8.882 LHC Physics

Experimental Methods and Measurements

b Hadron Lifetimes and Other Essentials
[Lecture 18, April 13, 2009]

Organization

General question

- any?

Project 2

- nobody handed in yet :-)

Project 3

- is available on the Web, lectures will enlighten the subject more, but you can get a full prototype going
- due May 2....

Final project: the conference

- May 19, 12:00 Kolker Room, *is that ok?*

Lecture Outline

b hadron lifetimes and other essentials

- motivation and theoretical introduction
- methodology and experimental challenges
- existing measurements
- project 3: outline

Convention used in the community

- *b* – quark of down-type pertaining to the third quark family
- *B* – meson containing one *b* antiquark and a non *b* quark
- *b* hadron – *B* meson or baryon containing a *b* quark
- charge conjugate states are generally implicit

Motivation

Gain access to CKM matrix elements

- *B* mesons have access to V_{cb}, V_{ub}, V_{td}, V_{ts} ← mixing (V_{td}, V_{ts}); lifetimes (V_{cb}, V_{ub})
- remember the CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V \times \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad \text{with} \quad V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

V is Cabbibo–Kobayashi–Maskawa matrix

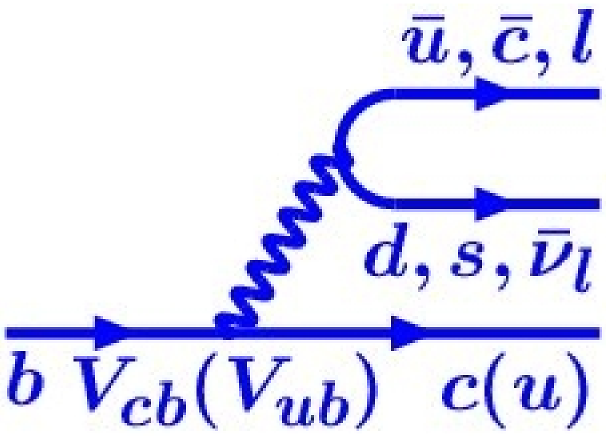
$$\text{Quarks} \quad \begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

Conventionally: down types primed

- d' is mixture of d, s and b as described by CKM matrix

Quarks and Hadrons

Lowest order: bare *b* quark width – spectator picture



$$m_{\ell\bar{\nu}_\ell}(b \to q) \approx \frac{-G_F}{\sqrt{2}} V_{bq} \cdot \bar{q}\gamma^\mu(1-\gamma_5)b \cdot \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell$$

$$\Gamma_{\ell\bar{\nu}_\ell}(b \to q) = \frac{G_F^2 m_b^5}{192\pi^3} \left|V_{qb}\right|^2 F\left(\frac{m_q}{m_b}\right)$$

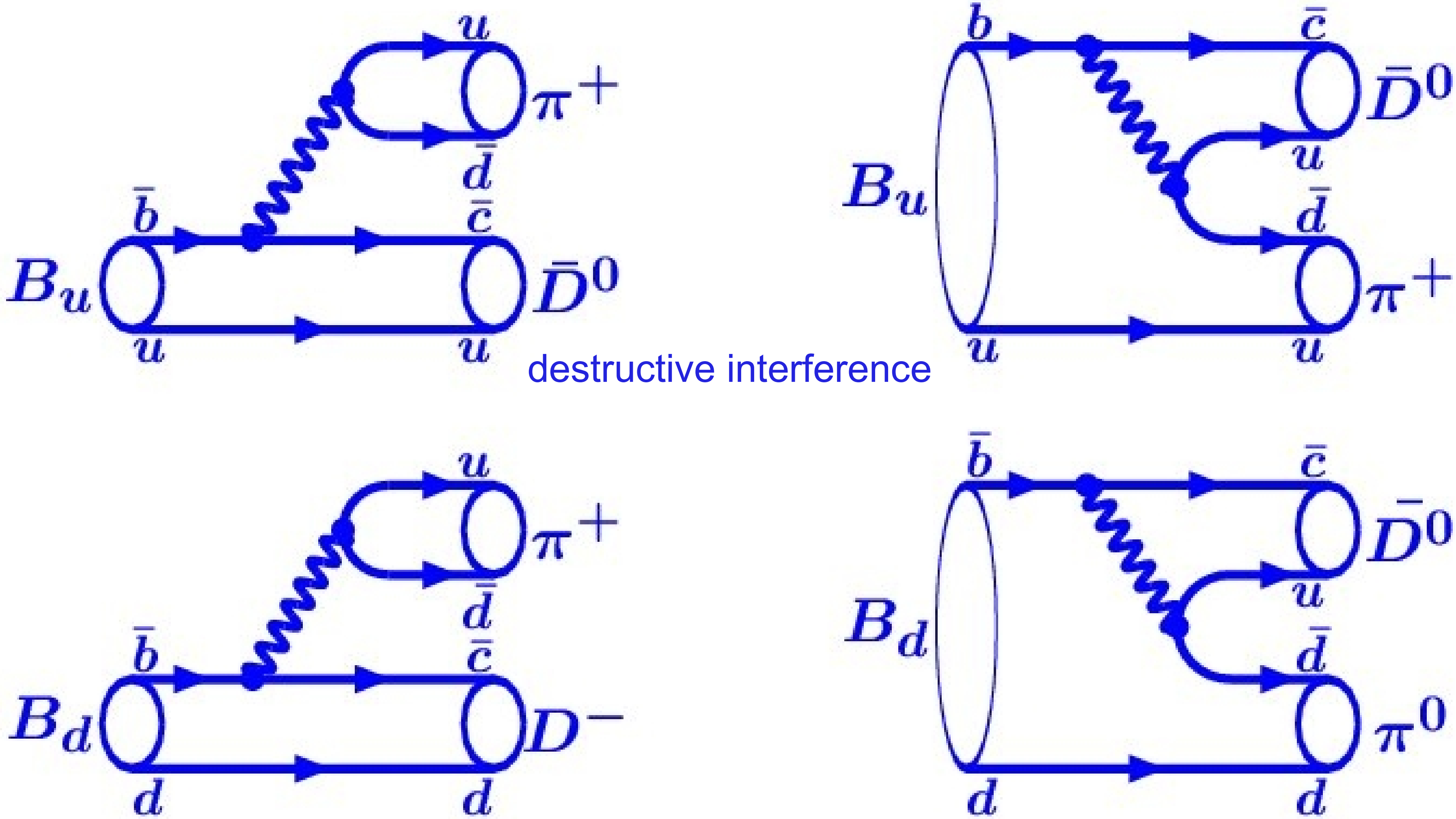
$$\frac{Br}{\Gamma} = \frac{1}{\Gamma_b} = \tau_b$$

receives modifications by quark and gluon clouds

Quarks and Hadrons

Hadronic effects on the width (*Γ*)

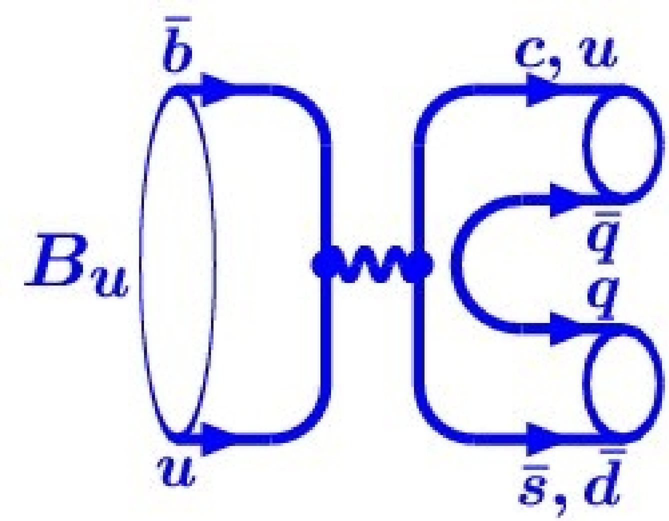
- Pauli interference (PI), causes $\tau_u > \tau_d$ (not obvious)



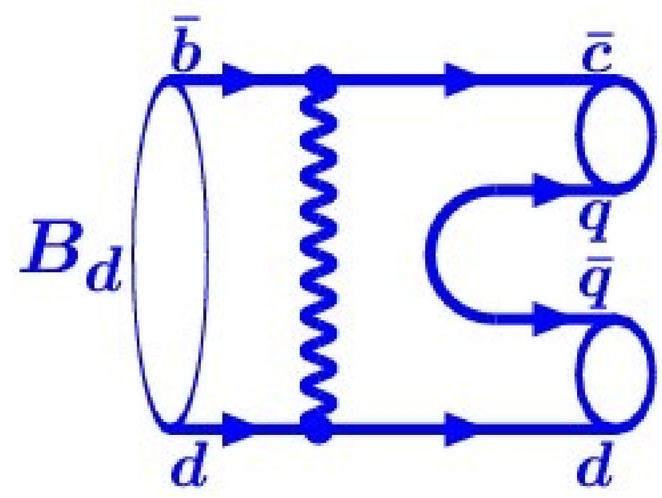
Quarks and Hadrons

Hadronic effects on the width (Γ)

- weak annihilation (WA)
- obviously opens channel for *u,c*
- shortens $\tau_{u,c}$



- weak exchange (WE) (baryons: *W* scattering)
- not obvious: spin conservation
- shortens τ_{baryon}



Some Theory

Heavy Quark Expansion (HQE)

$$\Gamma(H_Q \to f) = \frac{G_F^2 m_Q^5}{192\pi^3}|CKM|^2 \left[c_3^{(f)} \left\langle H_Q|\overline{Q}Q|H_Q \right\rangle + c_5^{(f)} \left\langle H_Q|\overline{Q}i\sigma GQ|H_Q \right\rangle \right.$$
$$\left. + \sum_i c_{6,i}^{(f)} \left\langle H_Q|(\overline{Q}\Gamma_i q)(\overline{q}\Gamma_i Q)|H_Q \right\rangle + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}^4}{m_Q^4}\right) \right]$$

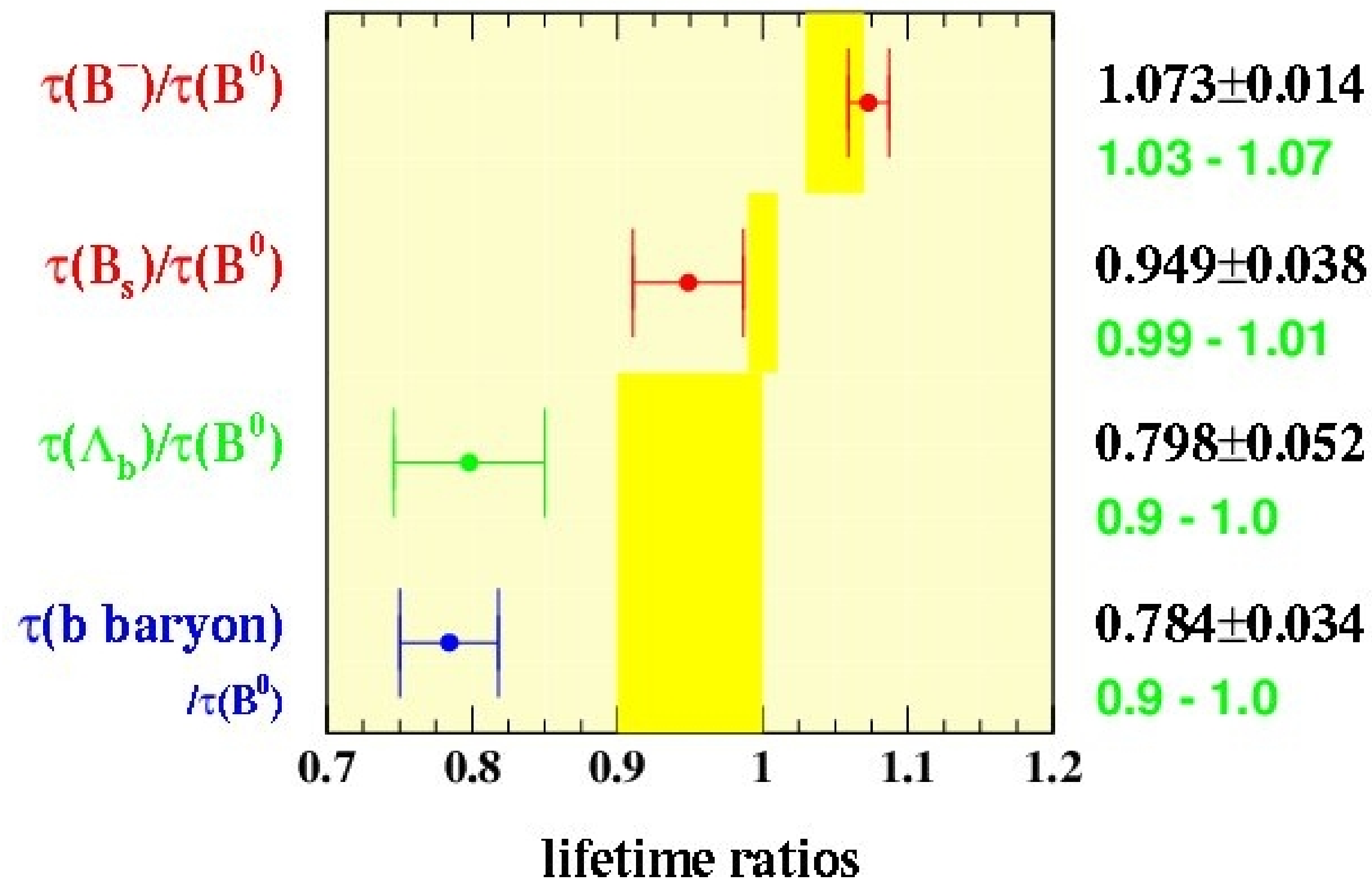
Details

- HQE assumes that quark is heavy: little influence from light quark
- PI, WA, and WE correction systematically included
- perturbative calculations give $c_n^{(f)} \sim 1/m_Q^{n-3}$
- lattice QCD (or sum rules): $\langle H_Q|O_n|H_Q\rangle \sim \Lambda_{\mathrm{QCD}}$
- measurements are so precise, theory is well behind.... so we do not measure CKM matrix but test HQE

Test Heavy Quark Expansion

Measure all *b* hadron lifetimes

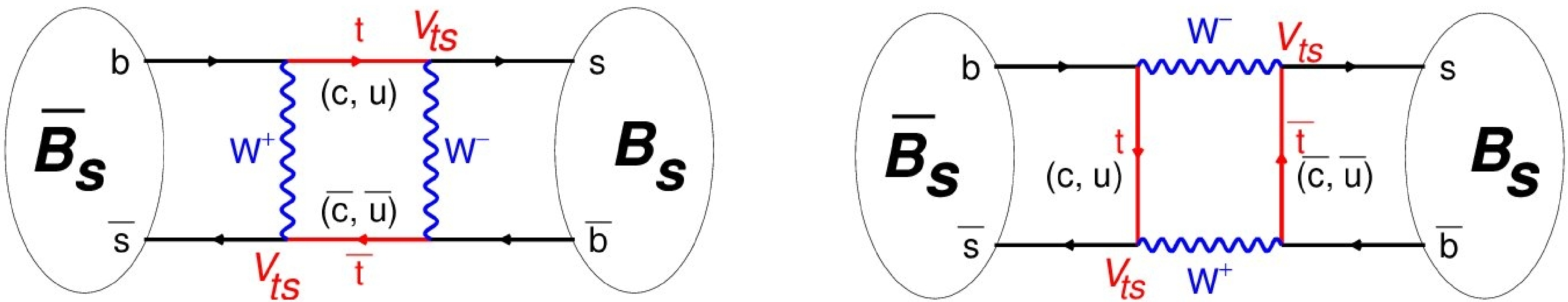
- form ratios for comparisons
- HFAG pages (http://www.slac.stanford.edu/xorg/hfag)



Motivation to Measure Δm, $\sin 2\beta$, γ, α

Gain direct access to CKM matrix elements

- 4 fundamental parameter Standard Model parameters
- problematic is always the non-perturbative QCD part
- works for B_d and B_s: frequency direct function of $|V_{tq}|^2$



Full calculation of above diagrams possible but

- large number of corrections because of quark/gluon cloud
- find quantities which are least affected
- find ways to intrinsically correct for hadronic effects

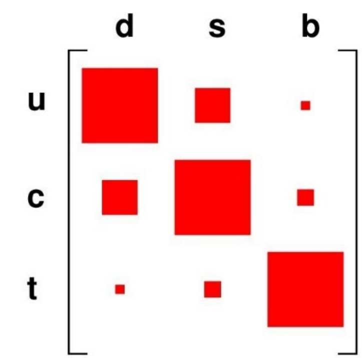
Motivation to Measure Δm, $\sin 2\beta$, γ, α

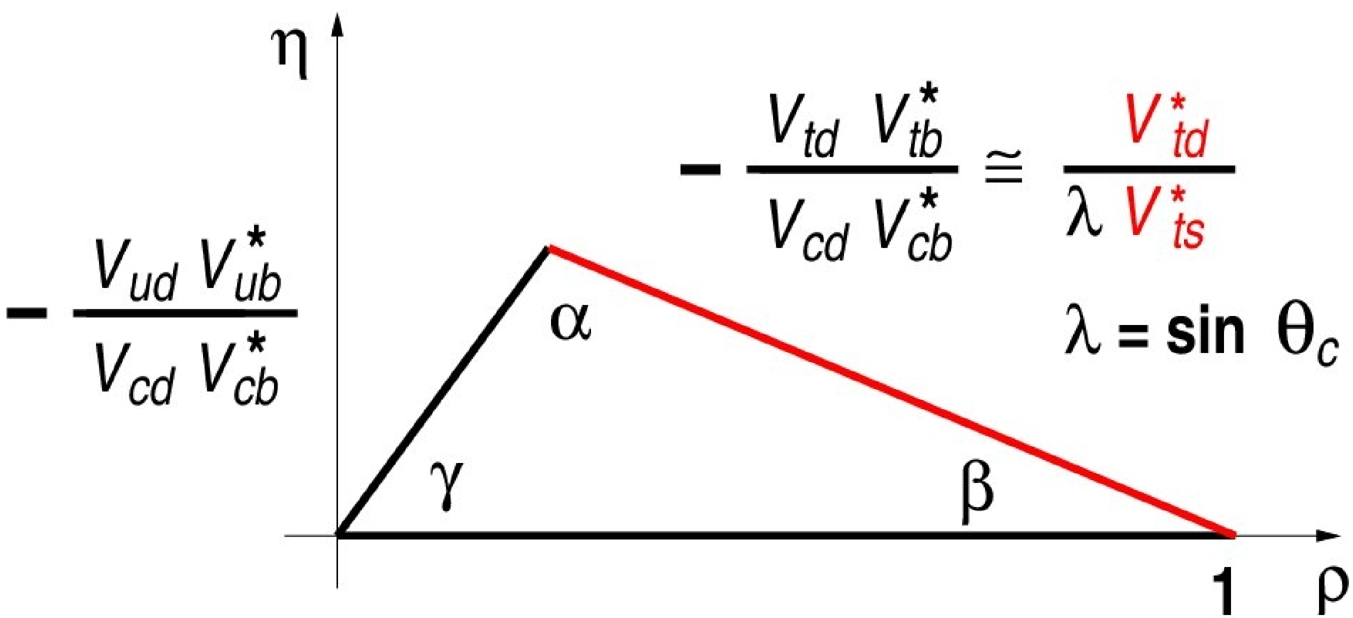
Unitarity condition: $V^{\dagger} V = 1$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\rightarrow V_{ud} V_{ub}^{*} + V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} = 0$$

$$\rightarrow 1 + V_{ud} V_{ub}^{*} / V_{cd} V_{cb}^{*} + V_{td} V_{tb}^{*} / V_{cd} V_{cb}^{*} = 0$$





Measure triangle in all possible independent ways and confirm its closure

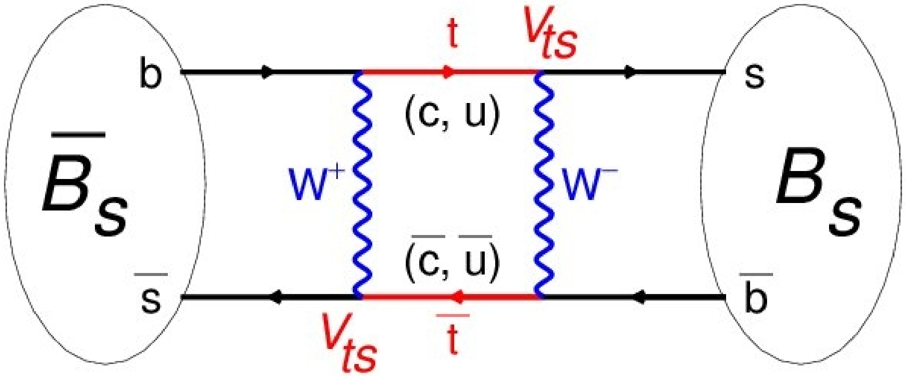
Theory Uncertainties - Δm

Theory prediction for B^0/B_s^0 mix through box diagram

$$\Delta m_q \propto m_{B_q} \hat{B}_{B_q} f_{B_q}^2 \left| V_{tb} V_{tq}^* \right|^2 \quad q = s, d$$

Lattice QCD calculations

$$\hat{B}_{B_d} f_{B_d}^2 = (246 \pm 11 \pm 25)\ \text{MeV}^2$$



Hadronic uncertainties limit $|V_{td}|$ determination to ≈ 11%

In ratio theory uncertainties are reduced

$$\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \frac{|V_{ts}|^2}{|V_{td}|^2} \quad \text{with} \quad \xi = 1.21^{+0.047}_{-0.035}$$

Determine $\frac{|V_{ts}|}{|V_{td}|}$ to ≈ 3.4%

Iain Stewart (MIT) is an expert of this, ask him

Bag Model and Form Factor

The MIT bag model

- 3 non-interacting quarks inside spherical cavity
- condition: vector current disappears on boundary
  - non-interacting → asymptotic freedom
  - vector current zero on boundary → confinement
- model adds a factor to the predictions which depends on the particular *b* hadron type B_h

Form factors

- describe more general the shape of the wave functions
- hadronic particles: wave function of the contained quarks

Non-trivial to derive here, remember their meaning

Experimentally ....

Various ways to measure lifetimes are possible

- inclusively reconstructed decays, ex. $B \to l\, X$
- semi-exclusively reconstructed decays, *ex.* $B \to l\, D\, X$
- exclusively reconstructed decays, ex. $B^0 \to D^{-} \pi^+ (\pi^+ \pi^-)$
- lots of data: exclusive modes (theory uncertainties small)

from PDG web site

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Semileptonic and leptonic modes			
Γ_1	$\ell^+ \nu_\ell$ anything	[a]	(10.9 ± 0.4) %	
Γ_2	$\overline{D}^0 \ell^+ \nu_\ell$	[a]	(2.15 ± 0.22) %	
Γ_3	$\overline{D}^*(2007)^0 \ell^+ \nu_\ell$	[a]	(6.5 ± 0.5) %	
Γ_4	$\overline{D}_1(2420)^0 \ell^+ \nu_\ell$		$(5.6 \pm 1.6) \times 10^{-3}$	
Γ_5	$\overline{D}_2^*(2460)^0 \ell^+ \nu_\ell$		$< 8 \times 10^{-3}$	CL=90%
Γ_6	$D^- \pi^+ \ell^+ \nu_\ell$		$(5.3 \pm 1.0) \times 10^{-3}$	
Γ_7	$D^{*-} \pi^+ \ell^+ \nu_\ell$		$(6.4 \pm 1.5) \times 10^{-3}$	

First Lifetime Measurement

Sample of high p_T leptons

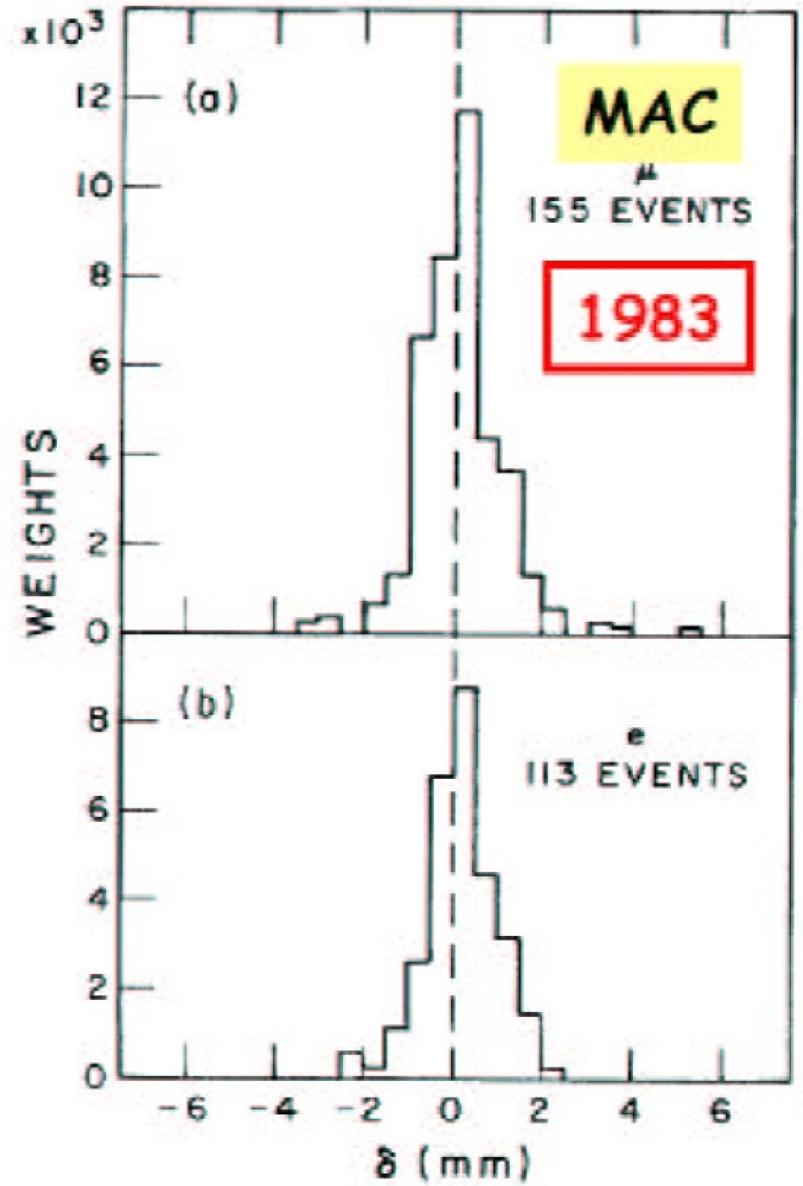
- lepton track impact parameter
- sign determined by jet direction
- 155 muon events
- 113 electron events

Experiments

- MAC: 1.8±0.8±0.4 ps PRL51(1983)1022
- Mark II: 1.2±0.4±0.3 ps PRL51(1983) 1316

Experimental details

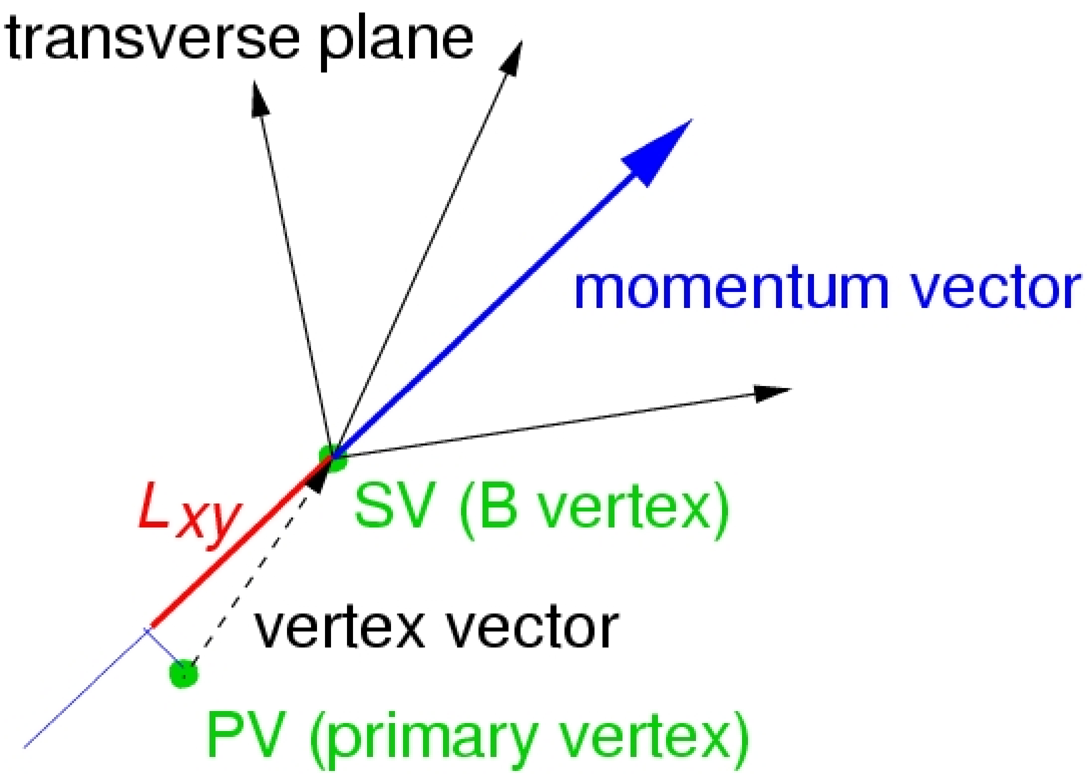
- e^+e^- at 29 GeV
- 109 pb^{-1}
- 3500 *bbbar* pairs



Experimental Ingredients

Decays of particle follow simple exponential

- $N(t) = N_0 \exp(-t/\tau)$



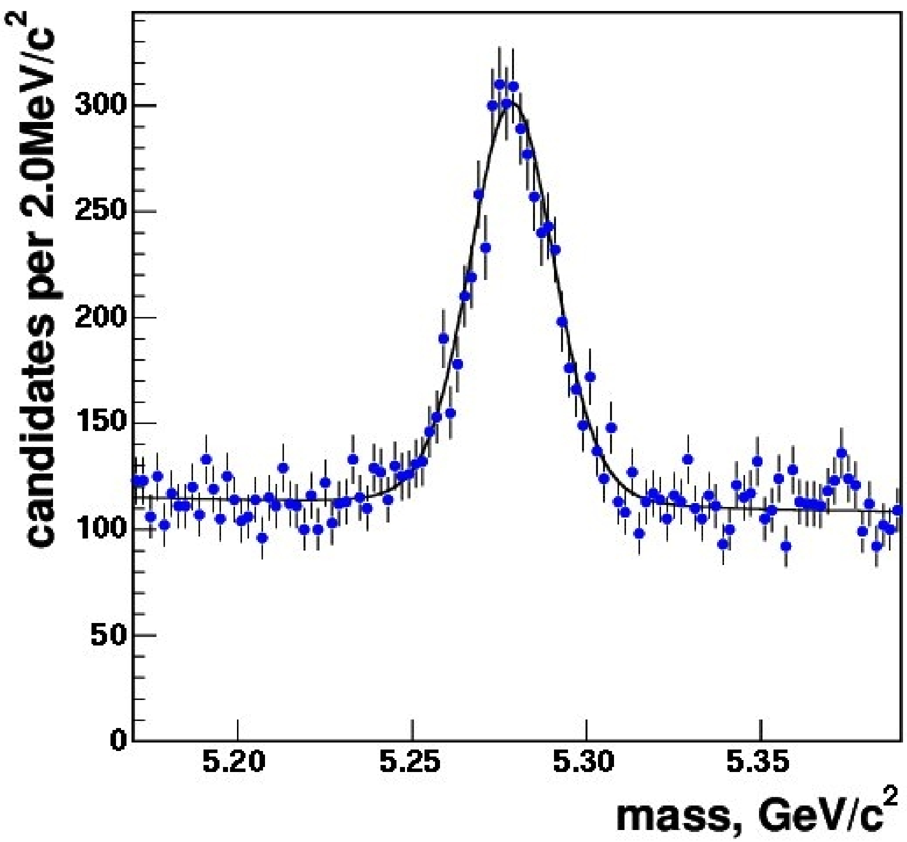
Need to measure

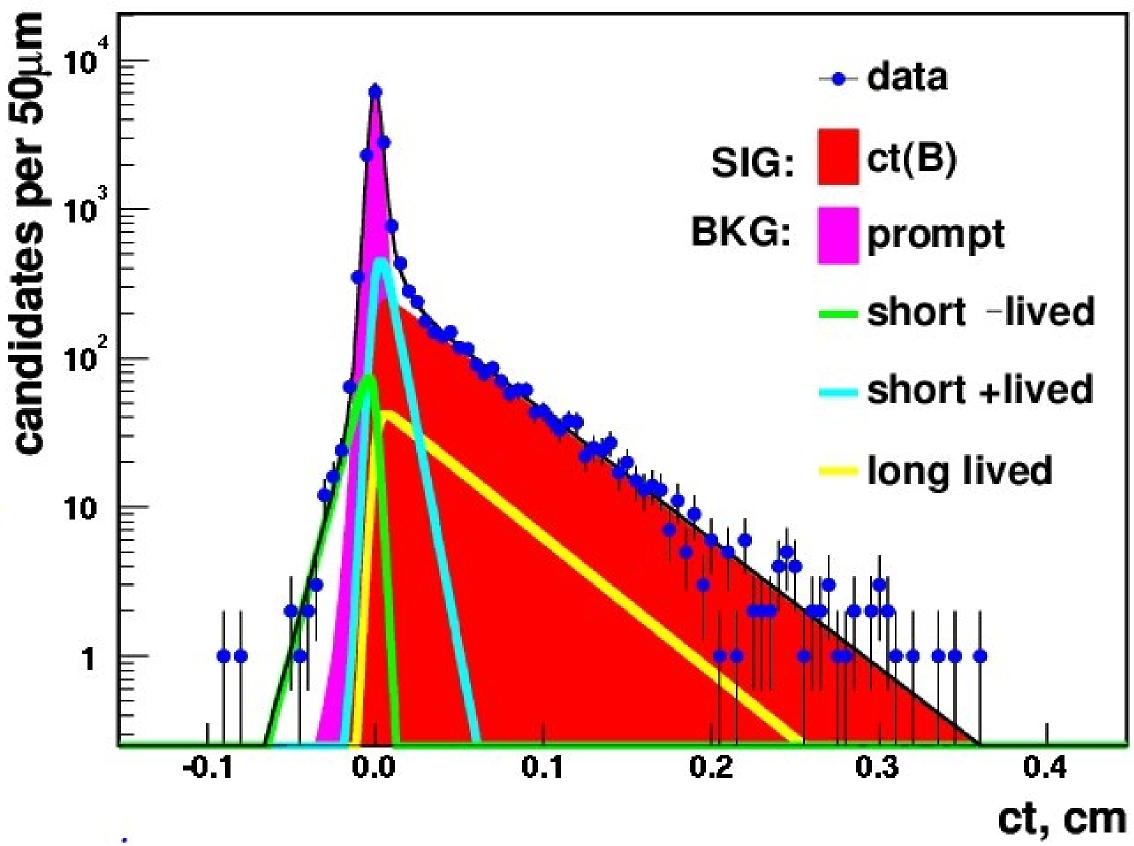
- proper time of *B* decay
  - geometric displacement in *r-phi* plane: $L_{xy} = \vec{p}_T \cdot \vec{r}_{xy}$
  - momentum in *r-phi* plane: $p_T(B)$
  - proper time: $ct = m(B)\, L_{xy}(B) / p_T(B)$
- distributions of number of candidates per proper time

Experimental Ingredients

In the data see signal and background

- background has no lifetime (some accidental lifetime)
  - mostly prompt, some mis-reconstructed, some real displaced
- proper time is smeared with detector resolution
- use event by event vertex resolution as measured





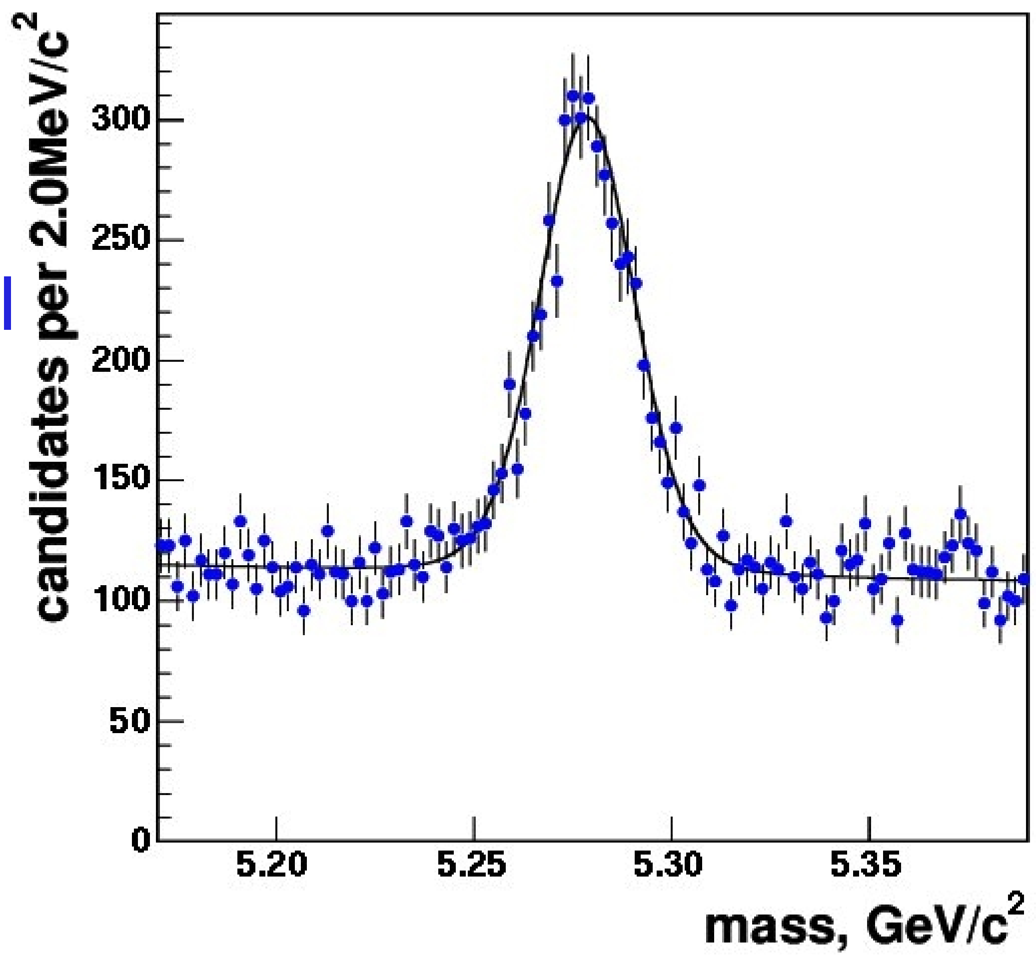
Experimental Ingredients

What we see in the reconstructed mass

- flat background: is mostly short lived
- Gaussian peak of signal

Significance of mass plot

- mass does not determine lifetime
- independent handle on signal and background:
  - sideband represent background
  - signal area can be cleanly corrected
  - likelihood does it all in one shot
  - for given *m* probability of signal or background is easily derived



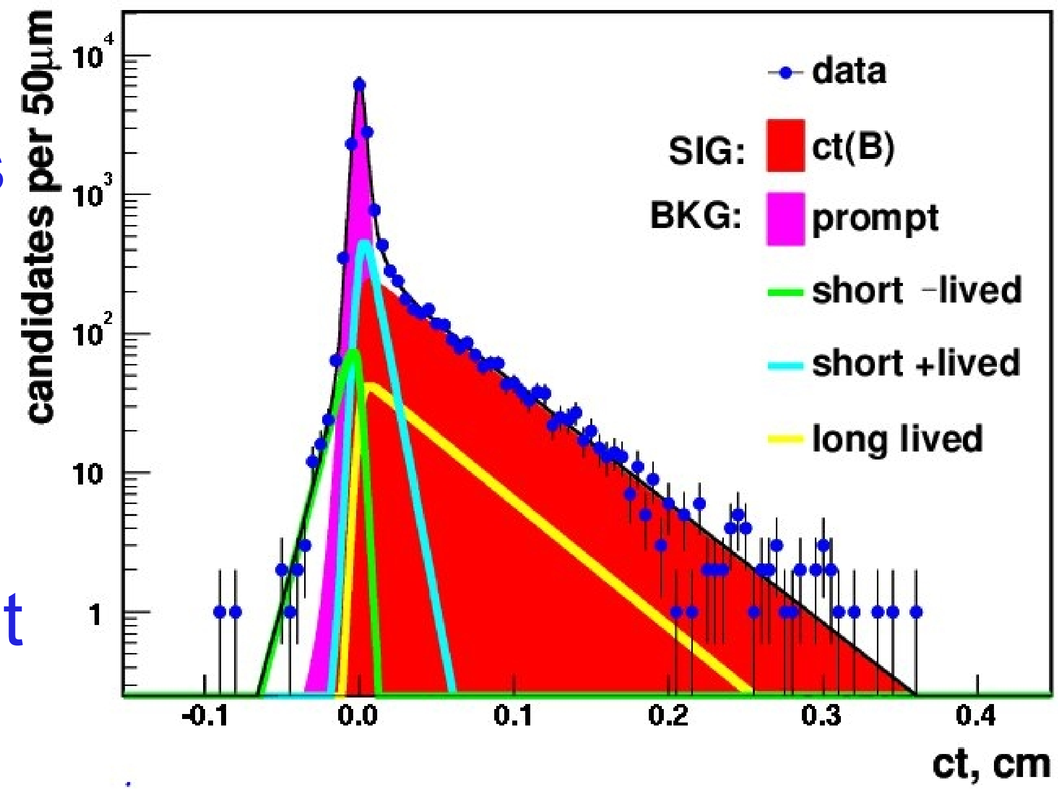
Experimental Ingredients

What we see in the proper time distribution

- plot shown in logarithmic scale (*y*): expect exponential
- expect long exponential tail consistent with signal lifetime (linear in log scale)
- expect a pronounced peak at zero *ct*: prompt background
- left side determines resolution function

Background details

- sideband show components
  - long lived
  - asymmetric short lived
- separate bg fit fixes all parameters
- sidebands have to represent bg properly



Existing Measurements

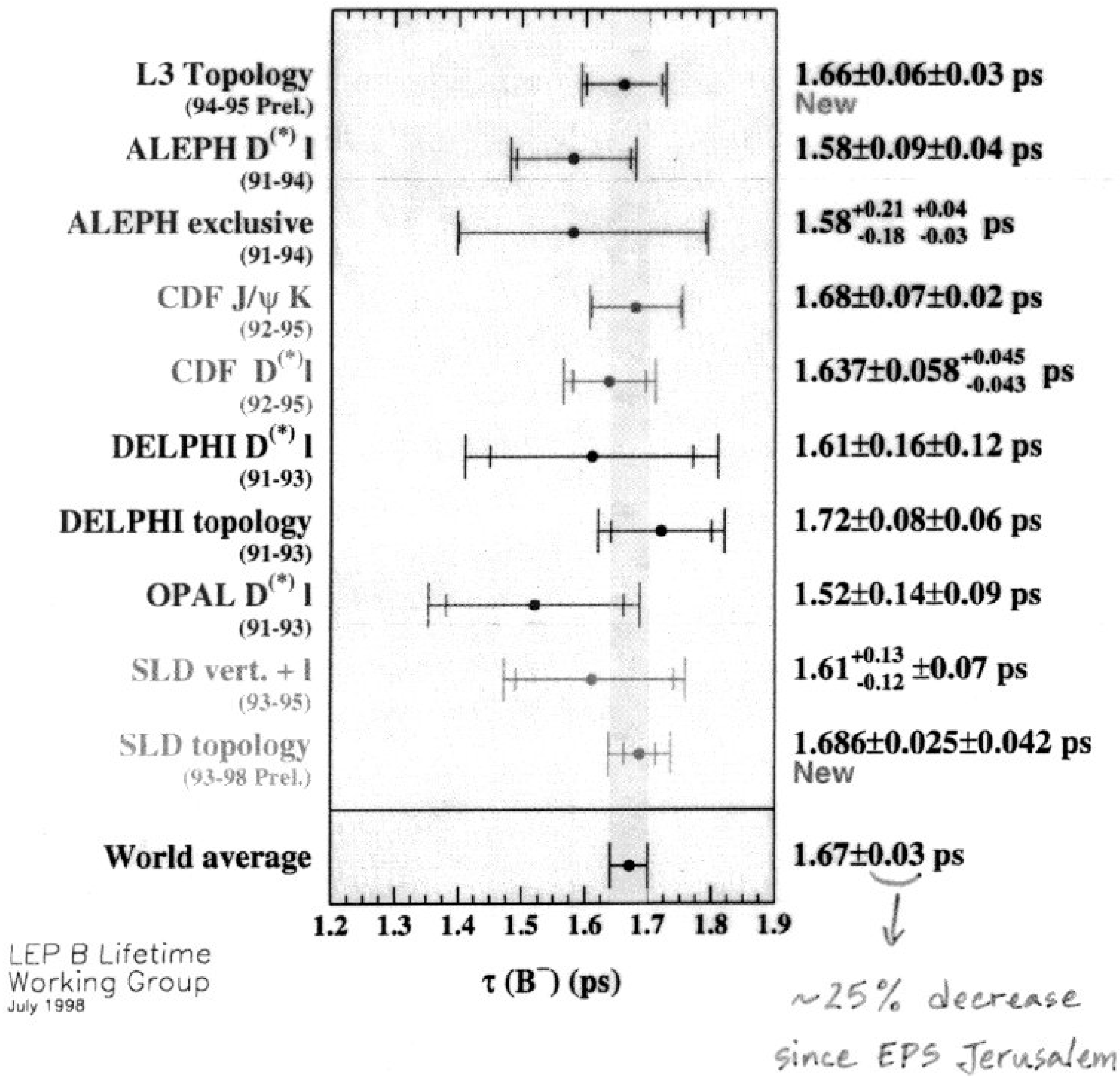
Archeology

- today we look only at ratios
- earlier on lifetimes per experiment were compared
- transparencies were copied in '98
- as you can see many measurements with various methods all consistent

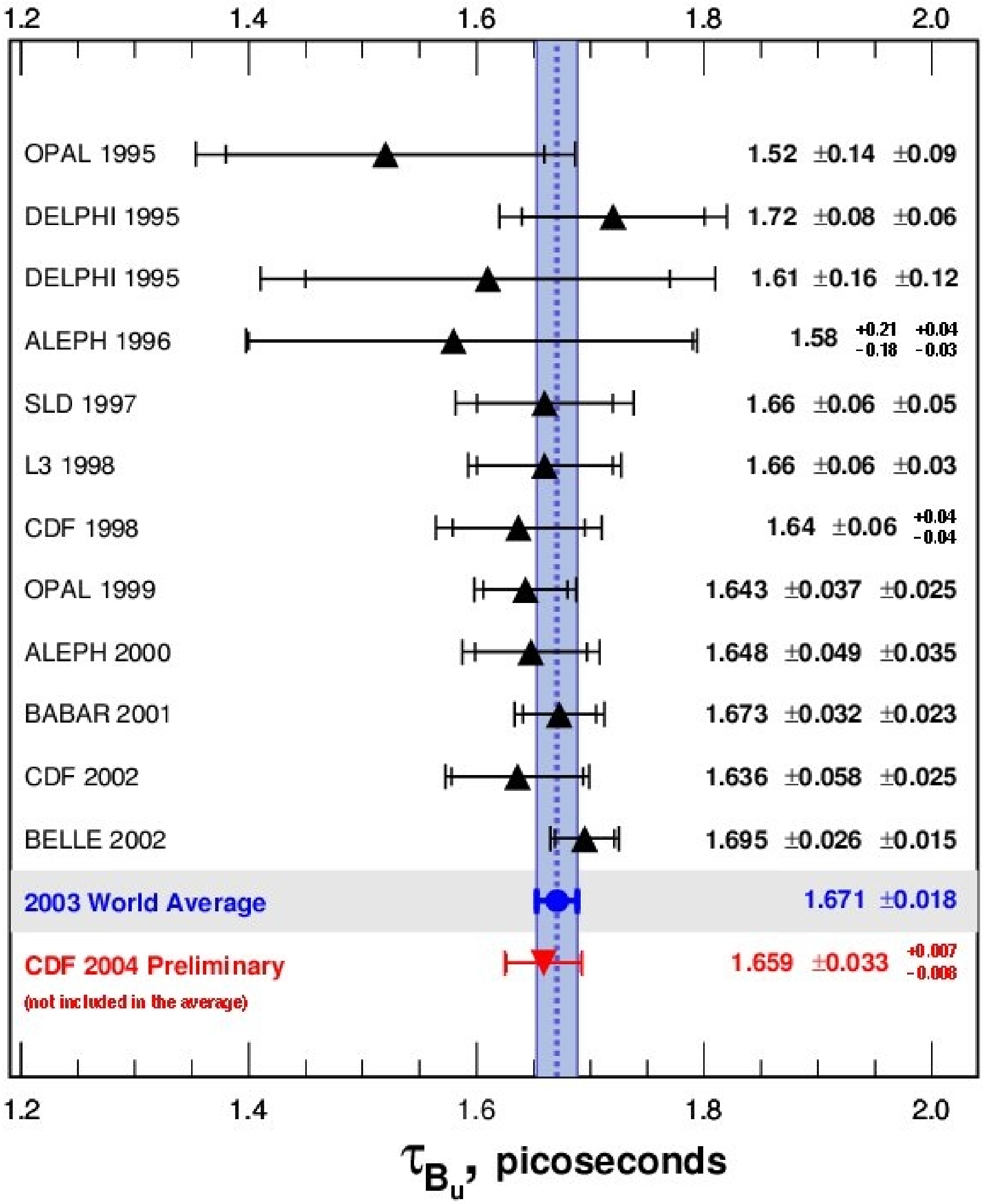
Lifetimes bit the dust

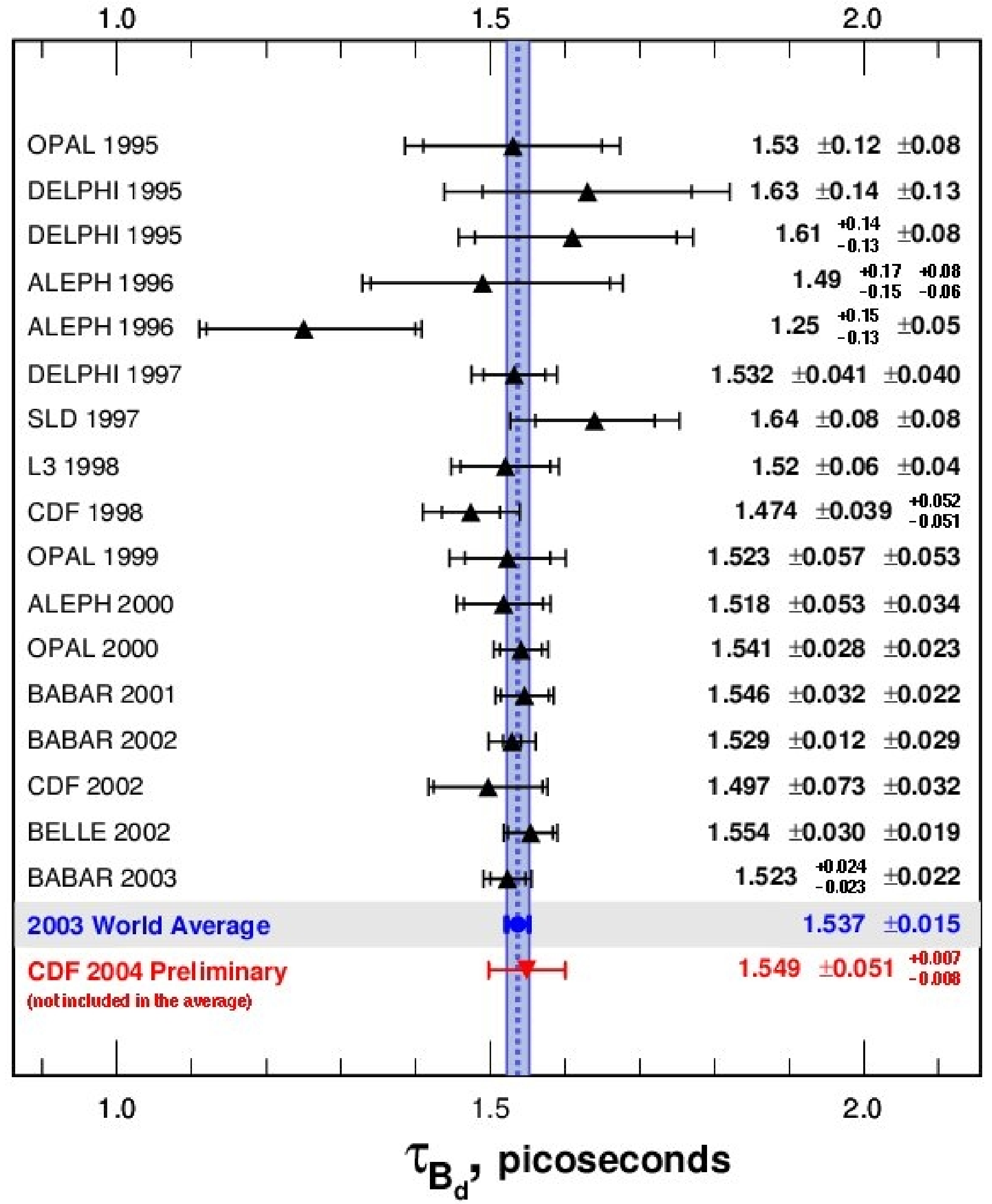
- experiments are too precise
- interest decreased
- Λ_B lifetime last interest ..

but also this one is settled by now

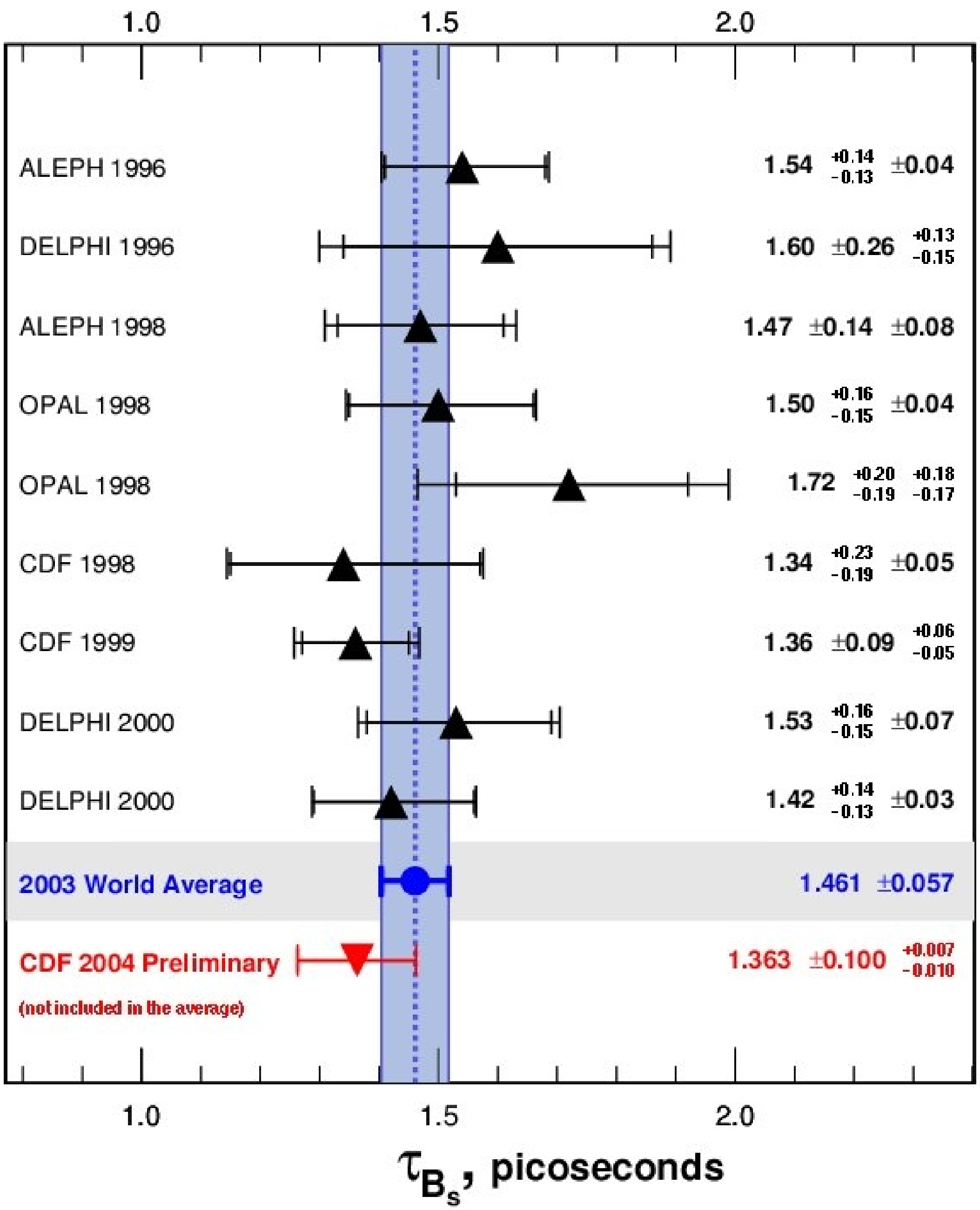


Existing Measurements





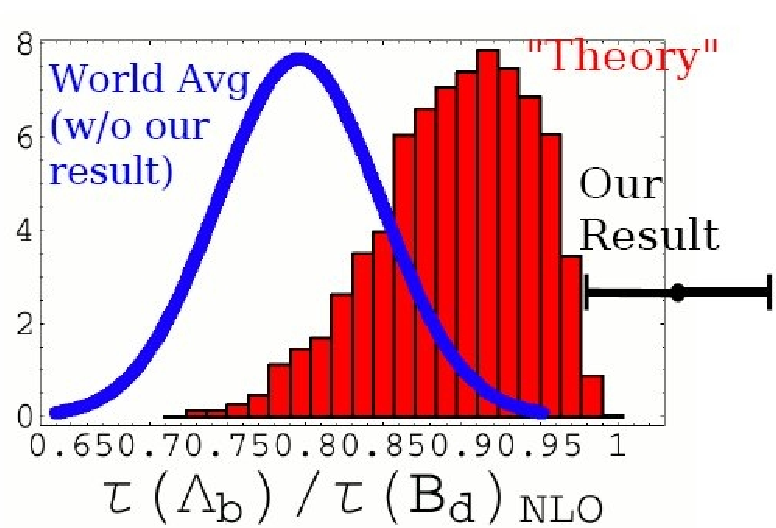
Existing Measurements

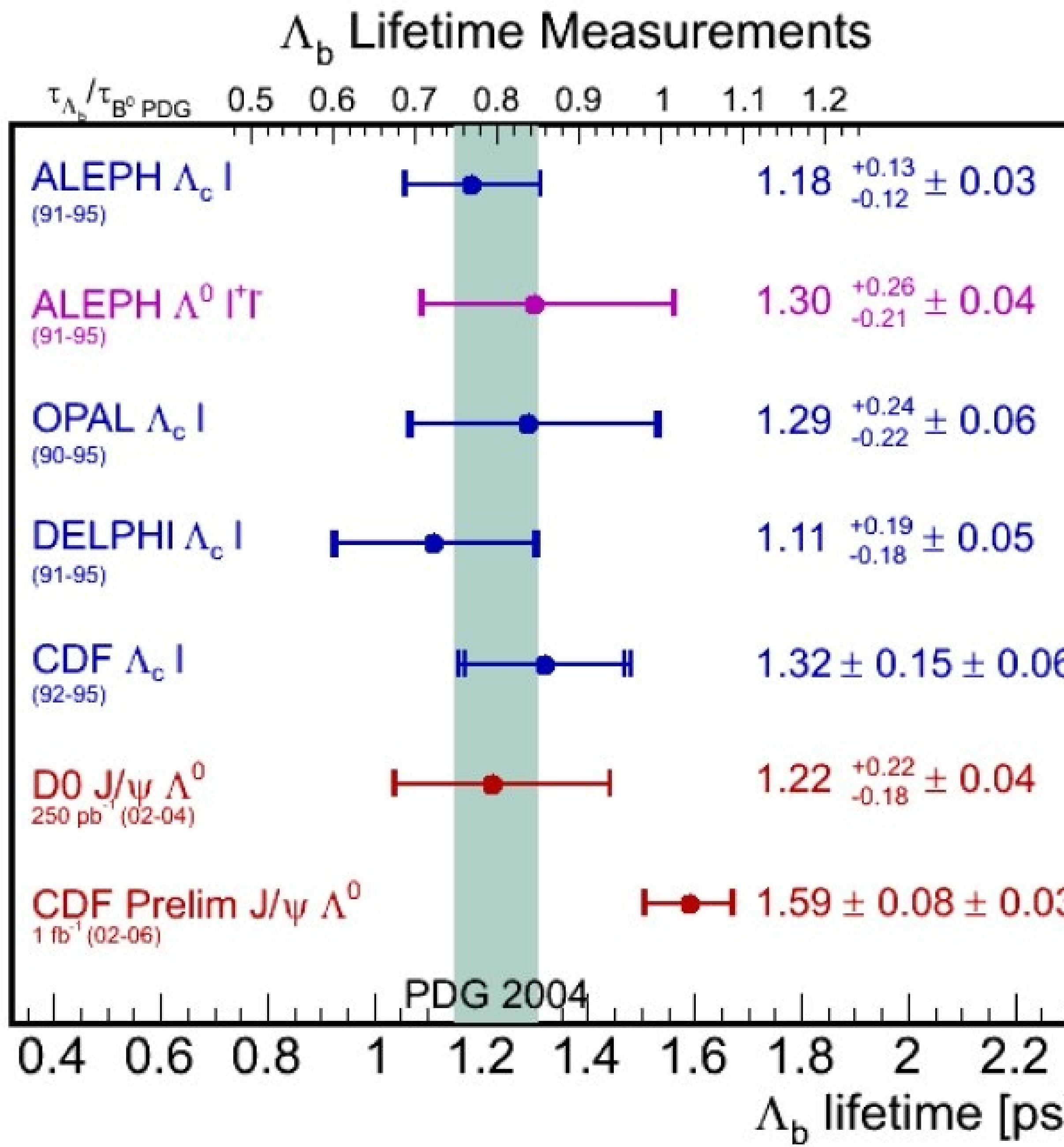


Existing Measurements

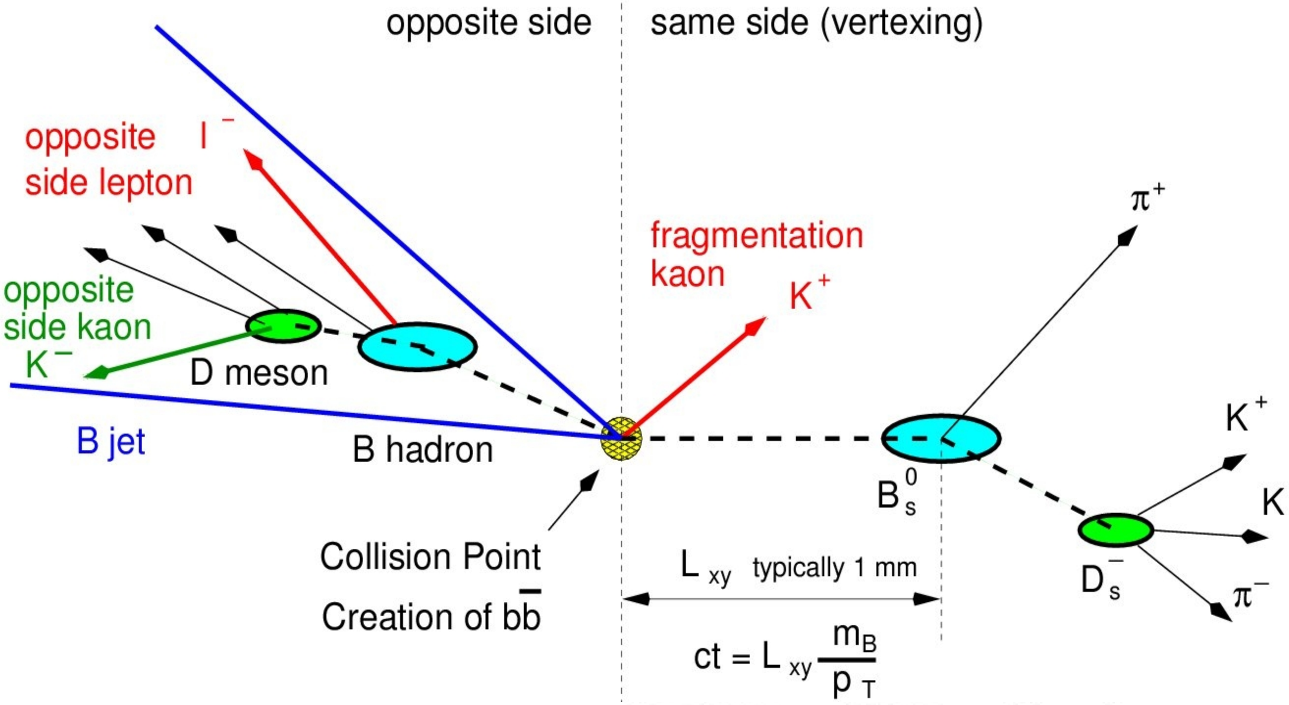
Λ_b case open....

- was too small for long time
- newest most precise result from CDF "too large"
- 3.1 standard devs with world average





Mixing Measurements

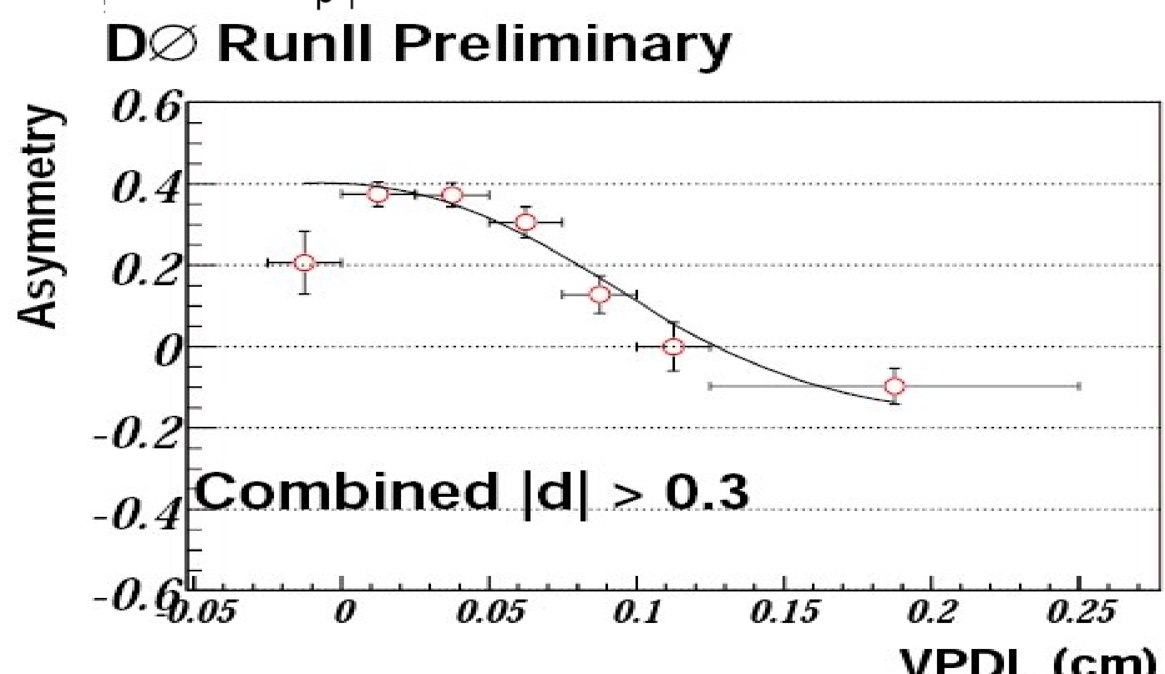


3 components needed

- flavor at birth
- flavor at decay
- proper time

B^0 mixing slow, 0.5 ps^{-1}

- do not see full frequency

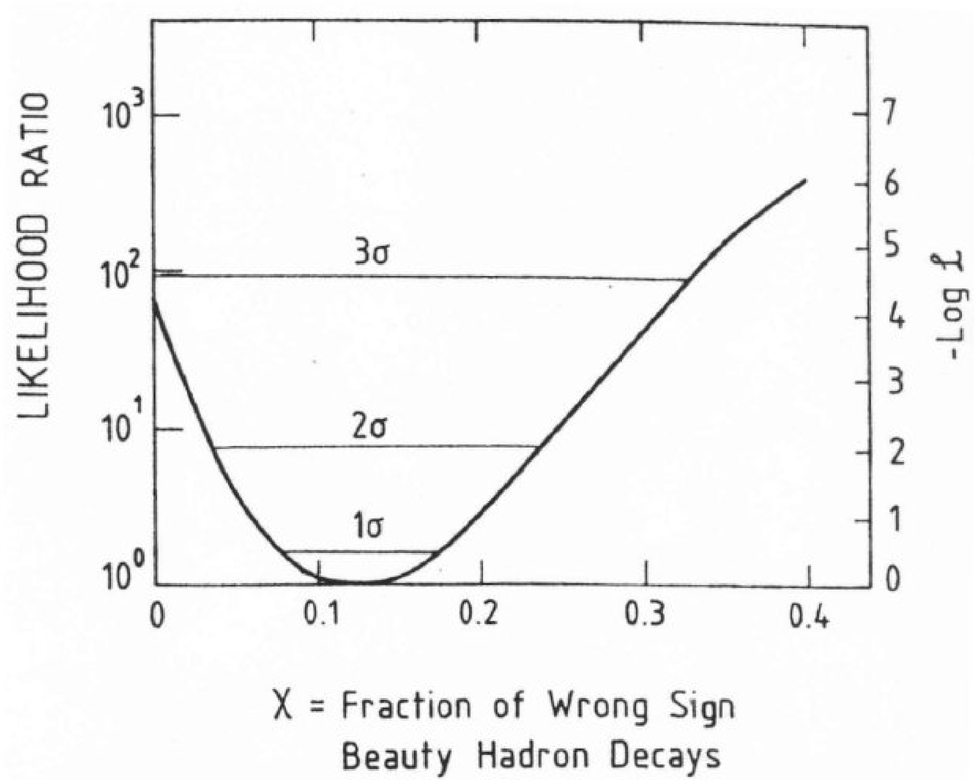


First B Mixing Measurement

Inclusive measurement at $p\bar{p}$ collider

PL B **186** (1987) 247

- signature: like sign high p_T leptons; UA1 got it first: 3 sigma



Argus at the time excluded this value at 90% CL

Start of the $p\bar{p}$ B physics success story

First B Mixing Measurement

At $\Upsilon(4S)$ resonance

+ $m_{\Upsilon(4S)}(10.580 \text{ GeV}) >$
  $> 2 \times m_B(5.279 \text{ GeV})$
+ $\Upsilon(4S) \to B^0\overline{B}^0 \to B_1^0 B_2^0$
+ 25 like sign events
+ 270 opposite sign events

Time integrated mixing

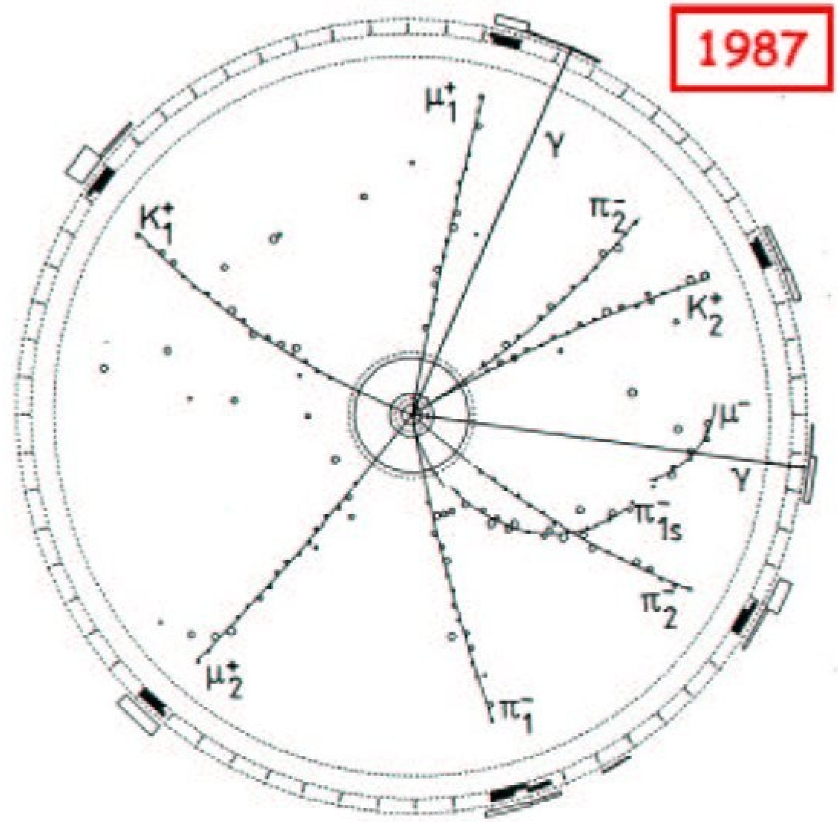
Argus $\chi_b = 0.17 \pm 0.05$ PL B **192** (1987) 245

+ slower than expected
+ indication for heavy top

Experimental details

+ e^+e^- at $\sqrt{s} = 10.58$ GeV
+ 113 pb^{-1} integrated luminosity
+ about 110,000 $b\overline{b}$ pairs

Start of the $\Upsilon(4S)$ success story

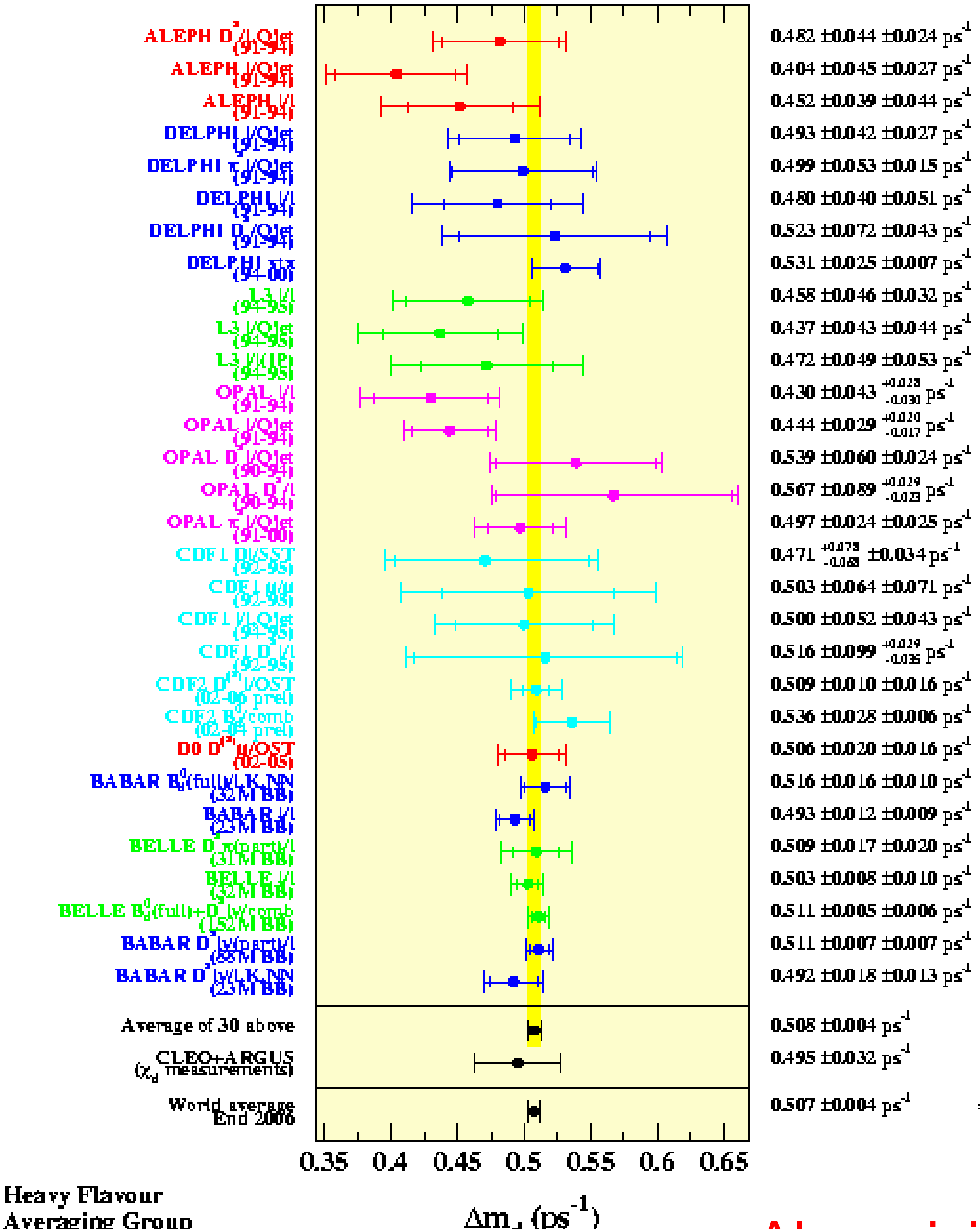


A like sign event!!

$B_1^0 \to D_1^{*-}\mu_1^+\nu_1; D_1^{*-} \to \overline{D}^0\pi_{1s}^-$

$B_2^0 \to D_2^{*-}\mu_2^+\nu_2; D_2^{*-} \to D^-\pi^0$

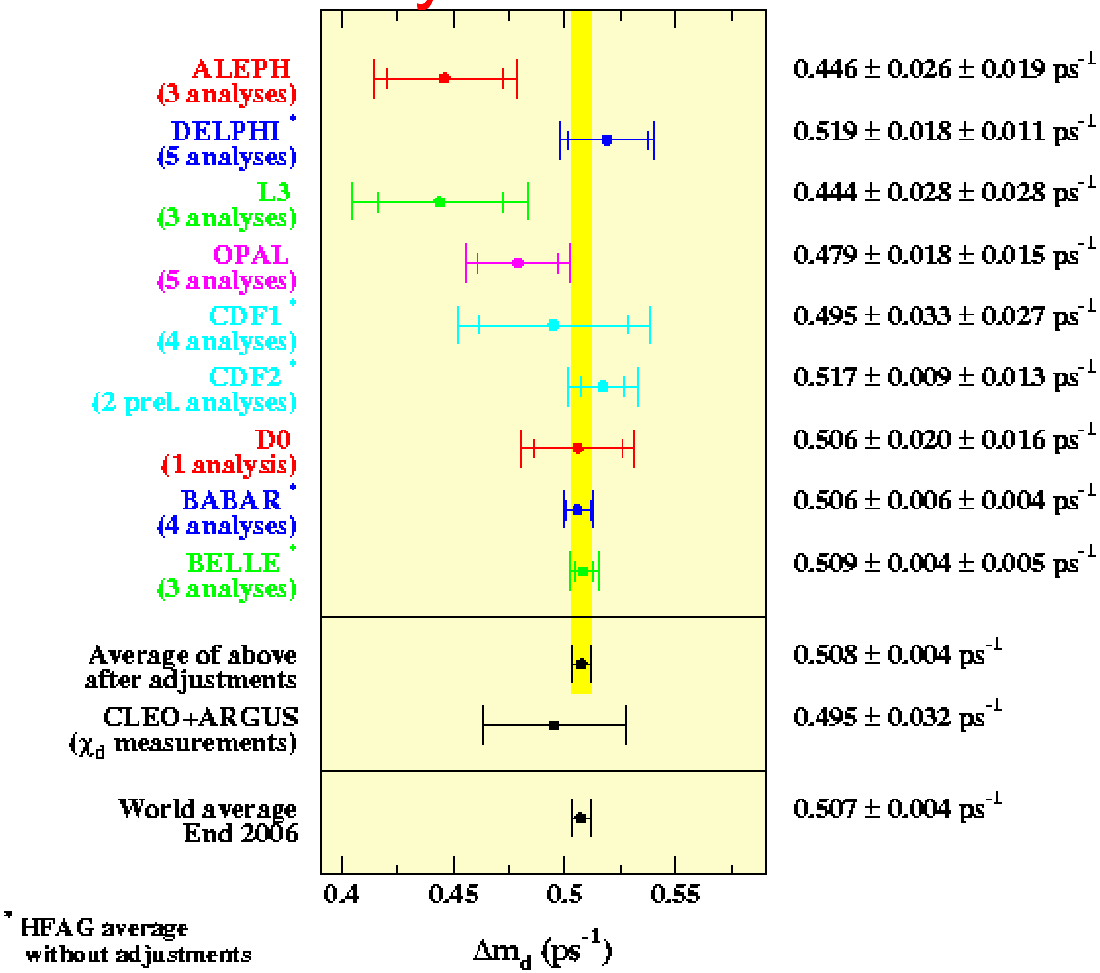
B^0 Mixing Measurements



Overall uncertainty: 0.8%

remember $\delta(\Delta m_s) < 0.5\%$

but theory ≈ 3.4%



Also mixing is not interesting until theory improves

Conclusion

Lifetime measurements

- *B* lifetime was first measured in 1983 (MAC, Mark II)
- a slew of measurements followed, all as expected
- big time is over, experiments are incredibly precise
- ultimate test of lifetimes: theory by calculating the ratios

Mixing measurements

- first B mixing result 1987 (UA1, Argus)
- a slew of measurements followed on B^0 mixing, B_s mixing only resulted in limits ....
- finally last year 2006 B_s mixing frequency was measured
- theory uncertainties a factor of 10 larger than experimental

Interesting weak *B* physics still out there

- γ, β, α and lifetime differences: $\Delta\Gamma$

Next Lecture

B Physics Trigger Strategies

- lepton based trigger
- high momentum, displaced track trigger
- combinations
- with jets....

Depending on how it goes I might show some more interesting *B* physics measurements