Observation of B_c Mesons in $\bar{p}p$ Collisions at $\sqrt{s}$=1.8 TeV

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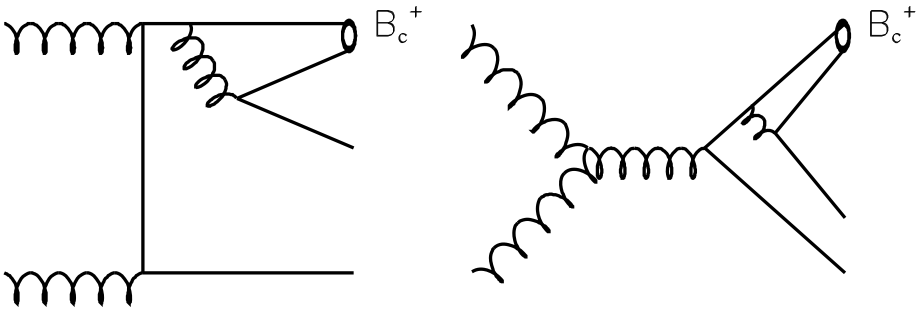
- Introduction
- Event Selection
- Background Estimates
- Statistical Significance
- B_c mass
- B_c lifetime
- B_c Production Cross Section
- Conclusions

The B_c Meson

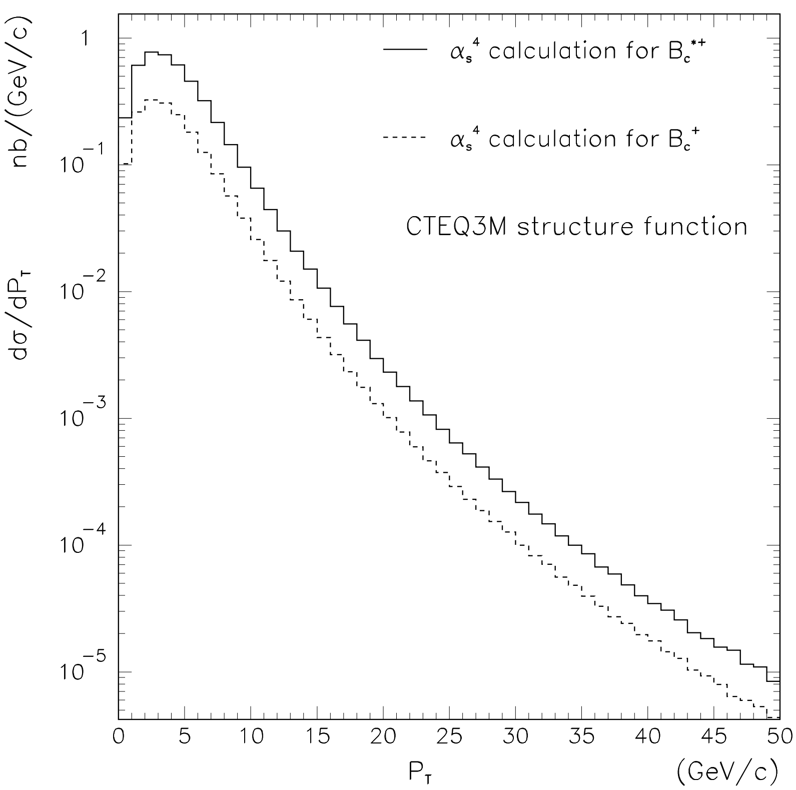
- The B_c meson is a bound state of the b and the c quark.
- The B_c Mass is predicted to be 6.27 ± 0.02 GeV/c^2
  E. Eichten et. al., PR D<u>49</u>, 5845(1994)
- The B_c lifetime is predicted to be between 0.4 and 1.4 ps. M. Beneke et. al., PR D<u>53</u>, 4991(1996)
- The B_c is a quarkonium system intermediate between J/ψ and the Υ families.
- Two heavy quarks; Reliable calculations
  - Spectroscopy
  - Weak Decays

Theoretical Calculations of B_c Production



$$\alpha_s^4 \text{ calculation} \longrightarrow \frac{\sigma(B_c)}{\sigma(b\bar{b})} \sim 10^{-3}$$

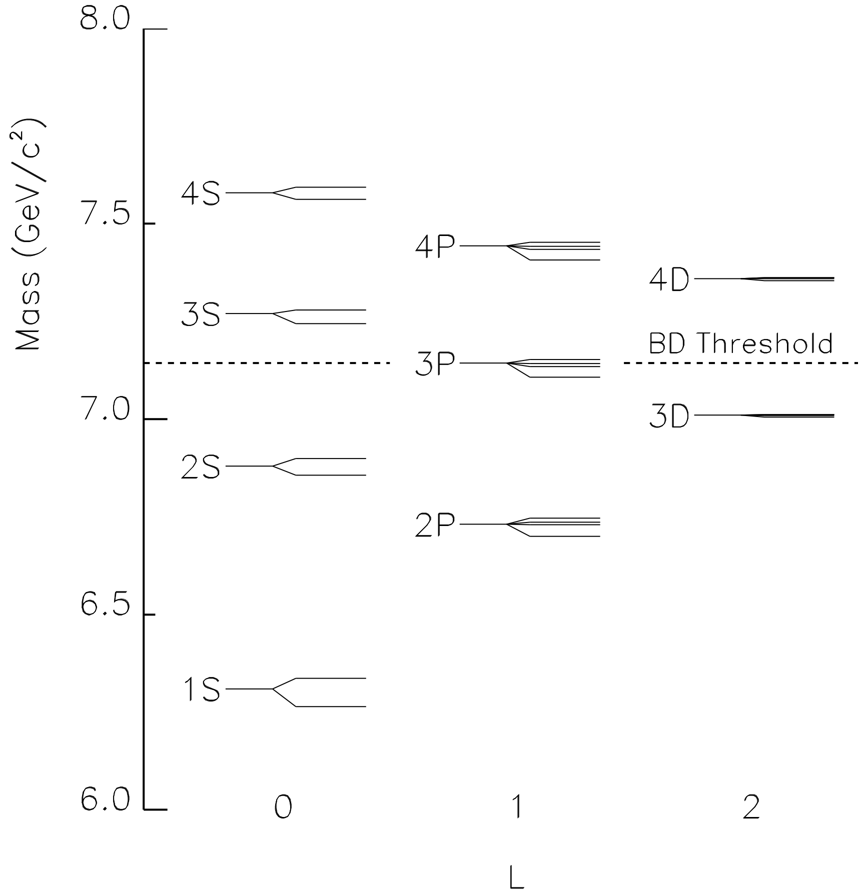
p_T spectrum for $B_c(1\,^1\mathrm{S}_0)$ and $B_c^*(1\,^3\mathrm{S}_1)$ by C. Chang *et. al.*, PRD 54(1996) 4344.



Mass Spectrum of $\bar{b}c$ Bound States

by E.J. Eichten and C. Quigg, PRD 49(1994) 5485.

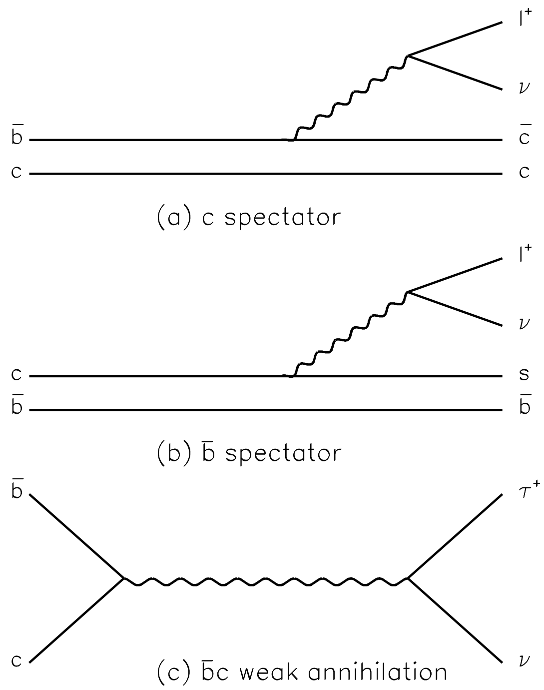
- Nonrelativistic QCD potential models



- $B_c^* \to BD$ above BD Threshold
- $B_c^* \to B_c + \gamma(\text{or } \pi\pi)$ under BD Threshold
- $6.25 \leq m(B_c) \leq 6.29$ GeV$/c^2$

Theoretical Calculations of B_c Lifetime

- The B_c meson decays only through weak interactions.



- The B_c lifetime depends on the model assumption of bound state effect.
  - Loosely bound

$$\Gamma_{\text{tot}} \sim \Gamma_b + \Gamma_c \sim \Gamma(B^0) + \Gamma(D^0)$$
$$\tau(B_c) \sim 0.3 \text{ ps}$$

  - Tightly bound

Free quark $\Gamma_Q \propto m_Q^5 \longrightarrow \Gamma'_Q \propto (m_Q - \mu_{\text{BE}})^5$

Relative reduction $\frac{\Gamma'_b}{\Gamma_b} \simeq \frac{1}{1.7}$ and $\frac{\Gamma'_c}{\Gamma_c} \simeq \frac{1}{6}$

$$\tau(B_c) \sim 1.4 \text{ ps}$$

The B_c lifetime is predicted in a wide range:

$$0.4 \text{ ps} < \tau(B_c) < 1.4 \text{ ps}$$

Previous B_c Meson Searches

LEP and CDF experiments have searched for B_c mesons in the modes including J/ψ:

- LEP searches:

  $B_c^+ \to J/\psi\pi^+$, $B_c^+ \to J/\psi\ell^+\nu$, $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$, $B_c^+ \to J/\psi a_1^+$

- CDF search:

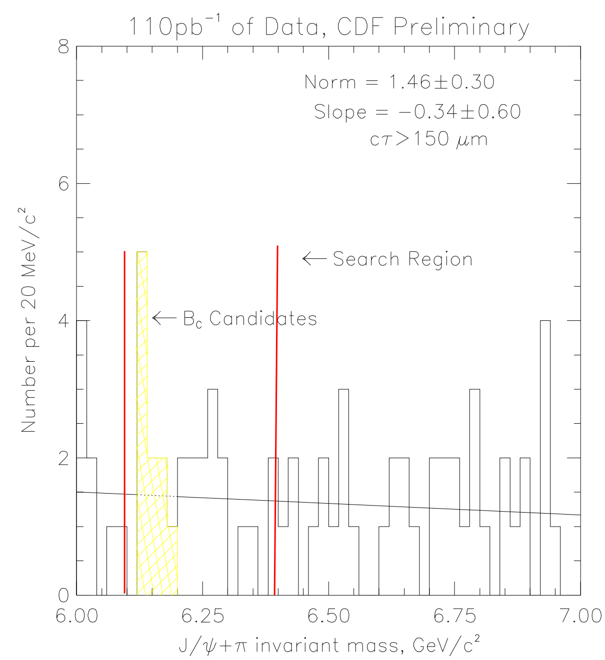
  $B_c^+ \to J/\psi\pi^+$

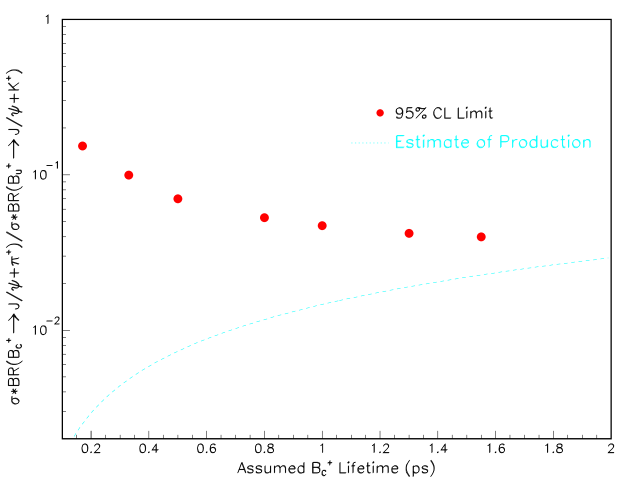
The B_c meson has not been observed yet.

Upper limits on the ratio $\dfrac{\sigma_{B_c}\mathcal{B}(B_c^+ \to \text{Decay Mode})}{\sigma_{B_u}\mathcal{B}(B_u^+ \to J/\psi K^+)}$

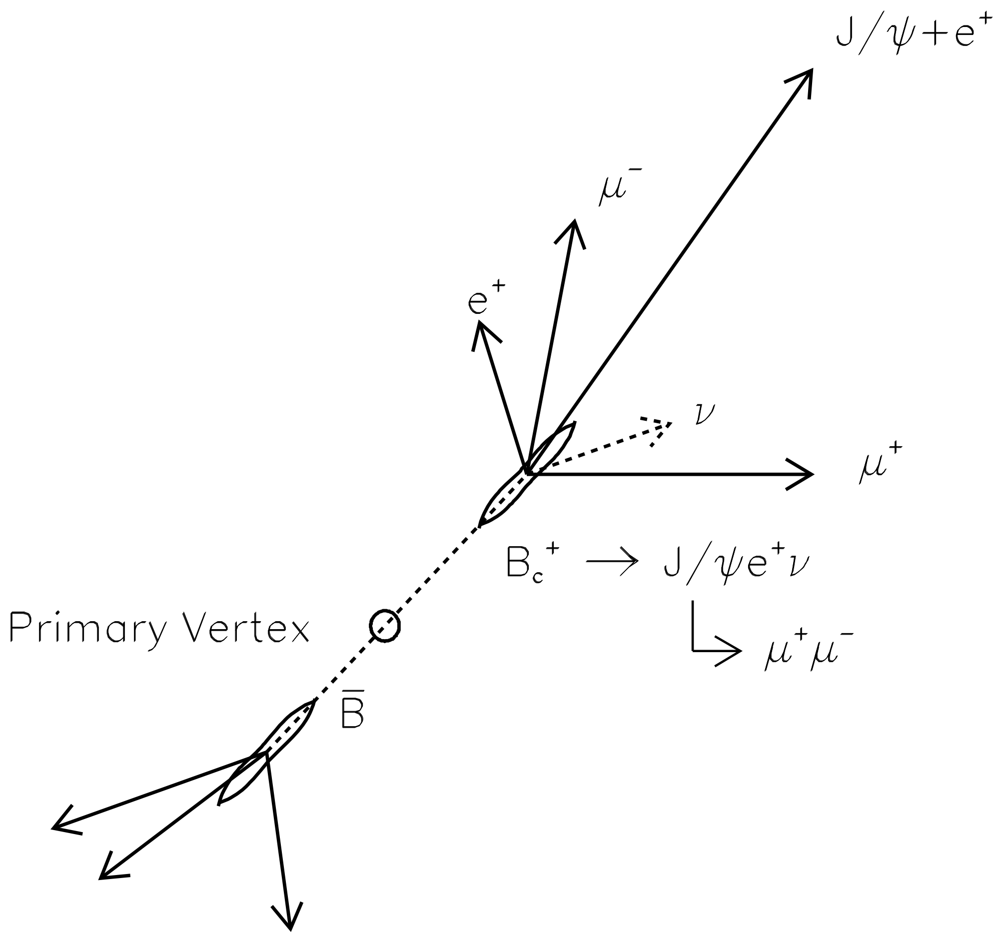
Experiment	Decay Mode	Upper Limits
ALEPH	$B_c^+ \to J/\psi\pi^+$	0.2 (90% CL)
	$B_c^+ \to J/\psi\ell^+\nu$	0.3 (90% CL)
DELPHI	$B_c^+ \to J/\psi\pi^+$	0.9 to 0.7 (90% CL)
	$B_c^+ \to J/\psi\ell^+\nu$	0.5 to 0.4 (90% CL)
	$B_c^+ \to J/\psi\pi^+\pi^-\pi^+$	1.5 (90% CL)
OPAL	$B_c^+ \to J/\psi\pi^+$	0.6 (90% CL)
	$B_c^+ \to J/\psi a_1^+$	0.3 (90% CL)
	$B_c^+ \to J/\psi\ell^+\nu$	0.4 (90% CL)
CDF	$B_c^+ \to J/\psi\pi^+$	0.15 to 0.04 (95% CL)

$B_c \to J/\psi\pi$ Search





Search for $B_c \to J/\psi \ell X$ at CDF



- Select a $J/\psi \to \mu^+\mu^-$ and a third lepton (e or μ)
- Signature: three leptons form a common displaced vertex
- Large branching ratio: $\mathcal{B}(B_c^+ \to J/\psi \ell^+ X) \approx 3\sim15\, \mathcal{B}(B_c^+ \to J/\psi \pi^+)$

$B_c \rightarrow J/\psi e X$ Signal and Candidate Events

CDF Trigger

Trigger System

Trigger	Description	Rate
Level I	Uses Detector Subsystems like μ Chambers, Calorimetry, ...	2000 Hz
Level II	Uses Combined Subsystems like μ Chambers + Tracking, ...	30 Hz
Level III	Full Event Reconstruction	10 Hz

- **Single Lepton Trigger (e or μ)**
  - $p_T(\ell) > 9.0$ GeV/c
- **Dilepton Trigger**
  - $\mu\mu$: $p_T(\mu) > 2.0$ GeV/c
  - $e\mu$: $p_T(\mu) > 2.5$ GeV/c and $E_T(e) > 5.0$ GeV/c^2

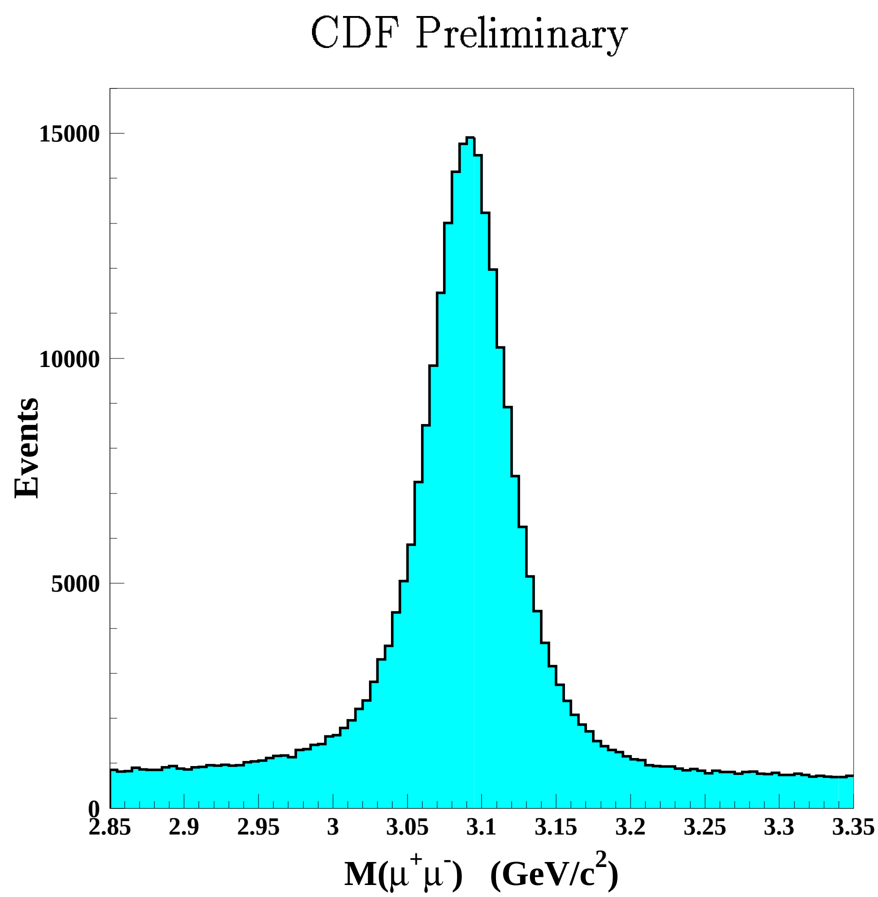
Run 0 (88-89) 4.5 pb^{-1}

Run 1 (92-95) 110 pb^{-1}

Run 2 (00-02) 2000 pb^{-1} (expected)

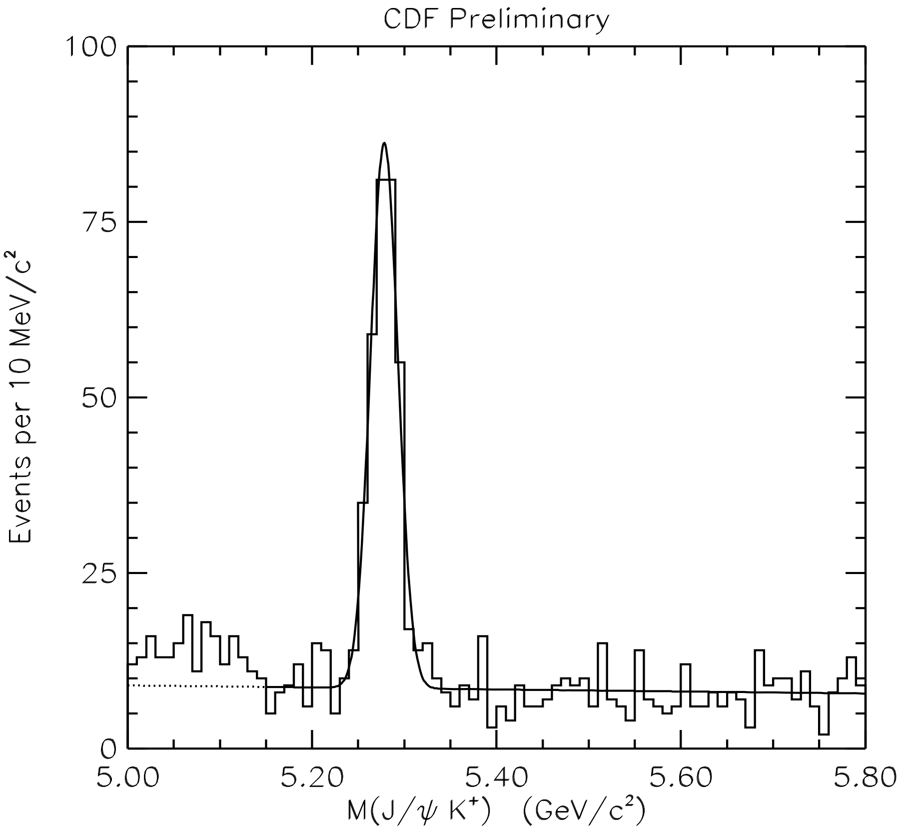
$J/\psi \rightarrow \mu^+\mu^-$ Selection

- Dimuon trigger with $p_T(\mu) > 2$ GeV/c.



- Select events in the J/ψ mass window $|m(\mu^+\mu^-) - m(J/\psi)| < 50$ MeV/c^2.
- We find 196,000 $\pm$ 500 $J/\psi \rightarrow \mu^+\mu^-$ events.

Mass Distribution of $B \to J/\psi K$ Candidate Events



- We find 290 ± 19 events.
- This sample is used for the normalization of
  - the $B\bar{B}$ background estimation and
  - the measurement of σ BR$(B_c \to J/\psi \ell \nu)$.

J/ψ + lepton Selection

- We reconstruct a common vertex of 3 leptons.
- We form an invariant mass of the $J/\psi + \ell$ and calculate "pseudo-proper decay length" $x \equiv \frac{m\left(J/\psi\ell\right)}{\left|\vec{p}_T\left(J/\psi\ell\right)\right|} L_{xy}$.
- B_c signal region:

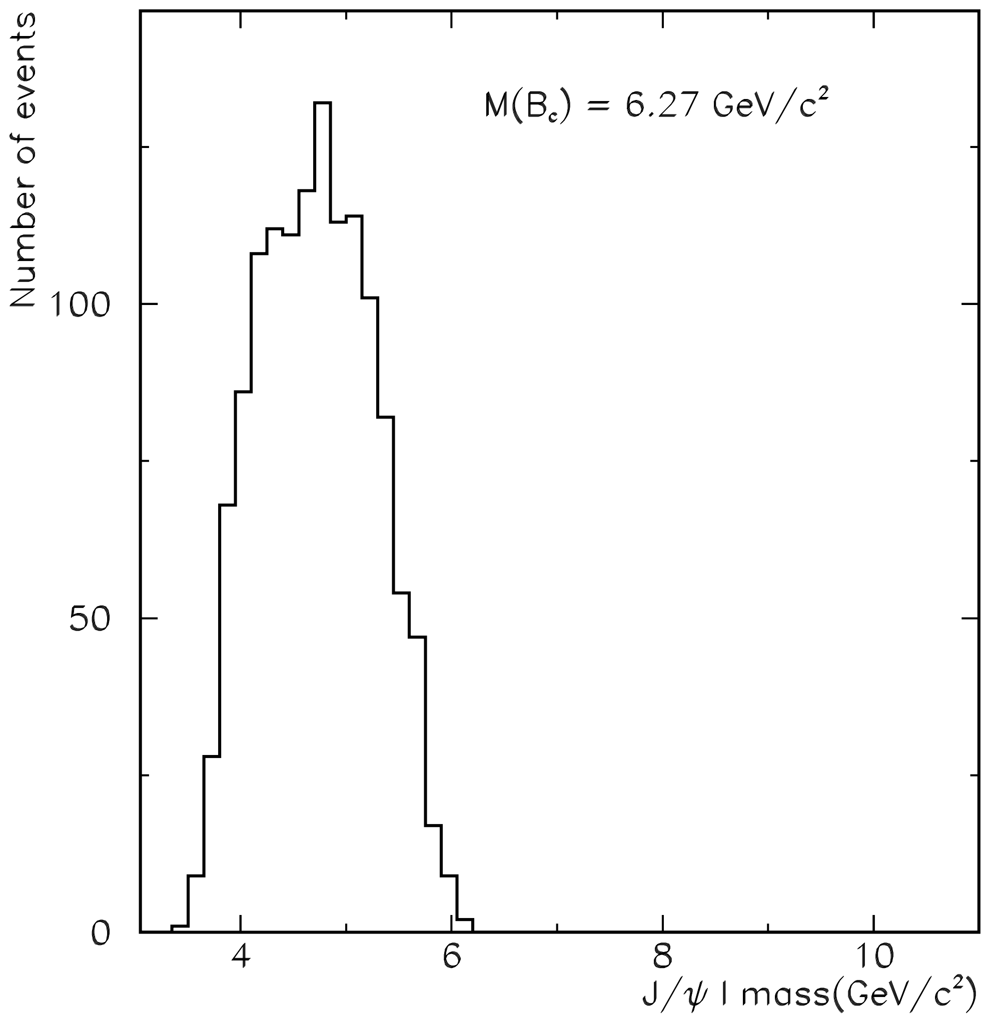
$$4 < m(J/\psi\ell) < 6 \text{ GeV}/c^2 \text{ with } x > 60 \ \mu\text{m}.$$

Third lepton Selection

- **Electron Identification**
  - $P_T > 2$ GeV/c
  - $0.7 < E/P < 1.5$
  - Had/EM < 0.1
  - dE/dX cut: (Q$_{CTC}$ - Q(e))/$\sigma > -1$
  - Preradiater chamber cut: CPR $>$ 4 mips
  - Shower max chamber cut: profile and position
  - conversioon electron rejected

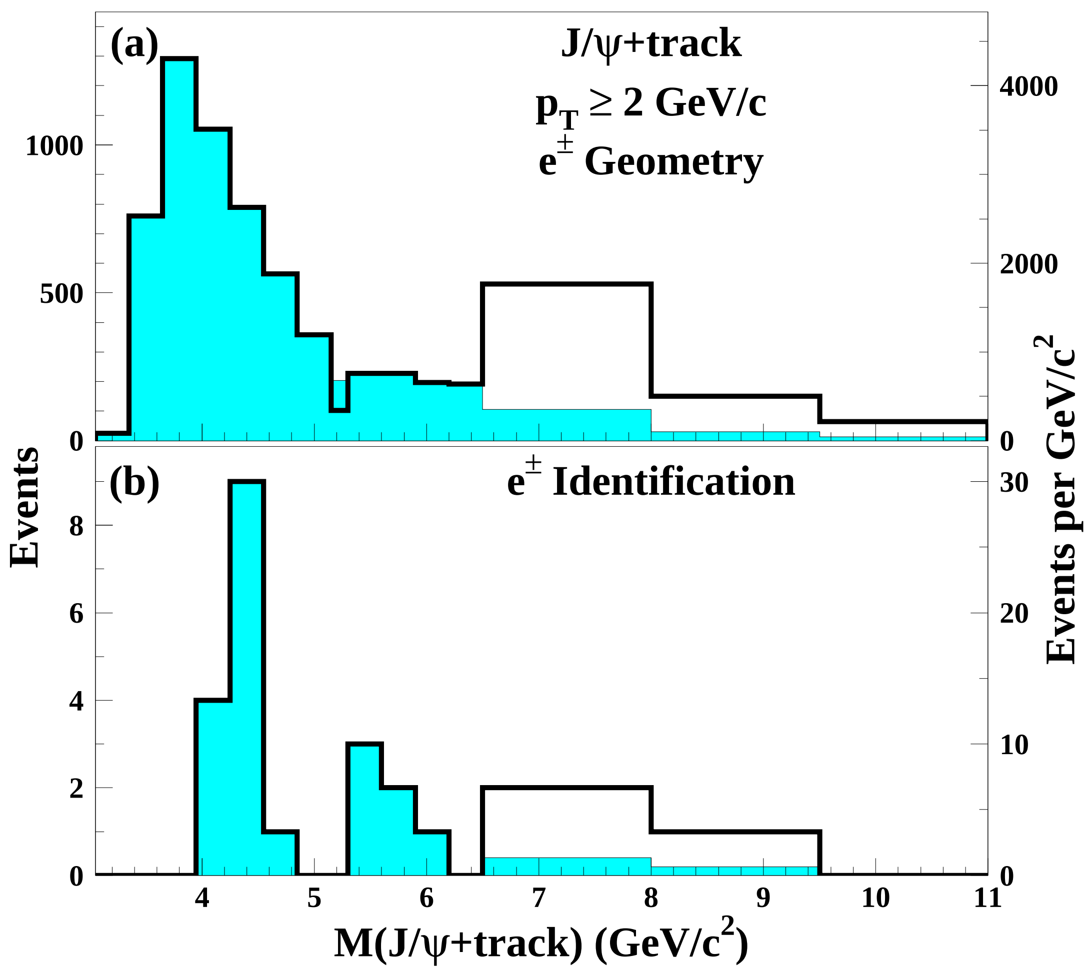
- **Muon Identification**
  - $P_T > 3$ GeV/c
  - track segment both in Central MUon chamber(CMU) and Central Muon UPgrade chamber (CMP)
  - track match between the muon chamber and the central tracking chamber

$J/\psi\ell$ Mass Distribution for the B_c Signal



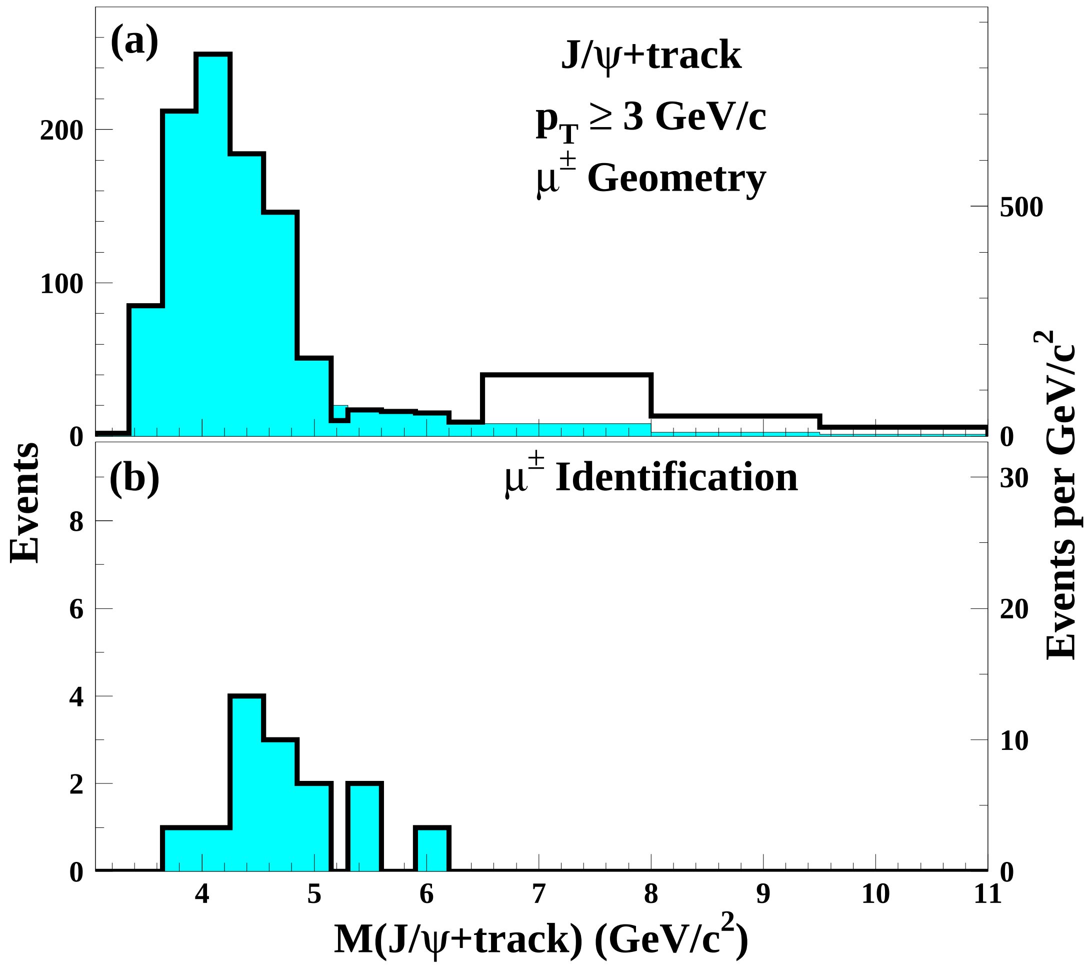
J/ψ + Track Mass Distribution: the Electron Fiducial Region

CDF Preliminary



J/ψ + Track Mass Distribution: the Muon Fiducial Region

CDF Preliminary



Background Estimates

Backgrounds to the $B_c \to J/\psi eX$ search

- **Fake Electron Background**
  - Fake rate is estimated using CDF jet event sample.
  - The events in the J/ψ + track sample are weighted by this fake rate.
  - The fake electron background is **$2.6 \pm 0.05 \pm 0.3$ events**.

- **Residual Conversions Background**
  - Assuming the track in the J/ψ + track sample are π^0, we simulate $J/\psi + \pi^0$ events.
  - Calculate N_s=N(residual)/N(rejected) using the simulation.
  - Multiply N_s by the the number of J/ψ+ conversions rejected in data to get the residual conversion background.
  - The residual conversion background is **$1.2 \pm 0.8 \pm 0.4$ events**.

- **$B\bar{B}$ Background**
  - $B\bar{B}$ background is estimated using Monte Carlo simulation.
  - $B\bar{B}$ background is **1.2 ± 0.5 events**.

Background Due to Charged Hadrons that may Fake an Electron

- Electrons are identified using Soft Lepton Tagging (SLT) algorithm.

$$fake\ rate\ (P_t, I) = \frac{\#\ of\ tagged\ tracks\ in\ JET20}{\#\ of\ tracks\ passing\ the\ fiducial\ cuts} \times (1 - f_e(I)), \quad (1)$$

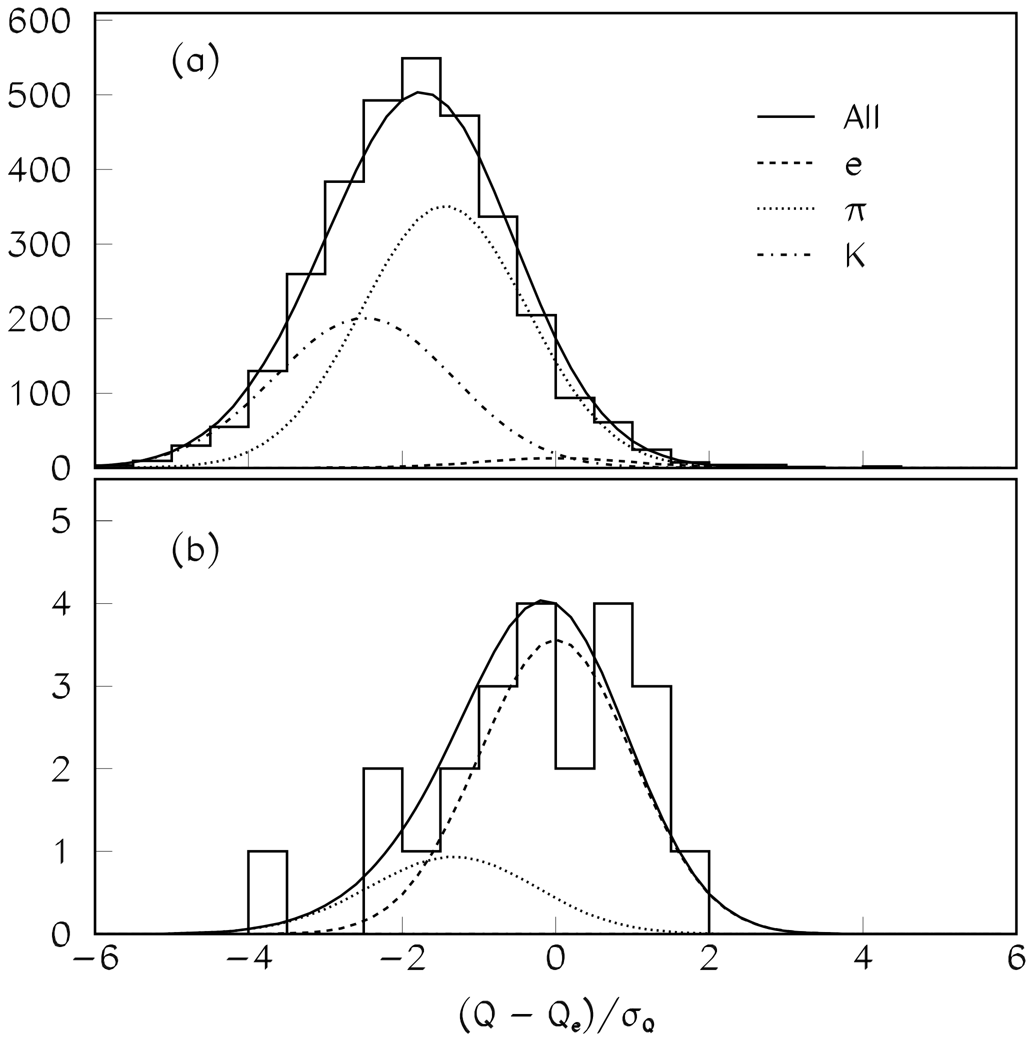
where JET20 means a jet events sample with a trigger jet E_T above 20 GeV, I means track isolation, and f_e is a fraction of true electrons.

- The sources of real electron are heavy flavour decay, Dalitz decay and conversions.

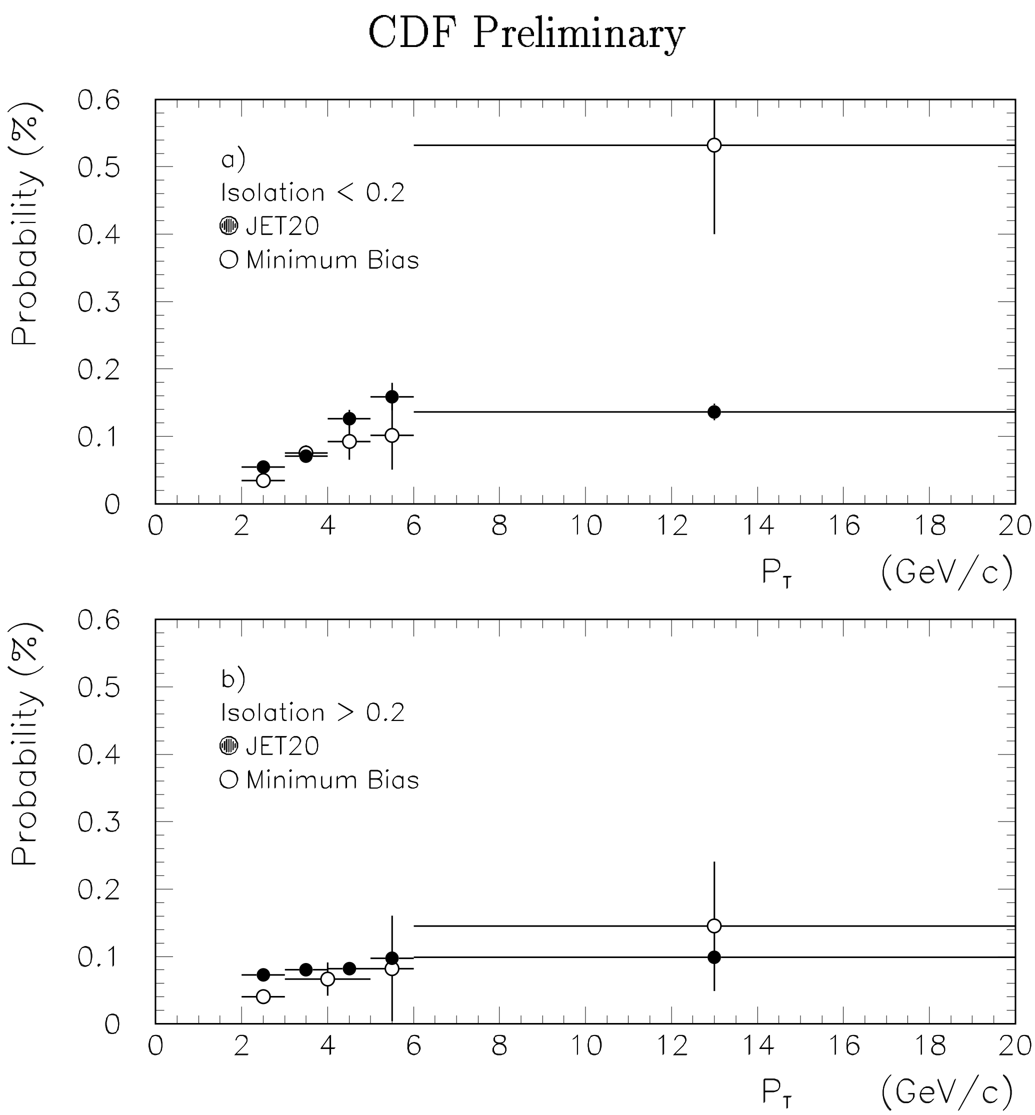
<table>
<tr><th></th><th>f_e from dE/dx</th><th colspan="2">f_e from heavy flavor + residual conversion</th></tr>
<tr><td rowspan="2">JET20</td><td rowspan="2">(73±3)%</td><td colspan="2">(74 ± 2) %</td></tr>
<tr><td>(31±1)%</td><td>(42±2)%</td></tr>
</table>

dE/dx plots for Tracks in the J/ψ + track sample

CDF Preliminary



Probability for a Charged Hadron to Fake an Electron



Isolation $= \Sigma P_T(\text{tracks in } \Delta R < 0.2 \text{ around } e\ ) \ / \ P_T(e)$

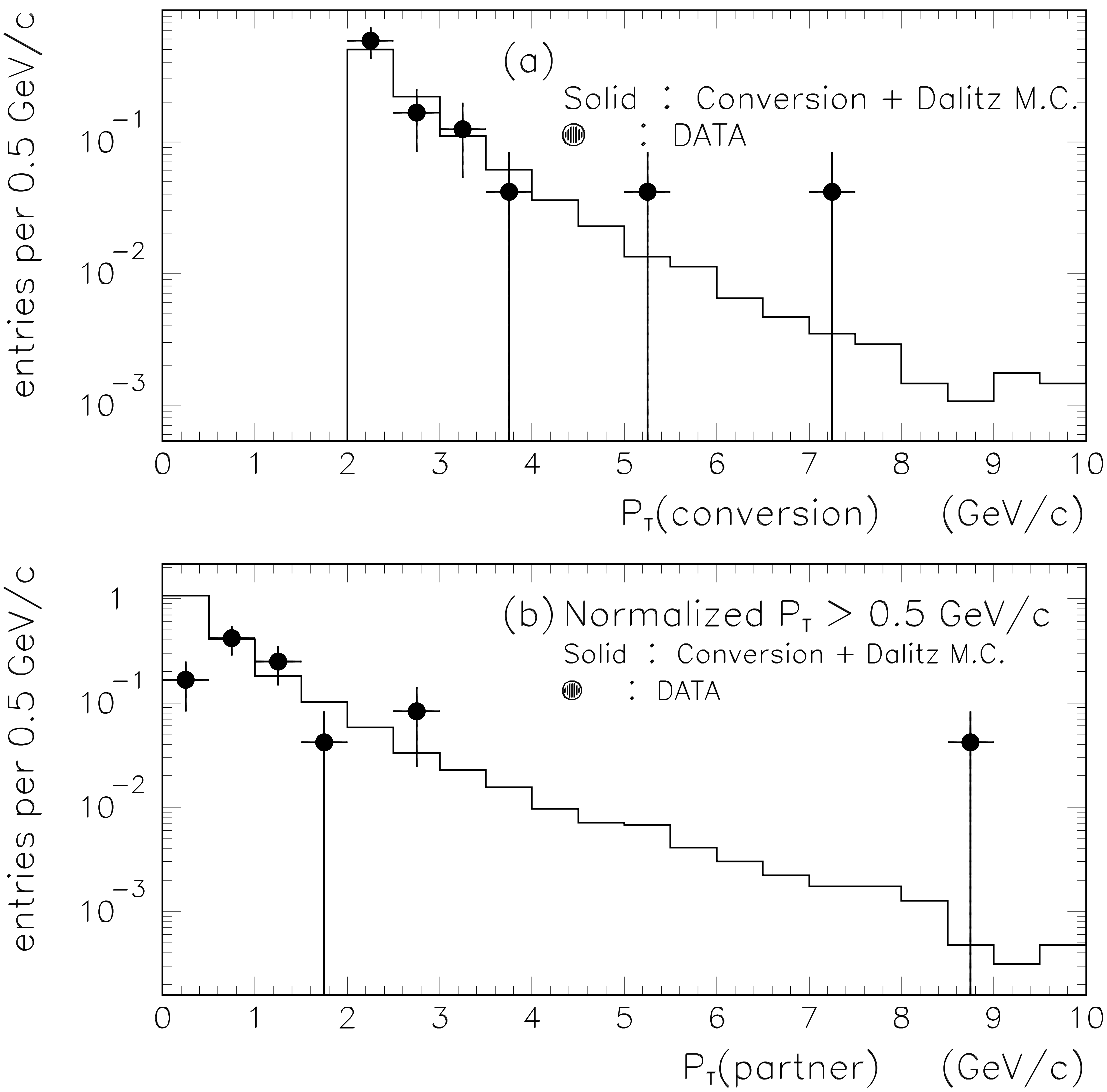
- Fake rates in the jet sample and the minimum bias sample are consistent with each other. The difference of 10% is assigned to the systematic uncertainty on the fake rate.

Residual Conversion Background

- Take J/ψ + track sample from data.
- Assume that the track is a π^0.
- Simulate the event in the CDF full simulation program.
- Use each event 100 time by random ϕ rotation.
- Calculate N_s=N(residual)/N(rejected) using the simulation.
- Multiply N_s by the the number of $J/\psi+$ conversions rejected in data to get the conversion background.

Residual Conversion Background

CDF Preliminary



$B\bar{B}$ Background for $B_c \rightarrow J/\psi e X$

- Generate $B\bar{B}$ events.
- Decay one B to $J/\psi + X$.
- Let the other B decay naturally.
- Detector Simulation with the CDF full simulation program.
- Require the Dimuon Trigger.
- The Monte Carlo data is normalized to actual data by:

$$F = \frac{N_{J/\psi K}(Data)}{N_{J/\psi K}(MC)}$$

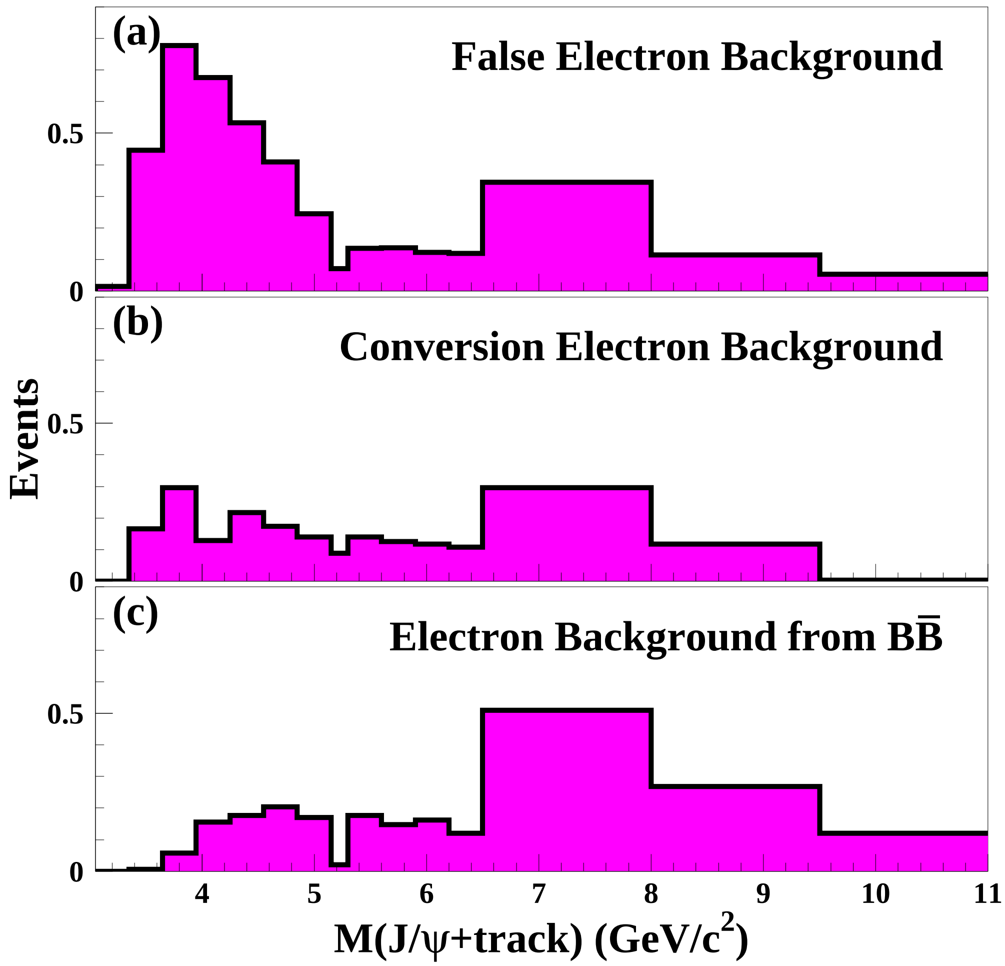
where,
$N_{J/\psi K}(Data)$ = number of $B_u \rightarrow J/\psi K$ events in data
$N_{J/\psi K}(MC)$ = number of $B_u \rightarrow J/\psi K$ events in MC

$B\bar{B}$ Background for Run 1a and Run 1b in the mass region 4-6 GeV is

1.2 ± 0.5 Events

Mass Distribution for Background to $B_c \to \mathbf{J}/\psi + e + X$

CDF Preliminary



Backgrounds to the $B_c \to J/\psi\mu X$ search

- **Decay In Flight Background**
  - The Decay in Flight background is estimated using the J/ψ + track sample from data.
  - The events in J/ψ + track sample are weighted by the probability for the track to be identified as a muon due to decay in flight, accounting for K/π ratio measured with dE/dX.
  - The decay in flight background is **5.5 $\pm$ 0.5 $\pm$ 1.3 events**.

- **Punch-Through Background**
  - The Punch-through background is estimated using the J/ψ + track sample from data.
  - The events in J/ψ + track sample are weighted by the probability for the third track to be identified as a muon due to punch-through.
  - The punch-through background is **0.88 $\pm$ 0.13 $\pm$ 0.33 events**.

- **$B\bar{B}$ Background**
  - $B\bar{B}$ background is estimated using Monte Carlo simulation.
  - $B\bar{B}$ background is **0.7 $\pm$ 0.3 events**.

Decay in Flight Background

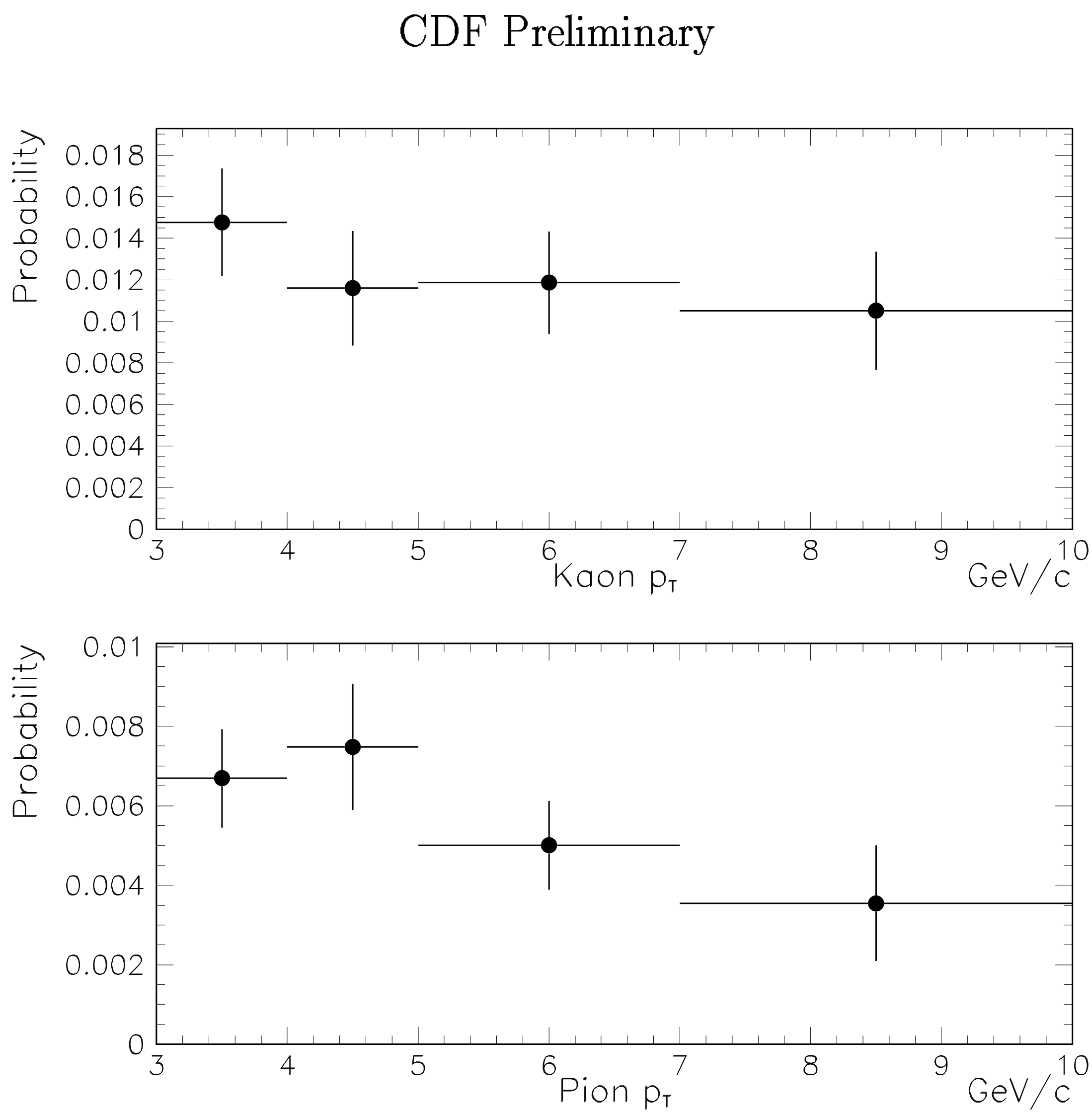
- The Decay in Flight background is estimated from the the J/ψ + track sample from data.
- The events in J/ψ + track sample are weighted by the probability for the track to be identified as a muon due to decay in flight.
- The decay in flight background is **5.5 $\pm$ 0.5 $\pm$ 1.3 events**.

Decay in Flight Background from B's

- Generate B's and force the Decay $B \to J/\psi + X$.
- Simulate event using the CDF full simulation program.
- Force K's or π's decay before they reach the CDF central muon chamber.
- Require the dimuon trigger.

$c\tau^*$ cut	Run 1a	Run 1b	Run 1a + Run 1b
60μm	0.79±0.23	3.87±1.12	4.66±1.14
85μm	0.79±0.23	3.74±1.08	4.53±1.10
100μm	0.79±0.23	3.53±1.02	4.32±1.05

Probability of a K or a π to be Identified as a muon due to Decay in flight.



Punch-through Background to $B_c \to J/\psi + \mu + X$.

- The Punch-through background is estimated from the the J/ψ + track sample from data.

- The events in J/ψ + track sample are weighted by the probability for the third track to be identified as a muon due to punch-through.

- The punch-through background is **$0.88 \pm 0.13 \pm 0.33$ events**.

$B\bar{B}$ Background for $B_c \rightarrow J/\psi \mu X$

- Generate $B\bar{B}$ events.
- Decay one B to $J/\psi + X$.
- Let the other B decay naturally.
- Detector Simulation with the CDF full simulation program.
- Require the Dimuon Trigger.
- The Monte Carlo data is normalized to actual data by:

$$F = \frac{N_{J/\psi K}(Data)}{N_{J/\psi K}(MC)}$$

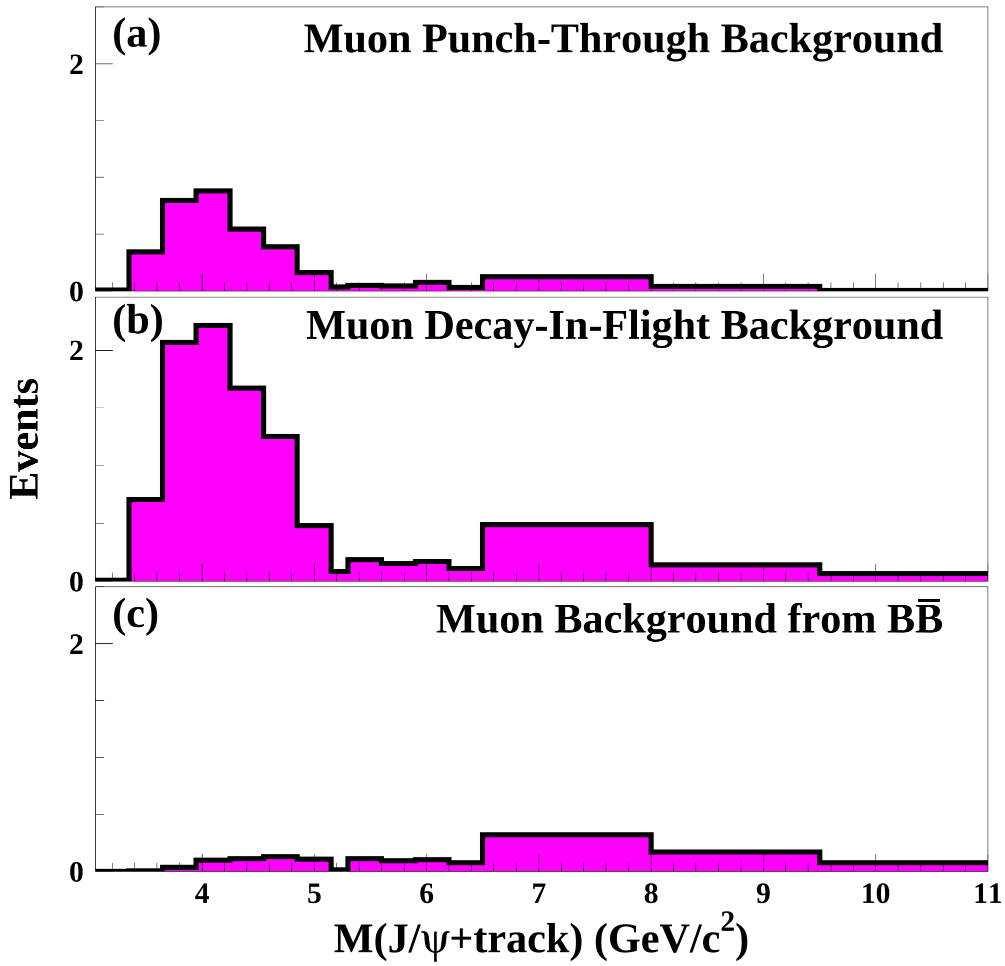
where,
$N_{J/\psi K}(Data)$ = number of $B_u \rightarrow J/\psi K$ events in data
$N_{J/\psi K}(MC)$ = number of $B_u \rightarrow J/\psi K$ events in MC

$B\bar{B}$ Background for Run 1a and Run 1b in the mass region 4-6 GeV is

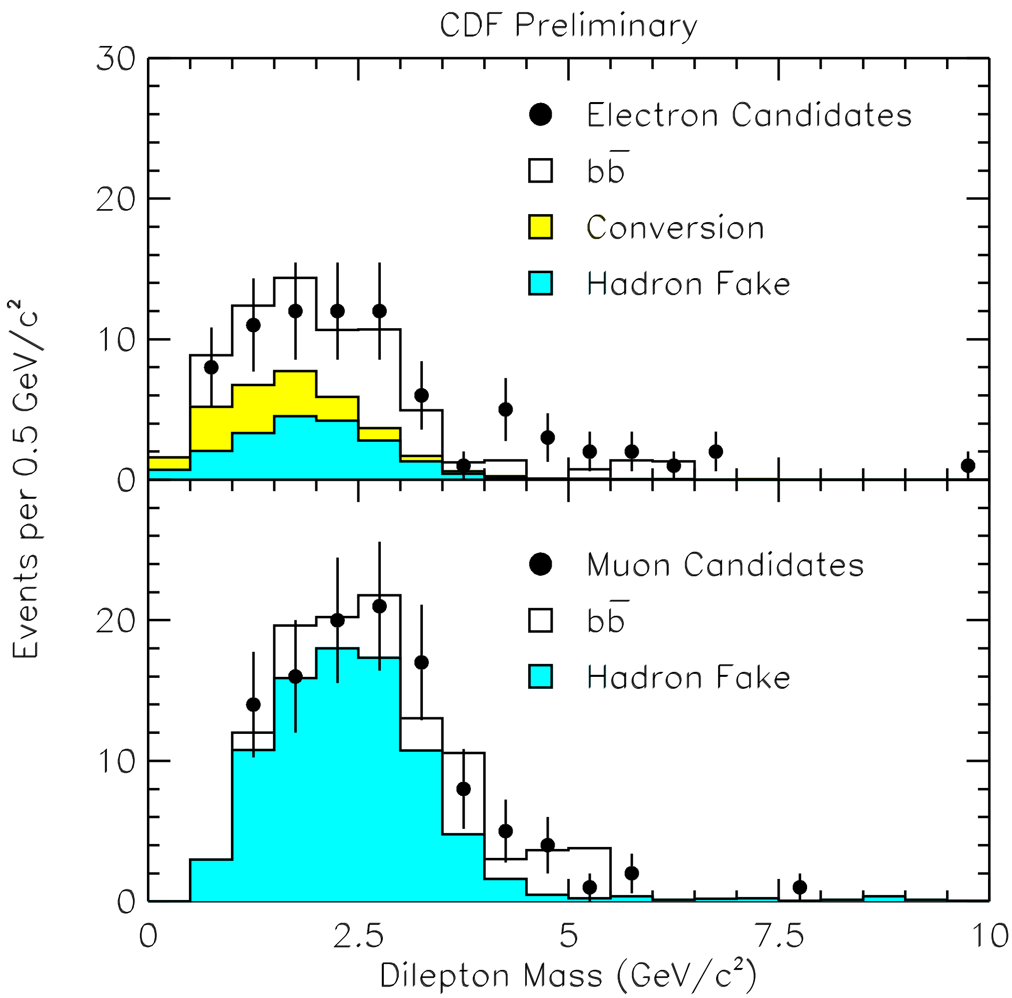
0.7 ± 0.3 Events

Mass Distribution for Background to $B_c \to \mathbf{J}/\psi + \mu + X$

CDF Preliminary



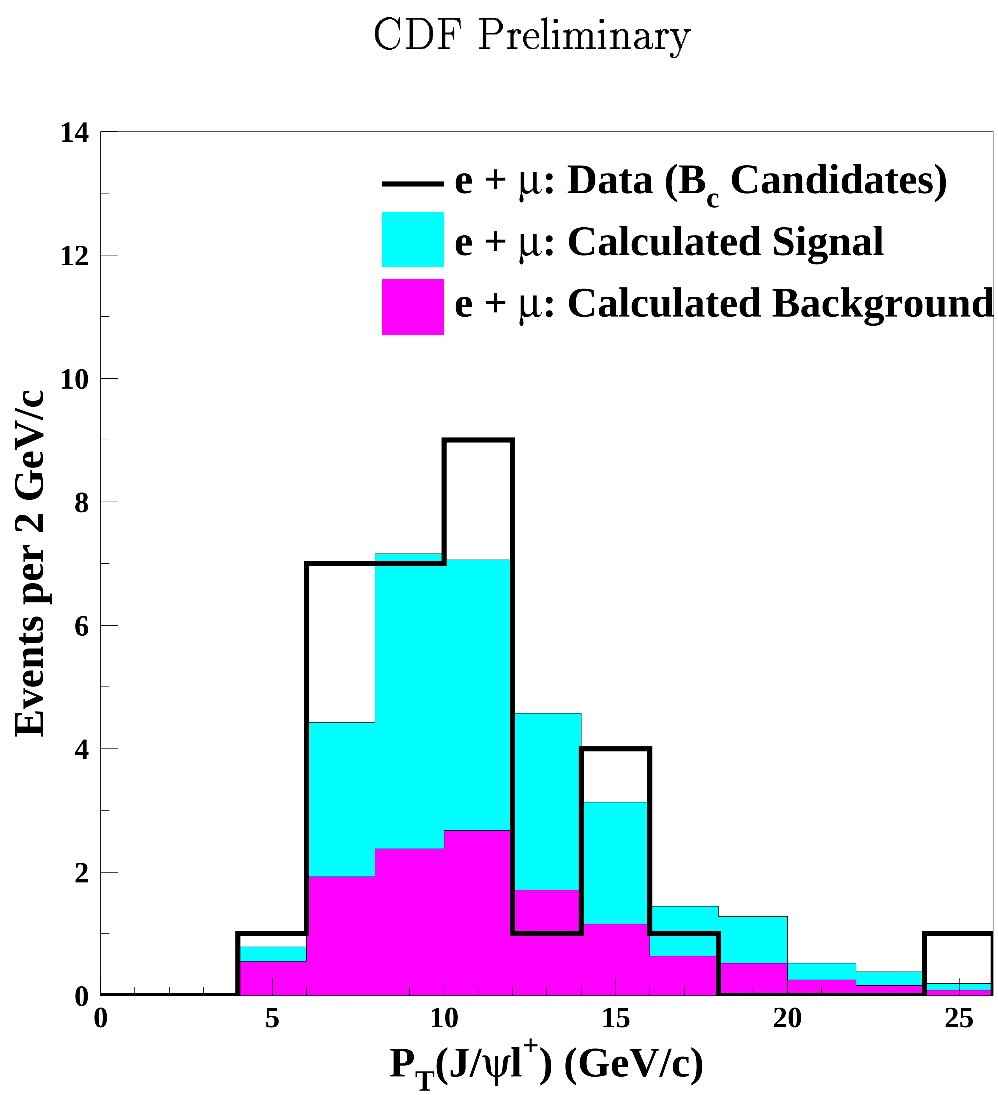
Test of the Background Estimates



- We use events with same-charge di-lepton, a trigger lepton and a tagged lepton.
- Both leptons were required to come from a displaced vertex and be within the same jet cone.
- This event sample is a background-rich sample, so good for the test of the background estimation.

This background-rich sample can be explained by our background estimates quantitatively.

P_T of J/ψ + Lepton System for Calculated Signal, Background and Candidates Events



B_c Signal and Background Summary

CDF Preliminary

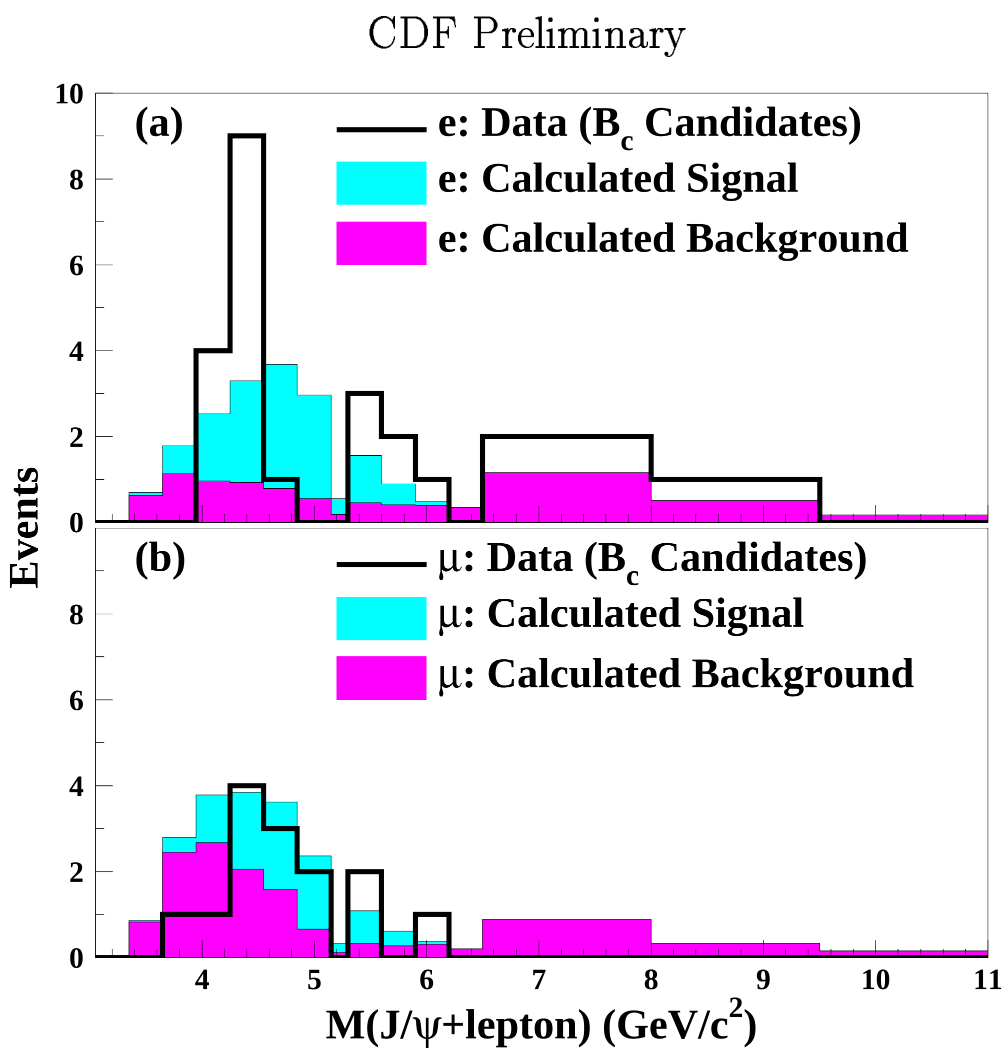
	$4.0 < M(J\psi\,\ell) < 6.0$ GeV$/c^2$	
	$J/\psi\, e$ results	$J/\psi\, \mu$ results
Misidentified leptons		
False Electrons	$2.6 \pm 0.05 \pm 0.3$	
Conversions	$1.2 \pm 0.8 \pm 0.4$	
Total False Muons		$6.4 \pm 0.5 \pm 1.3$
Punch-through		$0.88 \pm 0.13 \pm 0.33$
Decay-in-flight		$5.5 \pm 0.5 \pm 1.3$
$B\overline{B}$ bkg.	1.2 ± 0.5	0.7 ± 0.3
Total Background	5.0 ± 1.1	7.1 ± 1.5
Events observed in data	19	12
Net Signal	14.0	4.9
Combined	18.9	
$P_{Counting}$(Null)	2.1×10^{-5}	0.084

Statistical Significance from Mass Shape Analysis

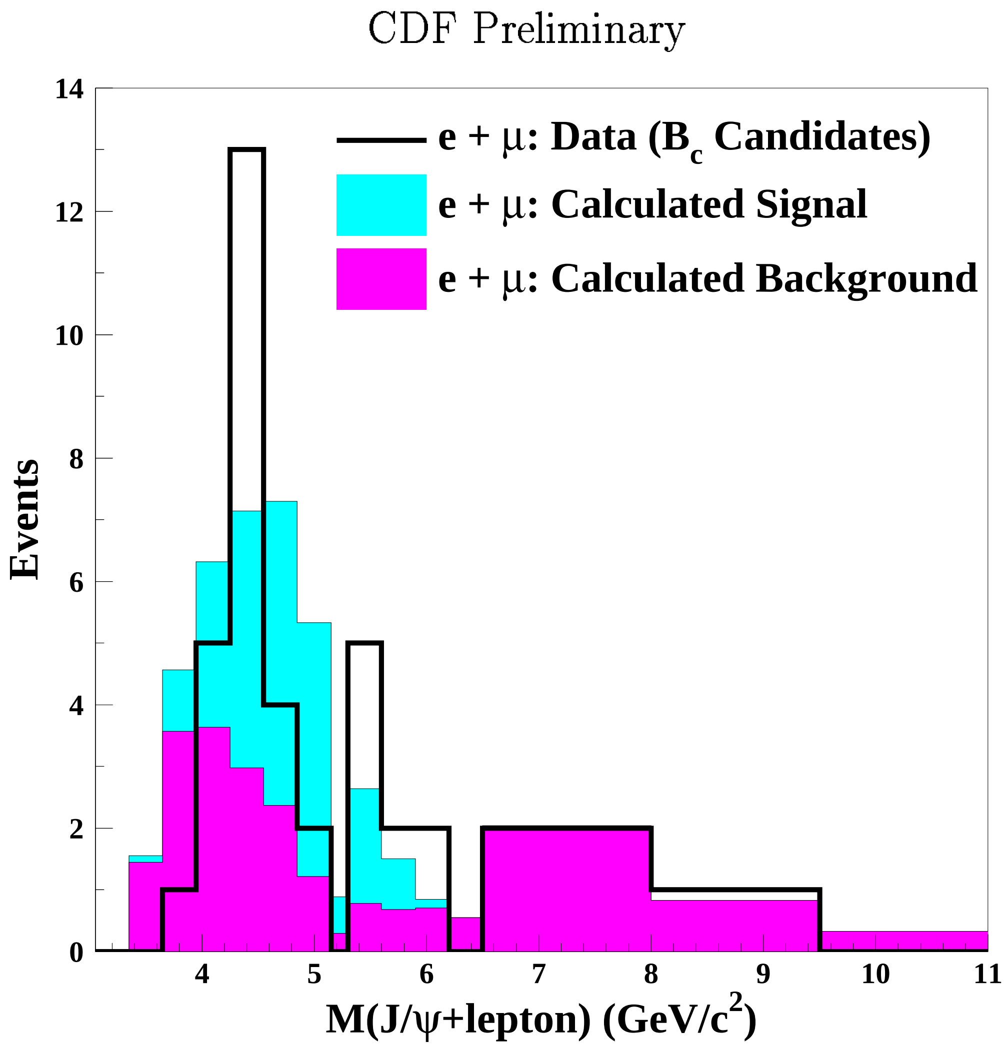
Using a likelihood method, we fit the observed mass distribution ($3.35 < m(J/\psi\ell) < 11.0$ GeV/c^2).

- It allows constraints such as the expected fraction of the two decay channels.
- Number of B_c events is the only unconstrained parameter. Other parameters are in the fit are constrained by their uncertainities.
- Number of B_c events returned by the fit: $N(B_c) = 20.4^{+6.2}_{-5.6}$.
- A test of the null hypothesis, *i.e.*, an attempt to fit the data with background alone, is rejected at the level of 4.8 standard deviations.

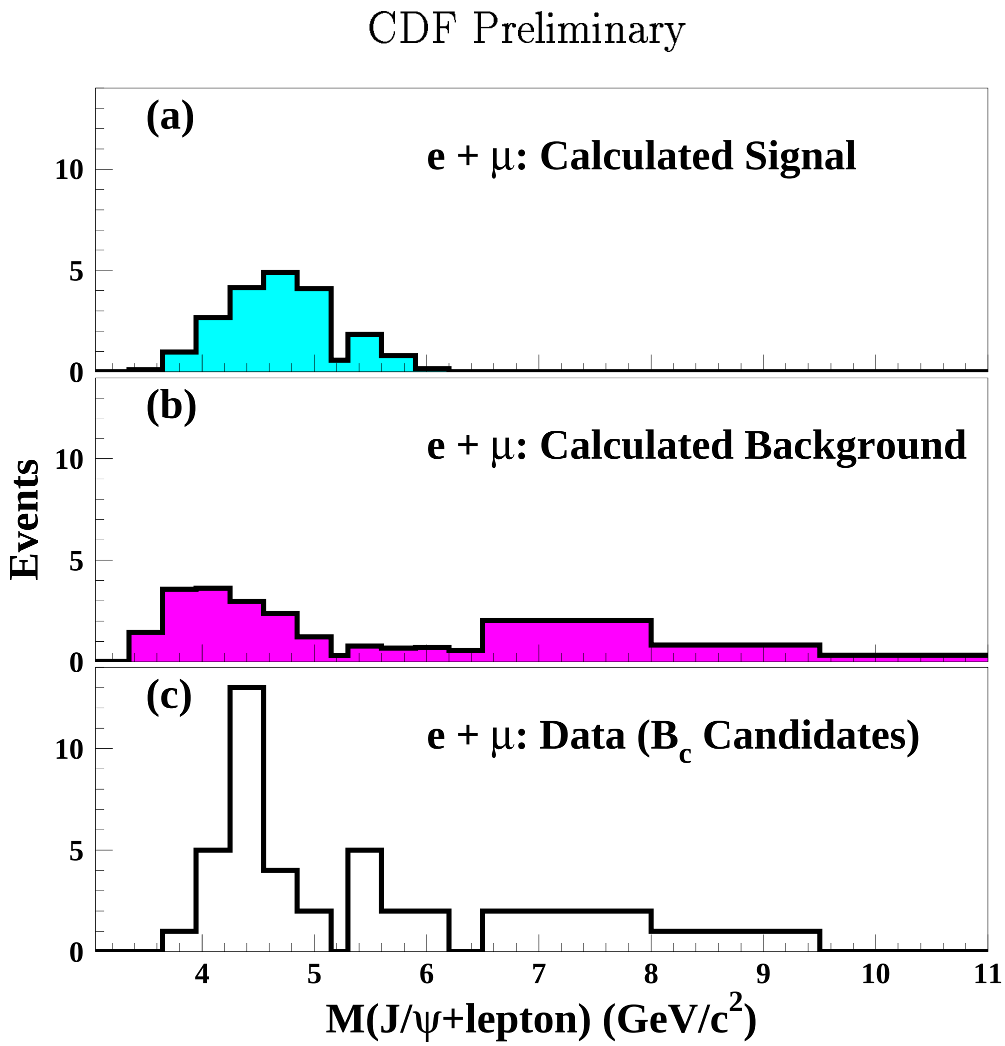
Binned Likelihood Fit: e and μ Individual Results



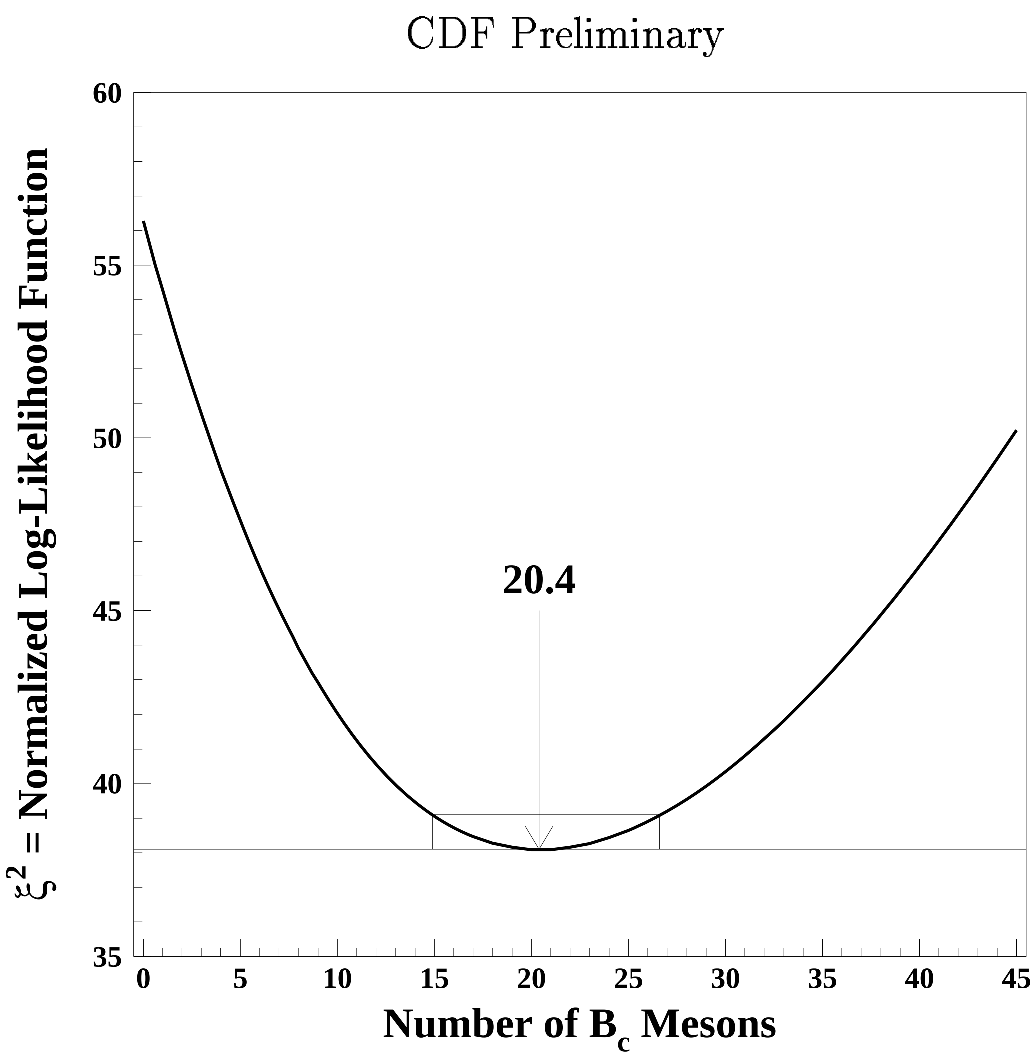
Binned Likelihood Fit: e and μ Combined Results



Mass Distributions of Calculated Signal, Background and Candidate Events



Likelihood Fit

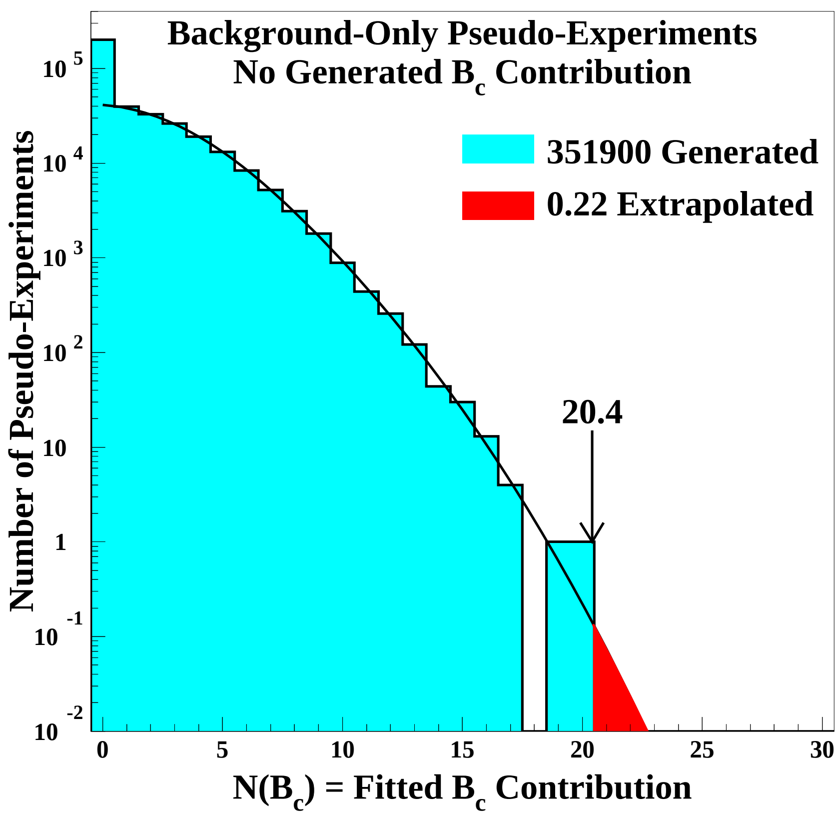


$$N(B_c) = 20.4\ ^{+6.2}_{-5.6}$$

Likelihood Analisys: The Null Hypothesis.

- To evaluate the probability that there is no B_c signal and that a statistical fluctuation in the background can explain the apparent excess in the data, we made pseudo-experiments without any B_c contribution.

CDF Preliminary

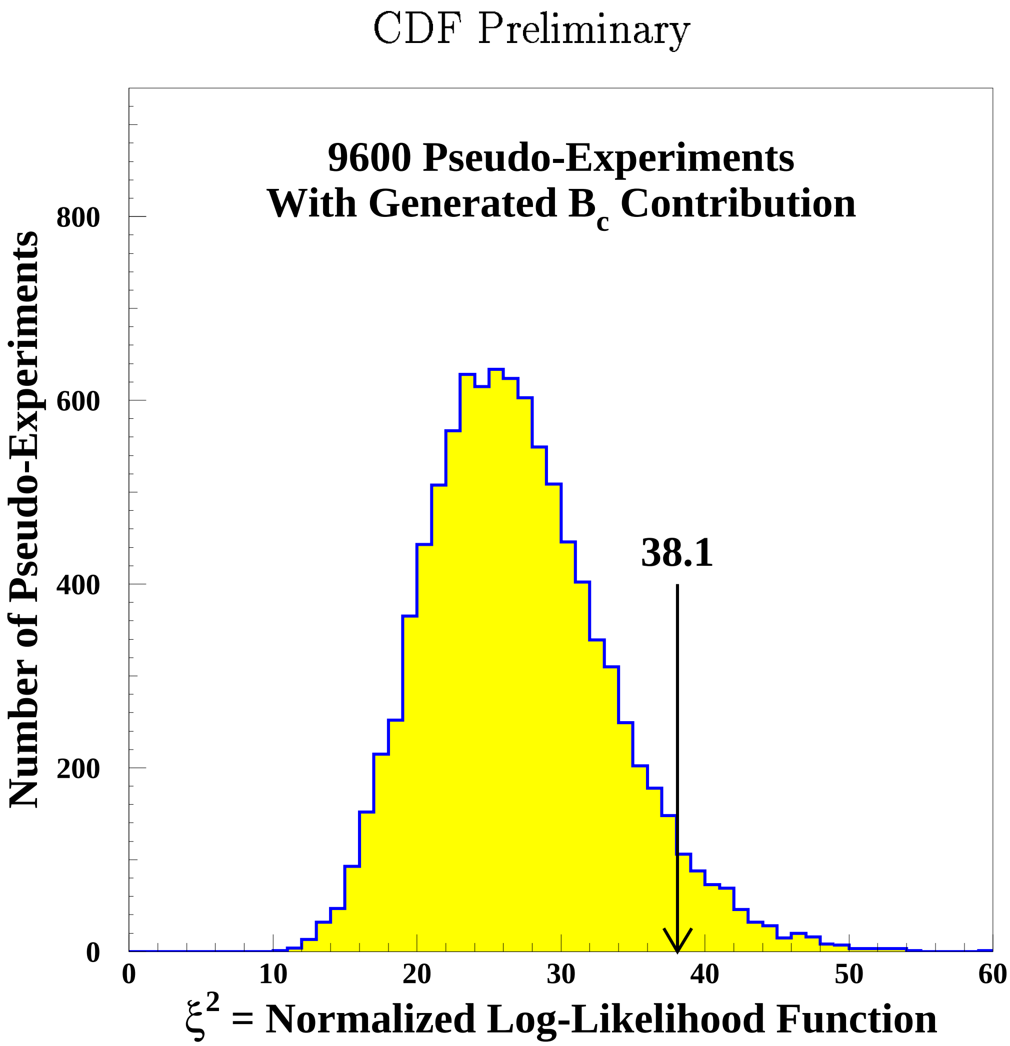


Probability(null) = 6.3×10^{-7} (4.8 σ)

Pseudo-Experiment (Toy Monte Carlo)

- For each background,
  - we allow the number of backgrounds to fluctuate according to Poisson statistics with the estimated number of background and its uncertainty, and obtain it to be N.
  - Then we generate N background events according to the $J/\psi\ell$ mass distribution for this background.
- Summing up all background events,
  - we have the $J/\psi\ell$ mass distribution for a new sample of background events which is equivalent to a CDF experiment with no B_c content.
  - we call this sample a pseudo-experiment data.
- We perform the same likelihood fit to this sample as to the CDF real experiment, and obtain a fitted number of B_c events.
- Repeating the above precedure, we obtain the distribution of the fitted number of B_c events.

Toy Monte Carlo of the CDF Experiment.



The $J/\psi\ell$ mass shape of the CDF data is consistent with the expectation from the B_c signal and the background at 5.9% C.L..

Likelihood Fit Results

CDF Preliminary

Input Constraint
(Results of Fit)

	$J/\psi\, e$ results	$J/\psi\, \mu$ results
False Electrons	$N'^{fe} = 4.2 \pm 0.4$ $(n'^{fe} = 4.2 \pm 0.4)$	
Found Conversions	$N'^{ce} = 2$ $(n'^{ce} = 2.2 \pm 1.4)$	
Conversion ratio	$R^{ce} = 1.06 \pm 0.36$ $(r^{ce} = 1.08 \pm 0.35$	
Unfound Conversions	2.1 ± 1.7 (2.4 ± 1.7)	
False Muons		$N'^{f\mu} = 11.4 \pm 2.4$ $(n'^{f\mu} = 9.2 \pm 2.3)$
$B\overline{B}$ bkg.	$N'^{Be} = 2.3 \pm 0.9$ $(n'^{Be} = 2.6 \pm 0.9)$	$N'^{B\mu} = 1.44 \pm 0.25$ $(n'^{B\mu} = 1.42 \pm 0.25)$
Total Background	8.6 ± 2.0 (9.2 ± 2.0)	12.8 ± 2.4 (10.6 ± 2.3)
Total Signal	$(n'^{\ell} = 20.4^{+6.2}_{-5.6})$	
Electron Fraction	$R^{\varepsilon} = 0.58 \pm 0.04$ $(r^{\varepsilon} = 0.59 \pm 0.04)$	
e and μ Signal	$(n'^{e} = 12.0^{+3.8}_{-3.2})$	$(n'^{\mu} = 8.4^{+2.7}_{-2.4})$
Signal + Background	23 (21.2 ± 4.3)	14 (19.0 ± 3.5)
$P_{Likelihood}$(Null)	6.3×10^{-7}, $4.8\ \sigma$	

B_c Mass

B_c Lifetime

B_c Production Cross Section

B_c **Mass**

- The stability of the B_c signal was checked by fitting the observed J/$\psi\ell$ mass distribution to a sum of the backgrounds and the signal for various assumed B_c mass.

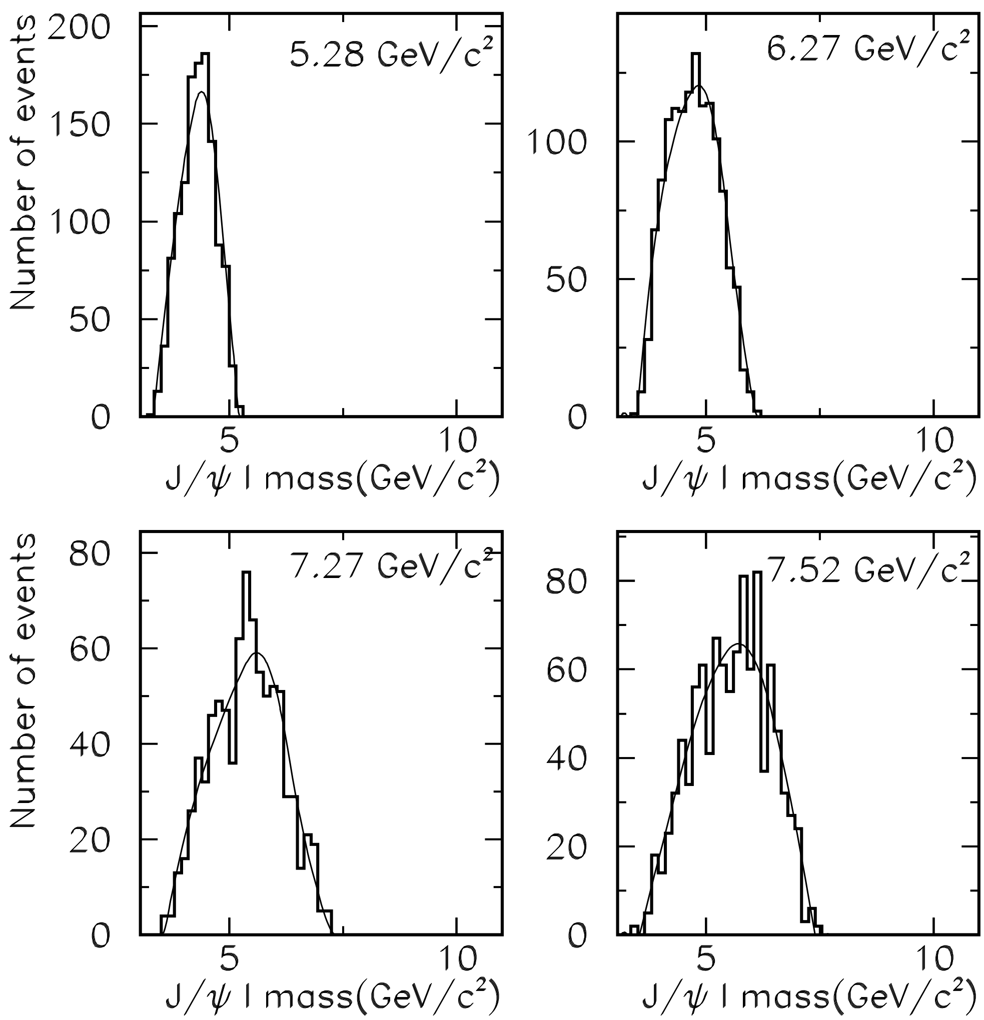
- $B_c \rightarrow J/\psi\ell\nu$ was generated using Monte Carlo for M(B_c) between 5.28 and 7.52 GeV/c^2.

- Each signal mass template was used in the fit to the mass spectrum for data.

- Best-fit log-likelihood value fits well with a parabolic function of the assumed B_c mass.

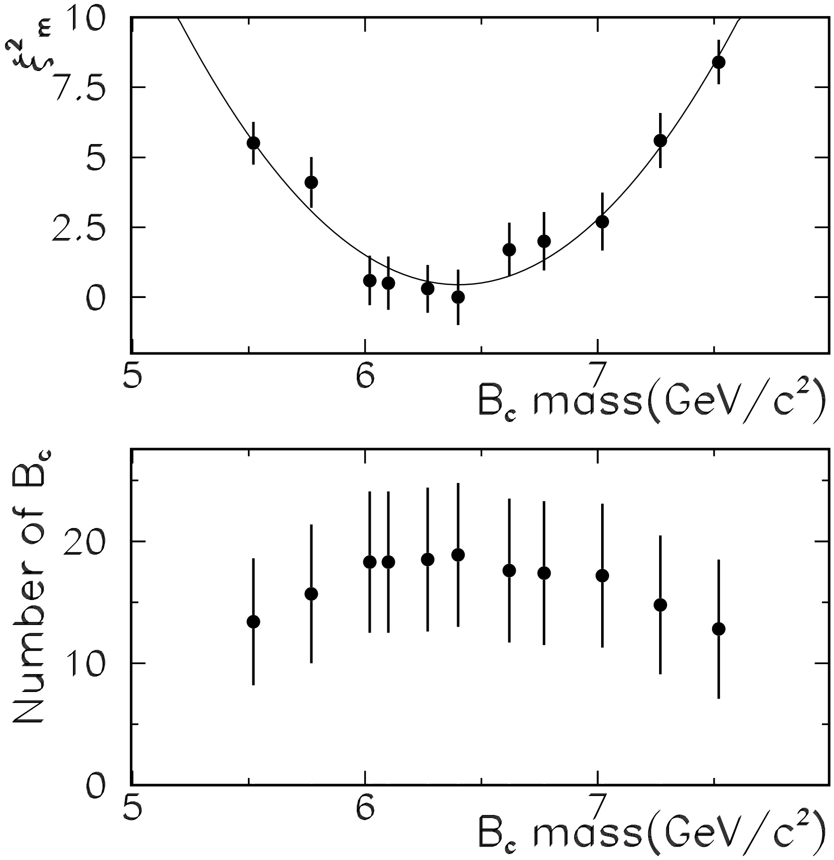
$$\xi_m = -2\ln\mathcal{L}(m) - (-2\ln\mathcal{L}(m = 6.40\,\mathrm{GeV}/c^2))$$

B_c Mass Templates



B_c Mass

CDF Preliminary

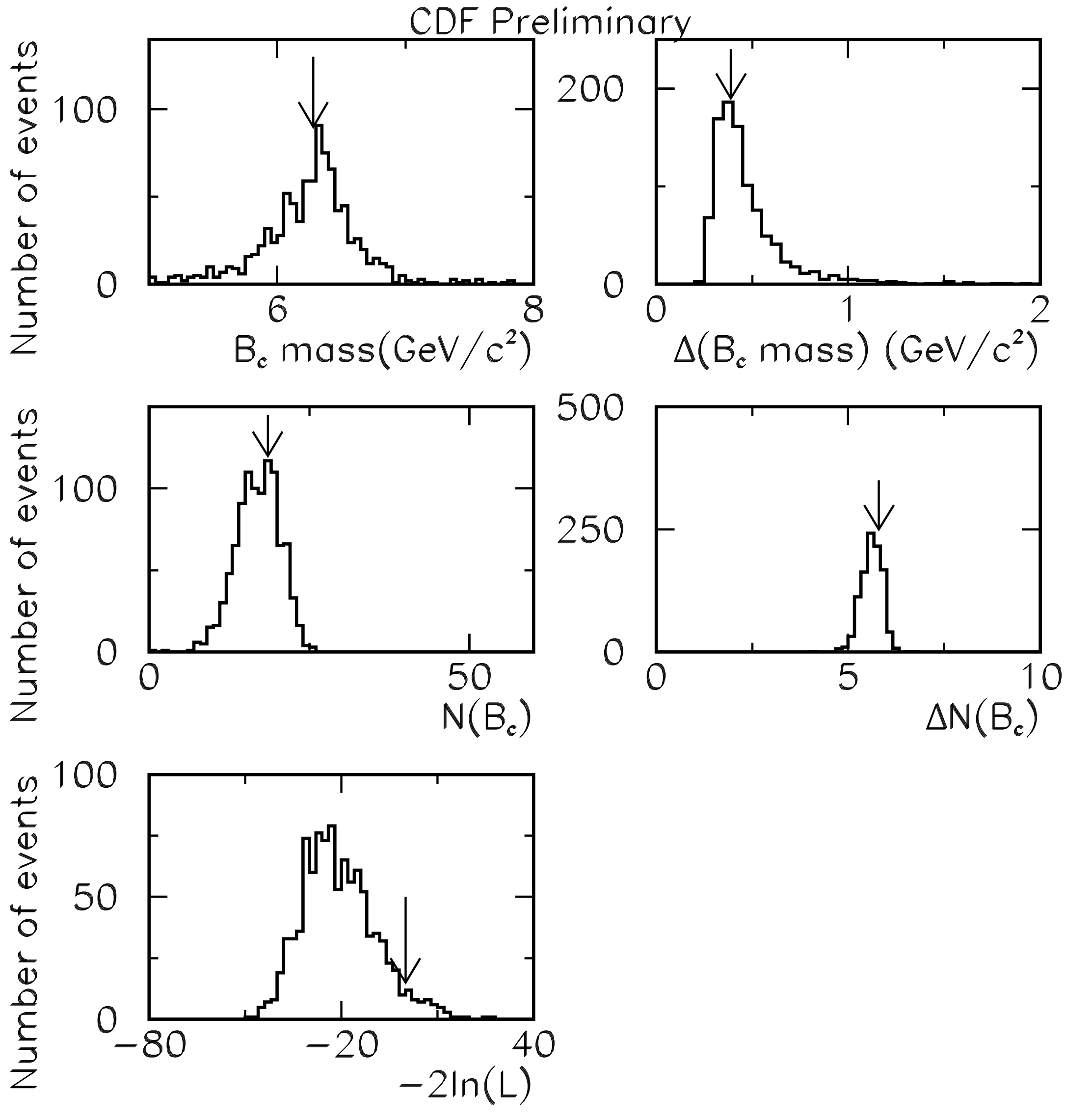


$M(B_c) = 6.40 \pm 0.39(stat) \pm 0.13(syst)$ GeV/c^2

Systematic Uncertainties.

- fitting procedures, estimated from the difference between binned and unbinned analyses (0.08 GeV/c^2),
- finite Monte Carlo statistics in the signal template (0.04 GeV/c^2),
- variations in the B_c mass distribution due to b-quark production spectrum (0.02 GeV/c^2),
- analysis with and without trigger simulation (0.02 GeV/c^2),
- distortion of the signal mass distribution arising from decay to higher-mass $c\bar{c}$ states rather than J/ψ(0.09 GeV/c^2).

Toy Monte Carlo: Test of the Mass Fits



The uncertainties on B_c mass and the number of B_c events are consistent with the expectation from Toy Monte Carlo including the B_c signal and the background.

B_c Lifetime

- There are three processes that dominate the B_c lifetime.
  - c quark spectator decay.
  - $\bar{b}$ quark spectator decay.
  - $\bar{b}c$ annihilation decay.

- There are various models that modify the free quark decay rates due to the bound state effects. Theoretical predictions for the the B_c lifetime varry from 0.4 ps to 1.35 ps (C. Quigg, B_c, FERMILAB-CONF-93265-T).

- In our analysis the information on the B_c lifetime is contained in the ct^* distribution. To measure the lifetime, the requirement $ct^* > 60\mu m$ is relaxed to $ct^* > -100\mu m$ and events only in the signal region are selected.

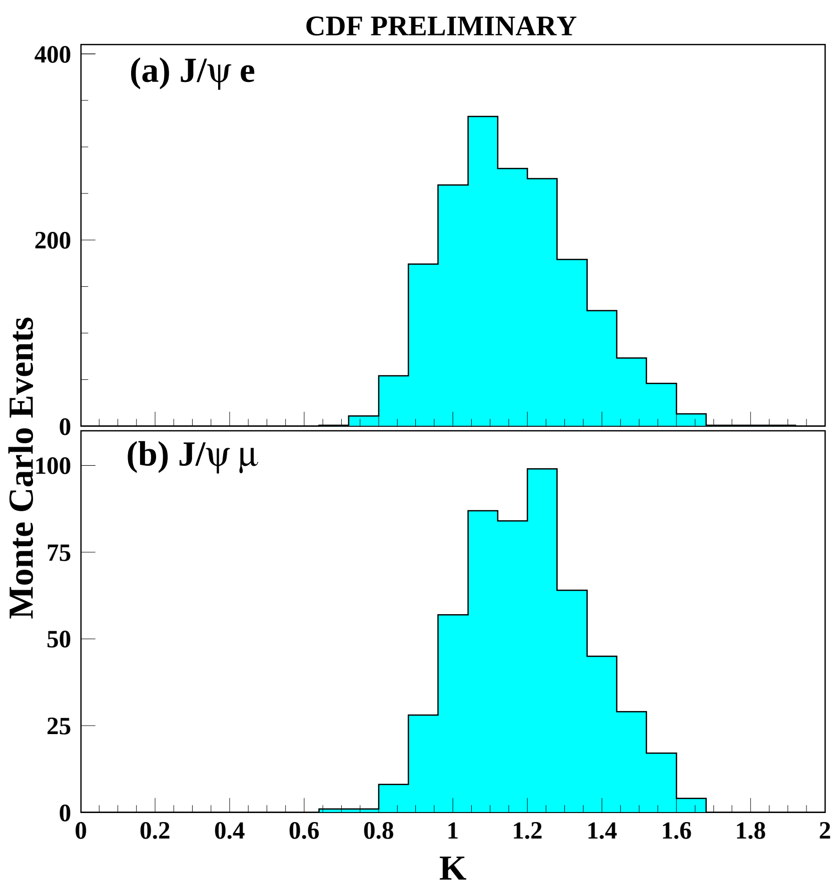
- This yields a sample of 71 events (42 $J/\psi e$ and 29 $J/\psi\mu$).

$$ct^* = \frac{M(J/\psi\ell)\cdot L_{xy}(J/\psi\,\ell)}{|p_T(J/\psi\,\ell)|}$$

B_c Lifetime
K Factor.

- Since the neutrino in $B_c \to J/\psi + \ell + \nu$ carries away the undetecded momentum, t^* is not the true proper time. $ct^* = ct/K$, where K for an event is given by

$$K = \frac{M(B_c^+)}{M(J/\psi\ell)} \times \frac{p_T(J/\psi\ell)}{p_T(B_c^+)}.$$



Background Distribution in ct^*

The general shape in $x = ct^*$ used for each of the backgrounds was a sum of three terms:

- a central Gaussian to account for prompt decays, *i.e.* events with the J/ψ decay point within the beam envelope,
- a right-side ($ct^* > 0$) exponential dominated by the decay of ordinary Bs in the background and
- a left-side ($ct^* < 0$) exponential to account for an observed low level background from daughters of B decay incorrectly associated with particles from the primary intraction vertex.

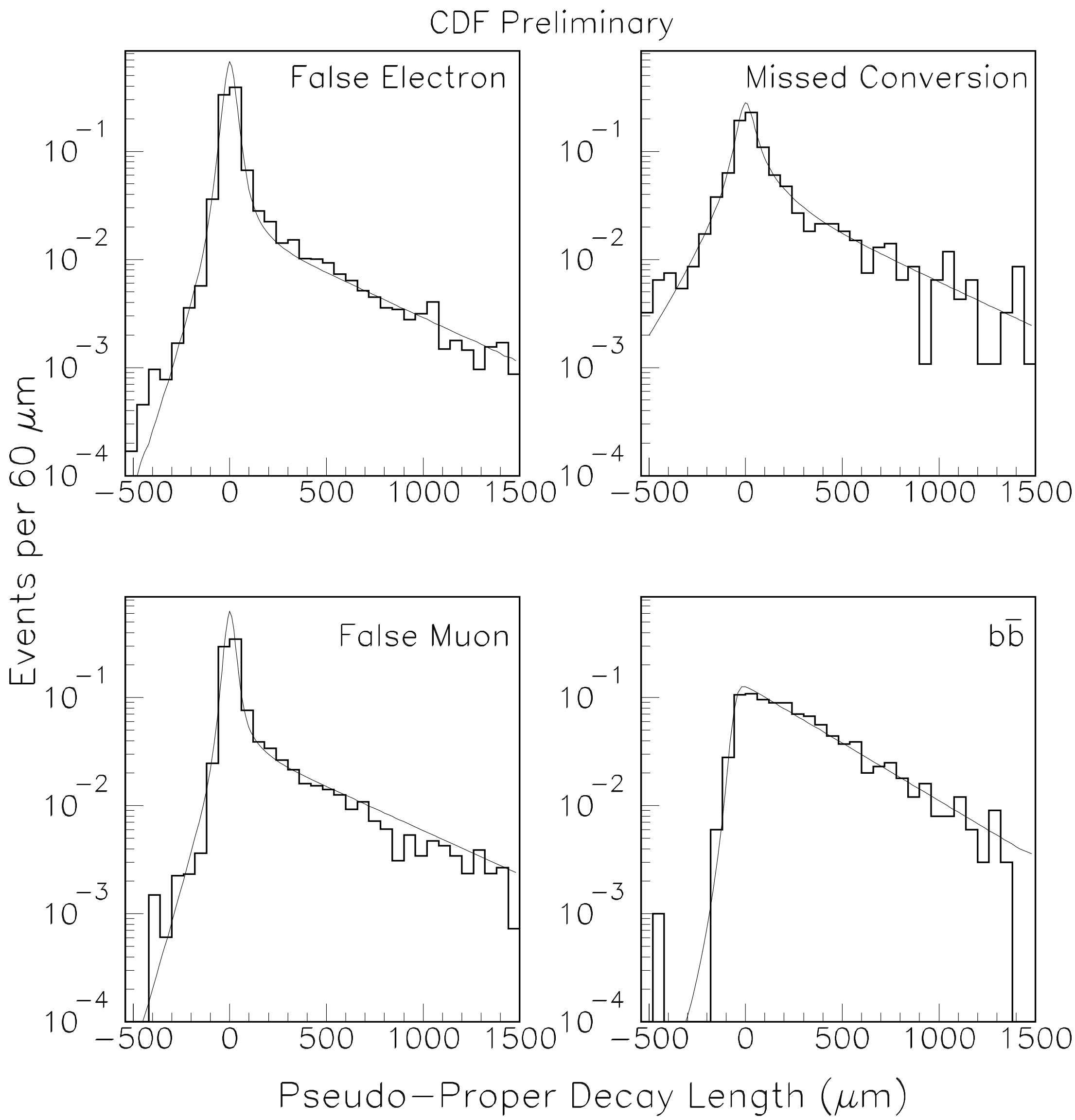
The exponentials were convoluted with a Gaussian resolution function. This sum can be written

$$\begin{aligned}\mathcal{F}^j(x) &= (1 - f^j_+ - f^j_-)G(x; s^j\sigma) \\ &+\frac{f^j_+}{\lambda^j_+}\theta(x)\exp\left(-\frac{x}{\lambda^j_+}\right)\otimes G(x; s^j\sigma) \\ &+\frac{f^j_-}{\lambda^j_-}\theta(-x)\exp\left(+\frac{x}{\lambda^j_-}\right)\otimes G(x; s^j\sigma).\end{aligned}$$

where

- $\theta(x) = 1$ for $x \geq 0$ and $\theta(x) = 0$ for $x < 0$.
- The index j stands for the various background contributions.
- The product $s^j\sigma$ is the one-standard-deviation width of the Gaussian distribution, where σ is the measurement uncertainty on x for each event and s^j is a fitted scale factor.

Background Distribution in ct^*



Background Distribution in ct^*.

- Our fitting procedure accounted for a difference between the relative pion and kaon fractions contributing to the prompt background and that contributing to background in the B-like region with $ct^* > 60\mu m$.
- The fit also allowed variation in the relative probability for pions and kaons to be falsely identified as electrons.

CDF Preliminary

$j \rightarrow$	fe	$f\mu$	ce	Be	$B\mu$
N''^j	13.2 ± 1.3	12.6 ± 2.8	See Note	1.5 ± 1.1	0.79 ± 0.34
f_+^j	0.199 ± 0.004	0.36 ± 0.01	0.45 ± 0.02	0.96 ± 0.01	0.98 ± 0.06
f_-^j	0.032 ± 0.004	0.034 ± 0.007	0.12 ± 0.02	$1 - f_+^{Be}$	$1 - f_+^{B\mu}$
λ_+^j (μm)	371 ± 15	445 ± 20	382 ± 27	371 ± 15	406 ± 16
λ_-^j (μm)	103 ± 9	96 ± 16	138 ± 27	65 ± 15	48 ± 21

Note: The number of conversion background events was calculated from identified conversions $N''^{ce} = 3$ and the ratio $R^{ce} = 1.06 \pm 0.36$.

B_c Signal Distribution in ct^*.

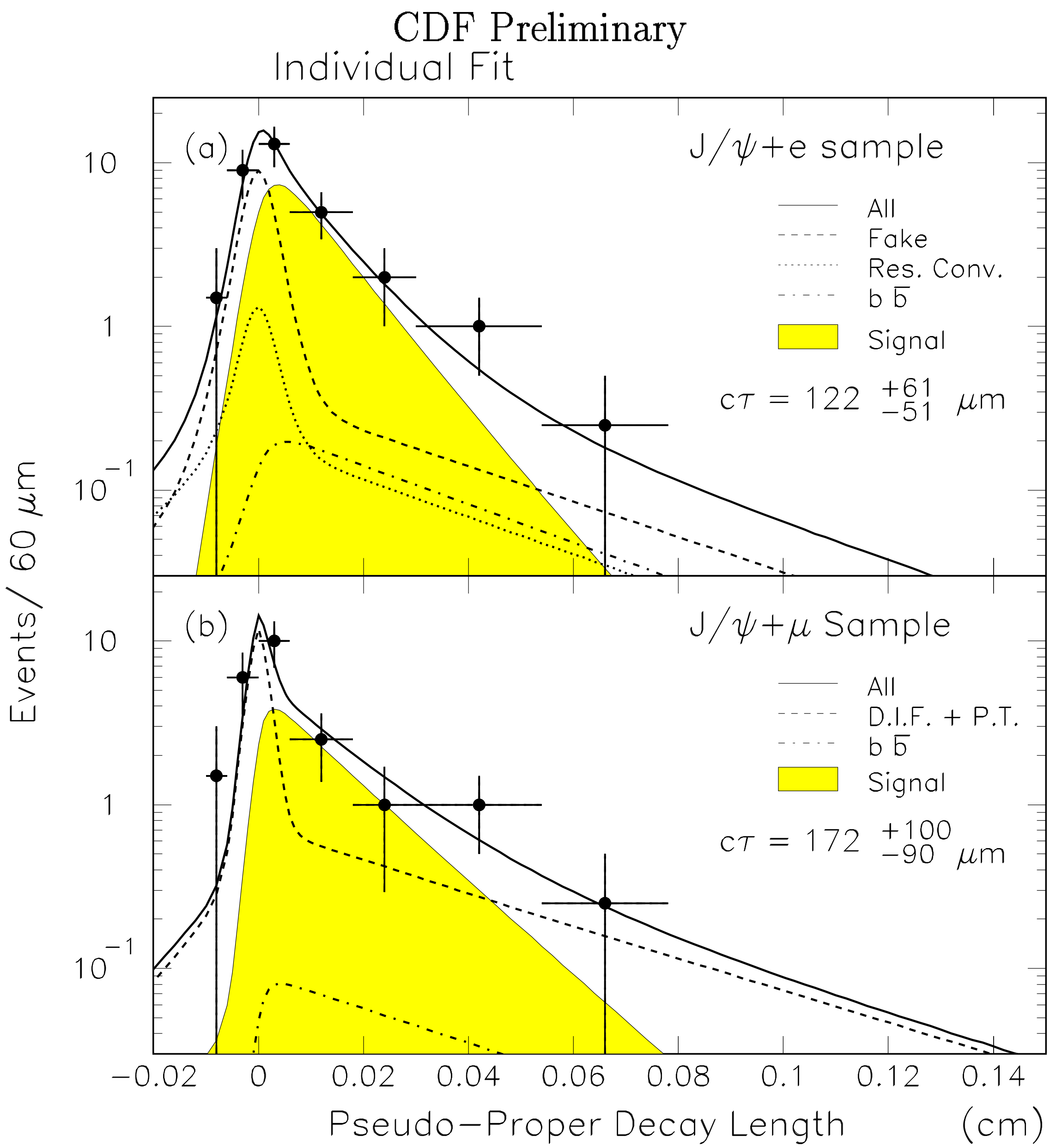
- We assumed an exponential decay for the contribution from B_c, but we convoluted it with the K distribution and a Gaussian distribution to account for measurement uncertainty.

$$\mathcal{F}^{\ell}_{sig}(x) \; = \; \int \left[H(K) \left(\frac{K}{c\tau} \right) e^{\left(-\frac{Kx}{c\tau}\right)} \otimes G(x; s^{\ell}\sigma) \right] dK$$

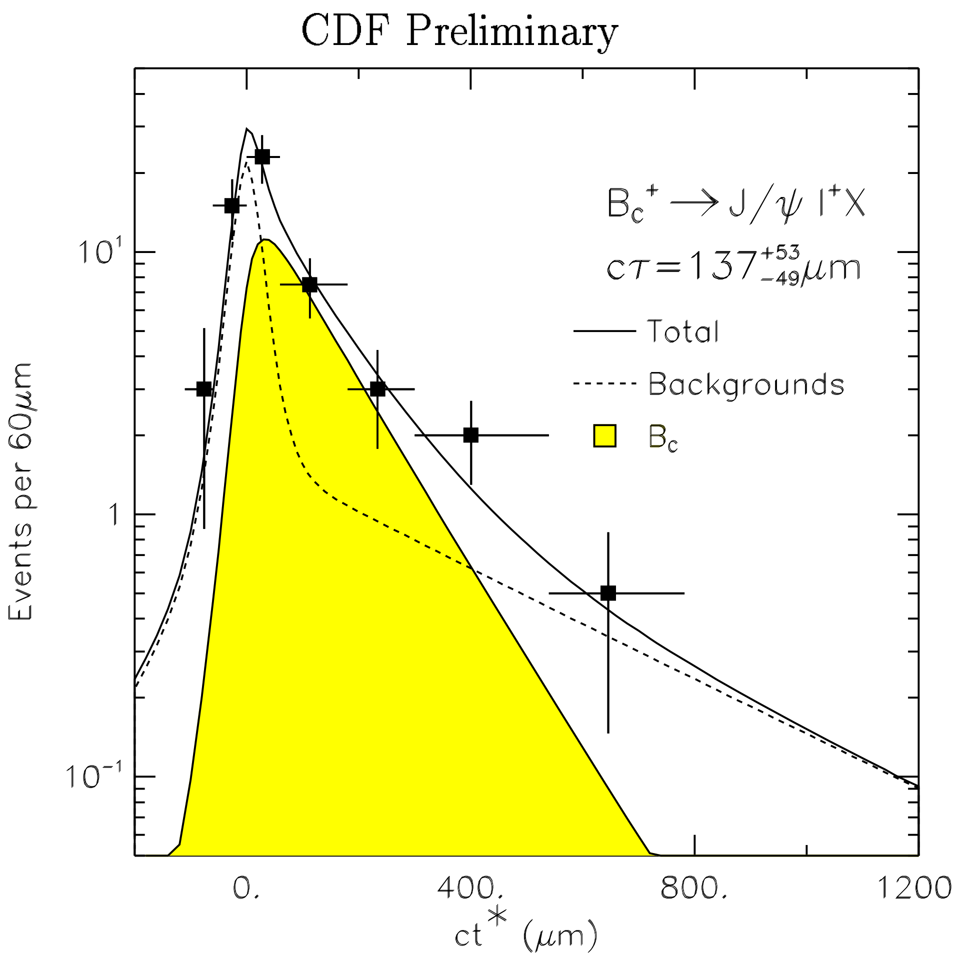
where $\ell = \mu$, e.

B_c Lifetime, Individual Fits

We fit the x distribution ($-0.01 < x < 0.15$ cm) to a sum of signal + background distribution.



B_c Lifetime, Combined Fit

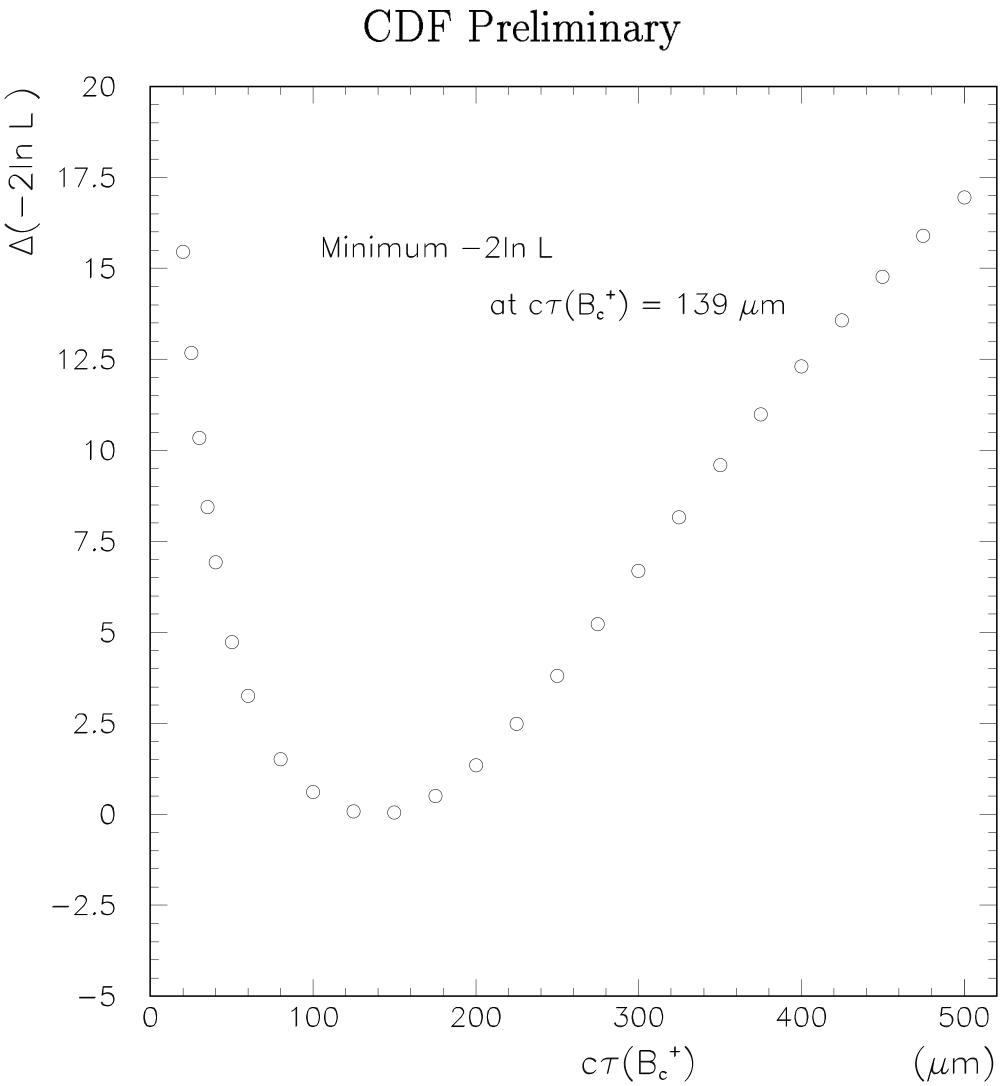


$$\tau(B_c) = 0.46\ ^{+0.18}_{-0.16}(\text{stat})\ \pm 0.03(\text{syst})\ \text{ps}$$

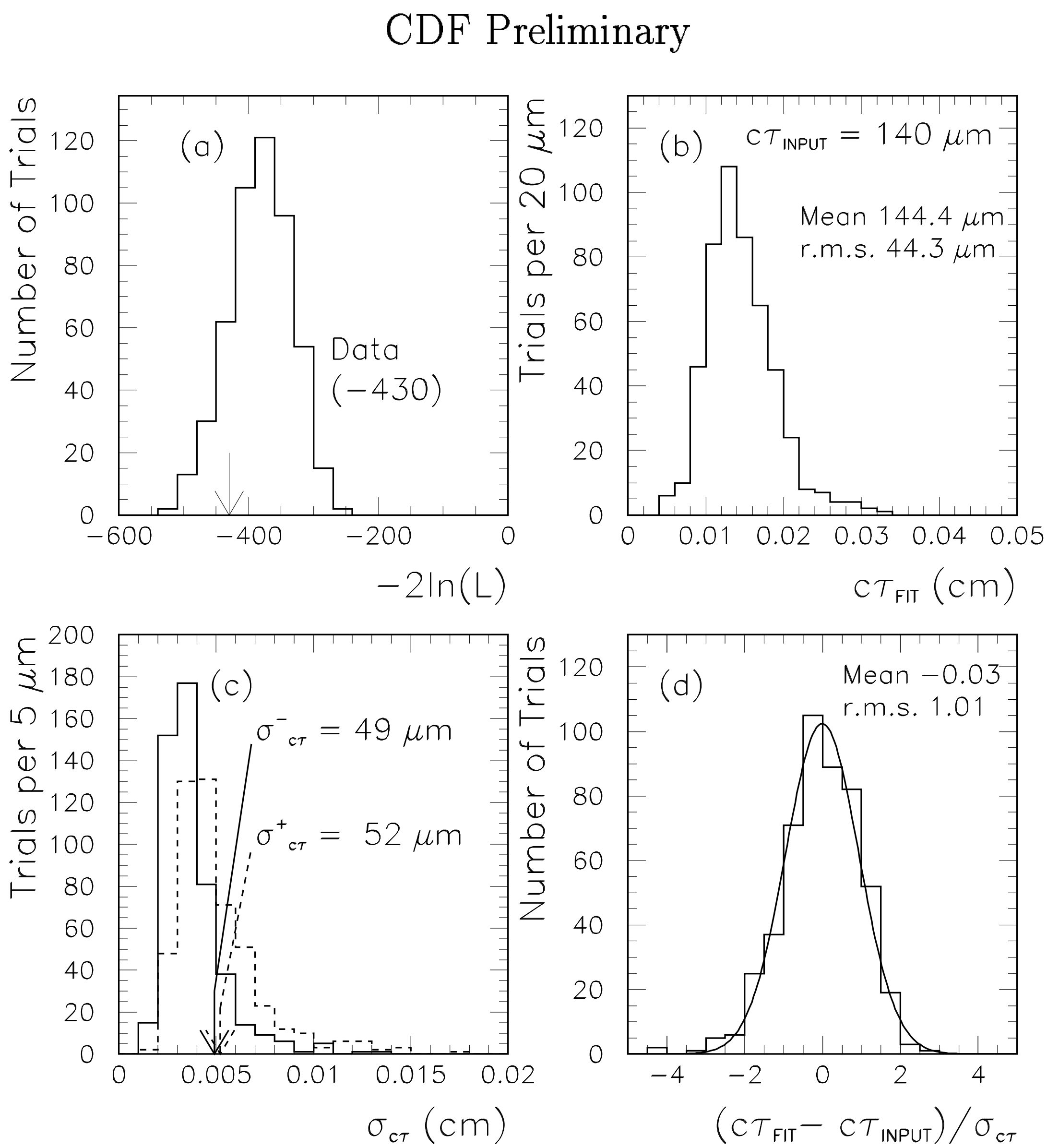
Systematic Uncertainties.

- fitting procedures, estimated from the difference between constrained and fixed parameters (0.014 ps),
- K distribution uncertainty due to production spectrum, B_c mass, higher $c\bar{c}$ states and decay model (0.016 ps),
- decay length resolution (0.028 ps),
- detector alignment (0.006 ps).

Likelihood Fit for Lifetime



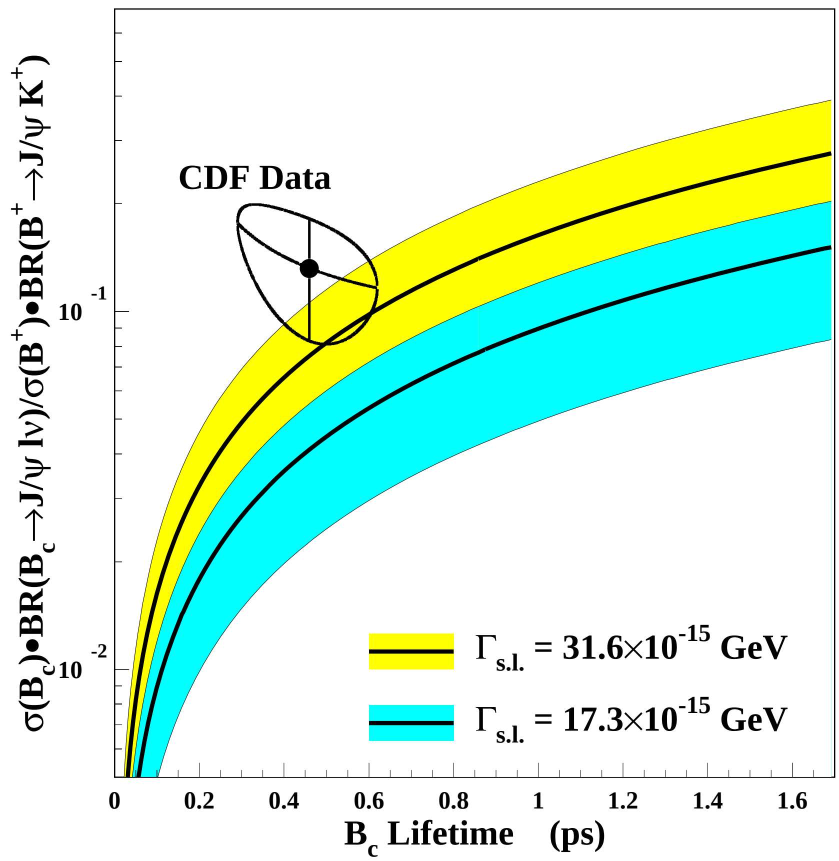
B_c Lifetime, Toy Monte Carlo



B_c Production Cross Section

$$\frac{\sigma_{B_c}\mathcal{B}(B_c^+ \to J/\psi \ell^+ X)}{\sigma_{B_u}\mathcal{B}(B_u^+ \to J/\psi K^+)}$$

CDF Preliminary



Shaded region is a theoretical prediction assuming:

$\sigma(B_c^+)/\sigma(\bar{b}) = 1.3 \times 10^{-3}$,
$\sigma(B^+)/\sigma(\bar{b}) = 0.378 \pm 0.022$,
$\mathcal{B}(B^+ \to J/\psi K^+) = (1.01 \pm 0.14) \times 10^{-3}$.

$$\frac{\sigma_{B_c}\mathcal{B}(B_c^+ \to J/\psi \ell^+ X)}{\sigma_{B_u}\mathcal{B}(B_u^+ \to J/\psi K^+)} = \mathbf{0.132} \ ^{+0.041}_{-0.037}\mathbf{(stat)} \ \pm \mathbf{0.031(syst)} \ ^{+0.032}_{-0.020}\mathbf{(lifetime)}$$

Systematic Uncertainties on B_c Production Cross Section

Systematic Uncertainties.

- Ratio of the efficiency for $B_c \to J/\psi e\nu$ events to that for $B \to J/\psi K$ events, R^K
  $R^K = 0.263 \pm 0.035(\text{syst})\ ^{+0.038}_{-0.062}(\text{lifetime})$
  * **Systematic Uncertainties on R^K**
    - Electron Identification (10 %)
    - Production spectrum (5 %)
    - Detector Simulation (5 %)
    - Monte Carlo Statistics (4 %)
    - Trigger Simulation (4 %)
    - Fragmentation (2 %)
- the decay of B_c to higher $c\bar{c}$ states (-6.7 %).

Conclusions

- We observe B_c mesons through their semileptonic decays, $B_c \rightarrow J/\psi \ell X$, where ℓ is an electron or a muon.
  - A fit to the $J/\psi\ell$ mass distribution yields $\mathbf{20.4^{+6.2}_{-5.5}}$ **events** from Bc mesons.
  - This excess is inconsistent with the background prediction by **4.8 σ ($Prob$ = 6.3 x 10^{-7})** .
- Properties of the B_c meson is measured to be:
  - $\mathrm{M}(B_c) = 6.40 \pm 0.39(\mathrm{stat}) \pm 0.13(\mathrm{syst})\ \mathrm{GeV/c^2}$
  - $\tau(B_c) = 0.46\ ^{+0.18}_{-0.16}(\mathrm{stat}) \pm 0.03(\mathrm{syst})\ \mathrm{ps}$
  - $\sigma \times \mathrm{BR}(B_c \rightarrow J/\psi \ell X)\ / \sigma \times \mathrm{BR}(B_u \rightarrow J/\psi K)$
    $= 0.132\ ^{+0.041}_{-0.037}(\mathrm{stat}) \pm 0.031(\mathrm{syst})\ ^{+0.032}_{-0.020}(\mathrm{lifetime})$

We thank the Fermilab staff and the technical staffs of the participating institutions for their essential contributions to this research. This work was supported by the U.S. Department of Energy and the National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Science, Culture, and Education of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China and the A. P. Sloan Foundation.

Normalized Binned Likelihood Function

Sums. We present here the two functions that, through their parameters, are adjusted for the best fit to the data distributions, D_i^μ and D_i^e.

$$\lambda_i^\mu = (1-r^\varepsilon)n'^\ell S_i^\mu + n'^{f\mu} f_i^{f\mu} j_i^{f\mu} + n'^{B\mu} j_i^B \quad (2)$$
$$\lambda_i^e = r^\varepsilon n'^\ell S_i^e + n'^{fe} f_i^{fe} j_i^{fe} + n'^{ce} r^{ce} j_i^{ce} + n'^{Be} j_i^B \quad (3)$$

$$\xi'^2 = -2\ln\left(\frac{\mathcal{L}}{\mathcal{L}_0}\right) \quad (4)$$
$$= 2\sum_i \left[(\lambda_i^\mu - D_i^\mu) - D_i^\mu \ln\left(\frac{\lambda_i^\mu}{D_i^\mu}\right)\right] \quad (5)$$

where ξ'^2 is the first part ξ^2 which we now write down in full.

$$\xi^2 = 2\sum_i \left\{\left[(\lambda_i^\mu - D_i^\mu) - D_i^\mu \ln\left(\frac{\lambda_i^\mu}{D_i^\mu}\right)\right] + \left[(\lambda_i^e - D_i^e) - D_i^e \ln\left(\frac{\lambda_i^e}{D_i^e}\right)\right]\right. \quad (6)$$
$$+ \left.\left[(j_i^{f\mu} - J_i^{f\mu}) - J_i^{f\mu} \ln\left(\frac{j_i^{f\mu}}{J_i^{f\mu}}\right)\right] + \left[(j_i^{fe} - J_i^{fe}) - J_i^{fe} \ln\left(\frac{j_i^{fe}}{J_i^{fe}}\right)\right]\right\} \quad (7)$$
$$+\sum_i \left\{\left(\frac{j_i^{ce} - J_i^{ce}}{\Delta J_i^{ce}}\right)^2 + \left(\frac{j_i^B - J_i^B}{\Delta J_i^B}\right)^2 + \left(\frac{f_i^{f\mu} - F_i^{f\mu}}{\Delta F_i^{f\mu}}\right)^2 + \left(\frac{f_i^{fe} - F_i^{fe}}{\Delta F_i^{fe}}\right)^2\right\} \quad (8)$$
$$+ \left(\frac{n'^{f\mu} - N'^{f\mu}}{\Delta N'^{f\mu}}\right)^2 + \left(\frac{n'^{fe} - N'^{fe}}{\Delta N'^{fe}}\right)^2 + \left(\frac{n'^{B\mu} - N'^{B\mu}}{\Delta N'^{B\mu}}\right)^2 + \left(\frac{n'^{Be} - N'^{Be}}{\Delta N'^{Be}}\right)^2 \quad (9)$$
$$+ 2\left[(n'^{ce} - N'^{ce}) - N'^{ce} \ln\left(\frac{n'^{ce}}{N'^{ce}}\right)\right] + \left(\frac{r^{ce} - R^{ce}}{\Delta R^{ce}}\right)^2 + \left(\frac{r^\varepsilon - R^\varepsilon}{\Delta R^\varepsilon}\right)^2 \quad (10)$$

Line 6 is the fit to the B_c candidate distributions. Lines 7 and 8 constrain the parent distributions for the various backgrounds and the shape-dependent fractions for the false lepton distributions. Lines 9 and 10 constrain the normalizations for the five background distributions, the Monte Carlo calculation of the expected ratio of electron to muon B_c events and the calculated ratio of residual to identified conversion-electron background events.

Unbinned Likelihood Function

The normalized probabilities for the muon and electron distributions are λ^μ/D^μ and λ^e/D^e, where

$$
\begin{aligned}
\lambda^\mu(m_i, M_{B_c}) &= (1-r^\varepsilon)n'^\ell S^\mu(m_i, M_{B_c}) + n'^{f\mu}F^\mu(m_i) + n'^{B\mu}J^B(m_i) \\
\lambda^e(m_j, M_{B_c}) &= r^\varepsilon n'^\ell S^e(m_j, M_{B_c}) + n'^{fe}F^e(m_j) + n'^{Be}J^{Be}(m_j) + n'^{ce}J^{ce}(m_j) \\
D^\mu &= (1-r^\varepsilon)n'^\ell + n'^{f\mu} + n'^{B\mu} \\
D^e &= r^\varepsilon n'^\ell + n'^{fe} + n'^{Be} + n'^{ce}
\end{aligned}
\tag{11}
$$

- $S_i^\mu \to S^\mu(m_i, M_{B_c})$ and $S_i^e \to S^e(m_i, M_{B_c})$ represent the normalized signal distributions.
- $F^\mu(m_i)$ and $F^e(m_i)$ represent the normalized false μ and false e background distributions.
- $J^B(m_i)$ represents the distribution of the $B\overline{B}$ background obtained from Monte Carlo calculations.
- $J^{ce}(m_i)$ represents the distribution for conversion and Dalitz decay electrons.

$$
\xi_m^2 = -2\ln\left(\frac{\mathcal{L}}{\mathcal{L}_{min}}\right) \tag{12}
$$

It is given by

$$
\begin{aligned}
\xi_m^2 &= -2\left\{\sum_i\left[\ln\left(\frac{\lambda^\mu(m_i, M_{B_c})}{D^\mu}\right)\right] + \sum_j\left[\ln\left(\frac{\lambda^e(m_j, M_{B_c})}{D^e}\right)\right]\right\} && (13) \\
&\quad -2\left\{-D^\mu + N'^\mu \ln D^\mu - D^e + N'^e \ln D^e\right\} && (14) \\
&+ \left(\frac{r^\varepsilon - R^\varepsilon}{\Delta R^\varepsilon}\right)^2 + \left(\frac{n'^{f\mu} - N'^{f\mu}}{\Delta N'^{f\mu}}\right)^2 + \left(\frac{n'^{B\mu} - N'^{B\mu}}{\Delta N'^{B\mu}}\right)^2 && (15) \\
&+ \left(\frac{n'^{fe} - N'^{fe}}{\Delta N'^{fe}}\right)^2 + \left(\frac{n'^{ce} - N'^{ce}}{\Delta N'^{ce}}\right)^2 + \left(\frac{n'^{Be} - N'^{Be}}{\Delta N'^{Be}}\right)^2 && (16) \\
&+ C
\end{aligned}
$$

where C was chosen so that $\xi_m^2 = 0$ at $\mathcal{L} = \mathcal{L}_{min}$. Line 13 is the fit to the B_c candidate distributions. Line 14 is the constraint to the total numbers of $J/\psi\,\mu$ and $J/\psi\,e$ events. Lines 15 and 16 constrain the ratio of e to μ signals and the number of background events for each background.

Unbinned Likelihood Function for the Lifetime Analysis

The normalized probabilities which combine both signal and background distributions in $x_i = ct_i^*$ for the $J/\psi\,\mu$ and $J/\psi\,e$ are Λ^μ/D''^μ and Λ^e/D''^e, where

$$\begin{aligned}
\Lambda^\mu(x_i, c\tau) &= (1-r^\varepsilon)n''^\ell \mathcal{F}^\mu_{sig}(x_i, c\tau) + n''^{f\mu}\mathcal{F}^{f\mu}(x_i) + n''^{B\mu}\mathcal{F}^{B\mu}(x_i) \\
\Lambda^e(x_j, c\tau) &= r^\varepsilon n''^\ell \mathcal{F}_{sig} S^e(x_j, c\tau) + n''^{fe}\mathcal{F}^{fe}(x_j) + n''^{Be}\mathcal{F}^{Be}(x_j) + n''^{ce}\mathcal{F}^{ce}(x_j) \\
D''^\mu &= (1-r^\varepsilon)n''^\ell + n''^{f\mu} + n''^{B\mu} \\
D''^e &= r^\varepsilon n''^\ell + n''^{fe} + n''^{Be} + n''^{ce}. \qquad (17)
\end{aligned}$$

$$\begin{aligned}
-2\ln\mathcal{L}^{comb} &= -2\ln(\mathcal{L}^e\mathcal{L}^\mu) \\
&= -2\sum_i^{N''^e}\ln\Lambda^e(x_i) - 2\sum_i^{N_{''\mu}}\ln\Lambda^\mu(x_i) \qquad (18)\\
&+\ 2\left[n_{''B_c} + n''^{fe} + n''^{ce}r^{ce} + n''^{Be} + n''^{f\mu} + n''^{B\mu} + \ln(N_{''e}!) + \ln(N_{''\mu}!)\right] \qquad (19)\\
&+\ \left(\frac{r^\varepsilon - R^\varepsilon}{\Delta R^\varepsilon}\right)^2 \qquad (20)\\
&+\ 2(n^{ce} - N''^{ce}\ln n^{ce} + \ln(N''^{ce}!)) + \left(\frac{r^{ce} - R^{ce}}{\Delta R^{ce}}\right)^2 \qquad (21)\\
&+\ \left(\frac{n^{f\mu} - N''^{f\mu}}{\Delta N''^{f\mu}}\right)^2 + \left(\frac{n^{B\mu} - N''^{B\mu}}{\Delta N''^{B\mu}}\right)^2 + \left(\frac{n''^{fe} - N''^{fe}}{\Delta N''^{fe}}\right)^2 + \left(\frac{n^{Be} - N''^{Be}}{\Delta N''^{Be}}\right)^2 \qquad (22)\\
&+\ \left(\frac{\rho - \rho_0}{\Delta\rho_0}\right)^2 + \left(\frac{\omega - \omega_0}{\Delta\omega_0}\right)^2 + \chi^2_{fe} + \chi^2_{ce} + \chi^2_{f\mu}. \qquad (23)
\end{aligned}$$

Note that terms $N''^e \ln D''^e$ and $N''^\mu \ln D''^\mu$ do not appear because they cancel between the denominator of the log-probability sum (Line 18) and the numerator of the Poisson constraint on the numbers of $J/\psi\,e$ and $J/\psi\,\mu$ events (Line 19). Line 20 is the constraint on the $J/\psi\,e$ fraction in the number of B_c events. Line 21 contains the Poisson constraint on the number of detected conversion electron background events and the Gaussian constraint on the ratio of undetected to detected background. Line 22 contains Gaussian constraints on the numbers of other types of background events. Finally, Line 23 provides constraints on ρ, ω, and the shape parameters for the background probability functions.