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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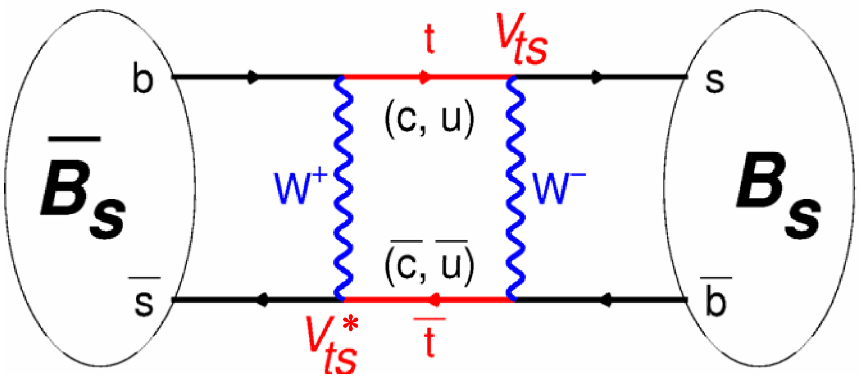
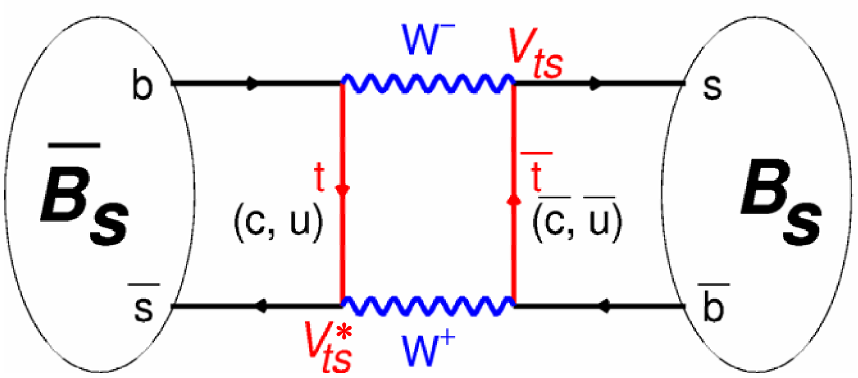
BROOKHAVEN NATIONAL LABORATORY

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→c$\overline{c}$s 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 $B_s - \bar{B}_s$ mixing.

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

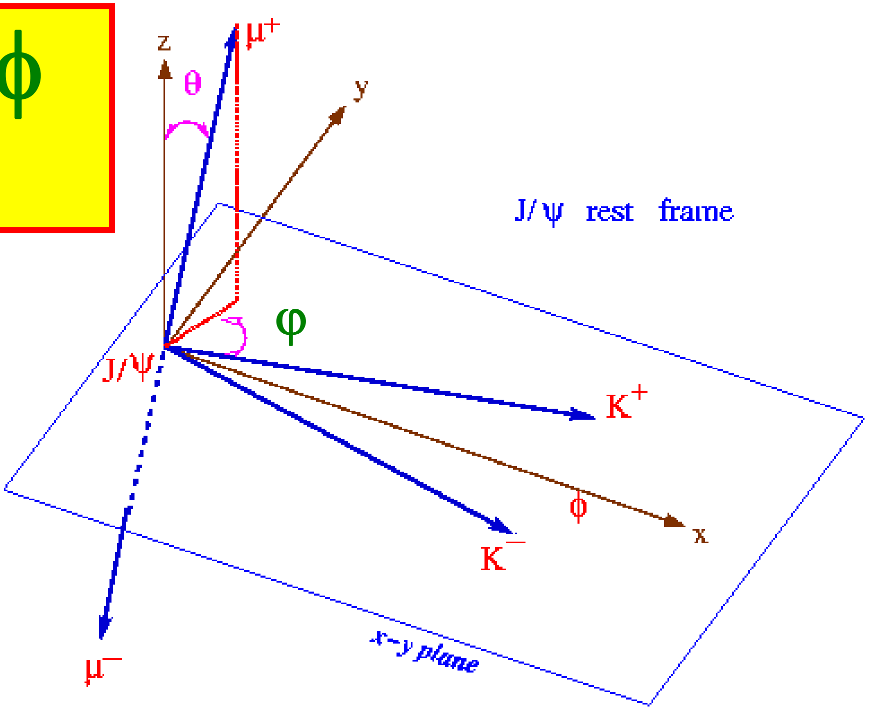
$$|B_L\rangle \approx \left(\frac{1+e^{i\delta\phi}}{2}\right)\left|B_s^{even}\right\rangle + \left(\frac{1-e^{i\delta\phi}}{2}\right)\left|B_s^{odd}\right\rangle$$

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

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

- 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**

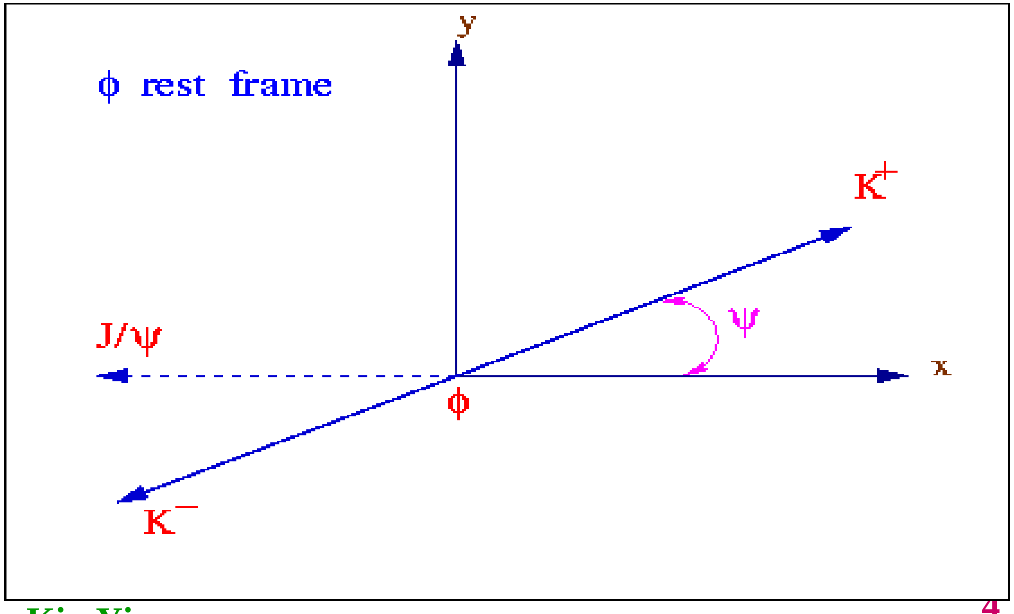
Three waves: S, P, D, **or** A_0, $A_{\parallel}$, $A_{\perp}$

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

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

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

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

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

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

correction for acceptances, kinematic cuts

- $\delta_1 \equiv Arg[A_\parallel(0)^* A_\perp(0)]$ and $\delta_2 \equiv Arg[A_0(0)^* A_\perp(0)]$ 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

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

30 parameters:	1	f_{sig} = signal fraction
	2	signal mass, width
	3	$A_{\perp}$, $\|A_0\|^2$-$\|A_{\|\|}\|^2$, 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)

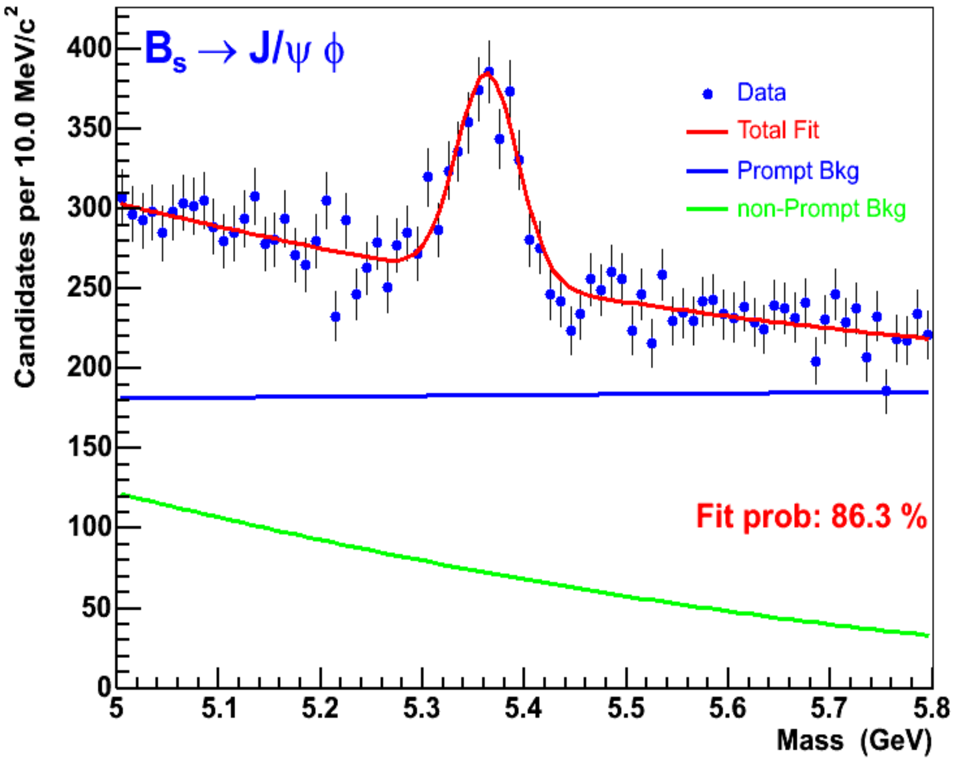
set $\delta\phi = 0$

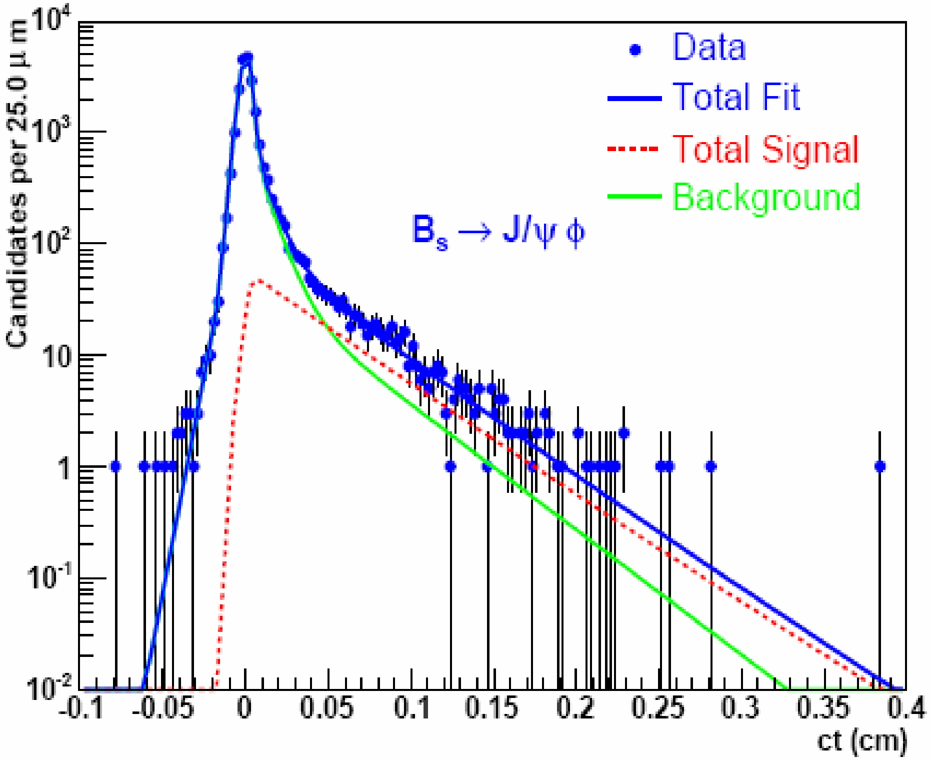
- CDF should have similar no. of parameters

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

Preliminary ~0.8 fb^{-1}

All events

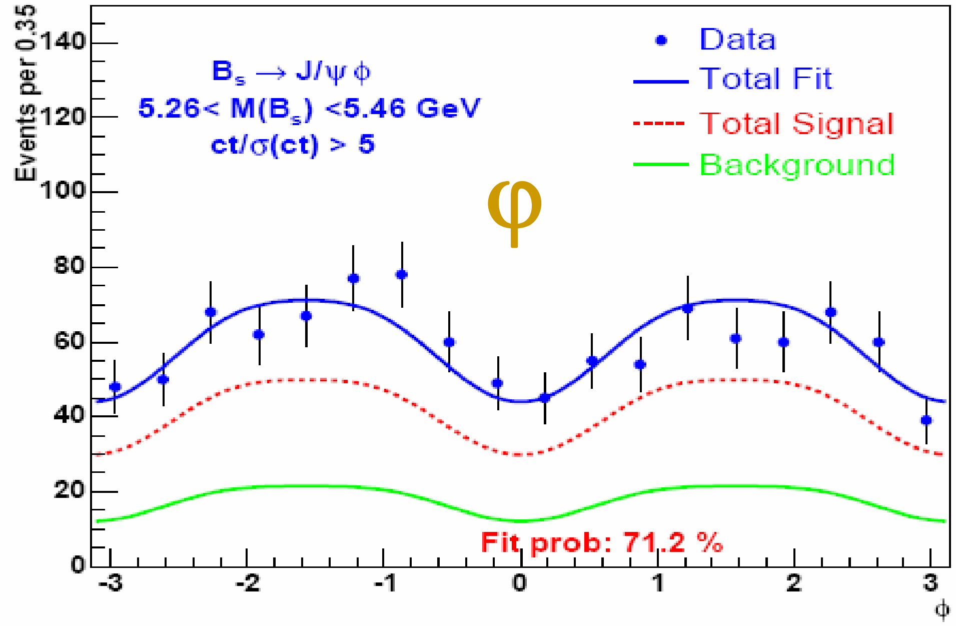


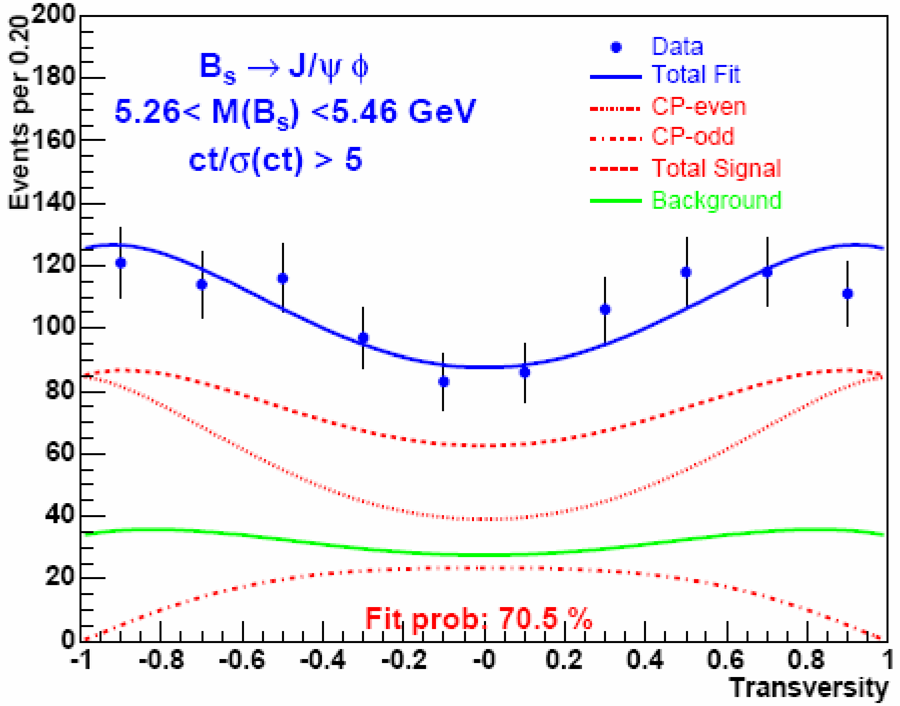


3 angle θ, φ, ψ analysis : $N_{signals} = 978 \pm 45$

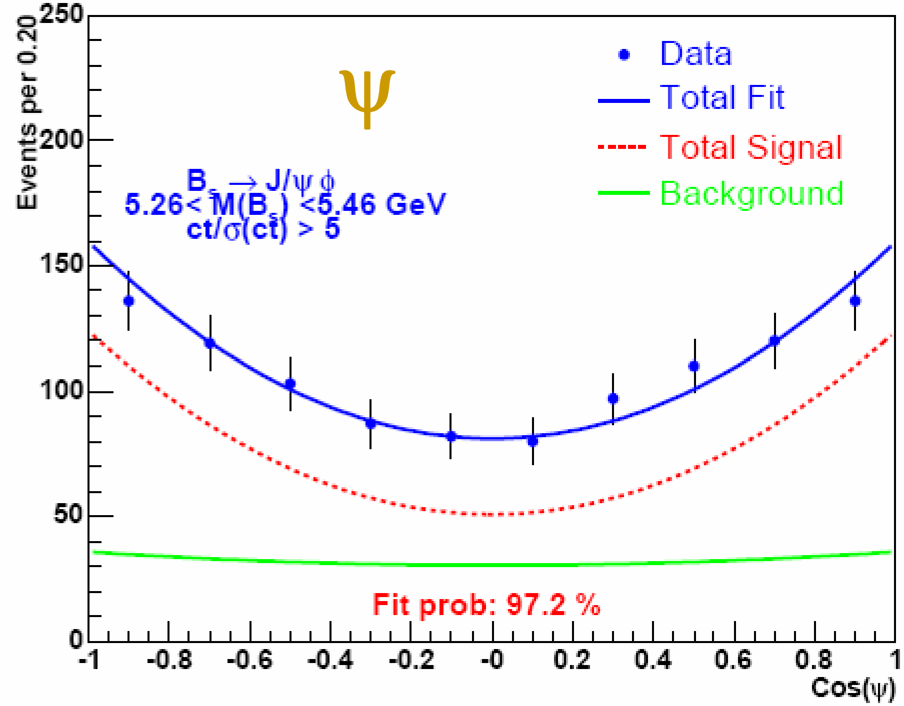
D0 (PRL 2005) used 1 angle, θ, 513 events

Data: Fit projections in signal regions

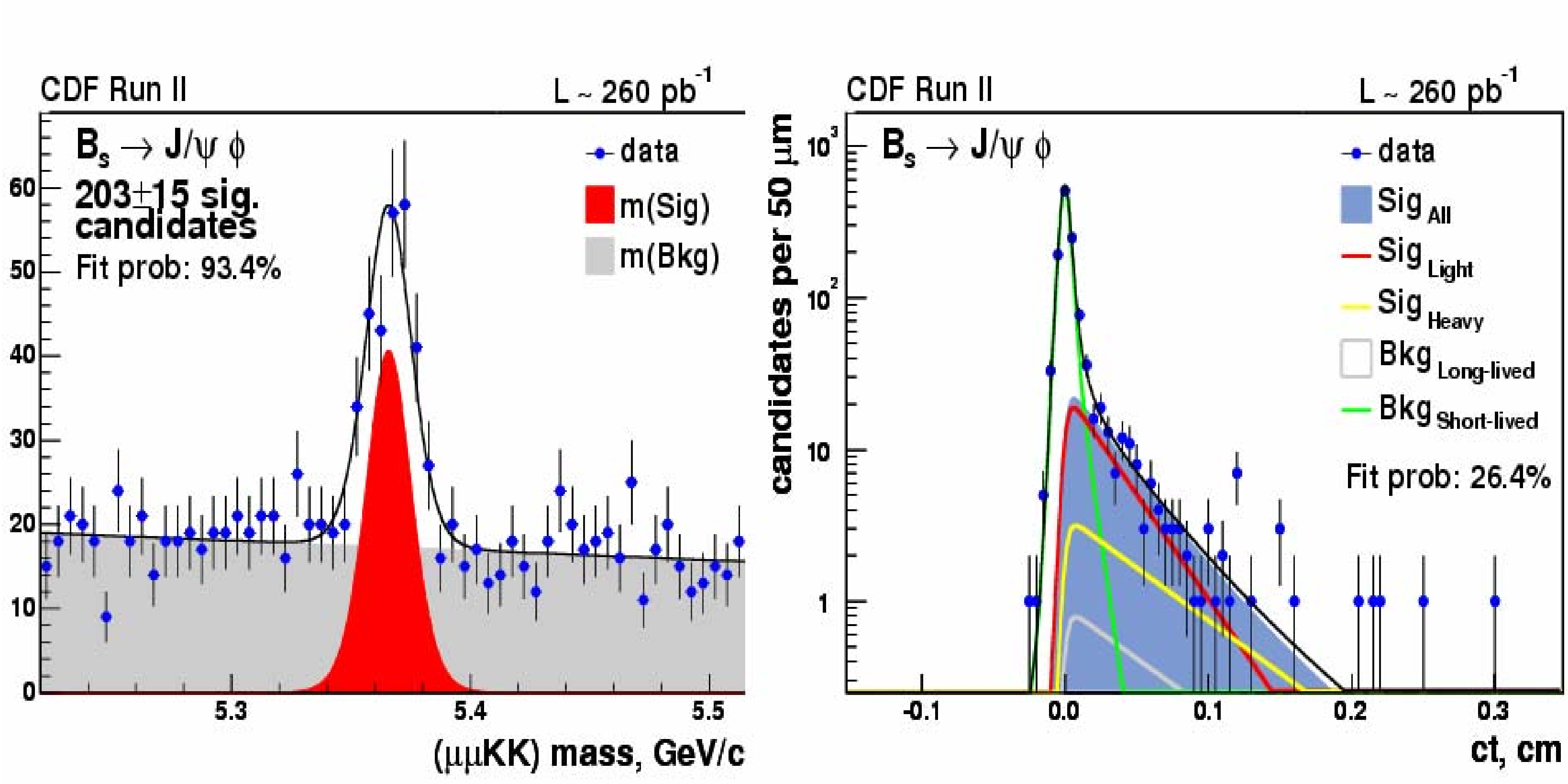




θ (transversity)



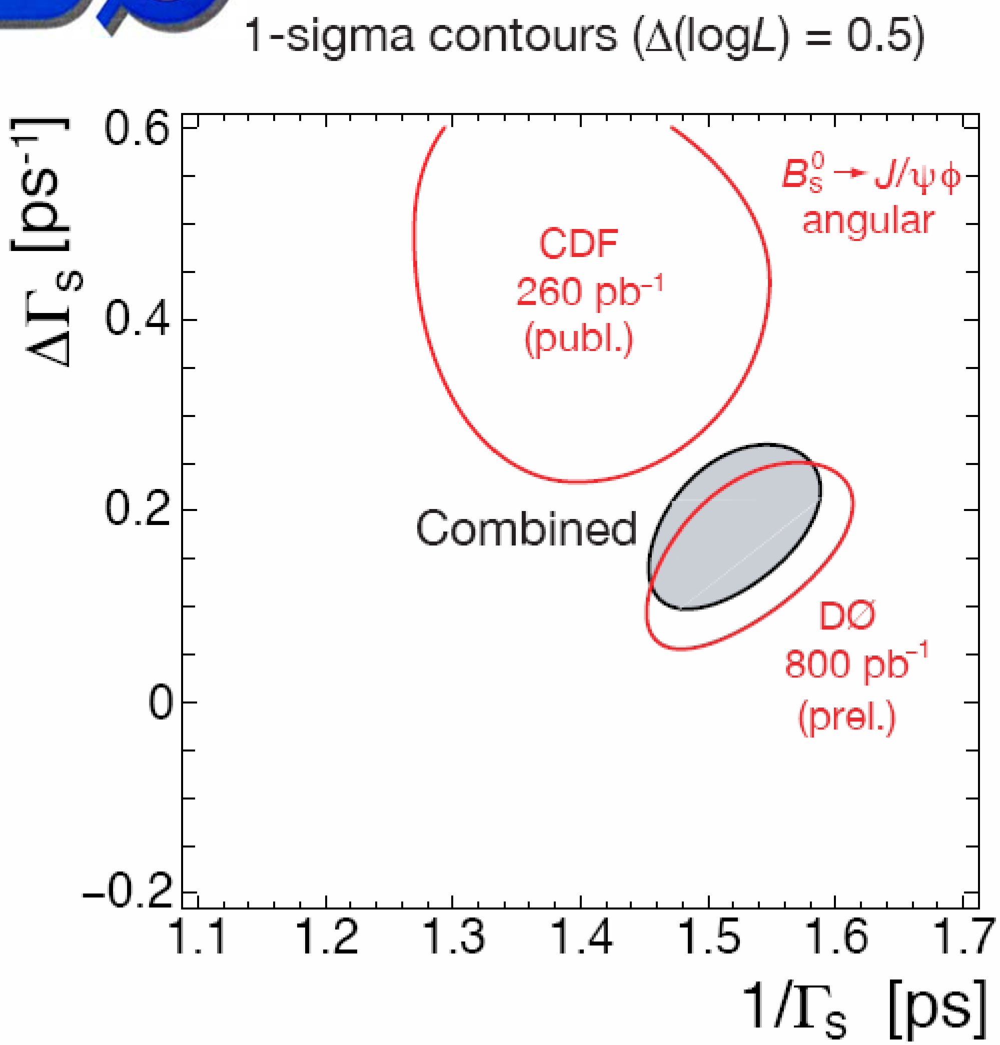
Earlier, PRL 94, 101803, 2005, CDF has used a similar 3 angle (θ, ϕ, ψ) fit/analysis with 260 pb^{-1} of data



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

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

- **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](hep-ex/0606005)

Combined:

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

$\bar{\tau} = 1/\Gamma$

$= 1.520 \pm 0.068\ \mathrm{ps}$

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

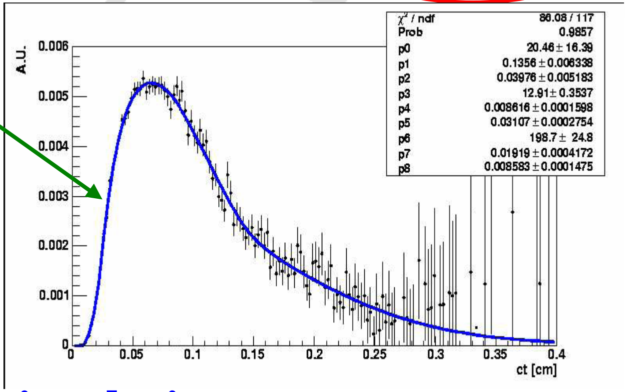
CP-even ⇒ lifetime of the CP-even state

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

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

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

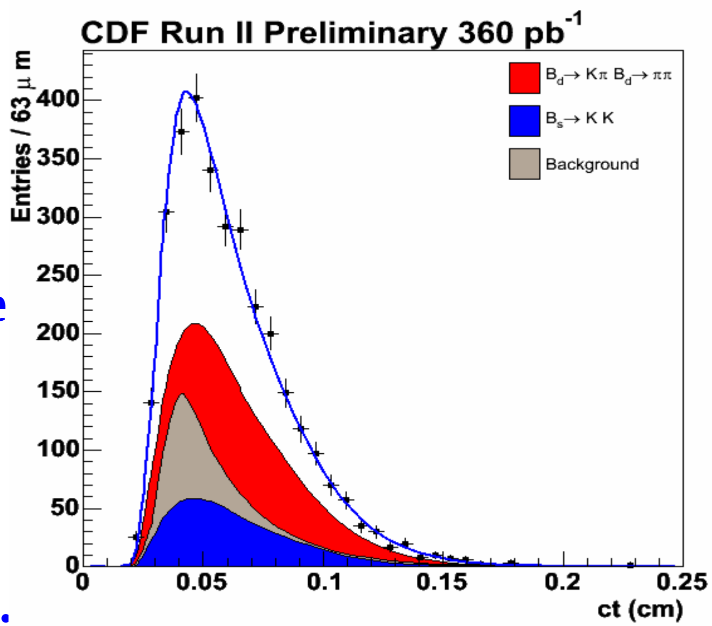
decay | **detector smearing** | **trigger bias**



- **Trigger bias for signal is extracted from detailed simulation.**
- **Procedure validated in unbiased $B \to J/\psi X$ 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.**

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

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

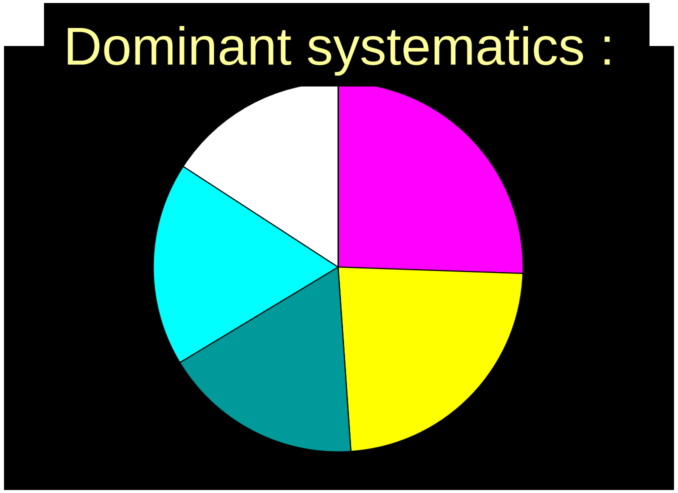


$B_s \to K^+K^-$ is CP-even (~ 5% uncertainty): has the lifetime of "light B_s" :

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

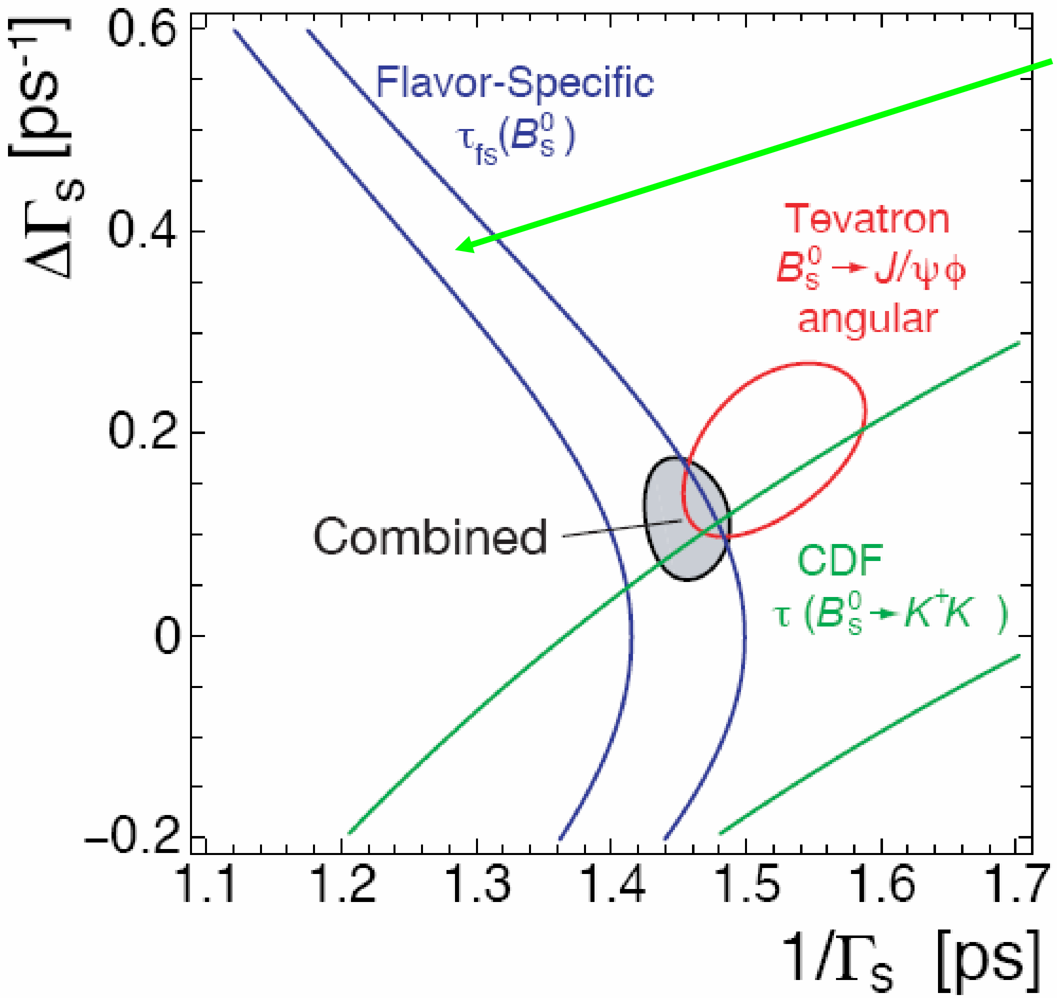
Combine with HFAG average $(\tau_L^2 + \tau_H^2)/(\tau_L + \tau_H)$:

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



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

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



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.,

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

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

- Fit to single exponential,

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

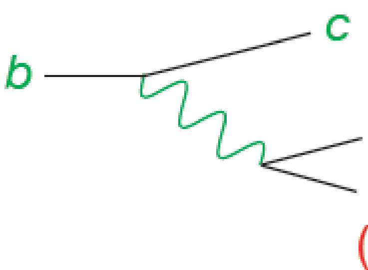
R. Van Kooten: hep-ex/0606005

$B_s \to D_s^{(*)+} D_s^{(*)-}$ *and* $\Delta\Gamma_S$

- Γ_{12} dominated by decay $b \to c\bar{c}s$ 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



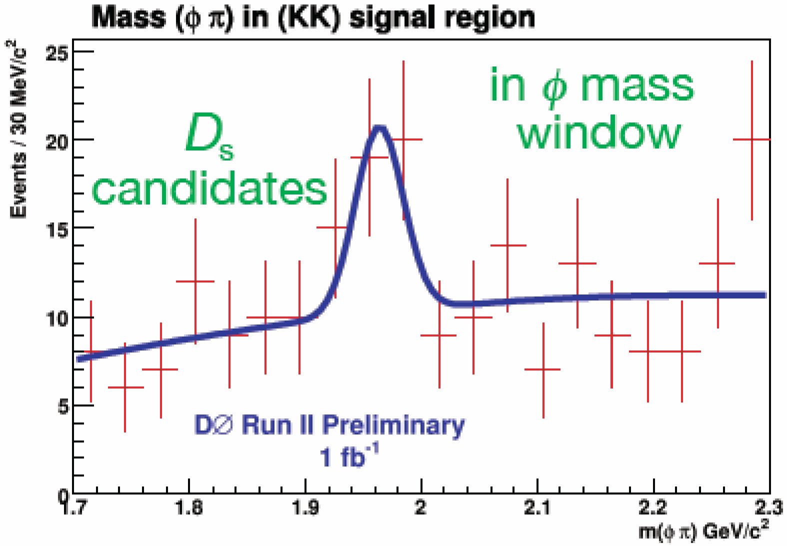
$B_s^0 \to D_s^+ D_s^-$ is pure CP even, and under various theoretical assumptions,

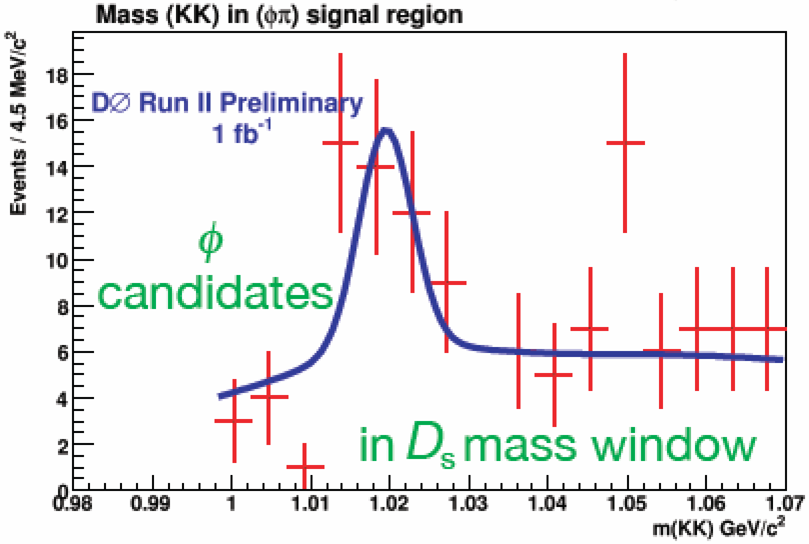
$B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ inclusive, also CP even to ~5%

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

Likely needs re-examination!!

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





- Measure ratio:

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

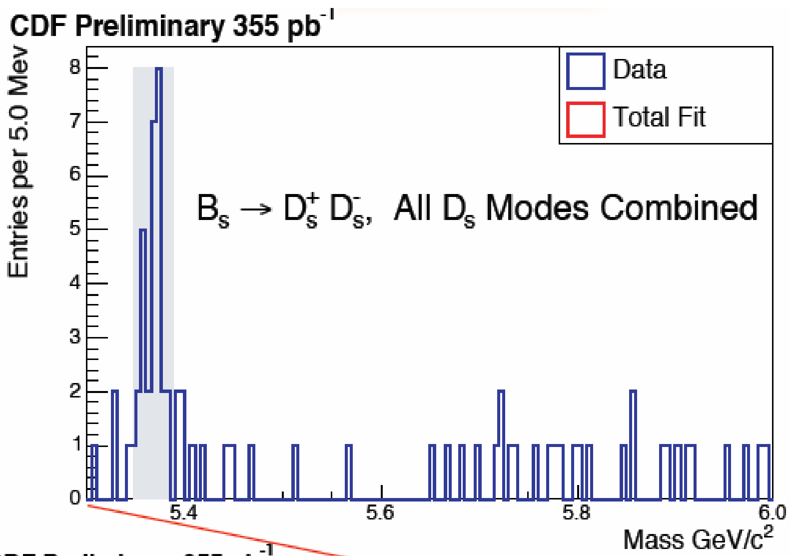
(many systematics cancel in the ratio)

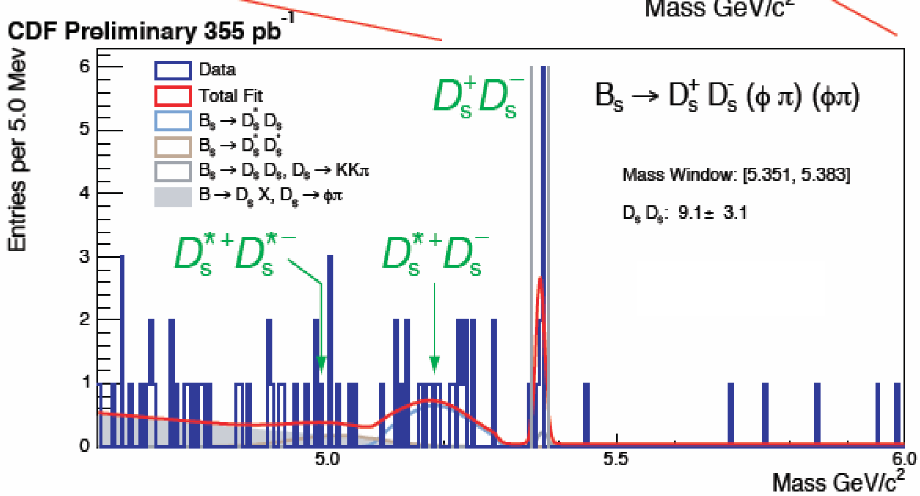
- Use new $Br(D_s \to \phi \pi)$ from BaBar, combined w/ PDG :

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

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

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



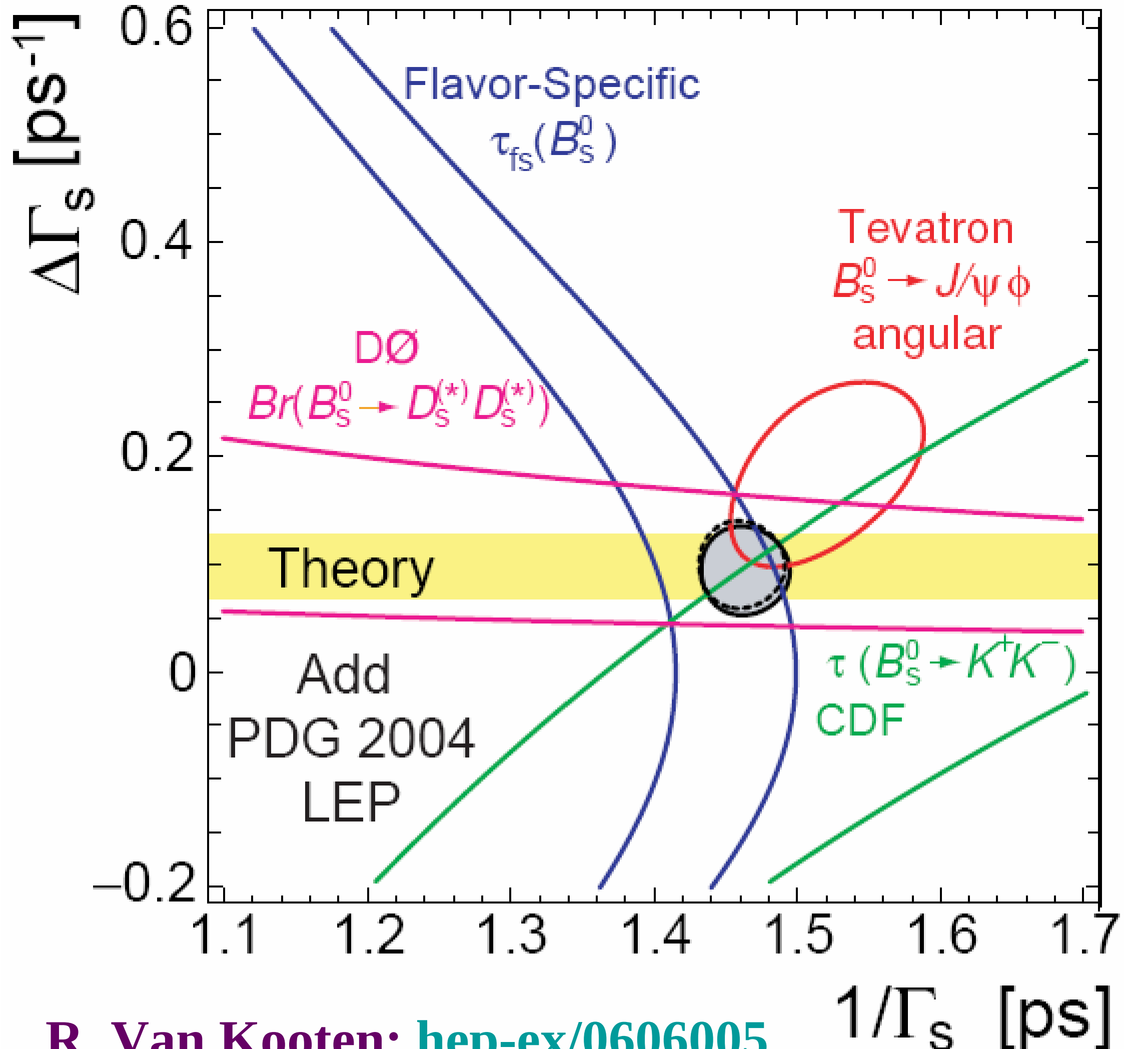


$$\frac{Br(B_s^0 \rightarrow D_s^+ D_s^-)}{Br(B^0 \rightarrow D_s^+ D^-)} =$$

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

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

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

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

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 $\to$ Vector – Vector
- Decay amplitude decomposed into 3 linear polarization states
  - A_0 = S + D wave $\Rightarrow$ P even
  - $A_{||}$ = S + D wave $\Rightarrow$ P even
  - $A_{\perp}$ = P wave $\Rightarrow$ P odd
- If CP violation neglected $\Rightarrow$ 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 $\Rightarrow$ measure two lifetimes

CKM Matrix and Unitarity triangle

Relates quark mass and weak eigenstates

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

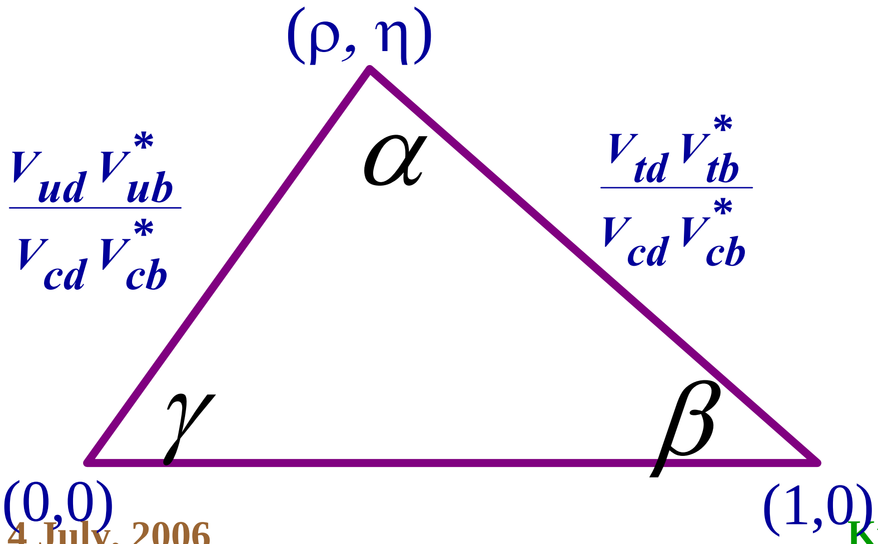
SM: CP-violating processes solely related to one phase in CKM.

'bd'

(THE unitary triangle)

Large effort in B physics

Mainly at B factories



'bs'

(A 'squashed' unitary triangle)

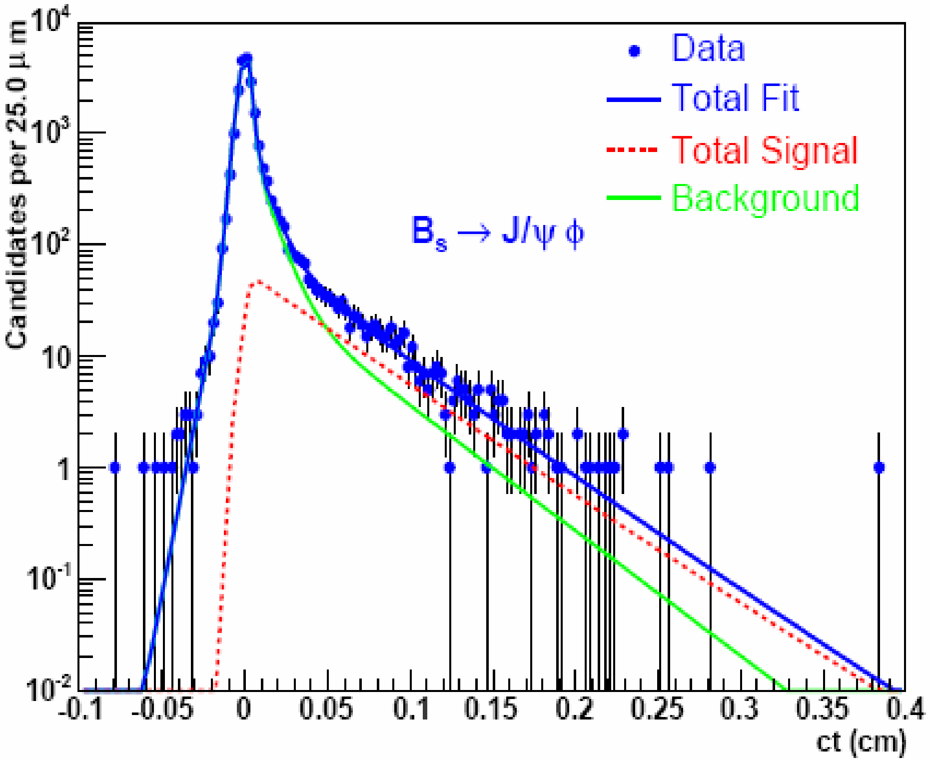
$\beta \rightarrow \beta_s$, small in SM

Interesting to check how small/big β_s really is.

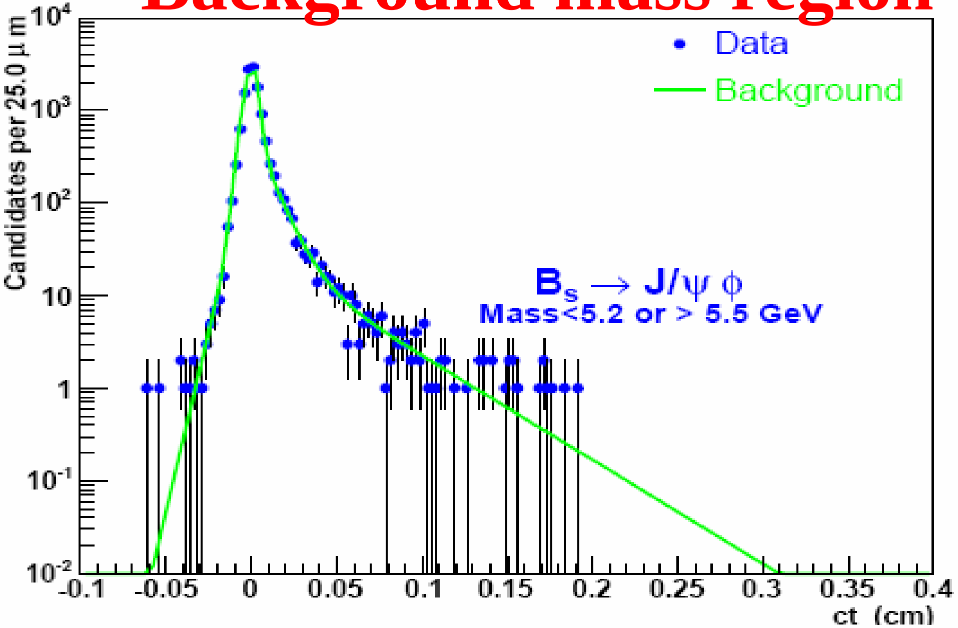
Currently: Tevatron domain

Fit projection (lifetime)

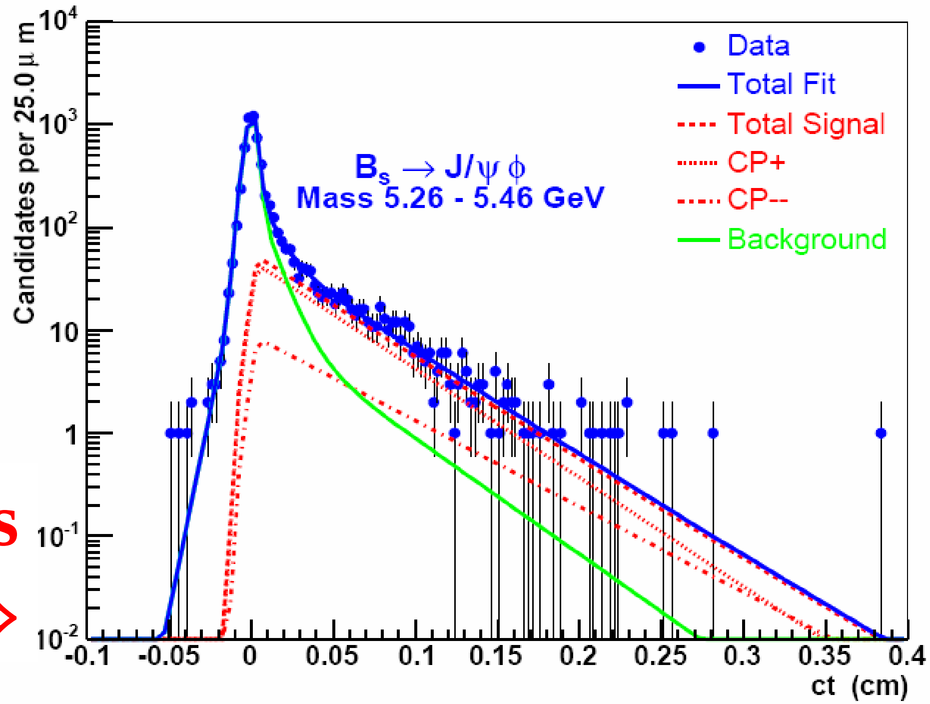
All events



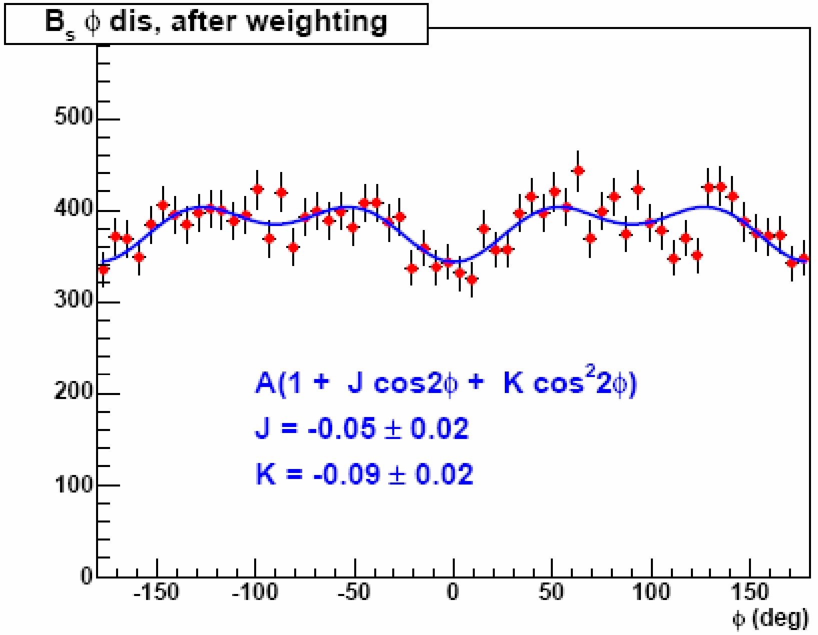
Background mass region



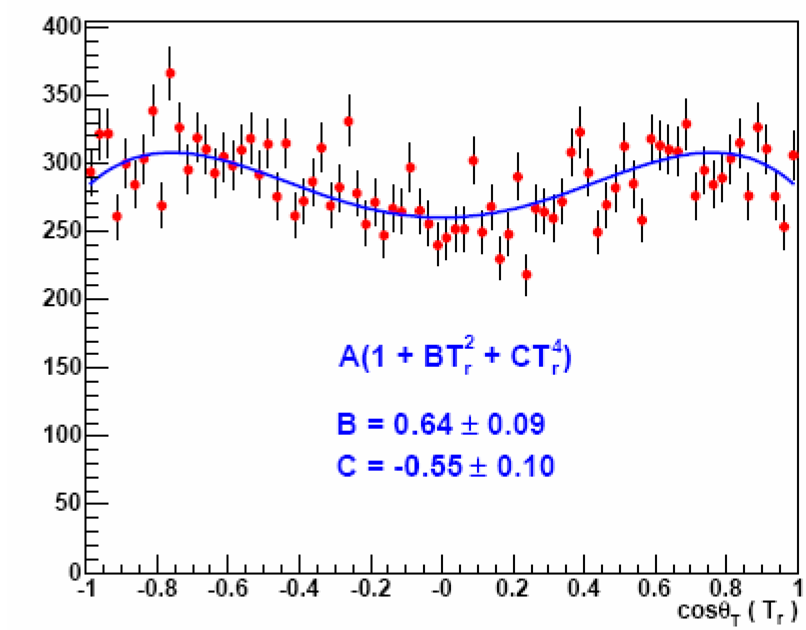
Signal mass region ⇒



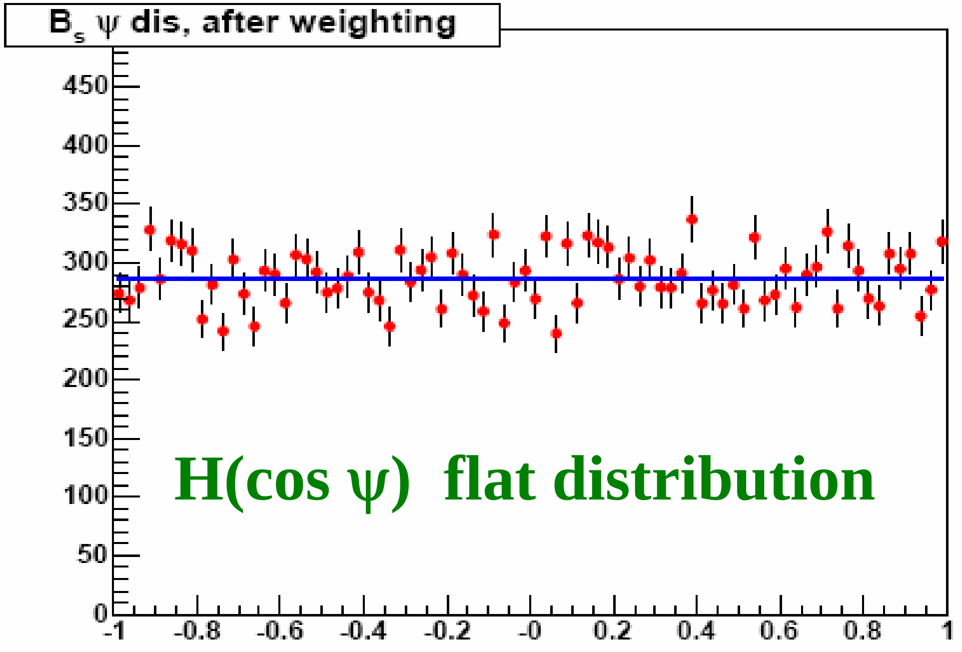
Detector Acceptance (MC & data)



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



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



$H(\cos\psi)$ flat distribution

Systematics

Source	$c\tau(B_s^0)$ μm	$\Delta\Gamma$ ps^{-1}	$R_\perp$	$\lvert A_0(0)\rvert^2 - \lvert A_\parallel(0)\rvert^2$	δ_1 - δ_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"

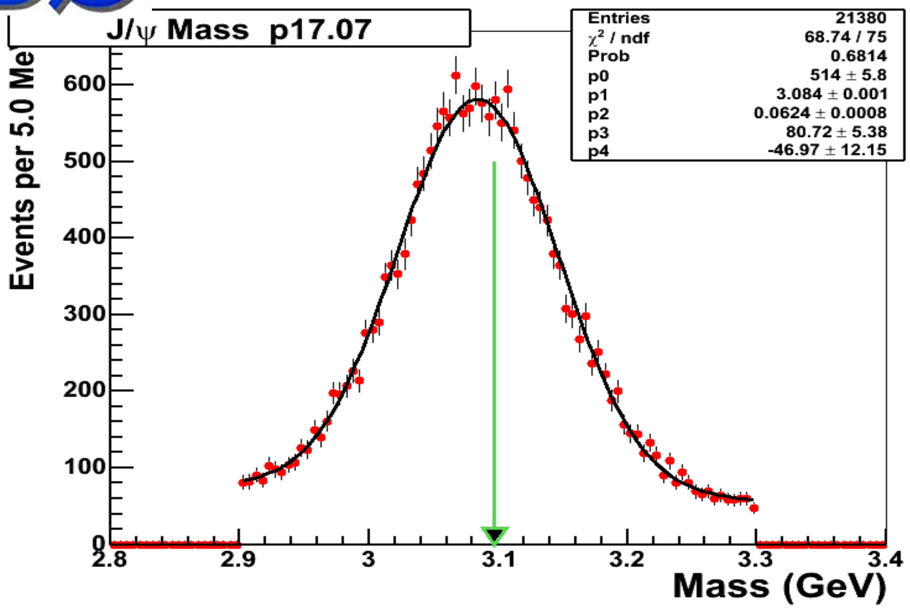
Some selection cuts

data before last Tevatron shutdown

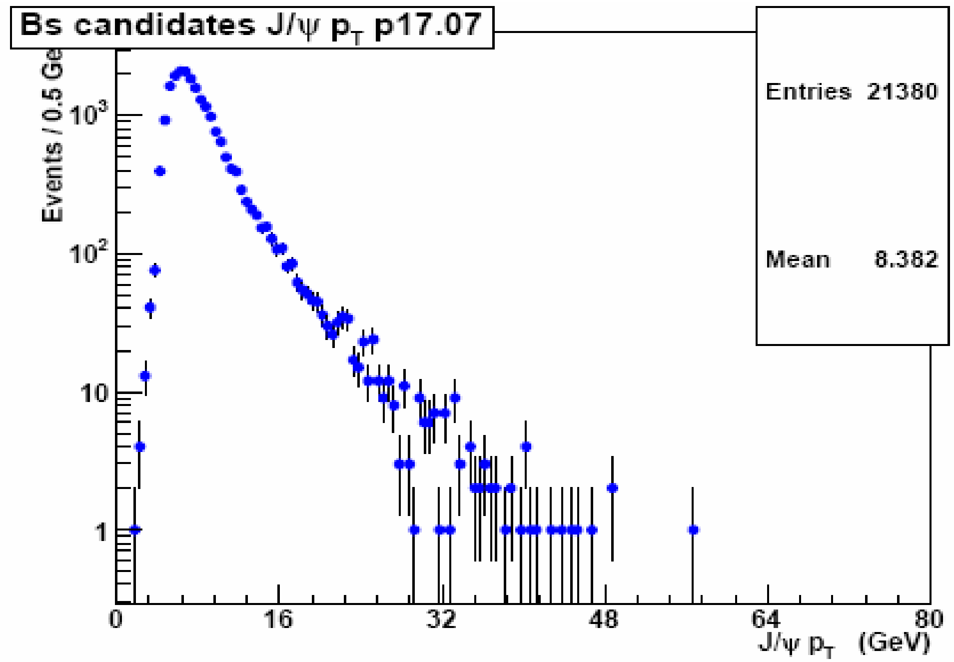
B_s candidate mass	$5.0 < M(J/\psi,\phi) < 5.8$ GeV
J/ψ candidate mass	$2.9 < M(\mu^+,\mu^-) < 3.3$ GeV
Non-J/ψ meson mass	$1.01 < M(K^+,K^-) < 1.03$ GeV
B_s p_T	> 6.0 GeV
J/ψ p_T	> 4.0 GeV if $\lvert\eta\rvert < 1.0$
ϕ p_T	> 1.5 GeV
J/ψ, ϕ χ^2	< 10.0
$K^\pm$ p_T	> 0.7 GeV
SMT hits each track (incl.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

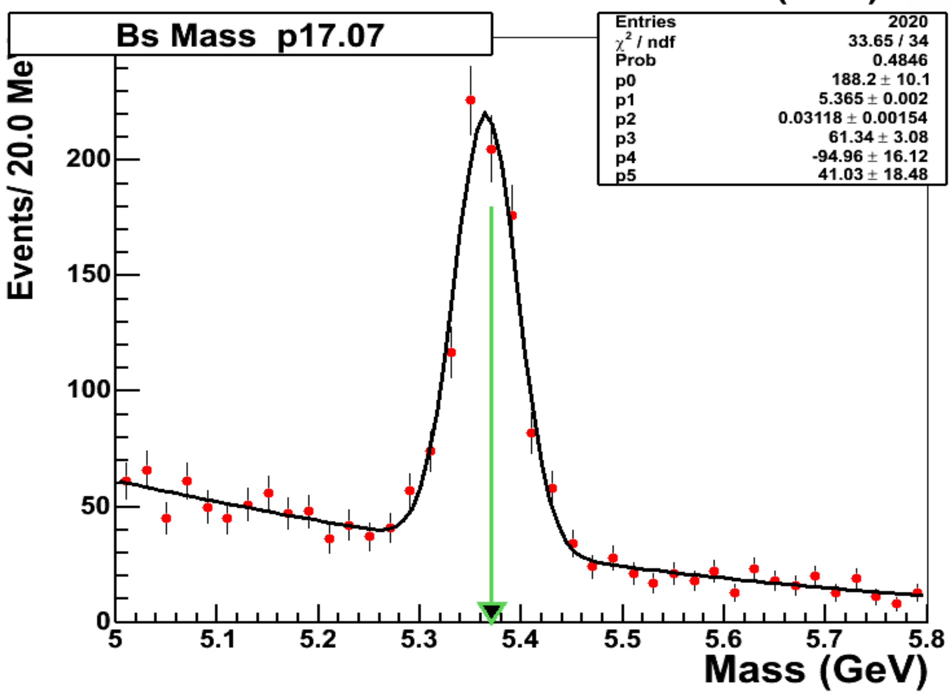
Data



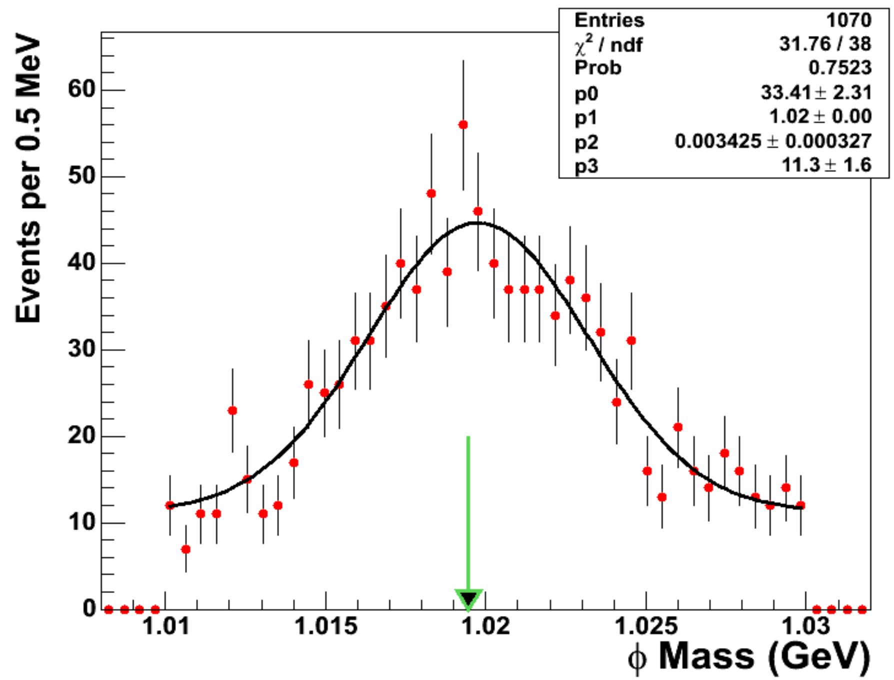
J/ψ Mass p17.07
Entries 21380
χ² / ndf 68.74 / 75
Prob 0.6814
p0 514 ± 5.8
p1 3.084 ± 0.001
p2 0.0624 ± 0.0008
p3 80.72 ± 5.38
p4 -46.97 ± 12.15
Events per 5.0 Me
Mass (GeV)



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)