Recent Heavy Flavor results from the Tevatron

- B^+,B^- asymmetries
- Forward-backward asymmetry of (Λ_b, $\bar{\Lambda}_b$)
- Indirect CP-violating asymmetries in $D^0 \longrightarrow K^+K^-$ and $D^0 \longrightarrow \pi^+\pi^-$
- $\dfrac{\sigma(B_c^+) * BR(B_c^+ \to J/\psi\mu^+\nu)}{\sigma(B^+) * BR(B^+ \to J/\psi K^+)}$

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For the CDF and D0 collaborations

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B^+,B^- asymmetries

- Recently there has been interest in forward-backward asymmetry in $t\bar{t}$ production since initial results were larger than SM prediction
- Forward-backward asymmetry in $b\bar{b}$ has same sources as forward-backward asymmetry in $t\bar{t}$
- Full reconstruction of $B^\pm$ has advantage that b quark charge known and no need to account for $B^0/\bar{B}^0$ oscillation
- Forward-backward asymmetry in B^+,B^- sensitive to same production asymmetries as $b\bar{b}$.

Forward B^-: Longitudinal momentum in p direction
Backward B^-: Longitudinal momentum in $\bar{p}$ direction

Forward B^+: Longitudinal momentum in $\bar{p}$ direction
Backward B^+: Longitudinal momentum in p direction

b quark content $\longrightarrow$ p
$\bar{b}$ quark content $\longrightarrow$ $\bar{p}$

$$A_{FB} \equiv A \equiv \frac{N_F - N_B}{N_F + N_B}$$

Fitting

<P_T> for $B^{\pm}$: 12.9 GeV

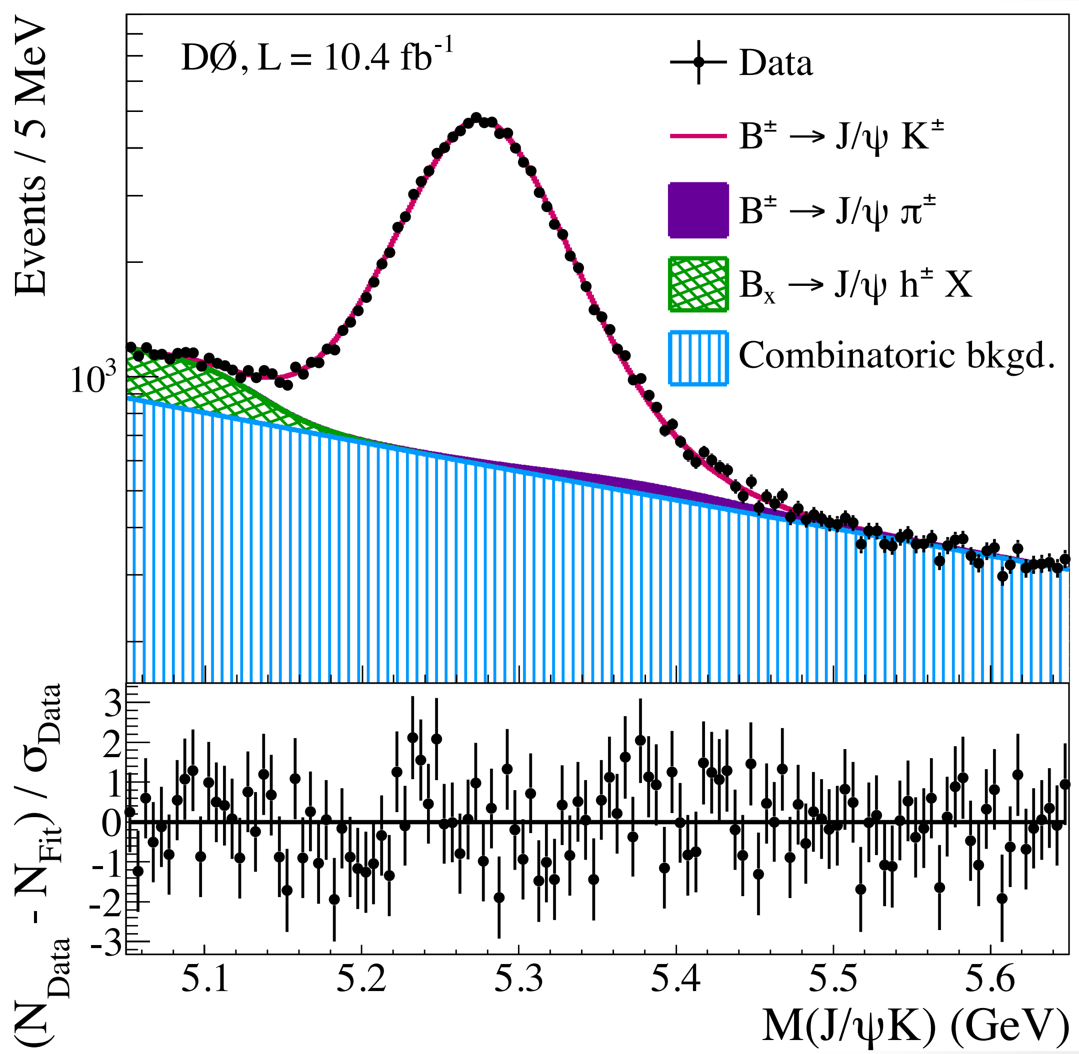
$B^{\pm} \longrightarrow J/\psi\ K^{\pm}$ with $J/\psi \rightarrow \mu^+\mu^-$

Events selected using both cuts and a BDT

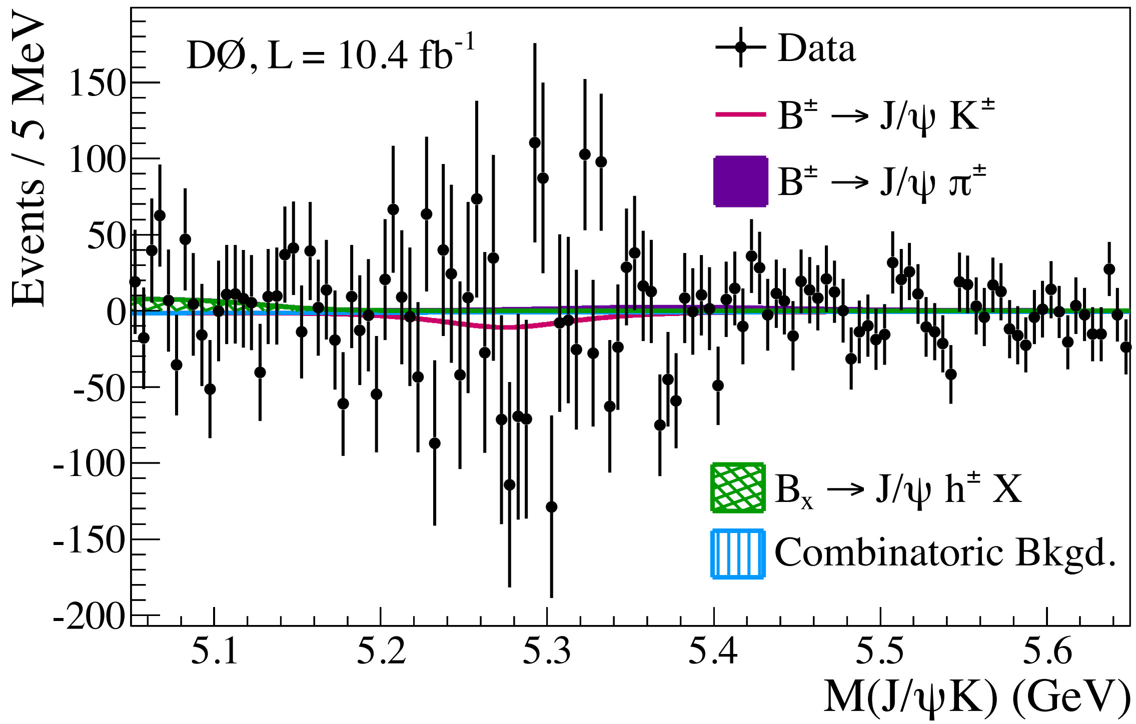
Unbinned maximum likelihood fit includes double Gaussian function for signal.

Backgrounds are described by $B \longrightarrow J/\psi\ \pi^{\pm}$, where pion is assigned kaon mass, partially reconstructed $B_x \longrightarrow J/\psi h^{\pm}\ X$ and combinatoric background

Forward + Backward events



Forward-Backward



Results are presented for 0.1 < |n| < 2.0
(Events near η=0 removed to remove any potential ambiguity
of sign of η due to resolution)

Results

Source	Uncertainty
Statistical	0.41%
Alternative BDTs and cuts	0.17%
Fit variations	0.06%
Reconstruction asymmetries	0.05%
Fit bias	0.02%
Systematic uncertainty	0.19%
Total uncertainty	0.45%

$A_{FB}(B^{\pm}) = -0.0024 \pm 0.0041(\mathrm{stat}) \pm 0.0019(\mathrm{sys})$

We observe no significant forward-backward asymmetry

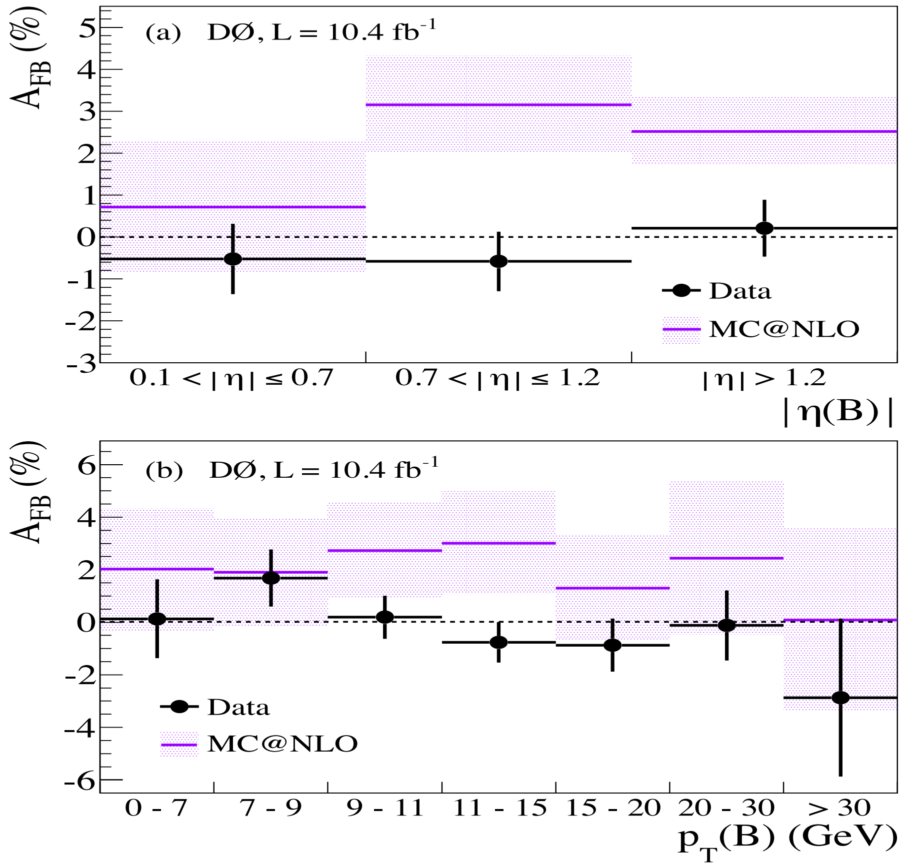
First measurement of this quantity

Comparison of $A_{FB}(B^{\pm})$ to MC@NLO

χ^2/dof

10.3/3 correlated sys
11.8/3 uncorrelated sys

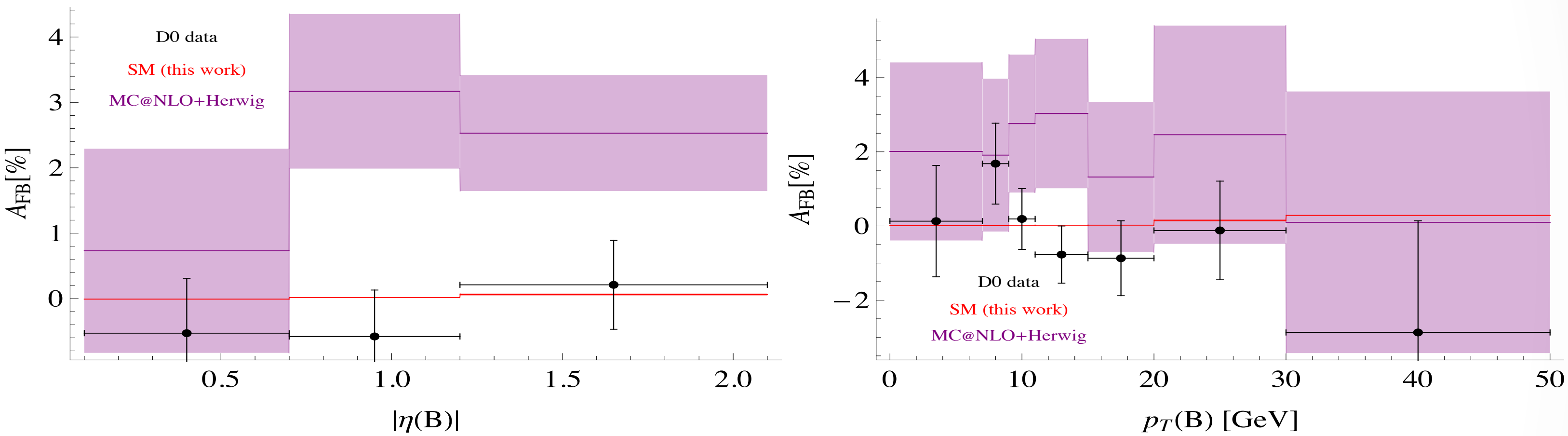
6.6/7 correlated sys
7.0/7 uncorrelated sys



Data systematically lower than MC@NLO at all η for P_T=9-30 GeV

Some tension with data and MC@NLO

Comparison to new calculation*



Better Agreement

* C. Murphy ArXiv:1504.02493

Forward-backward asymmetry of (Λ_b, $\bar{\Lambda}_b$)

- Forward Λ_b: longitudinal momentum in p direction
- Backward Λ_b: longitudinal momentum in $\bar{p}$ direction
- Forward $\bar{\Lambda}_b$: longitudinal momentum in $\bar{p}$ direction
- Backward $\bar{\Lambda}_b$: longitudinal momentum in p direction

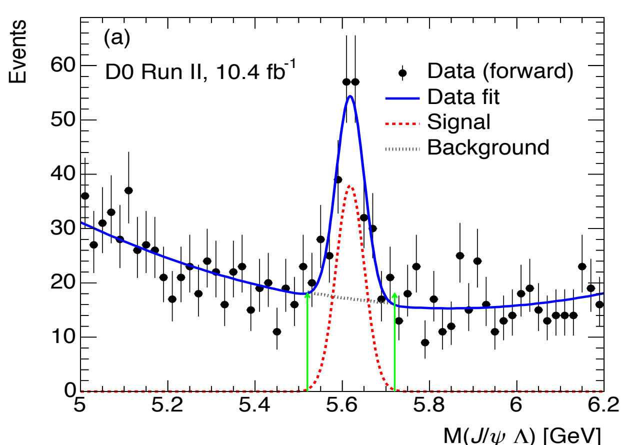
$$A_{FB} \equiv A \equiv \frac{N_F - N_B}{N_F + N_B}$$

Recently "string drag" mechanism proposed by J. Rosner may favor production of Λ_b baryons in proton beam direction and $\bar{\Lambda}_b$ baryons in anti-proton beam direction

arXiv:1503.03917
Phys. Rev. D 91 072008

Reconstructing Λ_b

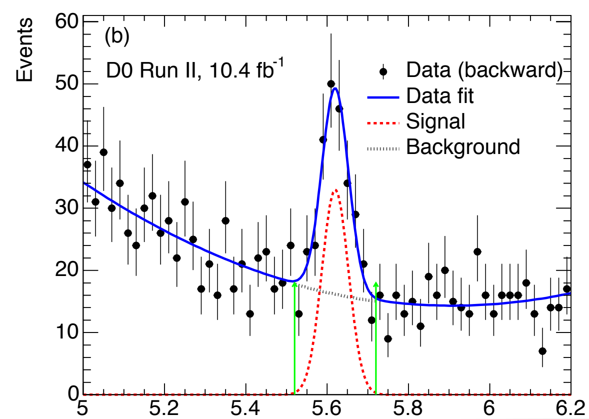
- Search for $\Lambda_b \longrightarrow J/\psi\ \Lambda$, $J/\psi \longrightarrow \mu^+\mu^-$, $\Lambda \longrightarrow p\pi^-$
- Cut based analysis
- Λ_b candidates fit using a binned maximum likelihood Gaussian signal and second order Chebyshev polynomial background
- Simulation: Pythia with CTEQ6L1 PDF or MC@NLO with CTEQ6M1 PDF with Herwig showering and hadronization and Evtgen for b hadron decay.
- Asymmetry measured in 4 rapidity bins



Forward

$0.5 < |y| < 1.0$

$\Lambda_b + \bar{\Lambda}_b$

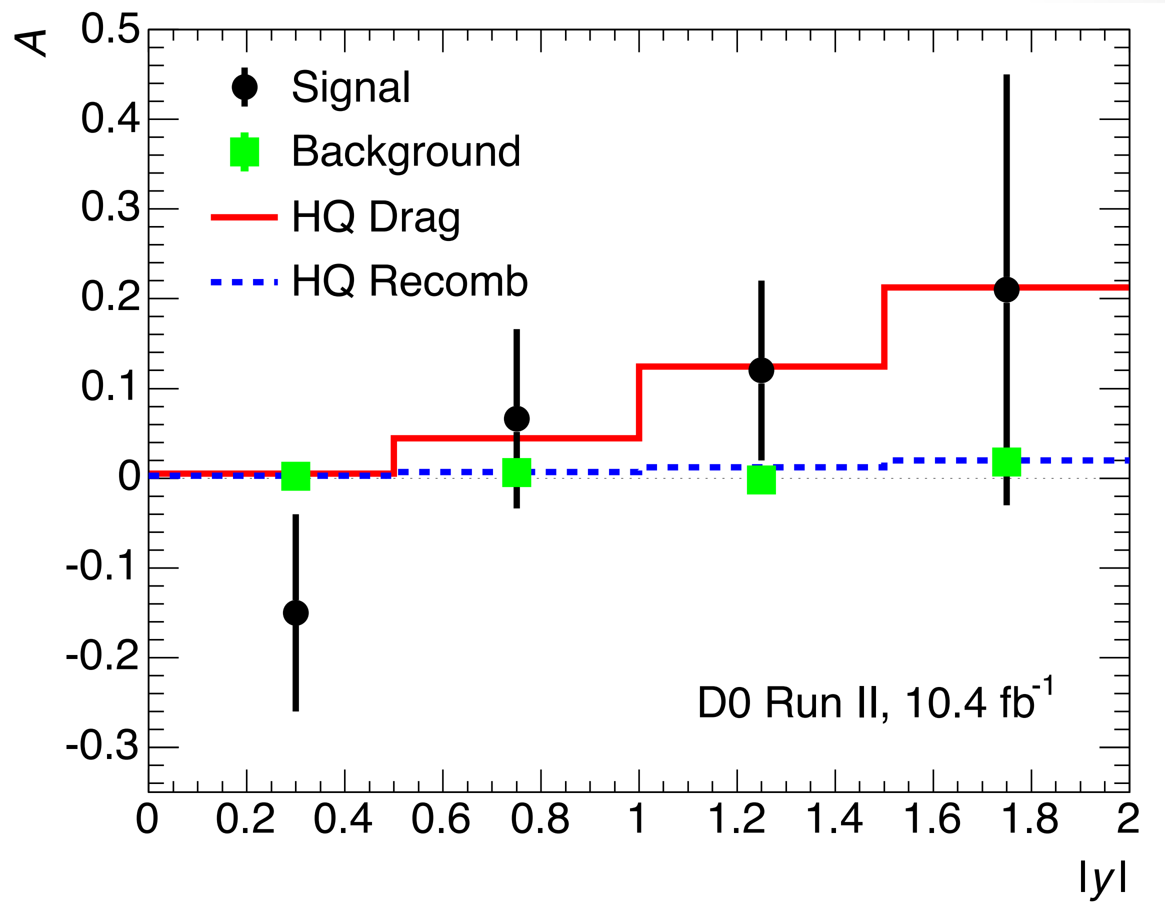


Backward

Asymmetry vs rapidity

$\langle P_T \rangle$ of Λ_b :9.9 GeV

0.1<|y|<2.0



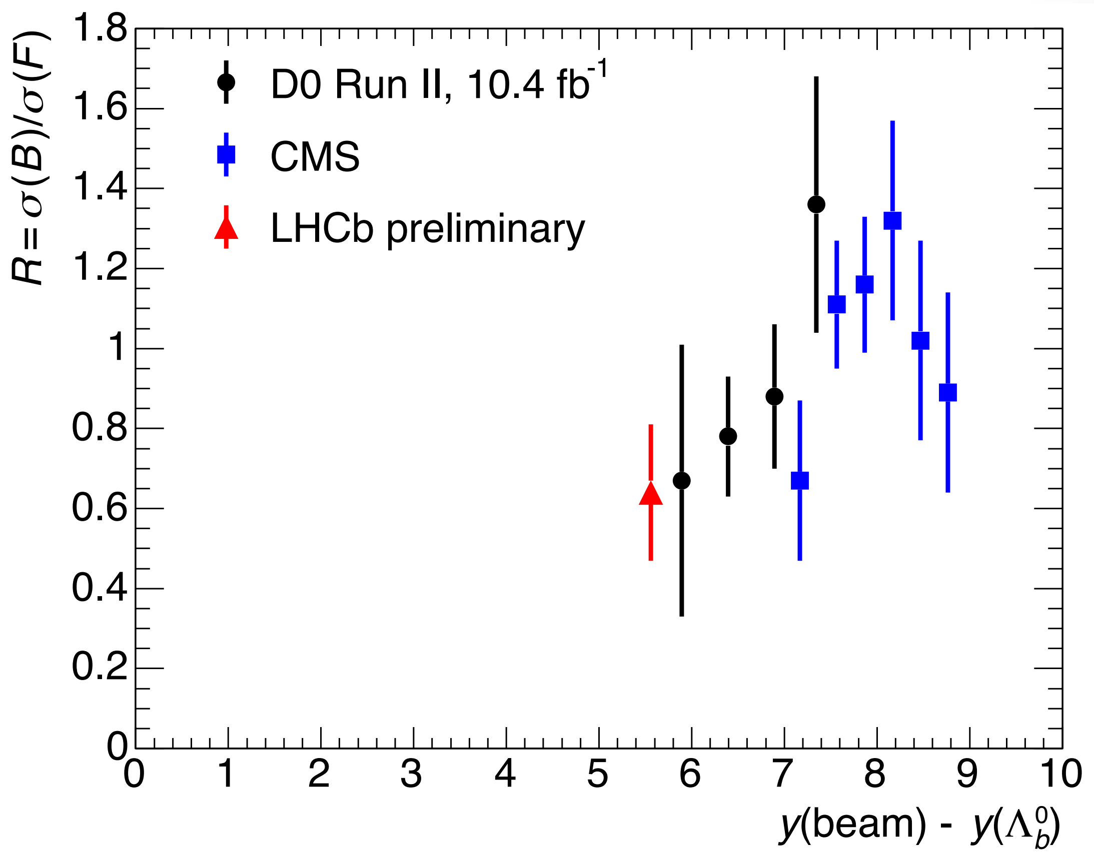
A_{FB}=0.04 ± 0.07(stat) ± 0.02 (sys)

|y|integrated from 0.1-2.0

Heavy Quark drag model fits observation

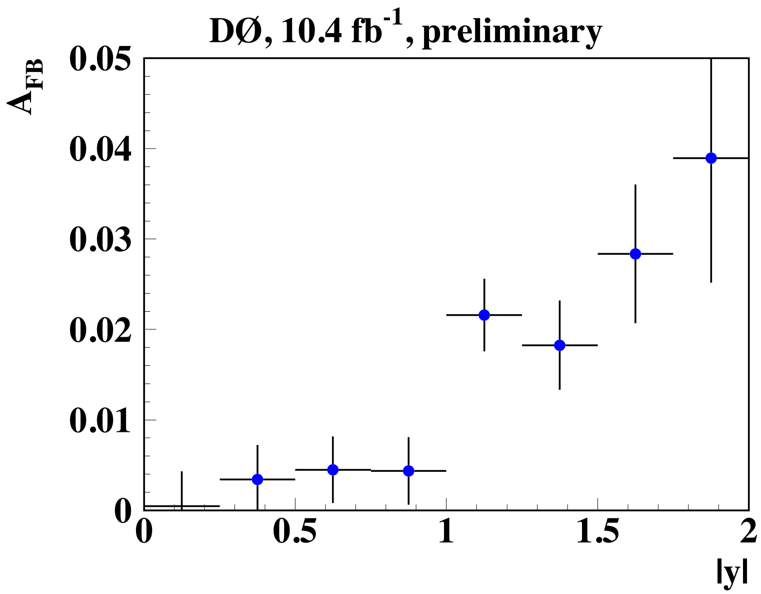
Ratio of $\overline{\Lambda}_b/\Lambda_b$ vs rapidity loss $y(beam)-y(\Lambda_b)$

Tendency of forward particles that share valence quarks with beam remnants to be emitted at larger rapidity values than their backward counterparts

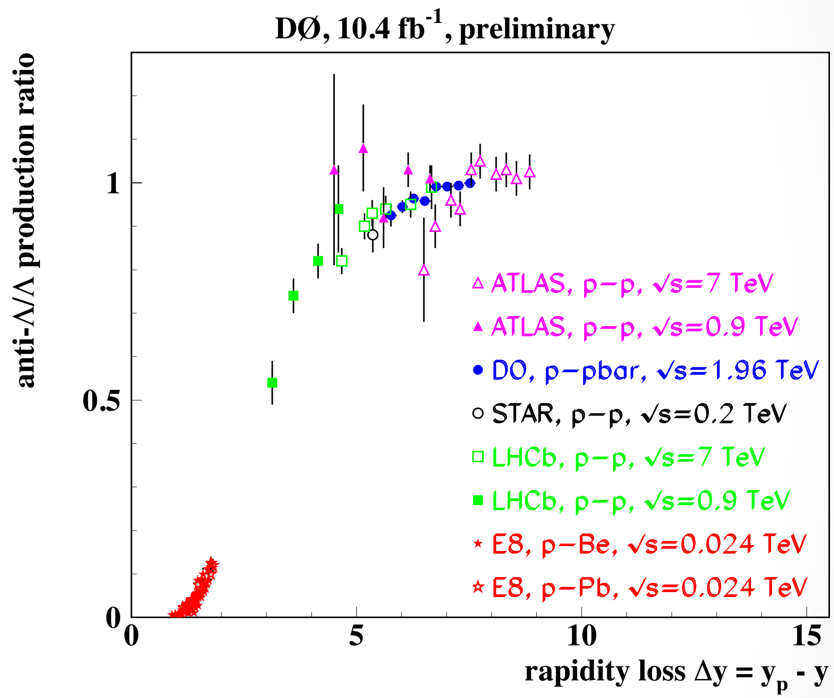


A_{FB} for Λ

$p\bar{p} \longrightarrow \Lambda(\bar{\Lambda})X$



$\bar{\Lambda}/\Lambda$ production ratio vs rapidity loss



A_{FB}=0.0115 ± 0.0005(stat) ± 0.0006(sys) D0 preliminary

Small but significant asymmetry

Indirect CP-violating asymmetries in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ at CDF

- Decay time dependent asymmetries in CP eigenstates provide a very powerful probe for CP violation.
- Asymmetries probe non-SM contributions in the oscillation and penguin transition amplitudes since non SM particles can be exchanged causing an enhancement relative to the SM expectations.
- Previous measurements are consistent with CP symmetry at $O(10^{-3})$ uncertainties.
- Independent measurement with similar precision helps constrain charm sector
- $D \rightarrow h^+h^-$ decays can be fully reconstructed, allowing precise decay time determination. Large signal yields and moderate backgrounds allow for a precise measurement

Measurement

$$A_{CP}(t) = \frac{d\Gamma(D^0 \to h^+h^-)/dt - d\Gamma(\bar{D}^0 \to h^+h^-)/dt}{d\Gamma(D^0 \to h^+h^-)/dt + d\Gamma(\bar{D}^0 \to h^+h^-)/dt}$$

Due to slow oscillation rate of charm mesons, A_{CP} can be approximated as

$$A_{CP}(t) \approx A_{CP}^{dir}(h^+h^-) - \frac{\langle t \rangle}{\tau} A_\Gamma(h^+h^-)$$

<t> mean decay time

τ CP-averaged D lifetime

Direct CP, depends on decay mode

Asymmetry between effective lifetimes $\hat{\tau}$ of charm and anti-charm. Primarily due to indirect CP violation

$D^{*\pm} \to D\, \pi^\pm_s$

Charge of pion provides D^0 vs $\bar{D}^0$ discrimination

$$A_\Gamma = \frac{\hat{\tau}(\bar{D}^0 \to h^+h^-) - \hat{\tau}(D^0 \to h^+h^-)}{\hat{\tau}(\bar{D}^0 \to h^+h^-) + \hat{\tau}(D^0 \to h^+h^-)}$$

Effective lifetimes found from single exponential fit to neutral mesons decays that may undergo oscillations

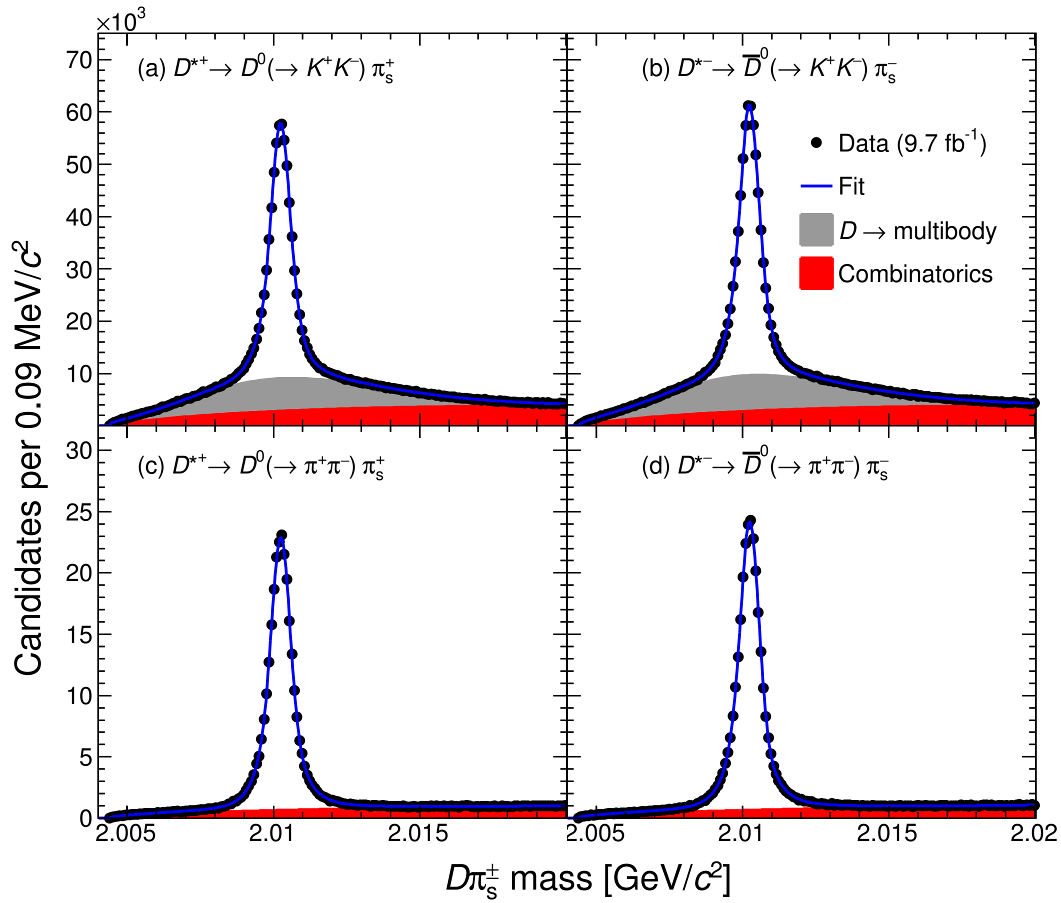
Yields

6.1 x 10^5 $D^0 \rightarrow K^+ K^-$
6.3 x 10^5 $\bar{D}^0 \rightarrow K^+ K^-$
2.9 x 10^5 $D^0 \rightarrow \pi^+\pi^-$
3.0 x 10^5 $\bar{D}^0 \rightarrow \pi^+\pi^-$

Sample divided into
30 bins of decay time between
0.15τ and 20τ

<t> determined from
$D^{*\pm} \rightarrow D(K^{\mp}\pi^{\pm})\pi^{\pm}_s$

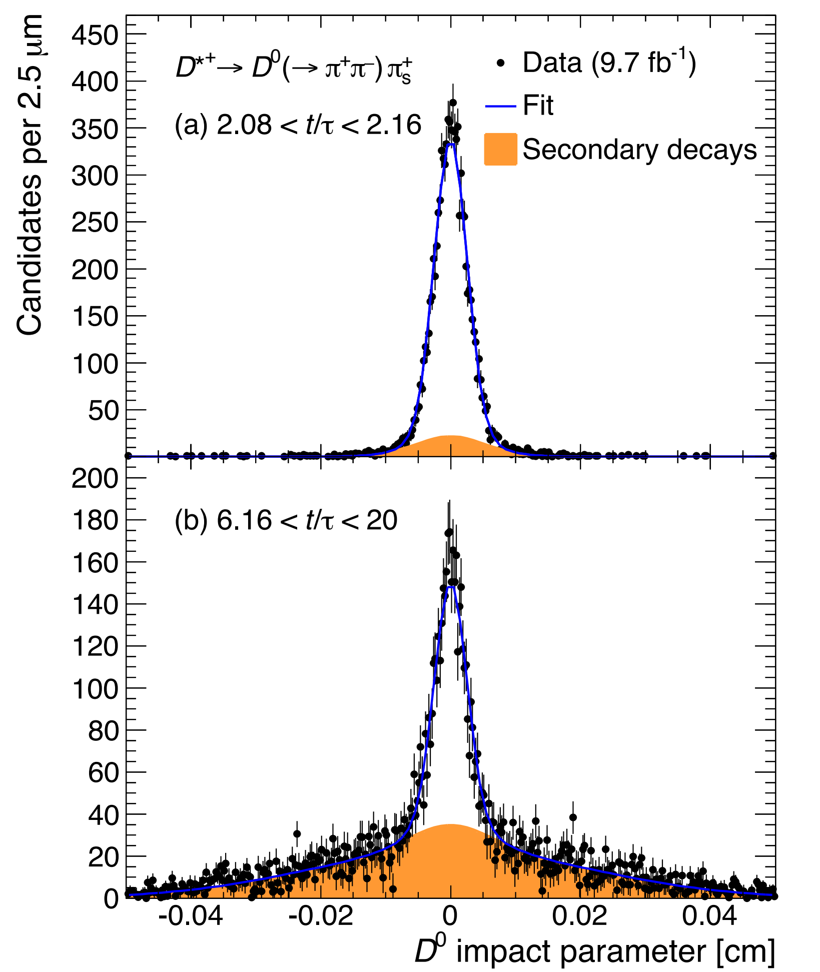
Trigger bias assumed to be
independent of D^0 flavor and
is accounted for when determining
<t>



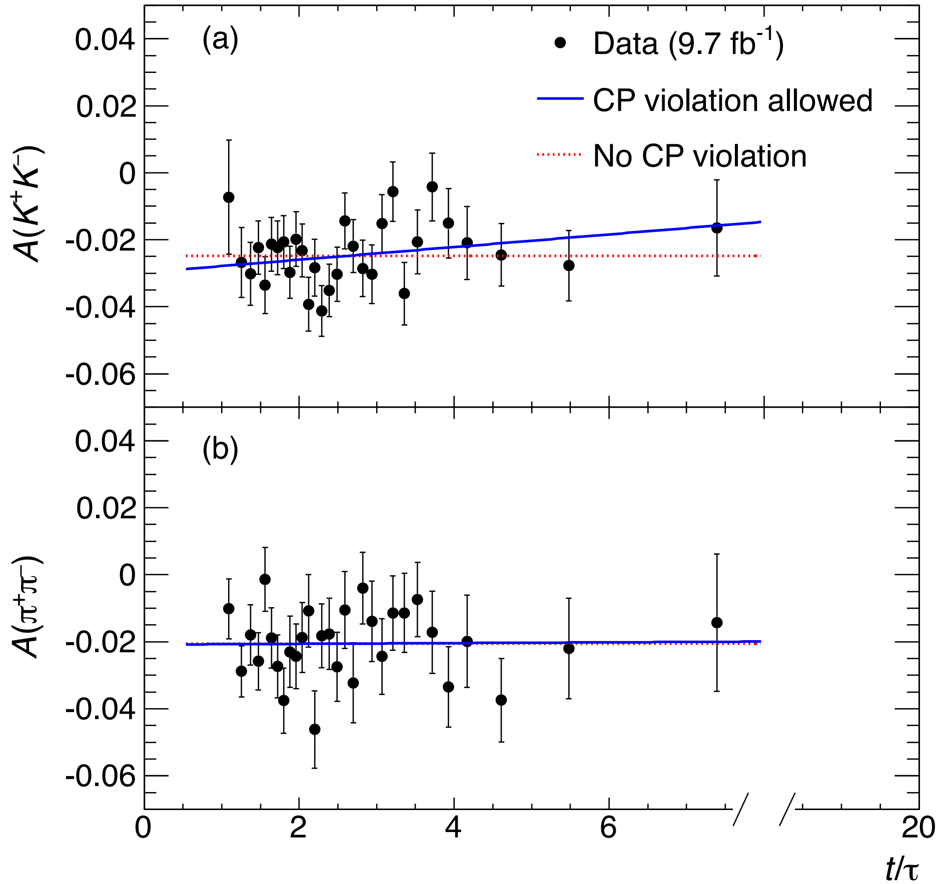
Relative signal and background yields
in signal region found for each decay time bin

Impact Parameter

Subtract impact parameter distribution of background found using sideband data



Results



$A_\Gamma(\pi^+\pi^-)$=(-0.1 ± 1.8(stat) ± 0.3 (syst)) x 10^{-3}

$A_\Gamma(K^+K^-)$=(-1.9 ± 1.5(stat) ± 0.4 (syst)) x 10^{-3}

Combined: A_Γ=(-1.2 ± 1.2) x 10^{-3}

Consistent with CP symmetry

PRD-RC 90, 111103 (2014)

Consistent with current best results and has competitive precision

Public note
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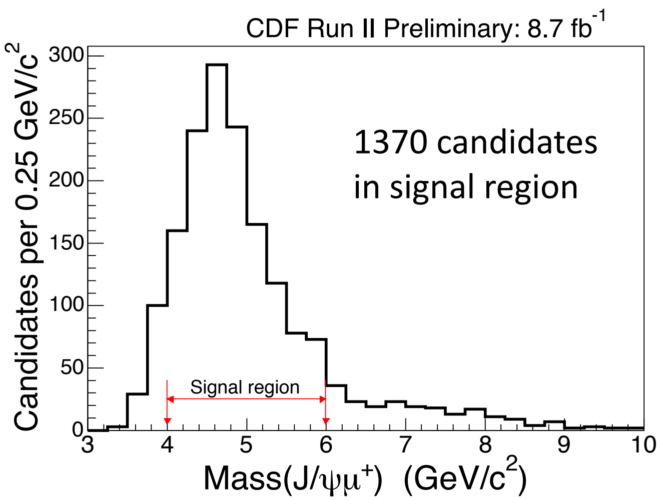
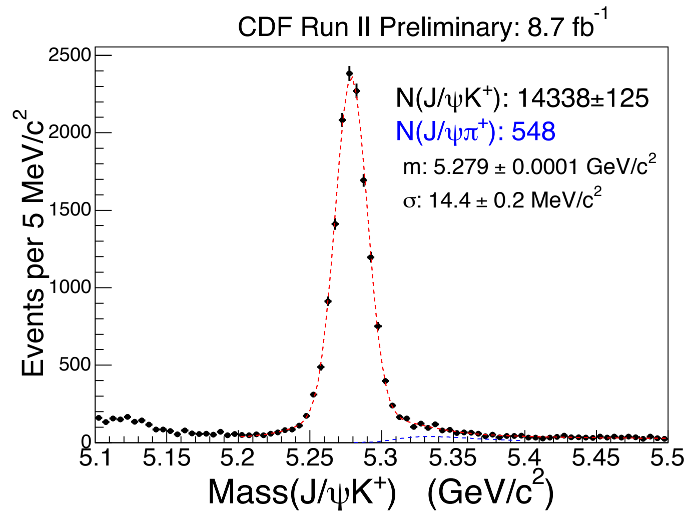
$$\frac{\sigma(B_c^+)*BR(B_c^+ \to J/\psi\mu^+\nu)}{\sigma(B^+)*BR(B^+ \to J/\psi K^+)}$$

Form J/ψ + track invariant mass



Track== muon for B_c^+ reconstruction



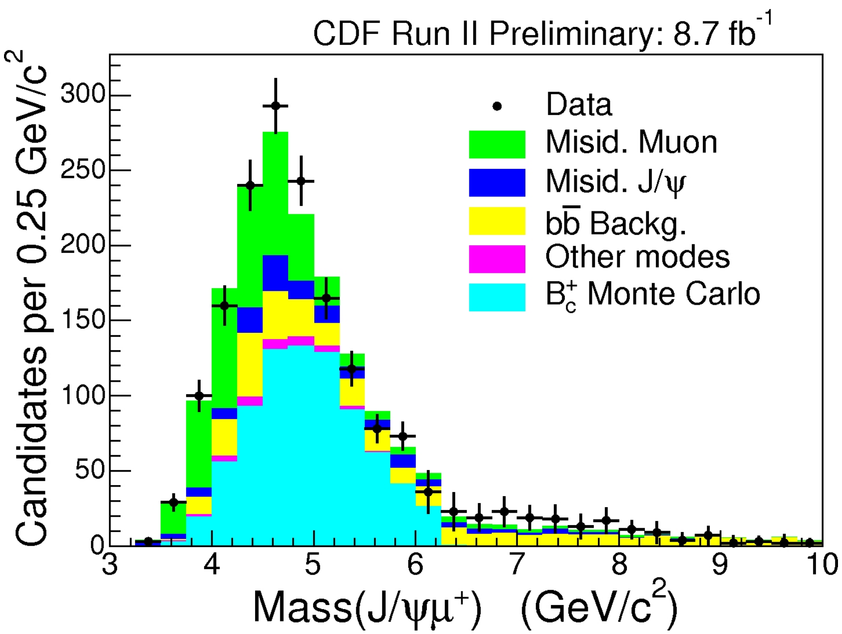
Track==Kaon for B^+ reconstruction

$J/\psi\ \pi^+$ fixed to 3.83% of $J/\psi\ K^+$

Track==π^+,K^+ or p for mis ID muon background

Results

$$\frac{\sigma(B_c^+) * BR(B_c^+ \to J/\psi\mu^+\nu)}{\sigma(B^+) * BR(B^+ \to J/\psi K^+)} = \frac{N_{B_c^+}}{N_{B^+}} \times \varepsilon_{rel}$$



ε_{rel}=4.093 ± 0.038(stat)$^{+0.401}_{-0.359}$ (sys)

systematics

	$\Delta\epsilon_{rel}$
B_c^+ lifetime	$^{+0.134}_{-0.147}$
B_c^+ spectrum	$^{+0.356}_{-0.303}$
B^+ spectrum	±0.055
XFT	±0.070
CMUP efficiency	$^{+0.092}_{-0.087}$
Total systematics	$^{+0.401}_{-0.359}$

	$\Delta\frac{\sigma(B_c^+)BR(B_c^+\to J/\psi\mu^+\nu)}{\sigma(B^+)BR(B^+\to J/\psi K^+)}$
B_c^+ background	$^{+0.0057}_{-0.0068}$
$\Delta\epsilon_{rel}$	$^{+0.0207}_{-0.0185}$
Total systematics	$^{+0.0214}_{-0.0197}$

CDF Preliminary

$$\frac{\sigma(B_c^+) * BR(B_c^+ \to J/\psi\mu^+\nu)}{\sigma(B^+) * BR(B^+ \to J/\psi K^+)} = 0.211 \pm 0.012(\text{stat})^{+0.021}_{-0.020}(\text{sys})$$

Conclusions

- D0 observes no significant forward-backward asymmetry for $B^{\pm}$. Some tension with MC@NLO
- D0 has measured the $\bar{\Lambda}_b/\Lambda_b$ production ratio and finds it is consistent with a universal function of rapidity loss
- Indirect CP-violating asymmetries in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ at CDF found to be consistent with CP symmetry
  $A_\Gamma = (-1.2 \pm 1.2) \times 10^{-3}$
- CDF measures $\frac{\sigma(B_c^+) * BR(B_c^+ \rightarrow J/\psi\mu^+\nu)}{\sigma(B^+) * BR(B^+ \rightarrow J/\psi K^+)} = 0.211 \pm 0.012(\text{stat})^{+0.021}_{-0.020}(\text{sys})$

Backup

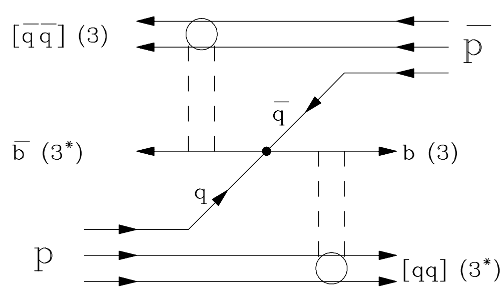
$B^{\pm}$ reconstruction

- $B^{\pm} \longrightarrow J/\psi\ K^{\pm}$ with $J/\psi \longrightarrow \mu^{+}\mu^{-}$
- Candidate events first found with cut based analysis based on track P_T, transverse decay length, $M(\mu^{+}\mu^{-})$, quality of three track vertex and pointing angle[1].
- Background rejection is improved with a BDT which includes kinematic variables such as, particle momenta, distances from $p\bar{p}$ vertex, decay lengths, pointing angles, isolation of muons and $B^{\pm}$, and azimuthal angle separation for various particle pairs
- Simulation: MC@NLO with CTEQ6M1 PDF and Herwig for parton showering and hadronization

[1] the angle between a particle's momentum vector and the vertex from the ppbar vertex to the particle's decay vertex, with vectors defined in the x-y plane

Asymmetry

- Hadroproduction of particles containing heavy quark Q proceeds through $q\bar{q}$ annihilations or g-g fusion followed by hadronization to the heavy quarks
- At NLO, QCD effects can introduce a small asymmetry (~1%) in Q and $\bar{Q}$ momenta
- Hadronization may also change direction of particle containing Q so can generate significant asymmetry
- Few studies of asymmetries of bottom baryons
- Recently "string drag" mechanism proposed by J. Rosner may favor production of Λ_b baryons in proton beam direction and $\bar{\Lambda}_b$ baryons in anti-proton beam direction



Yields

Signal region ↓

	3-4 GeV/c^2	4-6 GeV/c^2	6-10 GeV/c^2
B_c^+ candidates	132$\pm$11.5	1370$\pm$37.0	208$\pm$14.4
Misidentified J/ψ	11.5$\pm$2.4	96.5$\pm$6.9	25.0$\pm$3.5
Misidentified Muon	86.7	344.4	32.1
Double Fake	-5.1	-19.0	-5.2
$b\bar{b}$ Background	12.4$\pm$2.4	178.6$\pm$12.4	110.4$\pm$10.7
Other decay modes	2.6$\pm$0.1	30.0$\pm$0.2	0
Total background	108.1 ± 3.4	630.5 ± 14.2	162.3 ± 11.3
B_c^+ Excess	23.9$\pm$12.0	739.5$\pm$39.6	45.7$\pm$18.3
B_c^+ Monte Carlo, (scaled to signal region)	22.6$\pm$0.6	739.5$\pm$3.7	27.6$\pm$0.6

Backgrounds for B_c^+

- Mis ID J/ψ
  - Determined from J/ψ sidebands
- Mis ID third muon
  - Calculate probability that a muon is mis –ID based on probability for π, K or p to fake a muon
- $b\bar{b}$ background
  - J/ψ from one b hadron and a third muon from other $\bar{b}$ hadron
- Other decay modes