Time Dependent Angular Analysis of $B_{s(d)} \rightarrow J/\psi\ \Phi(K^{*0})$, and a Lifetime Difference in the B_s System

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CDF II Collaboration

Aug 28, 2004

DPF 2004, UC Riverside

Outline

- Motivation
- Analysis introduction
- Experimental technique and Fitting Model
- Results and crosschecks
- Conclusion and plans

Motivation:

- **B mixing**
  $\Rightarrow$ Mass eigenstates $B_{s,H}$ and $B_{s,L}$:
  $\Rightarrow$ Nearly CP eigenstates

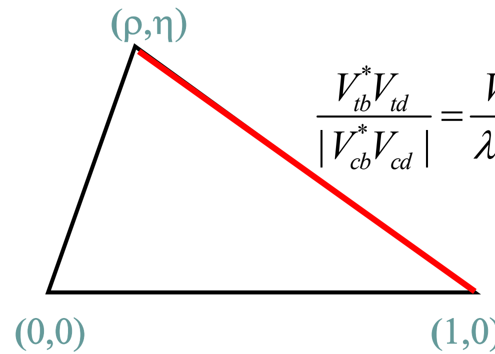
$$B_s^H = \frac{1}{\sqrt{2}}(|B_s\rangle + |\overline{B}_s\rangle) \rightarrow CP-odd$$

$$B_s^L = \frac{1}{\sqrt{2}}(|B_s\rangle - |\overline{B}_s\rangle) \rightarrow CP-even$$

- **SM predicts Lifetime Difference in B_s system**
  - On-shell transitions contribute to $\Delta\Gamma_s$
  - $\Delta\Gamma_s \Rightarrow \Delta m_s \Rightarrow \Delta m_d / \Delta m_s \Rightarrow |V_{td}|/|V_{ts}|$

$$\frac{\Delta\Gamma_s}{\Delta m_s} = (3.7^{+0.8}_{-1.5}) \times 10^{-3}, \quad \frac{\Delta\Gamma_s}{\Gamma} = 0.12 \pm 0.06$$

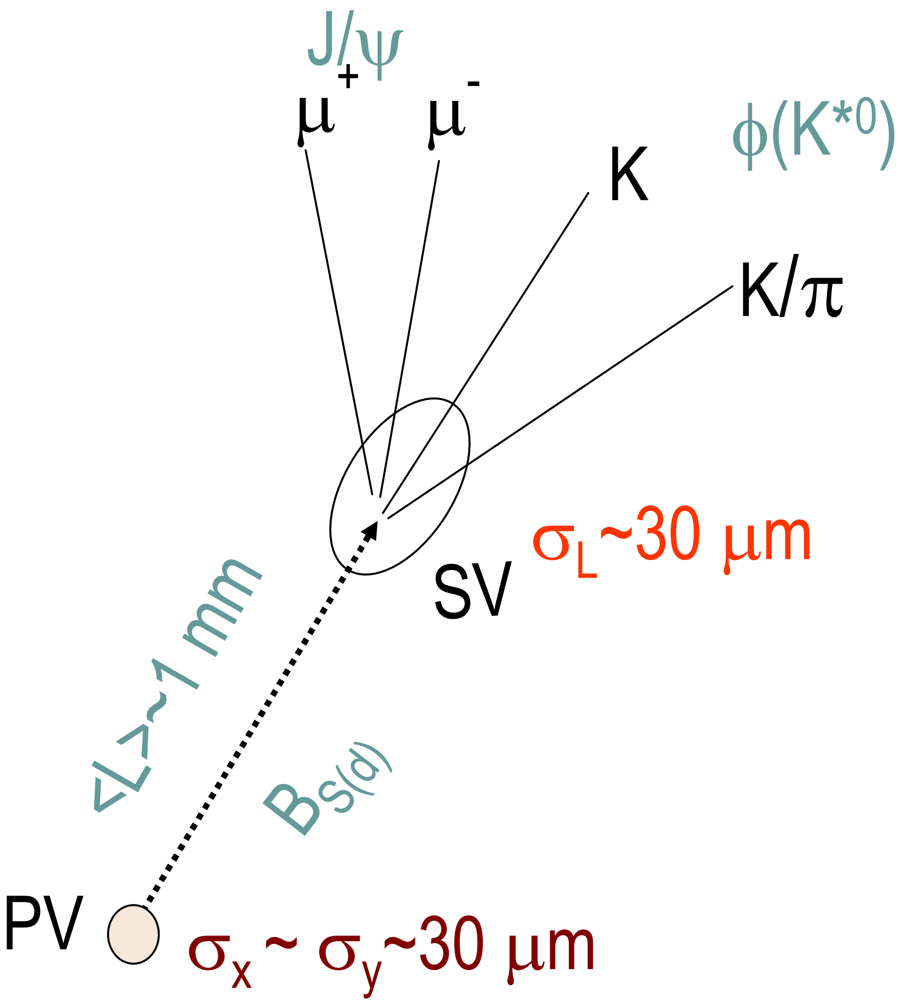
[B Physics at the Tevatron: Run II and Beyond Hep-ph/0201071]



$$\frac{V_{tb}^* V_{td}}{|V_{cb}^* V_{cd}|} = \frac{V_{td}}{\lambda V_{cb}} = \frac{V_{td}}{\lambda V_{ts}}$$

- **$B_{s(d)} \rightarrow J/\psi\ \phi(K^{*0})$: Pseudoscalar $\rightarrow$ Vector – Vector**
  - $0 \Rightarrow 1 \oplus 1$, Orbital L = 0, 1, 2 (S, P, D)
  - Three amplitudes (partial wave, helicity, or transversity basis)
- **Transversity basis: seperates CP (P) odd state nicely.**
  - A_0 = S + D wave $\Rightarrow$ CP(P) even
  - $A_{||}$ = S + D wave $\Rightarrow$ CP(P) even
  - $A_{\perp}$ = P wave $\Rightarrow$ CP(P) odd
- **Time dependent transversity analysis can isolate the two B states and determine $\Delta\Gamma_s$**
- **B_d decays: Sister Channel. Control sample, check if results are sensible.**

Event Reconstruction



- **CDF Run II up to 2/2004**
  - $L \sim 260\ pb^{-1}$
- **$J/\Psi \rightarrow \mu^+\mu^-$**
  - Muon detector
  - Di-Muon Trigger Path
- **$\phi \rightarrow K^+K^-$; $K^* \rightarrow K^+\pi^-$**
  - Well measured in Tracking Chamber (COT)
  - With Silicon Detector Hits
  - Mass window, p_T cut
- **$B_d \rightarrow J/\Psi K^*$; $B_s \rightarrow J/\Psi\phi$**
  - Vertex-fit, p_T cut
- **Primary Vertex from Beamline**

Transversity Basis

CP(P) Even

$$
\begin{aligned}
\frac{d^4\mathcal{P}}{d\vec{\rho}\,dt} \propto\ & |A_0|^2 \cdot g_1(t) \cdot f_1(\vec{\rho}) + \\
& |A_{\|}|^2 \cdot g_2(t) \cdot f_2(\vec{\rho}) + \\
& |A_{\perp}|^2 \cdot g_3(t) \cdot f_3(\vec{\rho}) \pm \\
& Im(A_{\|}^* A_{\perp}) \cdot g_4(t) \cdot f_4(\vec{\rho}) + \\
& Re(A_0^* A_{\|}) \cdot g_5(t) \cdot f_5(\vec{\rho}) \pm \\
& Im(A_0^* A_{\perp}) \cdot g_6(t) \cdot f_6(\vec{\rho}) \equiv \\
& \sum_{i=1}^{6} \mathcal{A}_i \cdot g_i(t) \cdot f_i(\vec{\rho})
\end{aligned}
$$

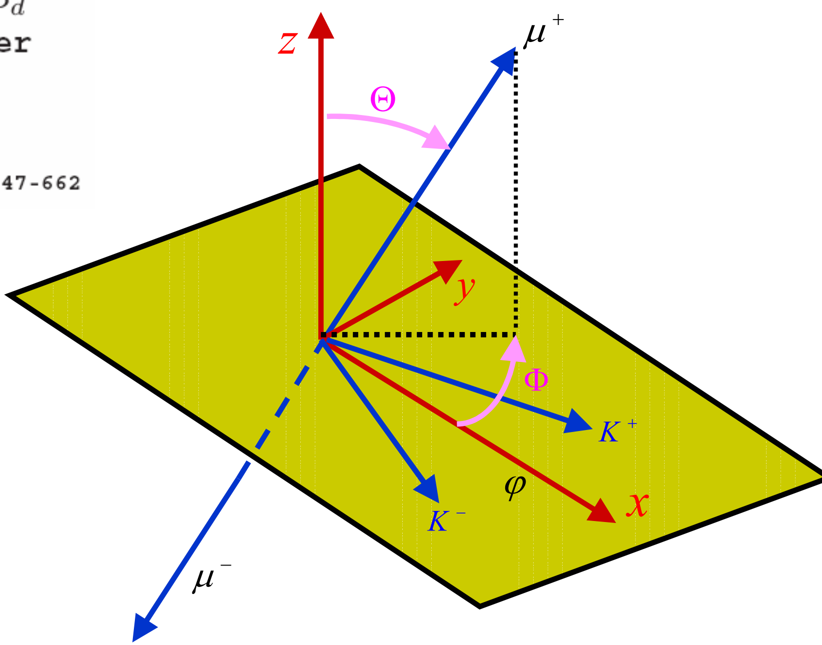
$$
\begin{aligned}
f_1(\vec{\rho}) &= 2\cos^2\psi(1-\sin^2\theta\cos^2\phi) \\
f_2(\vec{\rho}) &= \sin^2\psi(1-\sin^2\theta\sin^2\phi) \\
f_3(\vec{\rho}) &= \sin^2\psi\sin^2\theta \\
f_4(\vec{\rho}) &= -\sin^2\psi\sin 2\theta\sin\phi \\
f_5(\vec{\rho}) &= \frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\phi \\
f_6(\vec{\rho}) &= \frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\phi
\end{aligned}
$$

CP(P) ODD

$g_i(t)$ different for B_d and B_s and are rather non-trivial

A. Dighe et. al., Eur. Phys. J. C 6, 647-662

Interference Terms



Transversity angles are defined in J/ψ rest frame

φ (K^{*0}) flight direction ≡ positive x
KK (Kπ) plane ≡ xy plane

Time-Dependent Distribution

B_s:

$$\frac{d^4\mathcal{P}}{d\vec{\rho}\,dt} \propto |A_0|^2 \cdot e^{-\Gamma_L t} \cdot f_1(\vec{\rho}) + |A_\parallel|^2 \cdot e^{-\Gamma_L t} \cdot f_2(\vec{\rho}) + |A_\perp|^2 \cdot e^{-\Gamma_H t} \cdot f_3(\vec{\rho}) + Re(A_0^* A_\parallel) \cdot e^{-\Gamma_L t} \cdot f_5(\vec{\rho})$$

$$\boxed{\begin{array}{l} \Gamma_L = CP - \text{even} \\ \Gamma_H = CP - \text{odd} \end{array}}$$

- flavor blind decay
- $\delta\phi_{CPV} \approx 0.03$
- Δm_s is large

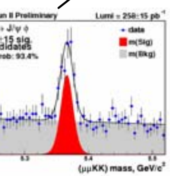
B_d:

$$\frac{d^4\mathcal{P}}{d\vec{\rho}\,dt} \propto \Big\{ |A_0|^2 \cdot f_1(\vec{\rho}) + |A_\parallel|^2 \cdot f_2(\vec{\rho}) + |A_\perp|^2 \cdot f_3(\vec{\rho}) \pm Im(A_\parallel^* A_\perp) \cdot f_4(\vec{\rho}) + Re(A_0^* A_\parallel) \cdot f_5(\vec{\rho}) \pm Im(A_0^* A_\perp) \cdot f_6(\vec{\rho}) \Big\} \cdot e^{-\Gamma_d t}$$

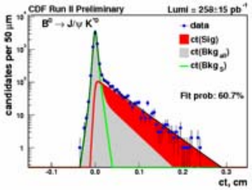
- flavor specific decay
- $\delta\phi_{CPV} = 2\beta$

Fitting Model

- **Unbinned likelihood fit, simultaneously fit angular, lifetime and mass distributions**
  - Mass: $Gaus(m, \varepsilon_m) + Pol_1(m)$
  - Lifetime + Amplitudes:



- $Gaus(\varepsilon_{ct}) \otimes (Sig(ct, \{A_i\}) + \Sigma_n Exp_n(ct)^{*}Bkg(\{B_i\}))$
  - Long-lived
    - Displaced J/ψ paired with (random) track
    - Reflections and partially reconstructed *B*
  - Short-lived
    - **Prompt J/ψ** paired with tracks (ct = 0)
    - Combinations with mis-measured tracks (ct > 0, ct < 0)
  - Background Angular Distribution (allow for S, P, D components)

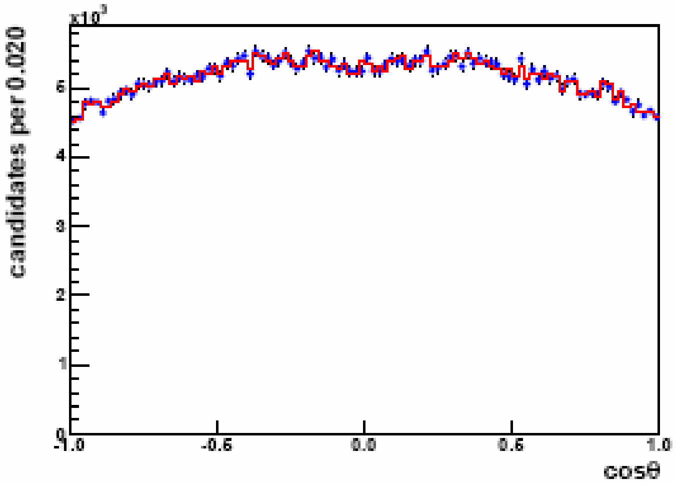


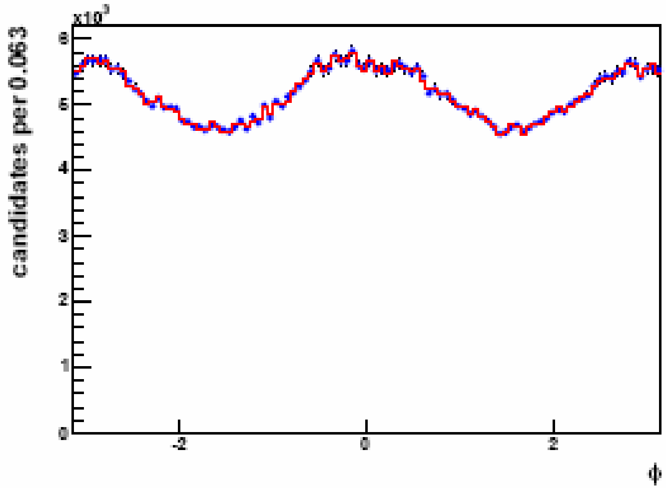
Errors on mass and ct are scaled by scaling factor S_m, S_{ct} (Floating in the fit)

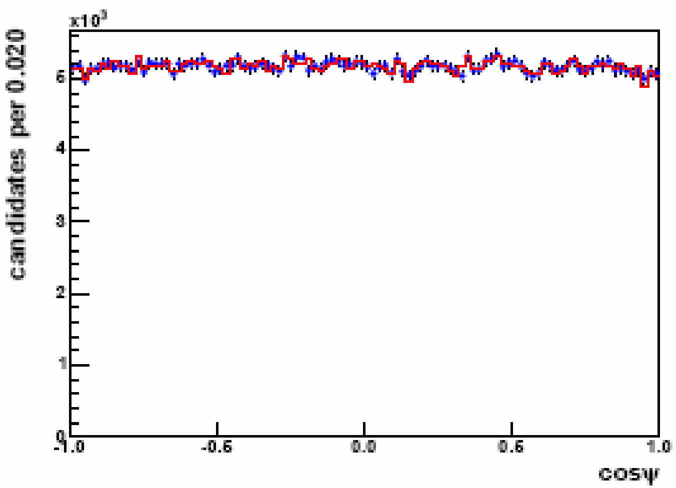
Majority of the background

- **Correction for detector efficiency and acceptance**

Detector Acceptance and Efficiency

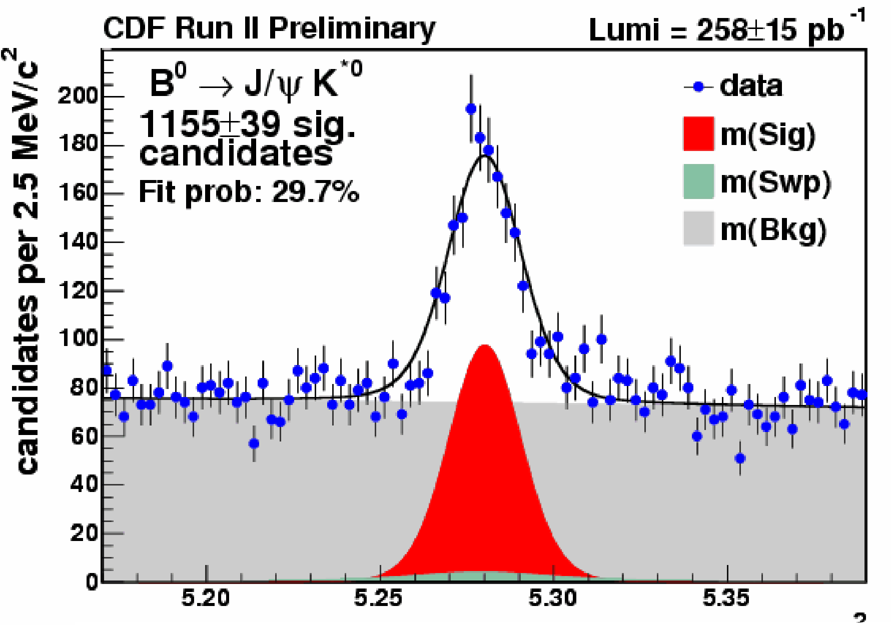


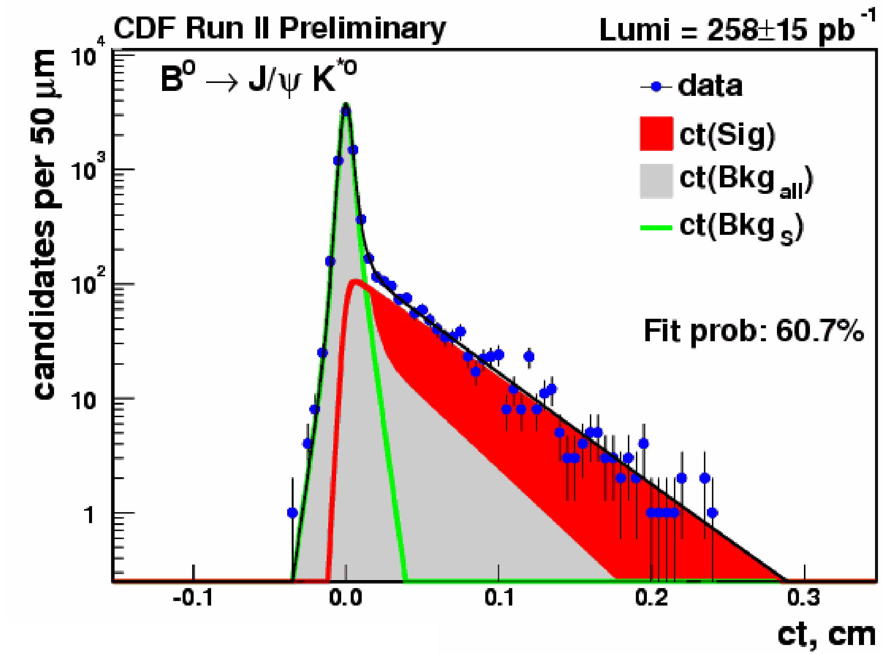




- 40 M Full MC decays generated flat in angular variables
- Shapes show effect of cuts and detector sculpting
- This sculpting is corrected for by including an additional normalization term in the likelihood function
- Realistic MC tests and Pull tests ensure the correctness of the treatment.

B_d Fit: Mass and Lifetime Projection





$$A_0 = 0.750 \pm 0.017 \pm 0.012$$

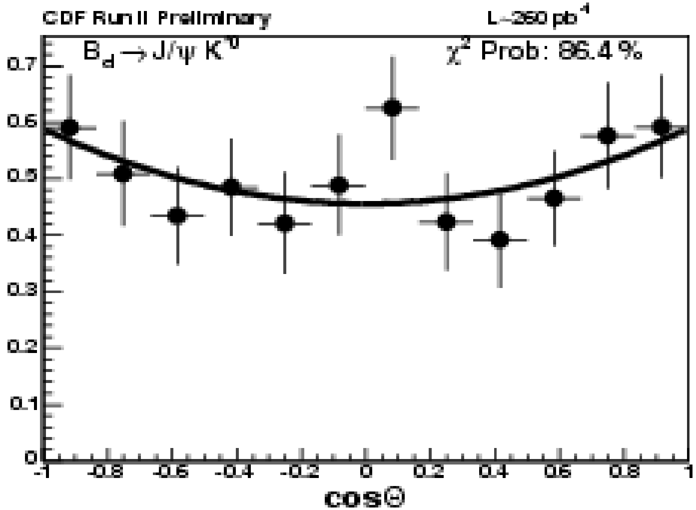
$$A_{||} = (0.473 \pm 0.034 \pm 0.006)e^{(2.86 \pm 0.22 \pm 0.07)i}$$

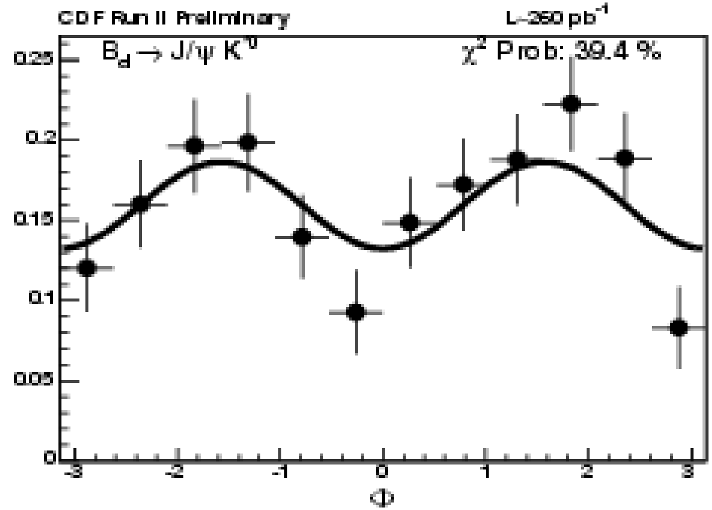
$$A_{\perp} = (0.464 \pm 0.035 \pm 0.007)e^{(0.15 \pm 0.15 \pm 0.04)i}$$

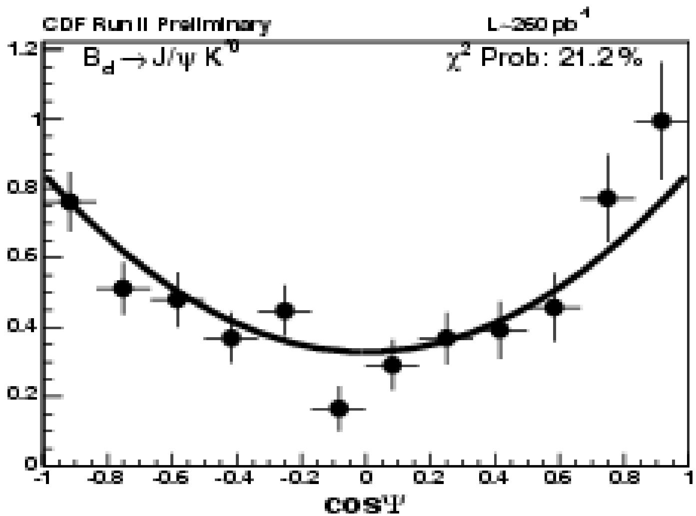
$$\tau_{B^0} = 1.54 \pm 0.05 \pm 0.02 \text{ ps}$$

vs. PDG = 1.537 ± 0.015 ps

Angular Projection (Bd)



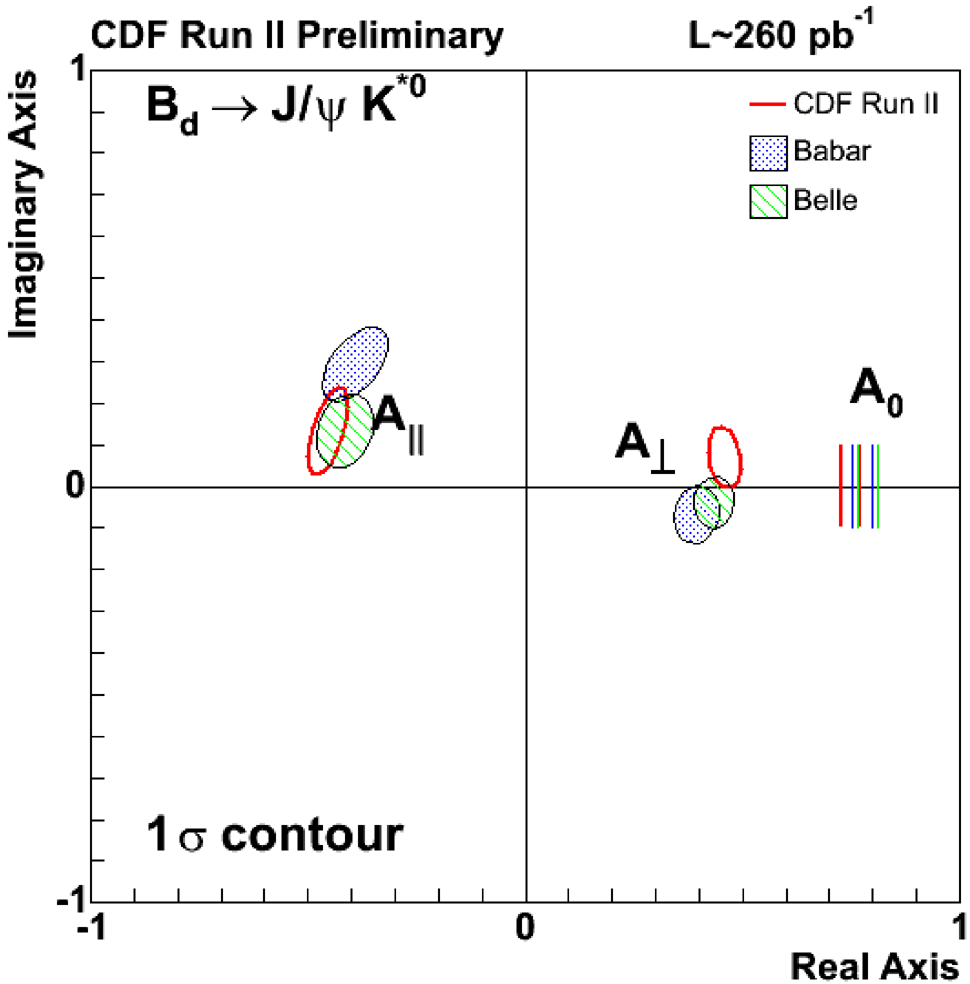




- **Projections:**
  - Sideband subtracted
  - Detector sculpting Corrected

Single variable projection

B_d Amplitudes vs. Babar/Belle



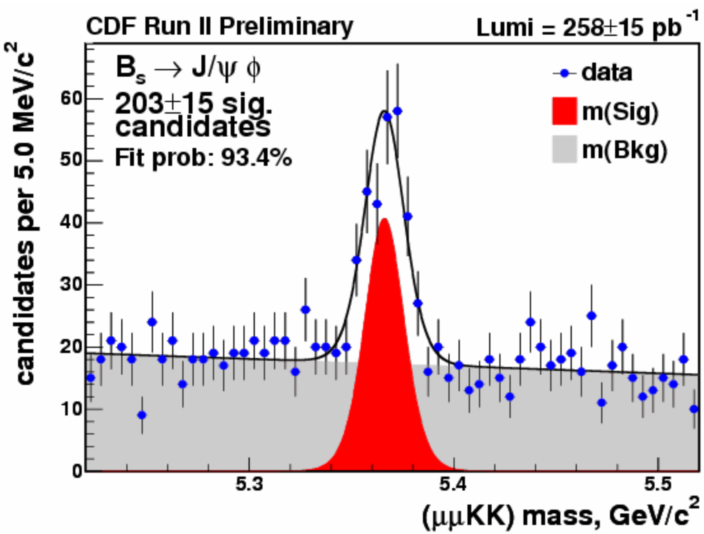
Babar PRL 87, 241801 (2001)

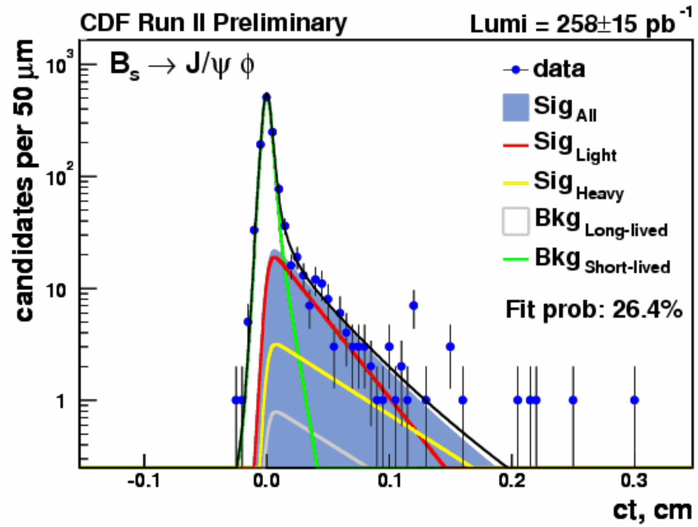
Belle P.L B538, 11 (2002)

Bs Unconstrained Fit

Fit data as described

Lifetime & Mass Projection





$$SM : \Delta\Gamma / \Gamma = 0.12 \pm 0.06$$

$$\begin{aligned}
A_0 &= 0.784 \pm 0.039 \pm 0.007 \\
A_{\|} &= (0.510 \pm 0.082 \pm 0.013) e^{(1.94 \pm 0.36 \pm 0.03)i} \\
|A_{\perp}| &= 0.354 \pm 0.098 \pm 0.003 \\
\tau_L &= 1.05\ ^{+0.16}_{-0.13} \pm 0.02 \text{ ps} \\
\tau_H &= 2.07\ ^{+0.58}_{-0.46} \pm 0.03 \text{ ps} \\
\Delta\Gamma/\Gamma &= 0.65\ ^{+0.25}_{-0.33} \pm 0.01 \\
\Delta\Gamma &= 0.47\ ^{+0.19}_{-0.24} \pm 0.01 \text{ ps}^{-1}
\end{aligned}$$

Bs Constrained Fit

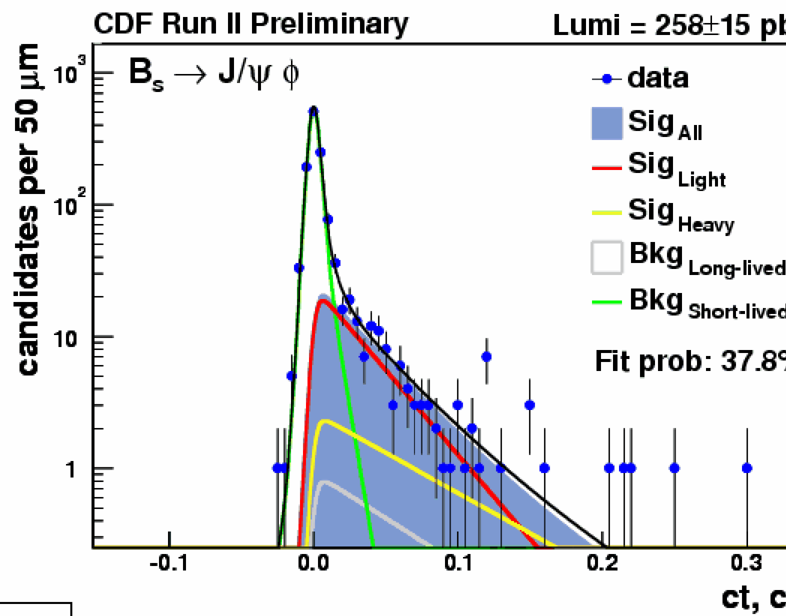
$$\text{Theory}: \Gamma_s / \Gamma_d = 1.00 \pm 0.01$$

$$\text{Experiment}: c\tau_d = 460.8 \pm 4.5\mu m$$

$$\tau_s \equiv \frac{2\tau_H \tau_L}{\tau_H + \tau_L} \xrightarrow{constrained} \tau_d$$

$$\text{Constrain}: c\tau_s \text{ to } 460.8 \pm 6.4\mu m \ \ (\sqrt{4.5^2 + 4.6^2})$$

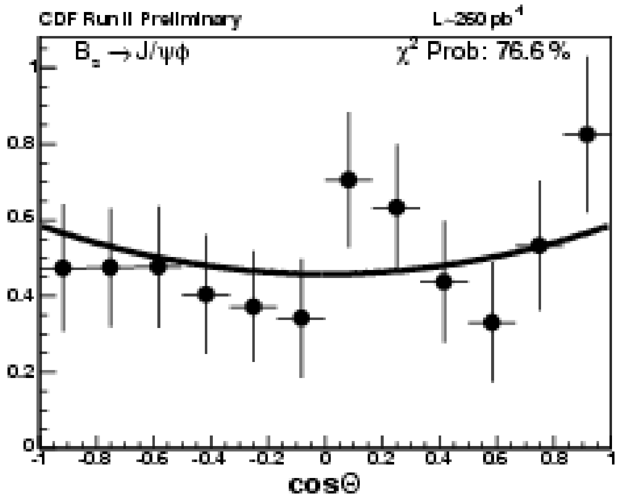
Gaussian constraint in the likelihood fit

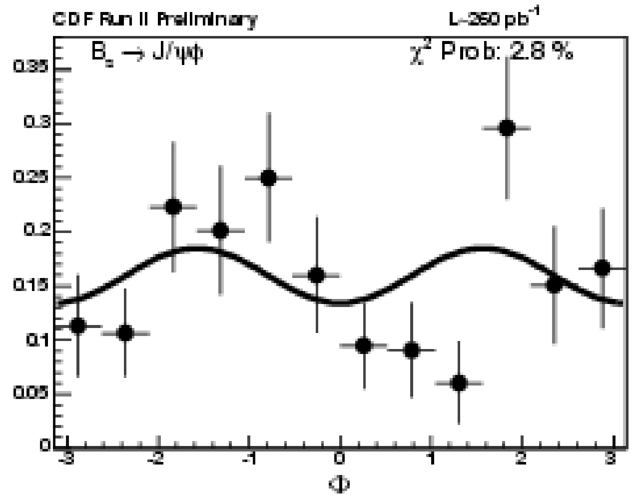


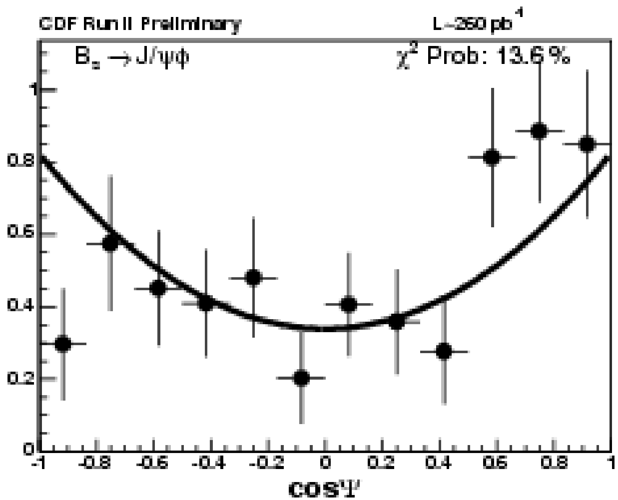
$$\begin{aligned}
A_0 &= 0.783 \pm 0.038 \pm 0.007 \\
A_{||} &= (0.539 \pm 0.070 \pm 0.013) e^{(1.91 \pm 0.36 \pm 0.03)i} \\
|A_\perp| &= 0.308 \pm 0.087 \pm 0.003 \\
\tau_L &= 1.13 {}^{+0.13}_{-0.09} \pm 0.02 \text{ ps} \\
\tau_H &= 2.38 {}^{+0.56}_{-0.43} \pm 0.03 \text{ ps} \\
\Delta\Gamma/\Gamma &= 0.71 {}^{+0.24}_{-0.28} \pm 0.01 \\
\Delta\Gamma &= 0.46 {}^{+0.17}_{-0.18} \pm 0.01 \text{ ps}^{-1}
\end{aligned}$$

$$SM: \Delta\Gamma / \Gamma = 0.12 \pm 0.06$$

Angular Projection (Bs)







- **Projections:**
  - Sideband subtracted
  - Acceptance Corrected

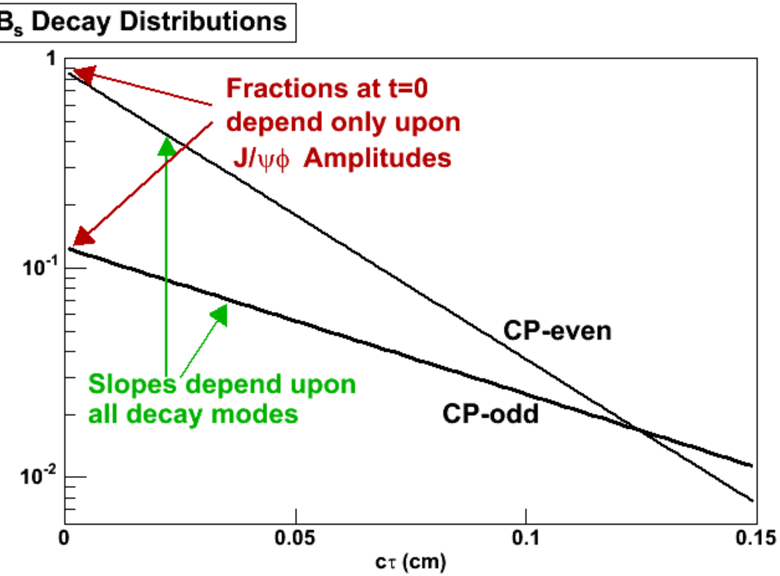
Single variable projection

Systematics

B_d	$c\tau$, μm	$\lvert A_0\rvert$	$\lvert A_\parallel\rvert$	$\lvert A_\perp\rvert$	$arg(A_\parallel)$	$arg(A_\perp)$
Bkg. ang. model	3.9	0.009	0.006	0.006	0.01	0.01
Eff. and acc.	–	–	–	–	–	–
$K \leftrightarrow \pi$ swap	–	0.002	0.002	0.002	0.01	–
Non-resonant decays	–	0.007	0.001	0.004	0.07	0.04
Bkg. lft. model	1.7	–	–	–	–	–
SVX alignment	1.0	–	–	–	–	–
Lft. bias	1.3	–	–	–	–	–
B_s cross-feed	–	–	–	–	–	–
Total	4.6	0.012	0.006	0.007	0.07	0.04

B_s	$c\tau_L$, μm	$\Delta\Gamma/\Gamma$	$\lvert A_0\rvert$	$\lvert A_\parallel\rvert$	$\lvert A_\perp\rvert$	$\arg(A_\parallel)$
Bkg. ang. model	3.7	0.007	0.007	0.013	0.003	0.03
Eff. and acc.	–	–	–	–	–	–
Unequal # B_s,$\bar{B}_s$	–	–	–	–	–	–
Bkg. lft. model	1.7	–	–	–	–	–
SVX alignment	1.0	–	–	–	–	–
Lft. bias	1.3	–	–	–	–	–
B_d cross-feed	5.0	0.008	–	0.003	0.001	–
Total	6.7	0.011	0.007	0.013	0.003	0.03

Cross Check: B_s CP odd fraction



Bs CP Odd

Cut (μm)	Fitted (%)	Predicted (%)
>0	20.1 +/- 9.0	--20.1--
>150	24.2 +/- 10.3	24.1
>300	29.6 +/- 12.7	28.6
>450	38.7 +/- 11.6	33.6

Bd P Odd

Cut (μm)	Fitted (%)
>0	21.6 +/- 4.4
>150	23.0 +/- 3.6
>300	23.0 +/- 4.0
>450	23.6 +/- 4.9

- **Fit to amplitudes ONLY, using different minimum lifetime cuts.**
  - The CP odd fraction increase in the B_s fit suggests significant lifetime difference in the two components
  - The predictions of the fraction using our measured lifetime difference are consistent with the angular fitting results
- **The CP odd fraction of B_d stays constant with different ct cuts. Consistent with our expectation.**

Betting Odds

How likely are we to observe this value of $\Delta\Gamma_s/\Gamma_s$ if the true value were zero(or 0.12)?

- 10000 Toy MC fits to estimate the probability of a fluctuation (with $\Delta\Gamma_s/\Gamma_s$ > our measurement)
  - P(measured | true = 0)
    - Unconstrained Fit: 0.65 – **1/315**
    - Constrained Fit: 0.71 – **1/718**
  - P(measured | true = 0.12)
    - Unconstrained Fit: 0.65 – **1/84**
    - Constrained Fit: 0.71 – **1/204**

Conclusions

- Time dependent angular analysis powerful tool
- Competitive $B_d \to J/\psi\, K^{*0}$ amplitudes measurements (agree well with BaBar/Belle)
- B_d lifetime agrees well with PDG

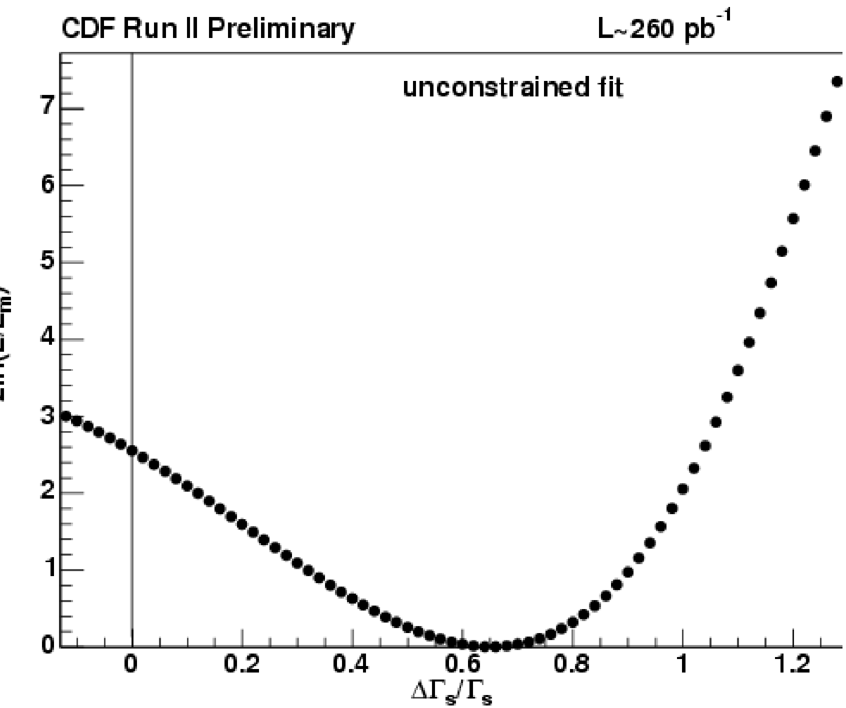
- ~200 $B_s \to J/\psi\Phi$ show evidence of lifetime difference in B_s system.
  - For constrained fit, we measured:

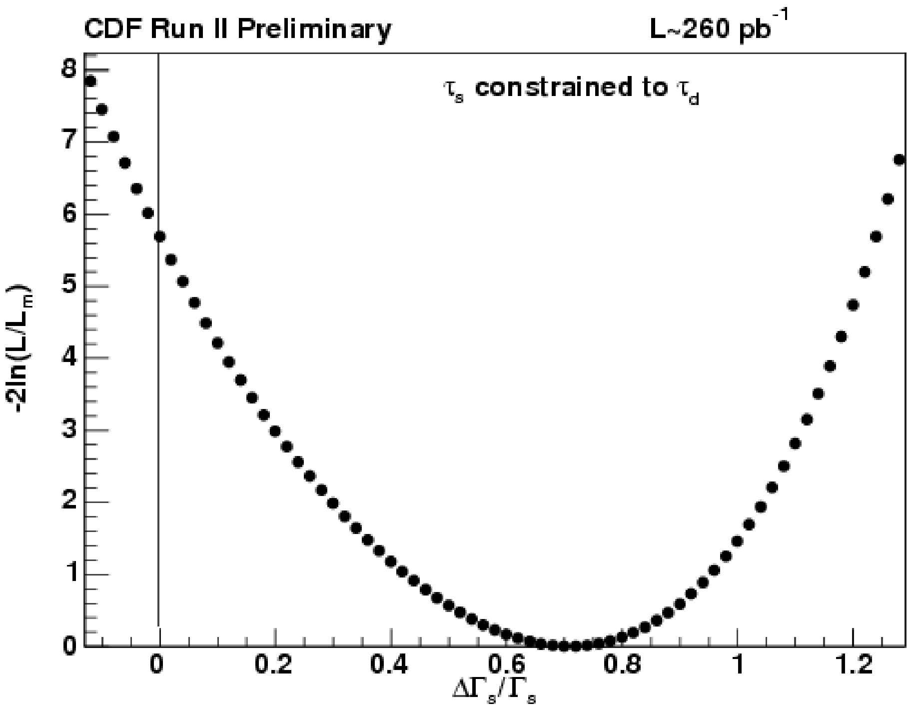
$$\Delta\Gamma_s = 0.46 \pm 0.18 \pm .01\ \mathrm{ps}^{-1} \qquad \frac{\Delta\Gamma_s}{\Gamma_s} = 0.71^{+0.24}_{-0.28} \pm 0.01$$

  - $\Delta\Gamma_s=0$ ruled out at ~1/700 odds (with $\Gamma_s = \Gamma_d$ constraints)
  - First measurement of B_s lifetime difference.
- More data coming underway!!! On the edge of Challenging Standard Model. ($\Delta\Gamma_s/\Gamma_s$(SM) = 0.12 +/- 0.06)

Backup Slides

Likelihood Scan





- **Scan in $\Delta\Gamma_s/\Gamma_s$, refit at each point letting other parameters float**

Main Fitting Results

	B_d	B_s Unconstrained Fit	B_s Constrained Fit	unit
M_B	5280.2 ± 0.8	5366.1 ± 0.8	5366.0 ± 0.8	MeV/c^2
A_0	0.750 ± 0.017	0.784 ± 0.039	0.783 ± 0.038	
$A_{\parallel}$	0.473 ± 0.034	0.510 ± 0.082	0.539 ± 0.070	
$A_{\perp}$	0.464 ± 0.035	0.354 ± 0.098	0.308 ± 0.087	
$\delta_{\parallel}$	2.86 ± 0.22	1.94 ± 0.36	1.91 ± 0.32	
$\delta_{\perp}$	0.15 ± 0.15			
$c\tau_B$	462 ± 15			μm
$c\tau_L$		$316\ ^{+48}_{-40}$	$340\ ^{+40}_{-28}$	μm
$c\tau_H$		$622\ ^{+175}_{-138}$	$713\ ^{+167}_{-129}$	μm
$c\tau_s$		$419\ ^{+45}_{-38}$	$\mathbf{460 \pm 6.2}$	μm
$\Delta\Gamma_s/\Gamma_s$		$65\ ^{+25}_{-33}$	$71\ ^{+24}_{-28}$	%
$\Delta\Gamma_s$		$0.47\ ^{+0.19}_{-0.24}$	$0.46\ ^{+0.17}_{-0.18}$	ps^{-1}
N_{sig}	1155 ± 39	203 ± 15	201 ± 15	

Other Fitting Parameters

Parameter	B_d result	B_s result	unit
f_s	0.151 ± 0.005	0.164 ± 0.012	
A	-1.06 ± 0.89	-2.2 ± 1.2	$(\text{GeV}/c^2)^{-1}$
S_m	1.65 ± 0.06	1.81 ± 0.12	
$\|B_0\|^2$	0.292 ± 0.009	0.318 ± 0.023	
$\|B_{\|\|}\|^2$	0.358 ± 0.017	0.385 ± 0.041	
$arg(B_{\|\|})$	1.60 ± 0.06	1.63 ± 0.13	
f_-	0.042 ± 0.014	$---$	
f_+	0.145 ± 0.019	0.124 ± 0.031	
f_{++}	0.044 ± 0.006	0.011 ± 0.007	
λ_-	47 ± 7	$---$	μm
λ_+	45 ± 6	66 ± 17	μm
λ_{++}	348 ± 40	634 ± 280	μm
S_{ct}	1.27 ± 0.02	1.33 ± 0.04	

Implication for Δm_s

$$\frac{\Delta\Gamma_s}{\Delta m_s} = (3.7^{+0.8}_{-1.5}) \times 10^{-3}$$

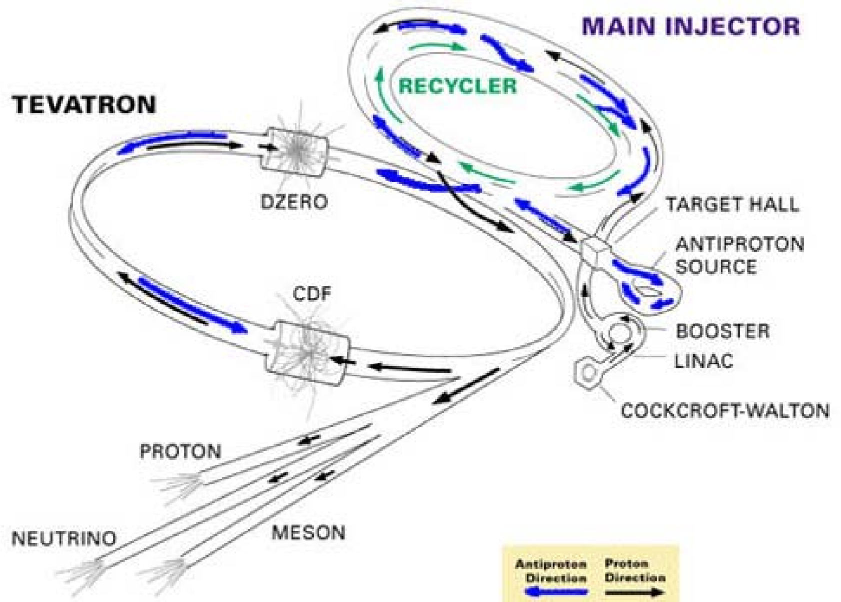
(B Physics at the Tevatron Report value)
(Beneke, et al hep-ph/9808385 NLO analysi

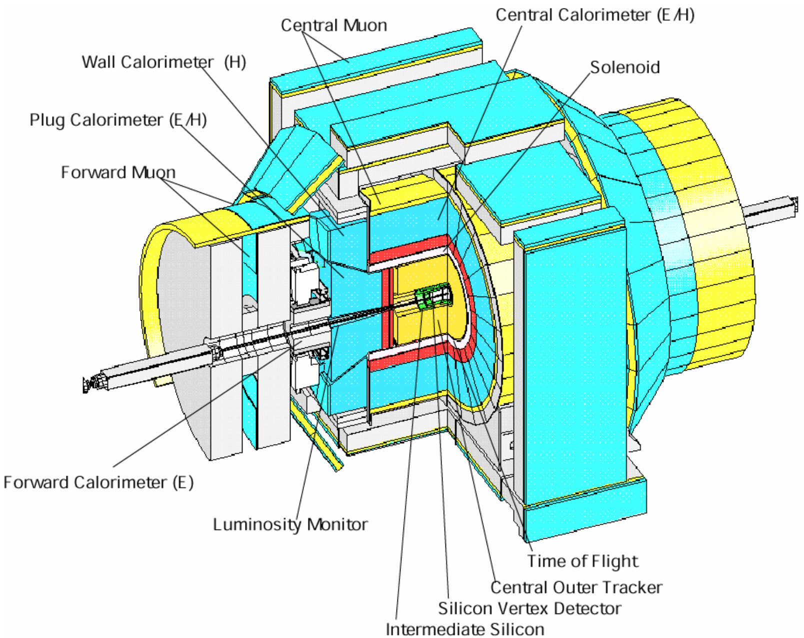
$$\boxed{\Delta m_s = 125^{+69}_{-55}\ ps^{-1}}$$

Using our constrained fit results

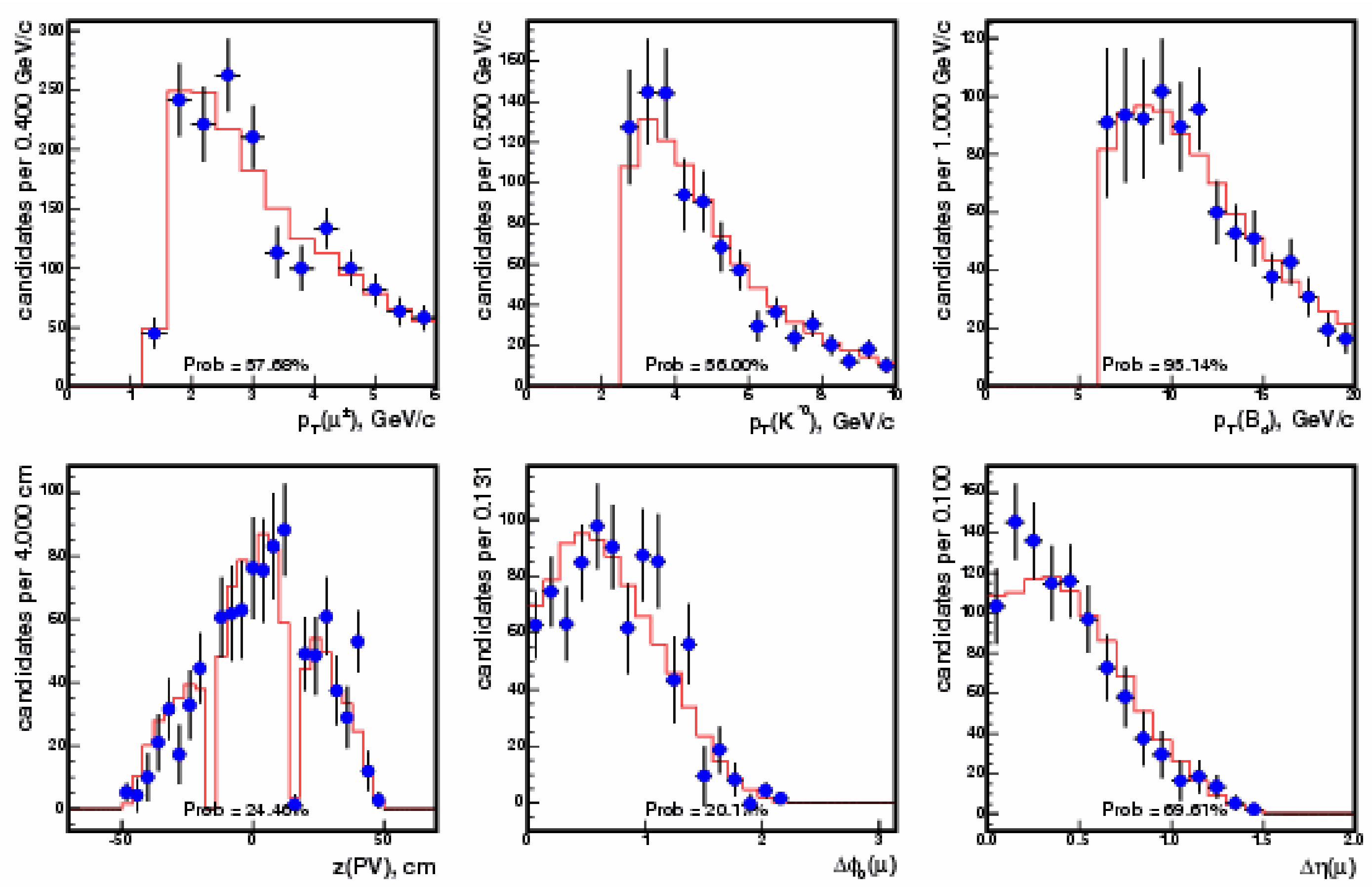
Current limit Δm_s > 14.9 ps^{-1} (95% C.L.)

Tevatron and CDF Run II

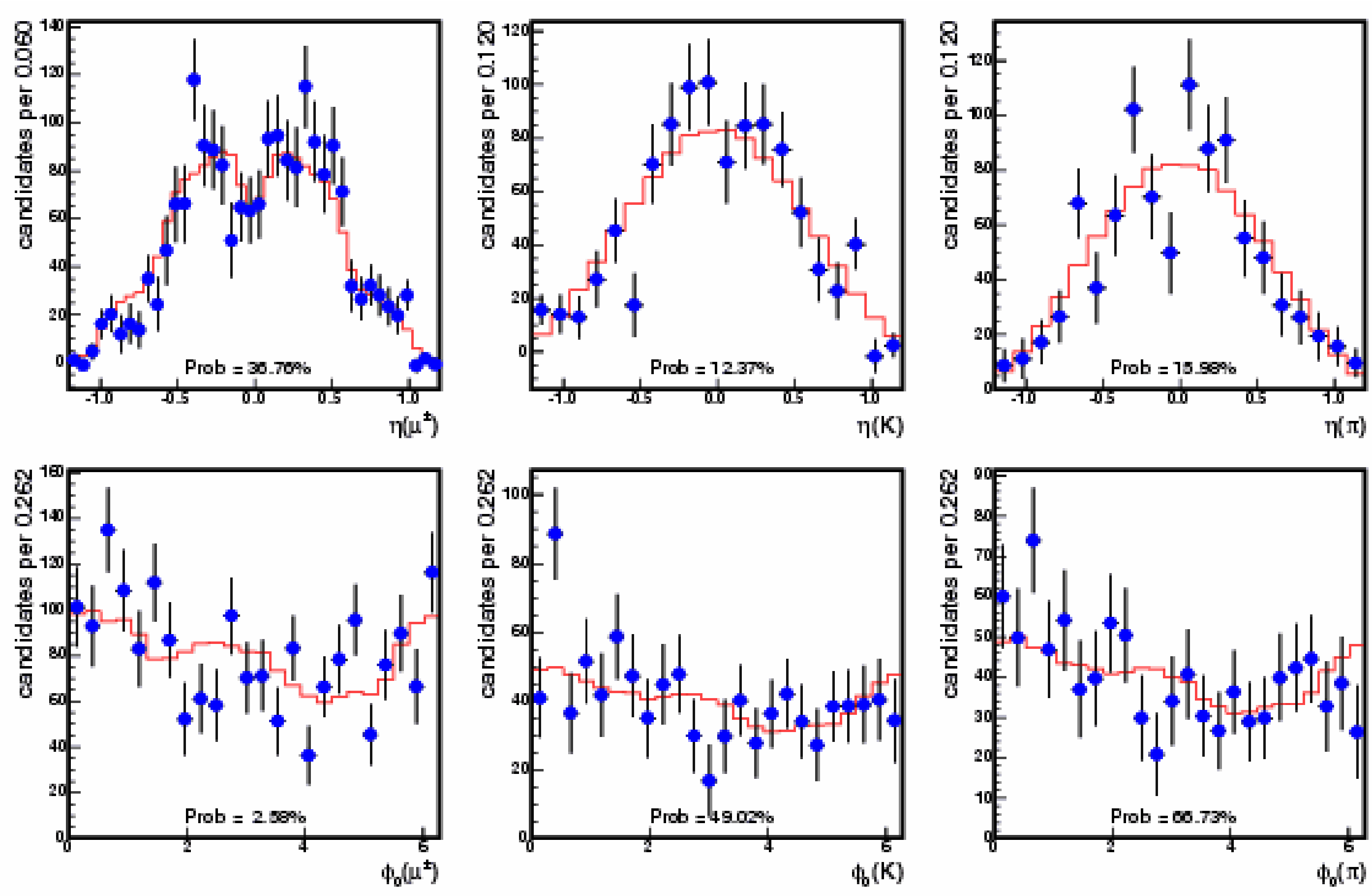




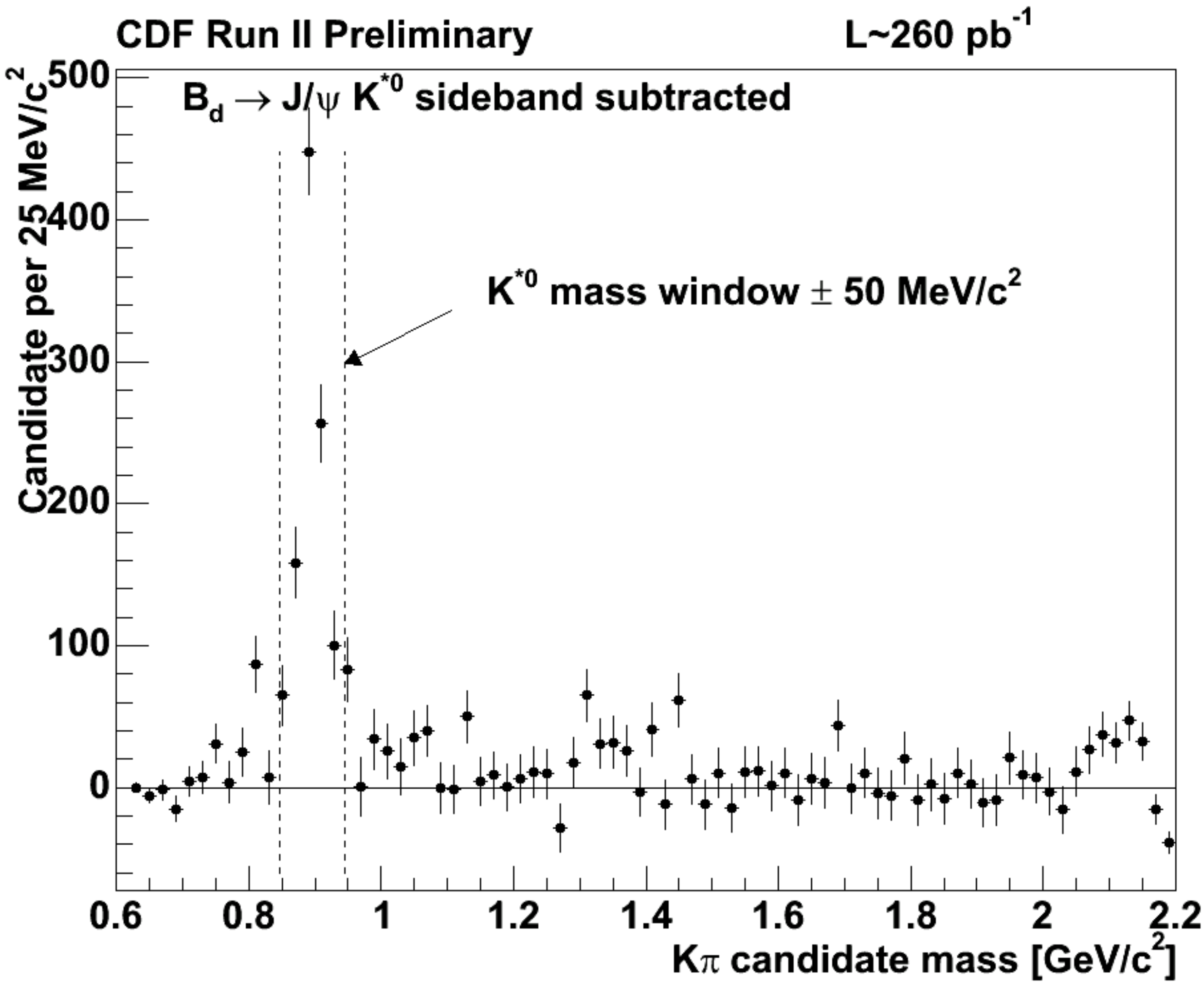
MC vs Data (B_d) (I)



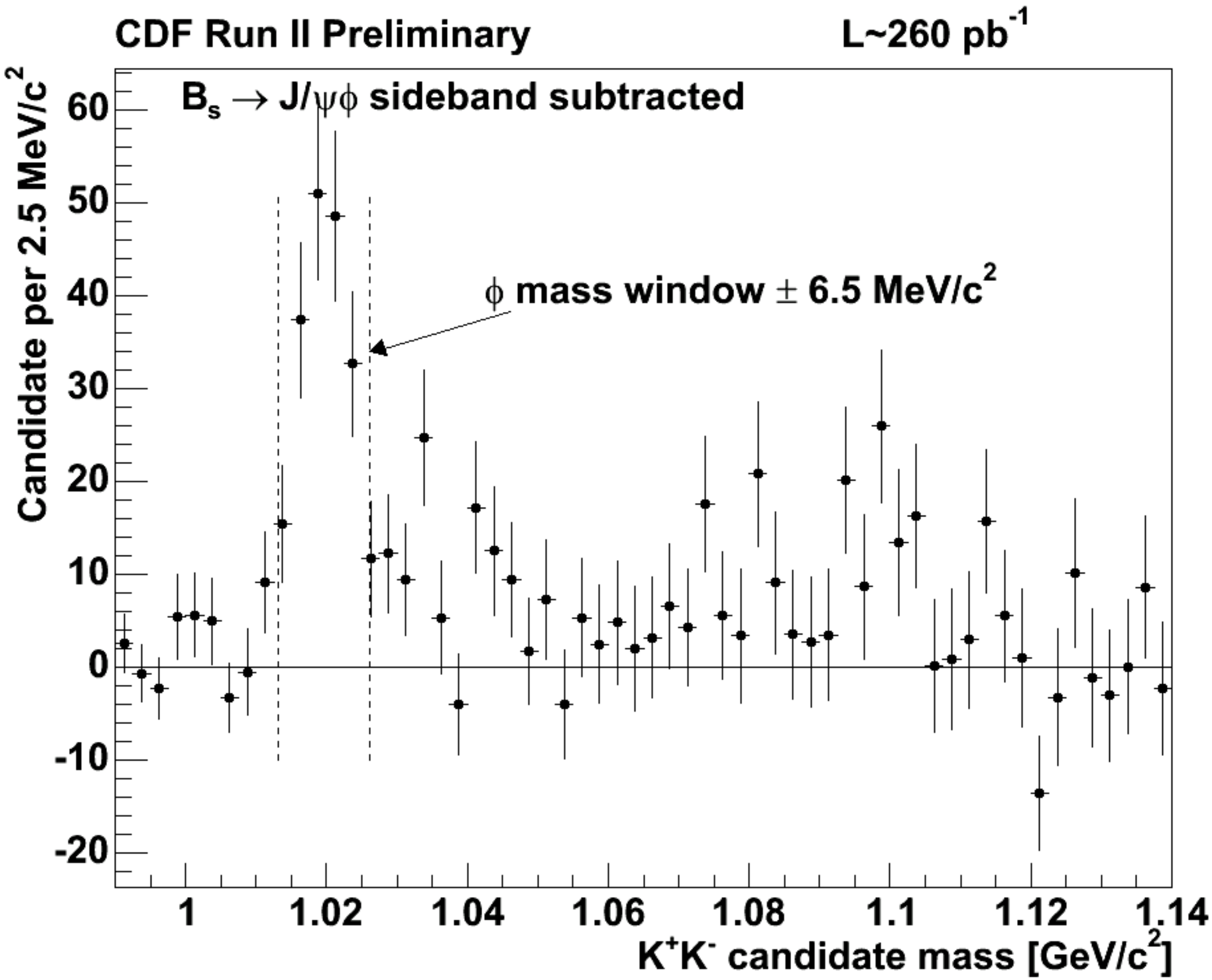
MC vs Data (B_d) (II)



B_d Sideband Subtracted $K\pi$



B_s Sideband Subtracted KK



Detector Acceptance Correction

$$\Omega(\{A_i\};\vec{\rho}) = \sum_i A_i f_i(\vec{\rho})$$

$$\Omega_{obs}(\{A_i\};\vec{\rho}) = \Omega(\{A_i\};\vec{\rho})\varepsilon(\vec{\rho})/\langle\varepsilon\rangle$$
$$= \sum_i A_i f_i(\vec{\rho})\varepsilon(\vec{\rho})/\langle\varepsilon\rangle$$

Log Likelihood function is

$$\log L = \log\left[\frac{1}{\langle\varepsilon\rangle}\Omega(\{A_i\};\vec{\rho})\varepsilon(\vec{\rho})\right]$$
$$= \log\left(\Omega(\{A_i\};\vec{\rho})\right) + \cancel{\log\left(\varepsilon(\vec{\rho})\right)} - \log\left(\langle\varepsilon\rangle\right)$$

$$\langle\varepsilon\rangle = \int_\rho d\vec{\rho}\left\{\sum_i A_i f_i(\vec{\rho})\varepsilon(\vec{\rho})\right\}$$
$$= \sum_i A_i \underbrace{\left\{\int_\rho d\vec{\rho} f_i(\vec{\rho})\varepsilon(\vec{\rho})\right\}}_{\xi_i\ ,\ fromMC}$$
$$= \sum_i A_i \xi_i,$$
$$\xi_i = \frac{1}{N_{MC}}\sum_{j=1}^{N_{MC}} f_i(\vec{\rho})$$

Does not depend on A_i, can be dropped in the minimization procedure.

Calculate ξ_i from Monte Carlo.

Include them into the likelihood function.

Detector Acceptance Correction