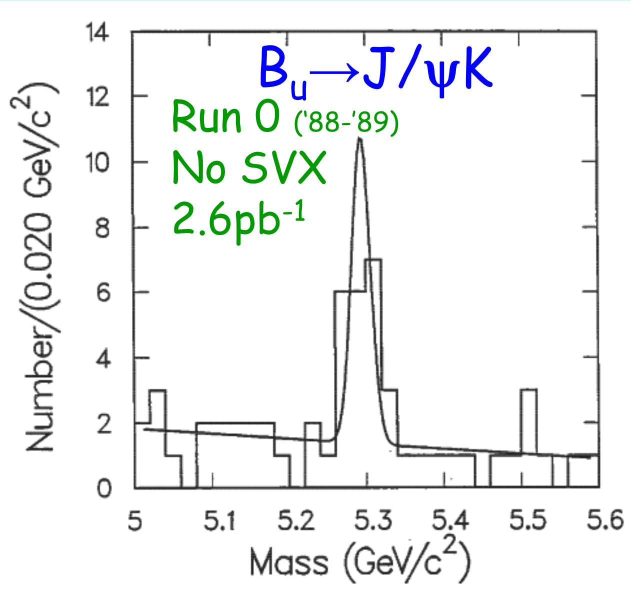
Bc and Suppressed Bs Decays at CDF

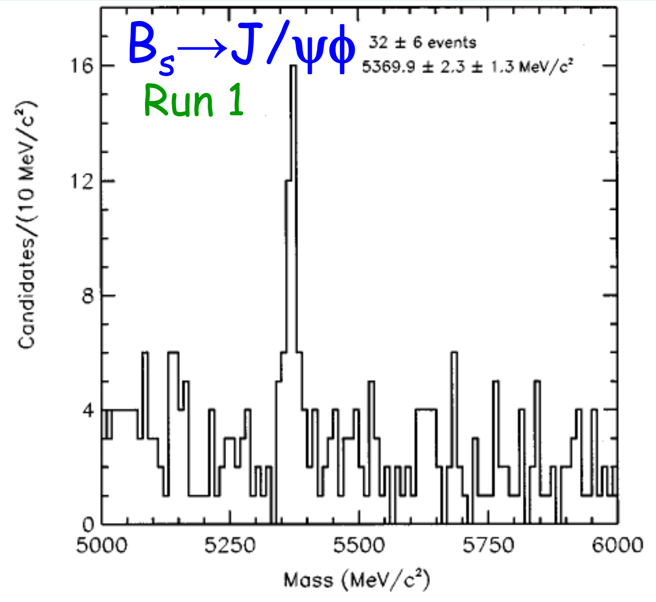
William Wester
Fermilab
for the CDF Collaboration

Very early and early CDF

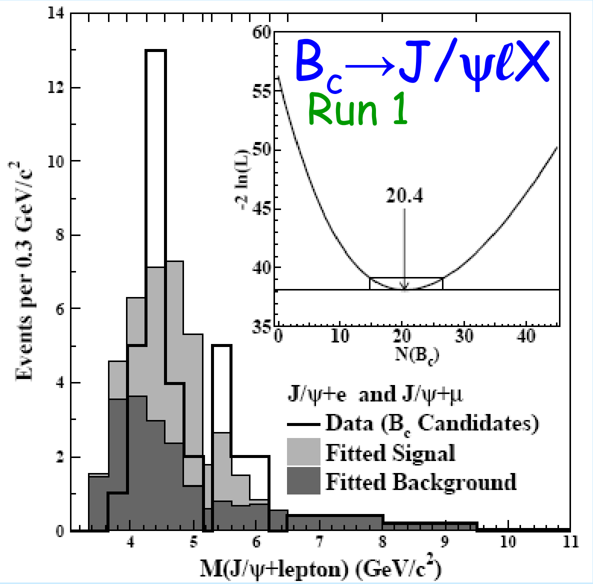
- Run 0 ('88-'89) ($4pb^{-1}$) saw the first sizable $J/\psi \rightarrow \mu^+\mu^-$ used to fully reconstruct B hadron decays
- Run I ('92-'96) ($110\ pb^{-1}$) added silicon with highlights including the observation of exclusive Bs->$J/\psi\phi$ and a first hint of Bc in semileptonic decays



PRL 68, 3403 (1992)



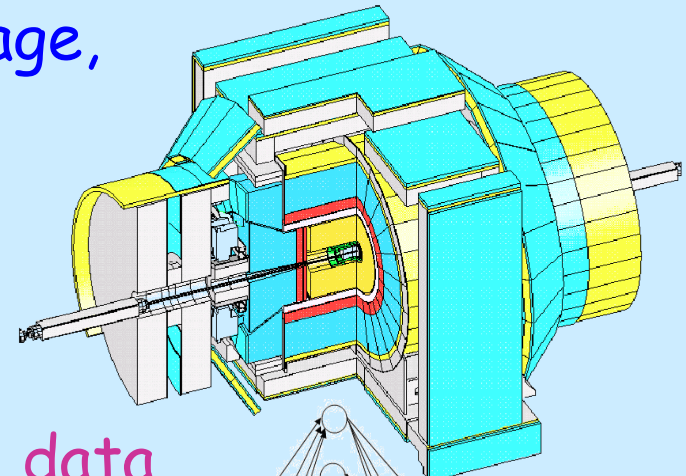
PRD 53, 3496 (1996)

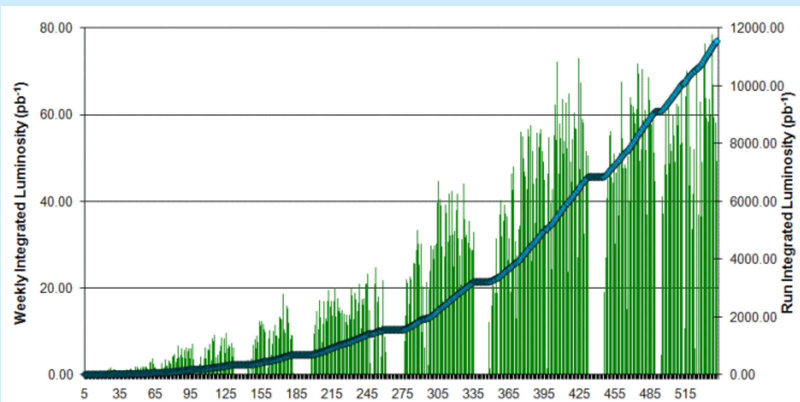


PRL 81, 2432 (1998)
PRD 58, 112004 (1998)

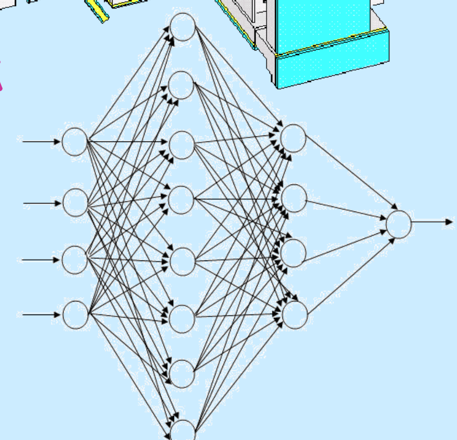
Advances in Run II for CDF in B Physics

Improved silicon, tracking, muon coverage, particle ID, L1 track and L2 displaced vertex triggers





Much more accumulated data over ~10 years

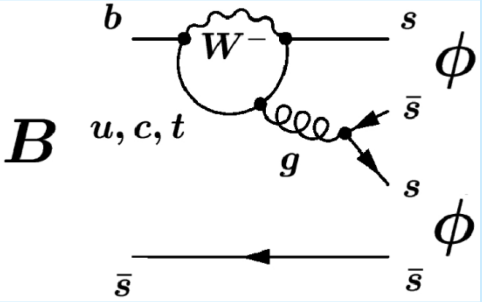


Improved analysis techniques

Study of production, decay, and properties give insight into the strong interaction, weak interaction, and possibilities of new physics

Bs→ϕϕ Reconstruction and BR Measurement

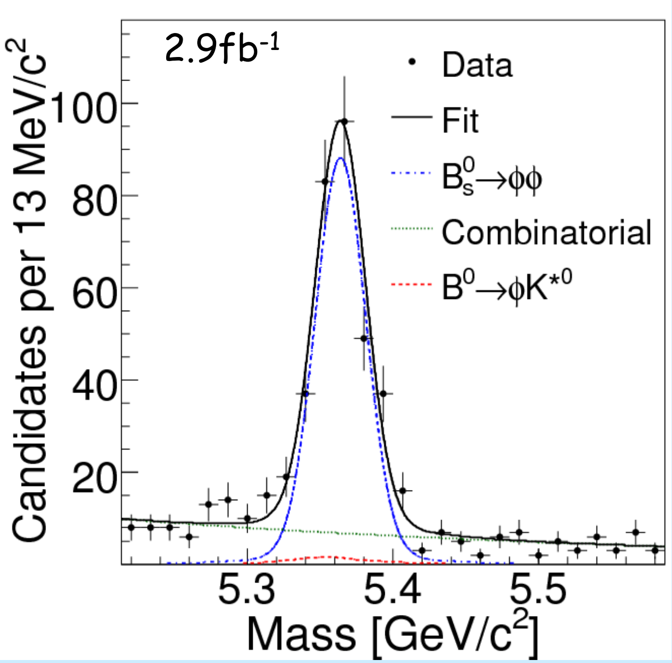
- Use 2.9fb^{-1} data collected with the two-track displaced vertex trigger
  - 2 tracks P_T>2 GeV/c with 120μm<d_0<2mm, opening angle 2°<|Δϕ|<90°, L_{xy}>200μm
  - $P_{T1}+P_{T2}$ > 4 – 6.5 GeV
- Optimized selection gives about 300 Bs→ϕϕ. Use MC for rel. eff.



$B_s \longrightarrow \phi\phi$ Variable	cut
L_{xy}	$> 330\mu m$
$P_T^{K\ min}$	> 0.7 GeV/c
χ^2_{xy}	< 17
d0(B)	$< 65\mu m$
$d0^{\phi}_{max}$	$> 85\mu m$

$B_s \longrightarrow J/\psi\phi$ Variable	cut
L_{xy}	$> 290\mu m$
P_T^{ϕ}	> 1.36 GeV/c
χ^2_{xy}	< 18
d0(B)	$< 65\mu m$
$P_T^{J/\psi}$	> 2.0 GeV/c

$|M_{KK}-M_{\phi}|<15MeV$



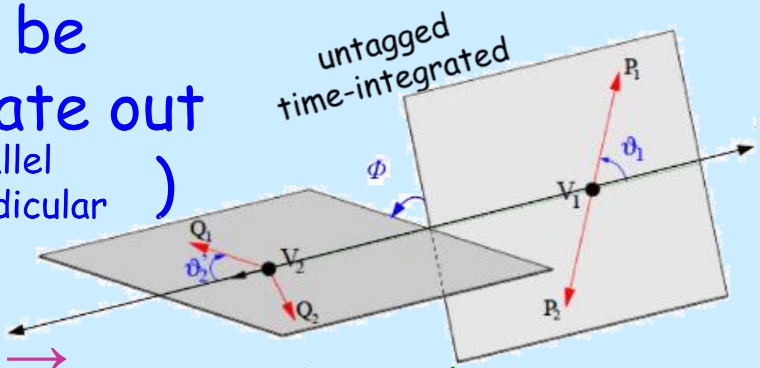
- Determine BR relative to Bs→J/ψϕ

$$\mathscr{B}(B_s \to \phi\phi) = [2.40 \pm 0.21(stat.) \pm 0.27(syst.) \pm 0.82(BR)] \times 10^{-5}$$

M. Dorigo, et al., arXiv:1107.4999

Bs→ϕϕ Polarization

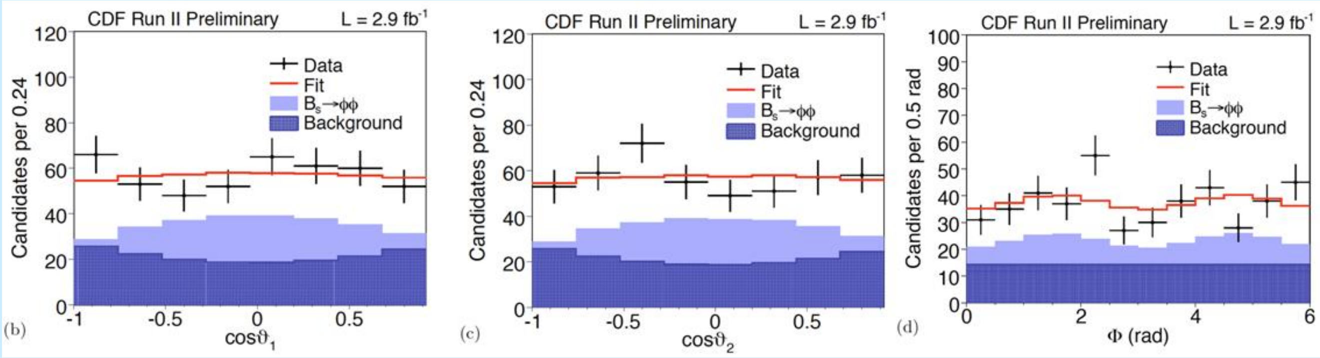
- Bs→ϕϕ is a PS → VV decay that can be analyzed in a helicity basis to separate out 3 amplitudes: 2 transverse ($^{\text{spins parallel}}_{\text{spins perpendicular}}$) and 1 longitudinal polarization



- Observable angles in Bs rest frame → helicity angles and polarization fractions

No single strong systematic

Cross check with Bs->J/ψϕ



Similar to other Penguin decays in that $f_L \approx f_T$ rather than $f_L \gg f_T$ "Polarization Puzzle"

- Likelihood fit to determine the polarization fractions

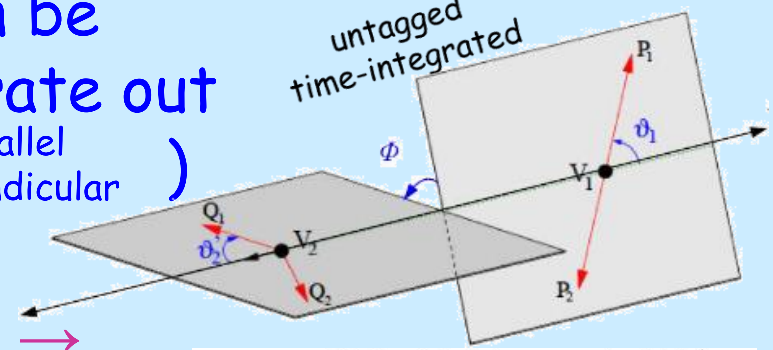
$f_L = 0.348 \pm 0.041\ (\text{stat}) \pm 0.021\ (\text{syst})$

$f_T = 0.652 \pm 0.041\ (\text{stat}) \pm 0.021\ (\text{syst})$

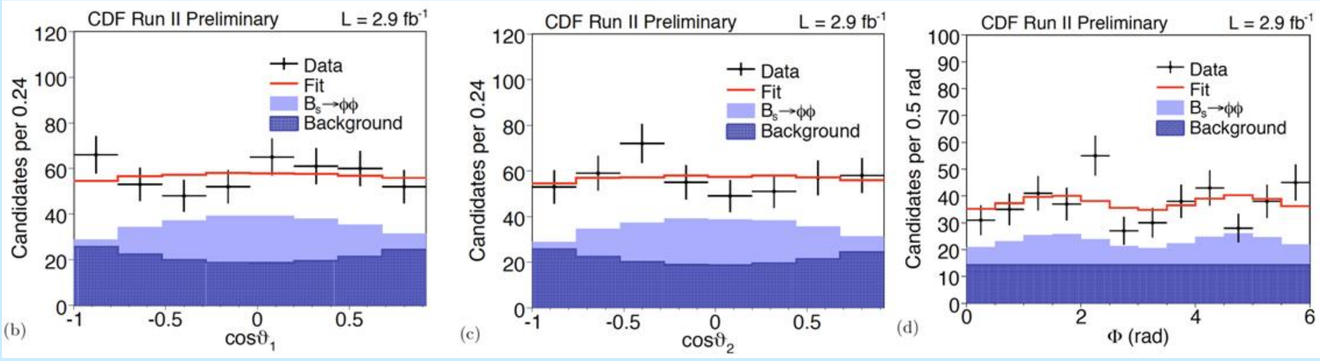
M. Dorigo, et al., arXiv:1107.4999

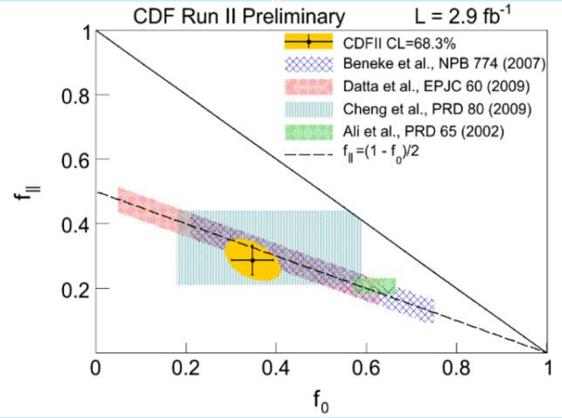
Bs→ϕϕ Polarization

- Bs→ϕϕ is a PS → VV decay that can be analyzed in a helicity basis to separate out 3 amplitudes: 2 transverse (spins parallel / spins perpendicular) and 1 longitudinal polarization



- Observable angles in Bs rest frame → helicity angles and polarization fractions





- Likelihood fit to determine the polarization fractions

M. Dorigo, et al., arXiv:1107.4999

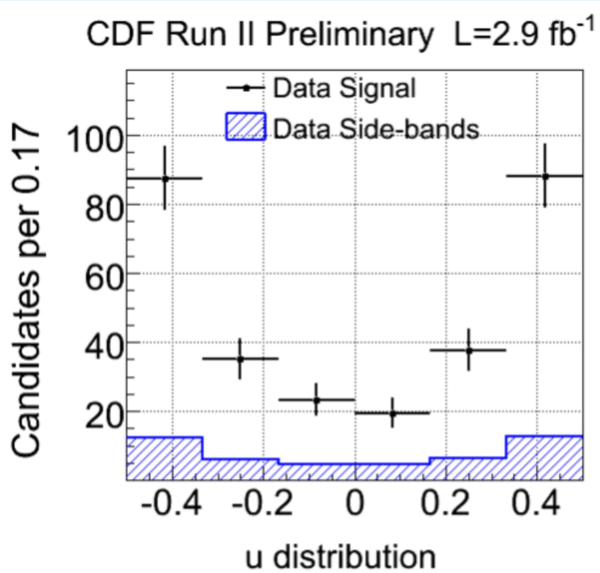
New physics or strong interaction effect?

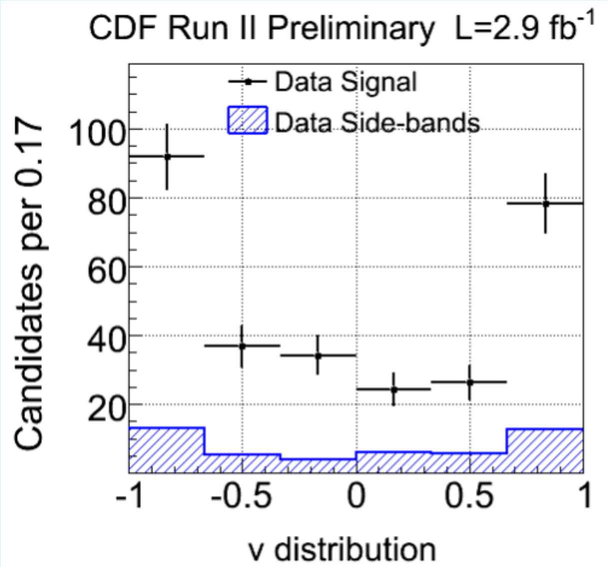
f_L = 0.348±0.041 (stat) ±0.021 (syst)

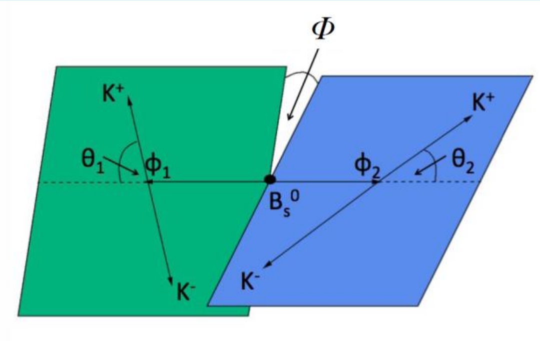
f_T = 0.652±0.041 (stat) ±0.021 (syst)

Bs→φφ, T-violating triple products asymmetries

- Triple products, $\vec{p} \times (\vec{\varepsilon_1} \times \vec{\varepsilon_2})$, are odd under T and thus have asymmetries sensitive to CP violation and possibly new physics.
- For $\Im(A_{\parallel} A_{\perp}^{\star})$, define u=cosΦ sinΦ with N(u>0) and N(u<0) and for $\Im(A_0 A_{\perp}^{\star})$, define v= sinΦ in bins of $\cos\theta_1 \cos\theta_2$







Main systematics include possible reflection or other B decay bkgds and the modeling of the combinatorial bkgd.

A_u = -0.007±0.064 (stat) ±0.018 (syst)

A_v = -0.120±0.064 (stat) ±0.016 (syst)

SM predicts 0

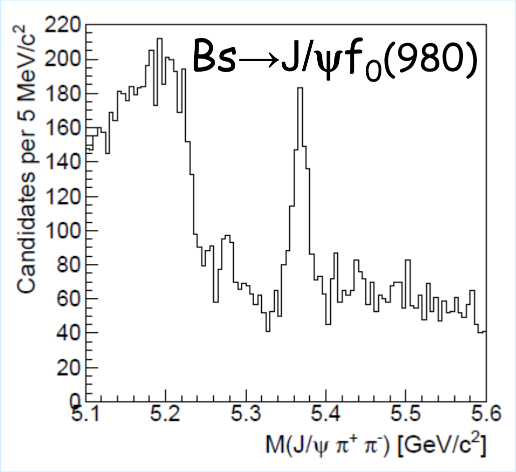
M. Dorigo, et al., arXiv:1107.4999

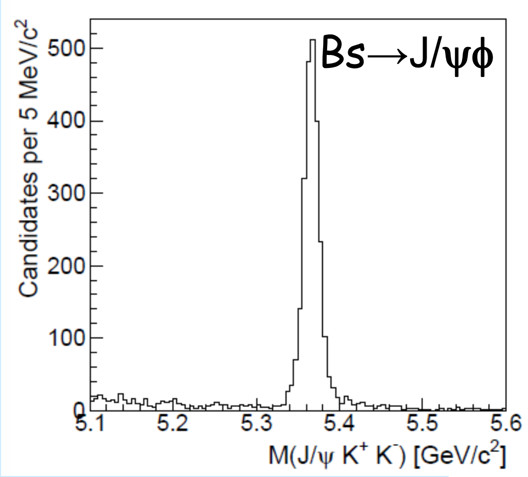
Bs→J/ψ f_0(980) Relative BR

- The decay Bs→J/ψf_0(980) is CP-odd and can be used with high enough statistics to look for CP violation in Bs

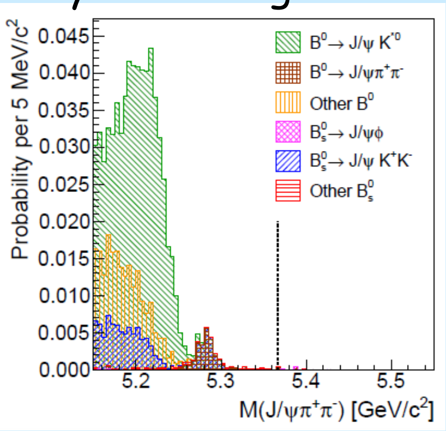
More details two talks hence, B. Abbott from D0

- The decay has only recently been observed by LHCb, Belle, CDF, and D0
- Neural Net selection using 3.8 fb^{-1}





Physics backgrounds



- Measure BR and relative fraction of Bs decay

$$R_{f_0/\phi} = \frac{\mathcal{B}(B_s^0 \to J/\psi f_0)}{\mathcal{B}(B_s^0 \to J/\psi \phi)} \frac{\mathcal{B}(f_0 \to \pi^+\pi^-)}{\mathcal{B}(\phi \to K^+K^-)}$$

$$\mathcal{B}(B_s^0 \to J/\psi f_0(980))\mathcal{B}(f_0(980) \to \pi^+\pi^-) = (1.63 \pm 0.12 \pm 0.09 \pm 0.50) \times 10^{-4}$$

$$R_{f_0/\phi} = 0.257 \pm 0.020(\text{stat}) \pm 0.014(\text{syst})$$

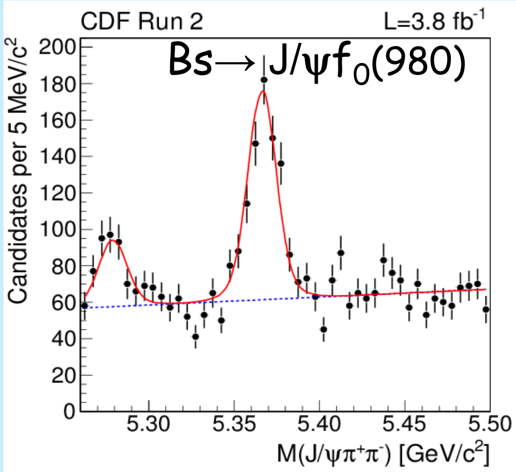
M. Fendt et al., arXiv:1106.3682

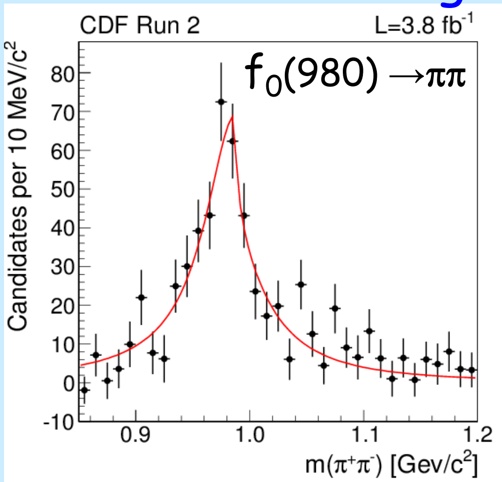
$Bs \to J/\psi\ f_0(980)$ Relative BR

- The decay $Bs \to J/\psi f_0(980)$ is CP-odd and can be used with high enough statistics to look for CP violation in Bs

More details two talks hence, B. Abbott from D0

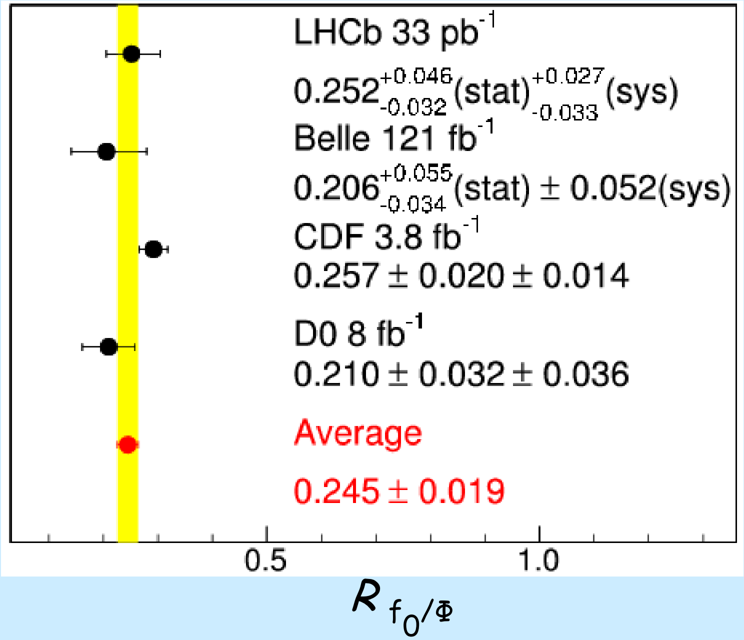
- The decay has only recently been observed by LHCb, Belle, CDF, and D0
- Likelihood fit to determine size of signal





Flatté function
Select on Bs peak then look at M($\pi\pi$)

Comparison of results



- Measure BR and relative fraction of Bs decay

$$\mathcal{B}(B_s^0 \to J/\psi f_0(980))\mathcal{B}(f_0(980) \to \pi^+\pi^-) = (1.63 \pm 0.12 \pm 0.09 \pm 0.50) \times 10^{-4}$$

M. Fendt et al., arXiv:1106.3682

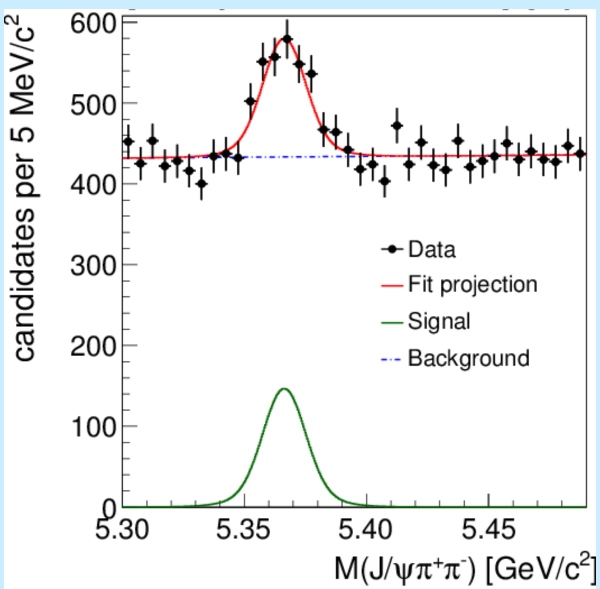
Bs→J/ψf_0(980) Lifetime in CP odd final state

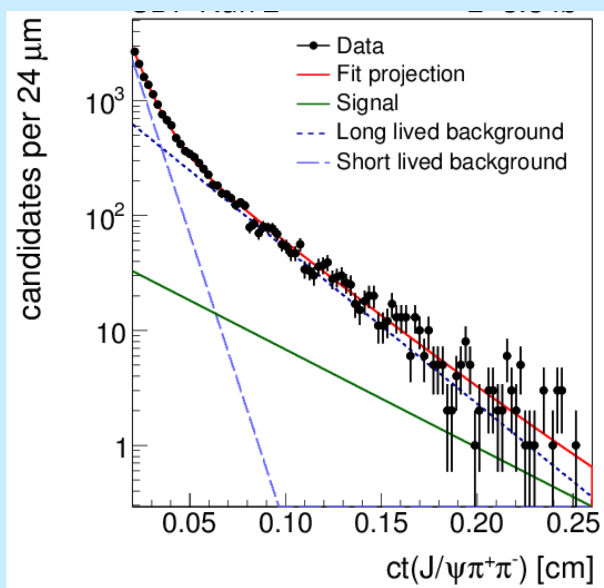
- In SM with no CP violation, the CP-odd lifetime is the lifetime of the heavy Bs state. $\tau_s^H = (1.630 \pm 0.030)$ ps $\tau_s^L = (1.427 \pm 0.023)$ ps. theoretically derived based upon other meas.
- Similar neural net selection using 3.8 fb^{-1} without a decay time variable but add variables such as the dipion mass.
- Fit for lifetime

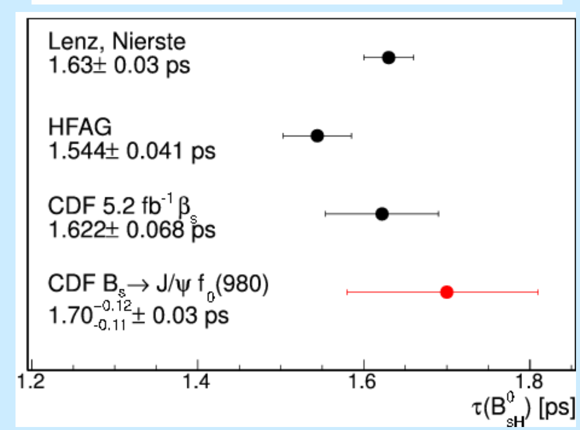
$$\mathcal{L} = \prod_{i=1}^{N} \quad [f_s \cdot P_s(m_i, t_i, \sigma_{ti}) + (1 - f_s) \cdot P_{cb}(m_i, t_i, \sigma_{ti})] .$$

$$\tau(B_s^0 \rightarrow J/\psi f_0) = 1.70^{+0.12}_{-0.11}(\text{stat}) \pm 0.03(\text{syst}) \text{ ps}$$

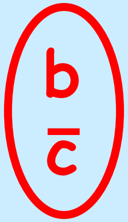
Source	Uncertainty [ps]
Background mass model	0.010
Signal mass model	0.005
Decay time uncertainty scale	(< 0.01)
Background decay time model	0.021
Decay time uncertainty model	(0.015)
SVX alignment	0.007
Total	0.03





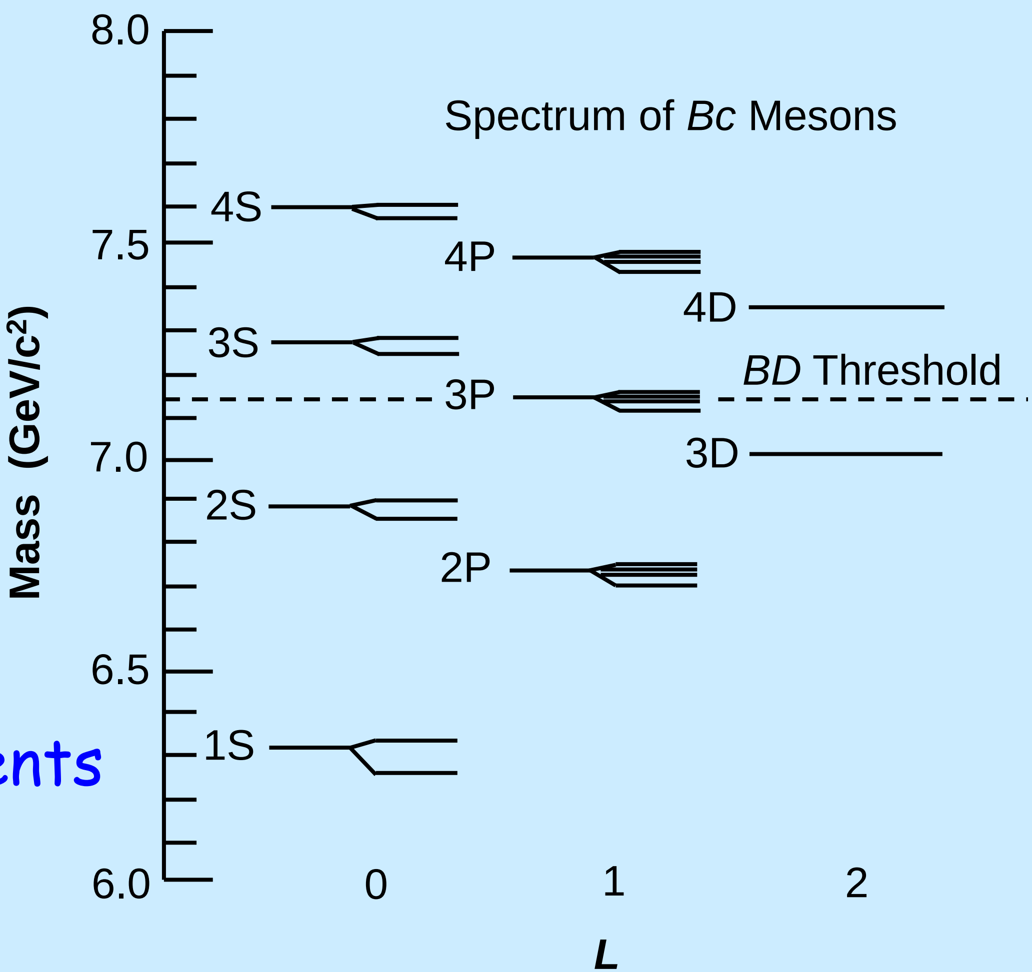


Bc Meson



- *b* quark *c* anti-quark

- Unique with two distinct heavy quarks
- A new bound system in which to make measurements
- CDF, D0, LHCb have observations



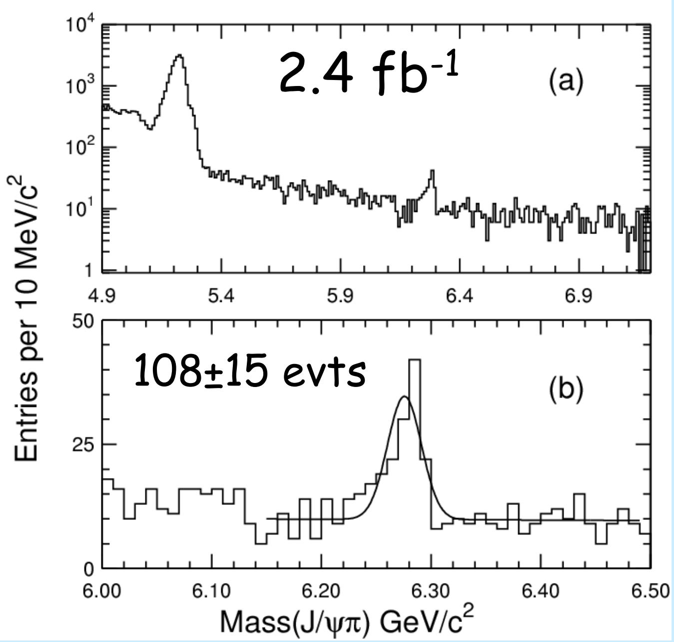
Phys.Rev. D49 5845 (1994)

$B_c \to J/\psi\ \pi$ Mass measurement

- Full reconstruction allows for the mass measurement
- Two pass selection tuned on Bu→J/ψK then look at J/ψπ

Selection variable	Standard	High-p_T
$p_T(Trk)$	>1.7 GeV/c	>2.5 GeV/c
$p_T(J/\psi Trk)$	>5 GeV/c	>6 GeV/c
$P(\chi^2)$	>0.1%	>1%
$\lvert d_{SV}(Trk)\rvert$	<100 μm	<80 μm
$\lvert d_{PV}(Trk)\rvert/\sigma_{d_{PV}(Trk)}$	>2.5	>3
$\lvert d_{PV}(B)\rvert/\sigma_{d_{PV}(B)}$	<2.5	<2
ct	>80 μm	>100 μm
σ_{ct}	<30 μm	<25 μm
β	<0.4 radians	<0.3 radians

If one standard selection requirement is failed, keep event if it passes other High-Pt requirements



PRL 100, 182002, 2008

Systematics include uncertainties in the alignment of tracking detectors, momentum calibration, and fit procedure (scale factor on mass resolution)

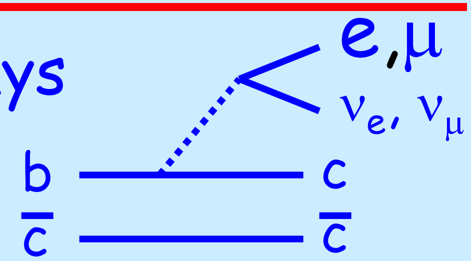
$$6275.6 \pm 2.9(\text{stat}) \pm 2.5(\text{syst})\ \text{MeV}/c^2$$

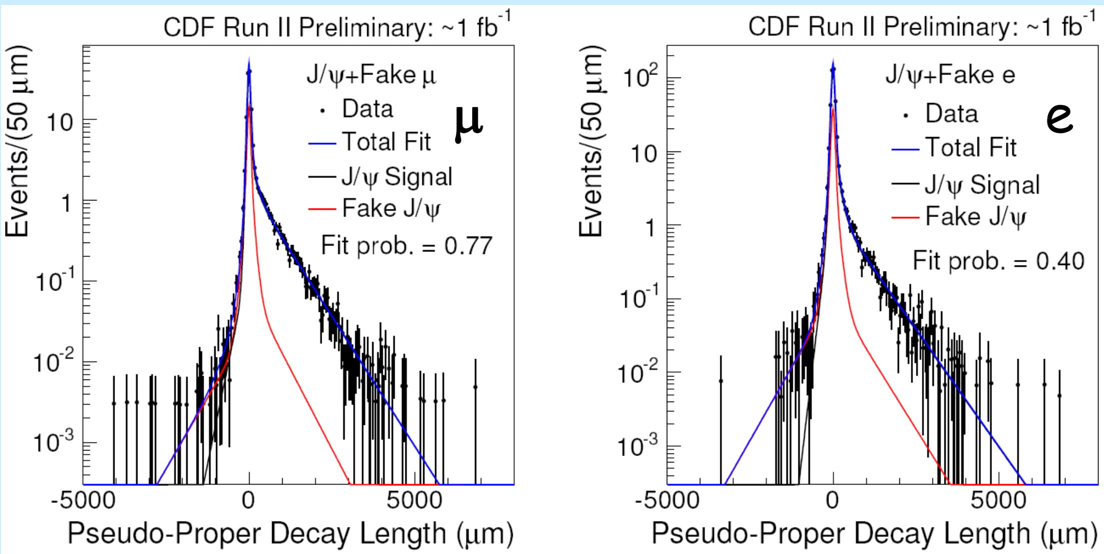
$M(Bc)_{D0}$ = 6300 ± 14 ± 5 MeV/c^2 PRL 101, 012001, 2008

$M(Bc)_{LHCb}$ = 6270.3 ± 1.4 MeV/c^2 (uncalibrated) M. Artuso, EPS 2011

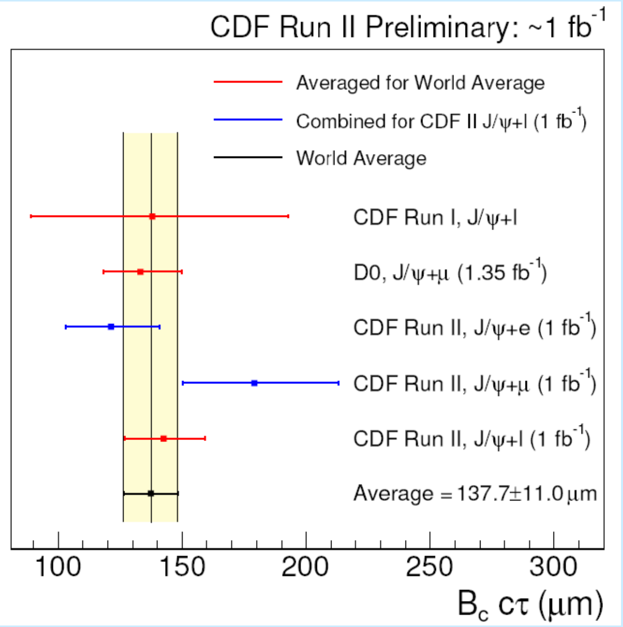
Bc Lifetime measurement

- First determinations from semileptonic decays
- Model backgrounds and missing ν





$$c\tau = 142.5^{+15.8}_{-14.8}\ (\text{stat.}) \pm 5.5\ (\text{syst.})\ \mu\text{m}$$



CDF-PUB-9294

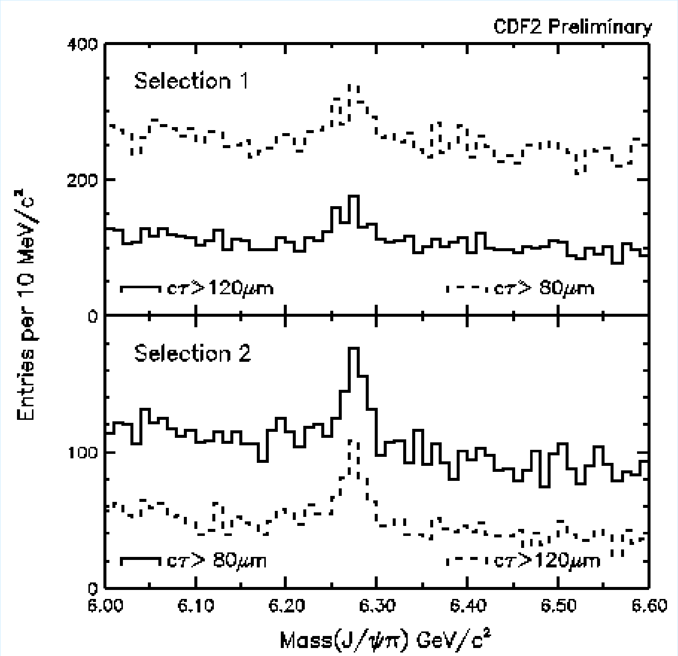
Bc → J/ψ π Lifetime measurement

New Result!

- Use 6.7 fb^{-1} and try two independent approaches
  - Selection 1: no dependence of selection on decay time
    - Fit procedure fixes background determined from sideband region
  - Selection 2: better S/N, but decay time dependence
    - Fit procedure uses sideband background parameters as a Gaussian constraint before fitting signal region
    - Requires MC input on the decay time

      time dependence

Selection variable	selection 1	selection 2
$P_T(\pi)$	> 2.0 GeV/c	> 2.0 GeV/c
$P_T(J/\psi\ \pi)$	> 6.5 GeV/c	> 6.5 GeV/c
$Prob(\chi^2_{\mathrm{CTVMFT}})$	$> 0.01\%$	$> 0.1\%$
$\sigma[M(J/\psi\pi)]$	-	< 40 MeV/c^2
$\sigma[c\tau(J/\psi\ \pi)]$	$< 100\ \mu$m	$< Max[35, 65 - 3 \times P_T(\mathrm{B})\mathrm{GeV}/c]\ \mu$m
2D Pointing angle, β_T	-	< 0.2 radians
$\lvert ip_{\mathrm{signif}}(J/\psi\pi$ wrt p.v.$)\rvert$	$< 2.0\ \sigma$	$< 2.0\ \sigma$
Track isolation (cone=0.7)	>0.6	>0.6
$c\tau_{\mathrm{MIN}}(J/\psi\ \pi)$	$> 120\ \mu m$	$> 80\ \mu m$

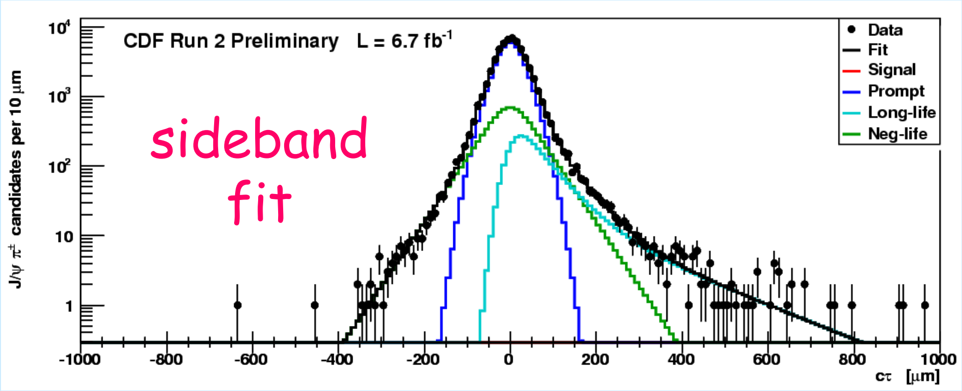


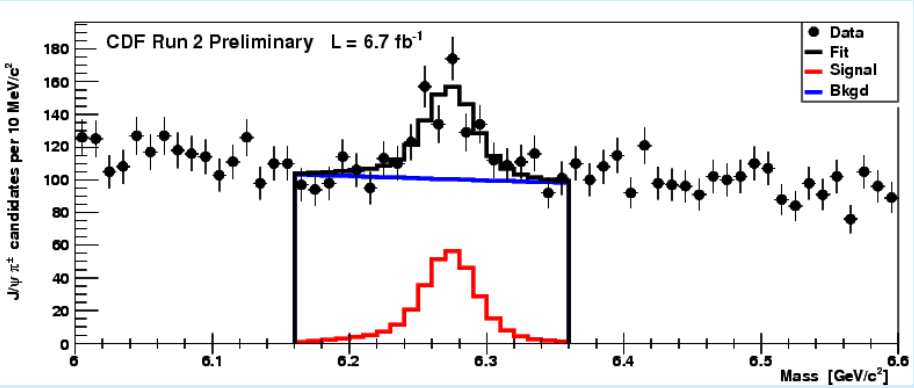
Selection 1 results

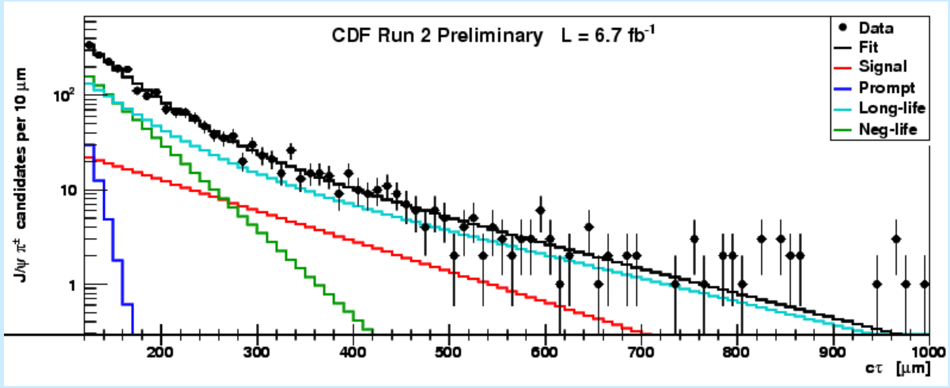
(will be a cross-check for selection 2)

- Likelihood fit with combined mass and decay time

$$L = \prod_i \left[f_s \cdot M_s(m_i, \sigma_{mi}) \cdot T_s(c\tau_i) + (1 - f_s) \cdot M_b(m_i) \cdot T_b(c\tau_i) \right]$$







$$c\tau(B_c^-) = (\ 135 \pm 16 \pm 10\ )\ \mu m$$

Largest systematic comes from varying the long-lived exponential in the background by ±1σ.

Selection 2

- Likelihood fit with combined mass and decay time

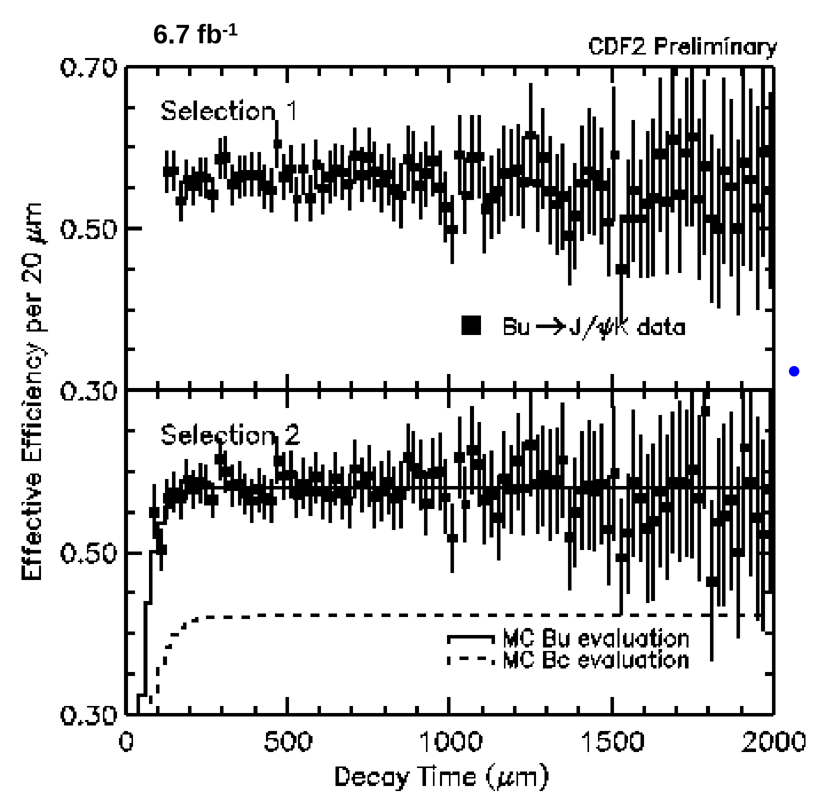
$$-2\ln(L) = -2\sum_{i=0}^{N_{sig}} \left[\ln\left(F_i(ct_i, M_i; c\tau, M_0, \sigma_M, N_M^0, b, N_B, \theta_1, \cdots \theta_7)\right)\right] + V_\theta^T \mathrm{Cov}_\theta^{-1} V_\theta,$$

Signal= Eff x exponential

$$S_i(ct_i; c\tau, \theta_6, \theta_7, \theta_8) = E(ct_i; \theta_6, \theta_7) \int_{ct'_{min}}^{ct'_{max}} d(ct') \frac{1}{\sqrt{2\pi}\sigma_{ct}} \exp\left(-\frac{(ct_i - ct')^2}{2\sigma_{ct}^2}\right) \frac{\exp(-ct'/c\tau)}{c\tau}$$

Background = 3 exponentials

$$B_i(ct_i; \theta_1, \cdots, \theta_5) = f_1 \frac{\exp(-ct_i/c\tau_1)}{c\tau_1(\exp(-ct_{min}/c\tau_1) - \exp(-ct_{max}/c\tau_1))} + f_2 \frac{\exp(-ct_i/c\tau_2)}{c\tau_2(\exp(-ct_{min}/c\tau_2) - \exp(-ct_{max}/c\tau_2))} + (1 - f_1 - f_2) \frac{\exp(-ct_i/c\tau_3)}{c\tau_3(\exp(-ct_{min}/c\tau_3) - \exp(-ct_{max}/c\tau_3))},$$



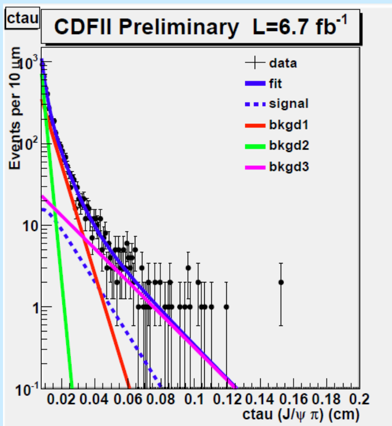
- Monte Carlo determination of the Efficiency vs decay time with a check using high statistics Bu→J/ψK decays

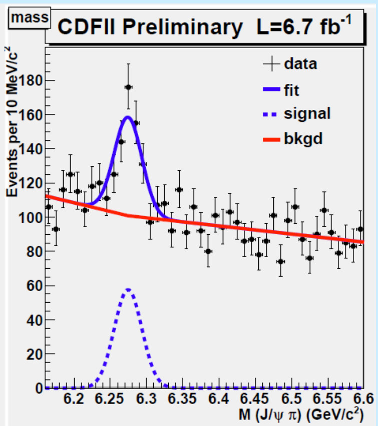
$$E(c\tau) = N \times (\, 1 - exp[-\,(c\tau - a)/b\,]\,)$$

Decay	N	a (μm)	b (μm)
$B^- \to J/\psi\ K^-$	0.5806 ± 0.0018	21.74 ± 12.37	34.49 ± 5.67
$B_c^- \to J/\psi\ \pi^-$	0.4213 ± 0.0028	26.76 ± 7.45	42.72 ± 4.75

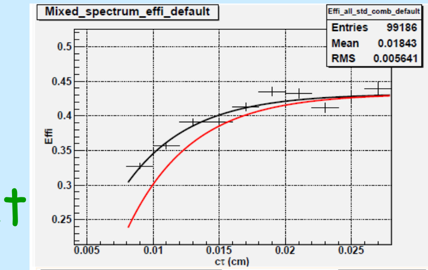
Systematic uncertainties

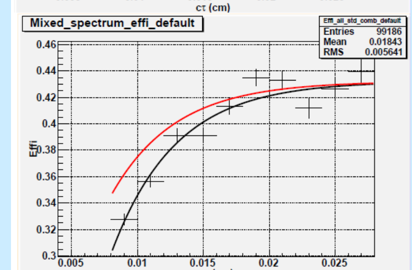
- Vary models of the efficiency vs decay time and the models of background mass and decay time distributions



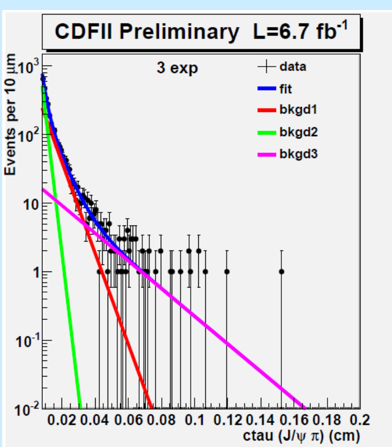


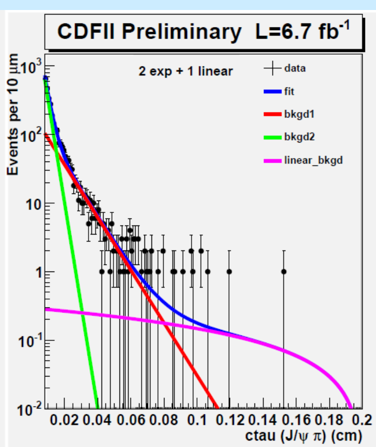
Vary bkgd mass model => 5μm effect





Vary eff vs decay time ⇒3μm effect



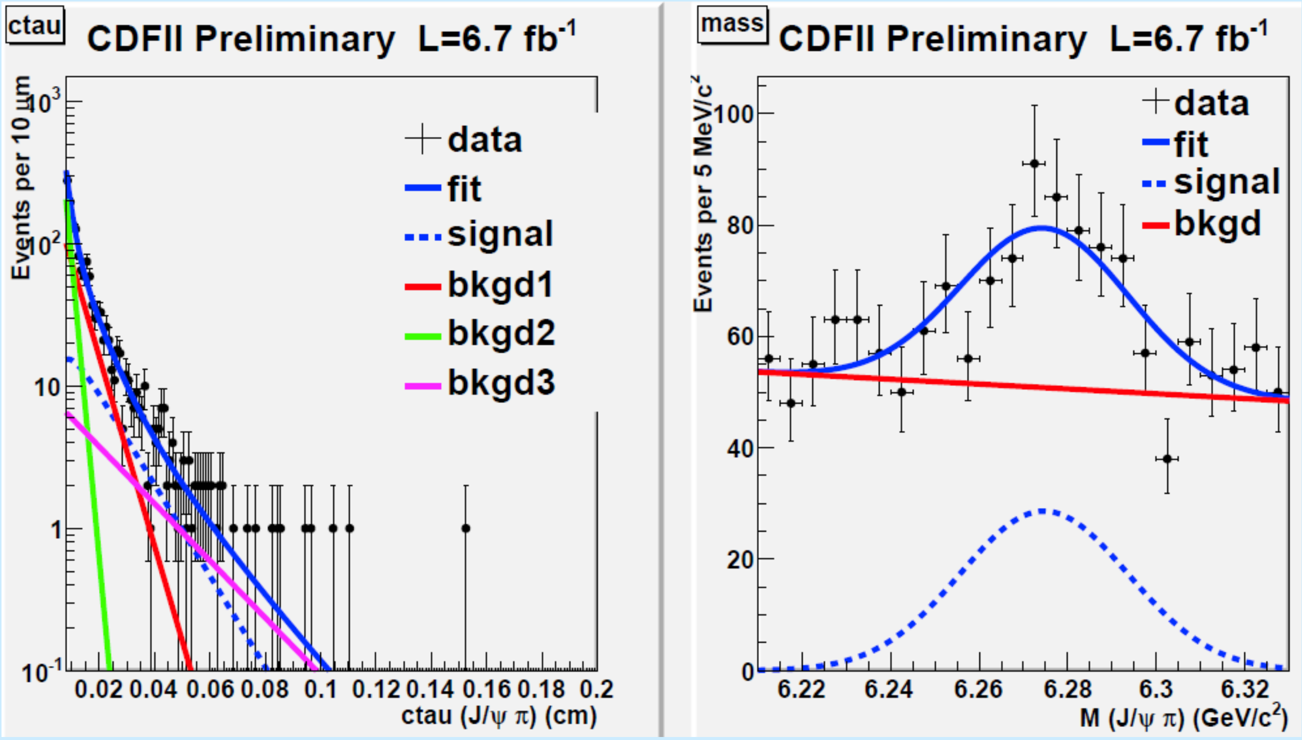


Vary bkgd decay time model => 4μm effect

Systematic	Selection 2
Calibration	2
Signal Mass Model	1
Signal Decay Time Model	3
Background Mass Model	5
Background Decay Time Model	4
Fitting Method	1
Other Tests	3
Total	8

Selection 2 results

- Projections in decay time and mass and final result



$$\tau(B_c^-) = (\ 0.452 \pm 0.048 \pm 0.027\ )\ \mathrm{ps}$$

$$c\tau(B_c^-) = (\ 136 \pm 14 \pm 8\ )\ \mu\mathrm{m}$$

First cτ result in this mode!

Summary

- CDF has a long history of utilizing fully reconstructed decays
- Recent results are presented for suppressed Bs decays
  - Bs → φφ
  - Bs → J/ψ f_0(980)

A_u = -0.007±0.064 (stat) ±0.018 (syst)
A_v = -0.120±0.064 (stat) ±0.016 (syst)

$$\tau(B_s^0 \to J/\psi f_0) = 1.70^{+0.12}_{-0.11}(\text{stat}) \pm 0.03(\text{syst})\ \text{ps}$$

- Recent results are presented in the Bc system including a new lifetime measurement in Bc→J/ψπ

$$\tau(B_c^-) = (\ 0.452 \pm 0.048 \pm 0.027\ )\ \text{ps}$$
$$c\tau(B_c^-) = (\ 136 \pm 14 \pm 8\ )\ \mu\text{m}$$