B Lifetimes and Mixing

Hal Evans Indiana University

for the CDF & DØ (BaBar & Belle) collaborations

Heavy Quarks & Leptons 2008

June 5-9, 2008 University of Melbourne

Outline

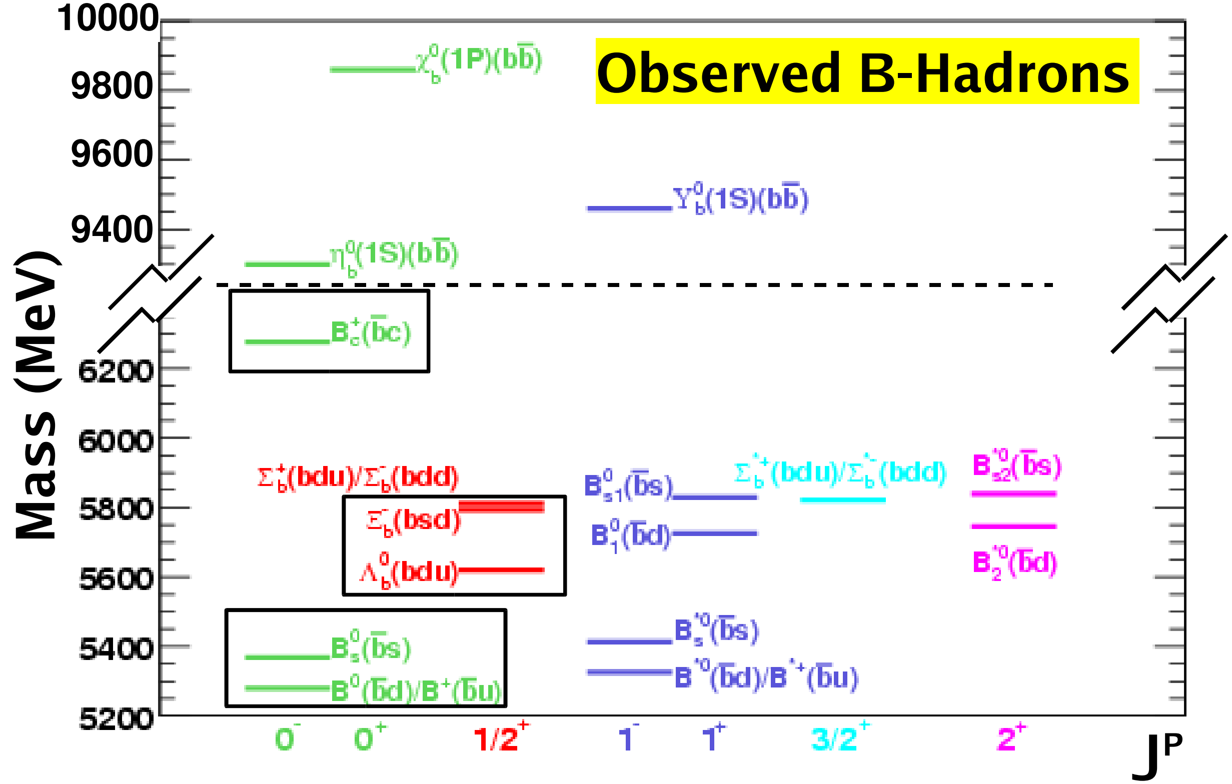
1) Why Measure Lifetimes? — Why Measure Mixing?

2) Experimental Features

3) Lifetime Measurements
   – B^0 $B^{\pm}$ B_s B_c Λ_b

4) Mixing Measurements
   – Δm_d Δm_s

5) Future Prospects

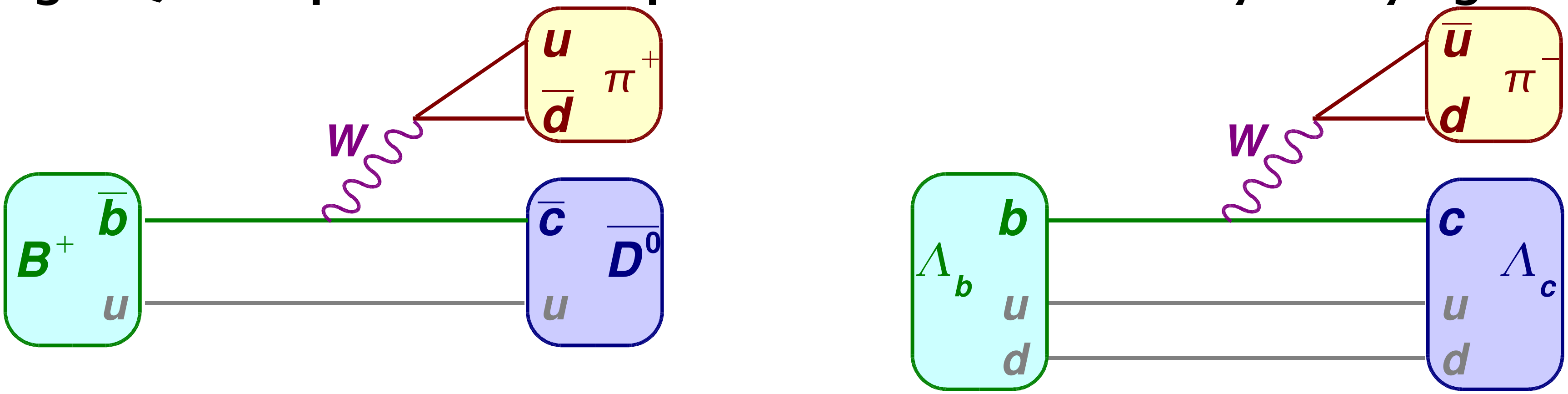


Note: concentrate on recent results (Tevatron), mention BaBar/Belle

See also:		
	Iain Bertram	Rare Decays, Mixing, and $\lvert V_{td} / V_{ts}\rvert$
	Manfred Paulini	B States
	Joe Boudreau	CPV in the B_s System

Weak B Lifetimes ⇒ QCD Test

Light Quark Spectators ⇒ equal lifetimes for all weakly decaying B-hadrons



Differences evaluated using Heavy Quark Expansion

$$\frac{\tau_1}{\tau_2} = 1 + \left(\frac{\Lambda_{QCD}}{m_b}\right)^2 \Gamma_2 + \left(\frac{\Lambda_{QCD}}{m_b}\right)^3 \left[\Gamma_3^{(0)} + \frac{\alpha_s}{4\pi}\Gamma_3^{(1)} + \dots\right] + \left(\frac{\Lambda_{QCD}}{m_b}\right)^4 \left[\Gamma_4^{(0)} + \dots\right] + \dots$$

spectator effects

meson / baryon differences

Also: important input to EW B measurements – mixing, ΔΓ, etc.

EW Symmetry Breaking ⇔ Mixing

EW Sym. Breaking ⇒ CKM Matrix ⇒ Different Quark Eigenstates

Weak

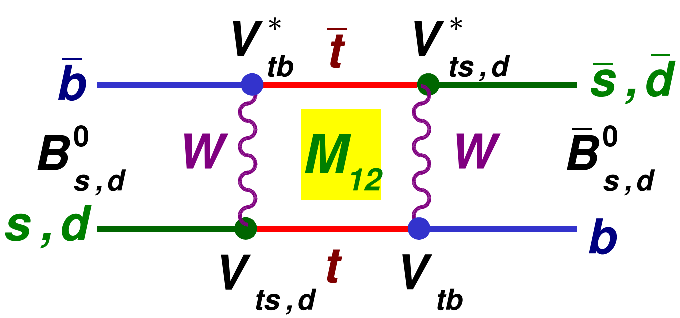
$$i\frac{d}{dt}\begin{pmatrix}|B^0(t)\rangle\\|\bar{B}^0(t)\rangle\end{pmatrix}=\begin{pmatrix}M-i\frac{\Gamma}{2} & M_{12}-i\frac{\Gamma_{12}}{2}\\ M_{12}-i\frac{\Gamma_{12}}{2} & M-i\frac{\Gamma}{2}\end{pmatrix}\begin{pmatrix}|B^0(t)\rangle\\|\bar{B}^0(t)\rangle\end{pmatrix}$$

CP $\quad |B^{odd/even}\rangle=|B^0\rangle\pm|\bar{B}^0\rangle$

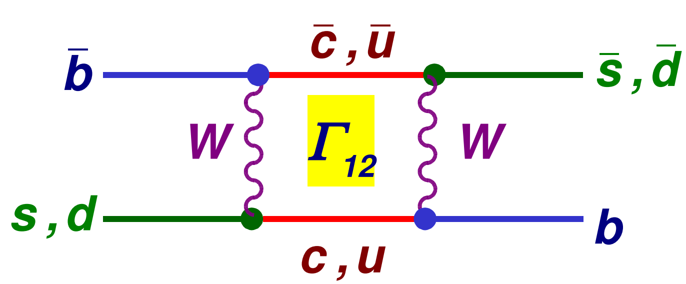
Mass $\quad |B^{H,L}\rangle=p|B^0\rangle\pm q|\bar{B}^0\rangle$

In the SM all this described by:
- 3 angles + 1 CPV phase

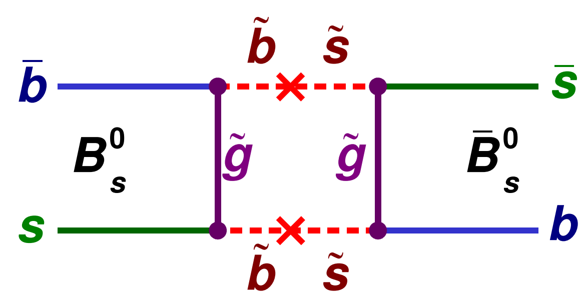
Beyond the SM
- *much* less constrained



sens. to New Phys



less sens. to New Phys



SUSY example

Observables & Expectations

Observables

$\Delta m = M_H - M_L \sim 2\,|M_{12}|$

$\Delta\Gamma_{CP} = \Gamma_{even} - \Gamma_{odd} \sim 2\,|\Gamma_{12}|$

$\Delta\Gamma = \Gamma_L - \Gamma_H = \Delta\Gamma_{CP}\cos\phi$

$\phi = \arg(-M_{12}/\Gamma_{12})$

$2\beta_s = -\arg[(V_{tb}/V_{ts}^*)^2/(V_{cb}/V_{cs}^*)^2]$

Meson	Δm/m	ΔΓ/Γ	φ	2β
K^0	7.0×10^{-15}	~1	0.007	~0
D^0	7.1×10^{-15}	0.006	~0	~0
B_d	6.4×10^{-14}	0.004	–0.091	0.76
B_s	2.4×10^{-12}	0.147	–0.004	0.04

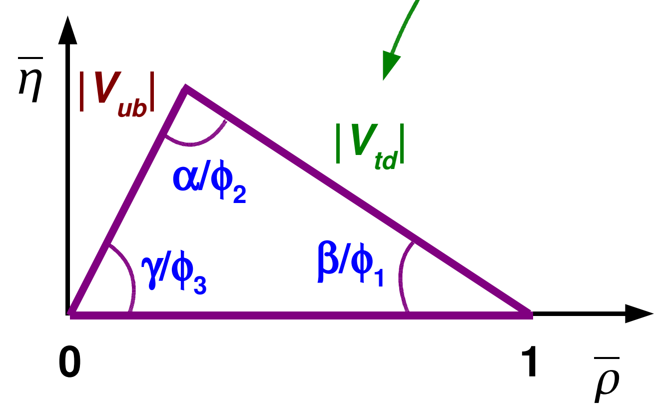
Beyond the SM

$\phi = \phi^{SM} + \phi^{NP}$

$2\beta = 2\beta^{SM} - \phi^{NP}$

$$\frac{\Delta m_d}{\Delta m_s} = \frac{M_{Bd}}{M_{Bs}} \frac{f^2_{Bd} B_{Bd}}{f^2_{Bs} B_{Bs}} \left|\frac{V_{td}}{V_{ts}}\right|^2$$

ratio reduces uncertainty
10.7% → 3.4%



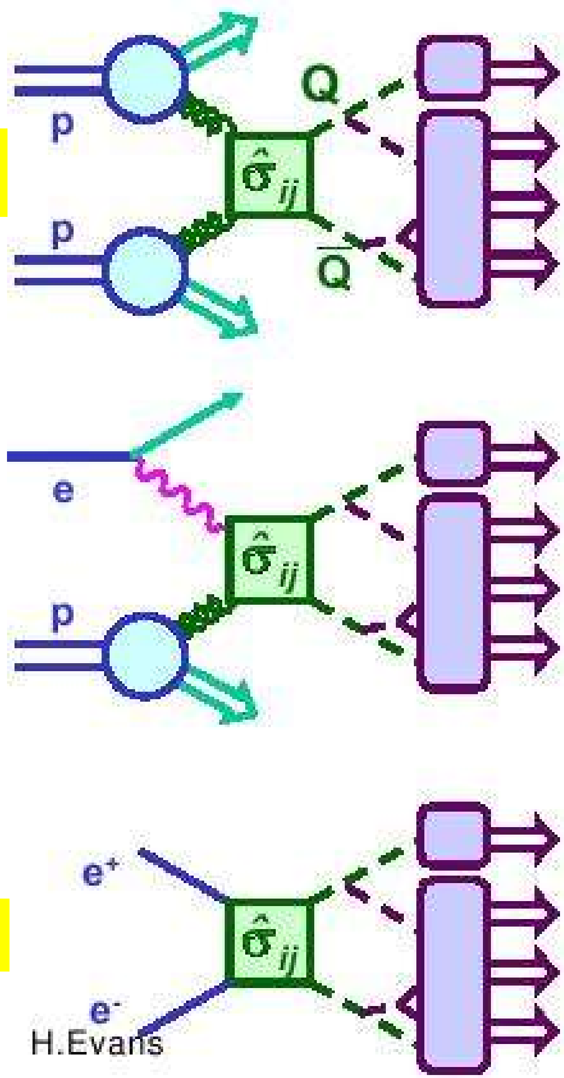
b's in the Wild

Incoming Particles | **Hard Interact** | **Outgoing Particles**

$p - \bar{p}$

$e - p$

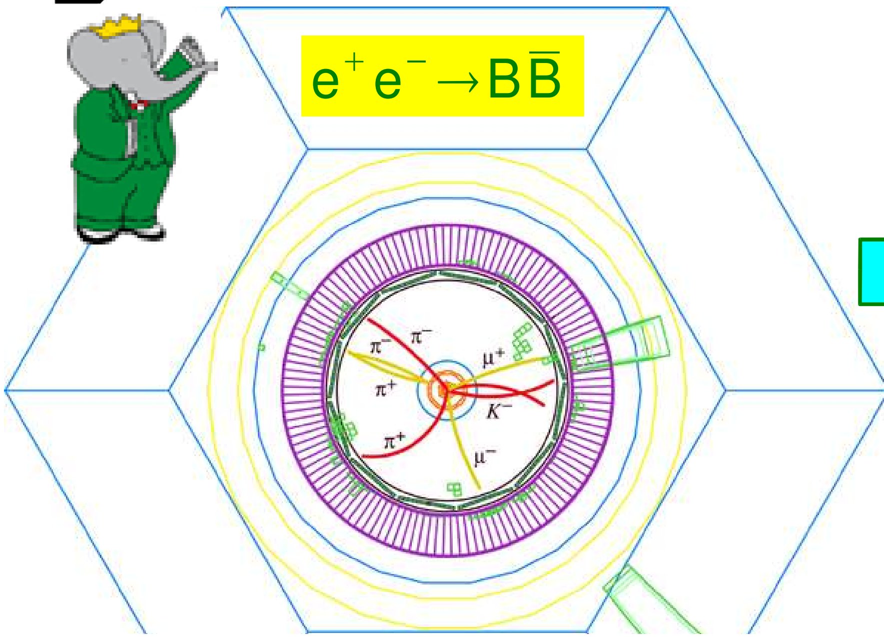
$e^+ - e^-$

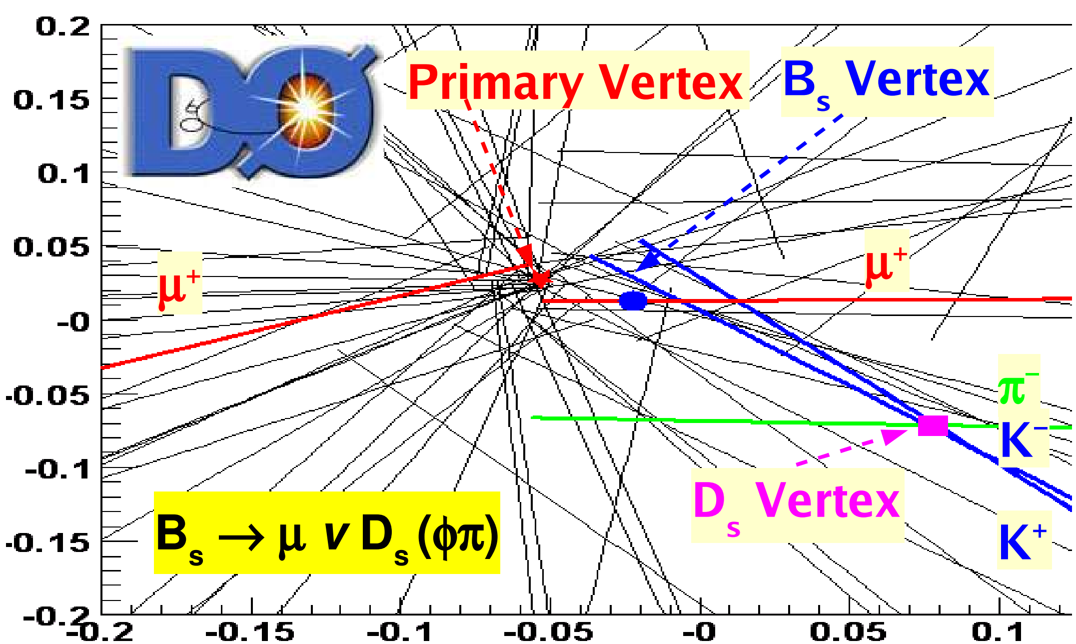


Machine	$\sqrt{s}$ (TeV)	$\sigma(bb)$ (μb)	Rate* (Hz)	<L> (mm)	B's
LHC (Atlas,CMS,LHCb)	14	500	50K	1.5	all
Tevatron (DØ,CDF)	1.96	100	6K	0.5	all
HERA (H1,Zeus)	0.32	~0.010		δ>0.1	all
Z-Fact (LEP, SLC)	0.09 (to 0.20)	0.007	0.035	3	all
B-Factories (BaBar,Belle,*CLEO*)	0.01	0.001	20	0.3	B_d, B^+

* in acceptance

Broad Experimental Challenges





Lifetime Analysis Overview

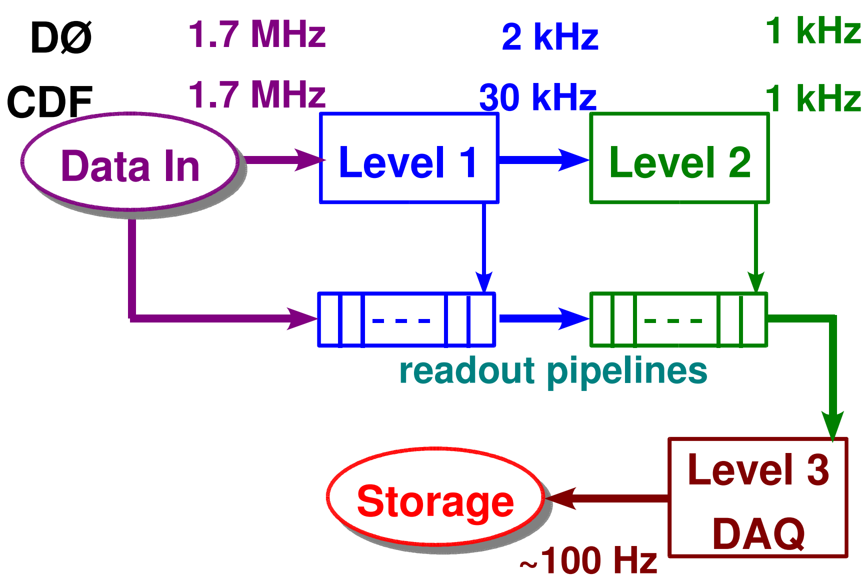
- Record Events   Trigger
- Reconstruct B   PID/Tracking
- Est. B momentum   Tracking
  - corr. for missing particles
- Meas. Decay Length   Vertexing
  - determine resolution
- Est. Proper Time
- Est. Backgrounds
  - sidebands and MC
- Fit for Lifetime (& other par's)
  - include resolutions, corrections, backgrounds, etc.

Triggering

Triggers are central to Tevatron B-Physics analyses

- *b*-event rate in accept ~6 kHz
- $\sigma(bb)/\sigma(\text{inelastic}) \sim O(10^{-3})$
- can only trigger (efficiently) on *specific* decay modes

3 Level Trigger Systems

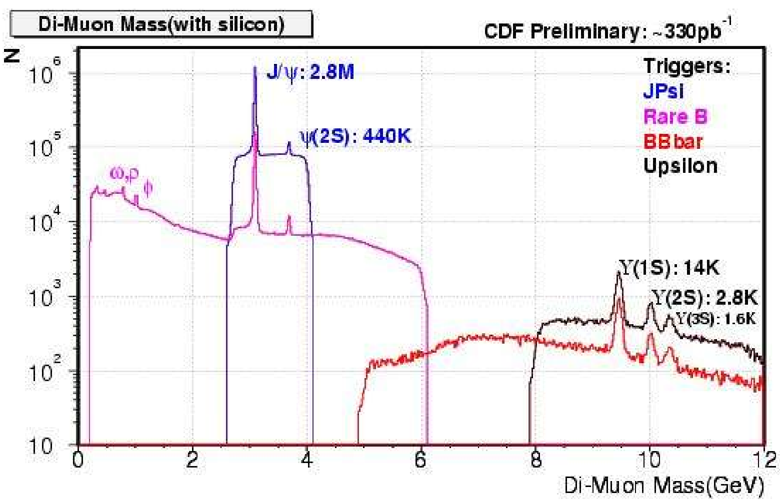


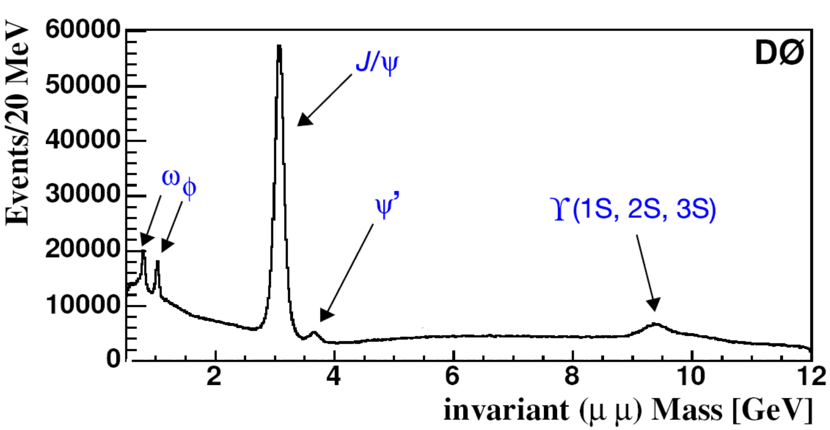
Trigger	CDF	DØ
2-Track	P_T(trk)>2.0 GeV $0.12<d_0<1$ mm $\Sigma P_T>5.5$ GeV	—
l + Displ Trk	$P_t^l>4$, $P_t^{trk}>2$ GeV $0.12<d_0<1$ mm	—
1-Muon	—	$P_T>3,4,5$ GeV or $P_T>5$ GeV & $d_0/\sigma(d_0)>3$ (luminosity dependent)
2-Muon	$P_T(\mu\text{'s})>1.5$ GeV	$P_T(\mu\text{'s})>2.0$ GeV

B-Reconstruction: Particle ID

Muons: a workhorse at the Tevatron

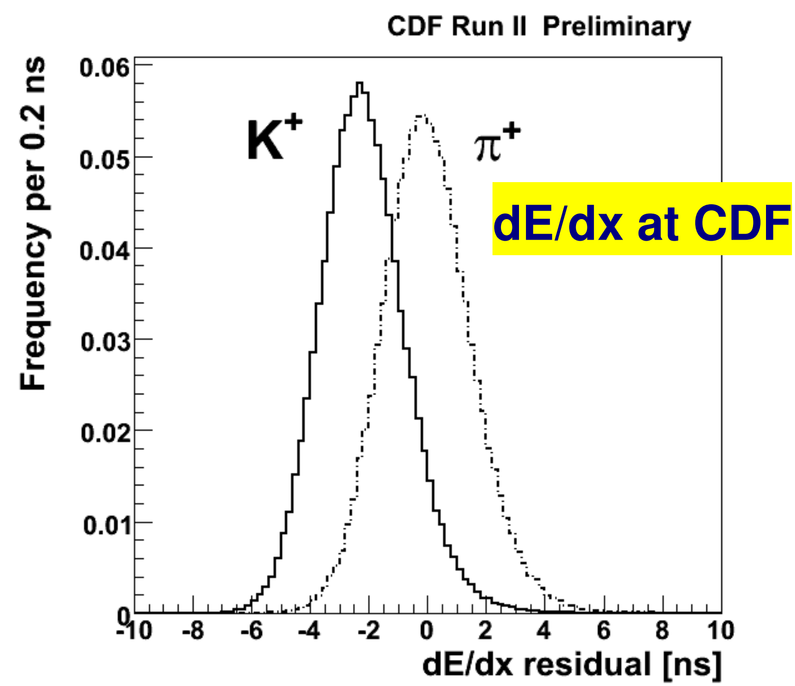
	Coverage	Shielding
DØ	$\lvert\eta\rvert < 2.0$	12-18 λ_I
CDF	$\lvert\eta\rvert < 1.0$	>5 λ_I





π/K Separation: hadronic final state

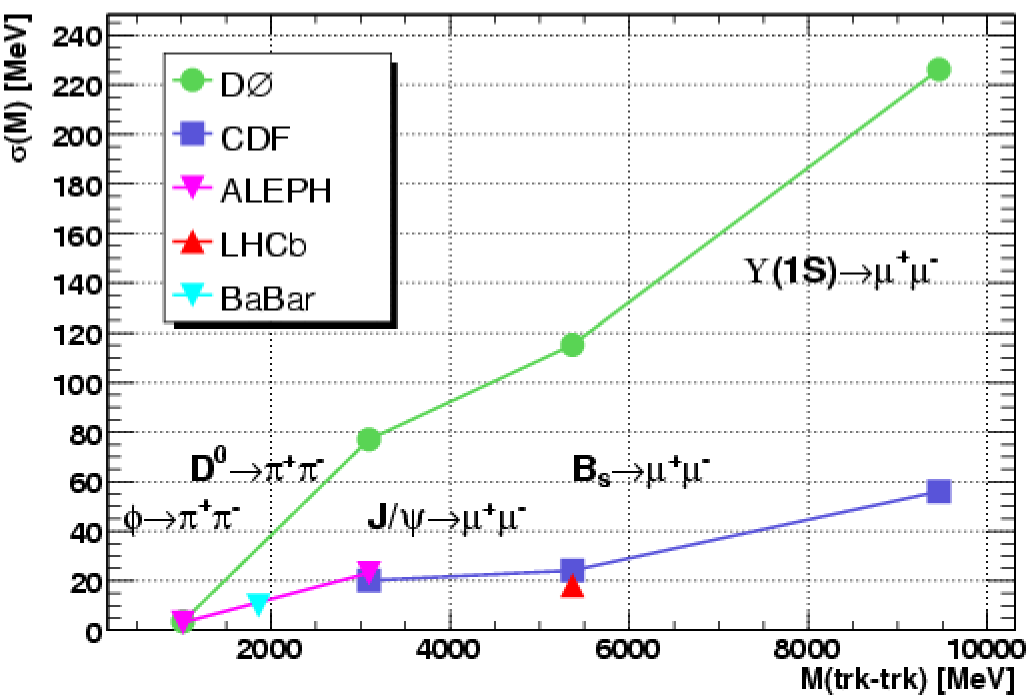
	Method	Sep.	Range
CDF	dE/dx (& TOF)	>1.4σ	$2 < p_T < 10$ GeV
BaBar	DIRC	>2.7σ	p < 4.2 GeV
Belle	aerogel (dE/dx & TOF)	ε(K)>80% fake(π)<10%	p < 4 GeV

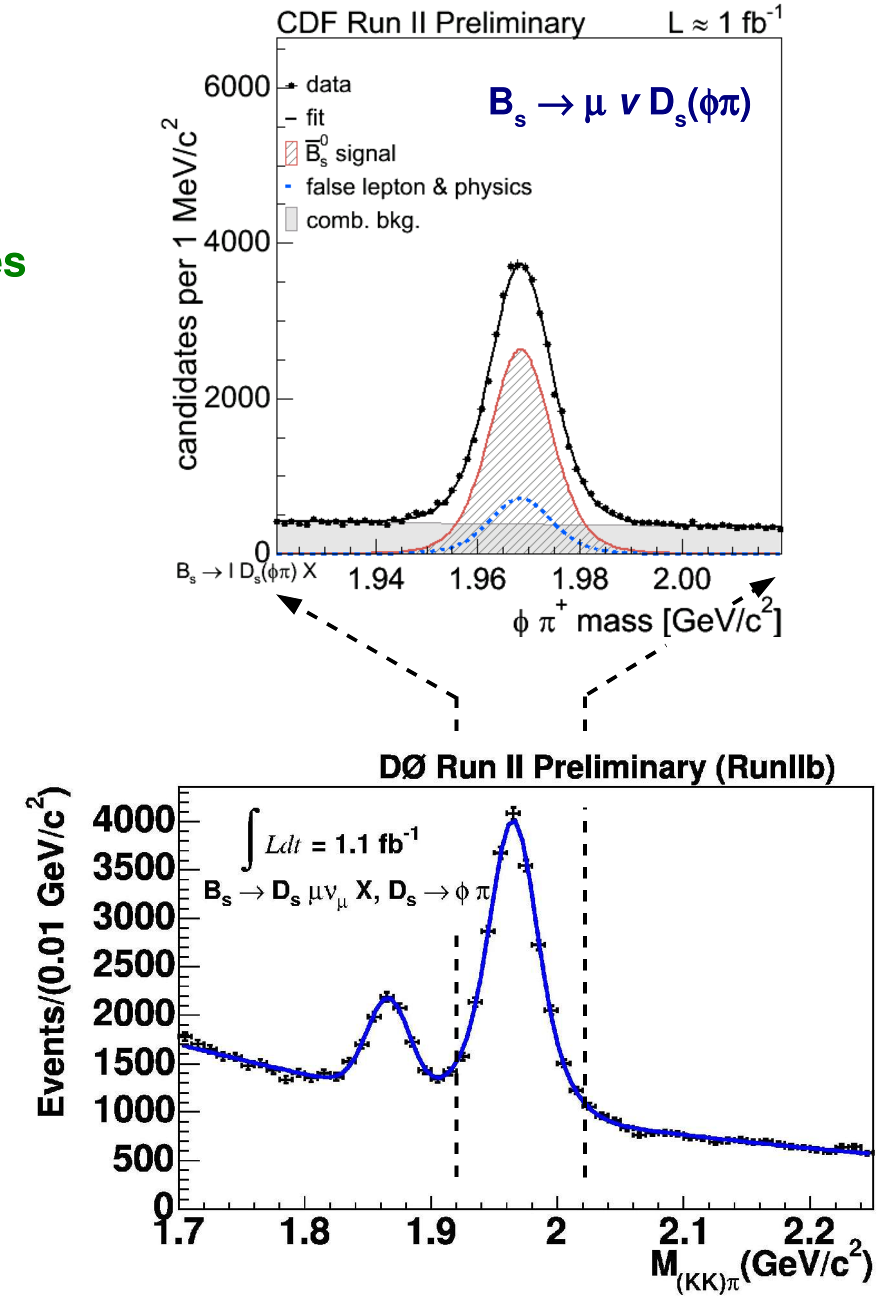


Tracking: Mass Resolution

Exp	B	Radii [cm]	|η| Range	<Space Pts>
CDF	1.4 T	1.5 – 137	< 2.0	>100
D0	2.0 T	2.8 – 52	< 3.0	20
		1.7 w/ Layer 0 → 25% gain in proper t res		

2-Track Mass Resolution

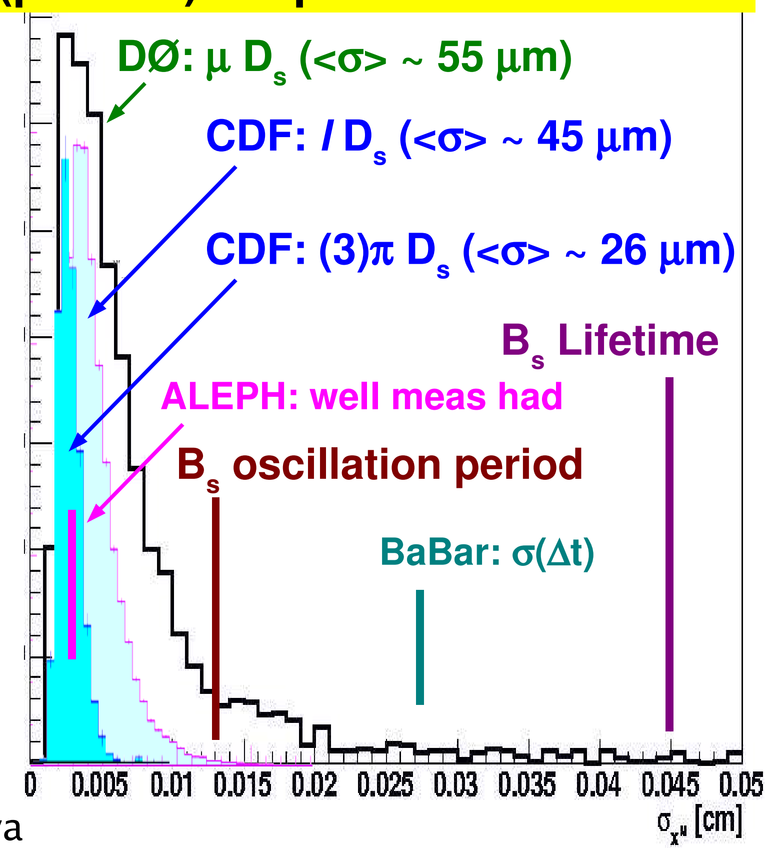




Tracking: Time Resolution

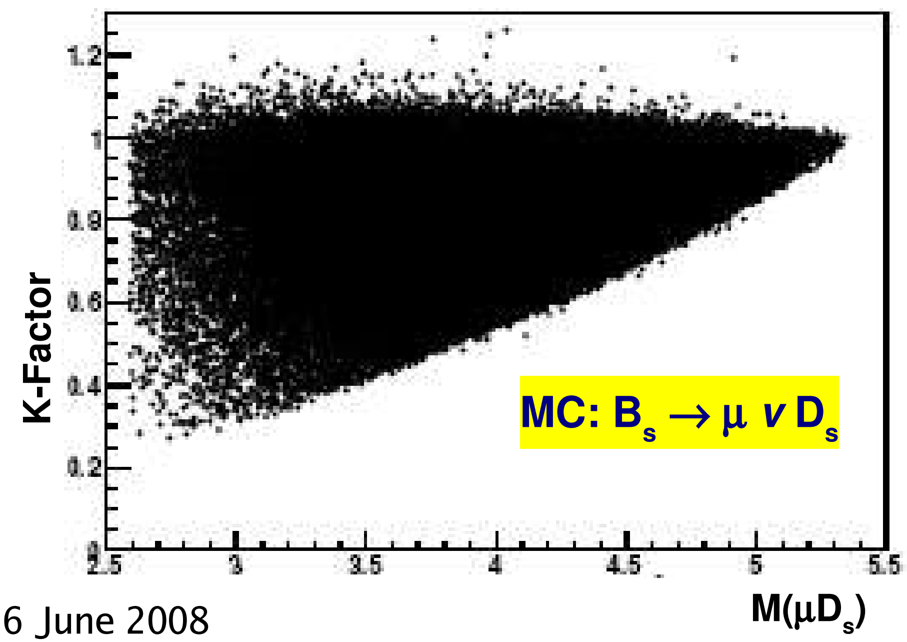
Exp	B	Radii [cm]	|η| Range	<Space Pts>
CDF	1.4 T	1.5 – 137	< 2.0	>100
D0	2.0 T	2.8 – 52	< 3.0	20
		1.7 w/ Layer 0 ⟶ 25% gain in proper time resolution		

(pseudo) Proper Time Resolution

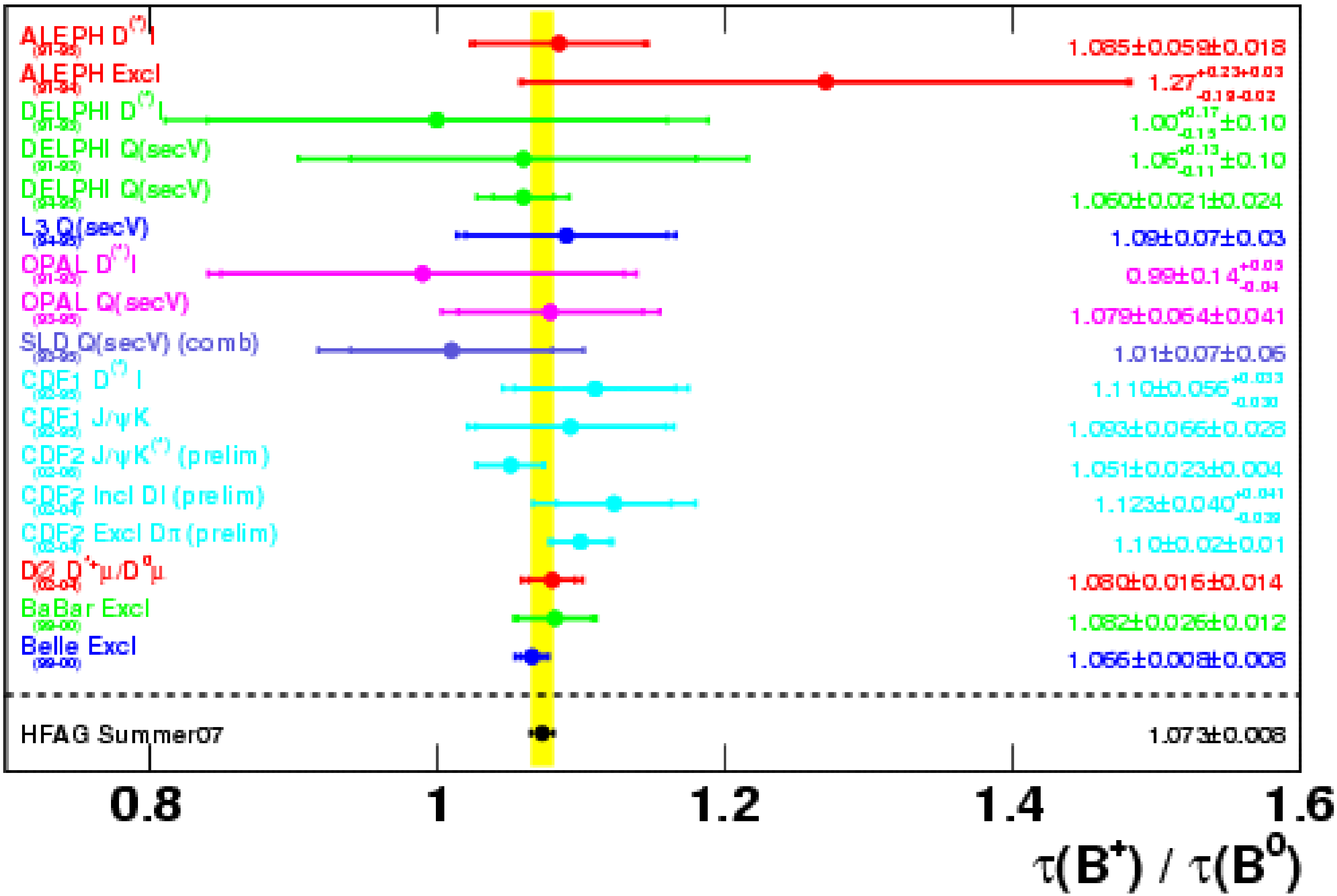


missing *ν*: semi-leptonic decays

$$ct = M_B \frac{L_{xy}^{meas}}{P_T^{meas}} K \qquad \left(K = \frac{P_T^{meas}}{P_T^B} \right)$$



B^0 and B^+ Lifetimes



B_s Lifetime

$\Delta\Gamma_s \neq 0 \Rightarrow$ different B_s lifetime measurements mean different things

1) $B_s \to$ Anything — unknown mix of Γ_{odd} and Γ_{even}
   - no longer used

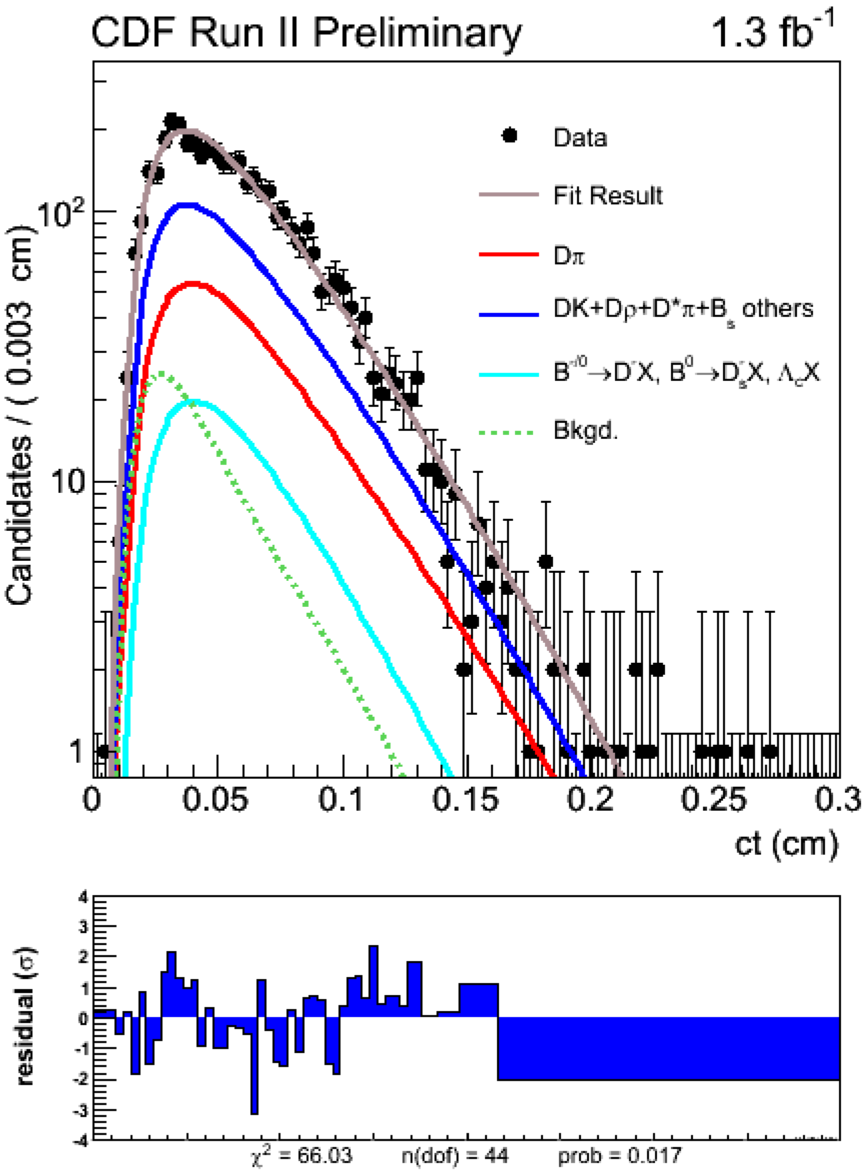
2) $B_s \to$ Flavor Specific — 50% CP-odd – 50% CP-even
   - DØ — semi-lept: PRL 97, 241801 (2006)
   - CDF — semi-lept: prelim (2005) & $B_s \to \pi D_s$: prelim (2008)

3) $B_s \to J/\psi\,\phi$ — fit for CP components
   - DØ — arXiv:0802.2855 (2008)
   - CDF — arXiv:0712.2348 (2007)

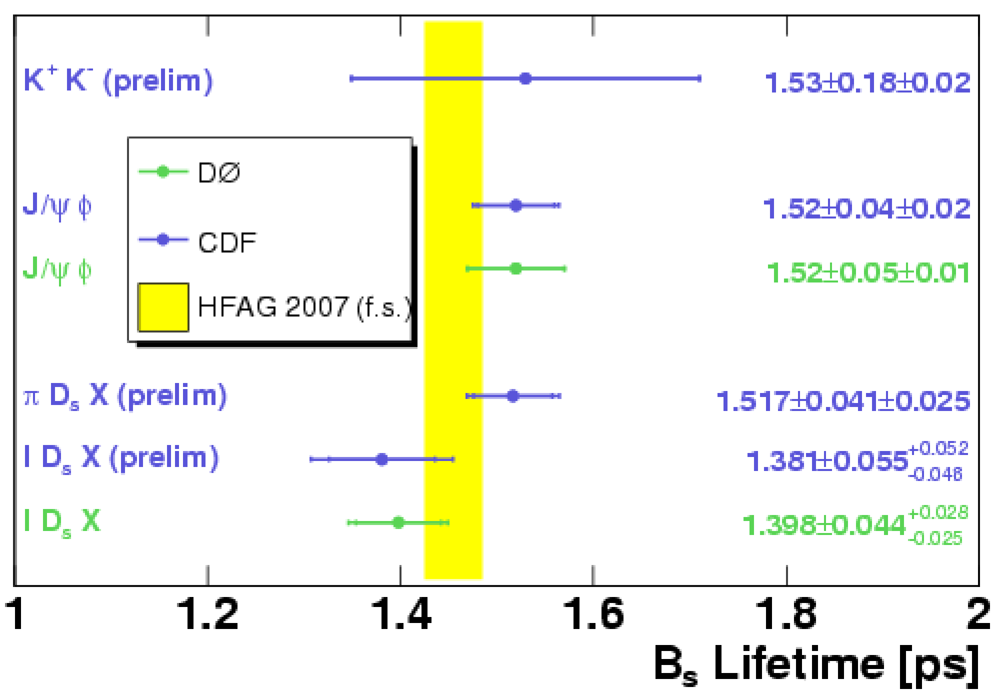
4) $B_s \to$ CP Specific — 100% odd or even
   - CDF — $B_s \to K^+ K^-$: prelim (2006)

Recent B_s Lifetime Results

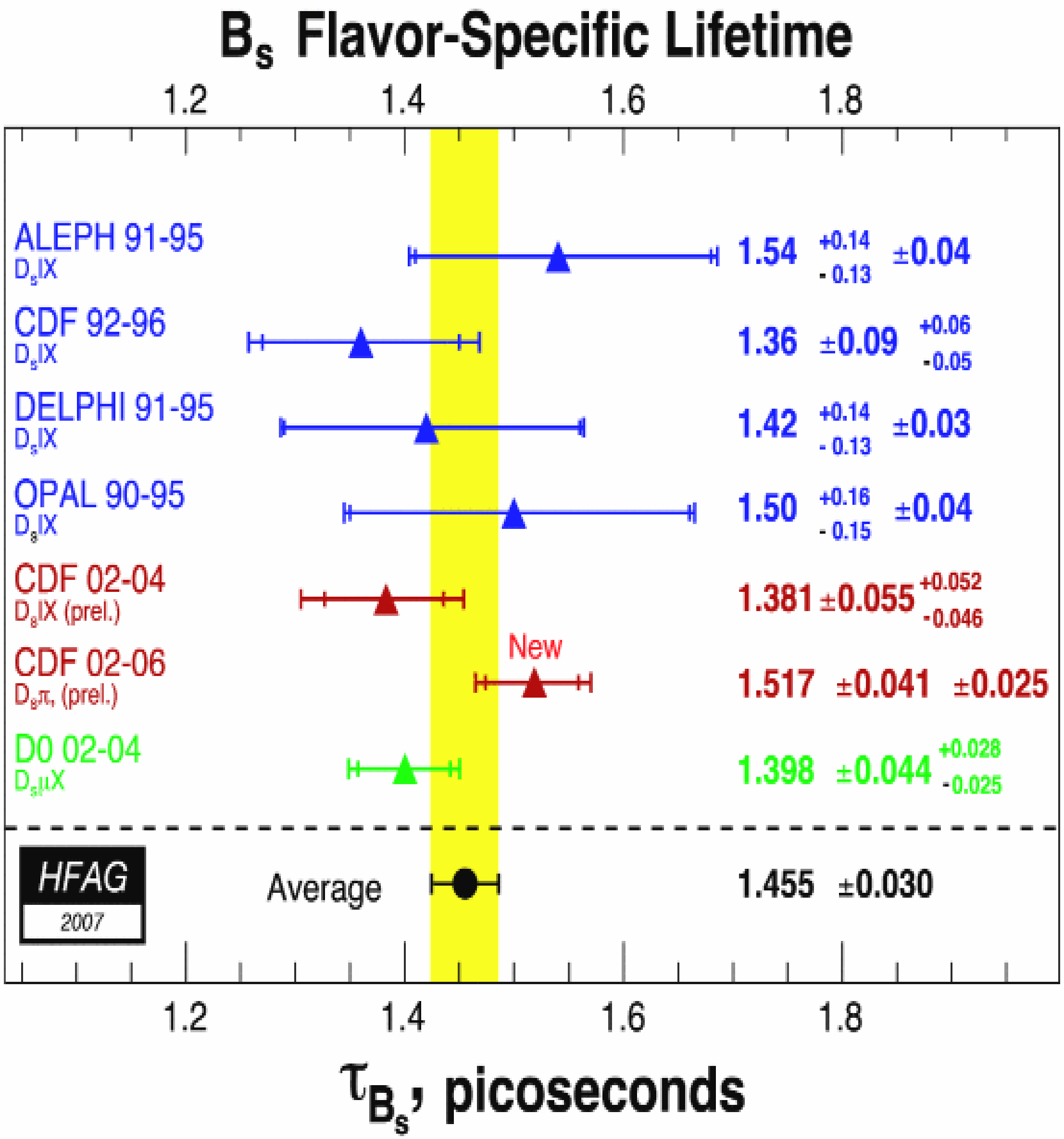
CDF: Full & Partial Reco $B_s \to \pi D_s X$

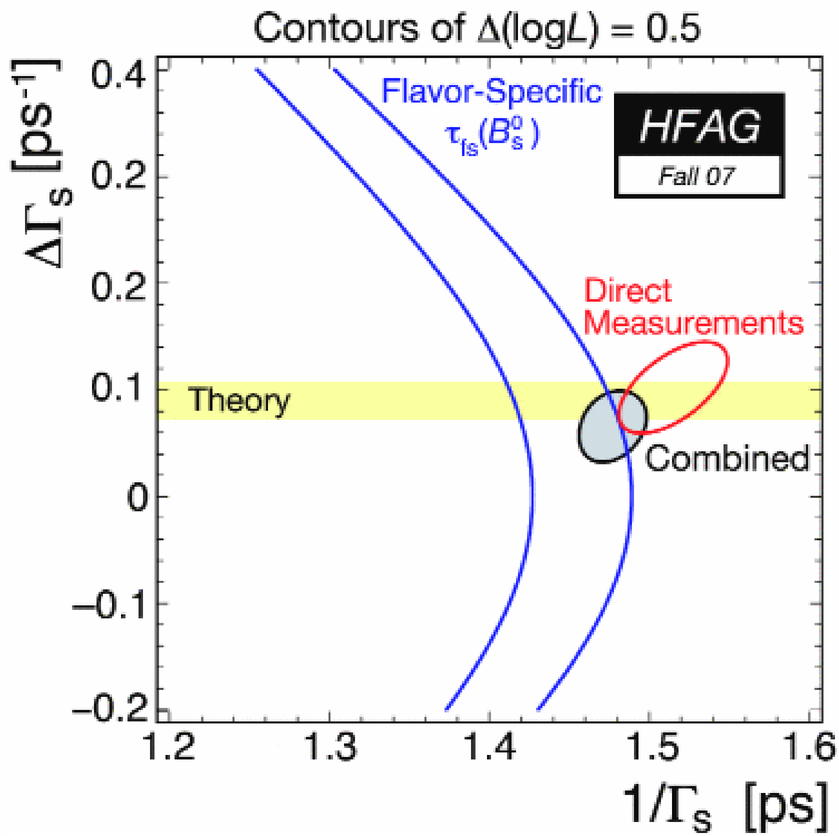


Mode	Lumi (fb^{-1})	Cand's	Signal
CDF $K^+ K^-$	0.36	3219	718 ± 55
CDF $J/\psi\ \phi$	1.7		2500
DØ $J/\psi\ \phi$	2.8	48047	1976 ± 65
CDF $h\ D_s$	1.3	5566	3340.3
CDF $l\ D_s$	0.36	2297	1155 ± 27
DØ $l\ D_s$	0.4		5176 ± 242



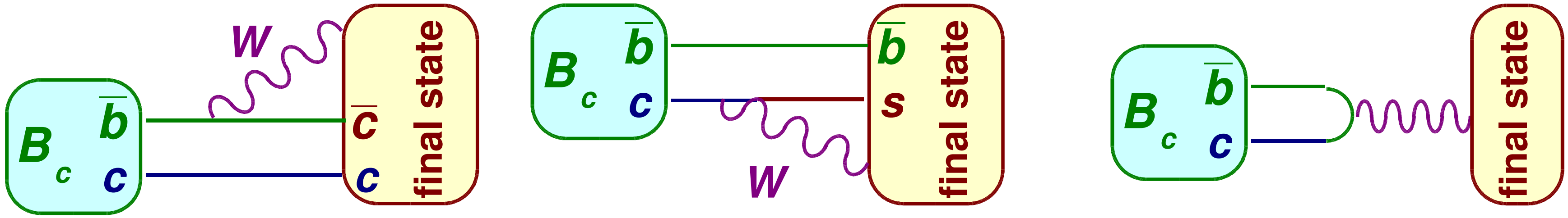
B_s Flavor Specific Lifetimes



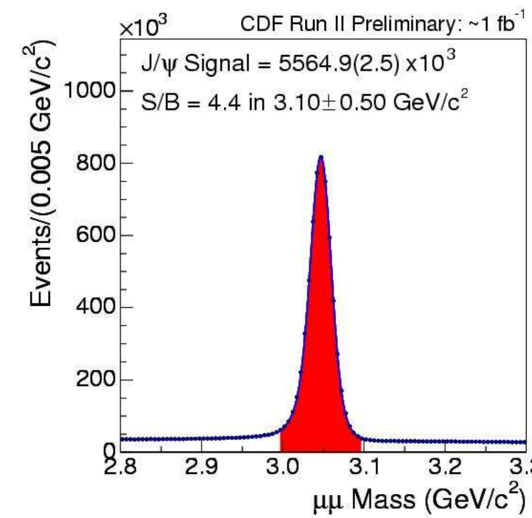


B_c Lifetime Measurements

Two heavy quarks ⇒ Increased decay possibilities



– theory predicts: $\tau(B_c) \sim \tau(B) / 3$

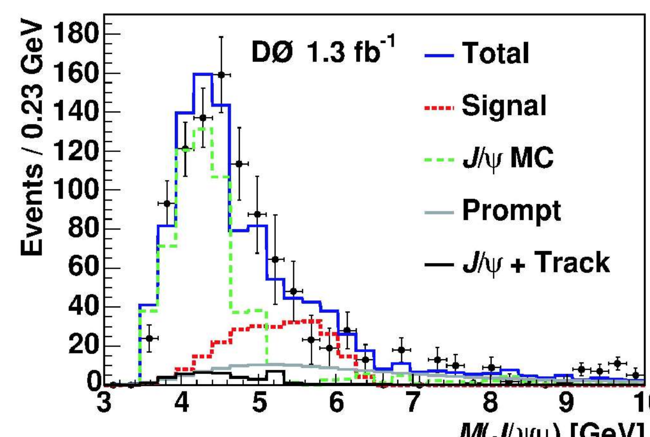


New Analyses: $B_c \to J/\psi(\mu^+\mu^-)\, \ell^{\pm} X$

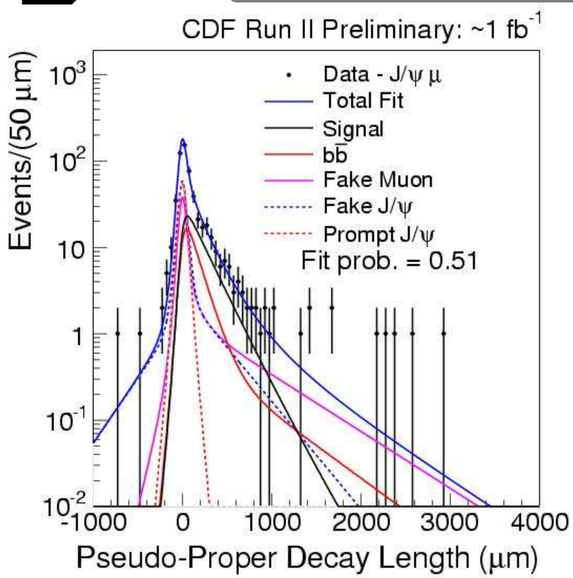
- CDF J/ψ μ,e prelim
- DØ J/ψ μ arXiv:0805.2614

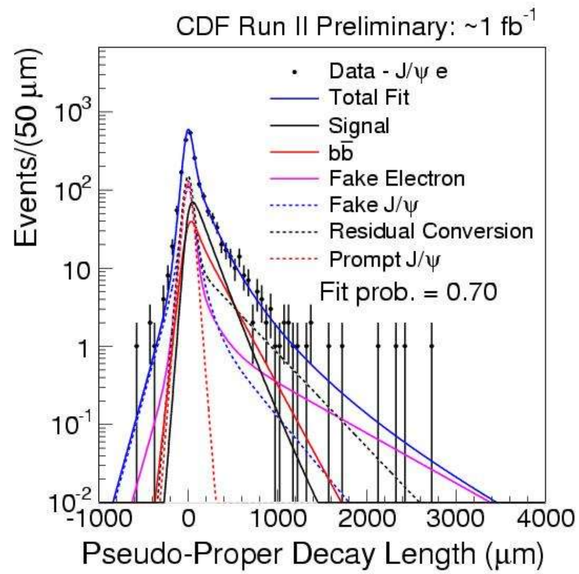
Mode	Lumi (fb^{-1})	Cand's	Signal
CDF J/ψ μ	1	572	257 ± 12
J/ψ e		1935	659 ± 44
DØ J/ψ μ	1.3	14753	881 ± 80

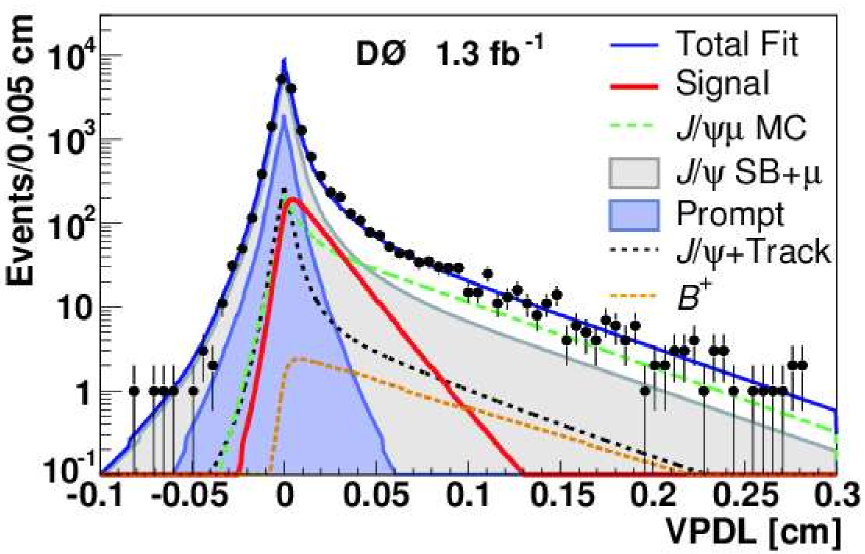
B_c + prompt J/ψ

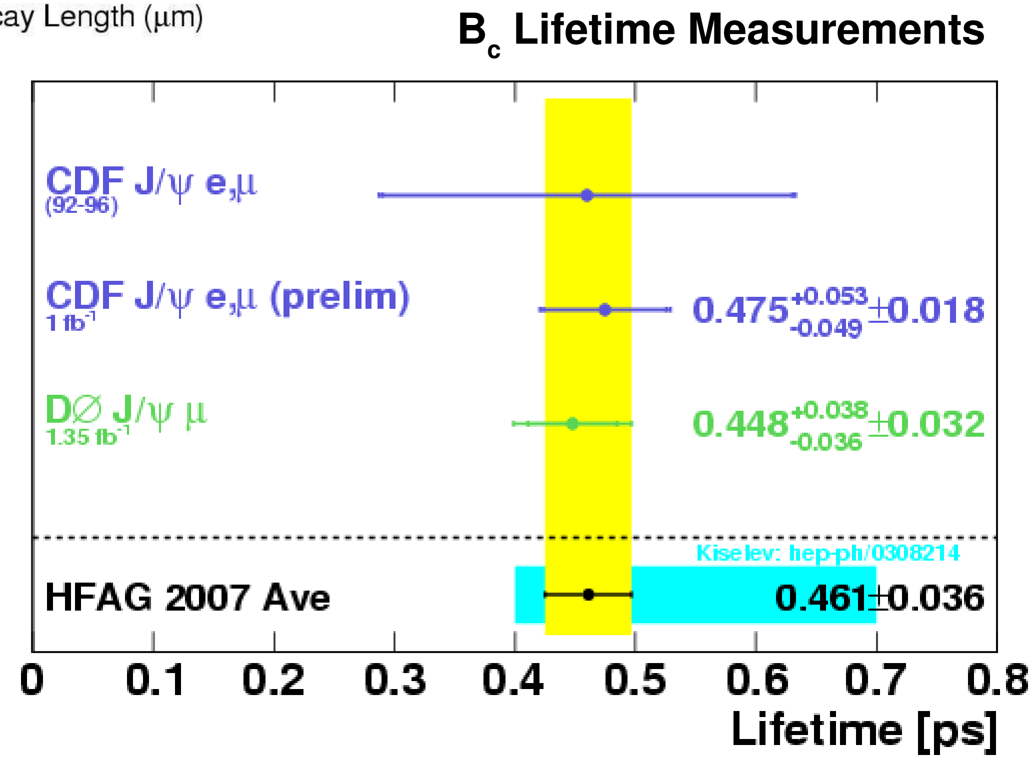


B_c Lifetime Measurements





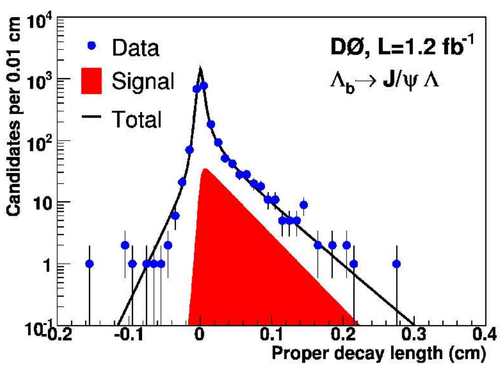


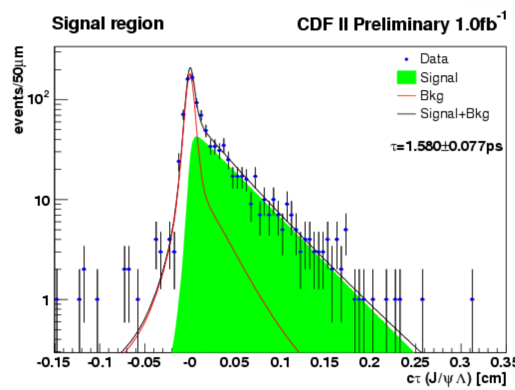


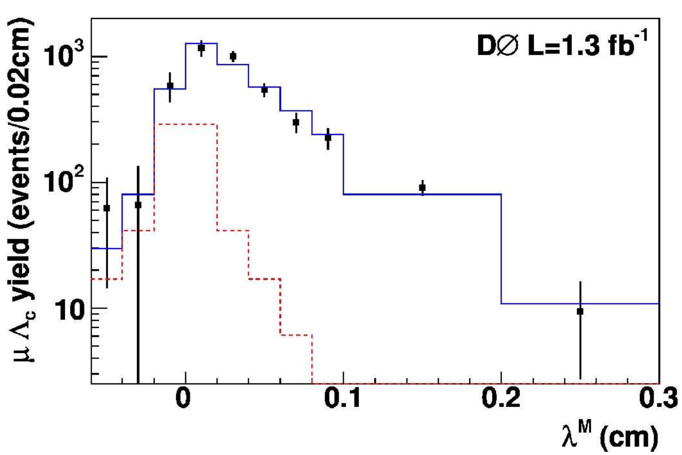
Λ_b Lifetime Measurements

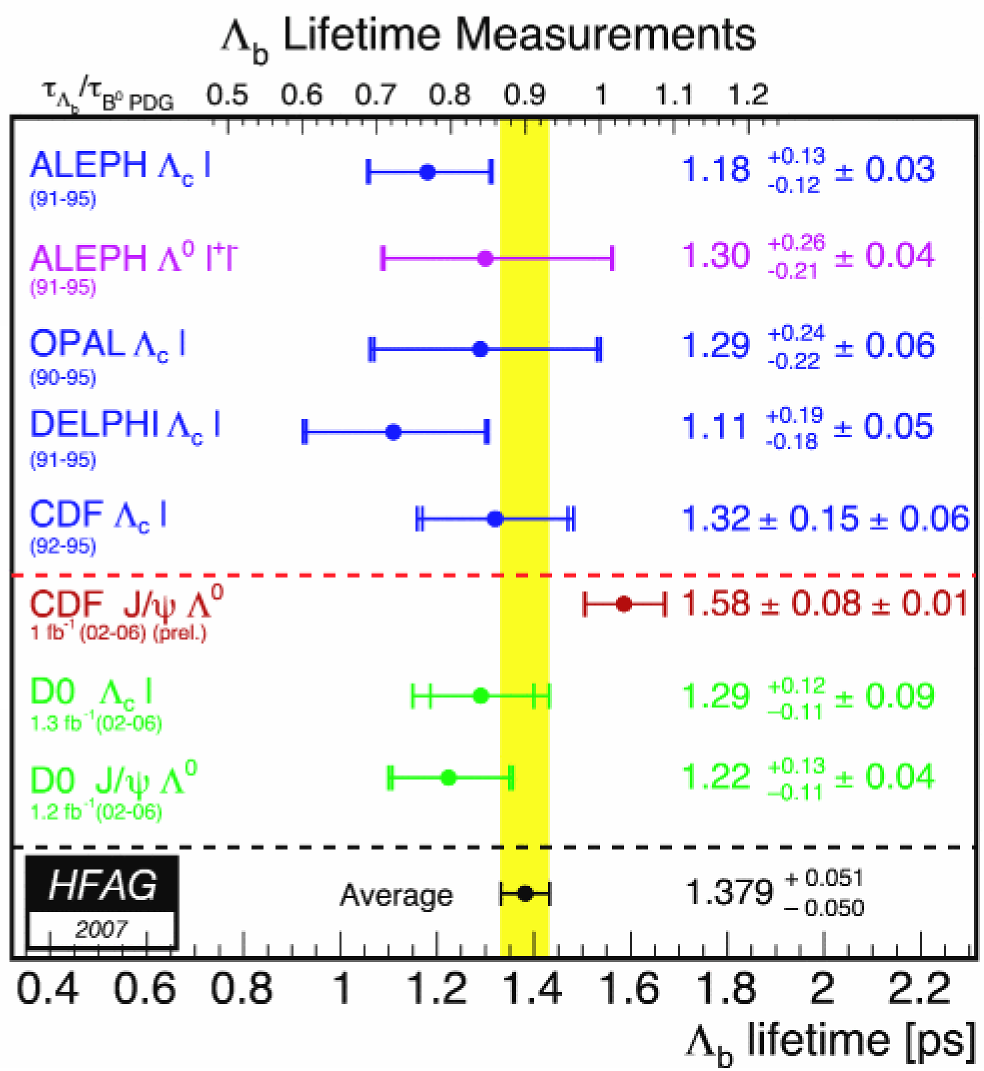
Recent Λ_b Lifetime Analyses

Mode		Lumi (fb^{-1})	Signal
CDF	$J/\psi(\mu^+\mu^-)\ \Lambda(p\pi)$	1.0	557 ± 40
DØ	$J/\psi(\mu^+\mu^-)\ \Lambda(p\pi)$	1.2	171 ± 20
	$\mu\ \Lambda_c(K_S p)\ X$	1.3	3727 ± 499

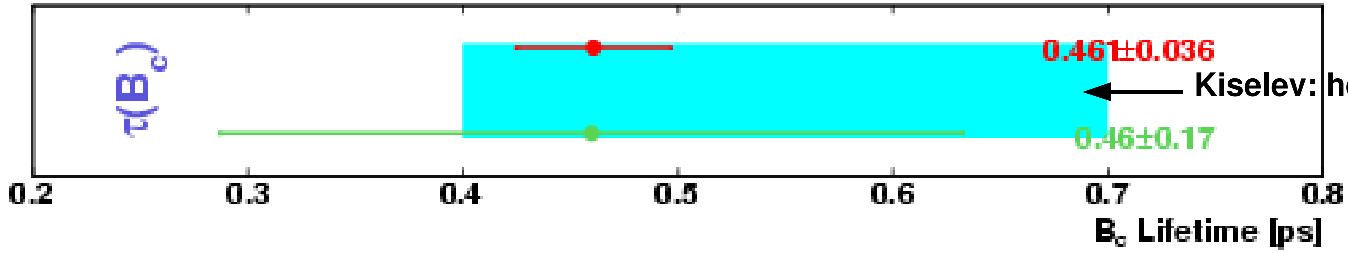


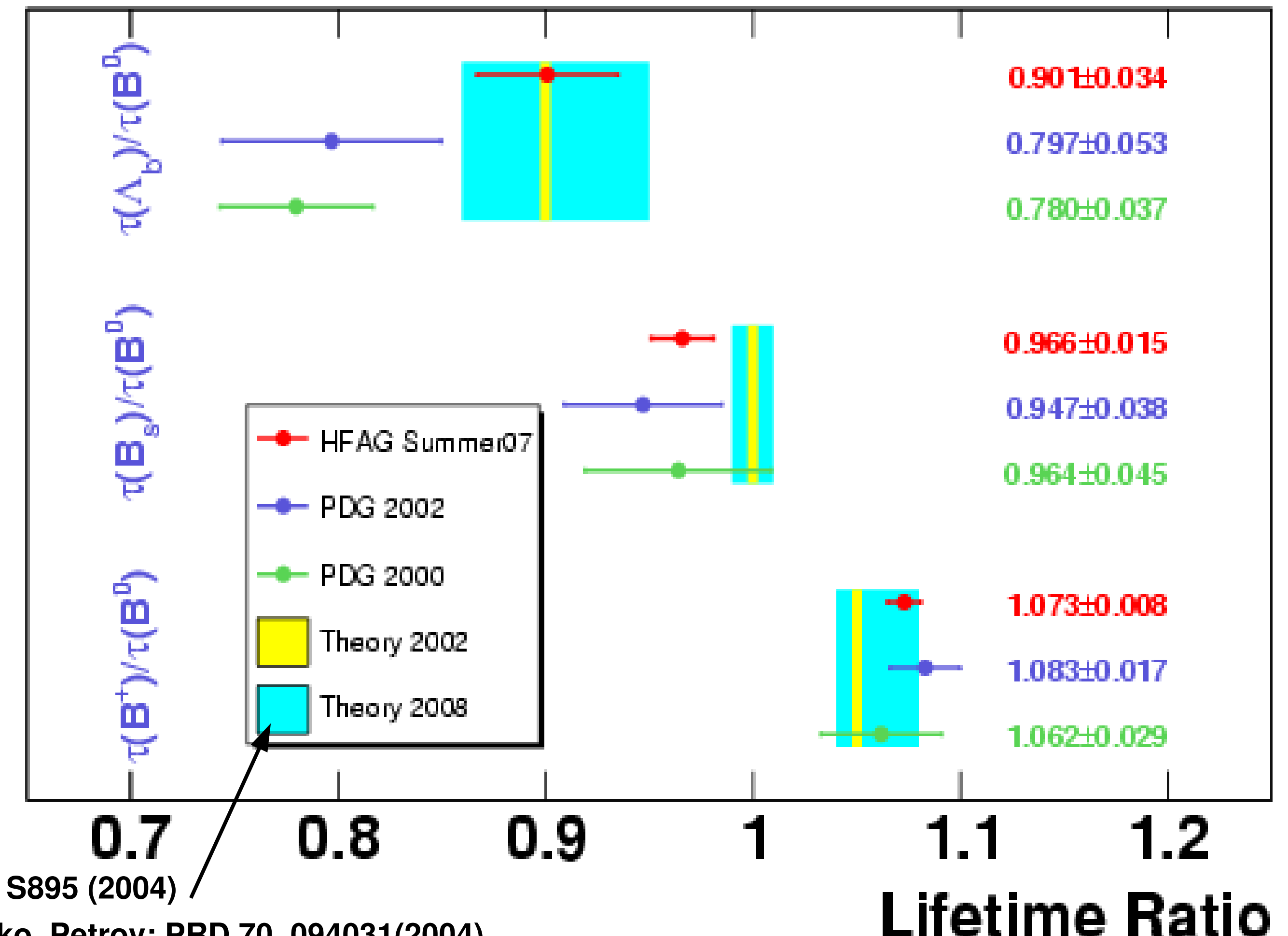






Lifetime Summary





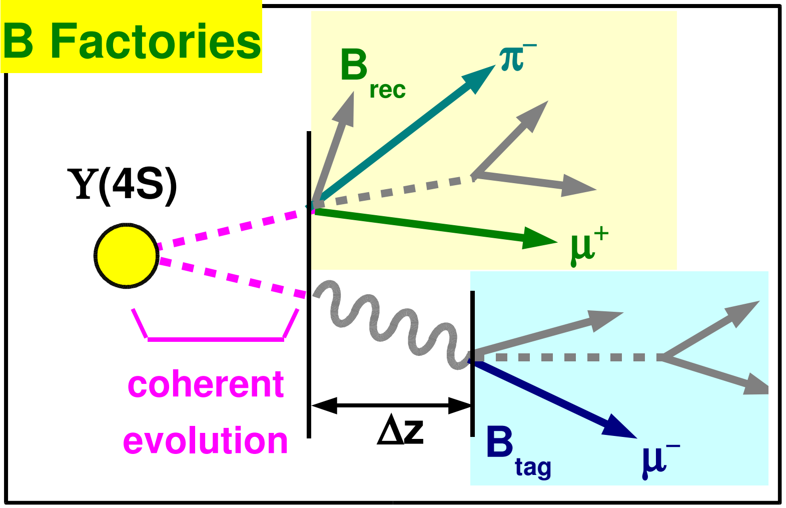
Tarantino: EPJ C33, S895 (2004)

Gabbiani, Onischenko, Petrov: PRD 70, 094031(2004)

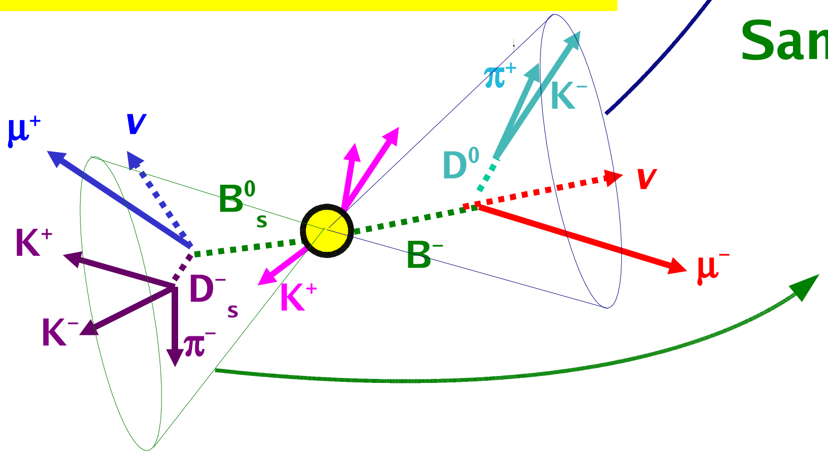
PRD 68, 114006 (2003)

Flavor Tagging for Mixing

B Factories



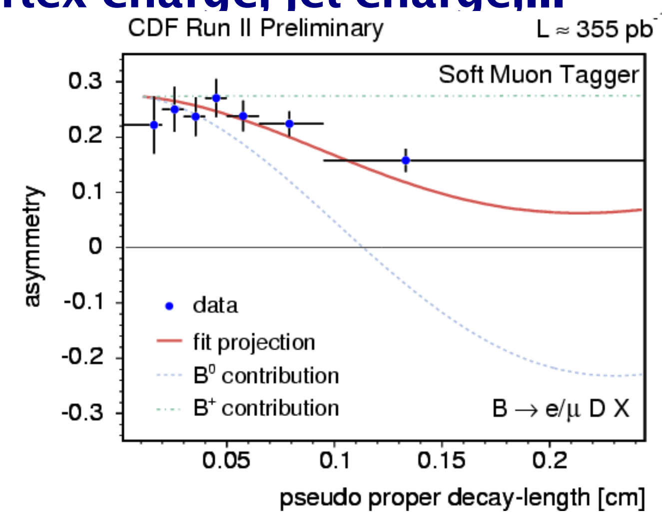
Hadron Colliders & Z→e⁺e⁻



$$\langle \text{Significance} \rangle = \sqrt{\frac{\epsilon D^2}{2} \frac{S}{\sqrt{S+B}}} \exp\left[\frac{-(\Delta m \sigma_t)^2}{2}\right]$$

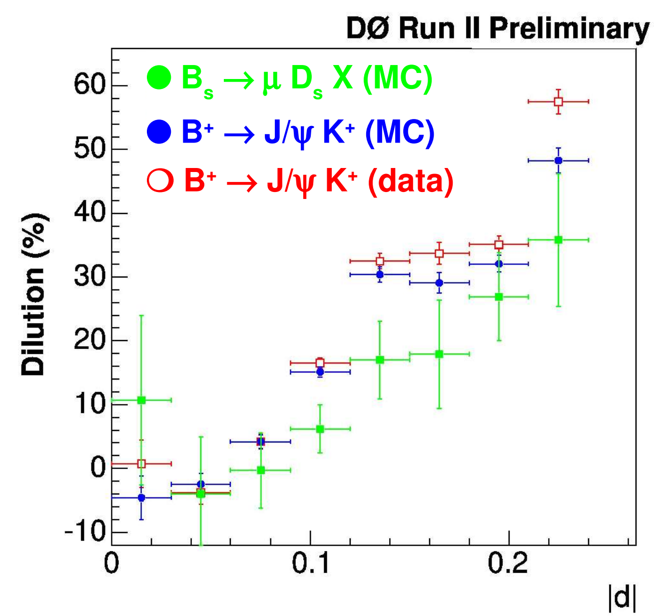
Opposite Side Tag

- lepton sign, vertex charge, jet charge,...
- measure in B_d mixing

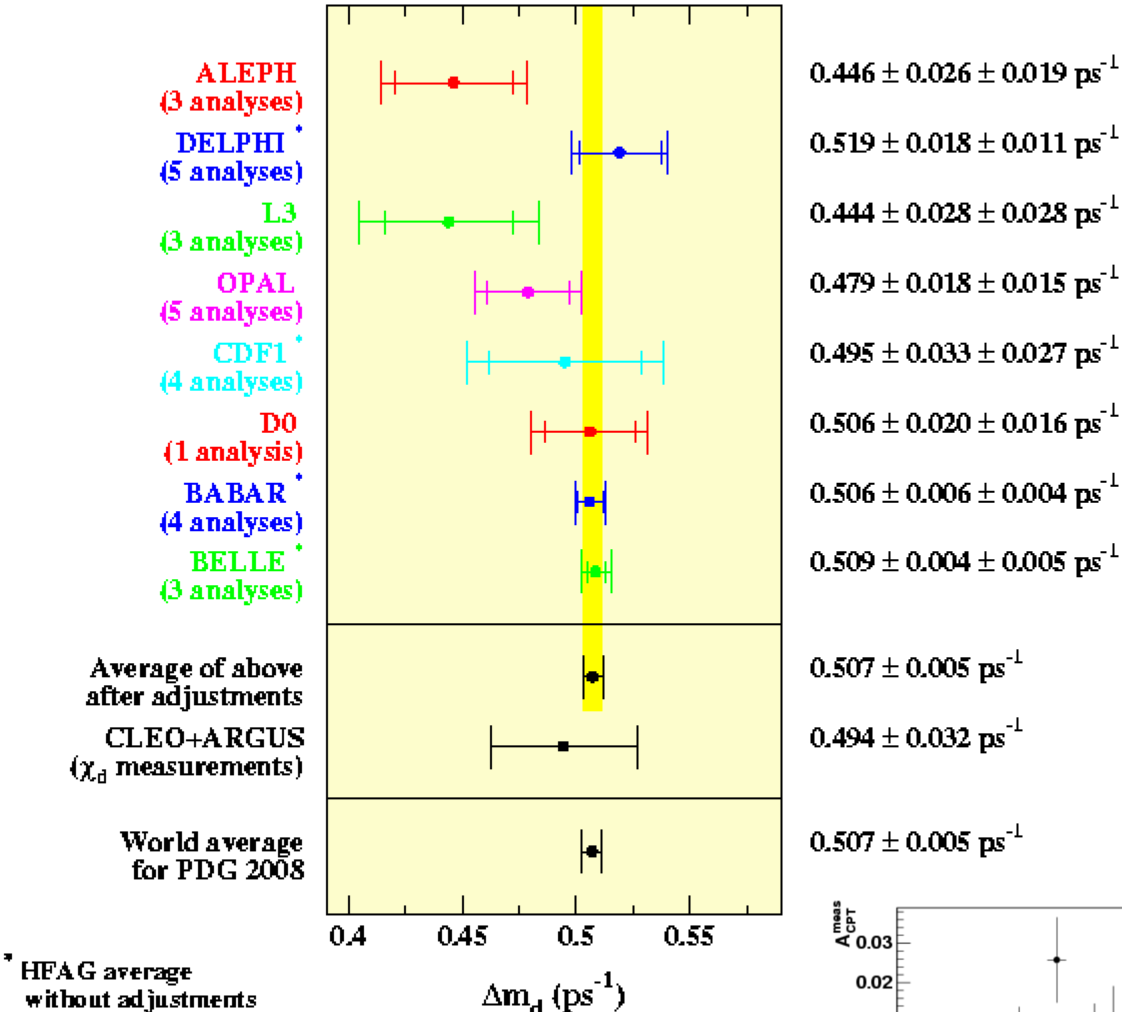


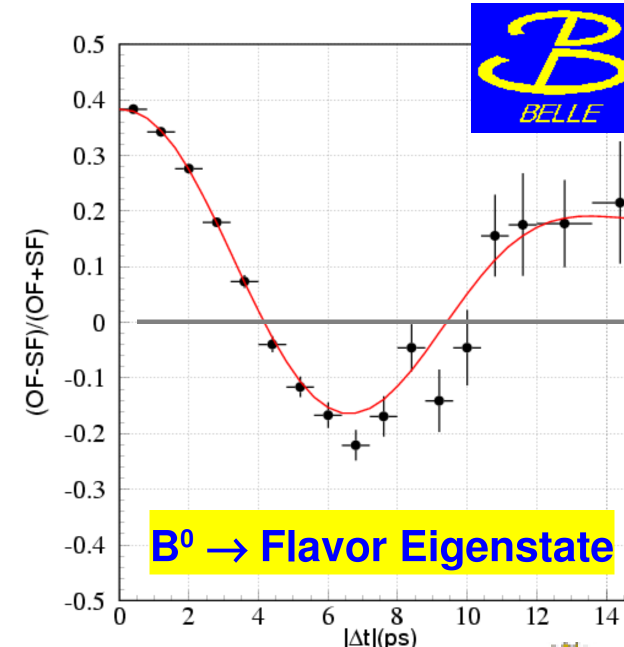
Same Side Tag

- "Kaon" charge, jet charge,...
- calib using control sample data vs MC
- check using consist $B_{d,s}$ mixing (A = 1)

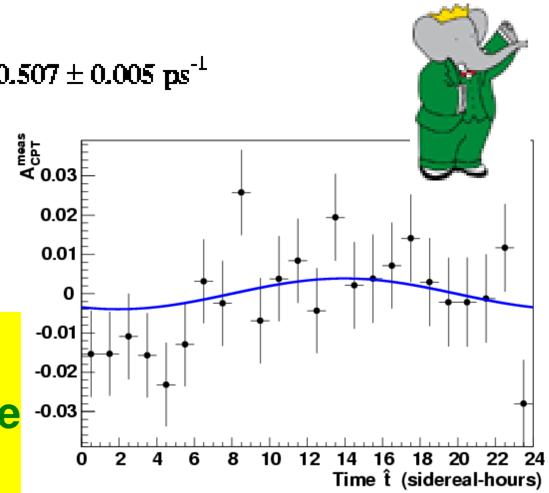


B_d Mixing



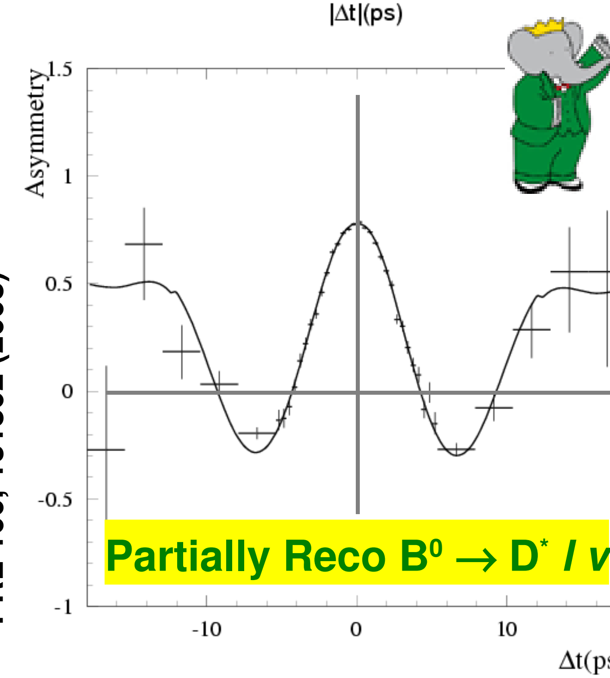


PRD 71, 072003 (2005)



CPT Test using sidereal dependence of B^0 mixing

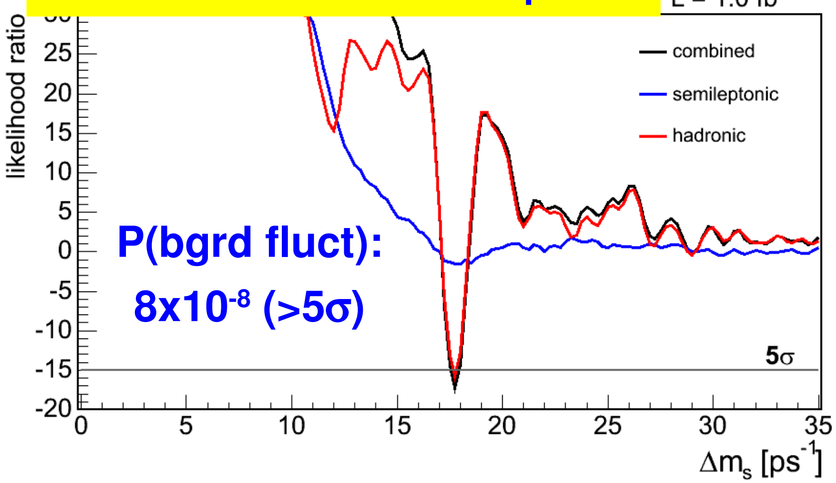
PRL 100, 131802 (2008)



PRD 73, 012004 (2006)

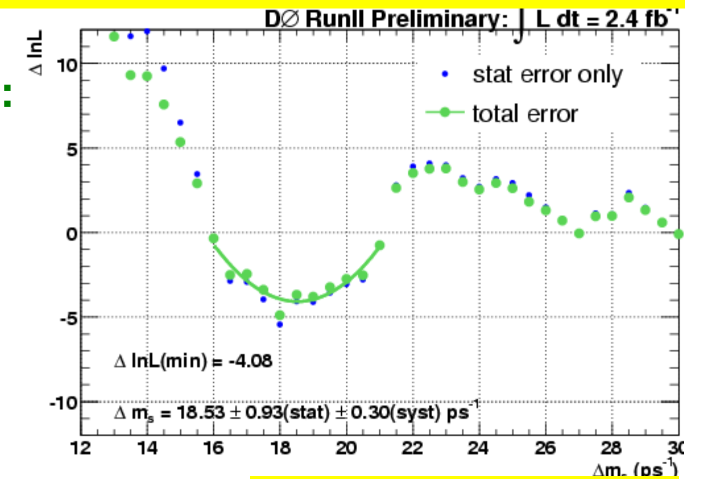
B_s Mixing

CDF: Combined – 1 fb^{-1} – Sep. 2006



DØ prelim: Comb – 2.4 fb^{-1} – Aug. 2007

P(bgrd fluct):
4x10^{-3} (2.9σ)



$\Delta m_s = 17.77 \pm 0.10 \pm 0.07$ ps^{-1}

			<εD²>		
Exp	**Mode**	**Sample**	**OST**	**SST**	**Sens [ps^{-1}]**
ALEPH	Hadronic	28.5	27%		13.6
DØ	$l\ D_s(\phi\pi, K^*K, K^0_s K)$	64,500	4.5%		25.4
	$D_s(\phi\pi)\ \pi$	249	2.5%		14.0
CDF	$l\ D_s$ (all)	61,500	1.8%	4.8%	19.3
	$D_s(\phi\pi, K^*K, 3\pi)\ (3)\pi$	8,700	1.8%	3.7%	30.7

$\Delta m_s = 18.53 \pm 0.93 \pm 0.30$ ps^{-1}

<CDF,DØ>

$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.2060 \pm 0.0012(\text{exp})^{+0.0081}_{-0.0060}(\text{theor}) = \sqrt{\frac{M_{Bs}}{M_{Bd}} \frac{f^2_{Bs} B_{Bs}}{f^2_{Bd} B_{Bd}} \frac{\Delta m_d}{\Delta m_s}}$$

±0.5% (Δm_d)

±0.3% (Δm_s)

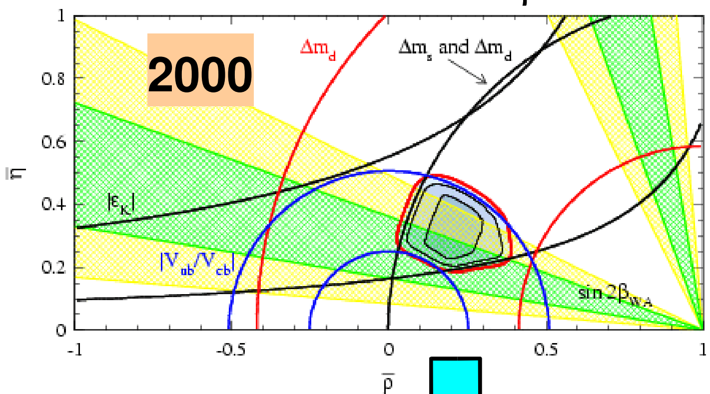
±3.4% ($f^2_{Bs} B_{Bs} / f^2_{Bd} B_{Bd}$)

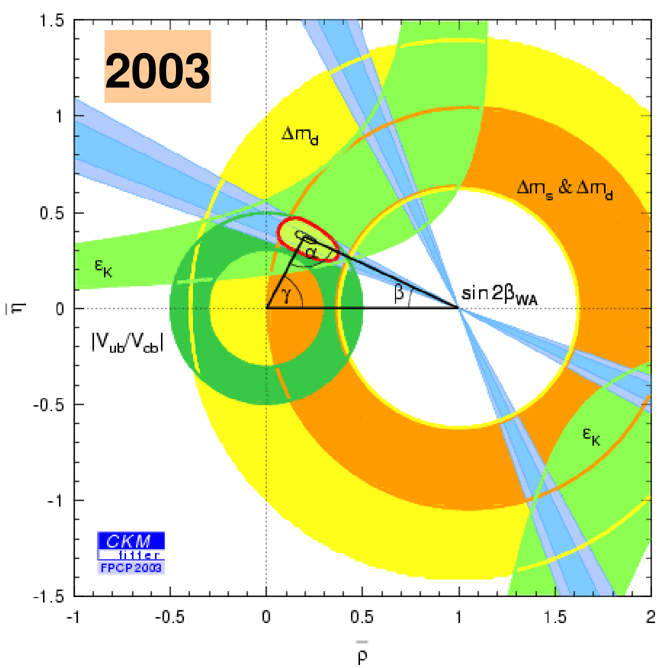
BaBar and Belle Ave: $0.200 \pm 0.016(\text{exp})^{+0.016}_{-0.015}(\text{theo})$ $\left(\frac{B \to \rho\gamma}{B \to K^*\gamma}\right)$

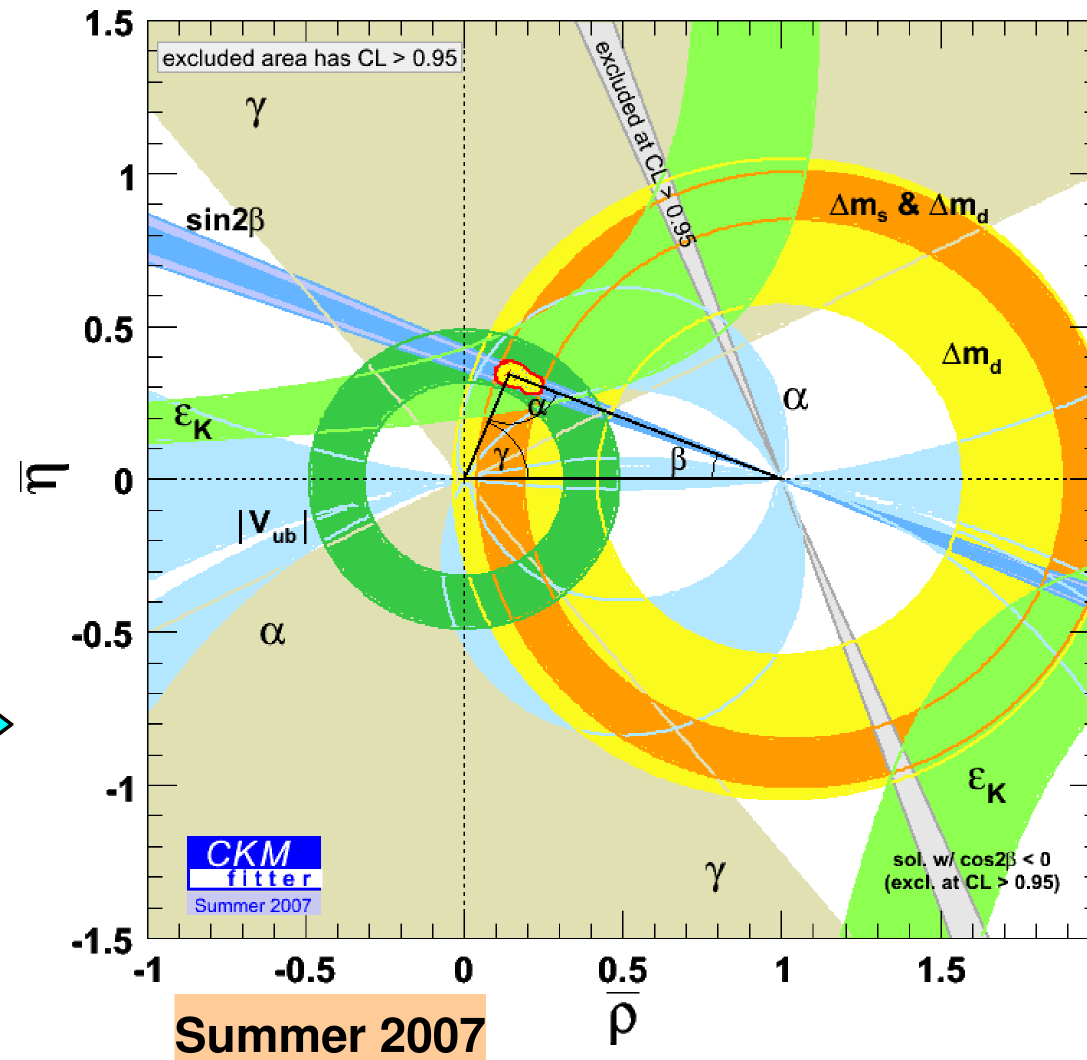
M.Okamoto hep-lat/0510113

Mixing and the U.T.

CKMFitter 2001: without sin 2β constraint







Consistent with Minimal Flavor Violation – but still room for Surprises !

Summary & Future Prospects

Remarkable Progress in B Physics since start of B-Factories & Run II

Measurement	Improvement in Accuracy since 2000
Lifetimes	factor of ~2 + significant advances in theory
B^0 mixing	>factor of 3
B_s mixing	1st observation – 0.3% accuracy

The Future

Measurement	Status
$\tau(B^0)$	systematics limited
$\tau(B_s)$	flavor specific: approaching syst limit
	$J/\psi\ \phi$ analysis will continue as part of CPV studies
B_c, Λ_b, Ξ_b, ...	statistics limited – focus of future lifetime work
Δm_d, Δm_s ($\lvert V_{td} / V_{ts} \rvert$)	dominated by theory error $\Rightarrow$ opportunity for lattice

Backup Slides

CKM Matrix and Mixing

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

$$\Delta m_q = \frac{G_F^2}{6\pi^2} \eta_B S\left(\frac{M_t^2}{M_W^2}\right) M_W^2 M_{Bq} \hat{B}_{Bq} f_{Bq}^2 |V_{tb} V_{tq}^*|^2$$