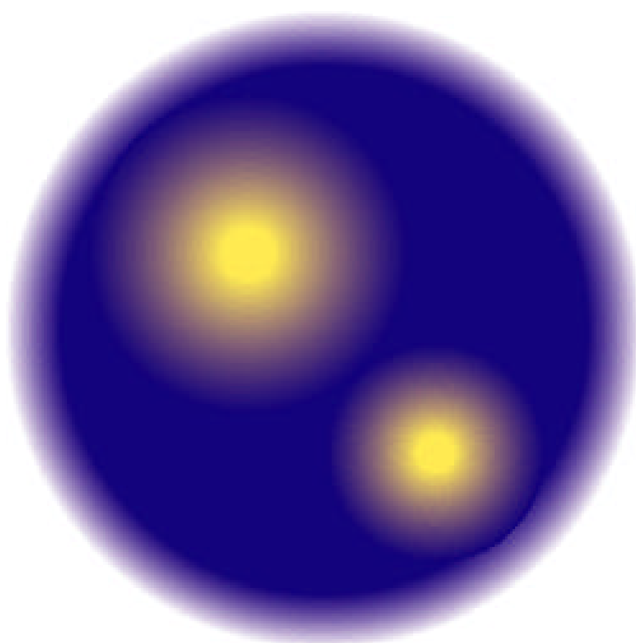
CDF Report on B_c

Prem P Singh

University of Illinois at Urbana-Champaign

Representing the CDF Collaboration



Workshop on B Physics at the Tevatron, Sep 23-25, 1999

Outline

- **Observation of the B_c Meson at CDF**
  - **Introduction**
  - **Selection**
  - **Background**
  - **Counting and significance**
  - **Mass**
  - **Lifetime**
  - **Cross Section**

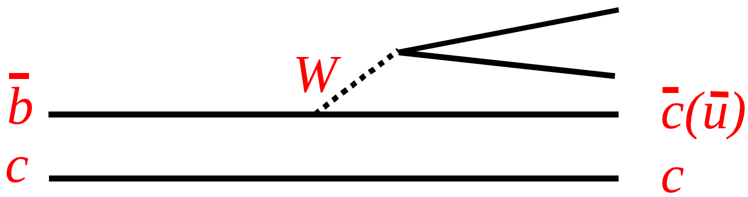
Meet the B_c

- **Only meson state with two different heavy quarks**
  - **Other quarkonia (*J*/y, ¡ , etc.) decay via strong interaction.** B_c **Decays weakly**
  - **Unique production process**
    - $gg \rightarrow B_c^+ + b + \bar{c}$
  - **Comparable timescales for decay of two heavy constituents**

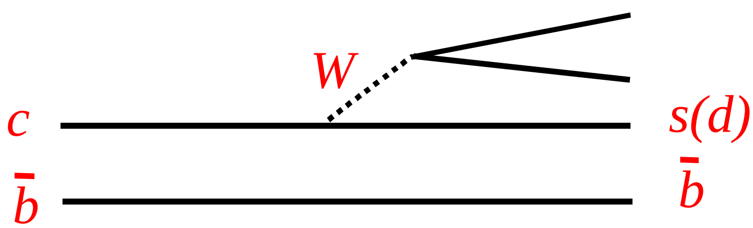
- **Quarkonia described by Quark Potential models**
  - **Opportunity to test with** B_c
  - **Expect:**
    - **Tightly bound:** $f(B_c) \approx 400$ M*eV*
    - **Ground state mass predictions: 6.1<**M**(**B_c**)<6.5** *GeV*

Decay Properties

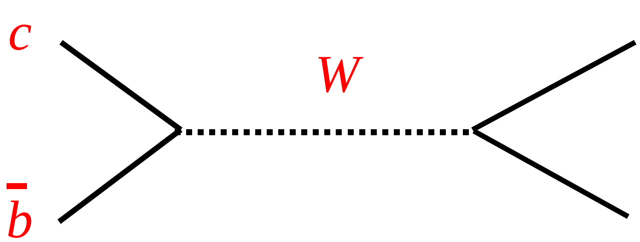
- **Three dominant processes:**
  - *b* **decay:** $J/y\ p^+$, $J/y\ D_s^+$, $J/y\ \ell^+ n$



  - *c* **decay:** $B_s^0 p^+$, $B_s^0\ \ell^+ n$



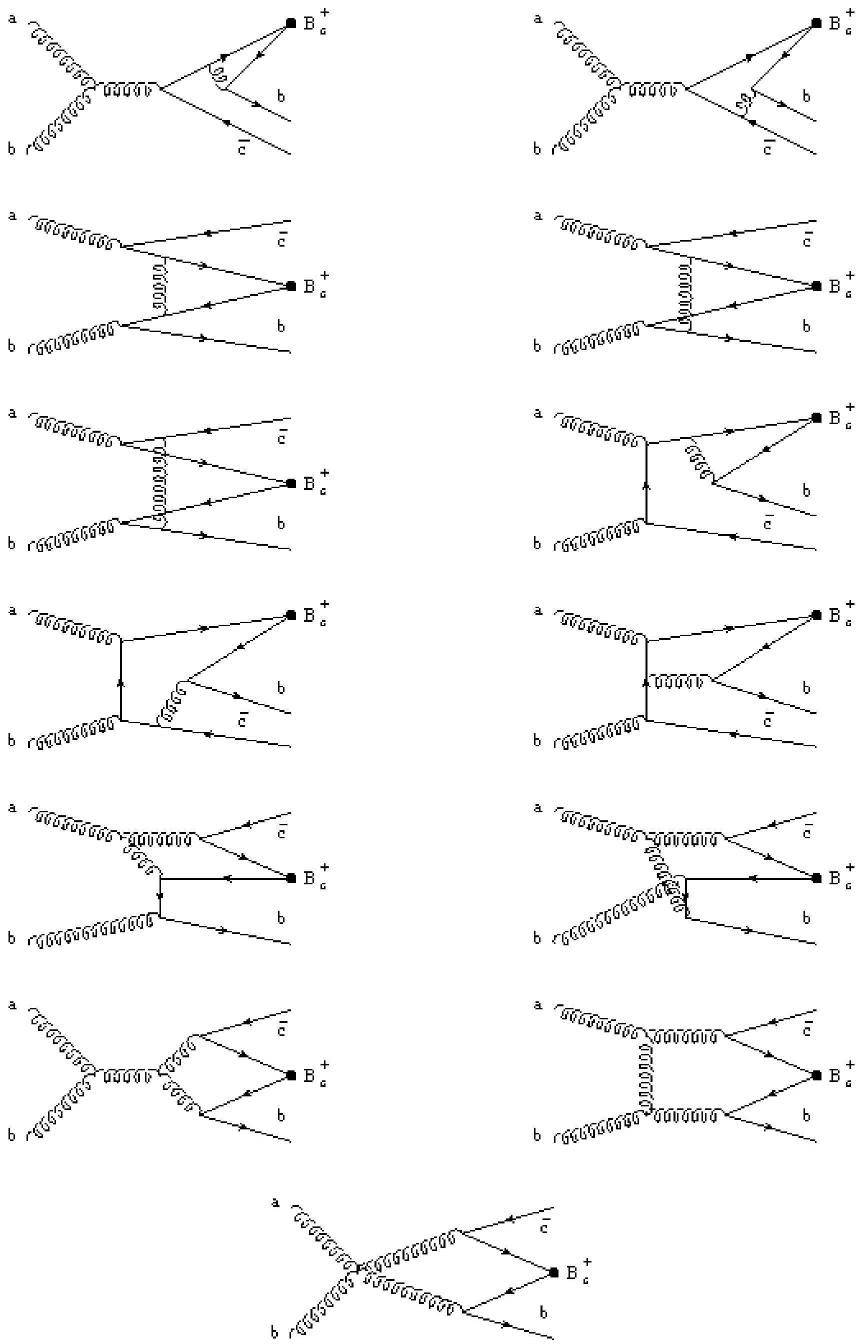
  - **Annihilation:** $t n_\tau$, ...



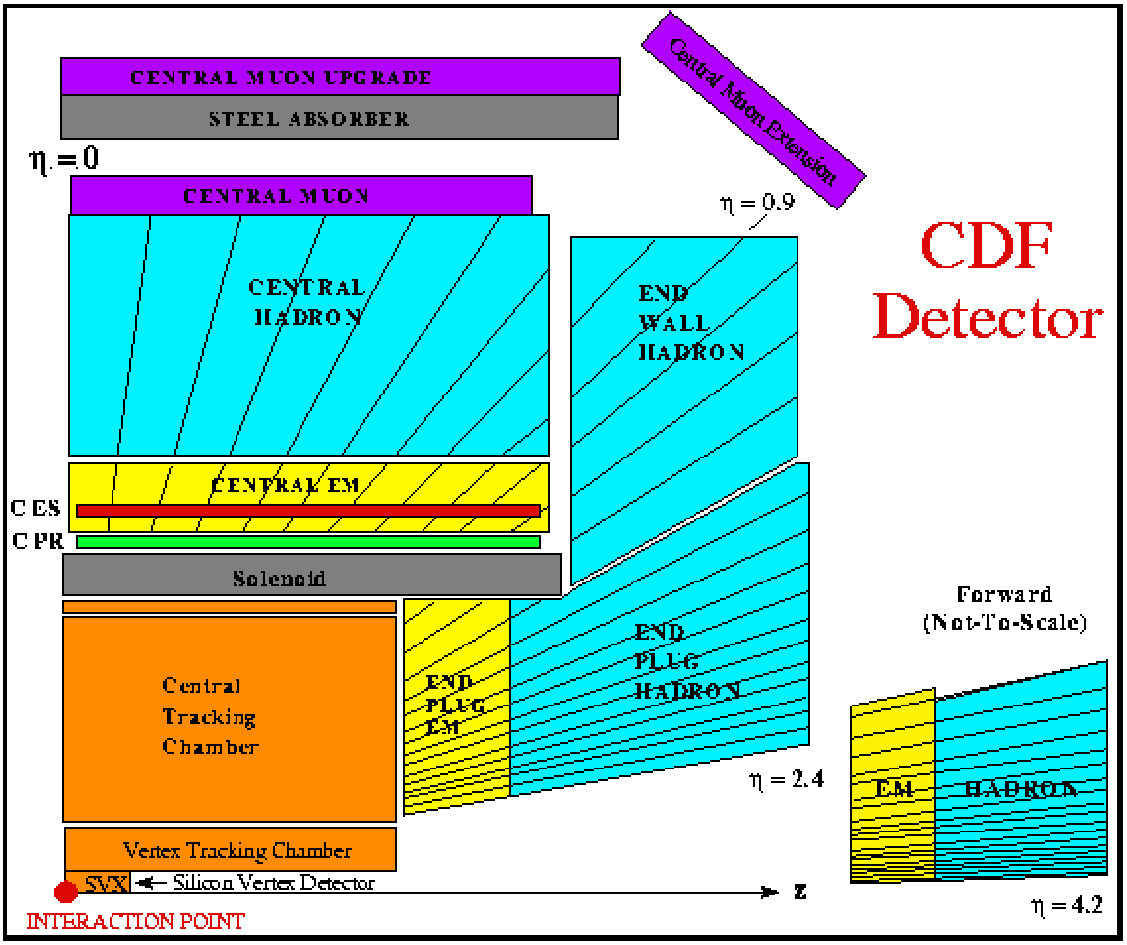
- **Naïvely expect factorization to apply**
  - $\Gamma=\Gamma_b+\Gamma_c+\Gamma_{bc}$; **Expect $\tau \sim 0.4$ - 0.7 ps**
  - **Bound-state effects may be large**
  - **Eichten and Quigg predict $\tau \sim 1.3$ ps**

Hadroproduction

- **Dominant process is** $gg \rightarrow B_c^+ b\bar{c}$
  - **Calculation requires 36 diagrams** $O(\alpha_s^4)$



CDF Detector

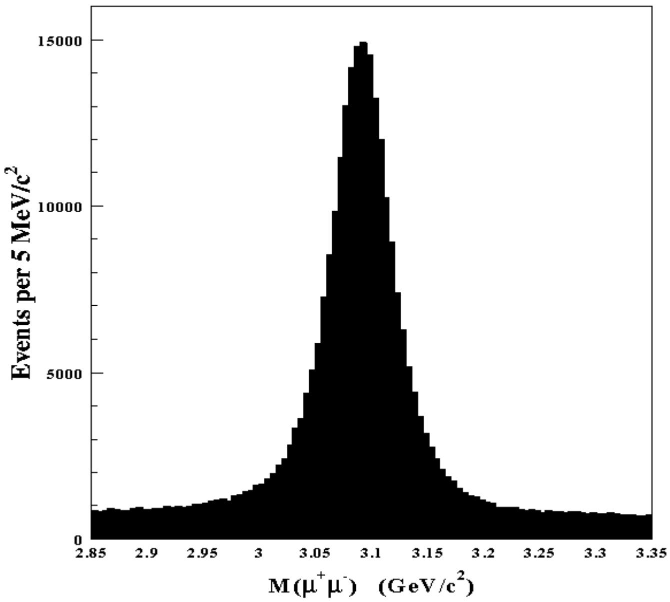


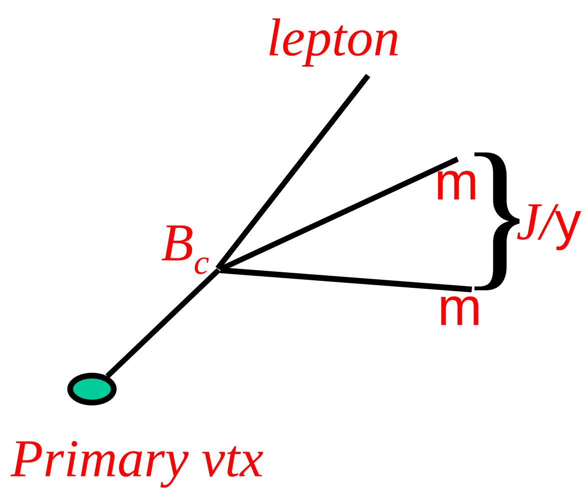
- **Tracking and lepton ID |η|<1**
- **$\delta d_0 = (13+40/p_t)\mu m$ for $z_0 < 25$ cm**
- **$\sigma_{beam} = 25\ \mu m$, $\sigma(z_0) = 25$ cm**
- **Datasets:**

Run	Year	Integraed Luminosity	Typical Luminosity ($\times 10^{30} cm^{-2} s^{-1}$)	Mean Number Interactions
1A	92-93	19	1-5	1
1B	94-95	90	5-15	1-3

Event Selection

- Select opposite sign di-muon pairs with $p_{T\mu} > 2\ GeV$
- Muons satisfy hardware trigger selections
- $|M_{\mu\mu} - M_{\psi}| < 50\ MeV$
- 200k events



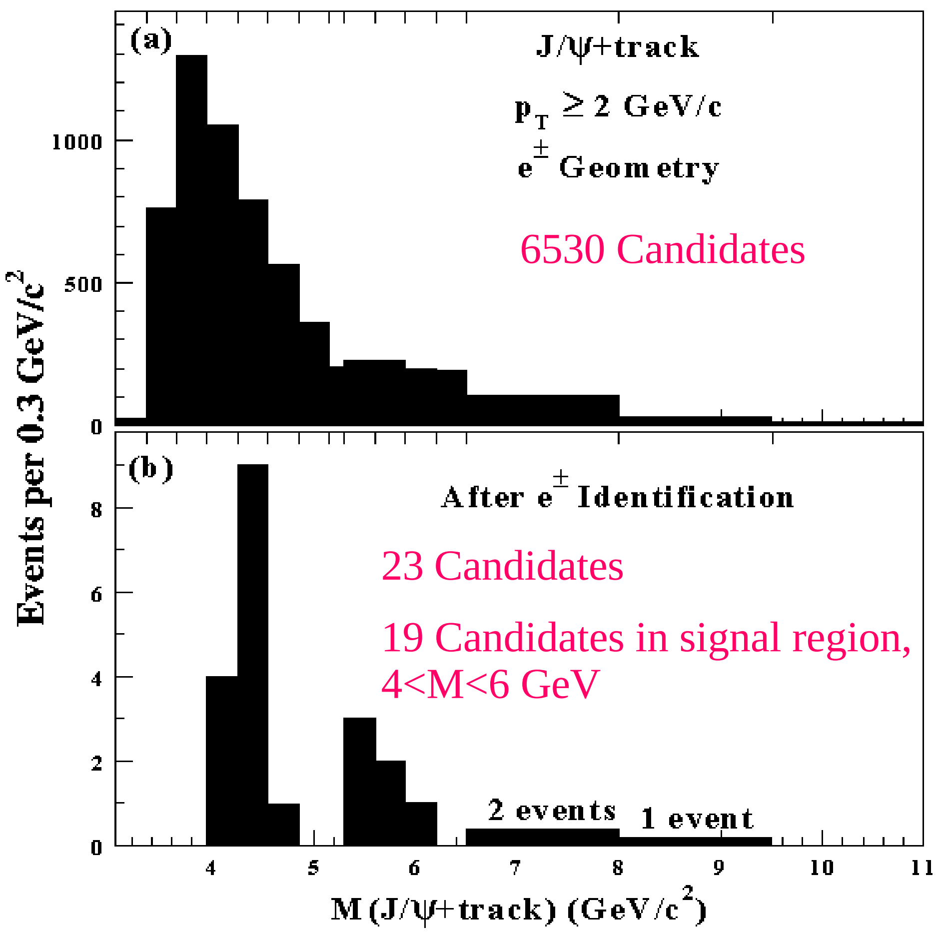


- J/ψ candidate constrained to known mass
- Third track in muon or electron fiducial region
- Opening angle between J/ψ and 3rd track < 90º
- Common decay vertex: *Prob*(χ^2)>1%
- Displacement

$$ct^{*} \equiv \frac{M(J/\psi\ \ell) \cdot L_{xy}(J/\psi\ \ell)}{p_T(J/\psi\ \ell)} > 60\ \mu m$$

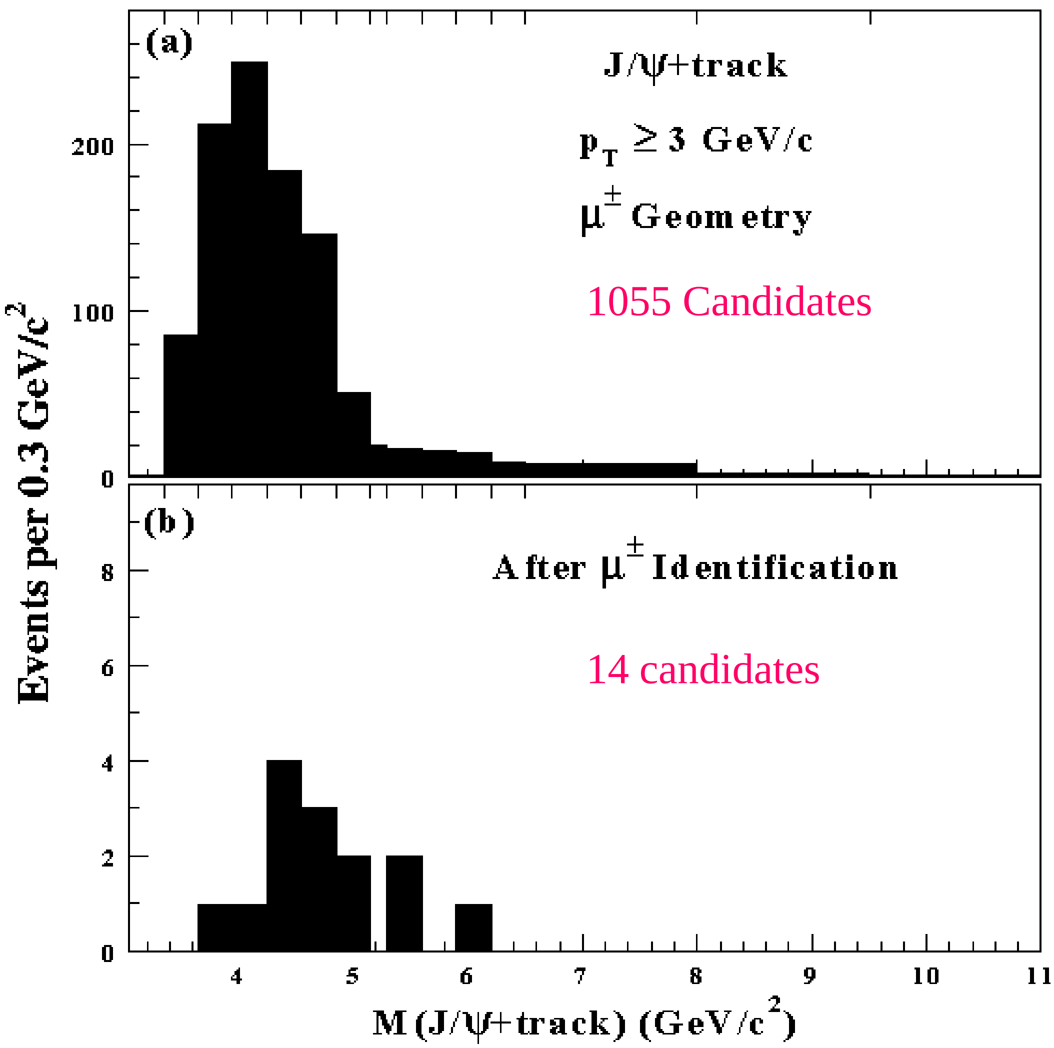
Selection: $B_c \to J/\psi\ e$

- **Electron ID**
  - **Central calorimeter energy (E/p)**
  - **Had/EM**
  - **Track match and shower profile in shower-max proportional chamber**
  - **dE/dx**
  - **Remove conversion candidates**



Selection: $B_c \to J/\psi\ \mu$

- **Muon ID**
  - **Penetrate 2nd layer filtering steel**
  - **Segement in inner and outer chambers matched to track**
  - $p_T > 3\ GeV$, $|\eta| < 0.6$



Background to $B_c \rightarrow J/\psi\ l$

- **Electron Channel**
  - **False Electron Background (Hadron mis-identified as an electron).**
  - **Real electrons from Photon Conversions and Dalitz decays (($\pi^0 \rightarrow \gamma e^+ e^-$)**
  - **BB-bar background**

$$B \rightarrow J/\psi + X$$

$$\mu\mu$$

$$\overline{B} \rightarrow \mu + X$$

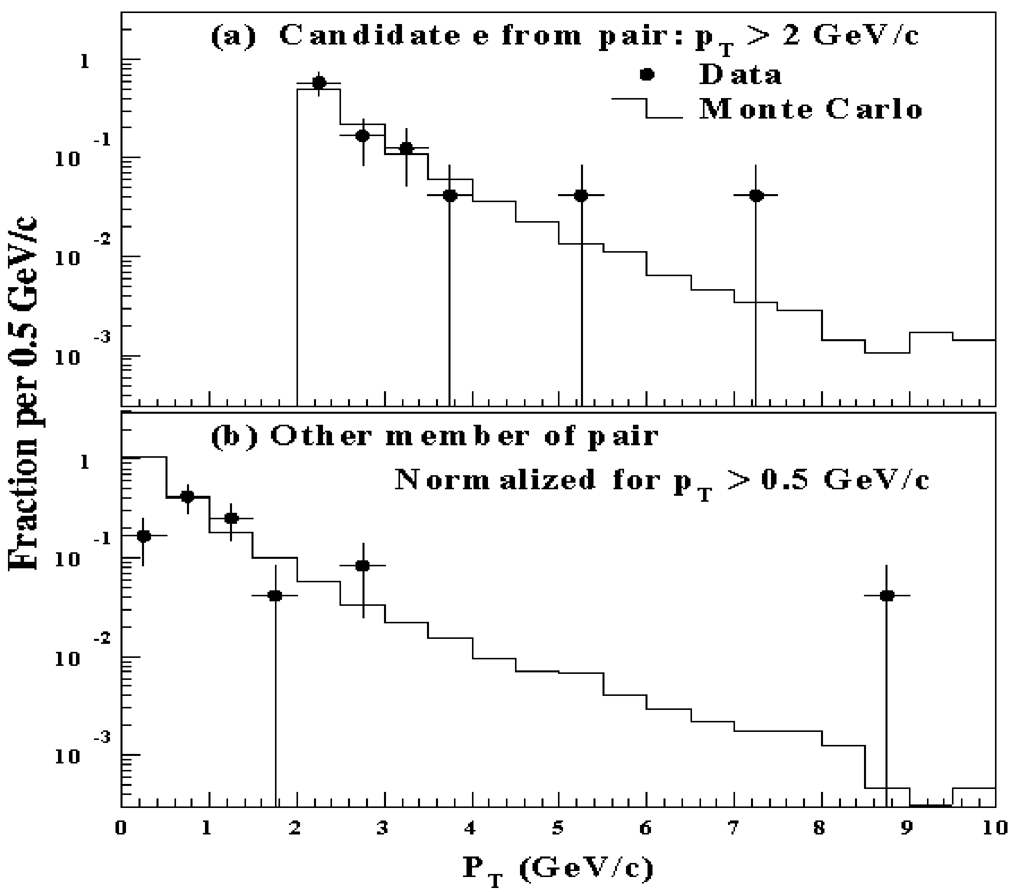
- **Muon Channel**
  - K **or** π **Decay in flight.**
  - **Mis-identification of** π **or** K **as a muon due to Punch through.**

$$B \rightarrow J/\psi + X$$

  - **BB-bar background**

Conversions

- **Estimate residual component using MC procedure**
  - **All tracks treated as charged pions and replaced with π^0**
  - **Determine ratio of found vs. missed conversion pairs: R_{conv}=1.06±0.36**



$$1.2 \pm 0.9 \text{ Events } (4 - 6 \text{ GeV})$$

Background: False *e*

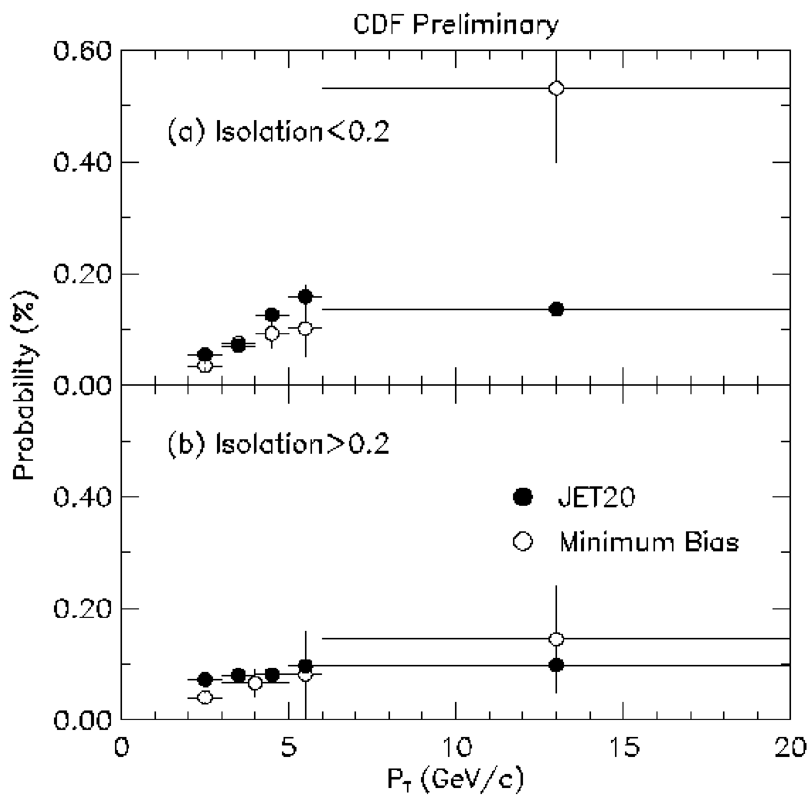
- Estimate backgound in electron-depleted samples
- Hadrons can shower early in calorimeter and mimic electrons

  - Jet and Minimum bias trigger selections
  - Correct for real electrons from conversions and heavy flavor using dE/dx:

$$f_m = \frac{N_e}{N_t}(1 - f_e)$$

  - Two regions of electron isolation:

$$I = \sum_{\Delta R<0.2} |\hat{p}| \Big/ E_T$$



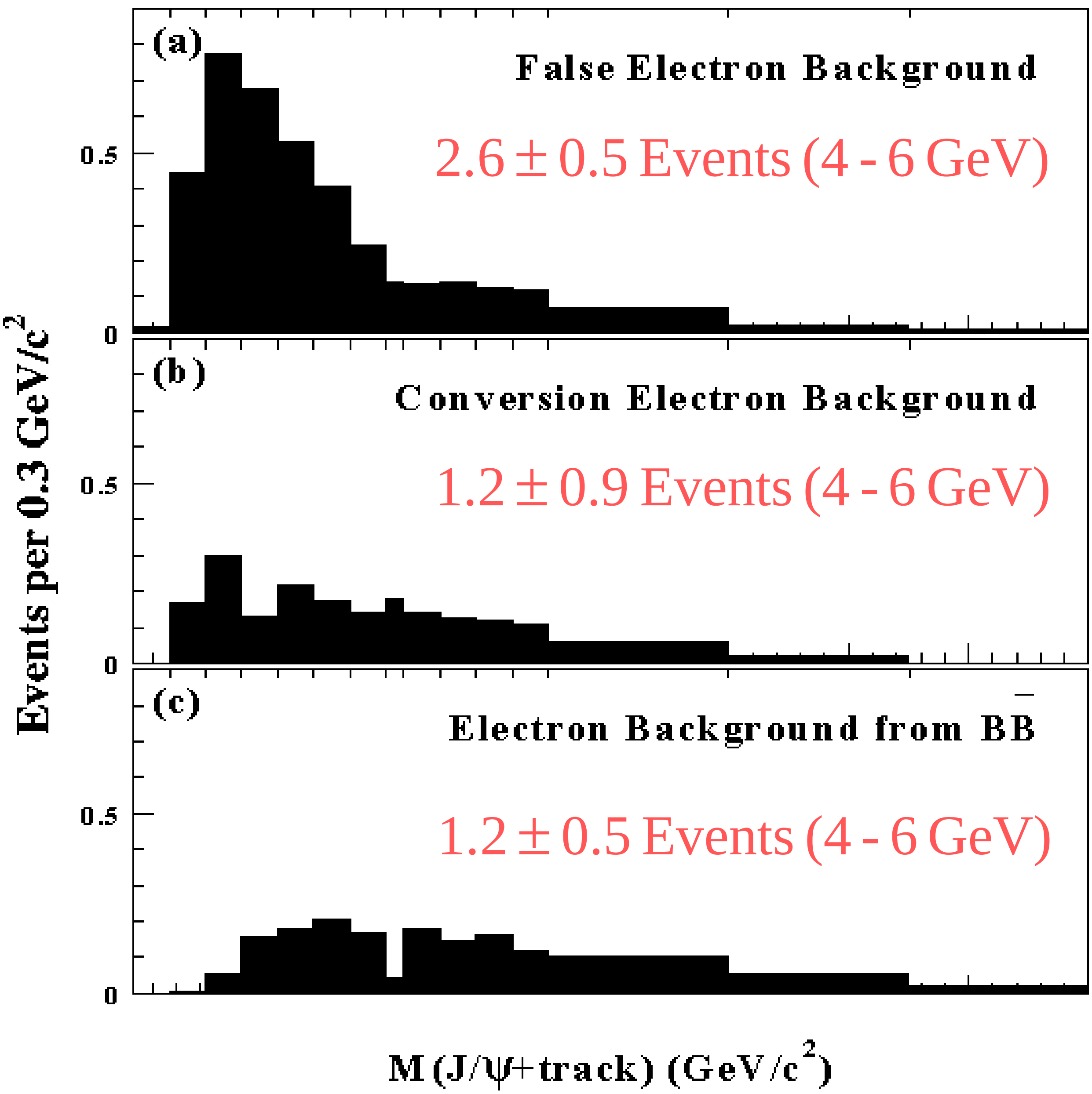
- Apply fake rate to *J/y* + track events

$$2.6 \pm 0.5 \text{ Events } (4 - 6 \text{ GeV})$$

Background: $B\bar{B}$

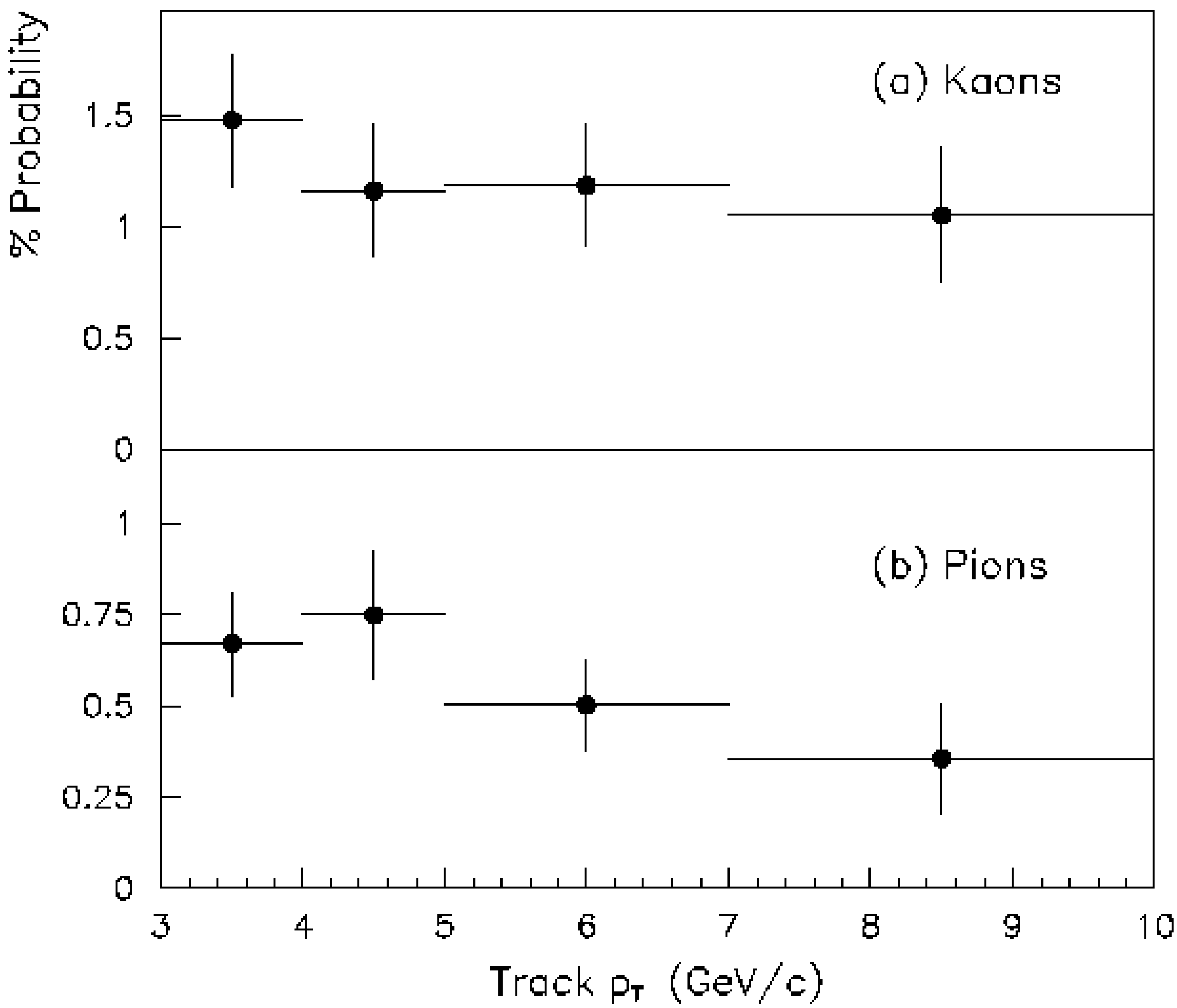
- **Monte Carlo Study**
  - $B \to J/\psi\ X,\ \bar{B} \to X\ell\nu$
  - **Use CLEO decay model (QQ)**
  - **Normalize to $B \to J/\psi\ K$**
  - **Expect 1.2±0.5 Events**

Electron Backgrounds



mBackground: Decay-in-flight

- **Full simulation of track reconstruction for** *B→J/y X* **events**
- **Fake-rate parameterized vs.** p_T
- *K*/p **rates from dE/dx:** f_{p}**= 0.56±0.04**
- **Expect 5.5±1.4 events in 4<***M(J/y* m*)***<6** *GeV*

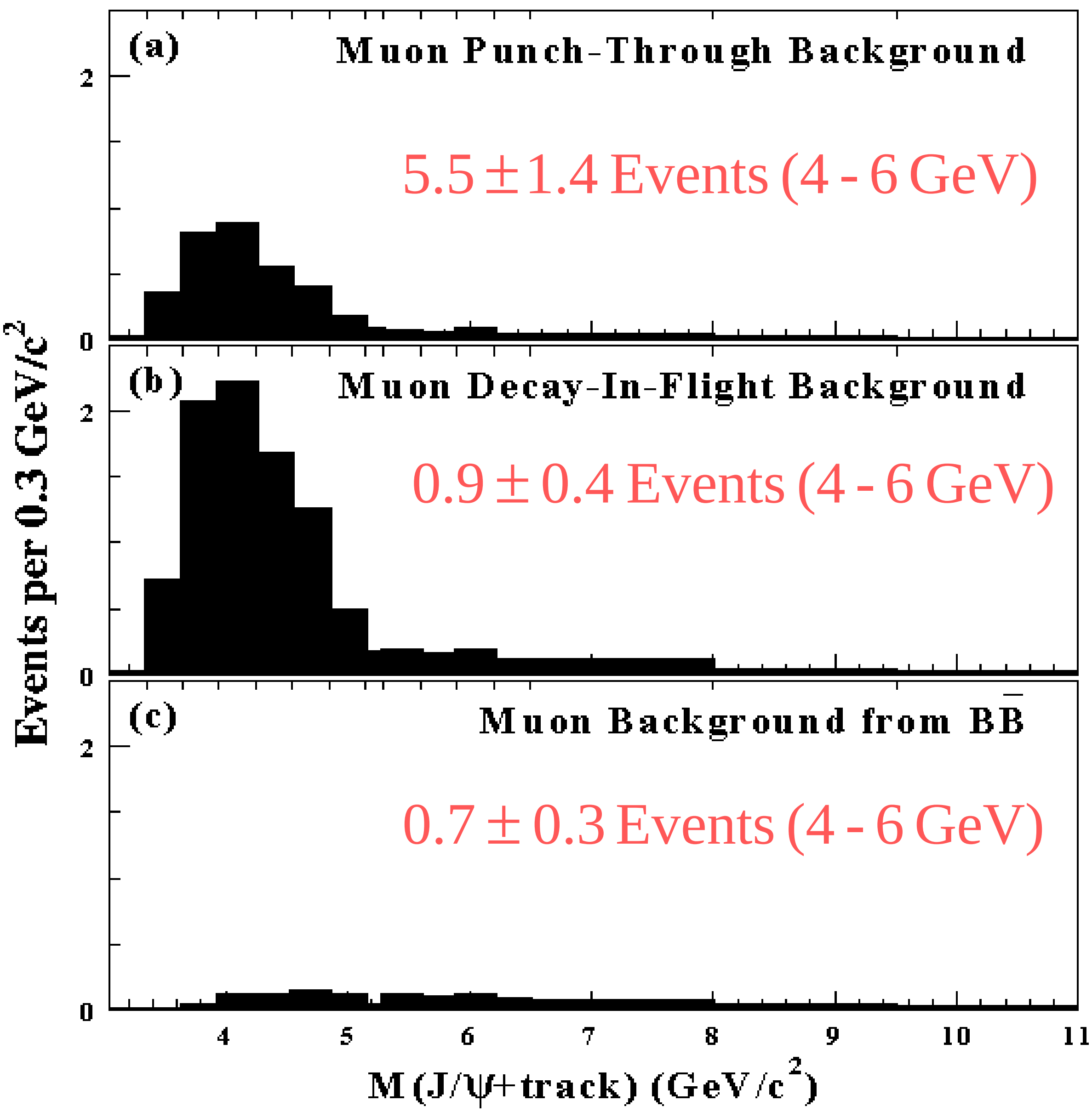


$$0.9 \pm 0.4 \text{ Events } (4 - 6 \text{ GeV})$$

Punch-through Background

- **Some hadrons can pass through calorimeter and filtering steel without interacting**
- **Calculate probability per track**
  - **Use measured absorbtion cross sections for** K^+, K^-, π^-
  - **Account for energy loss in steel**
  - **Apply fake rate to** J/ψ **+ track events: expect**
    0.9±0.4 events
- $\mathbf{B\bar{B}}$ **backgrounds as for** $J/\psi\ e$
  - **0.7±0.3 events**

Muon Backgrounds



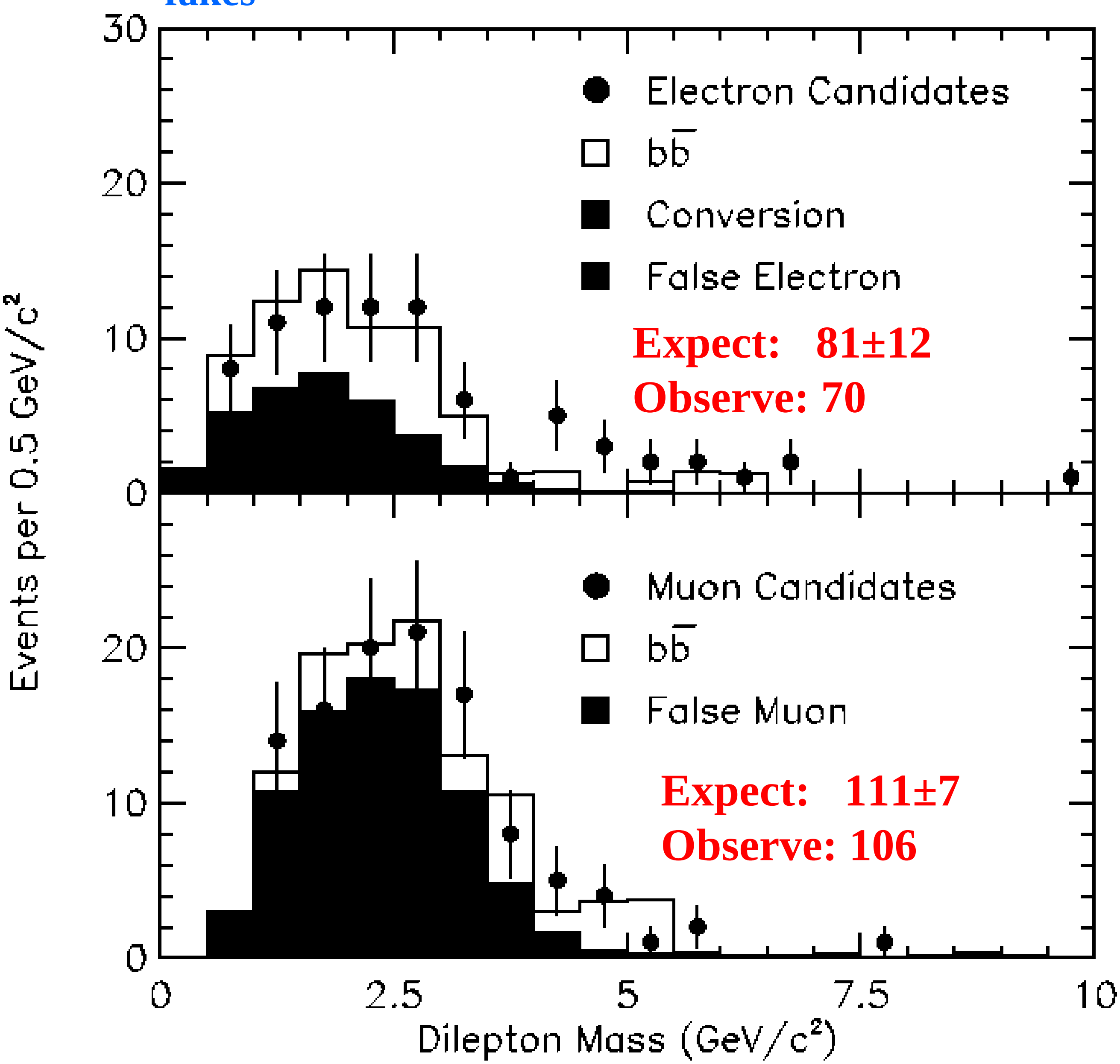
Event Yields: $4<M(J/\psi\ \ell)<6$ GeV

	$J/\psi\ e$ results	$J/\psi\ \mu$ results
Misidentified leptons		
False Electrons	2.6 ± 0.05 ± 0.3	
Conversions	1.2 ± 0.8 ± 0.4	
Punch-through		0.88 ± 0.13 ± 0.33
Decay-in-flight		5.5 ± 0.5 ± 1.3
$B\bar{B}$	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

$N(B_c)=18.9\pm5.6$ Events

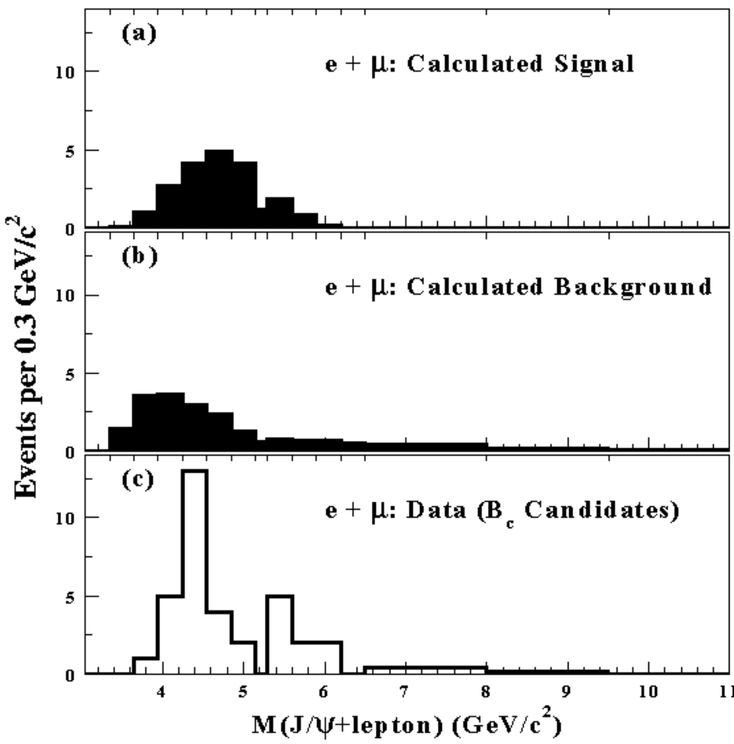
Background Check

- **Check fake rate calculations in orthogonal sample:**
  - **High-p_T single lepton triggers**
  - **Enrich *b* content by requiring secondary vertex**
  - **Same-sign leptons with $M_{\ell\ell}$<5 *GeV* are a sample of pure fakes**



Significance

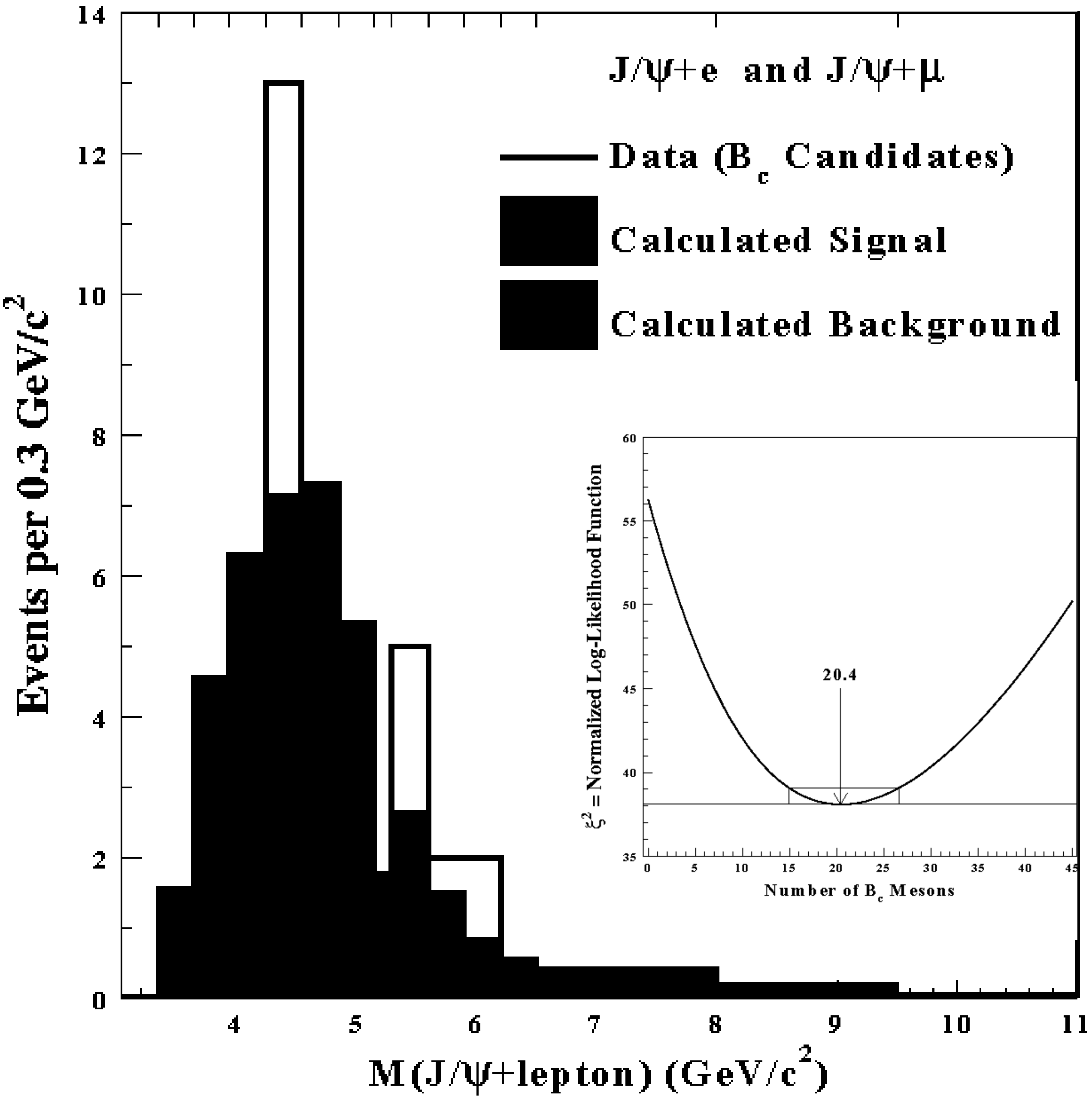
- Simple counting neglects features of data
  - Different shapes expected for signal and background
  - Expected ratio of efficiencies for electron and muon modes



- Construct likelihood fit
  - Gaussian constraints for background normalizations
  - Poisson constraints for shapes from J/ψ+track sample
  - Gaussian constraint on relative signal yields
  - Poisson constraint on number found conversions (2)
  - Assume $M(B_c)$=6.27 GeV
  - Binned, normalized
    - $\chi^2 = -2\, ln(L/L_0)$

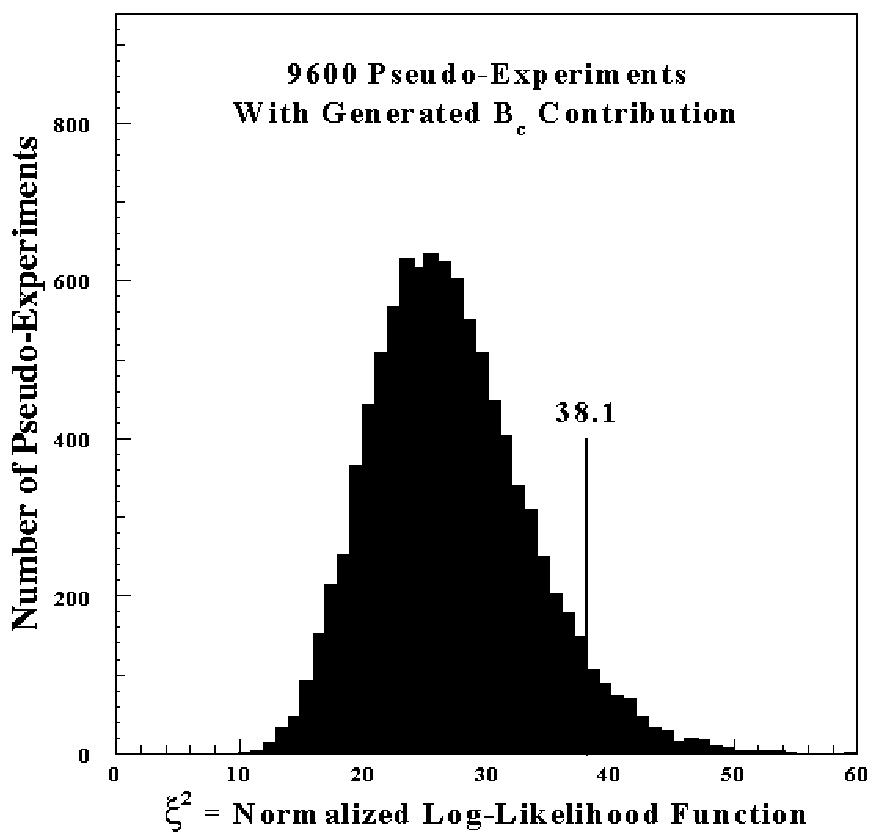
Fit Results

$N(B_c) = \mathbf{20.4^{+6.2}_{-5.5}}$ **Events**



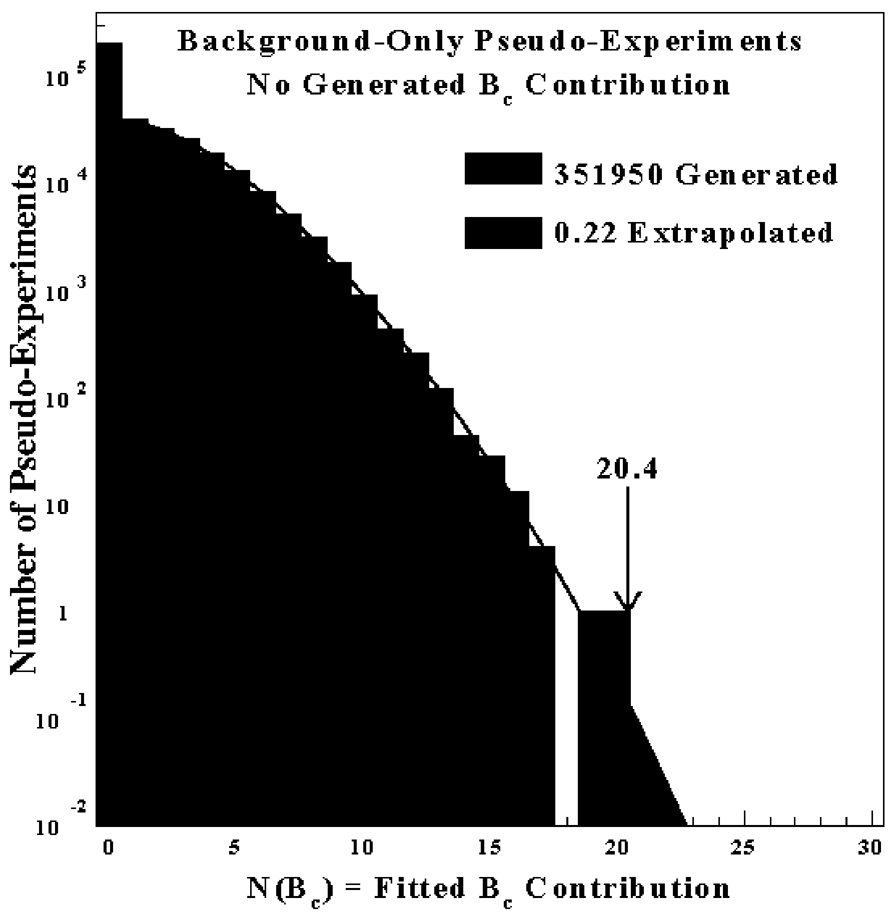
Test Fit Quality

- **Monte Carlo Procedure**
  - **Samples with statistical properties similar to data**
  - **Vary normalization of signal and backgrounds within measured uncertainties**
  - **Add yields and include Poisson fluctuations bin-by-bin**
  - **Fit using standard procedure**
  - **5.9% of trials have ξ^2> 38.1**



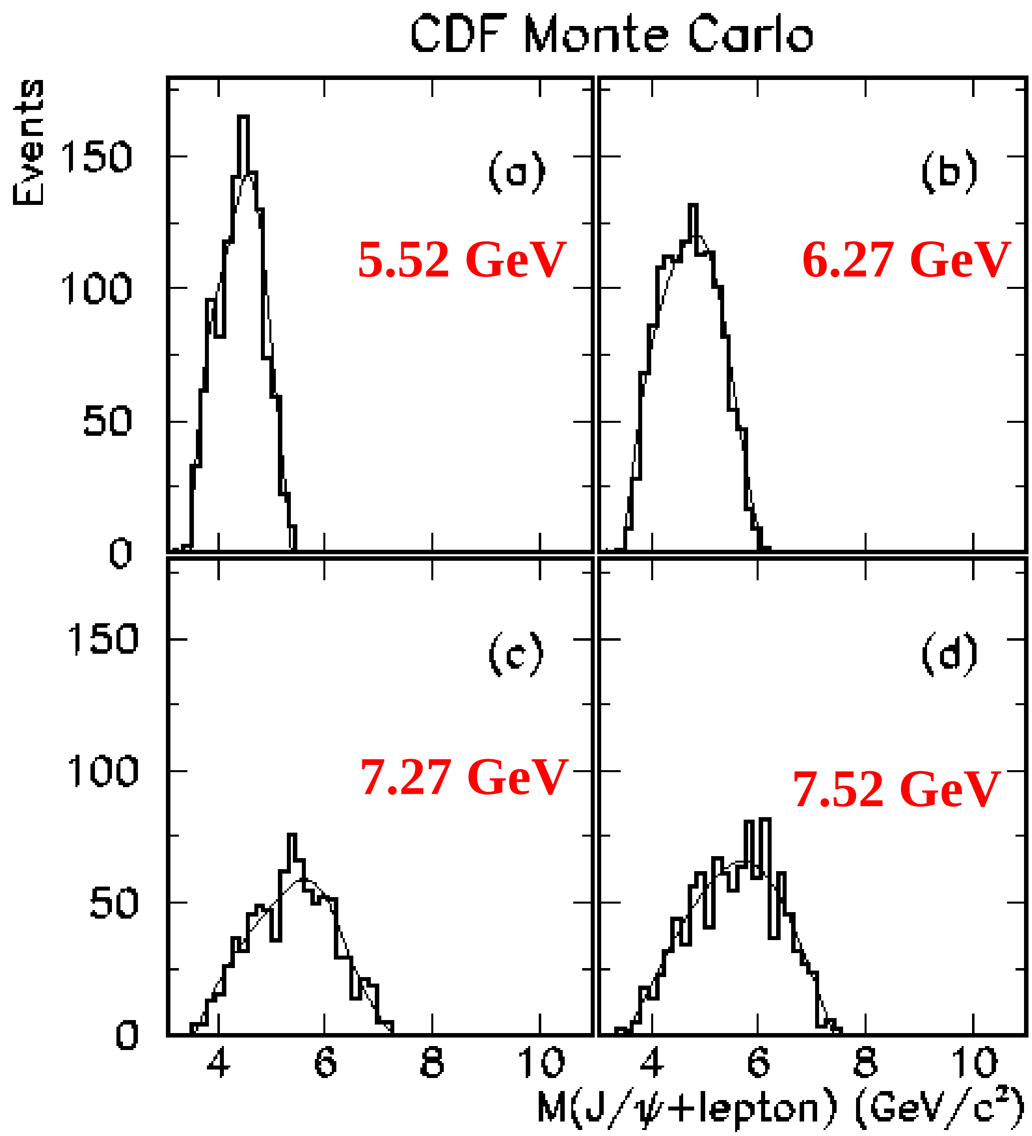
Null Hypothesis

- Repeat Monte Carlo trials with no B_c
- Tests whether data can be described by background alone
- In 351900 Trials, none has a B_c yield as large as 20.4
- Extrapolate to find probability of pure background fluctuation: **0.6×10^{-6}**



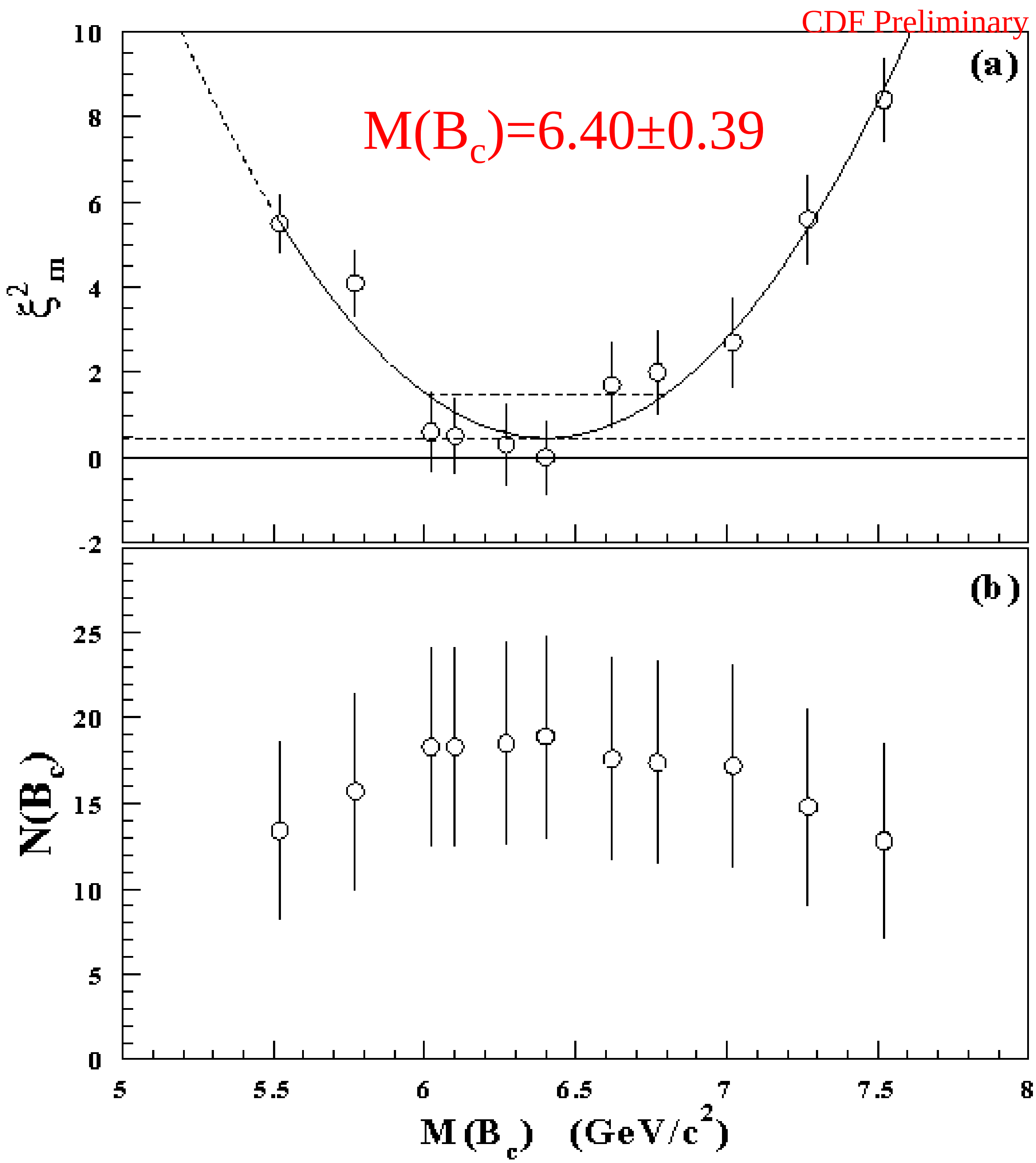
Mass Fit, 1

- **Create templates for various masses**
  - **Smooth with spline fit**



Mass Fit, 2

- **Spline fit to background shapes**
- **Unbinned likelihood fit**



Mass Fit, 3

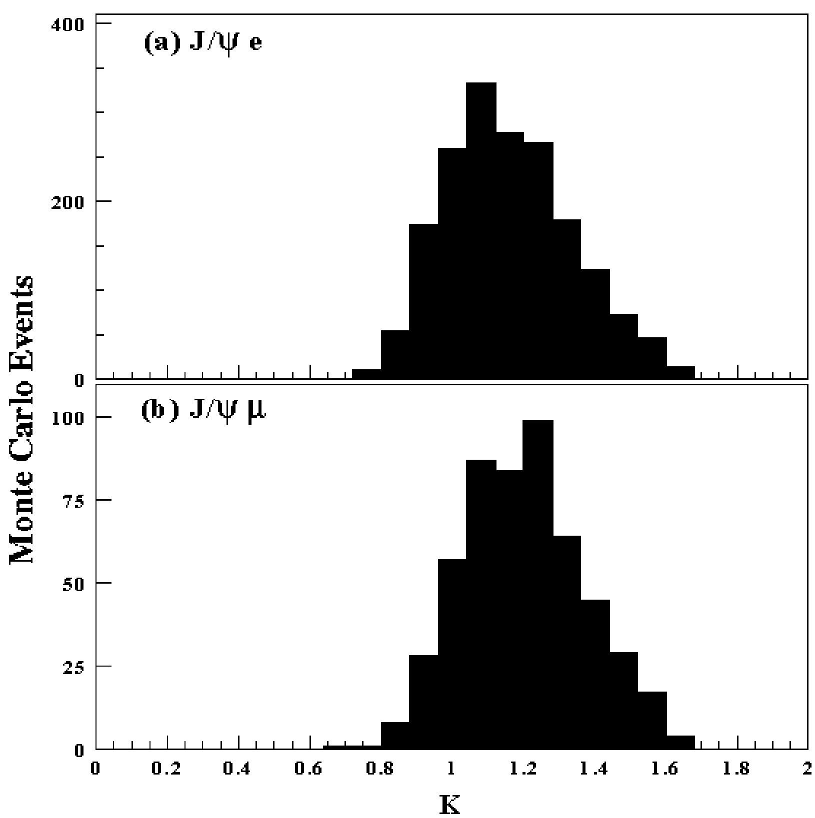
- **Systematic Uncertainties**
  - **Feed-down from higher-mass charmonium: 0.09** *GeV*
  - **Fitting procedure (difference from binned fit): 0.08** *GeV*
  - **Template Statistics: 0.04** *GeV*
  - **Variation in *b*-quark spectrum: 0.02** *GeV*
  - **Dimuon trigger: 0.02** *GeV*

$$\boxed{M(B_c) = 6.40 \pm 0.39 \pm 0.13\ GeV/c^2}$$

B_c Lifetime

- **Release ct^* cut and fit in this variable**
- **Require 4<$M(J/\psi\ \ell)$<6 GeV**
- $ct = L/\beta\gamma = (M/p_T)L_{xy}$
- **"K-factor" must be included to correct between observed mass and momentum to true value**

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



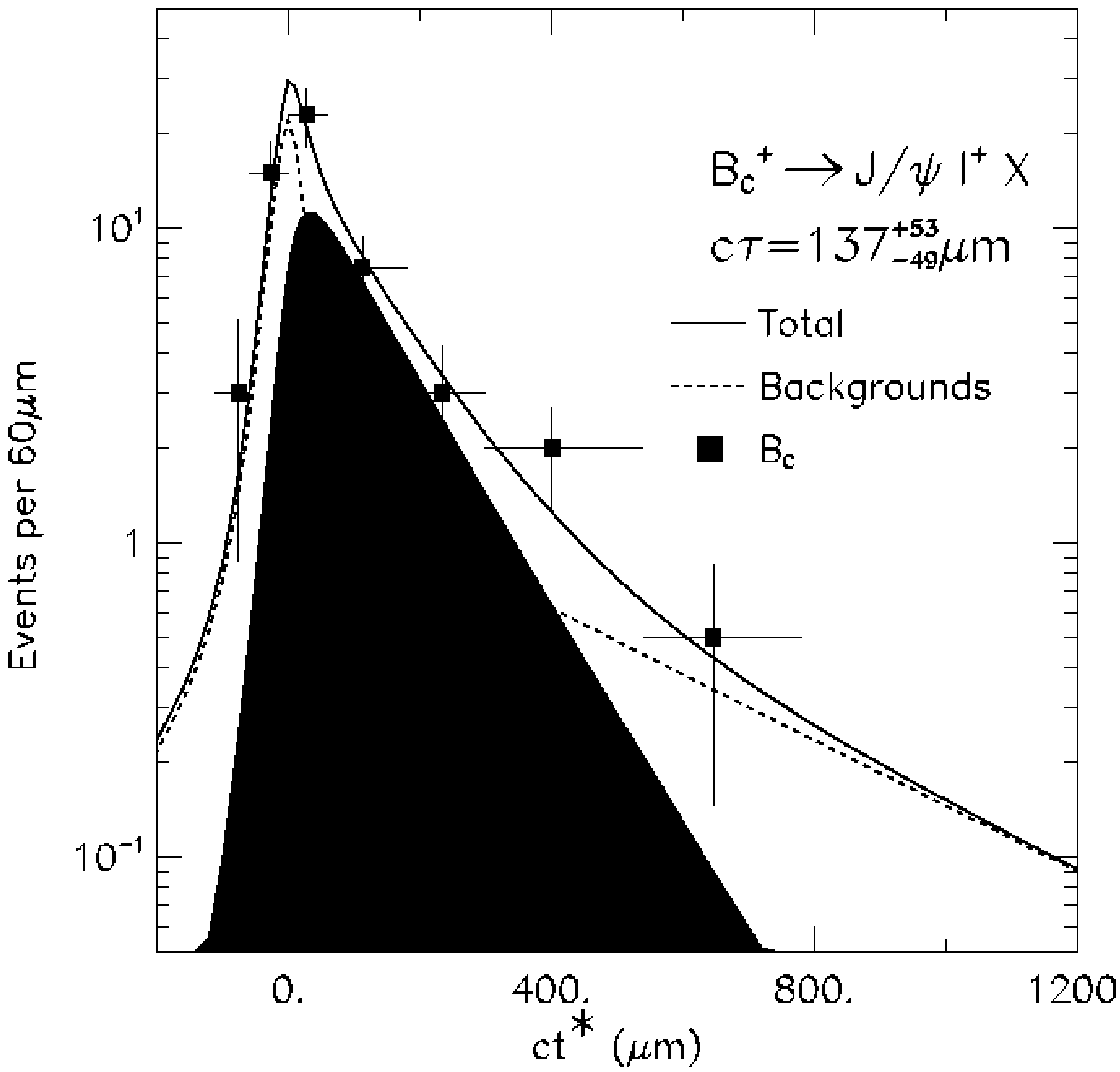
B_c Lifetime, Backgrounds

- Weight J/ψ + track events using same procedures to determine backgrounds vs. *ct**
- Three components:
  - Prompt Gaussian peak
  - Short exponential tail to negative lifetimes
  - Long exponential tail to positive lifetimes

$$F^j(x) = (1 - f_+^j - f_-^j)G(x; s\sigma) + \frac{f_+^j}{\lambda_+^j}\Theta(+x)\exp\left(-\frac{x}{\lambda_+^j}\right)G(x; s\sigma) + \frac{f_-^j}{\lambda_-^j}\Theta(-x)\exp\left(+\frac{x}{\lambda_-^j}\right)G(x; s\sigma)$$

Lifetime Fit Results

- **Combined fit**



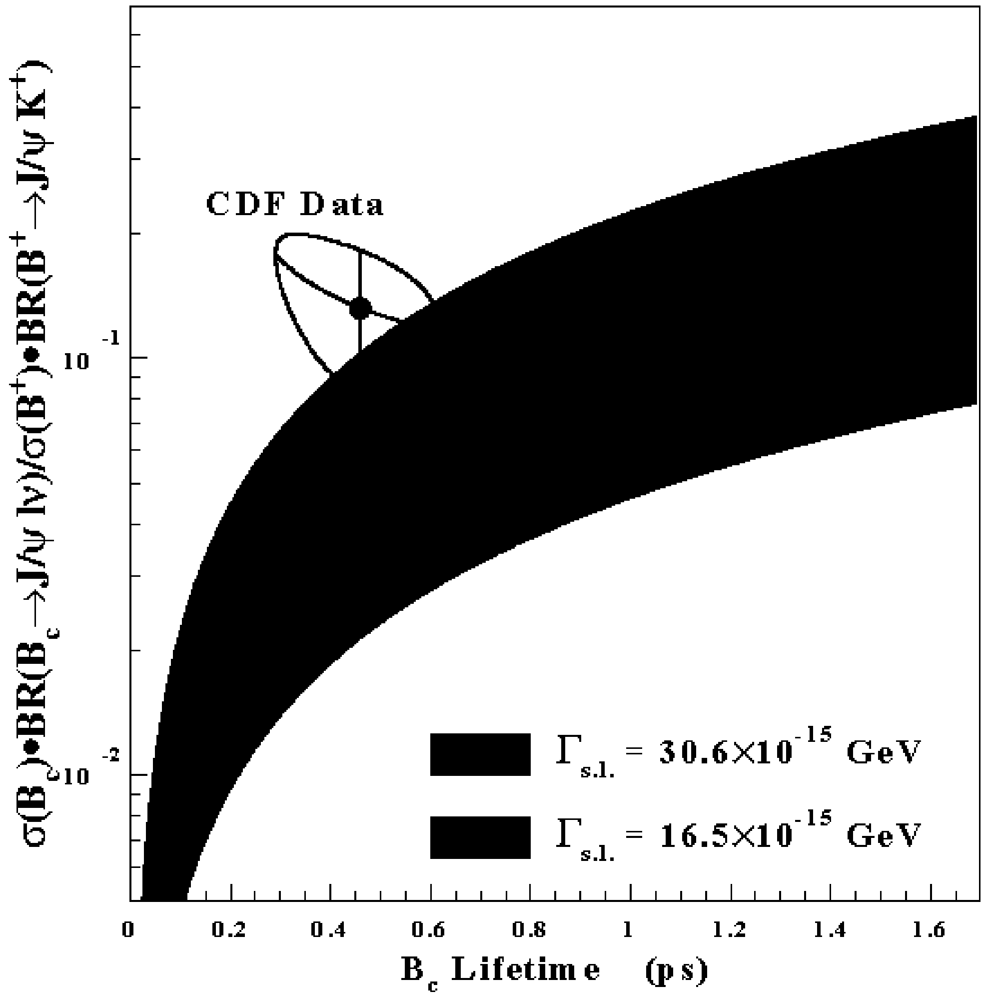
B_c Production

- **Measure production rate relative to similar reference mode $B^+ \to J/\psi\ K^+$**
  - **Identical selection procedure**
  - **Absolute normalization external to measurement**
- **Requires limited information**
  - **Yield from fit**
  - **Relative efficiency vs. B_c lifetime**
    - Exponential dependence
  - **Correction for other modes**
    - $\psi(2S)\ell\nu$, $J/\psi\ D_s$, $J/\psi\ \tau$
    - Correction factor 0.85±0.15
  - **Yield from** $B^+ \to J/\psi\ K^+$ (290±19 Events)

$$\frac{\sigma(B_c^+)\cdot Br(B_c^+ \to J/\psi\ \ell^+\nu)}{\sigma(B^+)\cdot Br(B^+ \to J/\psi\ K^+)} = 0.132^{+0.041}_{-0.037} \pm 0.031^{+0.032}_{-0.020}$$

Uncertainties: Statistical, Systematic and lifetime

B_c Production



- **Theory bands assume**
  - $V_{cb} = 0.041 \pm 0.005$
  - $\sigma(B_c^+)/\sigma(b) = 1.3\times10^{-3}$
  - $\sigma(B^+)/\sigma(b) = 0.378 \pm 0.022$
  - $Br(B^+\to J/\psi\, K^+) = 1.01 \pm 0.14) \times 10^{-3}$

Comparison with LEP Results

Experiment	final state (f.s.)	R(f.s.)
DELPHI	$J/\psi\ \pi^+$ $J/\psi\ \ell^+\nu$ $J/\psi\ \pi^+\ \pi^-\ \pi^+$	< (0.9 to 0.7) (90% C.L.) < (0.5 to 0.4) (90% C.L.) < 1.5 (90% C.L.)
OPAL	$J/\psi\ \pi^+$ $J/\psi\ a_1^+$ $J/\psi\ \ell^+\nu$	< 0.6 (90% C.L.) < 0.3 (90% C.L.) < 0.4 (90% C.L.)
ALEPH	$J/\psi\ \pi^+$ $J/\psi\ \ell^+\nu$	< 0.2 (90% C.L.) < 0.3 (90% C.L.)
CDF	$J/\psi\ \pi^+$ $J/\psi\ \ell^+\nu$	< (0.15 to 0.04) (95% C.L.) $0.132^{+0.041}_{-0.037} \pm 0.031^{+0.032}_{-0.020}$

Note: The ranges quoted for DELPHI and for CDF in $J/\psi\ \pi$ correspond to the assumed B_c lifetime range 0.4 to 1.4 ps.

- **OPAL and DELPHI combined have 4 $B_c^+ \rightarrow J/y\ p^+$ Candidates**
  - M=6.33±0.05 GeV
  - $\tau=0.28^{+0.10}_{-0.20}$ ps

Summary

- **CDF has observed the** B_c
  - **Significance over background >4.8σ**
  - $ct \;=\; 137^{+53}_{-49} \pm 9mm$
  - $M(B_c)$=**6.40±0.39 ±0.13** GeV/c^2
  - **Production rate consistent with expectation**
  - $s{\times}Br(B_c^{+})/\, s{\times}Br(B^{+}) = \; 0.132^{+0.060}_{-0.052}$
  - **Expect >40× increase in** B_c **yield for Run 2**
- **Prospects for Run II**
  - **The** $\mathbf{B_c}$ **will be studied in the fully reconstructed modes.**
    - **Precise mass and lifetime measurements.**