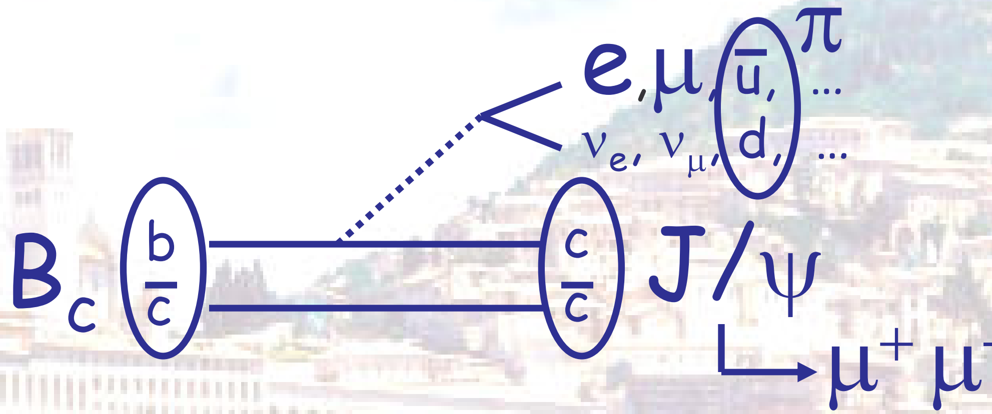
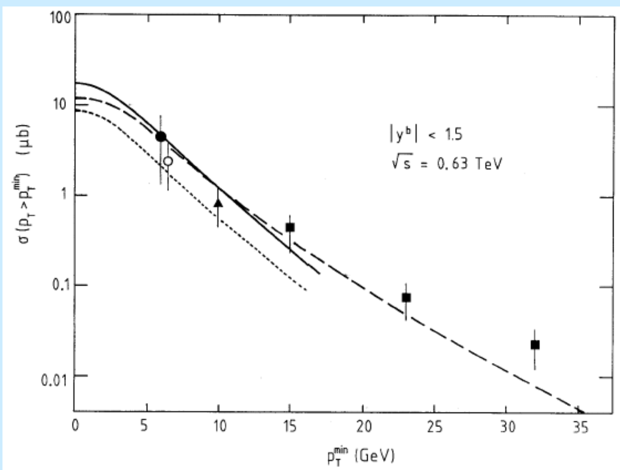
Bc at the Tevatron



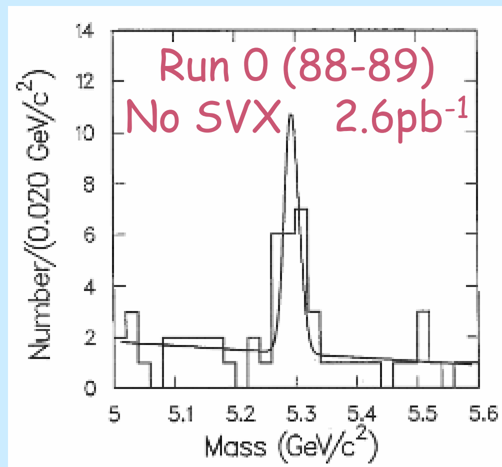
William Wester
Fermilab
for the CDF and DØ collaborations

Introduction

- B Physics at Hadron Colliders
  - UA1 cross section measurements
  - CDF fully reconstructed B->J/ψK$^{(*)}$



UA1 σ(b) in μ channel
PLB 213, 415 (1988)



CDF B_u->J/ψK
PRL 68, 3403 (1992)

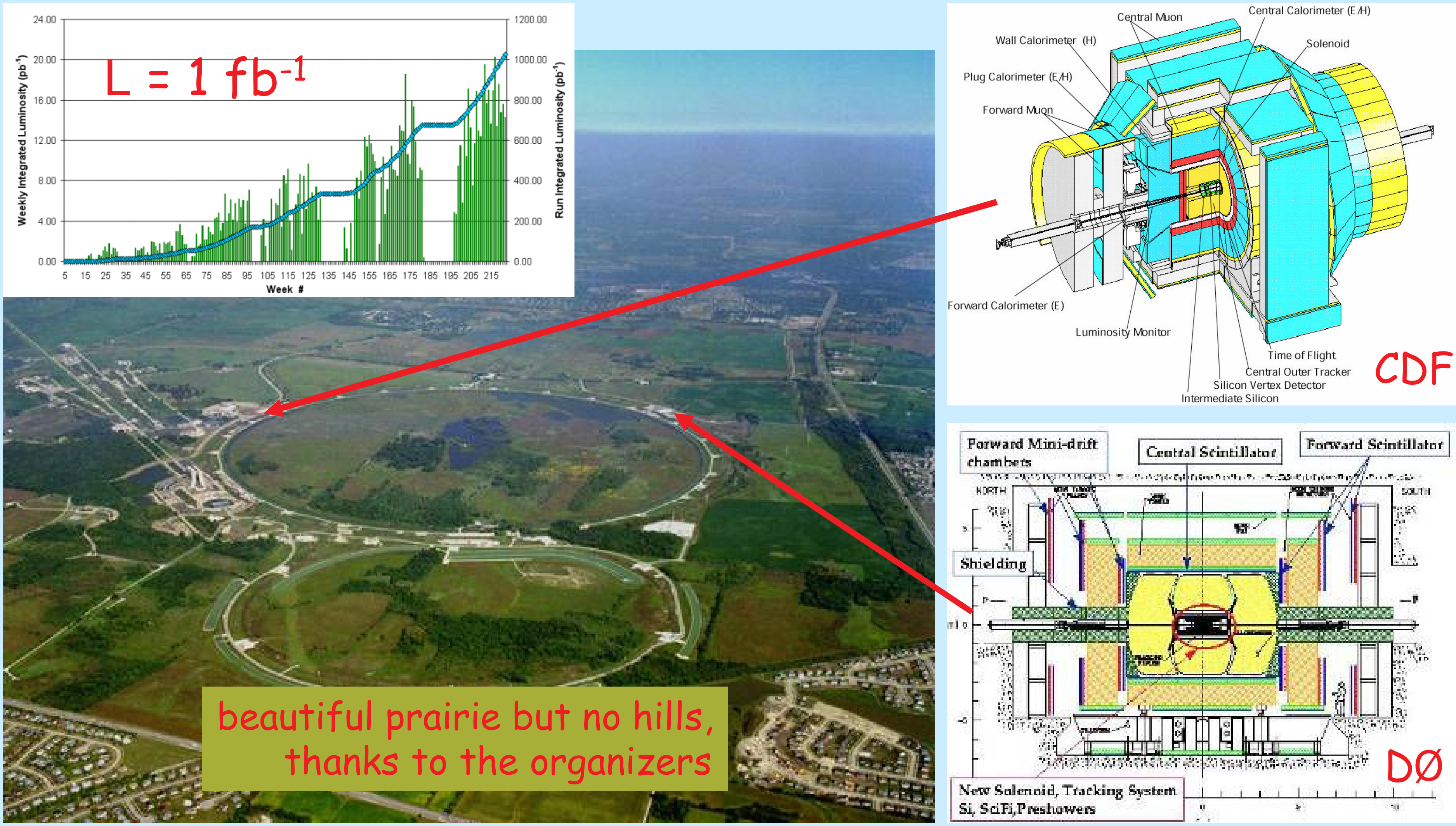
Since the 1980's ...

Advantages:
Large σ(b) x **L**
All mesons and baryons
Triggerable: l or J/ψ
Multipurpose detectors

Disadvantages: (perceived)
High backgrounds
Limited acceptance
Small Lorentz boost
Unknown initial state

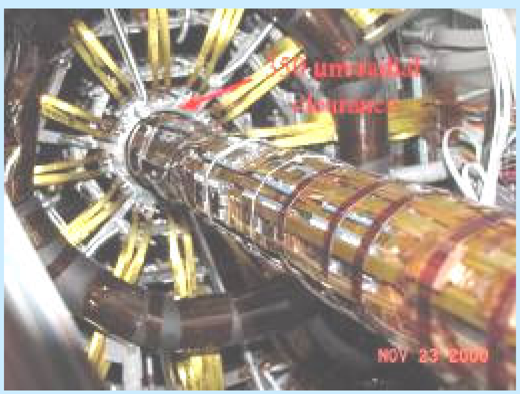
- Study of Bc highlights hadron collider advantages
  - Large cross section for producing triggerable low background decays not accessible at the B factories.

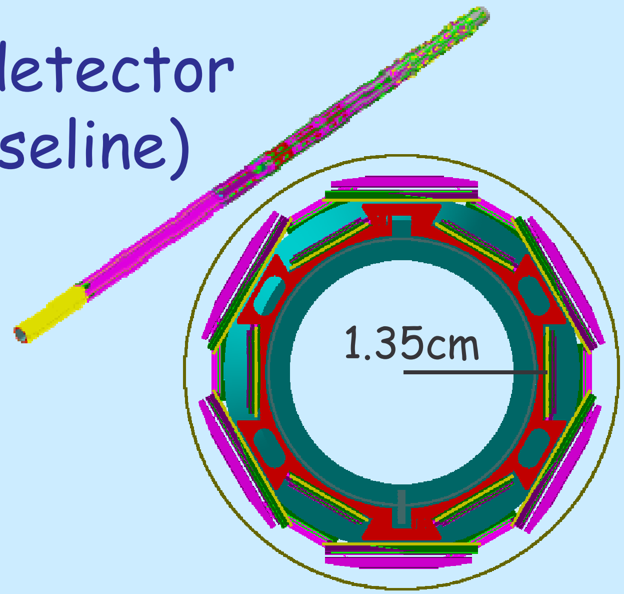
Tevatron in Run II

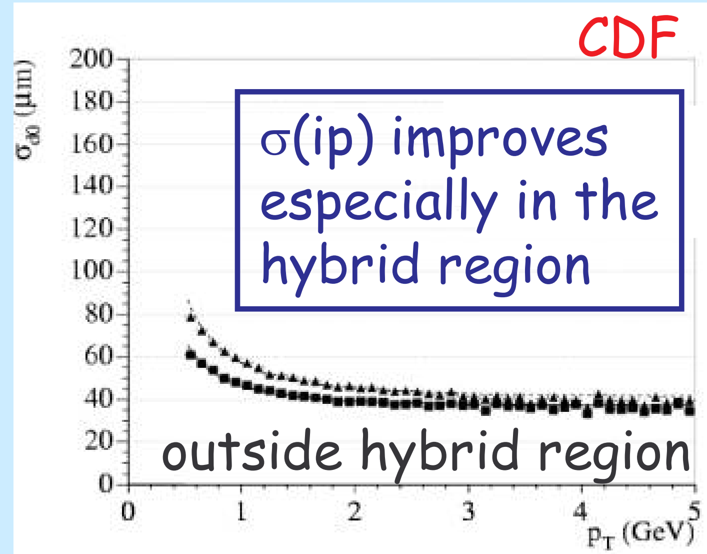


Innermost silicon layer

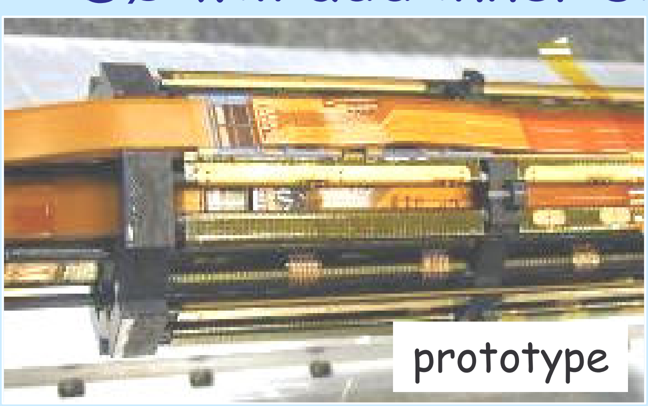
- CDF LayerØØ detector (beyond the baseline)

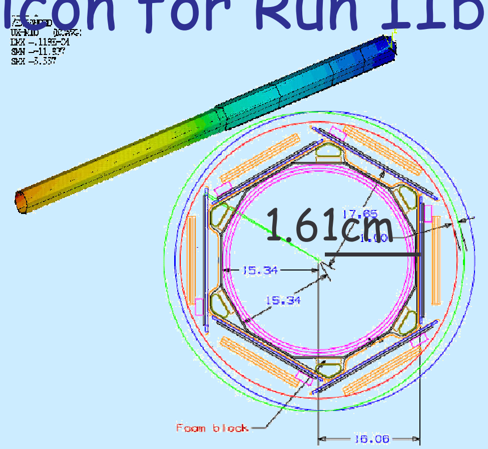


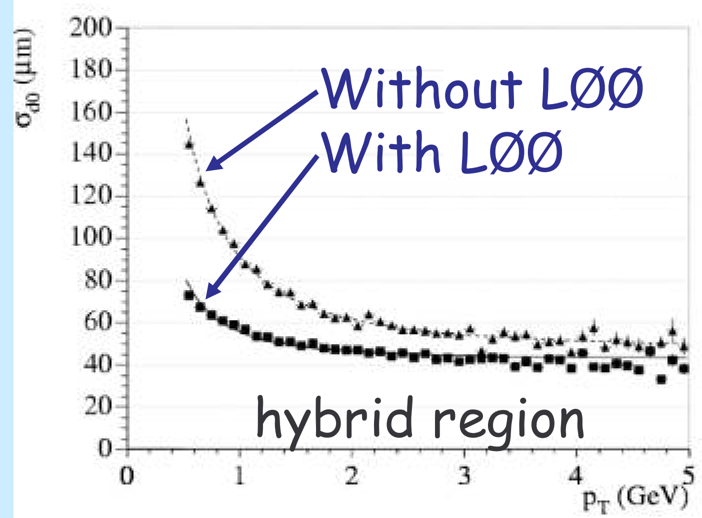




- DØ will add inner silicon for Run IIb



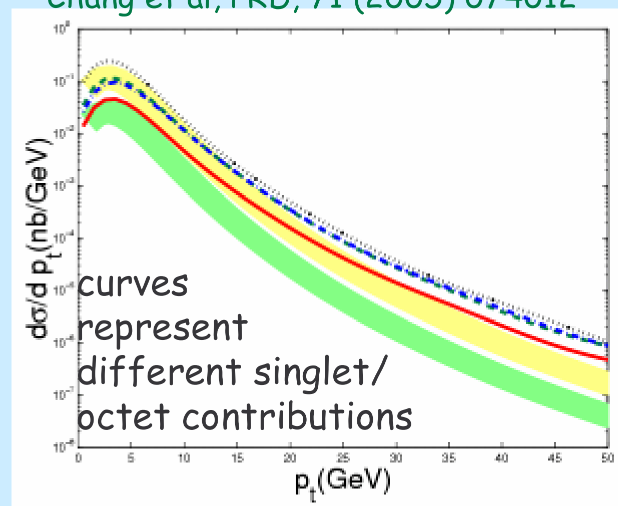




Bc properties

- Bc is a heavy-heavy system
  - Production: Factorization with two scales $M_b + M_c$ and contributions of color singlet / octet
    - Softer P_T distribution?
  - Decay: both b and c quarks can participate
    - Shorter *c-like* lifetime?
    - Large number of final state *BR*s.
  - Mass: new system for potential models and new lattice QCD calculations

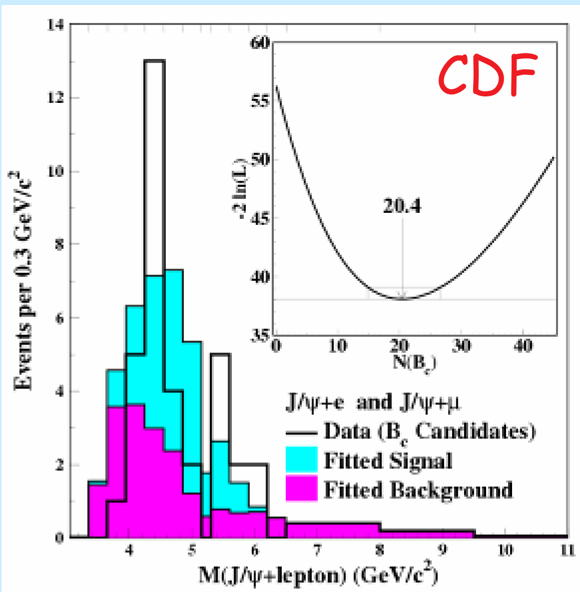
Chang et al, PRD, 71 (2005) 074012

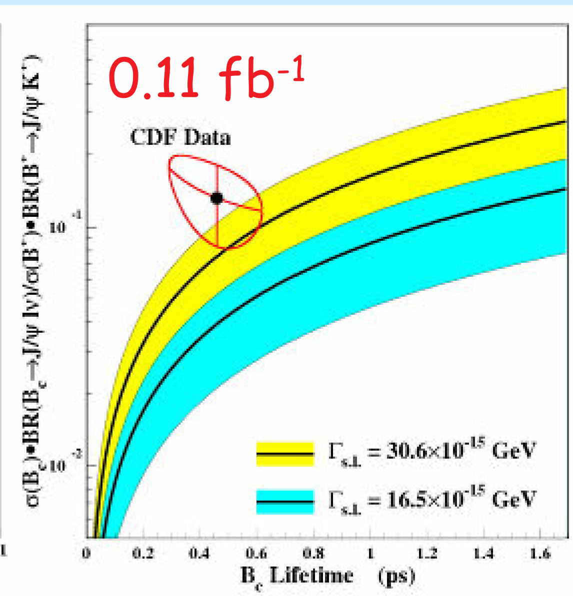


- All aspects of the theoretical work require experimental measurement => happening now at the Tevatron

CDF: Bc in Run I ('91-'96)

- A few candidate events at LEP and the CDF observation and measurements…



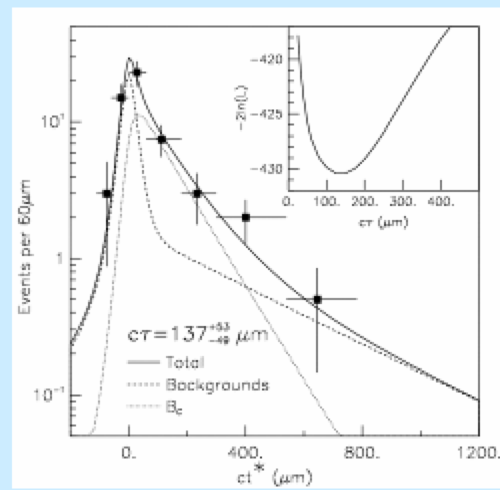


PRL 81, 2432 (1998) and PRD 58, 112004 (1998)

$20.4^{+6.2}_{-5.5}$ **signal events**

M=6.4±0.39±0.13 *GeV*

$c\tau = 0.46^{+0.18}_{-0.16}\ 0.03$ ps



Production measurement ($P_t(B)>6$ GeV/c $|\eta|<0.6$):

$$\frac{\sigma(B_c)\times B(B_c\to J/\psi l\nu)}{\sigma(B_u)\times B(B_u\to J/\psi K)} = 0.132^{+0.041}_{-0.037}(\text{stat})\pm 0.031\ (\text{syst})\ ^{+0.032}_{-0.020}(c\tau)$$

Note: assuming harder P_t spectrum in MC

Run II results: semi-leptonic decays

- B_c -> J/ψ + l with l = e, μ
- Not fully reconstructed (missing ν)
- Understanding backgrounds are key
  - $b\bar{b}$ events with the J/ψ from b and l from $\bar{b}$
  - Fake muons or fake electrons
  - Other backgrounds
- Study J/ψ+track and B_u->J/ψ K
- Look for B_c excess above background and make measurements

Bc in DØ

- Three muon final state: $B_c \to J/\psi\ \mu\ X$ (with $J/\psi \to \mu\mu$)
  - 0.21 fb^{-1} of data
  - 231 $J/\psi\mu X$ candidates (signal+background)
  - Use J/ψ+track control sample for background
    - prompt
    - non-prompt
- Combined likelihood fit
  - Signal + background
    - mass
    - pseudo-lifetime

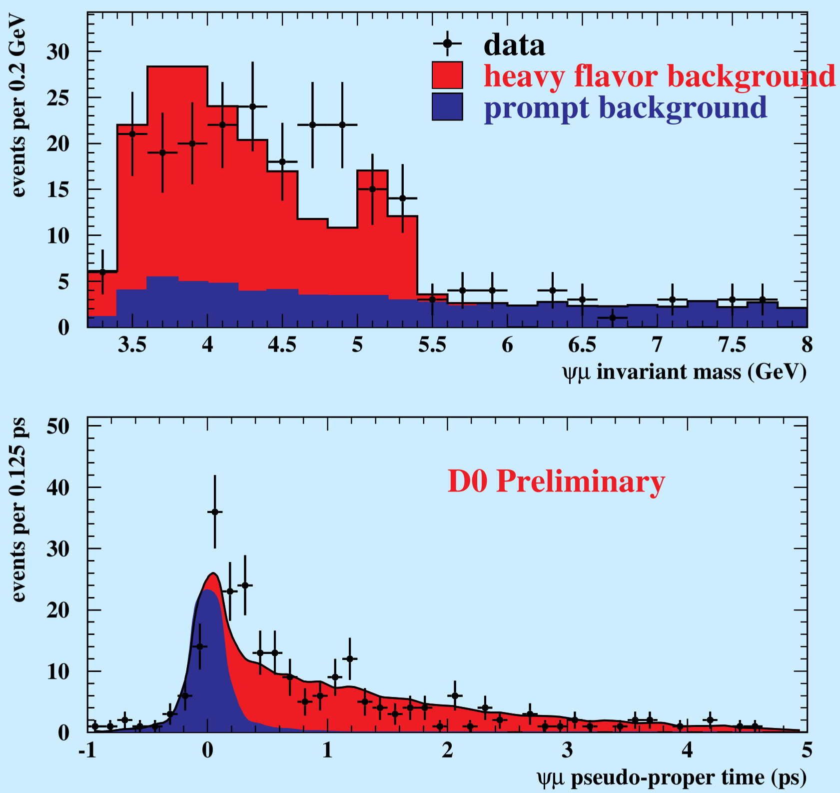
Scan Monte Carlo in steps of different mass.

Perform the fit with and without the Bc along with prompt and non-prompt data bkgd distributions.

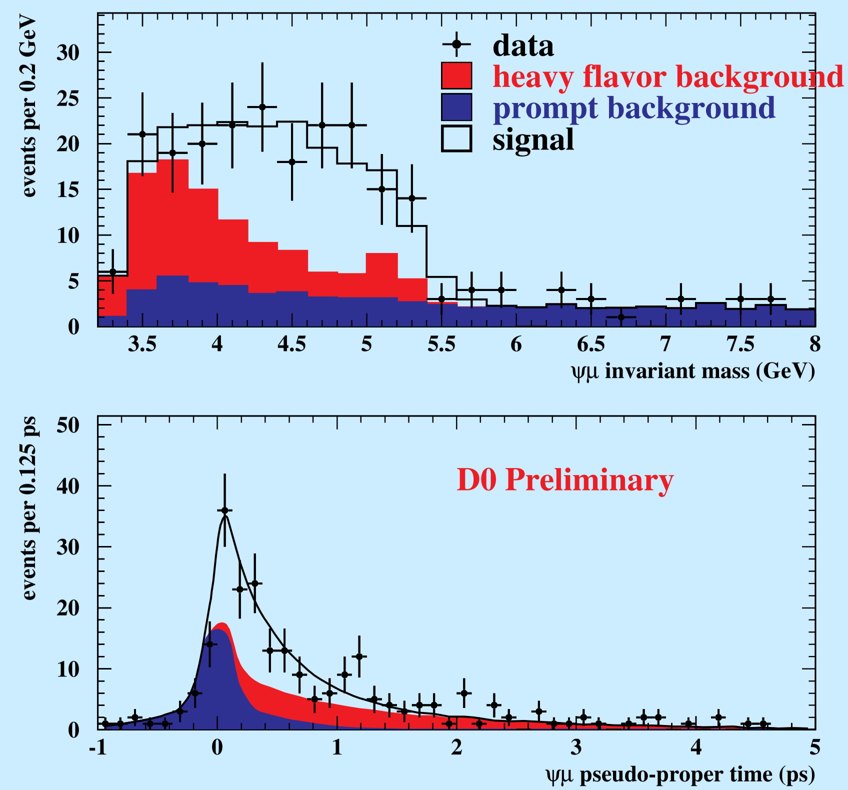
Cross-check the results using $\psi(2S)$ + μ/track (background dominated).

Fit with and w/o Bc

Background-only



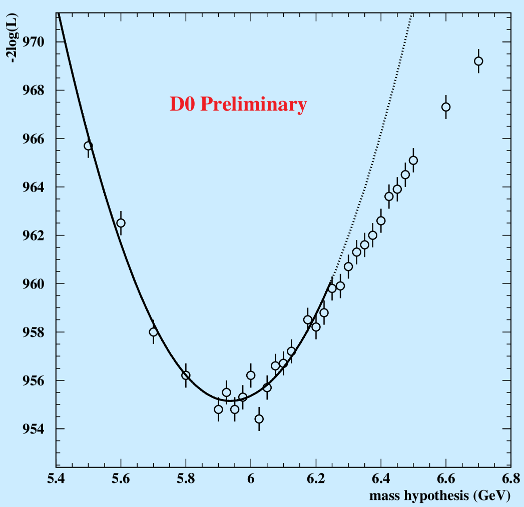
Include Bc contribution



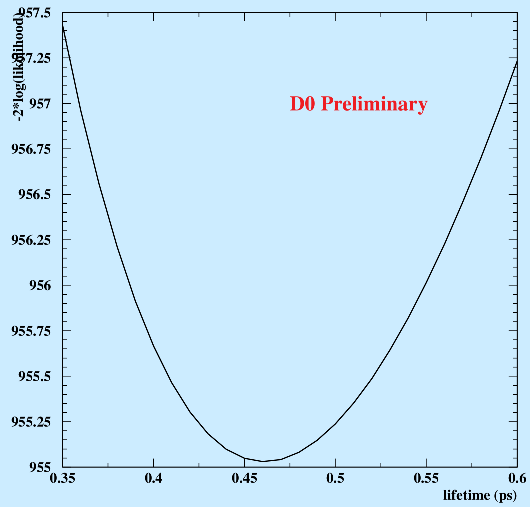
Background-only fit is poor compared with addition of signal: Δ2log(likelihood) is 60 for 5 dof

DØ: fits and results

Mass log likelihood



cτ log likelihood



N_{CAND}:

95 ±12 ±11

"first 5σ B_c result"

Mass:

$5.95^{+0.14}_{-0.13} \pm 0.34$ GeV

cτ:

$0.448^{+0.123}_{-0.096} \pm 0.121$ ps

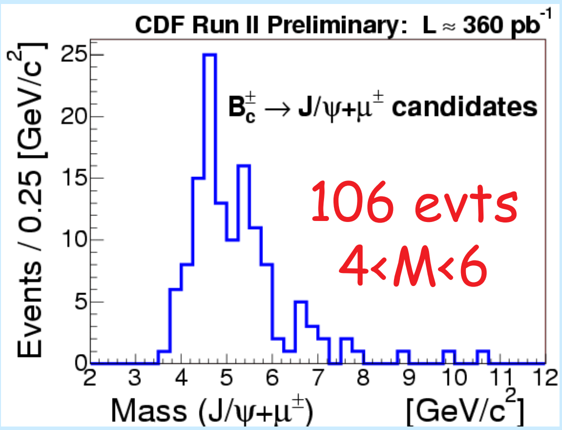
	Mass (GeV/c^2)	Lifetime (ps)	# Signal
Statistical	$^{+0.14}_{-0.13}$	$^{+0.118}_{-0.094}$	11.8
Limited statistics of background sample	0.06	0.013	3.0
Fraction non-resonant $B_c^+ \to J/\psi\mu^+\pi^0\nu$	0.14	0.022	6.7
Feed-down fraction from $B_c^+ \to J/\psi(2S)\mu^+\nu$	0.08	0.017	5.4
MC signal modeling: phase space vs. ISGW	0.16	0.023	4.4
MC signal modeling: HQET vs. ISGW	0.06	0.007	1.8
B_c p_T spectrum	0.05	0.004	0.8
Momentum binning	0.14	0.062	0.4
Alignment and primary vertexing algorithm	0.08	0.085	3.1
$\mathcal{P}_{\rm fit}$ selection criteria	0.06	0.028	–
Sensitivity to prompt/heavy relative bkgd fractions	0.15	0.036	–
Total systematic error	0.34	0.121	10.7

DØ Note: 4539-CONF

CDF: Bc -> $J/\psi\ \mu$ X

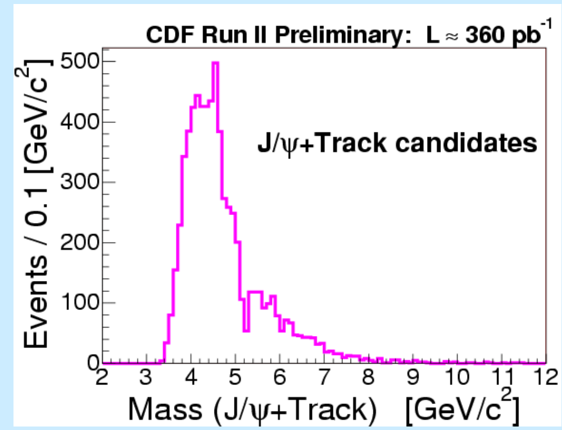
- Use 2.7M J/ψ's in 0.36 fb^{-1}
- Combine with third track with & w/o muon ID
  - P_T>3 GeV, $c\tau$ > 60μm, and $\Delta\phi(J/\psi - trk)$ < 90 deg
- Use B_u->$J/\psi K$ from data for normalization
- Use Monte Carlo of B_u and B_c for ε_{rel}
- Evaluate backgrounds in the data
  - Fake muons, $b\bar{b}$, fake J/ψ
- Estimate systematic uncertainties
- Fit data in 4-6 GeV for signal and backgrounds
  - Evaluate relative production of Bc to Bu

Fake muon background

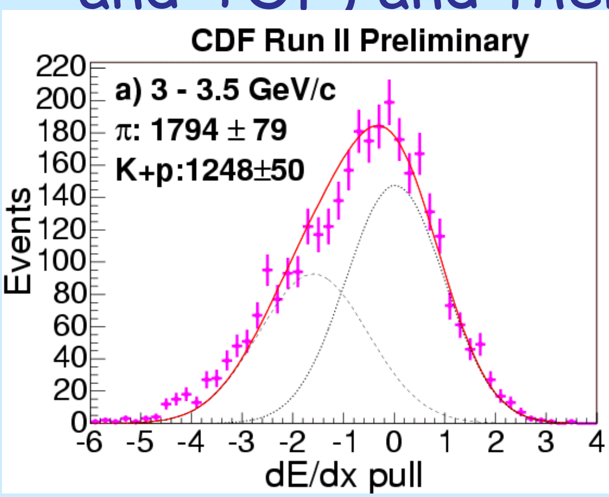


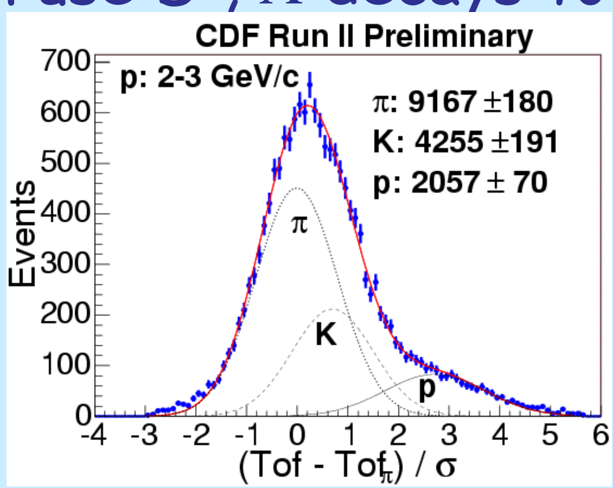
How many come from J/ψ+track where the track is a fake muon?

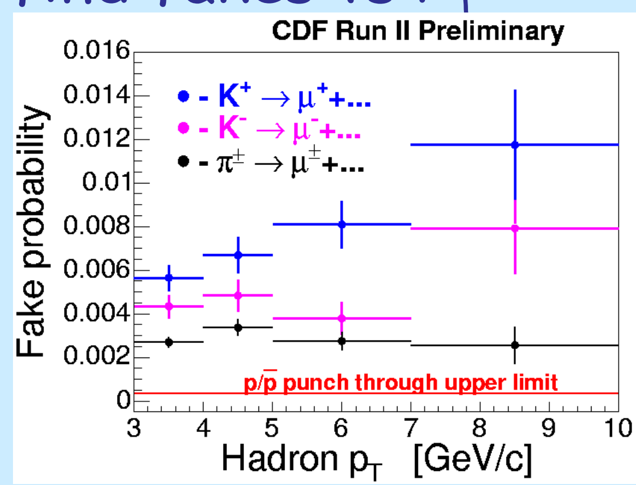
Fake muons primarily from decay in flight: 16.3±2.9 estimated in 4<M<6 GeV.



- Fake muons: determine π, K, p composition vs P_T (dE/dx and TOF) and then use D^*, Λ decays to find fakes vs P_T

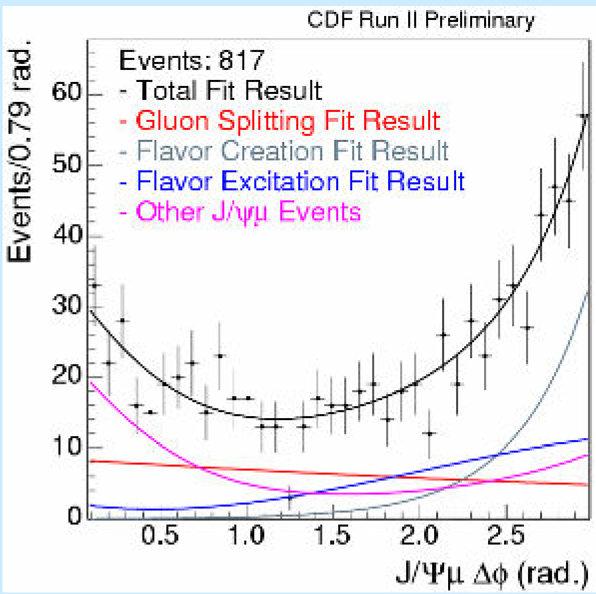


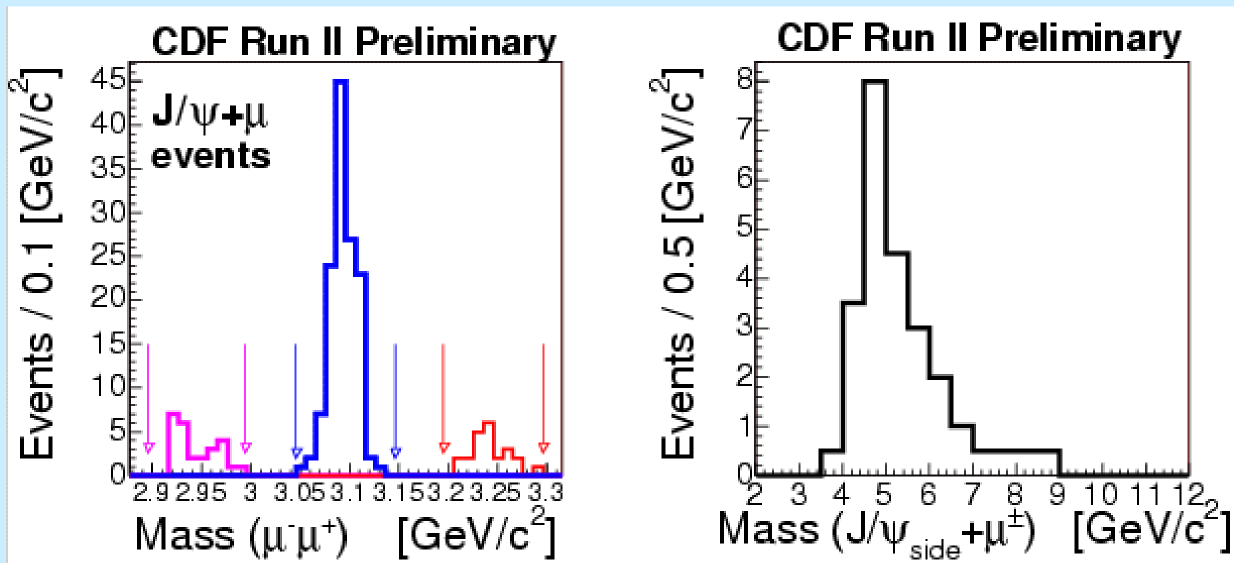




More backgrounds

- $b\bar{b}$ background from Pythia Monte Carlo normalized to B_u->$J/\psi K$ data using $\Delta\phi$ distributions (vary production)
- Fake J/ψ from J/ψ sidebands



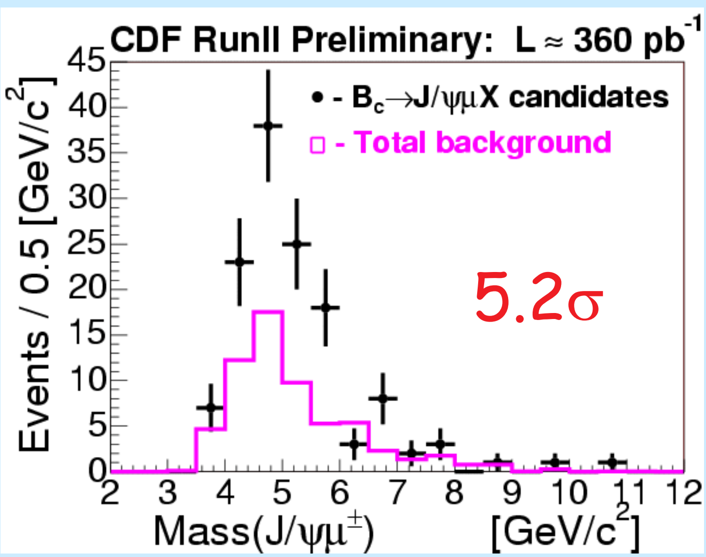


Backgrounds from the other b: 12.7±1.7 ±5.7 estimated in 4<M<6 GeV.

Backgrounds from fake J/ψ (no double counting): 19.0±3.0 estimated in 4<M<6 GeV.

Muon channel results

Mass window	3.0 – 4.0 GeV/c²	4.0 – 6.0 GeV/c² (signal)	6.0 – 10.0 GeV/c²
B_c candidates in mass window	7 ± 2.4	106 ± 10.3	19 ± 4.2
Fake muon background	3.9±0.7	16.3±2.9	2.2±0.4
BB background	0.6 ± 0.4 ± 0.1	12.7 ± 1.7 ± 5.7	6.0±1.1 ± 1.8
Fake J/ψ background	0.5 ± 0.5	19.0 ± 3.0	5.0 ± 1.7
Fake μ from $(J/\psi_{side} + Trk)$	0.3±0.1	2.0±0.5	0.7±0.2
Total Background	4.7±0.9	46.0±7.3	12.5±2.7
Events above background	2.5±2.8	60.0±12.6	6.5±5.1



Use MC for relative efficiency for Bc and Bu along with Bu->J/ψK to obtain:

$$\frac{\sigma(B_c)\times \mathcal{B}(B_c \to J/\psi l \nu)}{\sigma(B_u)\times \mathcal{B}(B_u \to J/\psi K)} =$$

$P_T(B)>4$ and $|y| < 1$

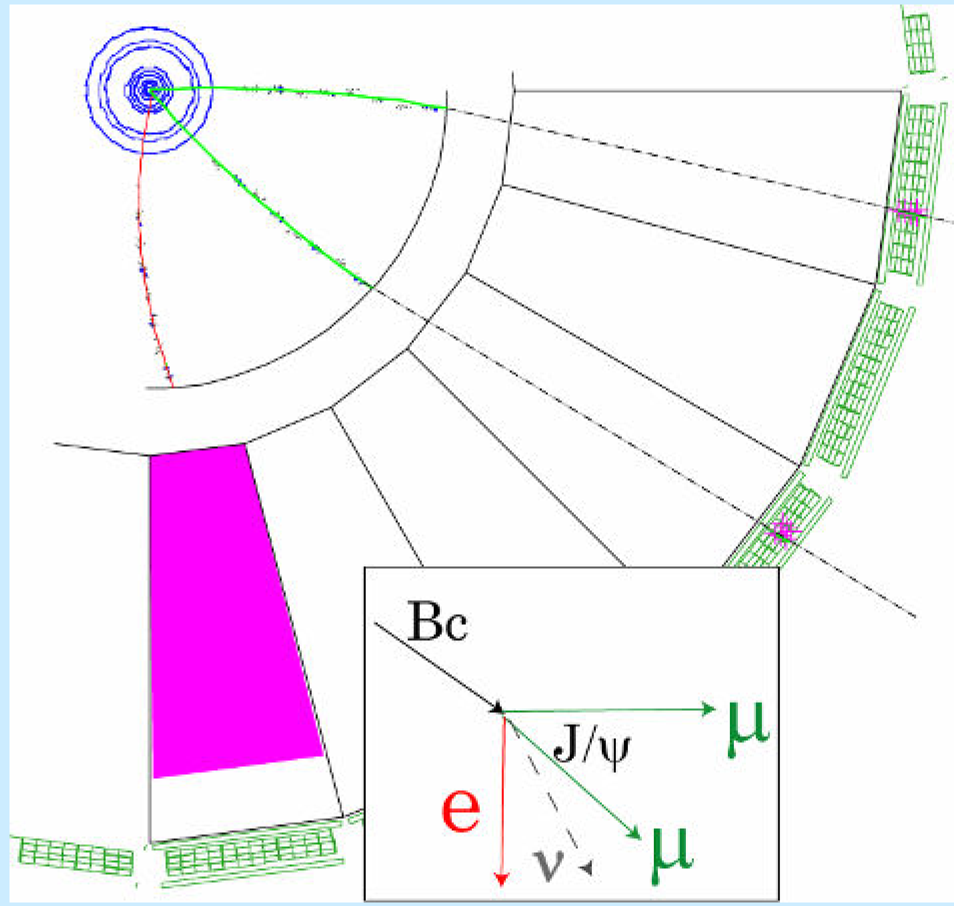
$$0.249 \pm 0.045 \pm 0.069 \pm^{0.082}_{0.033}$$

Other measurements from this sample are in preparation.

CDF Note: 7649

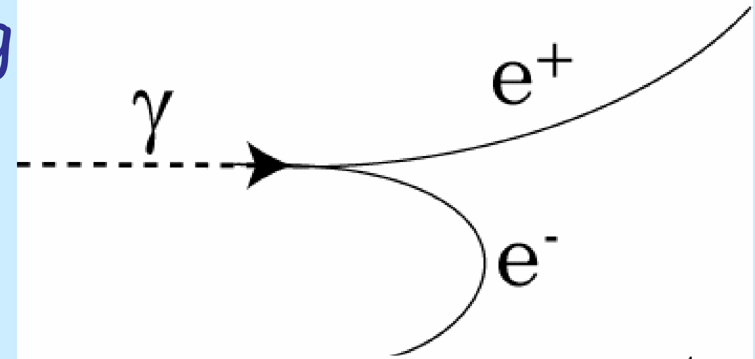
CDF: Bc -> J/ψ e X

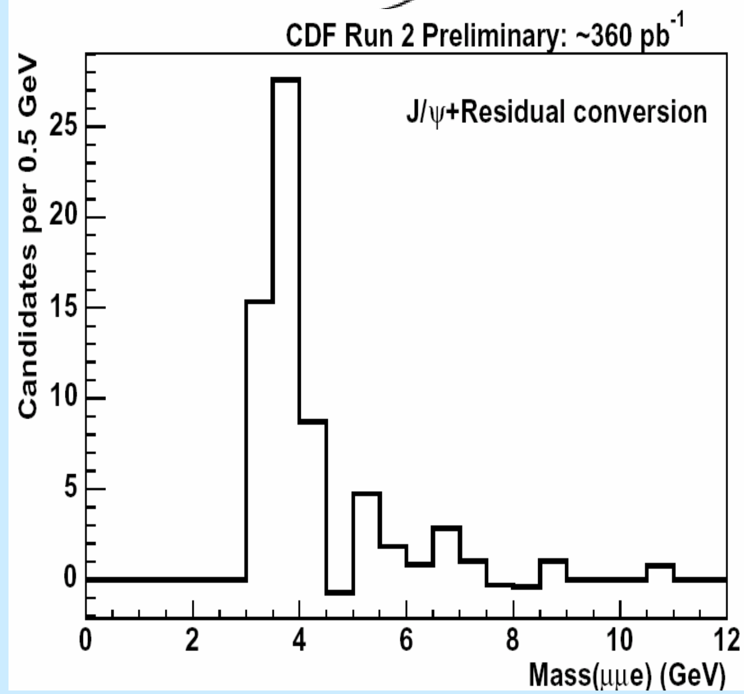
- Fake electron
  - Use J/ψ+track data
  - Estimate fake rate from data ($D^0 \rightarrow K\pi, \Lambda^0 \rightarrow p\pi$)
- Photon conversion
  - Use J/ψ+tagged conversion data
  - Conversion finding efficiency from MC
- $b\bar{b}$ background
  - $b \rightarrow J/\psi X$ and $\bar{b} \rightarrow eX$
  - PYTHIA $b\bar{b}$ Monte Carlo



Photon conversions

- Remove conversions by finding the partner track during the electron selection
- Evaluate the conversion finding efficiency from MC
- Calculate the residual conversion background as a function of $M(J/\psi e)$ using J/ψ+tagged conversions.
- Expected background
  - $14.54 \pm 4.38(\text{stat}) \pm 6.39\ (\text{syst})$





electron channel results

- Background

63.6±4.9(stat)±13.6(syst)

- Observed

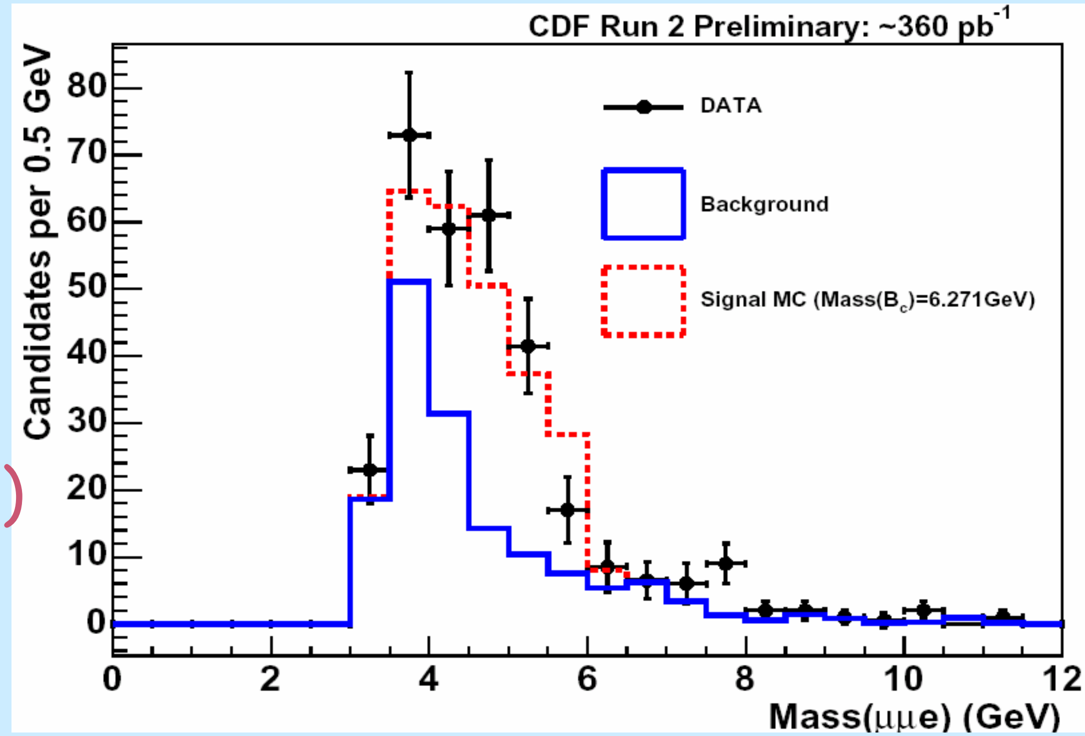
178.5±14.7(stat)±

- Excess

114.9±15.5(stat)±13.6(syst)

- Significance

5.9σ



$$\frac{\sigma(B_c)\times B(B_c \to J/\psi l\nu)}{\sigma(B_u)\times B(B_u \to J/\psi K)} =$$

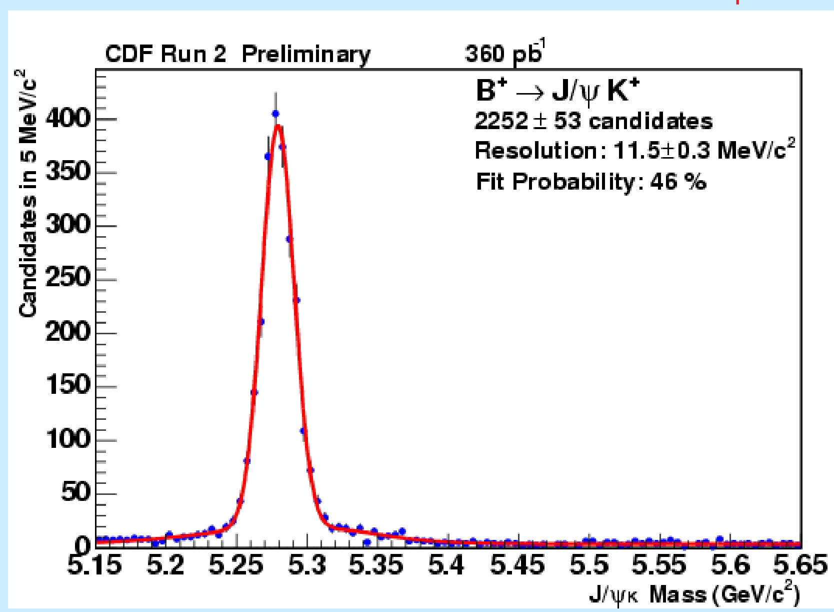
$P_T(B)>4$ and
$|y| < 1$

0.282±0.038(stat.)±0.035(yield)±0.065(acceptance)

CDF: Bc -> $J/\psi\ \pi$

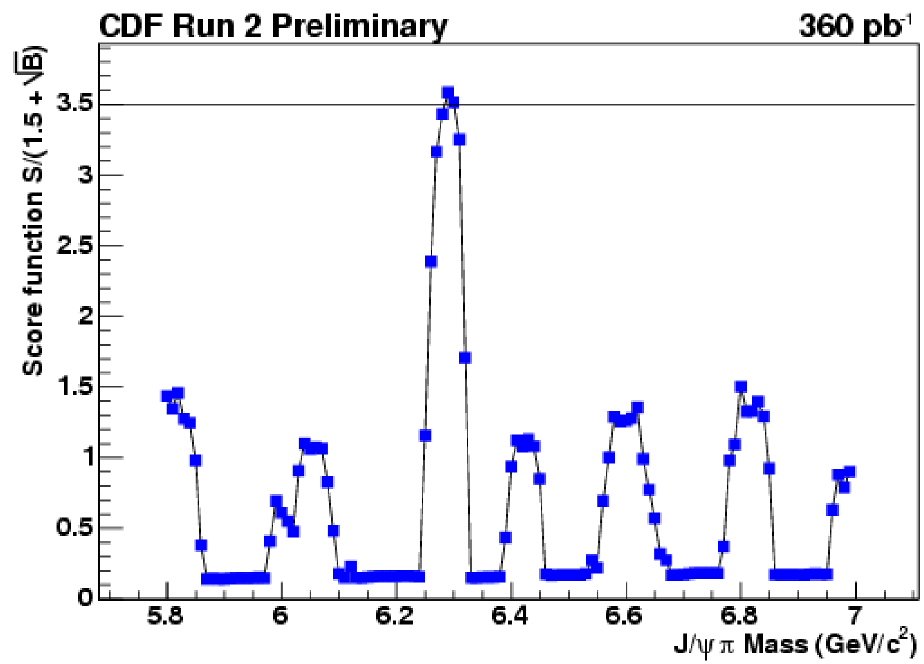
- Full reconstruction determines precise mass
- Estimate 10-50 events in $0.36fb^{-1}$
- Perform analysis "blind"
  - Optimize MC signal using a figure of merit
  - Collapse background into large discrete bins
  - Use predetermined threshold for positive result
- Tight requirements
  - Especially on π coming from displaced J/ψ vertex
- Perform cross-checks

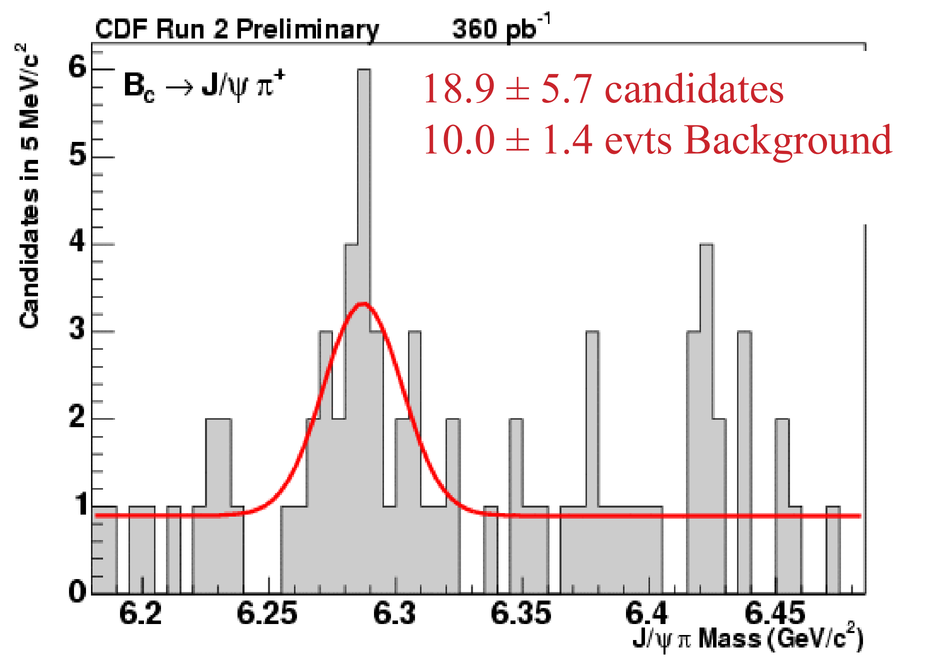
Bu->J/ψK



Results

- Small excess at 6.3 GeV above predetermined threshold





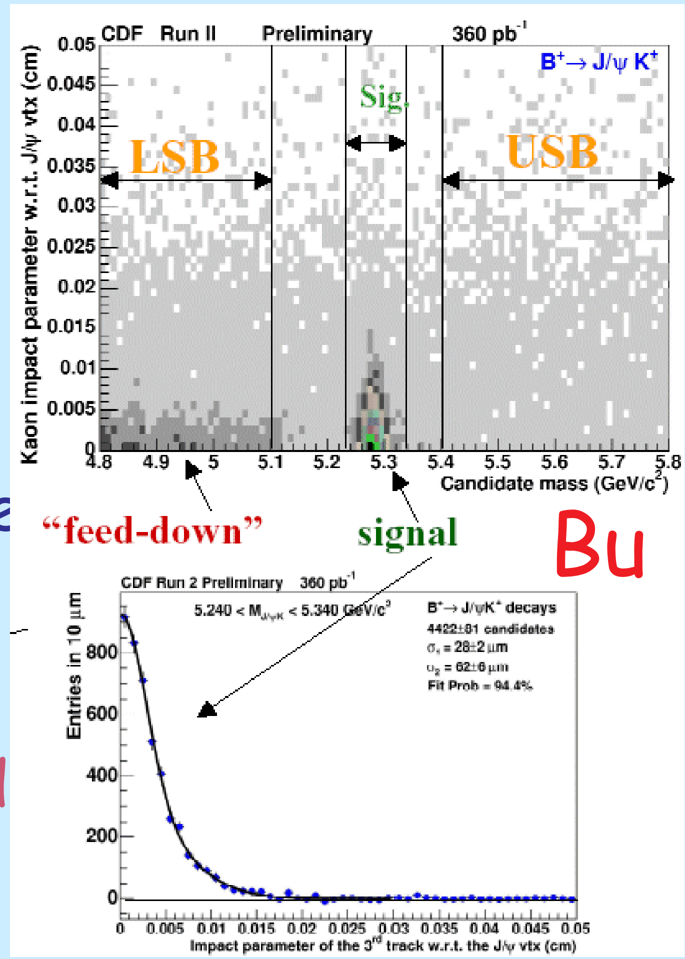
Monte Carlo: prob(bkgd) fluctuates to this signal is 0.3%

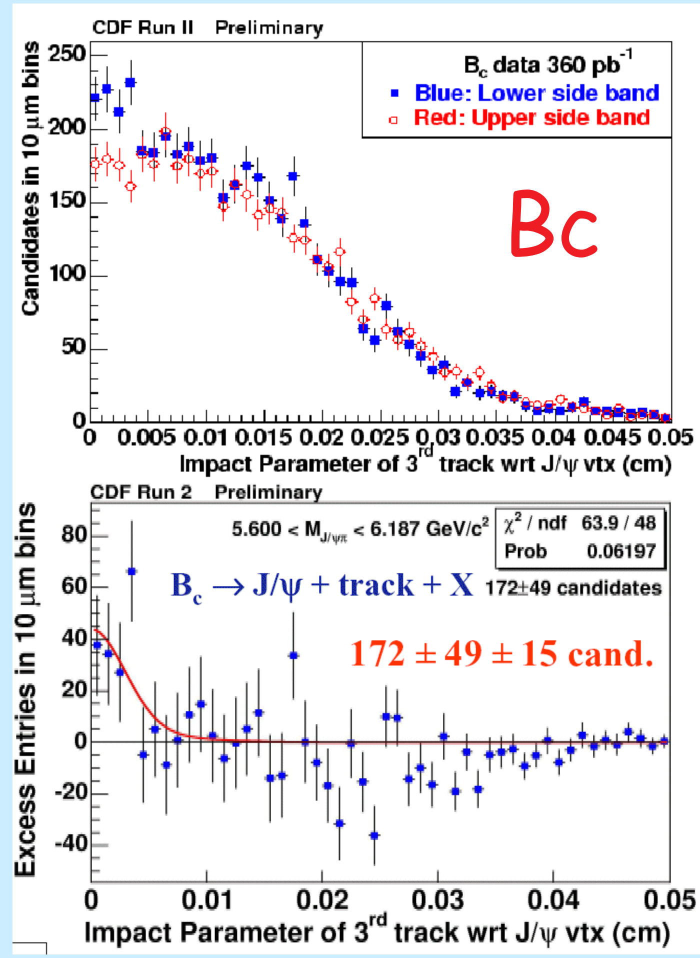
Mass = 6287.0 ± 4.8(stat.) ± 1.1(syst.) MeV/c^2

hep-ex/0505076

Cross check: partially reconstructed sample

- Look at partially reconstructed decays with $M < M_{Bc}$.
  - Relax cuts
  - 3rd track of partially reconstructed track should still point to the J/ψ vertex
  - Upper sideband should have no Bc





Recent lattice QCD calculation

- Recent calculation emphasizes new precision from 2+1 flavor lattice QCD with staggered quarks

PLB 453, 289 (1999)

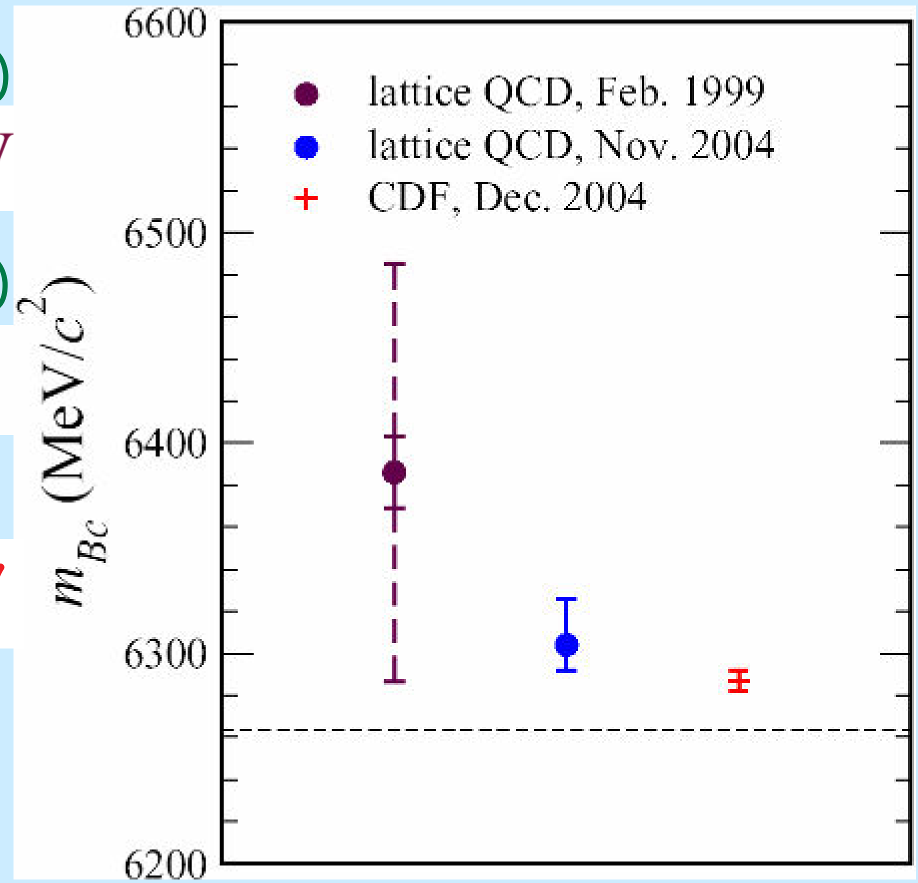
$$m_{B_c}^{n_f=0} = 6386 \pm 9 \pm 15 \pm 98 \text{ MeV}$$

PRL 94, 172001 (2005)

$$m_{B_c}^{2+1} = 6304 \pm 4 \pm 11^{+18}_{-0} \text{ MeV}$$

hep-ex/0505076

$$m_{Bc} = 6287.0 \pm 4.8 \pm 1.1 \text{ MeV}$$



Δ(theory-exp)= 17 MeV

Summary and conclusions

- The study of the Bc is happening in Run II
- Semi-leptonic decays observed $>5\sigma$
  - D0: $J/\psi\ \mu$ (tri-muon)
  - CDF: $J/\psi\ \mu$ and $J/\psi\ e$
- Small excess in CDF's $J/\psi\ \pi$ sample
  - Precision mass compared with theory
- Coming soon …
  - Production spectrum and lifetimes
  - Stronger fully reconstructed signal