B_s Lifetime Difference Measurements from Tevatron

B_s lifetime difference from various channels

- $B_s \rightarrow J/\psi + \phi$
- $B_s \rightarrow K^+ K^-$
- $B_s \rightarrow D_s^{(*)+} D_s^{(*)-}$

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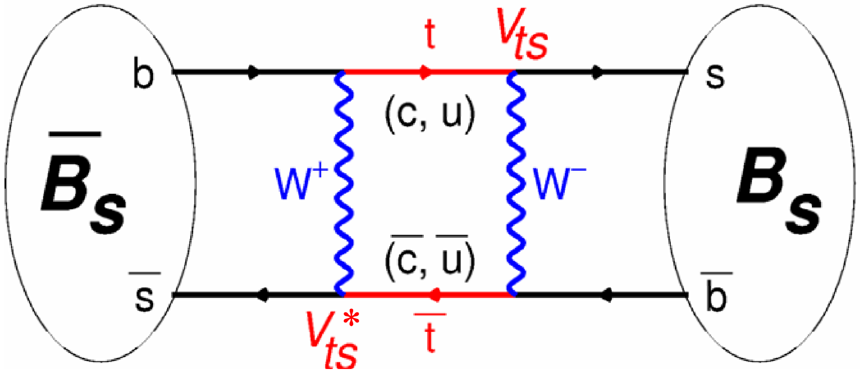
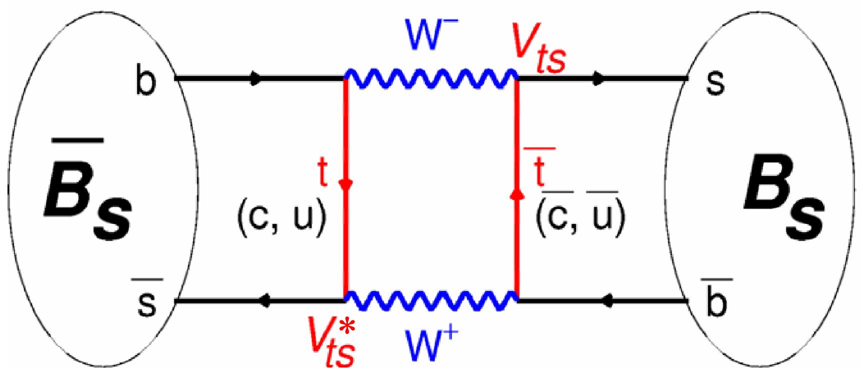
BEACH 2006, Lancaster, July 2-8, 2006

Neutral Meson Mixing





- **Quark mixing ⇒ non-diagonal Hamiltonian for** $\langle \overline{B} | H | B \rangle$

$$H = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

dominated by top quark contribution (→ M_{12})

dominated by b→cc̄s decay (→ Γ_{12})

- **Diagonalizing the Hamiltonian results in**
  - **two mass eigenstates** $|B_s^{Heavy}\rangle$ **and** $|B_s^{Light}\rangle$
  - **two masses** m_H **and** m_L**, with** $\Delta m \equiv m_H - m_L$
  - **two decay widths** Γ_H **and** Γ_L**, with** $\Delta\Gamma \equiv \Gamma_L - \Gamma_H$ **(> 0 in Standard Model)**

B_s System and CP violation

CP violating weak phase

$$e^{i\delta\phi} = \frac{V_{ts}V_{tb}^{*}}{V_{ts}^{*}V_{tb}}\frac{V_{cs}^{*}V_{cb}}{V_{cs}V_{cb}^{*}}$$

$2\beta_s \leftrightarrow \delta\phi$ (SM)

- In Standard Model, $\delta\phi \approx 2\lambda^2\eta \approx O(0.03)$, very small.
- Much larger measurement of $\delta\phi \Rightarrow$ a striking signal of new physics in $B_s - \overline{B}_s$ mixing.

$B_s \rightarrow J/\psi + \phi$

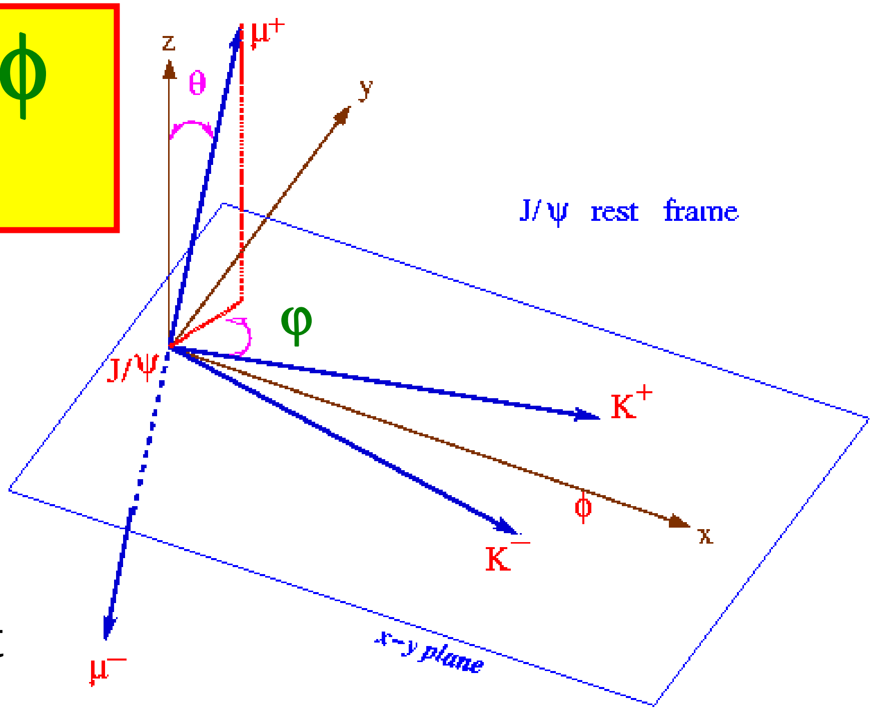
$$|B_L\rangle \approx \left(\frac{1+e^{i\delta\phi}}{2}\right)|B_s^{even}\rangle + \left(\frac{1-e^{i\delta\phi}}{2}\right)|B_s^{odd}\rangle$$

$$|B_H\rangle \approx -\left(\frac{1-e^{i\delta\phi}}{2}\right)|B_s^{even}\rangle + \left(\frac{1+e^{i\delta\phi}}{2}\right)|B_s^{odd}\rangle$$

$B_s \rightarrow K^+ K^-$ & $B_s \rightarrow D_s^{(*)+} D_s^{(*)-}$

- New physics tends to increase $\delta\phi \Rightarrow$ smaller $\Delta\Gamma$
- Any dependence on Δm_s cancels in untagged samples.

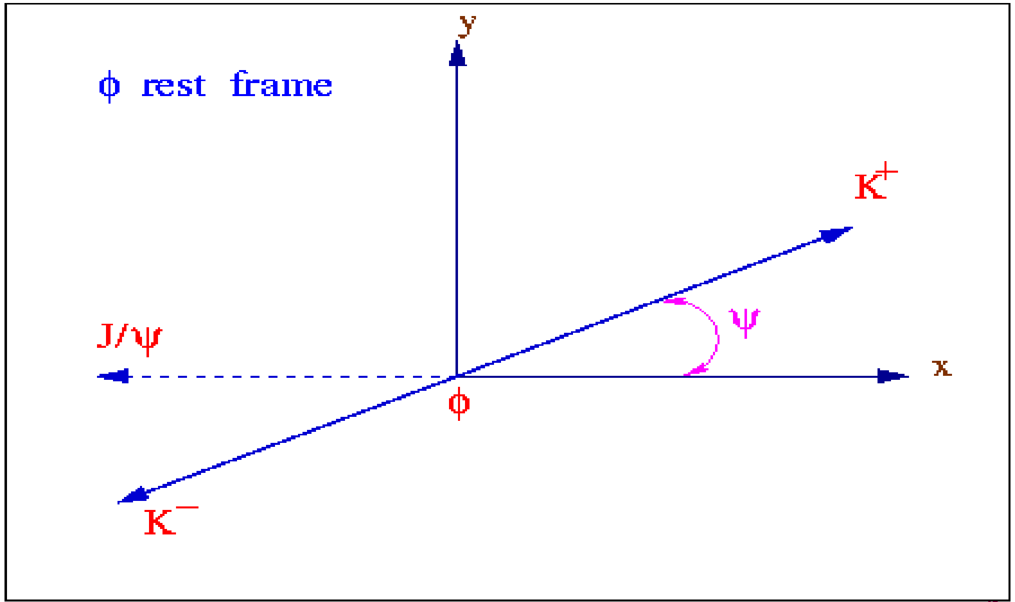
Untagged $B_s \rightarrow J/\psi + \phi$ Decay



$B_s \rightarrow J/\psi\ \phi$:
Pseudoscalar → Vector Vector decay

Three waves: S, P, D, or A_0, $A_\parallel$, $A_\perp$

Both CP-even and CP-odd present, but separated in angular distributions
⇒measure two lifetimes



S, D (Parity, CP even) :
linear combination of A_0, $A_\parallel$

P (Parity, CP odd) : $A_\perp$

$R_\perp = |A_\perp(t=0)|^2$

Untagged B_s Decay Rate in Time & Angles

$$\frac{d^3\Gamma \rightarrow J/\psi(\rightarrow l^+l^-)\,\phi(\rightarrow K^+K^-)}{d\cos\theta\, d\phi\, d\cos\psi\, dt} \propto \frac{9}{16\pi}\Big[\, 2|A_0(0)|^2 e^{-\Gamma_L t}\cos^2\psi(1-\sin^2\theta\cos^2\phi)$$

$$+ \sin^2\psi\left\{|A_{||}(0)|^2 e^{-\Gamma_L t}(1-\sin^2\theta\sin^2\phi) + |A_\perp(0)|^2 e^{-\Gamma_H t}\sin^2\theta\right\}$$

$$+ \frac{1}{\sqrt{2}}\sin 2\psi\left\{|A_0(0)||A_\perp(0)|\cos(\delta_2-\delta_1)e^{-\Gamma_L t}\sin^2\theta\sin^2 2\phi\right\}$$

$$+ \left\{\frac{1}{\sqrt{2}}|A_0(0)||A_\perp(0)|\cos\delta_2\sin 2\psi\sin 2\theta\cos\phi\right\}\frac{1}{2}\left(e^{-\Gamma_H t} - e^{-\Gamma_L t}\right)\delta\phi$$

$$- \left\{\frac{1}{\sqrt{2}}|A_{||}(0)||A_\perp(0)|\cos\delta_1\sin^2\psi\sin 2\theta\sin\phi\right\}\frac{1}{2}\left(e^{-\Gamma_H t} - e^{-\Gamma_L t}\right)\delta\phi\,\Big]\; H(\cos\psi)\,F(\phi)\,G(\cos\theta)$$

correction for acceptances, kinematic cuts

- $\delta_1 \equiv \mathrm{Arg}[A_{||}(0)^* A_\perp(0)]$ and $\delta_2 \equiv \mathrm{Arg}[A_0(0)^* A_\perp(0)]$ are CP-conserving strong phases
- No dependence on Δm_s

Maximum Likelihood Fit

Simultaneous fit to mass, proper decay length and 3 angles using an unbinned maximum log-likelihood method

$$\mathcal{L} = \prod_{i=1}^{N} [\, f_{sig}\, \mathcal{F}^{i}_{sig} + (1 - f_{sig})\, \mathcal{F}^{i}_{bck} \,]$$

30 parameters:	1	f_{sig} = signal fraction
	2	signal mass, width
	3	$A_\perp$, $\lvert A_0\rvert^2$-$\lvert A_{\parallel}\rvert^2$, 1 strong phase
	1	$c\tau = c / \bar{\Gamma}$, $\bar{\Gamma} = (\Gamma_L + \Gamma_H)/2$
	1	$\Delta\Gamma = \Gamma_L - \Gamma_H$
	3	bkg mass (1 prompt, 2 long-lived)
	1	σ(ct) scale
	6	bkg ct shape
	4	bkg transversity (2 prmpt + 2 long-lived)
	4	bkg angle φ (2 prompt + 2 long-lived)
	2	bkg angle ψ (1 prompt + 1 long-lived)
	2	bkg "interference" (1 prompt + 1 bkg)

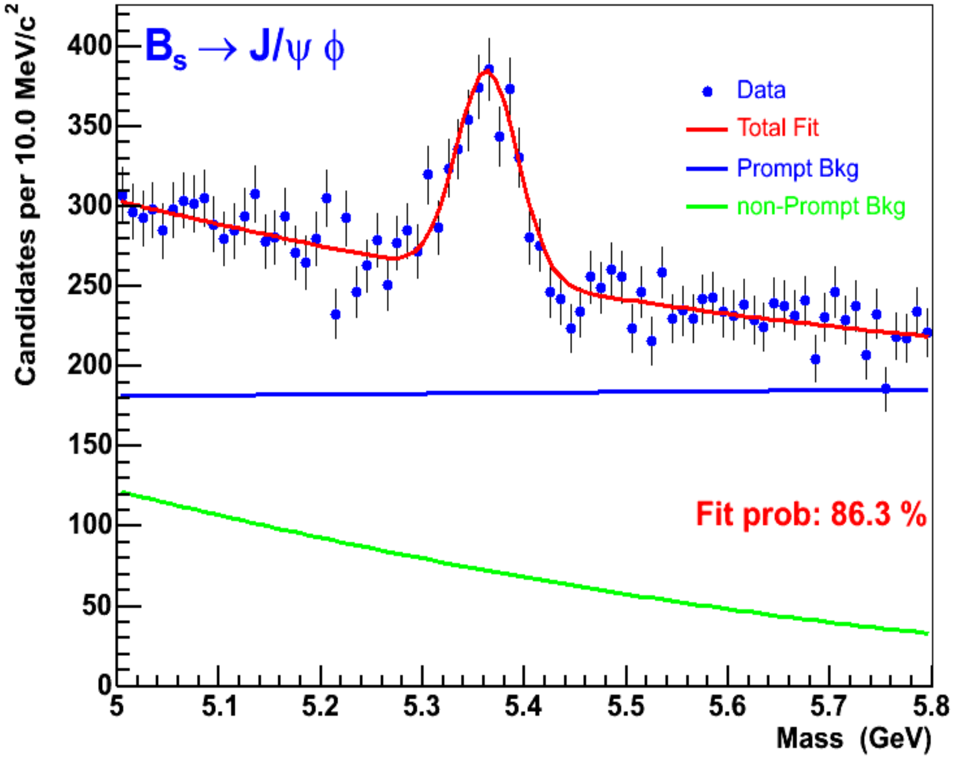
set $\delta\phi = 0$

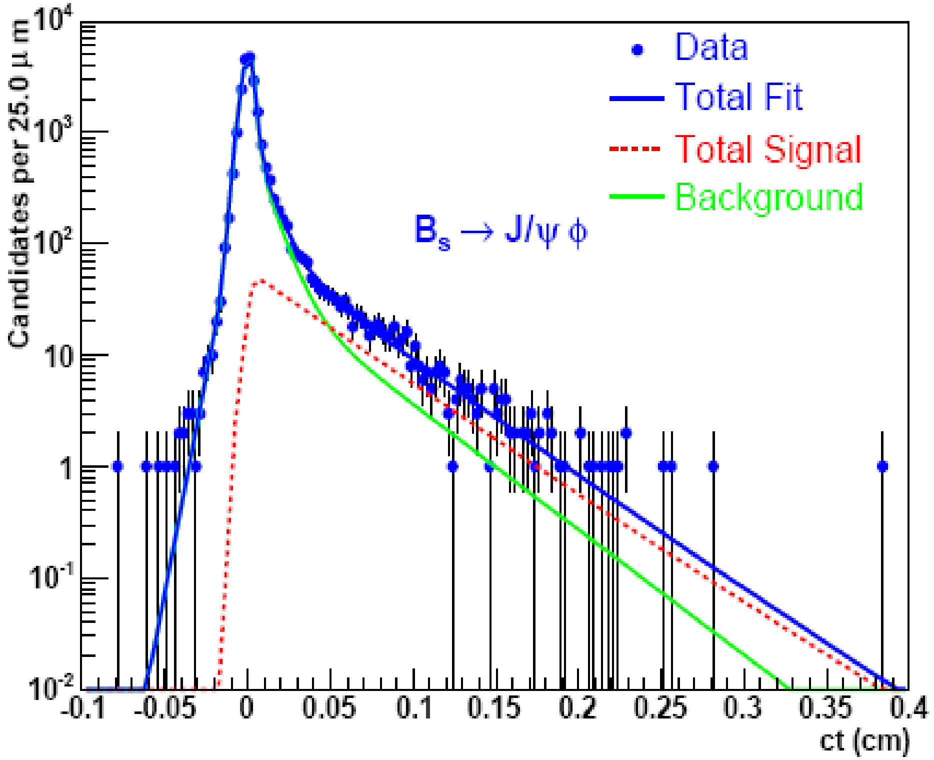
- CDF should have similar no. of parameters

$B_s \to J/\psi + \phi$ and $\Delta\Gamma$

All events

Preliminary **~0.8 fb^{-1}**



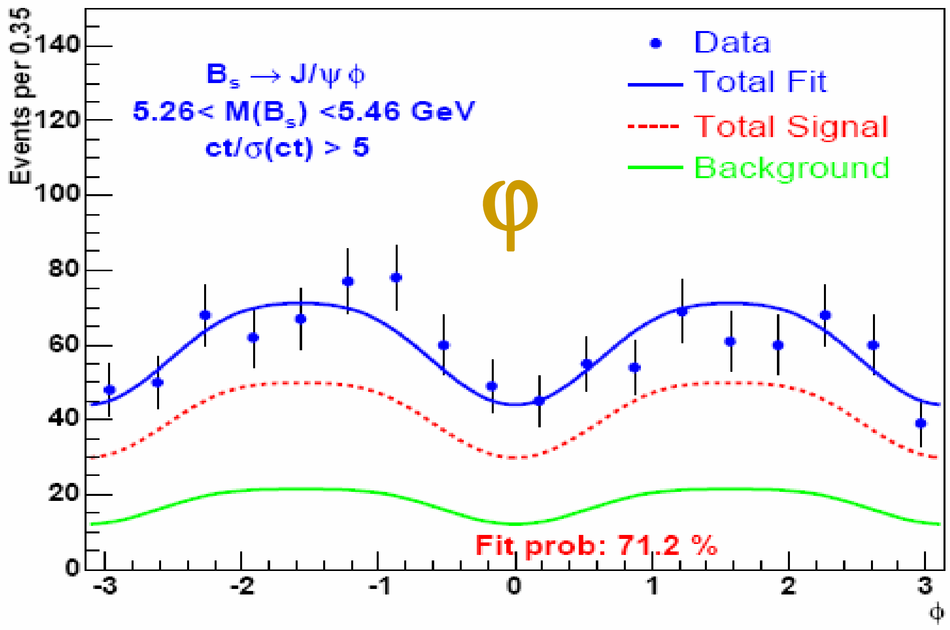


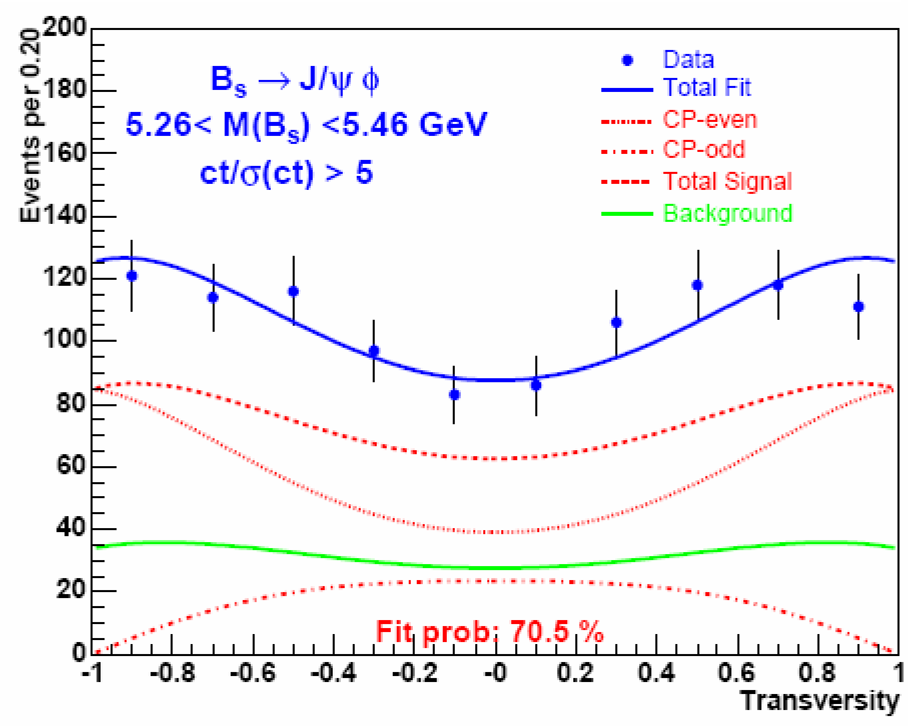
3 angle θ, φ, ψ analysis : **$N_{signals}$ = 978 ± 45**

D0 (PRL 2005) used 1 angle, θ, **513 events**

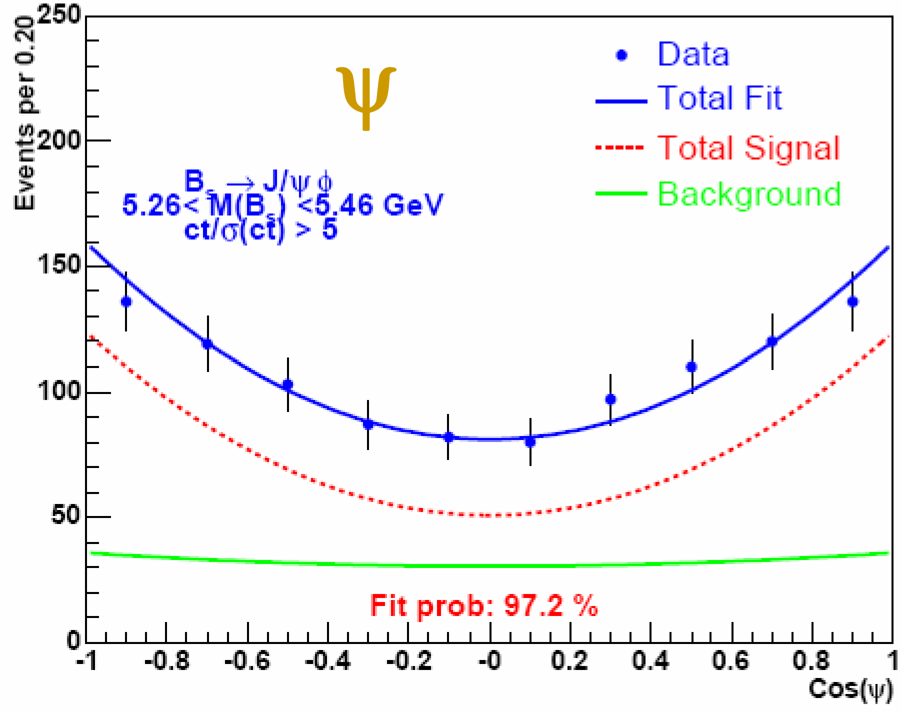
Data:

Fit projections in signal regions

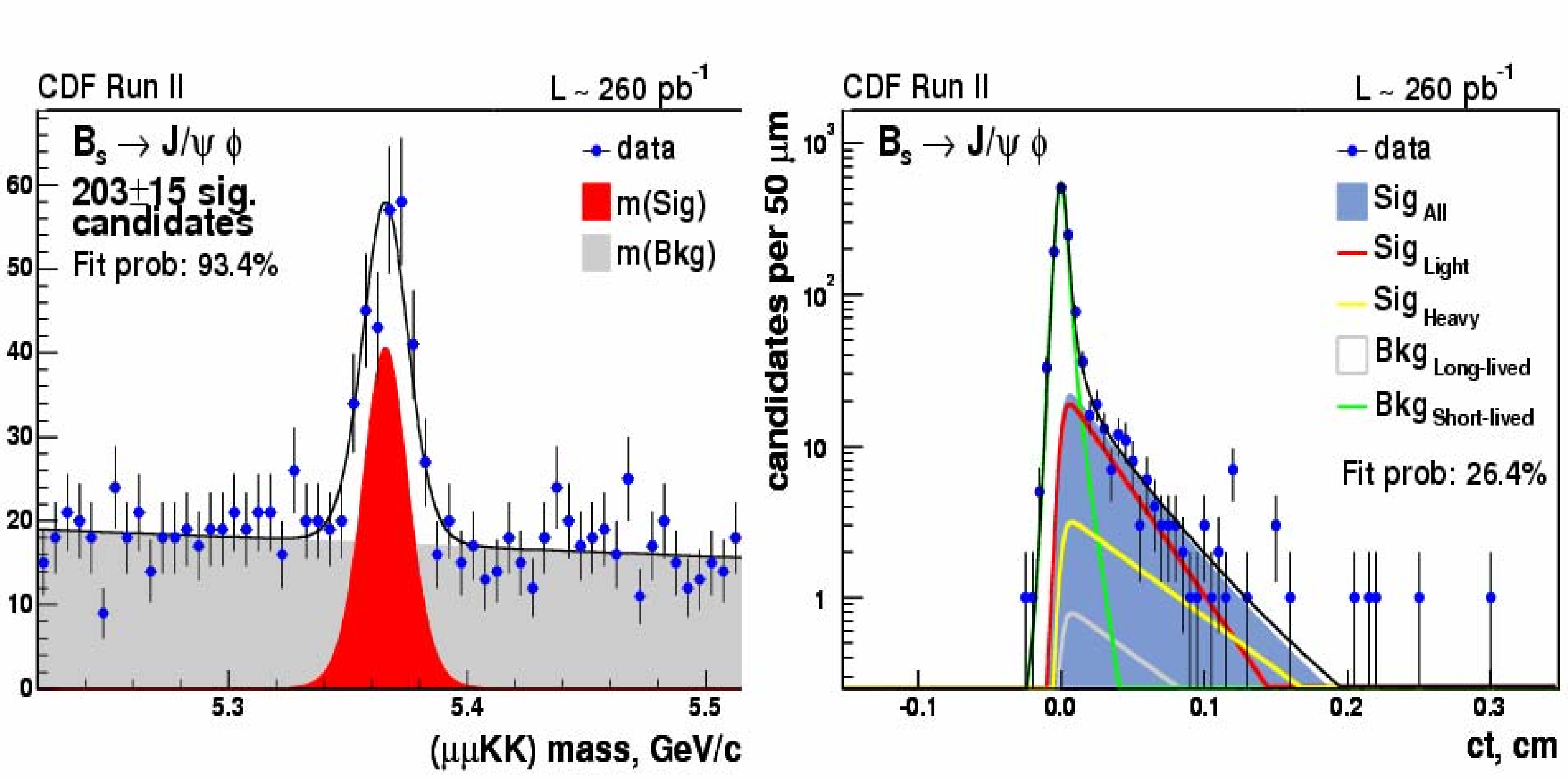




θ (transversity)



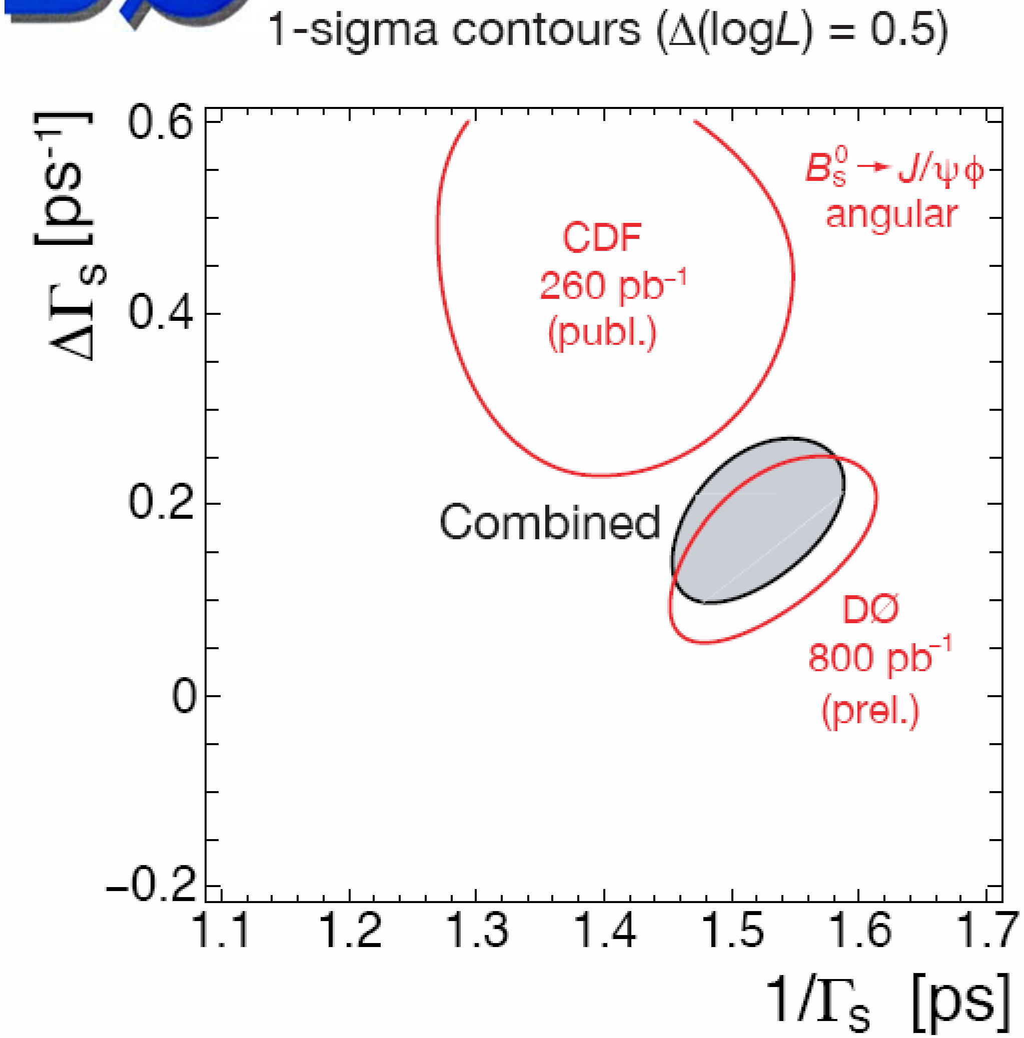
Earlier, PRL 94, 101803, 2005, CDF has used a similar 3 angle (θ, ϕ, ψ) fit/analysis with 260 pb^{-1} of data



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

$$\overline{\tau}(B_s^0) = 1.53 \pm 0.08^{+0.01}_{-0.03} \text{ ps}$$
$$\Delta\Gamma = 0.15 \pm 0.10^{+0.03}_{-0.04} \text{ ps}^{-1}$$
$$R_\perp = |A_\perp(0)|^2 = 0.19 \pm 0.05 \pm 0.01$$
$$|A_0(0)|^2 - |A_{||}(0)|^2 = 0.35 \pm 0.07 \pm 0.01$$
$$\delta_1 - \delta_2 = 2.5 \pm 0.4 \pm 0.02$$

- **With δ_1 free and $\delta_2 = 0$, we obtain $\delta\phi = -0.9 \pm 0.7$;**
- **CP-violating angle $\delta\phi$ ~consistent with 0 (no CP violation) within statistical uncertainty of ± 0.7.**
- **Working on to constrain all these δ_1/δ_2 and $\delta\phi$ better.**



R. Van Kooten: hep-ex/0606005

Combined:

$$\Delta\Gamma = 0.18 \pm 0.09 \text{ ps}^{-1}$$

$$\bar{\tau} = 1/\Gamma$$
$$= 1.520 \pm 0.068 \text{ ps}$$

$B_s \to K^+K^-$ lifetime analysis

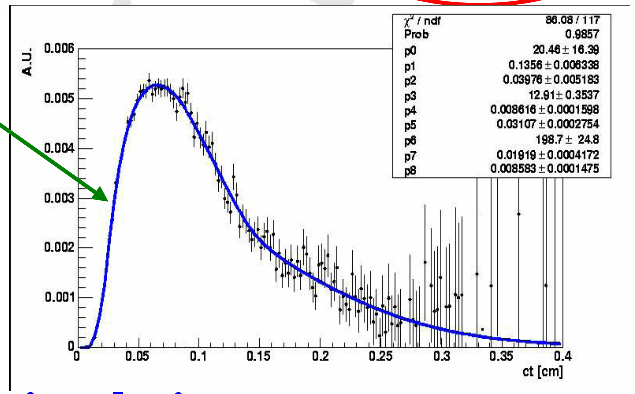
CP-even ⇒ lifetime of the CP-even state

Add lifetime information to the fit of composition (of various hadronic states):

$$\mathscr{L} \sim \wp^m(m_{\pi\pi}|\alpha)\wp^p(\alpha, p_{\rm tot})\wp^{\rm PID}(dE/dx_1, dE/dx_2|\alpha, p_{\rm tot})\wp^{\rm life}(ct).$$

$$\wp^{\rm life}(ct) = \exp(ct) \times {\rm Gauss}(ct) \times \varepsilon(ct)$$

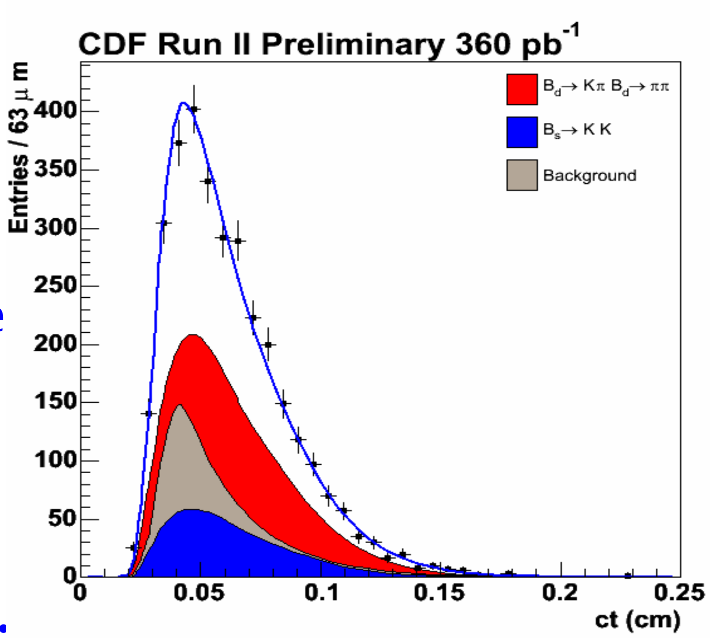
decay **detector smearing** **trigger bias**



- **Trigger bias for signal is extracted from detailed simulation.**
- **Procedure validated in unbiased *B → J/ψX* decays from dimuon trigger.**
- **Check that lifetime fits of samples <u>with/without</u> applying track-trigger cuts yield consistent results.**
- **Lifetime p.d.f for background is extracted from higher mass data sideband.**

$B_s \rightarrow K^+K^-$ lifetime results (360 pb^{-1})

	$c\tau(B^0)$ [μm]	$c\tau(B_s^0 \rightarrow K^+K^-)$ [μm]
both free	452 ± 24	463 ± 56
$c\tau(B^0)$ constrained to PDG	–	458 ± 53

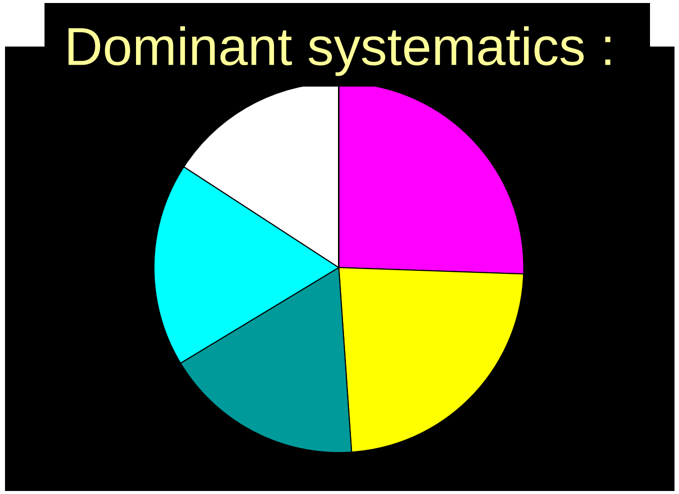


$B_s \rightarrow K^+K^-$ is CP-even (~ 5% uncertainty): has the lifetime of "light B_s" :

$$\tau_L = 1.53 \pm 0.18\ (stat.) \pm 0.02\ (syst.)\text{ps}$$

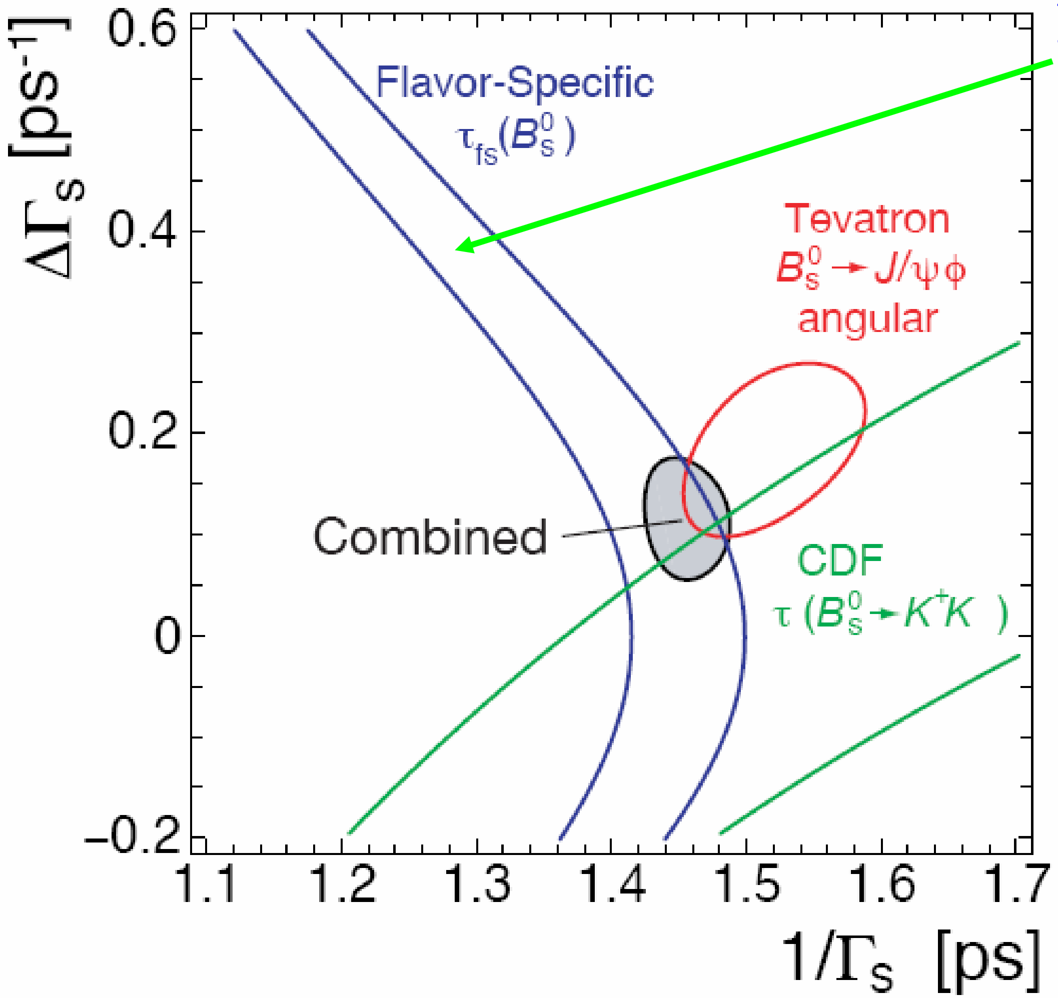
Combine with HFAG average $(\tau_L^2 + \tau_H^2)/(\tau_L + \tau_H)$:

$$\frac{\Delta\Gamma_s^{\text{CP}}}{\Gamma_s} = -0.08 \pm 0.23\ (stat.) \pm 0.03\ (syst.)$$



- **detector alignment;**
- **dE/dx model;**
- **input $p_T(B)$ in simulation;**
- **trigger-bias.**
- **lifetime model of background;**

1-sigma contours ($\Delta(\log L) = 0.5$)



R. Van Kooten: [hep-ex/0606005](hep-ex/0606005)

Precise measurement of flavor-specific decays further constrain $\Delta\Gamma_s$ and Γ_s.

See E. de la Cruz-Burello's talk !

- Flavor-specific decays, e.g.,

  $B_s^0 \to D_s^+ \mu^- \nu \quad \bar{B}_s^0 \to D_s^- \mu^+ \nu$

  50% CP odd, 50% CP even at time, $t = 0$

- Fit to single exponential,

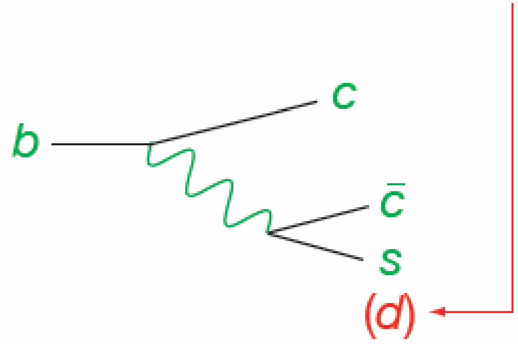
$$\tau_{fs}(B_s^0) = \frac{1}{\Gamma_s} \frac{1 + (\Delta\Gamma_s/2\Gamma_s)^2}{1 - (\Delta\Gamma_s/2\Gamma_s)^2}$$

$B_s \rightarrow D_s^{(*)+} D_s^{(*)-}$ *and* $\Delta\Gamma_s$

- Γ_{12} dominated by decay $b \rightarrow c\bar{c}s$ from decays into final states common to both B_s^0 $(\bar{b}s)$ and $\bar{B}_s^0$ $(b\bar{s})$

- $\Delta\Gamma_s$: CP-even final states, $\Delta\Gamma_s \uparrow$
  CP-odd final states, $\Delta\Gamma_s \downarrow$

For B_d^0, analogous diagram Cabibbo suppressed, Γ_{12} negligible



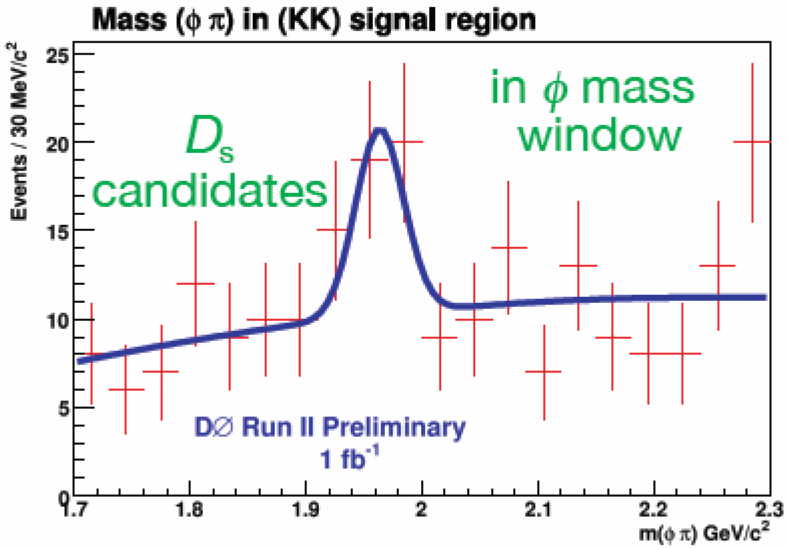
$B_s^0 \rightarrow D_s^+ D_s^-$ is pure CP even, and under various theoretical assumptions,

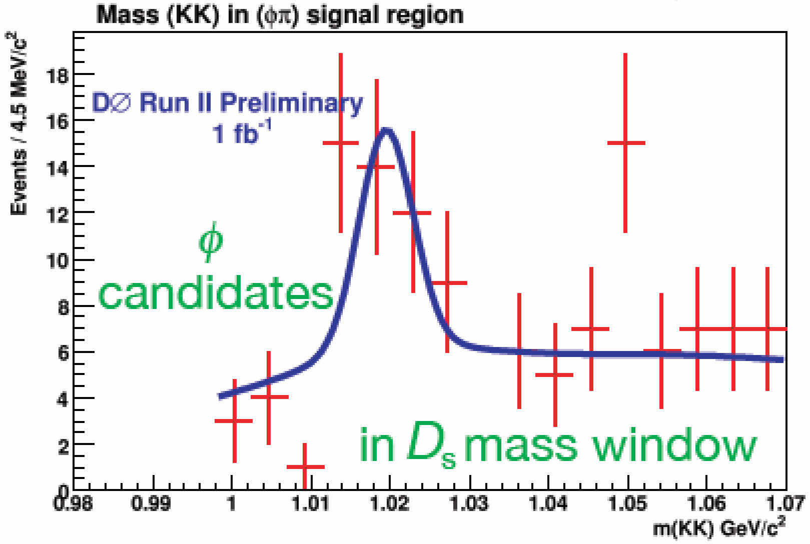
$B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-}$ inclusive, also CP even to ~5%

(Phys. Lett. **B316** (1993) 567)

Likely needs re-examination!!

$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} \sim \frac{2Br(B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-})}{1 - Br(B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-})/2}$$





- Measure ratio:

$$R = \frac{Br(B_s^0 \to D_s^{(*)+} D_s^{(*)-}) \cdot Br(D_s \to \phi \mu \nu)}{Br(B_s^0 \to \mu \nu D_s^{(*)-})}$$

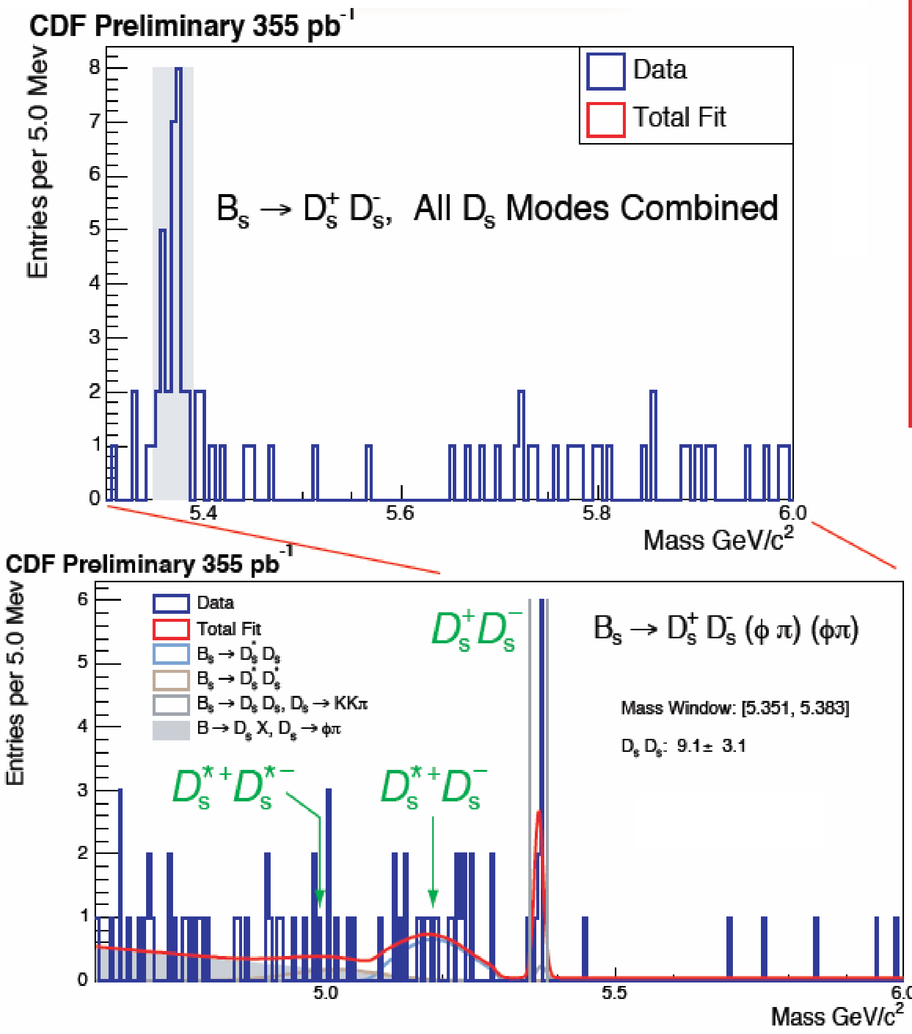
(many systematics cancel in the ratio)

- Use new $Br(D_s \to \phi \pi)$ from BaBar, combined w/ PDG :

$Br(B_s^0 \to \mu \nu D_s^{(*)-})$, $Br(D_s \to \phi \mu \nu)$

$$Br(B_s^0 \to D_s^{(*)+} D_s^{(*)-}) = \\ = 0.071 \pm 0.032\ (\text{stat})\ ^{+0.029}_{-0.025}\ (\text{syst})$$

$B_s \rightarrow D_S^+ D_S^-$ (exclusive hadronic mode)

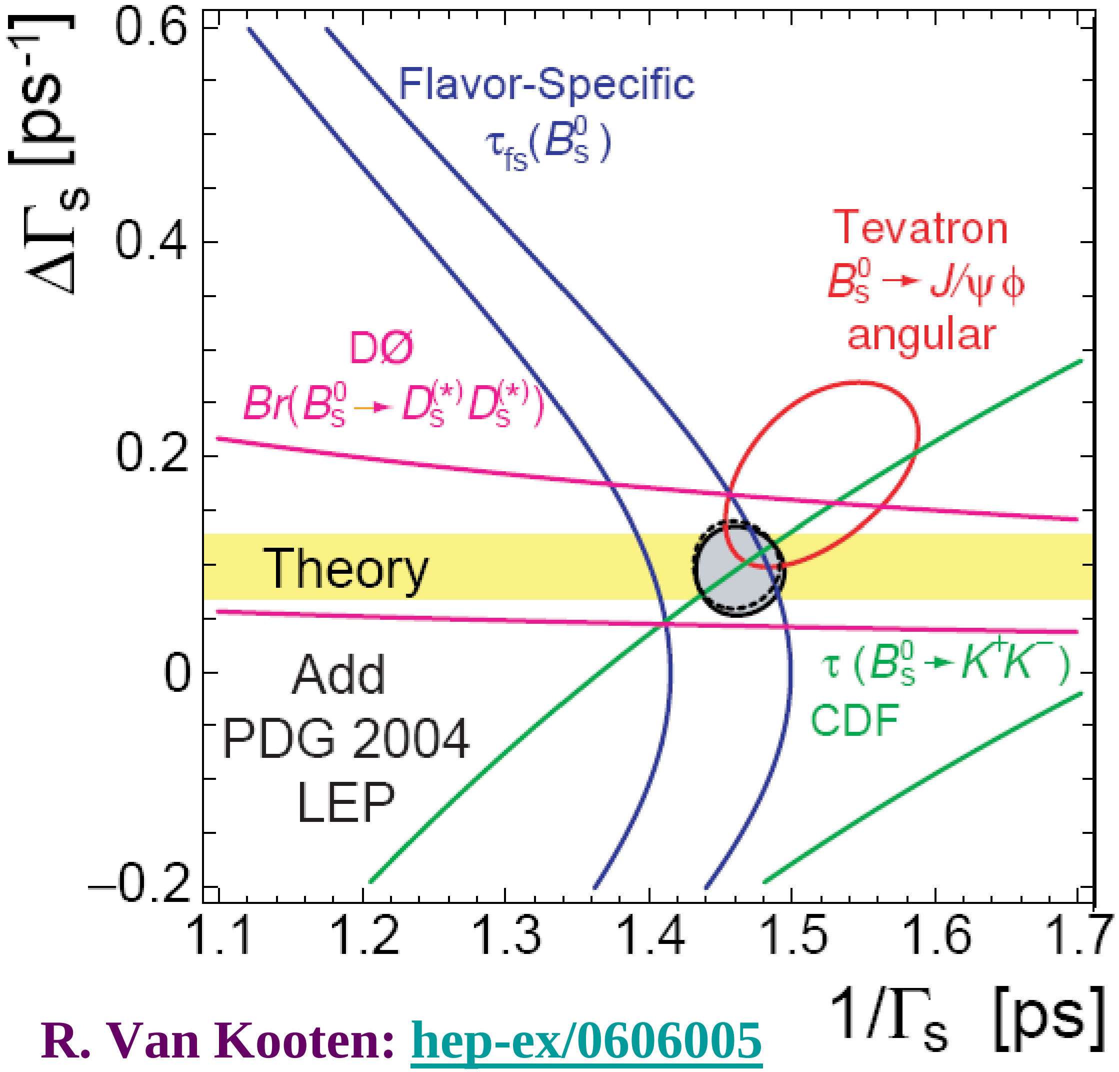


$$\frac{Br(B_s^0 \rightarrow D_s^+ D_s^-)}{Br(B^0 \rightarrow D_s^+ D^-)} =$$

$$= 1.67 \pm 0.41\ (\text{stat.}) \pm 0.12\ (\text{syst.}) \pm 0.24\ (f_s/f_d) \pm 0.39\ (Br_{\phi\pi})$$

Use Br($D_s \rightarrow \phi\pi$) from PDG

- **1st observation of this fully reconstructed decay**
- **Working on to extract $\Delta\Gamma_S$**
- **good prospect with 1 fb^{-1}**



- Unofficial world average

$$\Delta\Gamma_s = 0.097\,^{+0.041}_{-0.042}\ \mathrm{ps}^{-1}$$

$$\bar{\tau} = \frac{1}{\Gamma_s} = 1.461 \pm 0.030\ \mathrm{ps}$$

2.3 σ from zero, new physics tends to reduce the measured $\Delta\Gamma_s$

R. Van Kooten: hep-ex/0606005

$\frac{\Delta\Gamma_s}{\Delta m_s}$ comparison between expt. and theory

- **Updating from Phys. Lett. B 459, 631 (1999) by U. Nierste:**

⇒ SM prediction:

$$\frac{\Delta\Gamma_s}{\Delta m_s} = (47 \pm 8) \times 10^{-4}$$

- **Expt. meas. from $\Delta\Gamma_s$ and latest Δm_s:**

$$\frac{\Delta\Gamma_s}{\Delta m_s} = \frac{0.097 \pm 0.042 \text{ ps}^{-1}}{17.31^{+0.33}_{-0.18} \pm 0.07 \text{ ps}^{-1}}$$

$$= (56 \pm 24) \times 10^{-4}$$

Disappointingly in agreement with Standard Model prediction !

Summary

$$\Delta\Gamma_s = 0.097\,^{+0.041}_{-0.042}\ \mathrm{ps}^{-1} \qquad \bar{\tau} = \frac{1}{\Gamma_s} = 1.461 \pm 0.030\ \mathrm{ps}$$

- **CP eigenstate mixures and branching fraction measurements now give a "world average" of $\Delta\Gamma_s$ ~2.3 σ away from zero;**
- **Results are consistent with SM so far;**
- **More results from Tevatron (and elsewhere) will pin $\Delta\Gamma_s$ down to greater accuracy.**

BACKUP

Lifetime Difference & CP violation

- $B_s \to J/\psi\,\phi$: **Pseudoscalar → Vector – Vector**
- **Decay amplitude decomposed into 3 linear polarization states**
  - A_0 **= S + D wave ⇒ P even**
  - $A_{\parallel}$ **= S + D wave ⇒ P even**
  - $A_{\perp}$ **= P wave ⇒ P odd**
- **If CP violation neglected ⇒ interpreted as lifetimes of 2 mass eigenstates:**
  - $B_{s,\mathrm{Light}} \approx$ **CP even**
  - $B_{s,\mathrm{Heavy}} \approx$ **CP odd**
  - **angular distributions are different**
- **Angular analysis separates CP eigenstates ⇒ measure two lifetimes**

CKM Matrix and Unitarity triangle

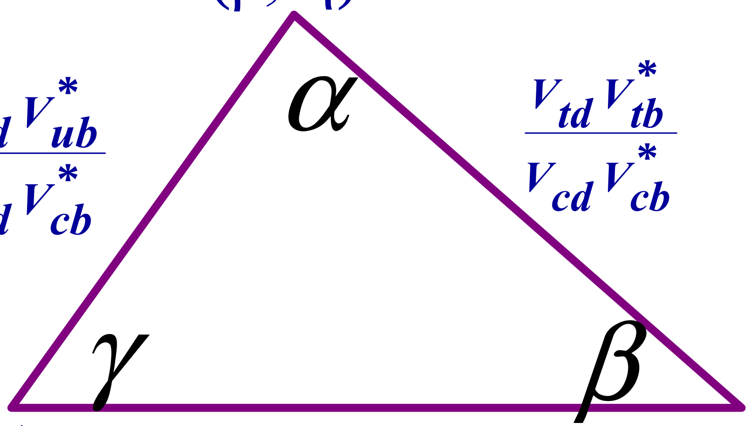
Relates quark mass and weak eigenstates

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

SM: CP-violating processes solely related to one phase in CKM.

'bd'
(THE unitary triangle)
Large effort in B physics
Mainly at B factories

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \qquad \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}$$



'bs'
(A 'squashed' unitary triangle)

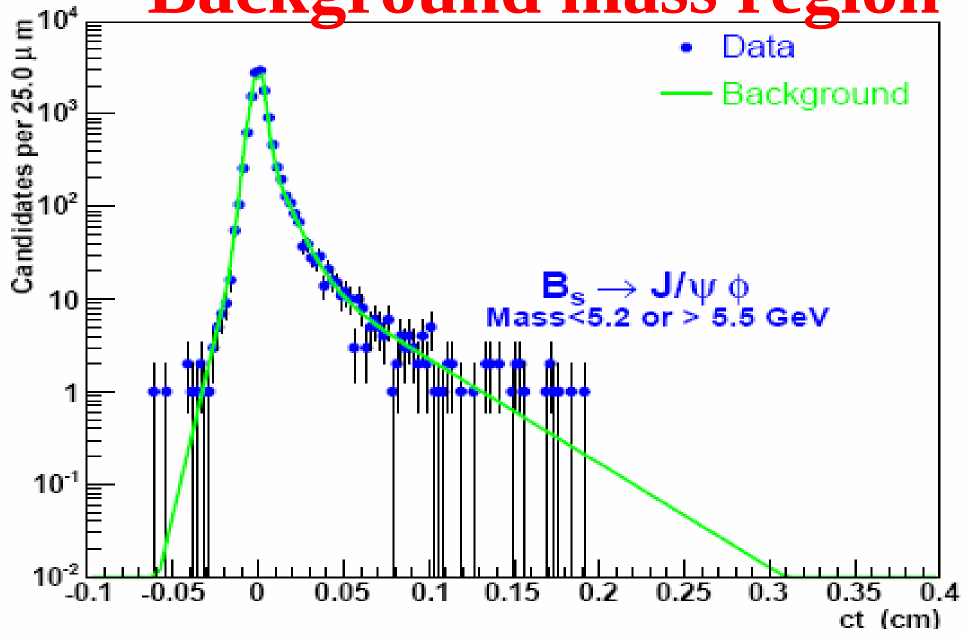
$\beta \rightarrow \beta_s$, small in SM

Interesting to check how small/big β_s really is.

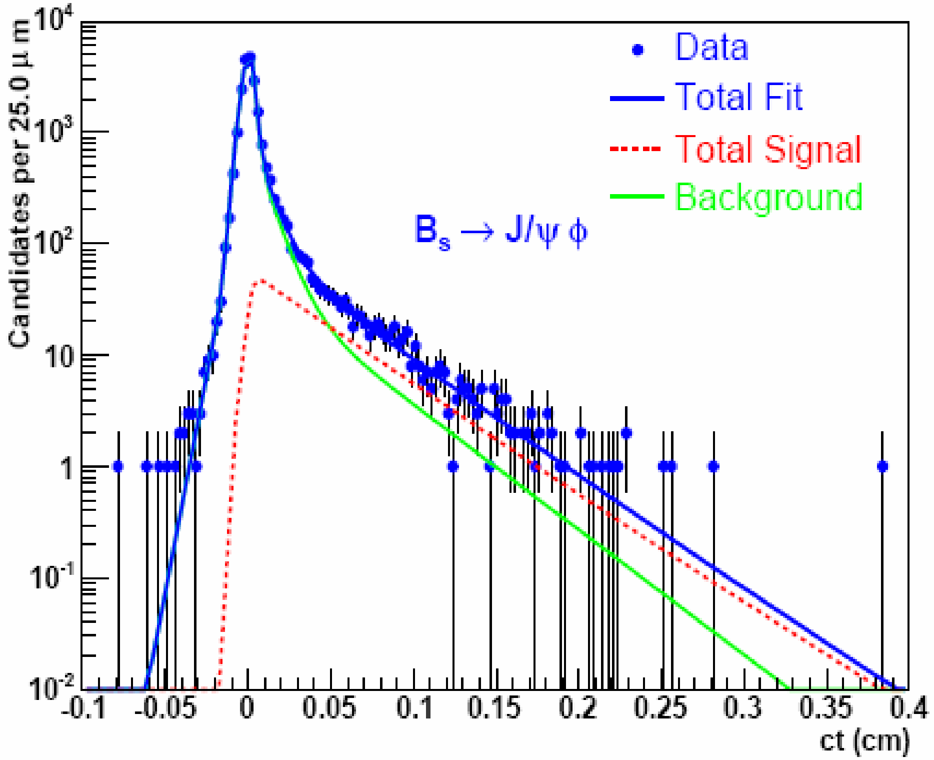
Currently: Tevatron domain

Fit projection (lifetime)

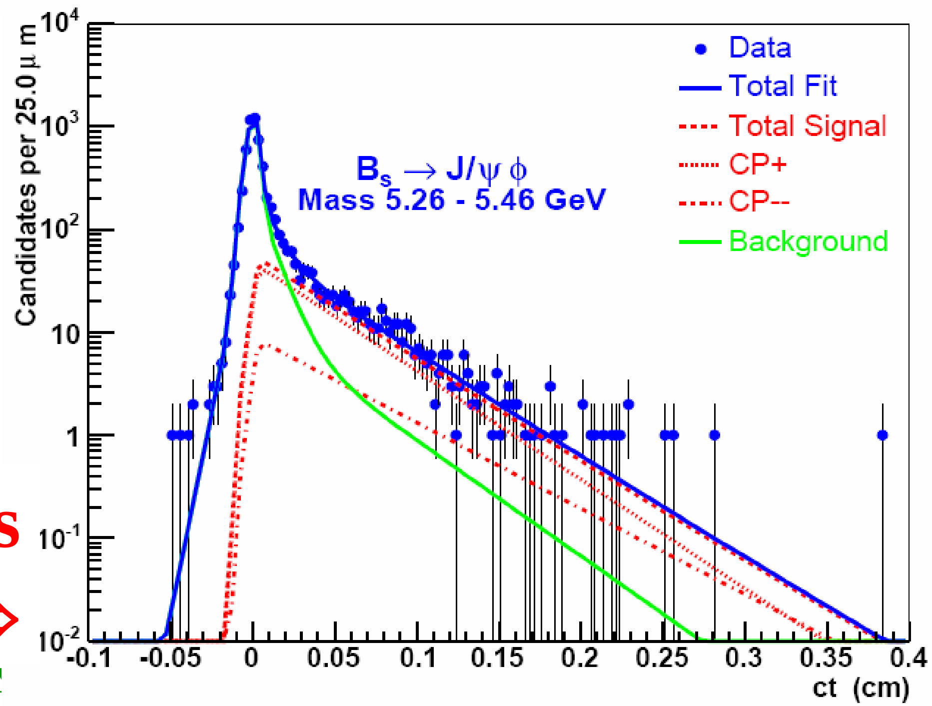
Background mass region



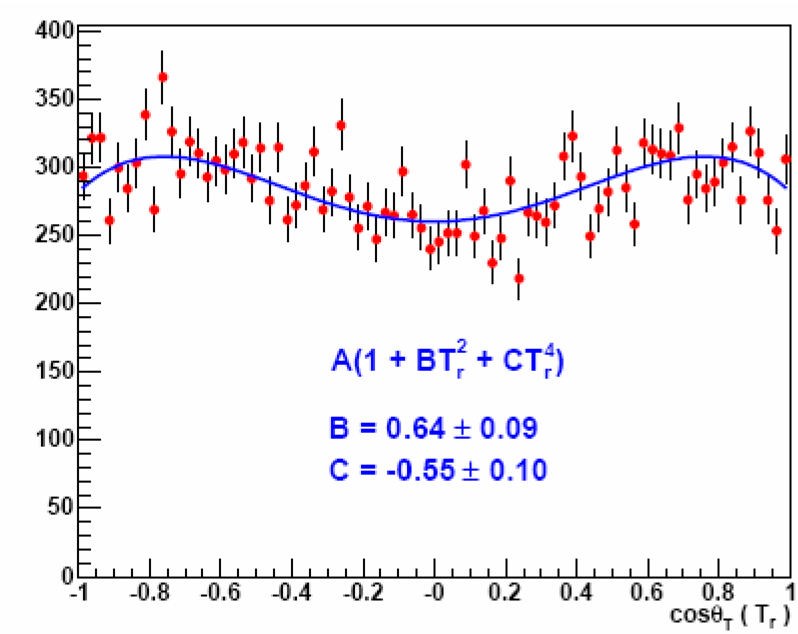
All events



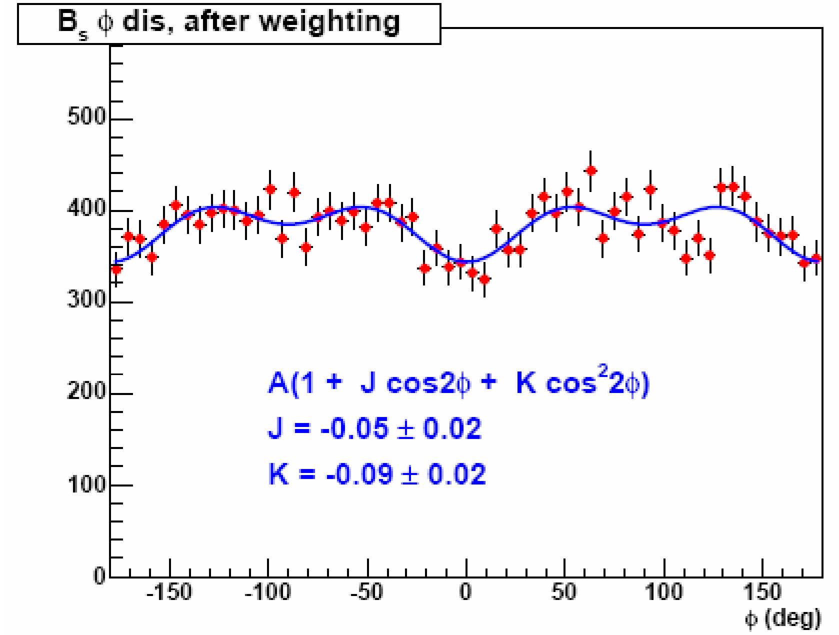
Signal mass region ⇒



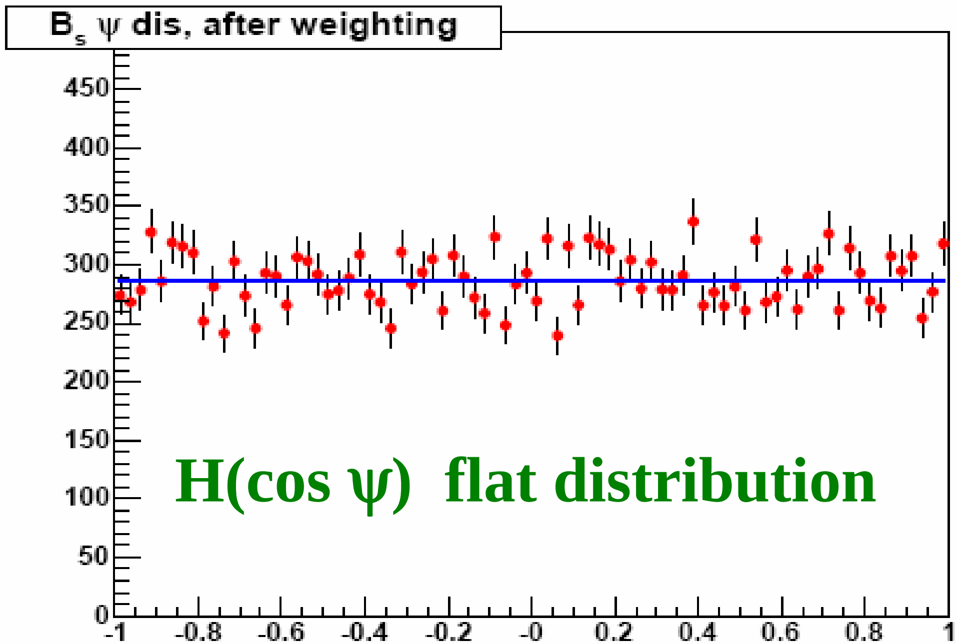
Detector Acceptance (MC & data)



$G(\cos\theta) = 1 + B\cos^2\theta + C\cos^4\theta$



$F(\phi) = 1 + J\cos(2\phi) + K\cos^2(2\phi)$



H(cos ψ) flat distribution

Systematics

Source	$c\tau(B_s^0)$ μm	$\Delta\Gamma$ ps^{-1}	$R_\perp$	$\lvert A_0(0)\rvert^2 - \lvert A_\parallel(0)\rvert^2$	$\delta_1 - \delta_2$
Acceptance vs. θ, φ, ψ	± 0.5	± 0.001	± 0.003	± 0.01	± 0.02
Procedure test	± 2.0	± 0.025	± 0.01	–	–
Detector alignment	± 2.0	–	–	–	–
ct definition	1.3	0.001	-0.001	-0.002	-0.009
"Outlier"	-7.5	-0.03	0.01	0.0	0.0
Total	$-8.0, +3.2$	$-0.04, +0.03$	± 0.01	± 0.01	± 0.02

- **One "outlyer" → treat its effect as systematic uncertainty**

  Event Run #: 210344 Event #:23385781

  unlikely signal or background

  Signal: mass 2.3 σ from peak, lifetime 8.5 x mean

  Bkg: 10.2 x mean for "right slope long"

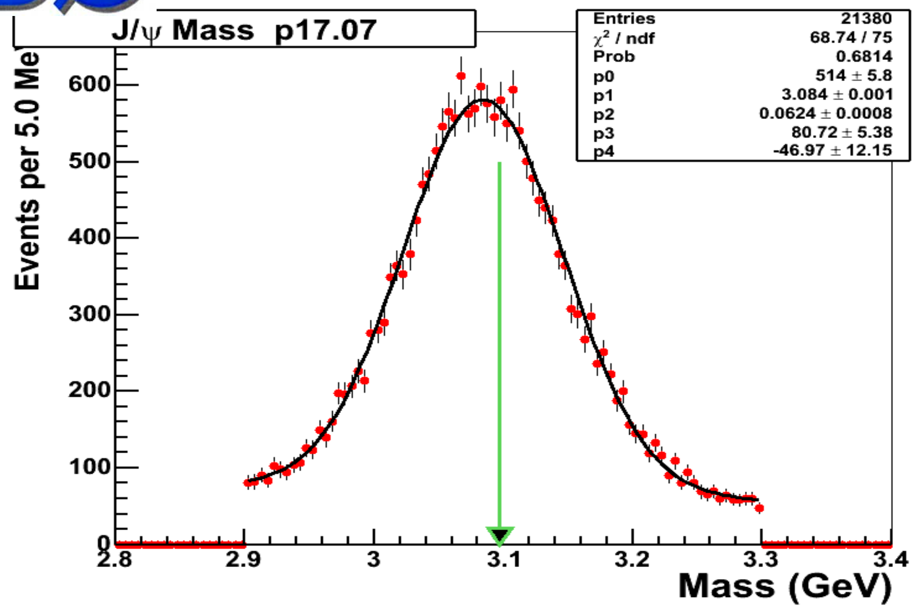
Some selection cuts

data before last Tevatron shutdown

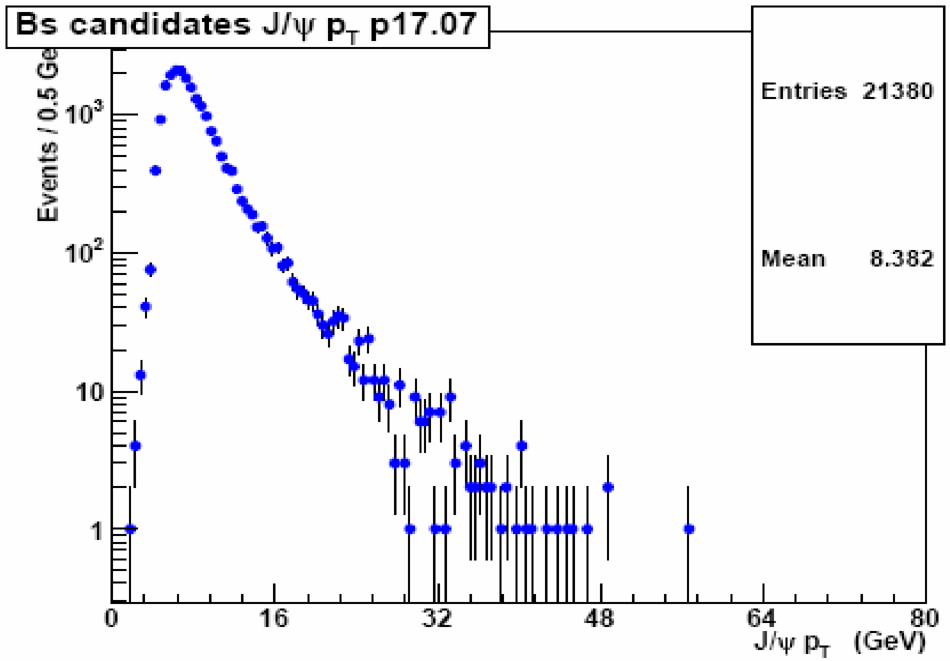
B_s candidate mass	$5.0 < M(J/\psi,\phi) < 5.8$ GeV
J/ψ candidate mass	$2.9 < M(\mu^+,\mu^-) < 3.3$ GeV
Non-J/ψ meson mass	$1.01 < M(K^+,K^-) < 1.03$ GeV
B_s p_T	> 6.0 GeV
J/ψ p_T	> 4.0 GeV if $\lvert\eta\rvert < 1.0$
ϕ p_T	> 1.5 GeV
J/ψ, ϕ χ^2	< 10.0
$K^\pm$ p_T	> 0.7 GeV
SMT hits each track (incl. fdisk)	>1
SMT+CFT hits on track	>7
B candidate decay length error	< 0.006 cm

Total number of $B_s \rightarrow J/\psi\ \phi$ candidates: 21380 (PRL 2005: 9699)

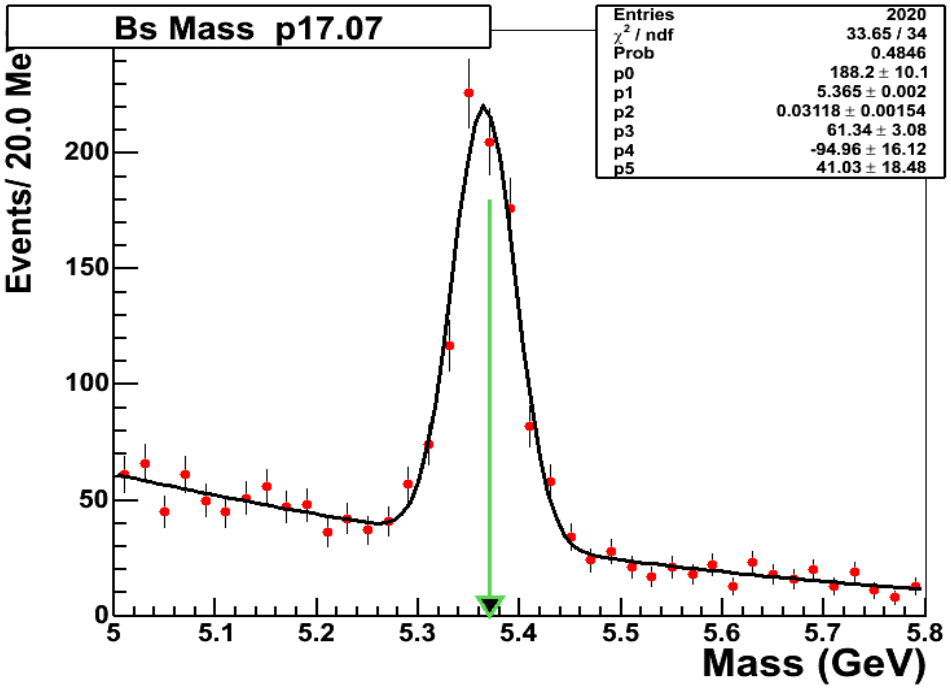
Data



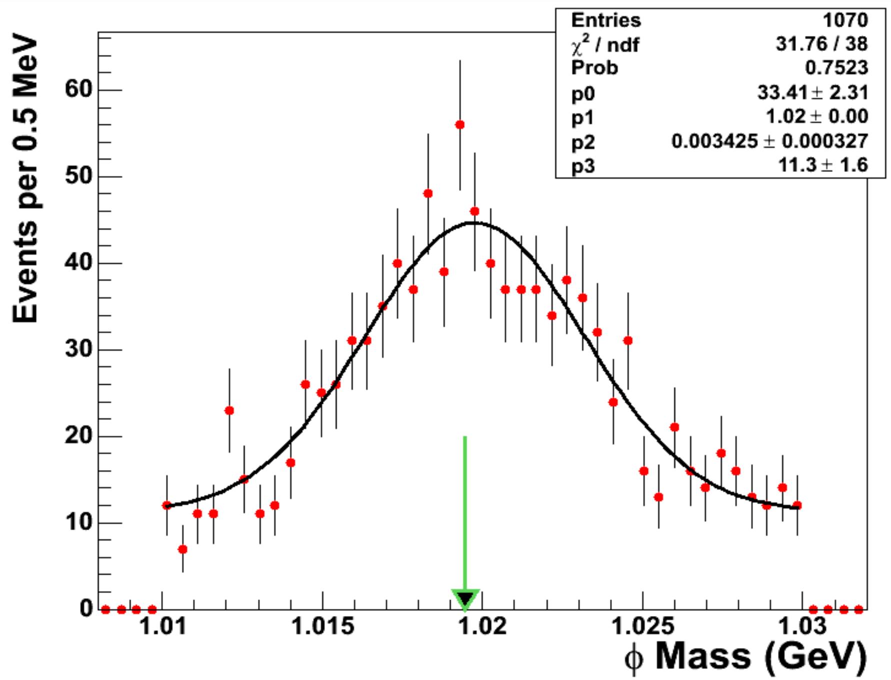
J/ψ Mass p17.07
Entries 21380
χ² / ndf 68.74 / 75
Prob 0.6814
p0 514 ± 5.8
p1 3.084 ± 0.001
p2 0.0624 ± 0.0008
p3 80.72 ± 5.38
p4 -46.97 ± 12.15
Events per 5.0 Me
Mass (GeV)



Bs candidates J/ψ p_T p17.07
Entries 21380
Mean 8.382
Events / 0.5 Ge
J/ψ p_T (GeV)



Bs Mass p17.07
Entries 2020
χ² / ndf 33.65 / 34
Prob 0.4846
p0 188.2 ± 10.1
p1 5.365 ± 0.002
p2 0.03118 ± 0.00154
p3 61.34 ± 3.08
p4 -94.96 ± 16.12
p5 41.03 ± 18.48
Events/ 20.0 Me
Mass (GeV)



Entries 1070
χ² / ndf 31.76 / 38
Prob 0.7523
p0 33.41 ± 2.31
p1 1.02 ± 0.00
p2 0.003425 ± 0.000327
p3 11.3 ± 1.6
Events per 0.5 MeV
φ Mass (GeV)