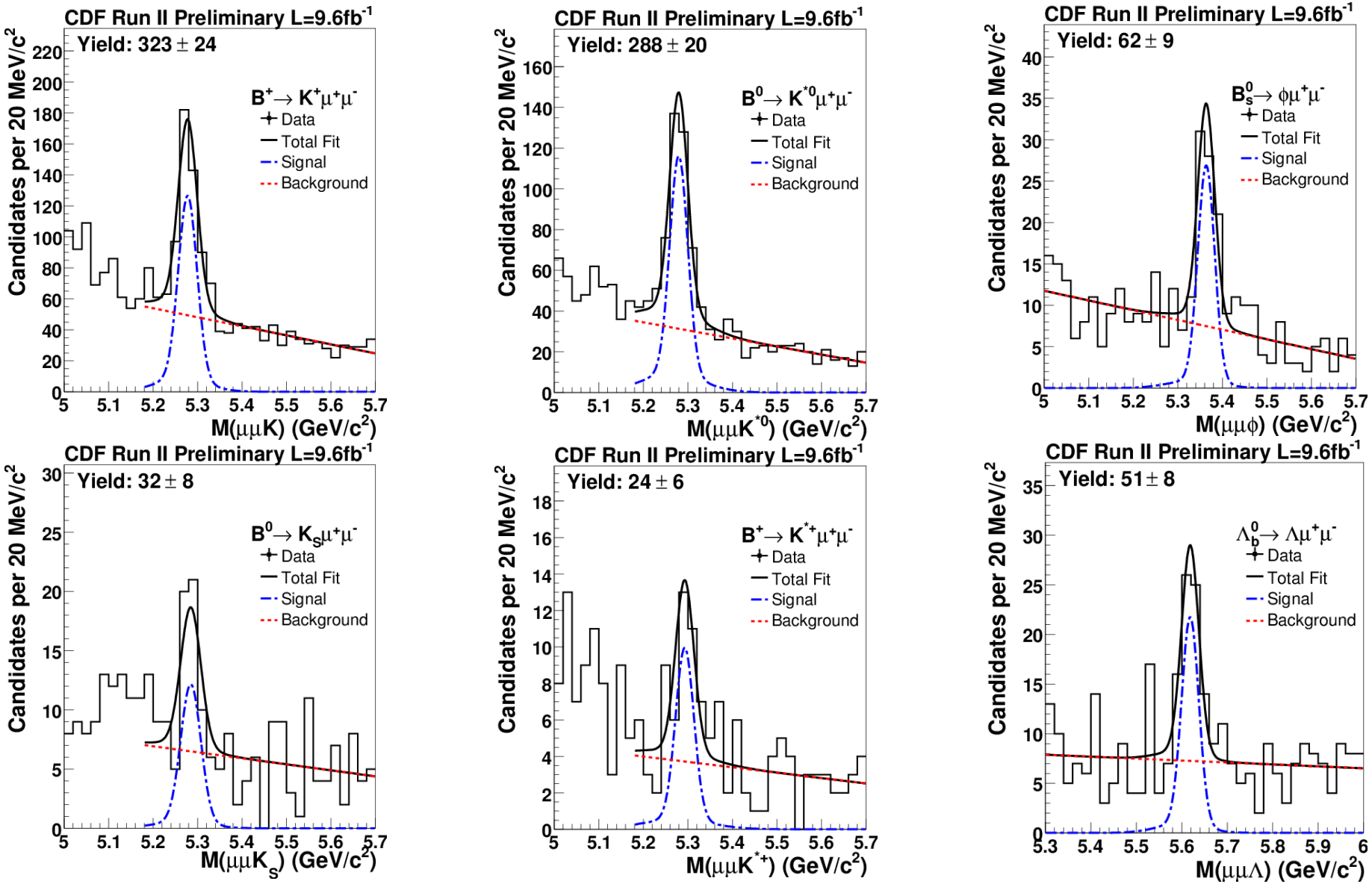
Analysis Flow

- Measure non-resonant modes w.r.t. corresponding resonant modes ($J/\psi \to \mu^+\mu^-$)
- Use dimuon trigger
- Optimize selection with multivariate discriminant
- Measure $\mathcal{B}$, absolute and as a function of $q^2 = M^2_{\mu^+\mu^-}$
- Angular measurements as a function of q^2

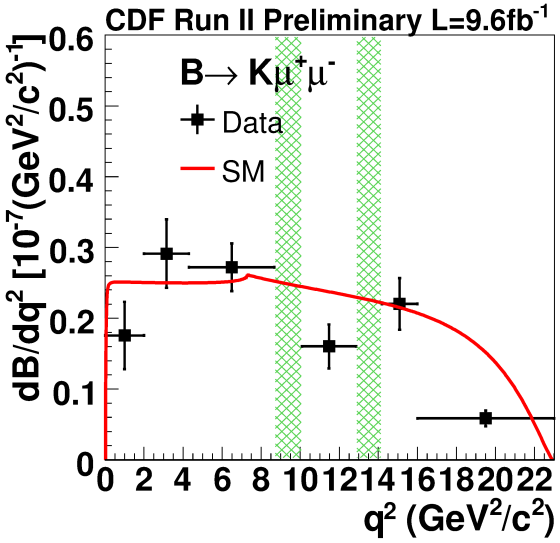
Signal and Control

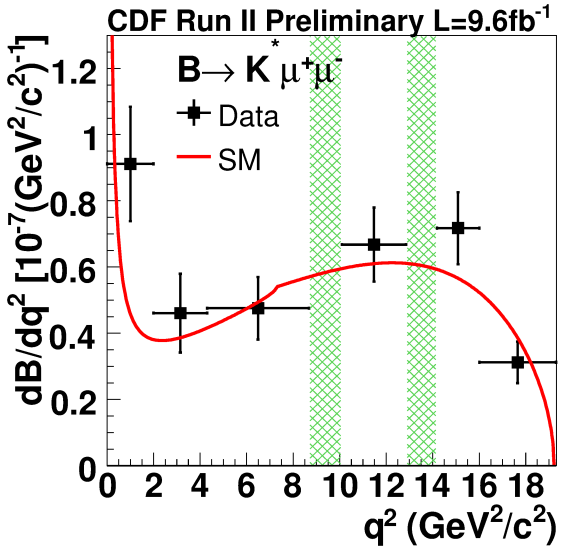
Signal Mode	Hadron Decay
$B^+ \to \mu^+\mu^- K^+$	-
$B^0 \to \mu^+\mu^- K^{*0}$	$K^{*0} \to K^+\pi^-$
$B^0_s \to \mu^+\mu^- \phi$	$\phi \to K^+K^-$
$B^+ \to \mu^+\mu^- K^{*+}$	$K^{*+} \to K_s\pi^+$
$B^0 \to \mu^+\mu^- K_s$	$K_s \to \pi^+\pi^-$
$\Lambda_b \to \mu^+\mu^- \Lambda$	$\Lambda \to p\pi^-$

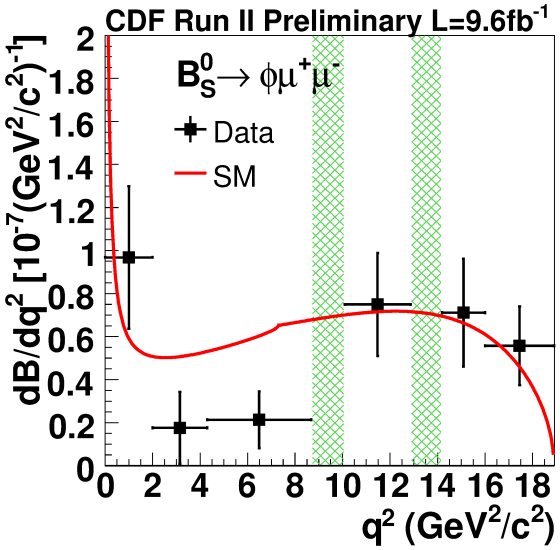
Yields

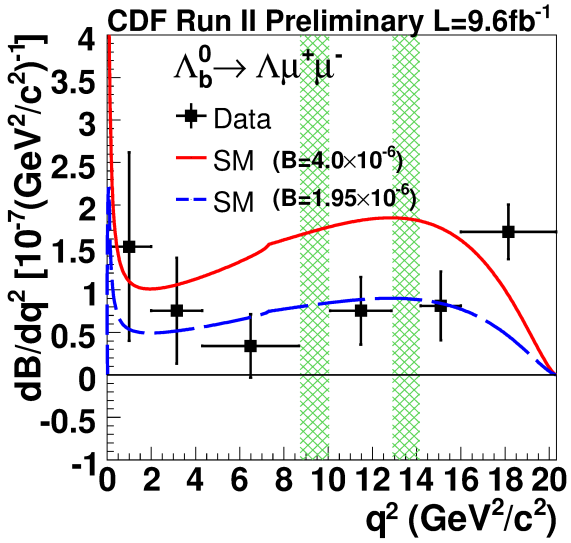

CDF Run II Preliminary L=9.6fb^{-1}
Yield: 323 ± 24
$B^+ \to K^+\mu^+\mu^-$
Data
Total Fit
Signal
Background
Candidates per 20 MeV/c^2
M($\mu\mu$K) (GeV/c^2)
CDF Run II Preliminary L=9.6fb^{-1}
Yield: 288 ± 20
$B^0 \to K^{*0}\mu^+\mu^-$
Data
Total Fit
Signal
Background
Candidates per 20 MeV/c^2
M($\mu\mu K^{*0}$) (GeV/c^2)
CDF Run II Preliminary L=9.6fb^{-1}
Yield: 62 ± 9
$B_s^0 \to \phi\mu^+\mu^-$
Data
Total Fit
Signal
Background
Candidates per 20 MeV/c^2
M($\mu\mu\phi$) (GeV/c^2)
CDF Run II Preliminary L=9.6fb^{-1}
Yield: 32 ± 8
$B^0 \to K_S\mu^+\mu^-$
Data
Total Fit
Signal
Background
Candidates per 20 MeV/c^2
M($\mu\mu K_S$) (GeV/c^2)
CDF Run II Preliminary L=9.6fb^{-1}
Yield: 24 ± 6
$B^+ \to K^{*+}\mu^+\mu^-$
Data
Total Fit
Signal
Background
Candidates per 20 MeV/c^2
M($\mu\mu K^{*+}$) (GeV/c^2)
CDF Run II Preliminary L=9.6fb^{-1}
Yield: 51 ± 8
$\Lambda_b^0 \to \Lambda\mu^+\mu^-$
Data
Total Fit
Signal
Background
Candidates per 20 MeV/c^2
M($\mu\mu\Lambda$) (GeV/c^2)

Differential BR





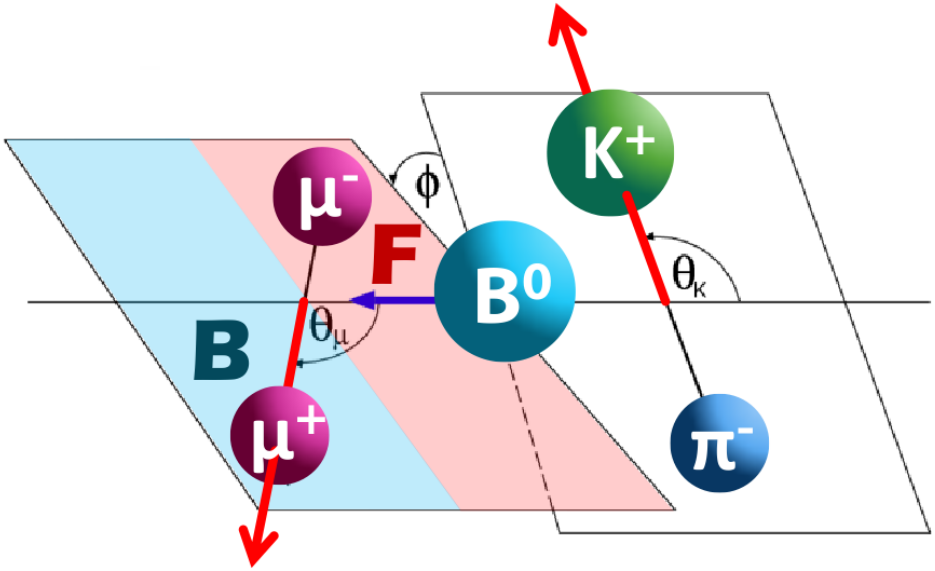




Green bands are resonance vetos (J/ψ and Ψ)

No significant deviation from SM in $B \to K^{(*)}\mu^+\mu^-$

Angular Observables

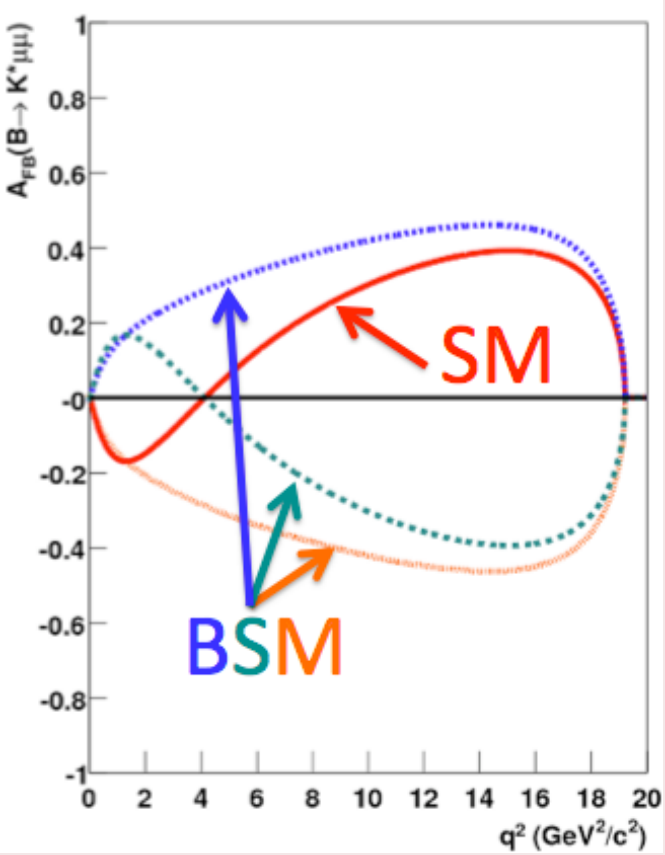


- Sensitive to NP
- For $B^0 \to \mu^+\mu^- K^*$ there are many prediction from several new physics models

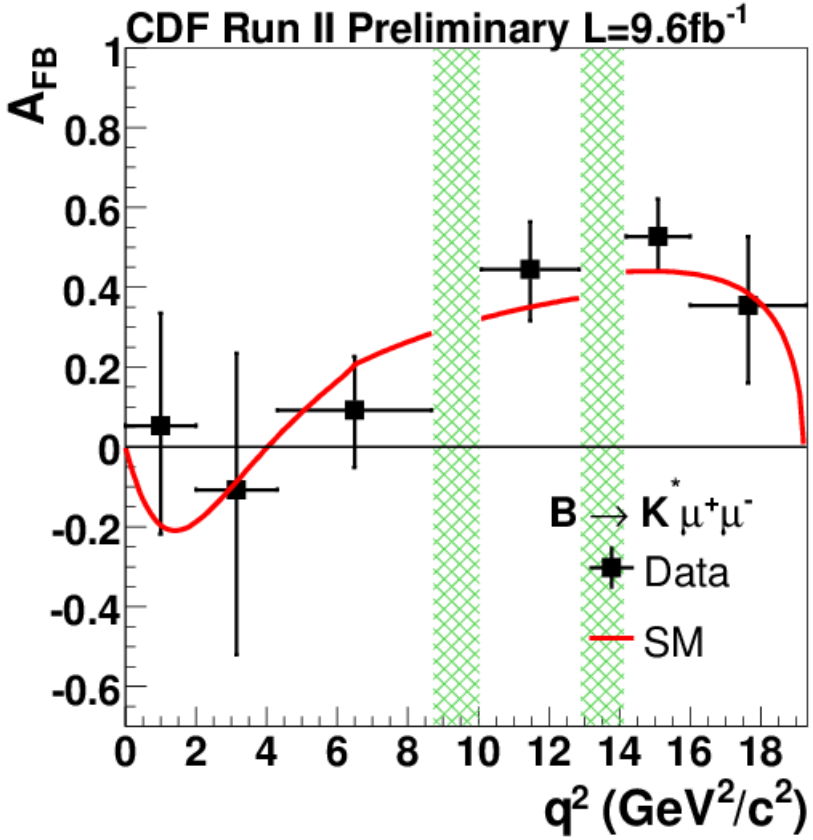
- $\cos\theta_\mu \to A_{FB}$
- $\cos\theta_K \to F_L$

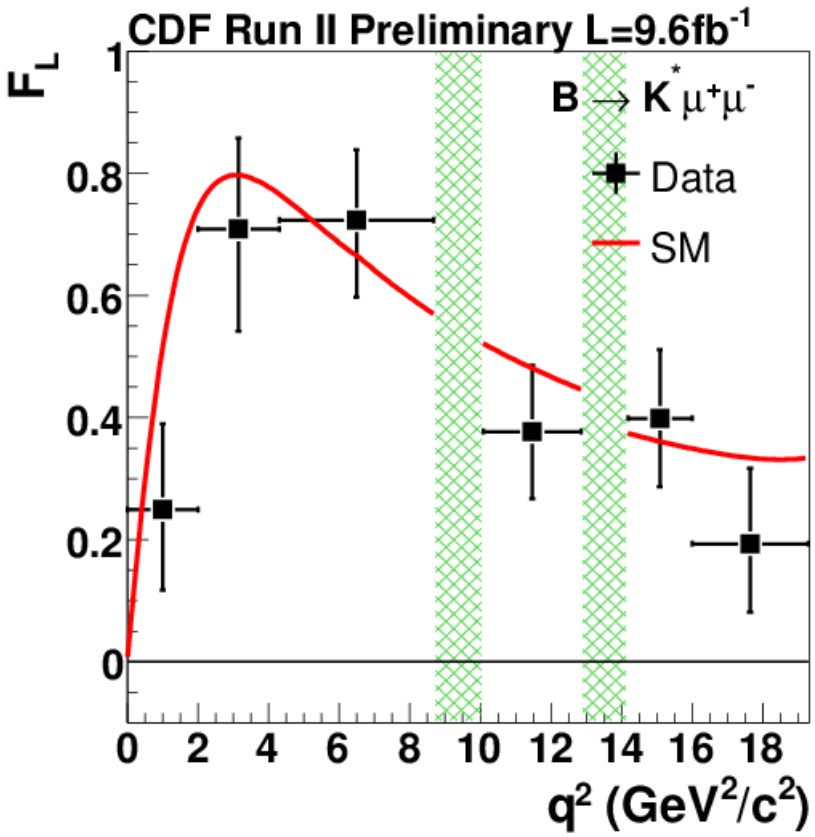
NP predictions

- Many NP scenarios



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





Green bands are resonance vetos (J/ψ and Ψ)

Consistent with previous measurement

No significant deviation from SM with current statistics

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

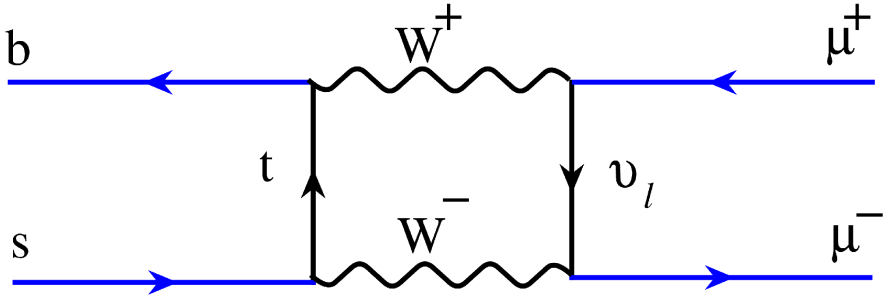
and

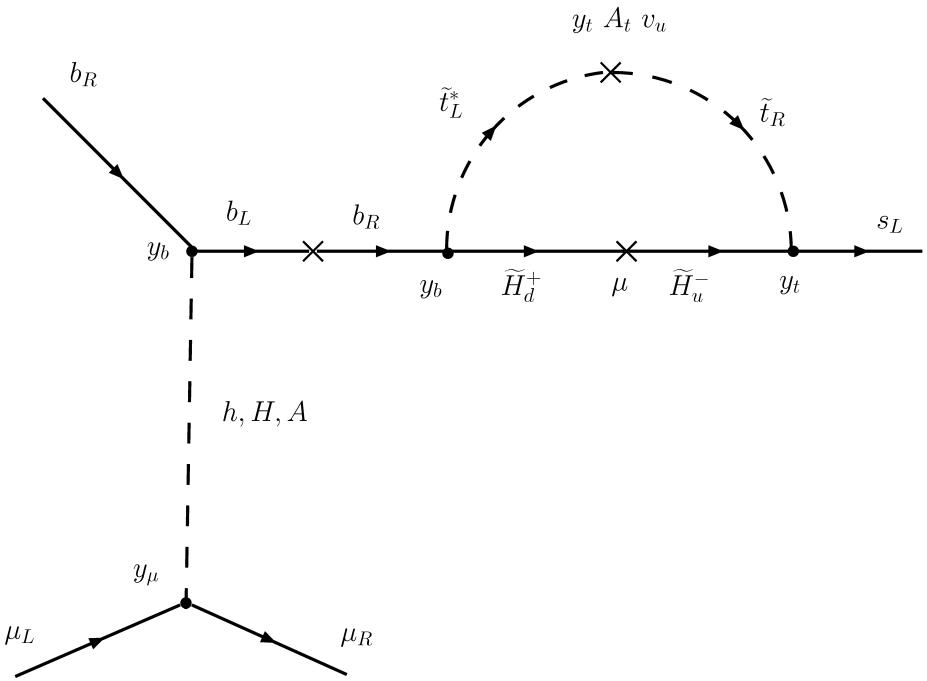
$$B_d \to \mu^- \mu^+$$

Using 10 fb^{-1}

Motivation

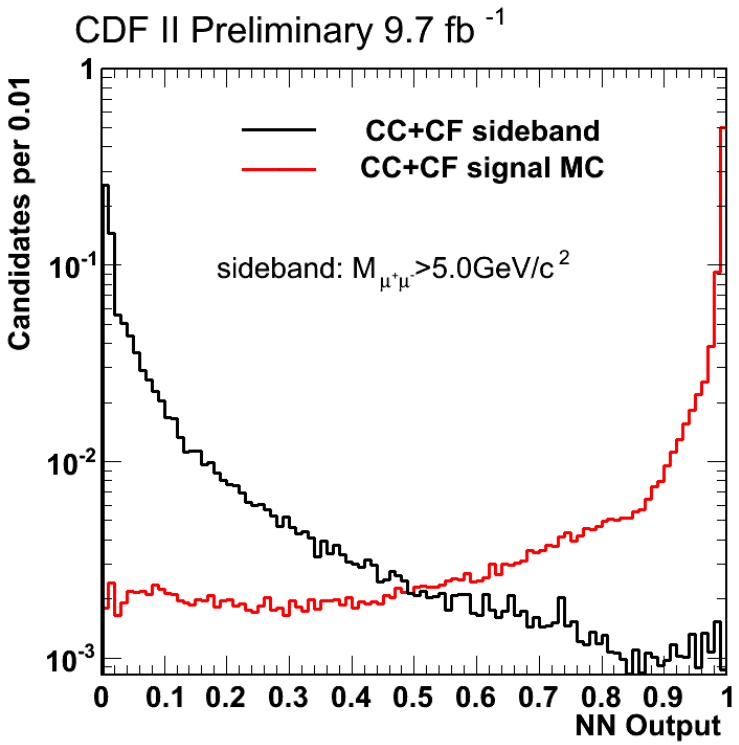
- $B_s \to \mu^+\mu^-$ can only occur through higher order FCNC diagrams in Standard Model (SM)
- Suppressed by the GIM Mechanism and helicity
- SM predicts very low rate with little SM background:
  $\mathcal{B}(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$
  $\mathcal{B}(B_d \to \mu^+\mu^-) =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



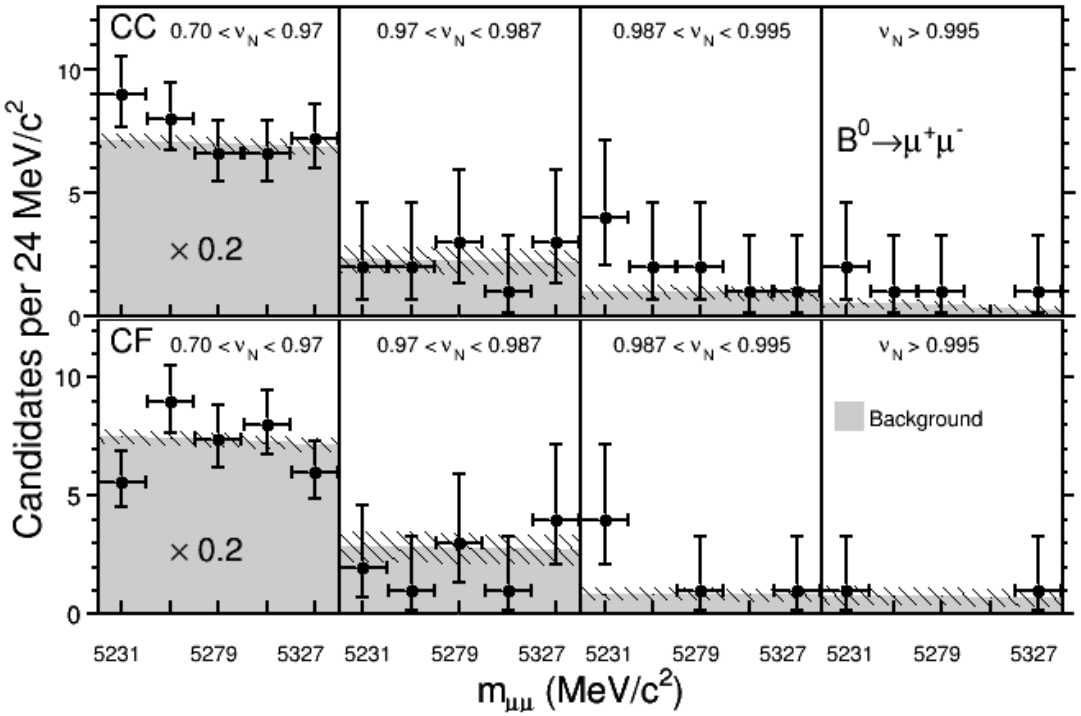


Analysis Description

- 2 Muons ⇒ dimuon trigger
- Blind ourselves to di-muon signal mass region
- Optimize selection criteria a priori
  - Multi-variate discriminant using vertex and kinematic variables
- Use mass sidebands to estimate dominant background in signal region
- Build confidence in background estimates by employing same methods on control regions
- Unblind and statistically interpret result



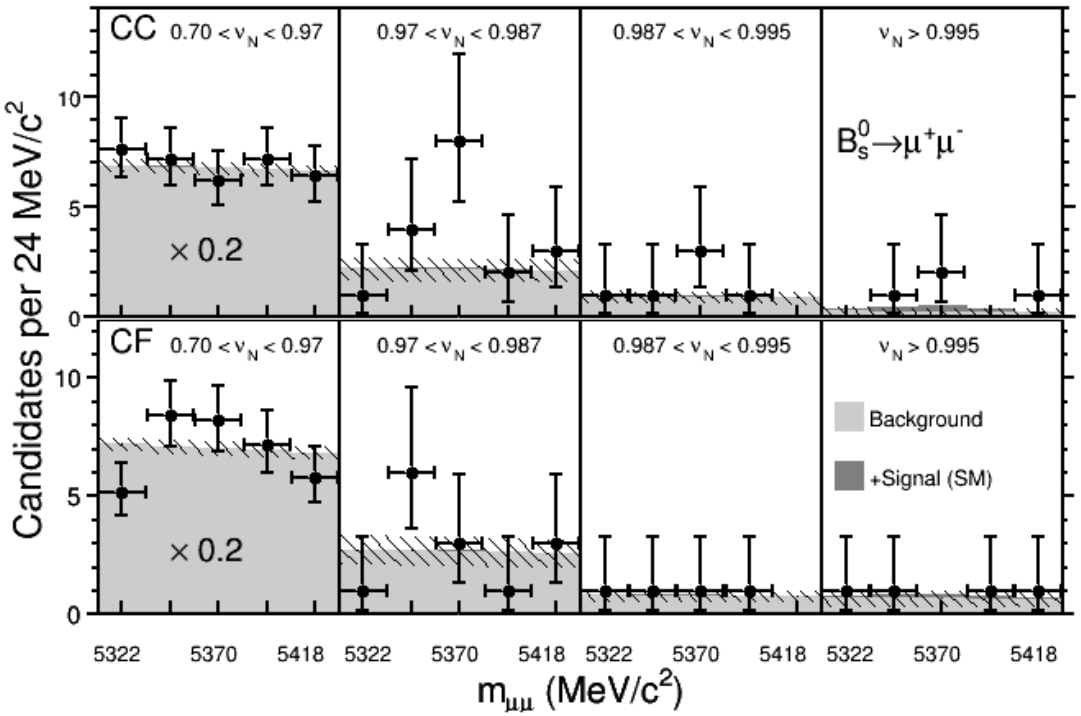
Results: B_d^0



- 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: $\mathcal{B}(B_d^0 \to \mu^+\mu^-) < 4.0 \times 10^{-9}$ @ 95% C.L.
- **No excess in B_d^0 mass region (p-value=41%)**

B_d^0 limit: $\mathcal{B}(B_d^0 \to \mu^+\mu^-) < 4.6 \times 10^{-9}$ @ 95% C.L.

Results: B_s^0

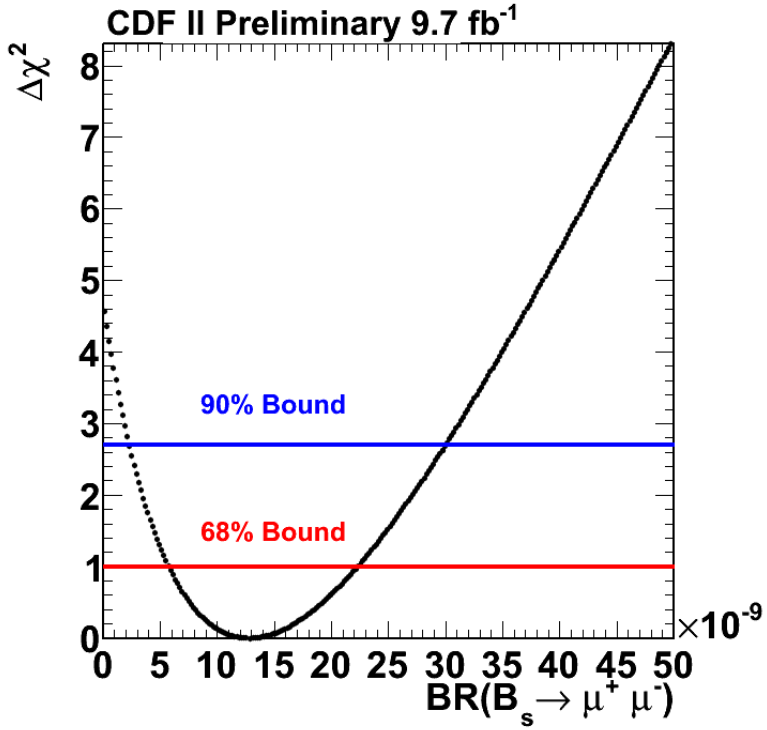


- Dark gray: Expected SM signal
- Expected limit: $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 1.3 \times 10^{-8}$ @ 95% C.L.
- **Excess over background-only in central region (the most sensitive)**
  - p-value for background only hypothesis: 0.94%
  - p-value for SM+background hypothesis: 7.1%

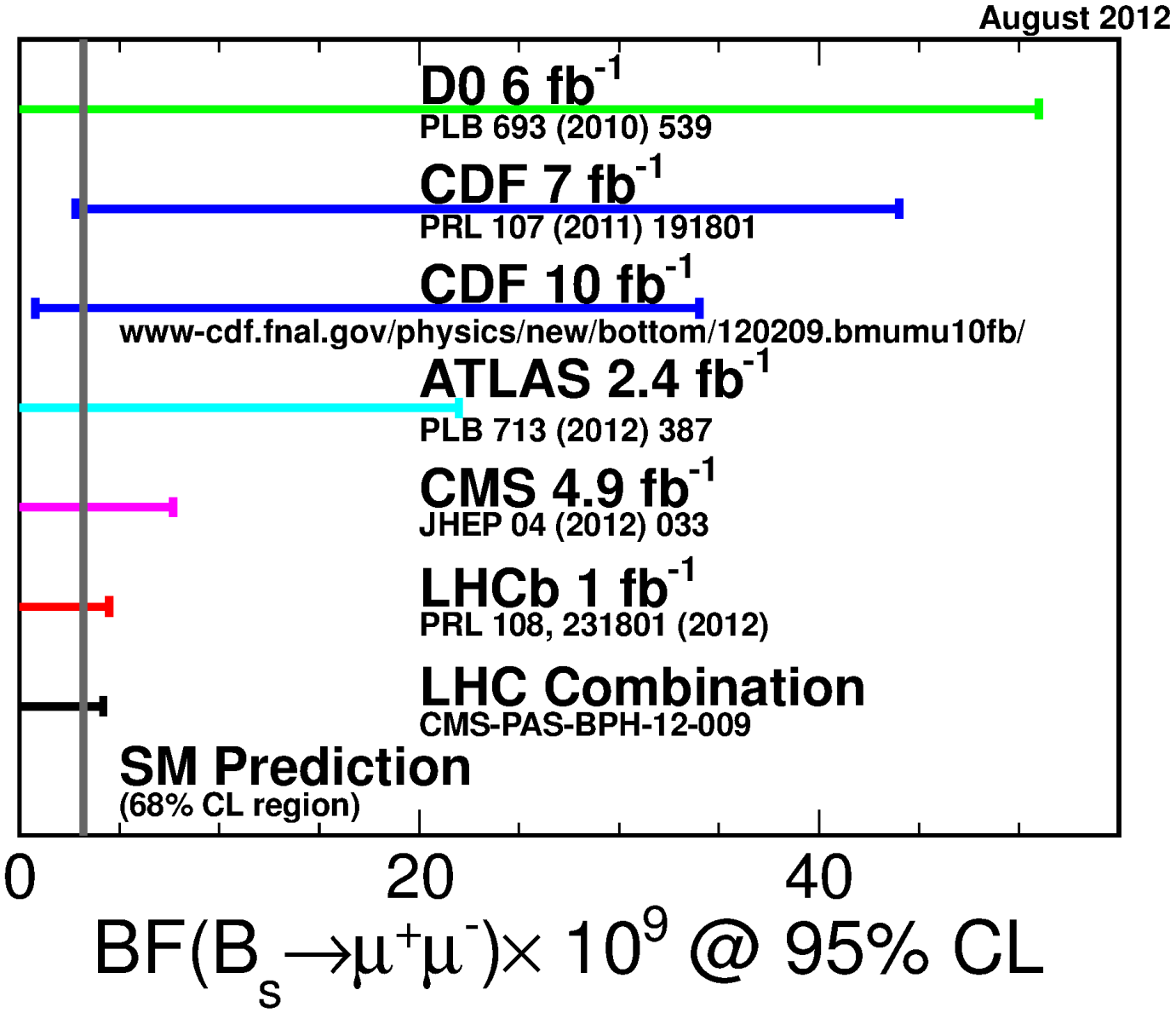
B_s^0 **limit:** $\mathcal{B}(B_s^0 \to \mu^+\mu^-) < 3.1 \times 10^{-8}$ **@ 95% C.L.**

B_s^0: Central Values, Bounds and P-Values

- Includes all systematics
- 90% Bound:
  $2.2 \times 10^{-9} < \mathcal{B}(B_s^0 \to \mu^+\mu^-) < 3.0 \times 10^{-8}$
- Stable: No large deviation when only using subset of bins



Current Experimental Status



Summary

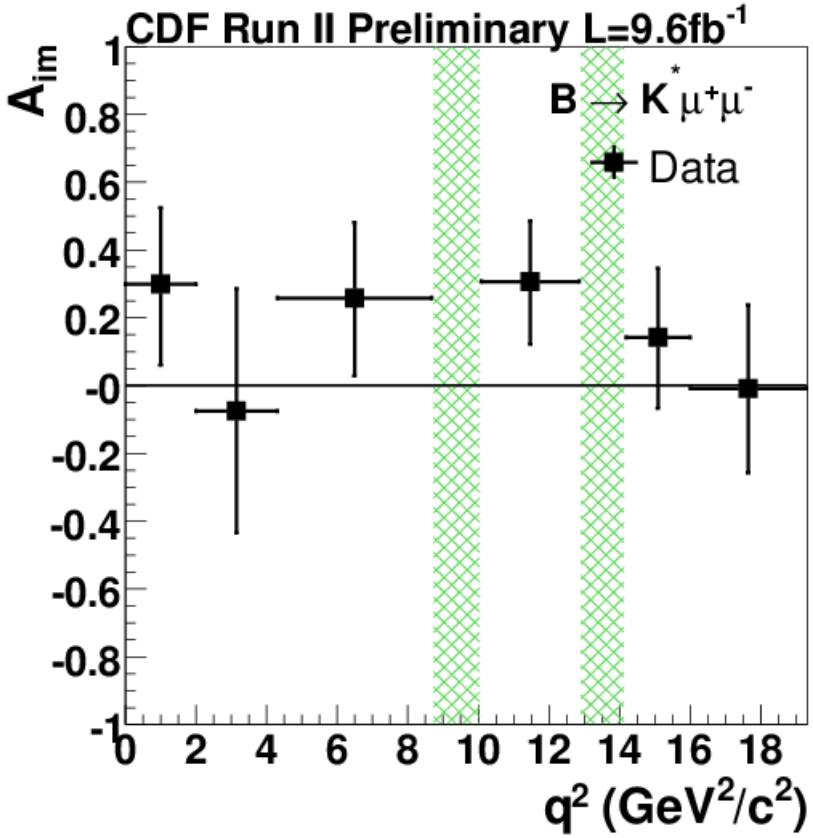
- New results, many with full Run II data set
- CP violation in $B_s^0 \to J/\psi\phi$ close to SM
- $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ in agreement with SM
- $H_b \to h^+ h'^-$ is good tests of SM
- $D \to h^+ h^-$ needs more work to be understood (better predictions)
- $B_s^0 \to \mu^+\mu^-$ and $b \to s\mu^+\mu^-$ in agreement with SM

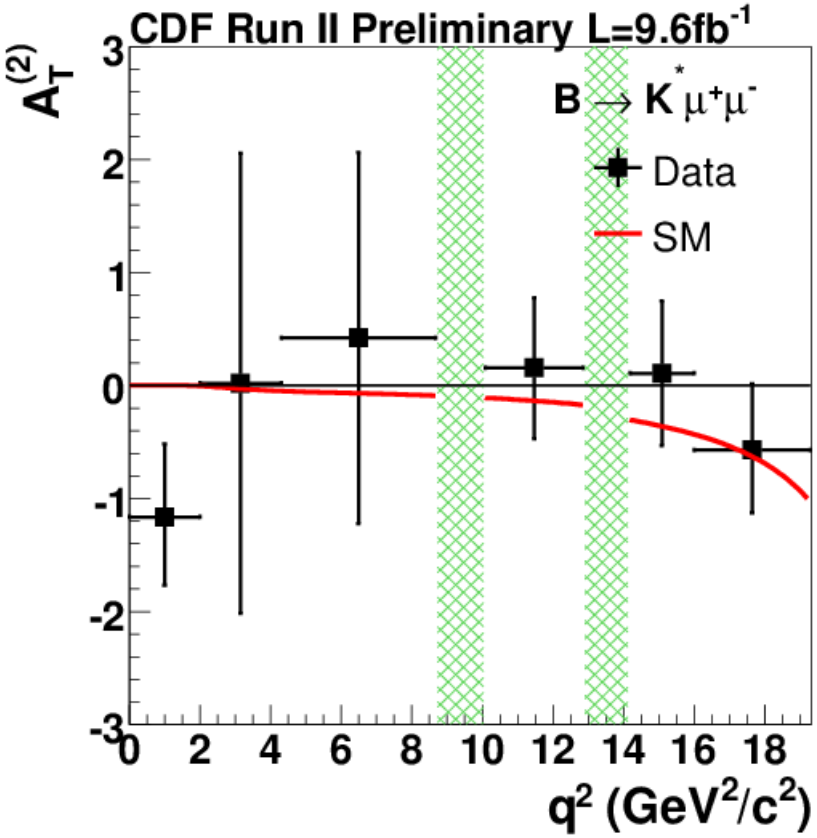
- **More results with full Run II statistics coming**
- **CDF Run II powerful complimentary environment for flavor physics**
- **Results have strongly constrained NP models**

Backup

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

A_{Im} and A_T sensitive to right handed currents $\to$ NP





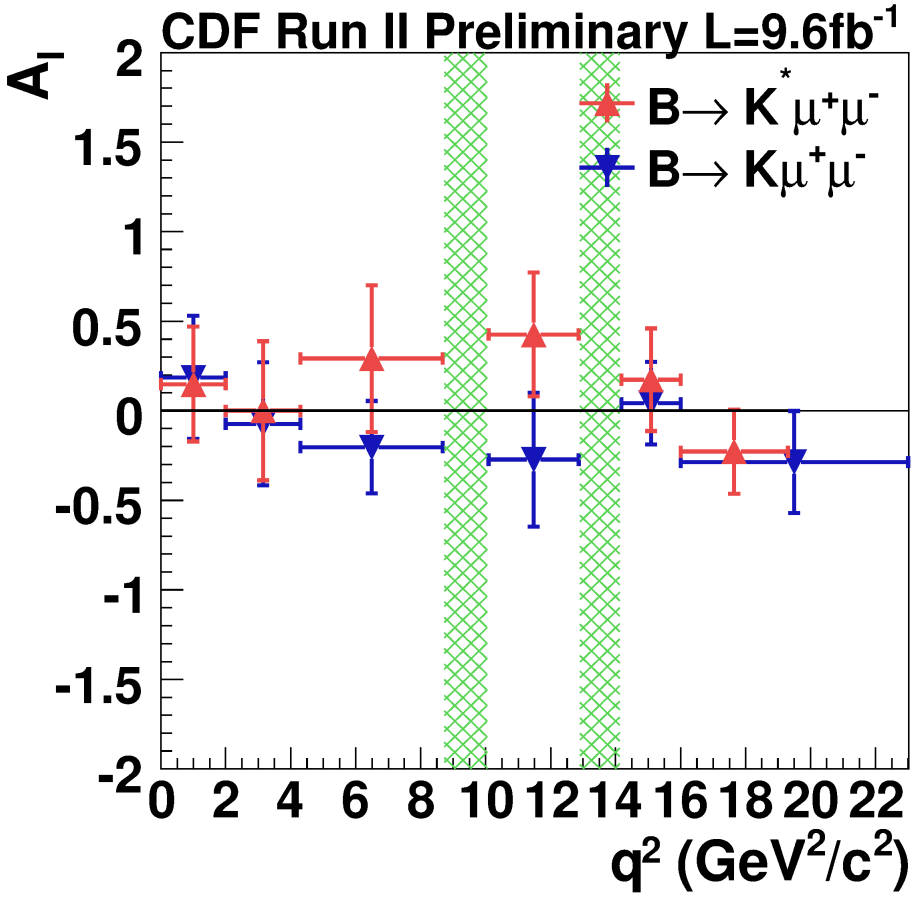
Green bands are resonance vetos (J/ψ and Ψ)

Consistent with previous measurement

No significant deviation from SM with current statistics

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

- LHCb saw asymmetry



No significant deviation from SM with current statistics