Lifetimes, mixings and widths of neutral b and c hadrons

Review of the results on

-D^0 mixing

-Neutral B meson widths

-B hadron lifetimes

See other talks in this session and Tuesday for CPV in mixing

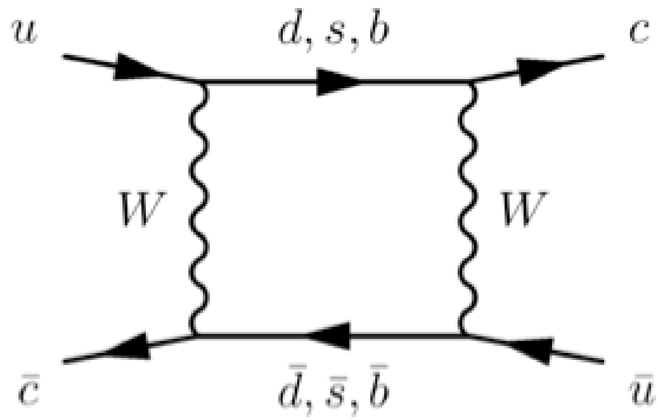
Sneha Malde
University of Oxford

D^0 mixing

Meson Mixings and Width differences

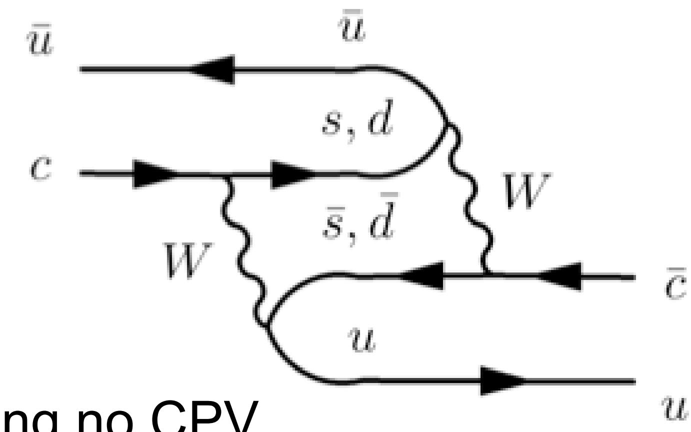
Taking the D^0 meson as an example:

Flavor	Mass
$\|D^0(c\bar{u})\rangle$	$\|D^1(M_1,\Gamma_1)\rangle$
$\|\overline{D^0}(\bar{c}u)\rangle$	$\|D^2(M_2,\Gamma_2)\rangle$



Short range

Long range



$$|D^1\rangle = p|D^0\rangle + q|\overline{D^0}\rangle$$

$$|D^2\rangle = p|D^0\rangle - q|\overline{D^0}\rangle$$

$|p|^2 + |q|^2 = 1, p = q = 1/\sqrt{2}$ assuming no CPV

Meson Mixings and Width differences

Useful to define these mixing parameters

$$x = \frac{M_1 - M_2}{\Gamma}$$

$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

	x	y
K^0 (1957)	0.95	0.99
B^0 (1987)	0.78	~0
B_s (2006)	26	0.15
D^0 (2007)	0.0098	0.0083

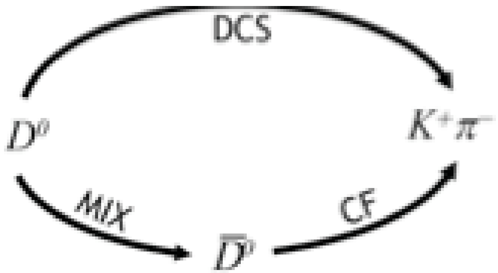
D system also mixes the least

D meson - fraction of one oscillation has occurs in ~10 lifetimes

D^0 mixing - “Wrong Sign” Decays

Tag flavor of the D^0 by using decay $D^{*+} \to D^0 \pi^+$

Right sign: $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$ Cabibbo favored decay (CF)



Doubly Cabibbo suppressed decay (DCS)

$D^{*+} \to D^0 \pi^+$, $D^0 \to K^+$, π^-;

Mixing then Cabibbo favored decay

$D^{*+} \to D^0 \pi^+$, $D^0 \to \bar{D}^0$, $\bar{D}^0 \to K^+ \pi^-$

$$\frac{dN_{WS}}{dt}(t) \propto e^{-\Gamma t}\left[\underbrace{R_D}_{\text{DCS}} + \underbrace{y'(\Gamma t)\sqrt{R_D}}_{\text{Interference}} + \underbrace{\frac{x'^2 + y'^2}{4}(\Gamma t)^2}_{\text{Mixing}} \right]$$

Can only measure x'^2 and y'

non-0 value is signature of mixing

$$x' = x\cos\delta + y\sin\delta$$

$$y' = y\cos\delta - x\sin\delta$$

δ is the strong phase

Experimental ingredients

Time dependent measurements

Accurate measurement of production and decay vertex

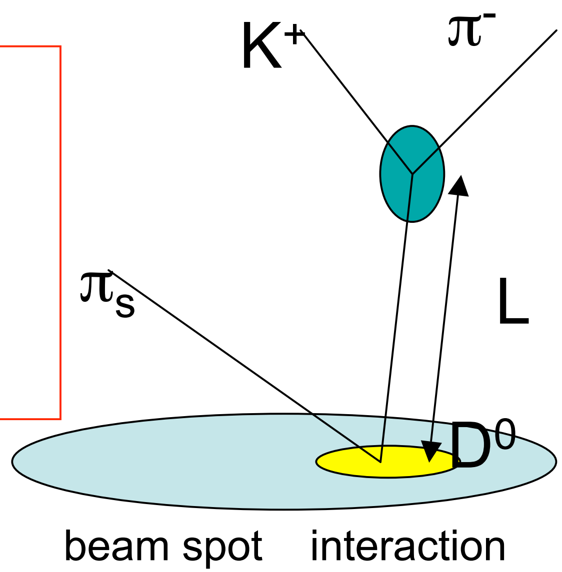
Silicon vertex detectors

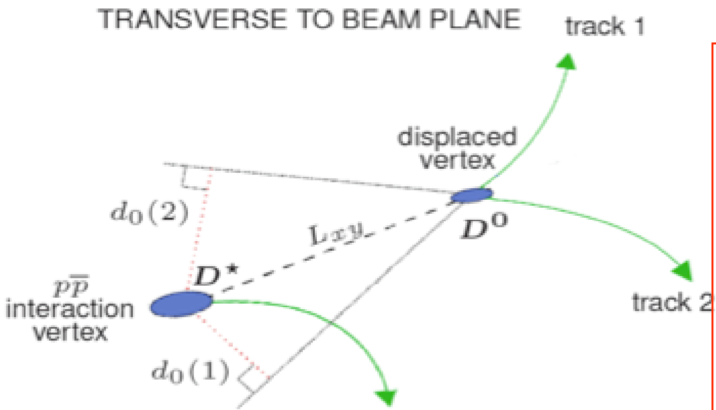
BaBar

3-D flight path

L ~ 200 μm

σ_L ~ 100 μm





CDF

Measurement in transverse plane

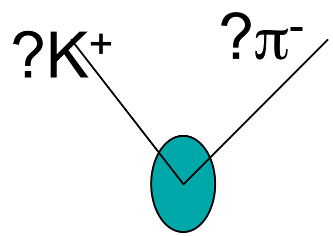
Trigger requires displaced vertex

L_{xy}>200 μm

Analysis requires L_{xy} / σ_{Lxy}>4

Experimental ingredients (2)

Identification of pion from kaon



Excellent at BaBar and Belle [purpose built detector components]

Statistical separation at CDF. Add cut: WS events require a RS mass cut to reduce doubly misidentified tracks

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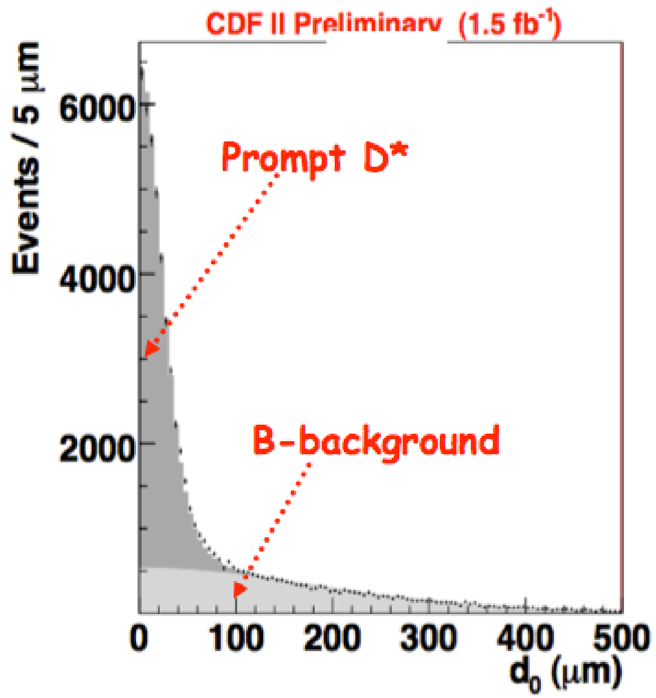
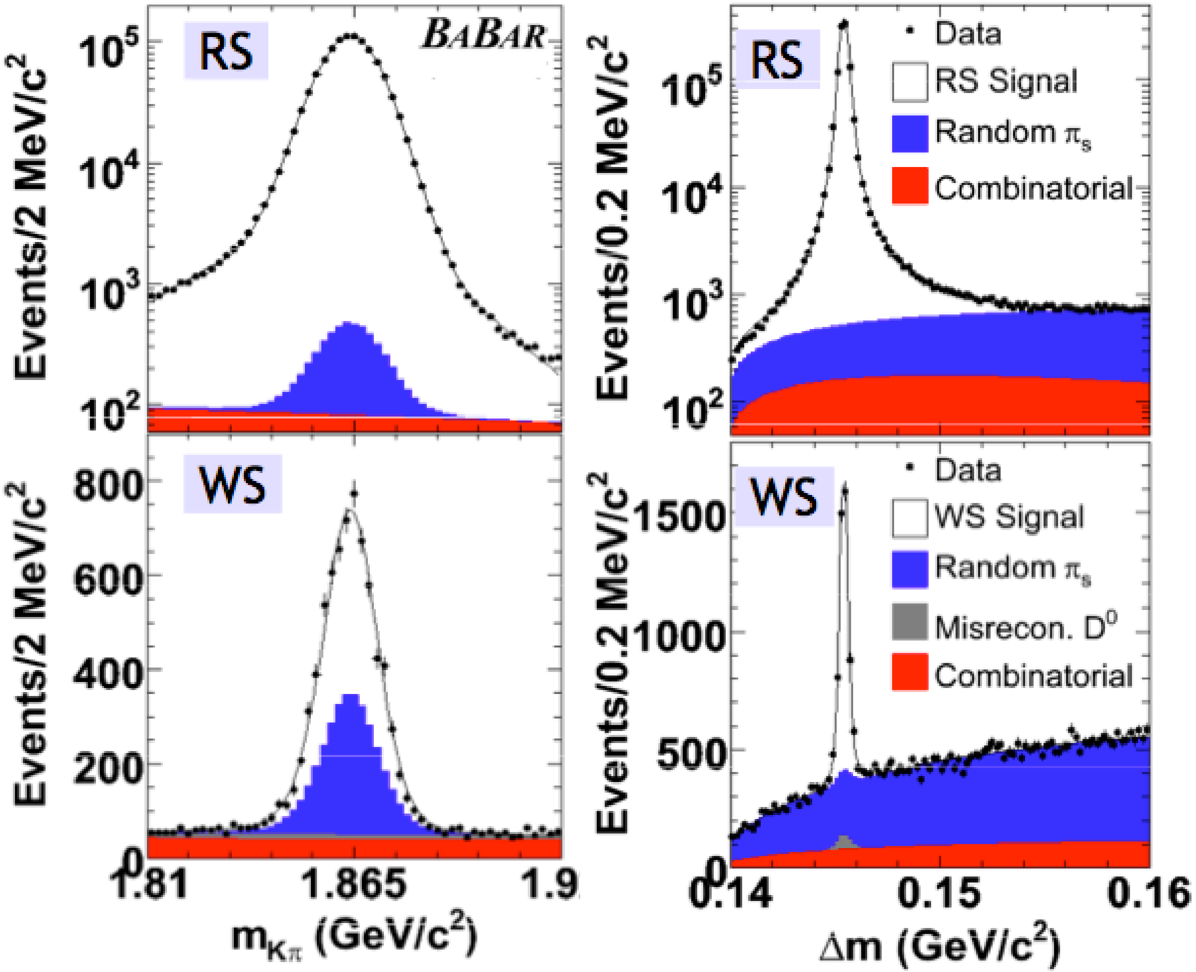
Removal of D* from B bkg

B factories: Minimum momentum requirements in the CM frame.

CDF: Analysis of the IP distribution to determine secondary production contribution



Analysis strategy

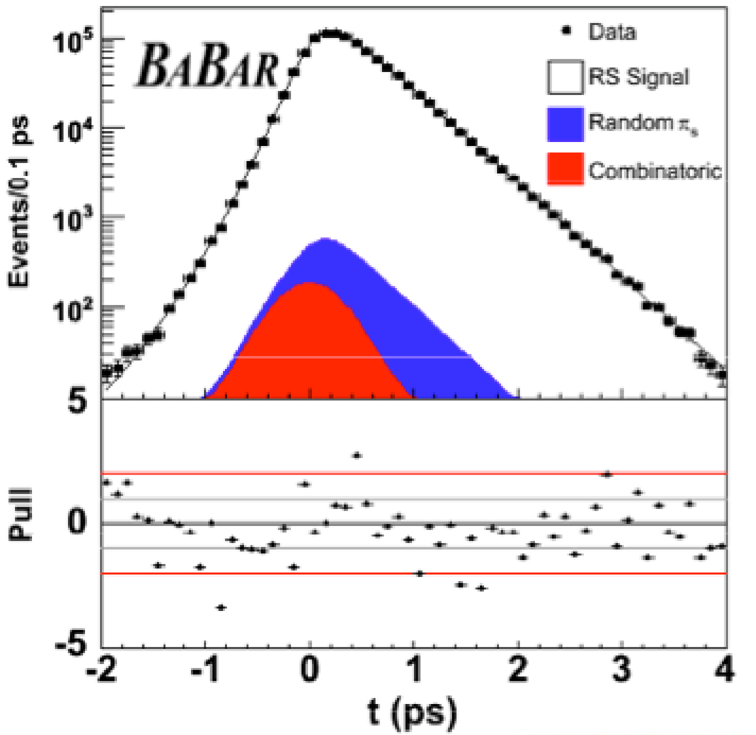


RS: 1141500±1200 WS: 4030±90

Sample composition determined from fit to $m_{K\pi}$ and Δm ($m(D^*) - m(D^0)$)

384 fb^{-1}

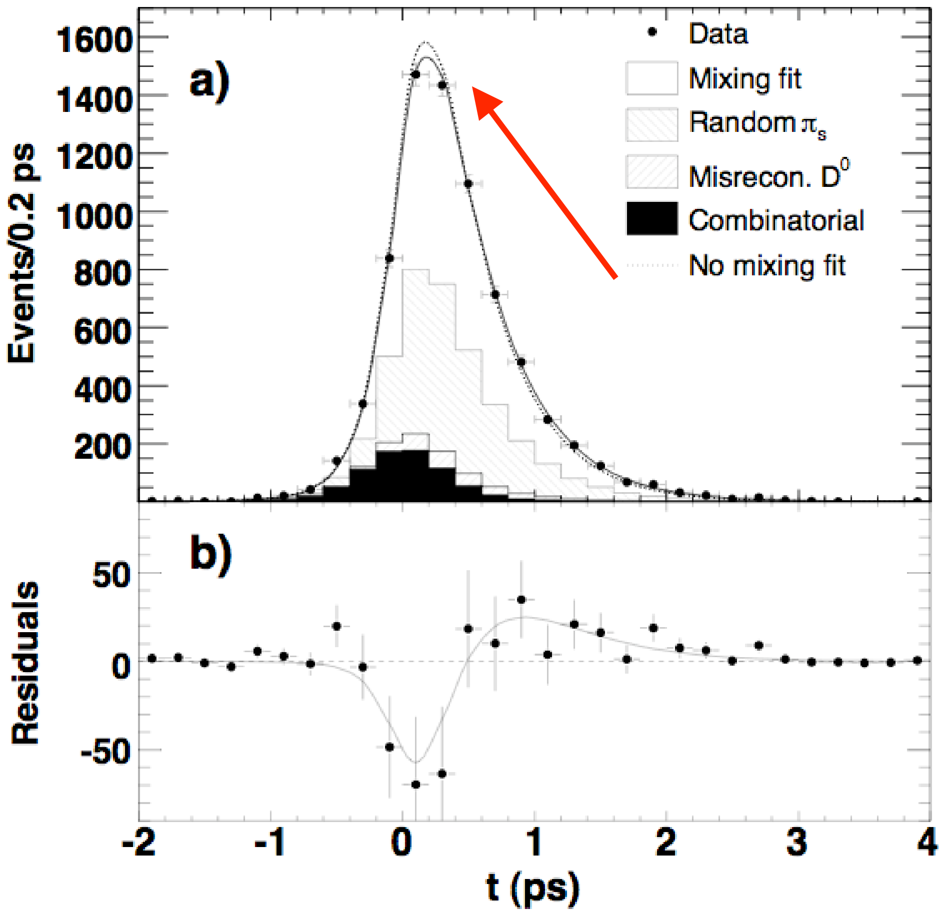
Time fit including mixing



Lifetime (exponential) and resolution fitted in the RS sample.

$\tau(D^0)$ consistent with PDG

In WS fit resolution fixed from RS fit

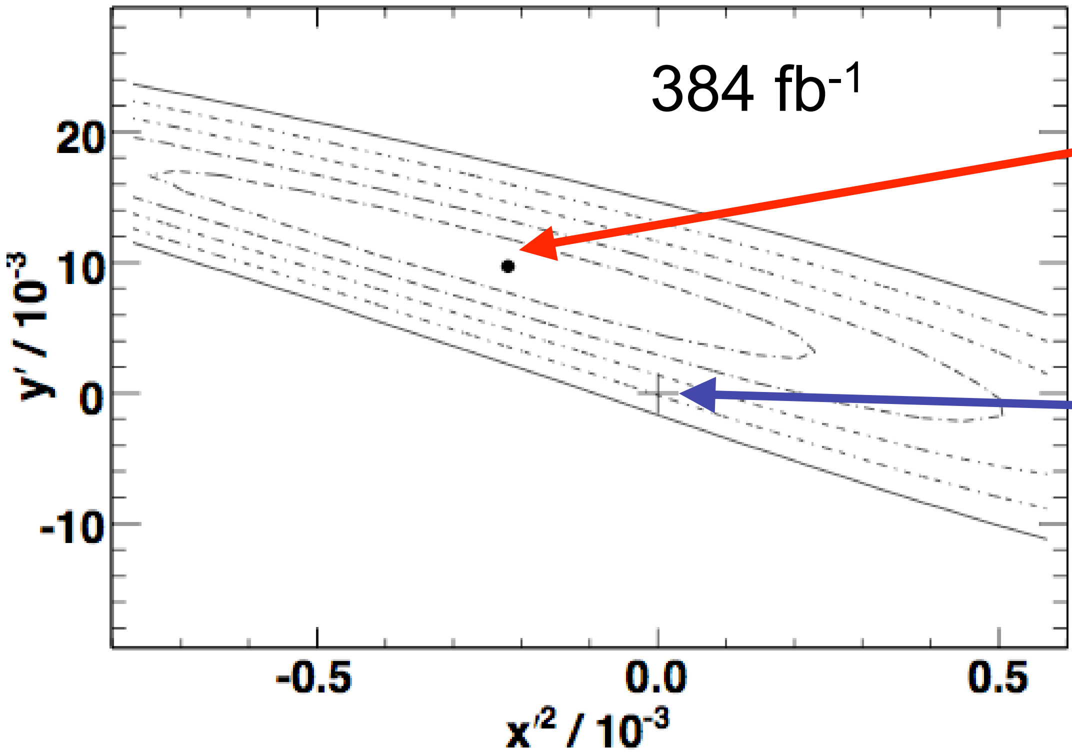


WS fit with mixing parameters provides better fit to data

PRL 98 211802

Allowed x'^2 y' contours

Current status using the WS decays:



Best fit point

Inconsistent with mixing at 3.9σ

No mixing point

R_D: $(3.03 \pm 0.16 \pm 0.10) \times 10^{-3}$

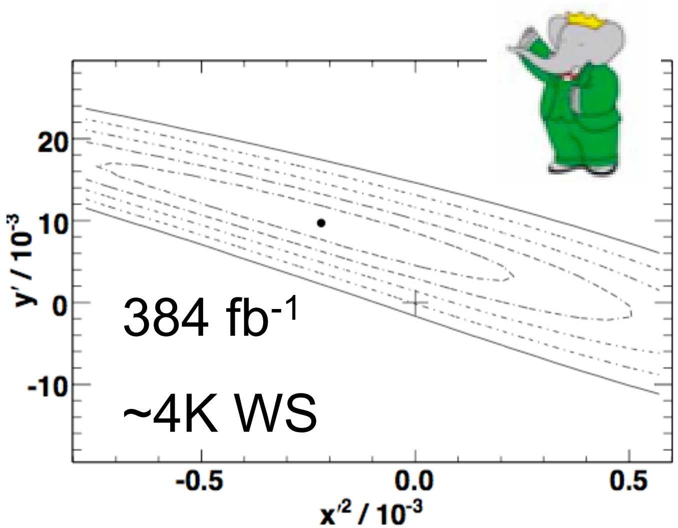
x'^2: $(-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$

y': $(9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$

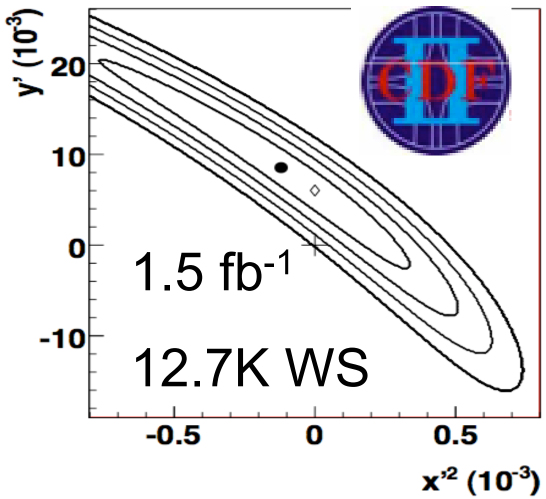
PRL 100 121802

PRL 96 151801

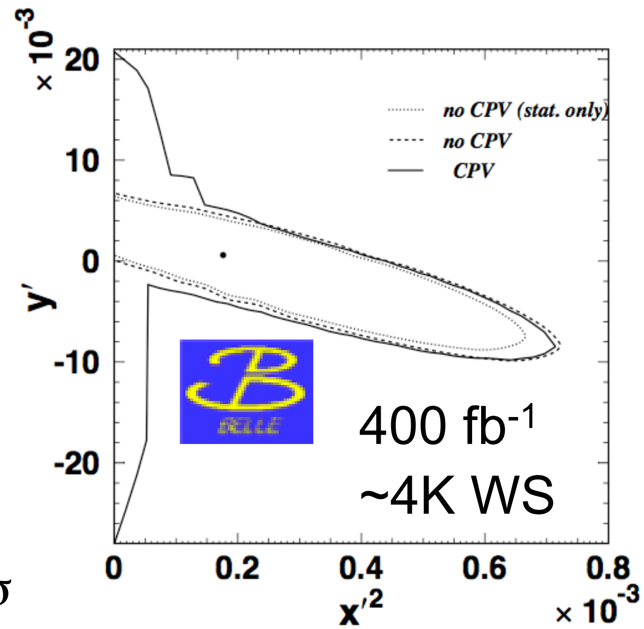
WS analysis at other experiments



Evidence of mixing at 3.9σ



Evidence of mixing at 3.8σ



No mixing point at 2.0σ

Agreement between the 3 experiments

Different production methods

Different analysis methods

PRL 100 121802

PRL 96 151801

Time-dependent amplitude analysis of $D^0 \rightarrow K_s hh$

Allows direct measurement of x and y

D* used to tag whether $D^0/\overline{D^0}$

Dalitz plot s+= $M(K_s\ h^+)$ s- = $M(K_s\ h^-)$

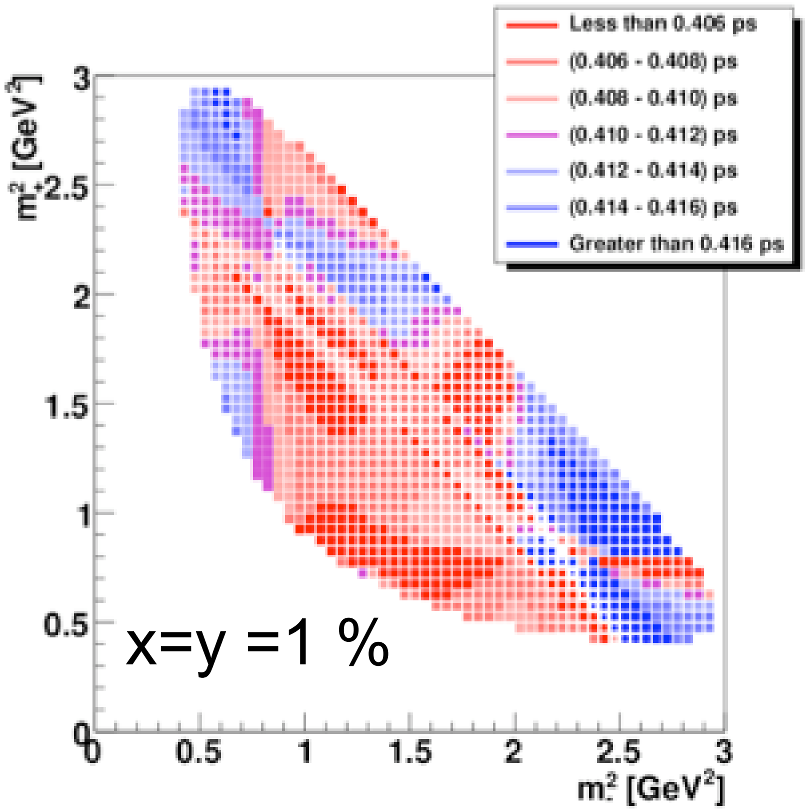
In the absence of CPV:

$A(s+,s-) = \overline{A}(s-,s+)$

Distribution of events across Dalitz space . vs. $t(D^0)$

Variation ➔ signature of mixing.

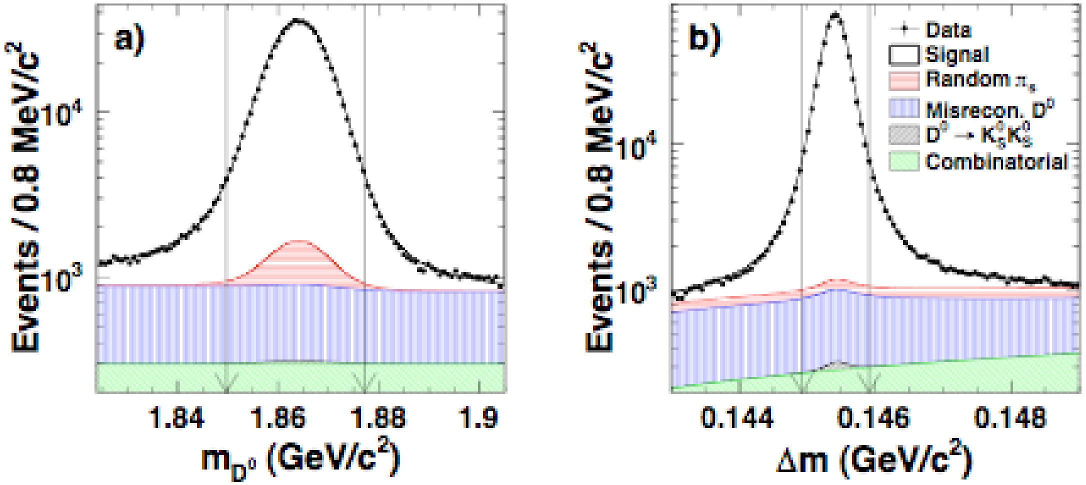
Sensitivity to x and y comes mainly from regions with interference of CF and DCS, or CP eigenstates



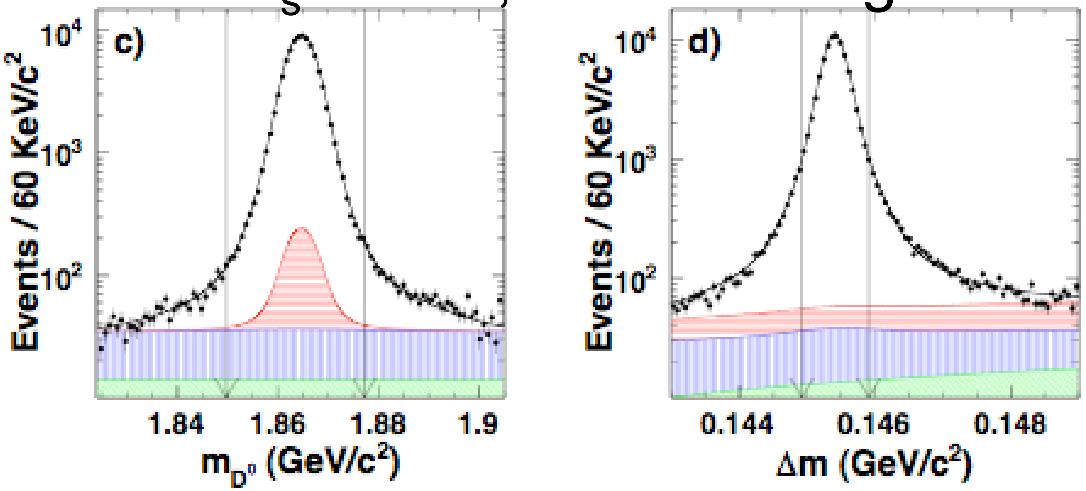
Example of mean lifetime in different regions of the DP

Yields and Purities

D➔$K_s\pi\pi$ 540,800 ± 800 signal



D➔K_sKK 79,900 ± 300 signal



<u>First stage</u>

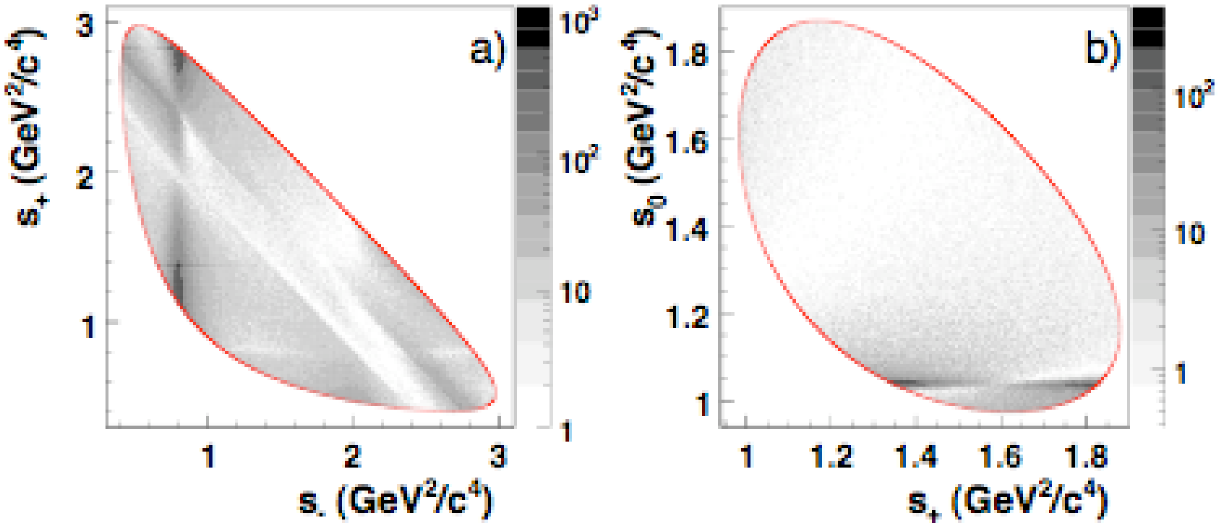
Fit the signal and the background shapes using the m and Δm

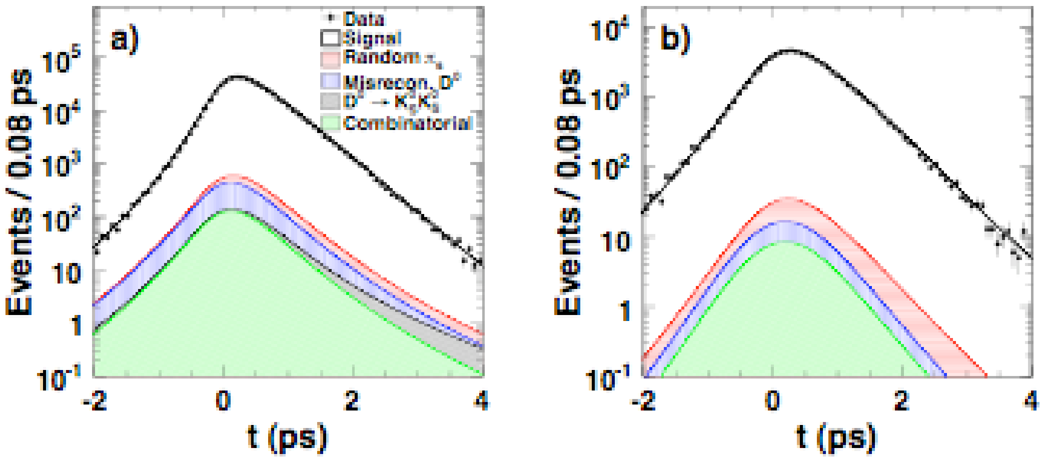
Fix the bkg component types and define the signal regions

Purity 98.5 % ($K_s\pi\pi$)

99.2 % (K_sKK)

Time dependent amplitude fit



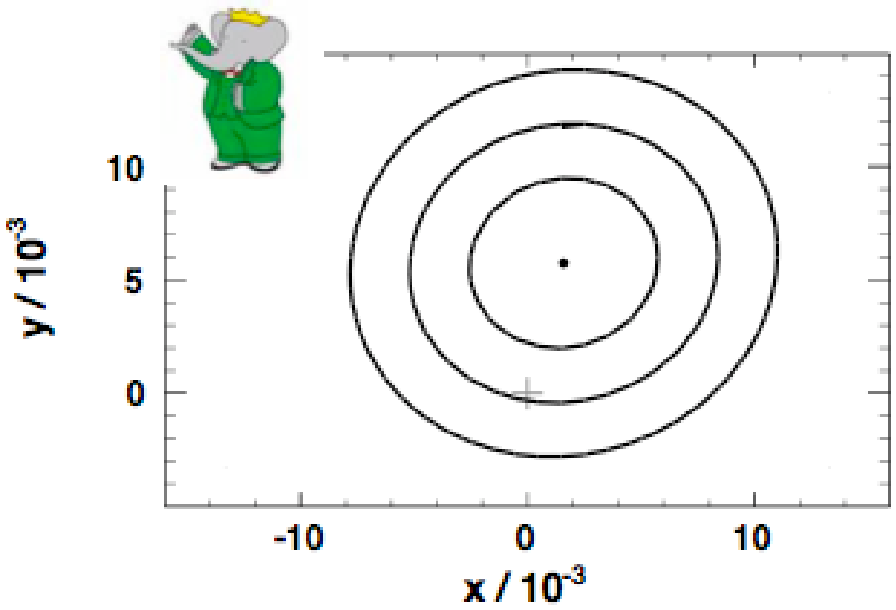


Amplitude model is defined by coherent sum of quasi-two body amplitudes.

x and y determined from a likelihood fit.

PDF based on A(s^+,s^-) and the decay time.

x , y values



Dis-favours no mixing hypothesis at 1.9σ

x= (0.16±0.23±0.12±0.08)%

y =(0.57±0.20±0.13±0.07)%

Most precise single measurement of x

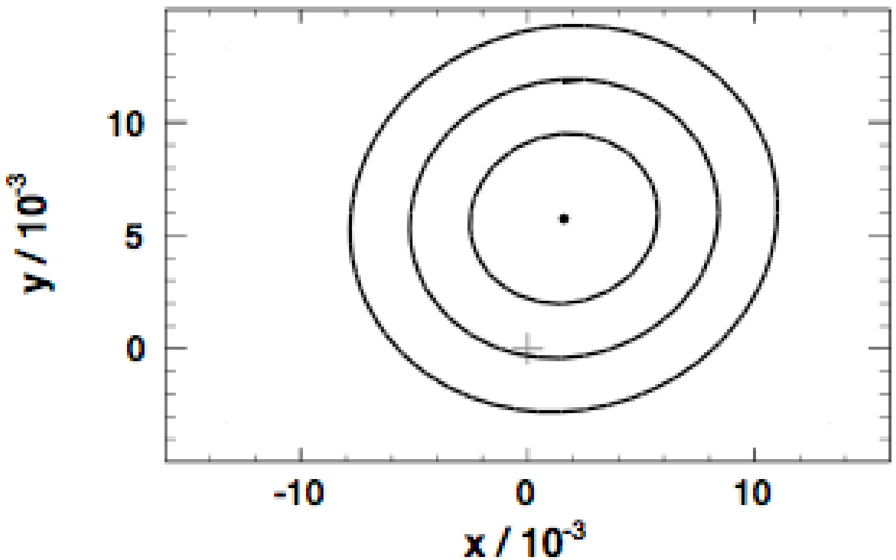
Consistent between the two decay channels

468.5 fb^{-1}

PRL 105 081803

PRL 99 131803

x , y values



x= (0.16±0.23±0.12±0.08)%

y =(0.57±0.20±0.13±0.07)%

Most precise single measurement of x

Consistent between the two decay channels

Belle $K_s\pi\pi$ analysis 540 fb^{-1}

$x = 0.80 \pm 0.29^{+0.09}_{-0.07}{}^{+0.10}_{-0.14}$ %

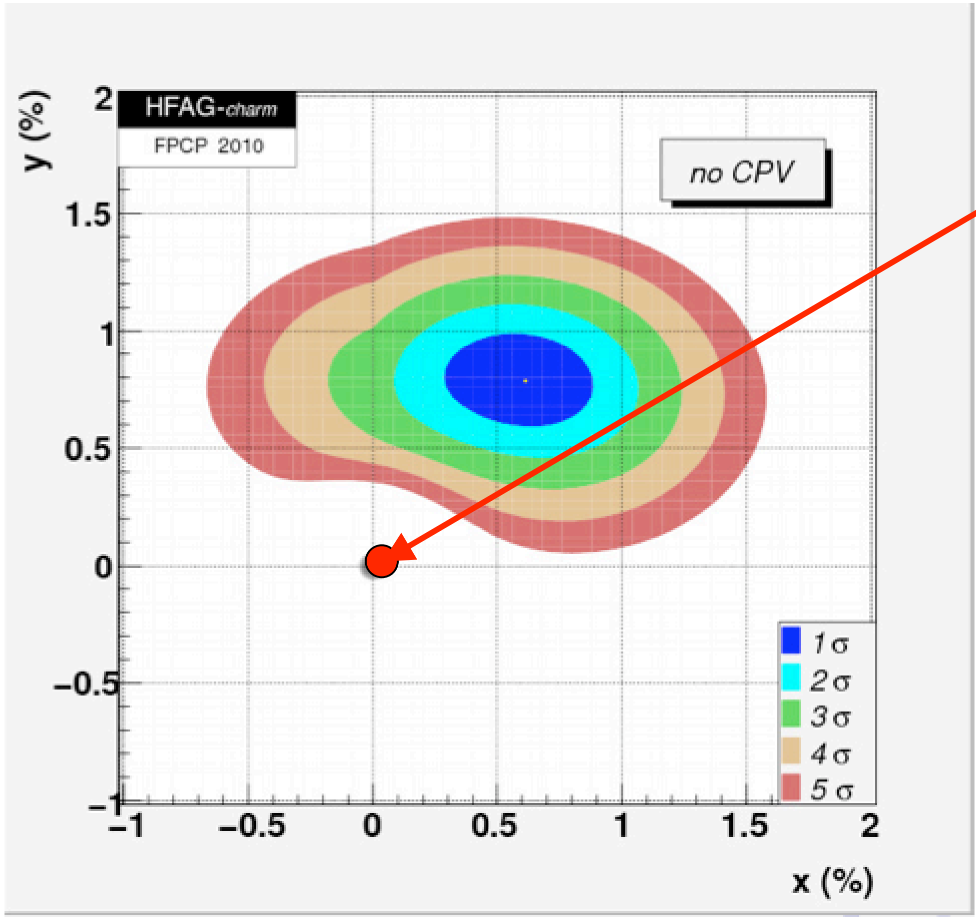
$y = 0.33 \pm 0.24^{+0.08}_{-0.12}{}^{+0.06}_{-0.08}$ %

PRL 105 081803

PRL 99 131803

Status today

While no one measurement has observed mixing at 5σ the combined evidence is clear:



No mixing point excluded at 10 σ level

Prospects:

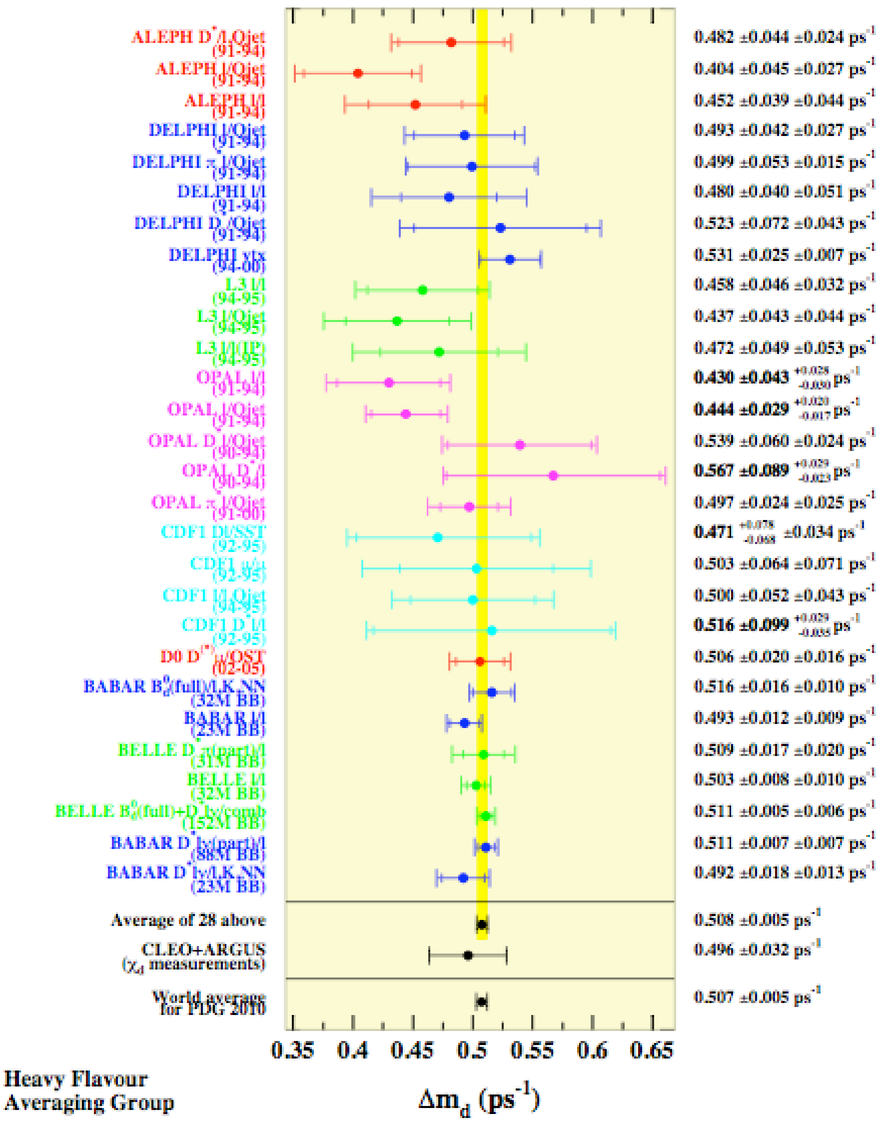
CDF has much more data to analyse

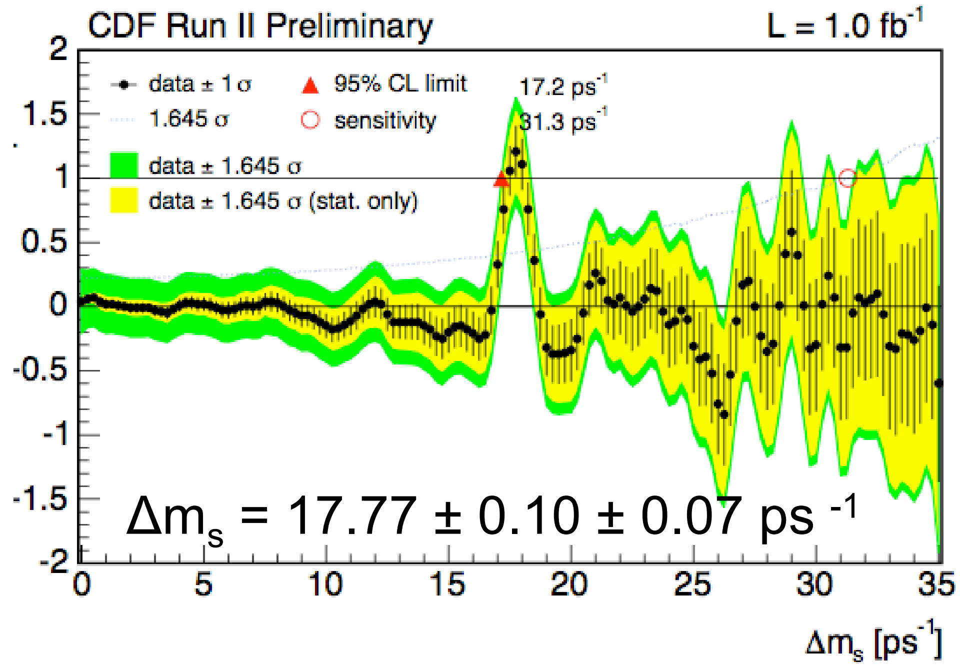
Results from LHCb soon

M. Gersabeck

B meson width difference

Neutral B meson mixing





B^0 mixing first seen in 1987

$\Delta m_d = 0.507 \pm 0.005\ ps^{-1}$

Confirmed by many experiments

B_s mixing so far only at the Tevatron

B_q Width Difference

Width difference provides extra test of the standard model

$$\frac{\Delta\Gamma_d}{\Gamma_d} = 41^{+9}_{-10} \bullet 10^{-4}$$

$$\frac{\Delta\Gamma_s}{\Gamma_s} = 0.13 \pm 0.04$$

BaBar measured

sign $\mathrm{Re}(\lambda_{cp})\Delta\Gamma/\Gamma = 0.009 \pm 0.037$

Uses B decay in a CP eigenstate

Smaller difference for B_d

Width differences caused by existence of final states to which both the B^0 and $\overline{B}^0$ can decay.

Involves $b \rightarrow c\bar{c}q$, Cabibbo suppressed if q=d

see Tuesday's talk U. Nierste

B_q Width Difference

Width difference provides extra test of the standard model

$$\frac{\Delta\Gamma_d}{\Gamma_d} = 41^{+9}_{-10} \bullet 10^{-4}$$

$$\frac{\Delta\Gamma_s}{\Gamma_s} = 0.13 \pm 0.04$$

Additionally can be used as a test of NP

$$\Delta\Gamma_s = \Delta\Gamma_s^{SM} \cos(2\beta_s)$$

Assuming no CPV B_s^L is CP even, B_s^H is CP odd

Measure lifetimes in CP specific modes ($\Delta\Gamma^{CP}$)

Measure $\Delta\Gamma$ directly $B_s \rightarrow J/\psi\phi$

Use branching ratios $B_s \rightarrow D_s D_s$

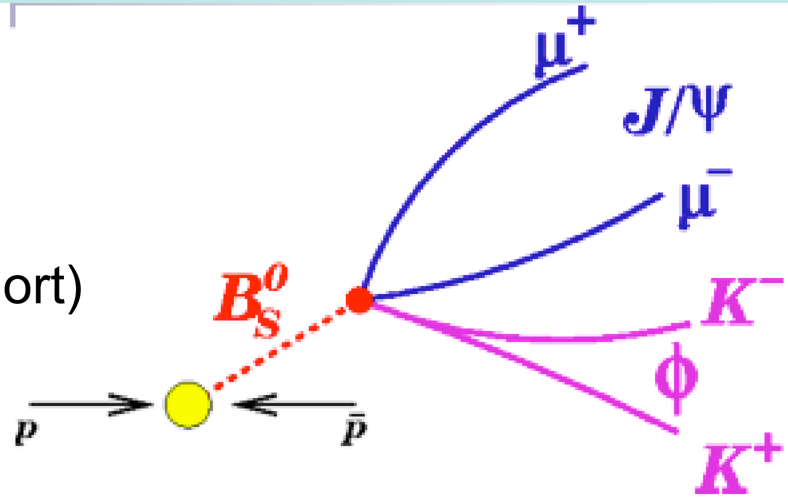
$B_s \rightarrow J/\psi\phi$

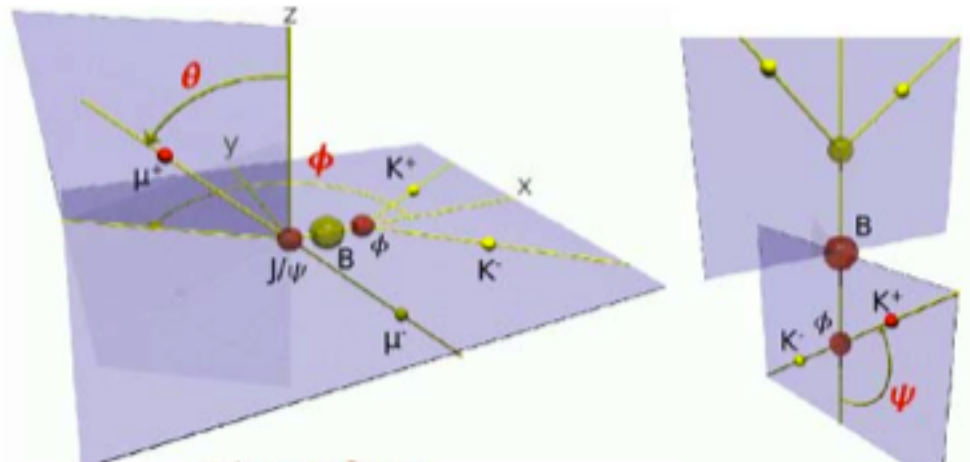
B_s(spin-0) ➔ J/ψ (spin-1) ϕ(spin-1)

3 angular momentum states

L=0 (s-wave), 2 (d-wave) CP even (short)

L=1 (p-wave), CP odd (long)





J/ψ rest frame

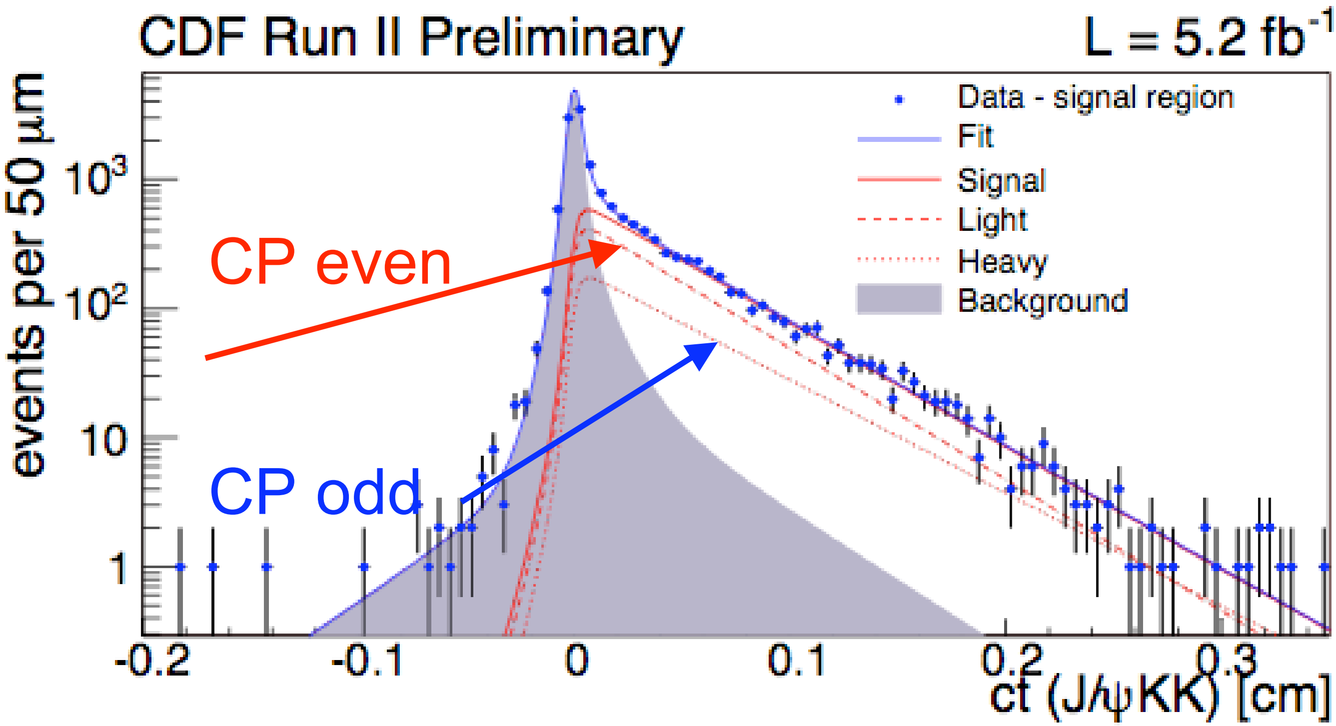
φ rest frame

Three decay angles

$p(\theta, \phi, \psi)$

Describe the angular direction of the decay products

Measurement of width difference



Simultaneous fit to the mass, lifetime, and angular distributions

-provides separation of CP odd and even

Allows measurement of the mean lifetime and width difference

$$\tau_s = 1.53 \pm 0.025\ (\text{stat.})\ \pm 0.012\ (\text{syst.})\ \text{ps}$$
$$\Delta\Gamma\ =\ 0.075 \pm 0.035\ (\text{stat.}) \pm 0.01\ (\text{syst.})\ ps^{-1}$$

5.2 fb^{-1}

$$\bar{\tau}_s = 1.45 \pm 0.04 \pm 0.01\ \text{ps}$$
$$\Delta\Gamma_s = 0.15 \pm 0.06 \pm 0.01\ \text{ps}^{-1}$$

6.2 fb^{-1}

Using Branching Fractions

Decay B_s ➔ $D_s^+D_s^-$ CP Even ; B_s ➔ D_s^{*+} D_s^{*-} CP Even to within 5 %

Under various theoretical assumptions $2 \times Br\left(B_s \to D_s^{(*)+} D_s^{(*)-}\right) \sim \frac{\Delta\Gamma}{\Gamma}$

see Tuesday's talk U. Nierste

"under various theoretical assumptions"

- i.e don't draw too many conclusions from a Branching fraction measurement

Nonetheless, $\tau(B_s$ ➔ $D_s^+D_s^-)$ is interesting

Using Branching Fractions

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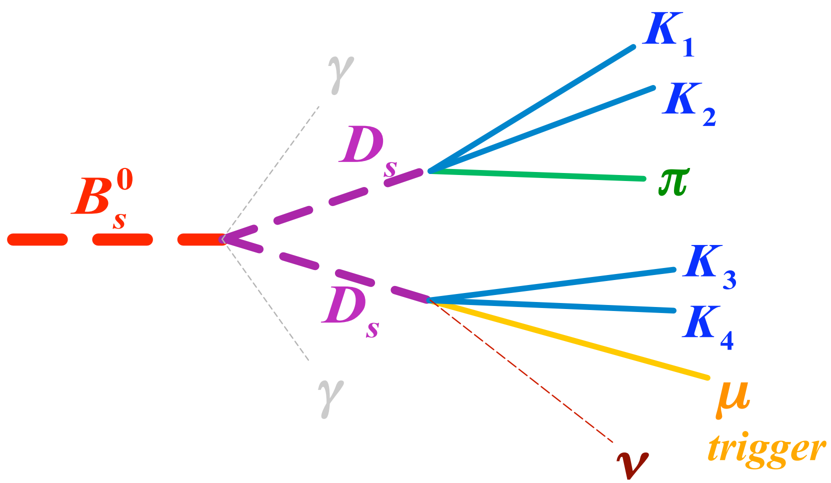

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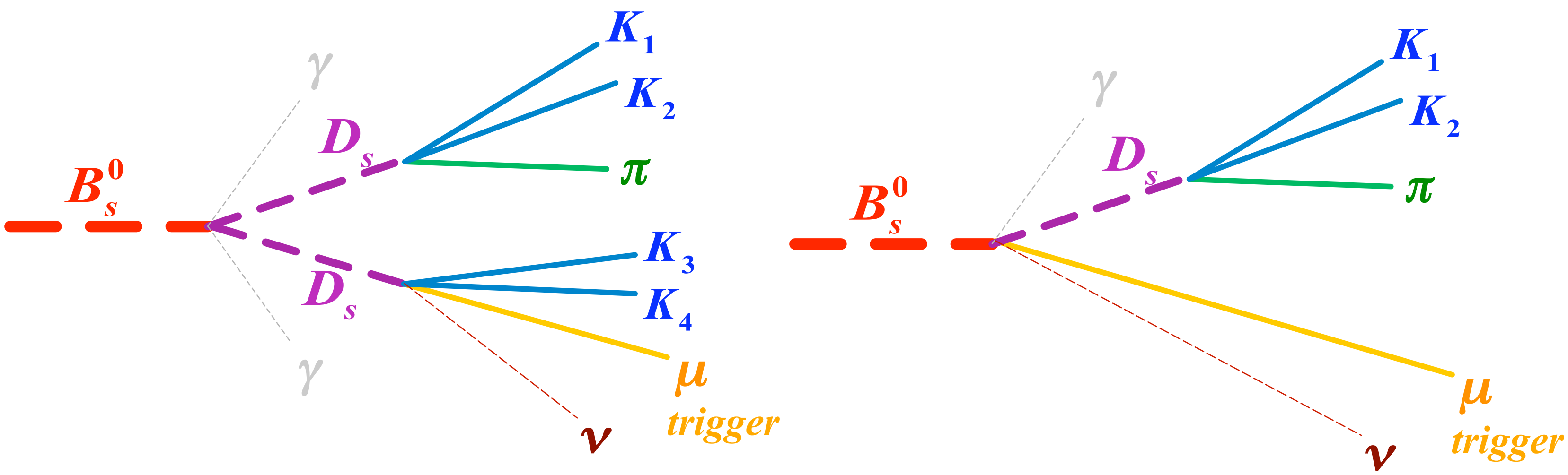

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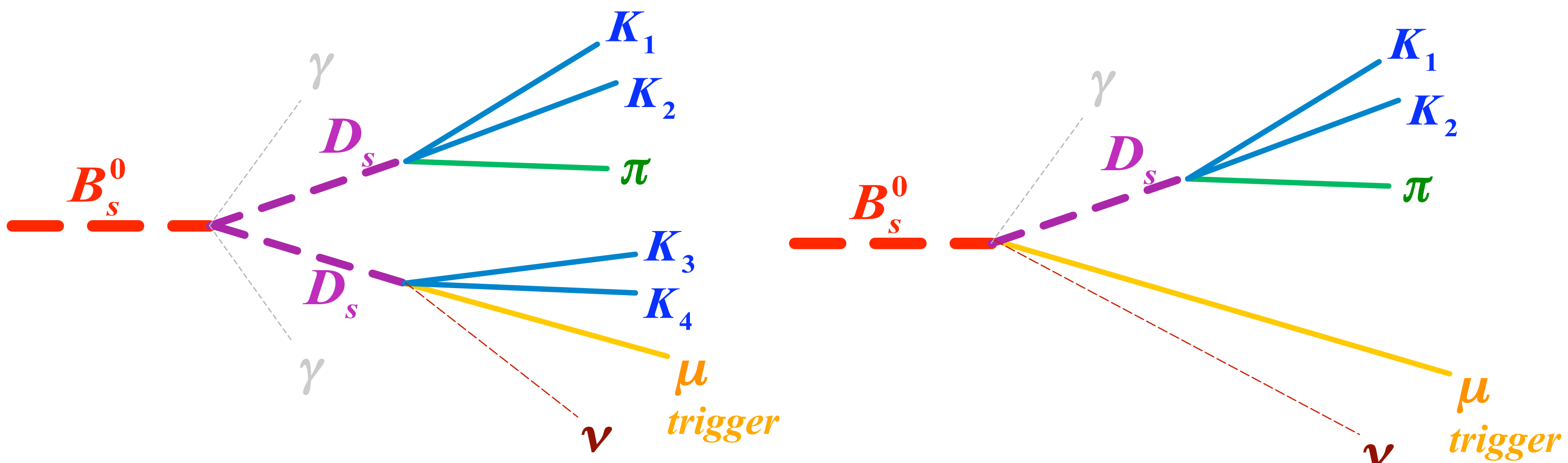


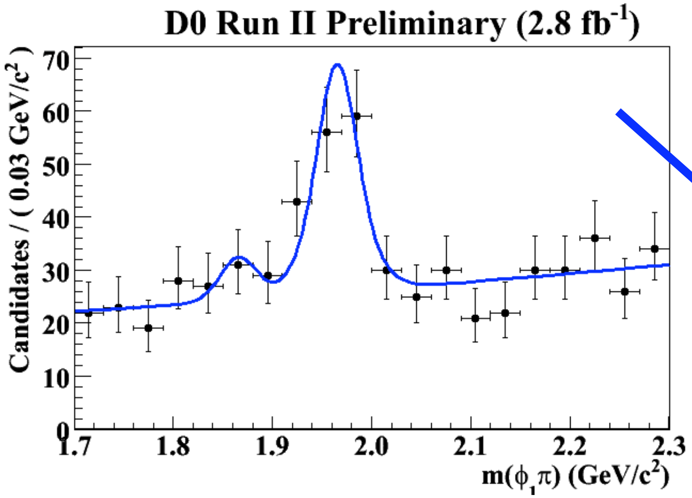
$$\frac{N(B_s \rightarrow D_s^{(*)} D_s^{(*)})}{N(B_s \rightarrow D_s^{(*)} \mu\nu)} = 2R \cdot \frac{\varepsilon(B_s \rightarrow D_s^{(*)} D_s^{(*)})}{\varepsilon(B_s \rightarrow D_s^{(*)} \mu\nu)}$$

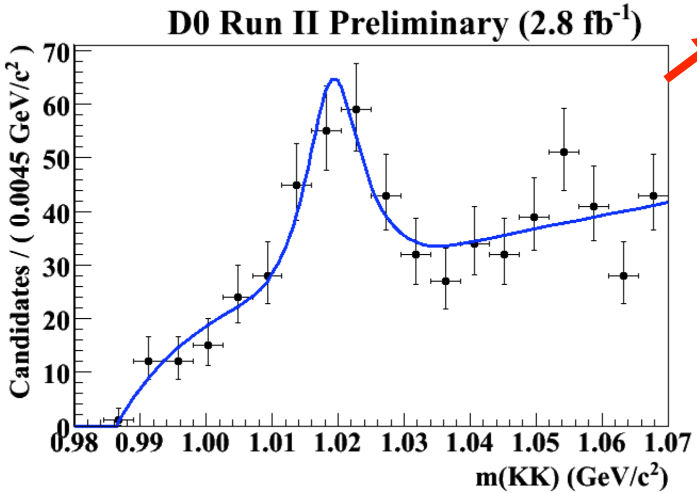
$$R \equiv \frac{Br(B_s \rightarrow D_s^{(*)} D_s^{(*)}) \cdot Br(D_s \rightarrow \varphi\mu\nu) \cdot Br(\varphi \rightarrow K^+ K^-)}{Br(B_s \rightarrow D_s^{(*)} \mu\nu)}$$

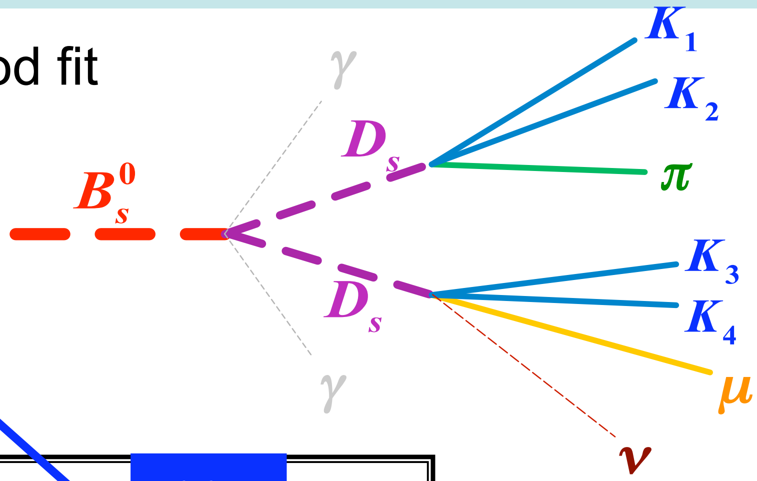
Many detector related systematics cancel

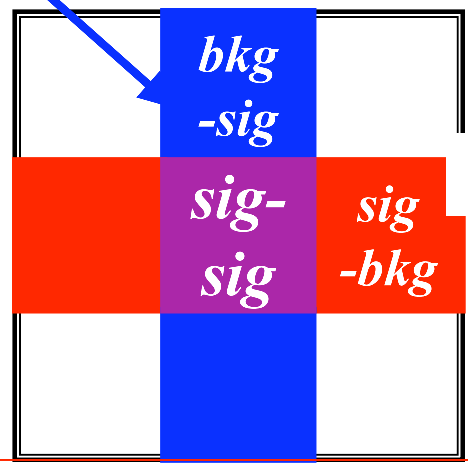
Branching fraction measurement

2-D likelihood maximum likelihood fit









N $_{sig}$= 26.6± 8.4 events

$$\mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-}) = 0.035 \pm 0.015.$$

$$\frac{\Delta\Gamma_s}{\Gamma_s} = 0.072 \pm 0.030.$$

“Width difference” without a lifetime fit

CDF also working towards update

B_s B_d Λ_b Lifetimes

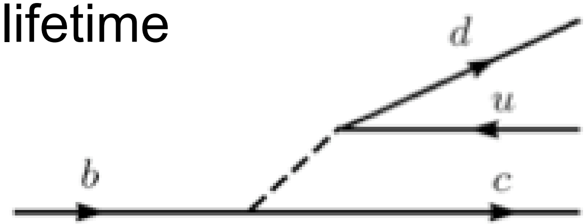
Lifetimes

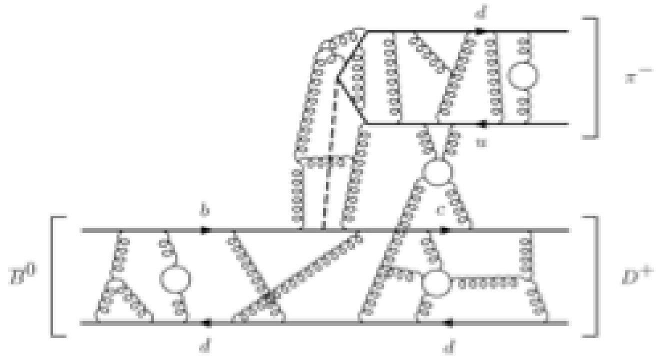
Spectator model: all B hadrons have the same lifetime

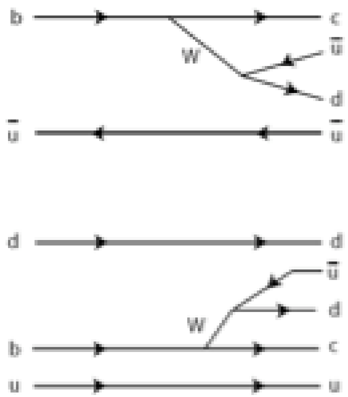
Difference from light quark interactions

In general $\tau(B_u) > \tau(B_d) \sim \tau(B_s) > \tau(\Lambda_b)$

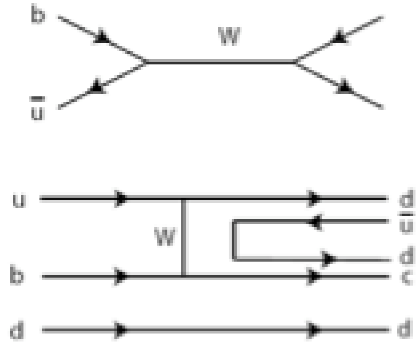
Understand these differences qualitatively







Pauli interference: prolongs lifetimes +3% Λ_b, +5% B_u cf B_d



Weak scattering: reduces lifetimes -7% Λ_b, cf. B_d

Lifetimes important for understanding the interactions of quarks inside hadrons. Ratios predicted by HQE

HQE is used to calculate Γ_{12} and semileptonic asymmetry

arXiv:0802.0977

Recent B_s lifetime results

Theoretical prediction:

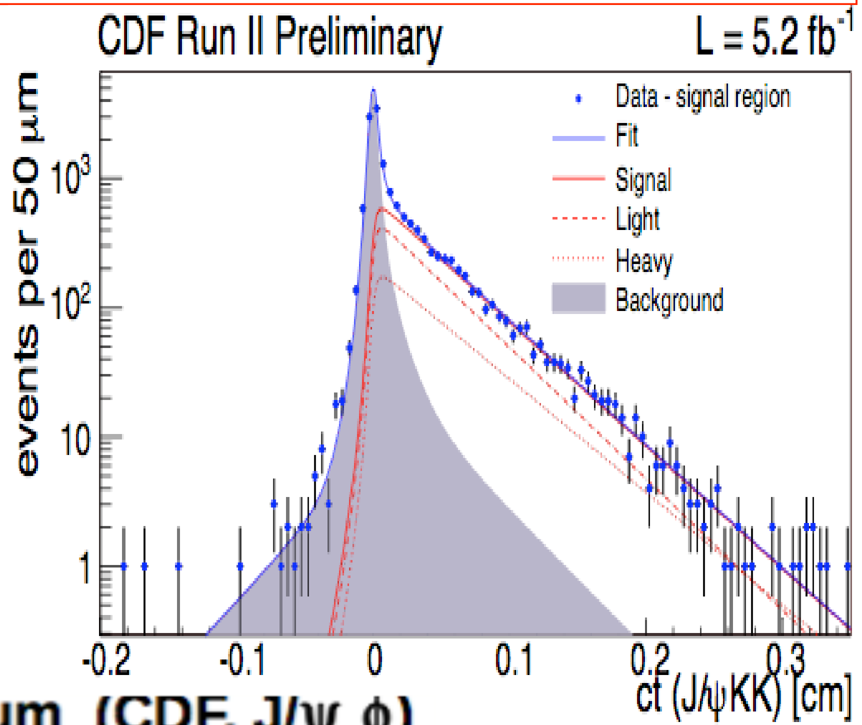
$\tau(B_s)=(1.00\pm0.01)\tau(B_d)$ (theory)

End of 2006 small experimental tension

$\tau(B_s)=(0.950\pm0.019)\tau(B_d)$ (exp)

Recent $B_s \rightarrow J/\psi\phi$ results give most accurate $\tau(B_s)$

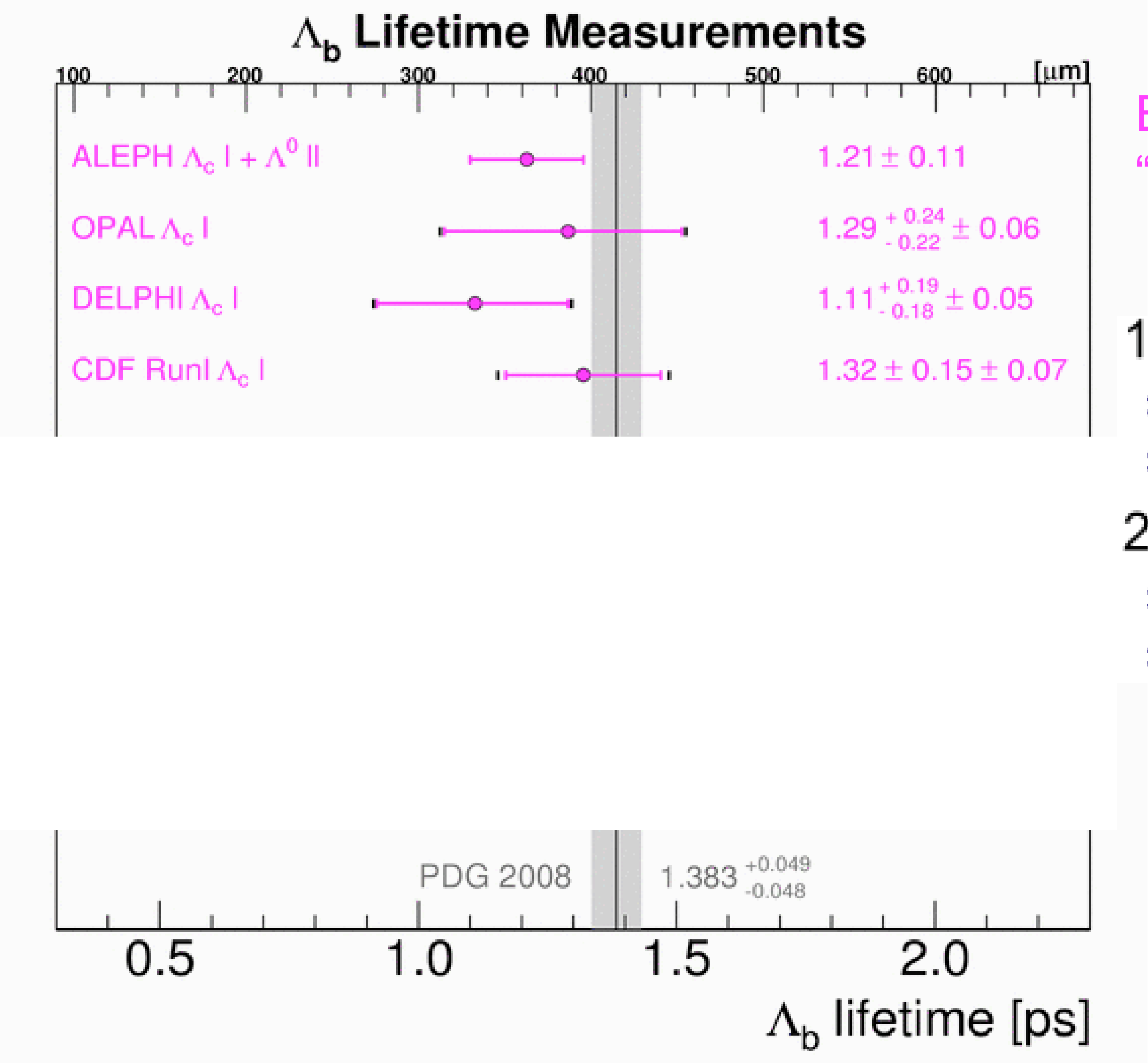
Similarity of s,d quark, hard to introduce differences



$c\tau_s$ = 458.7 ± 7.5(stat.) ± 3.6 (syst.) μm (CDF, J/ψ φ)

$c\tau_d$ = 459 ± 2.7 μm PDG world average

Λ_b " puzzle" - historical overview



Early measurements were "low" cf to theory predictions

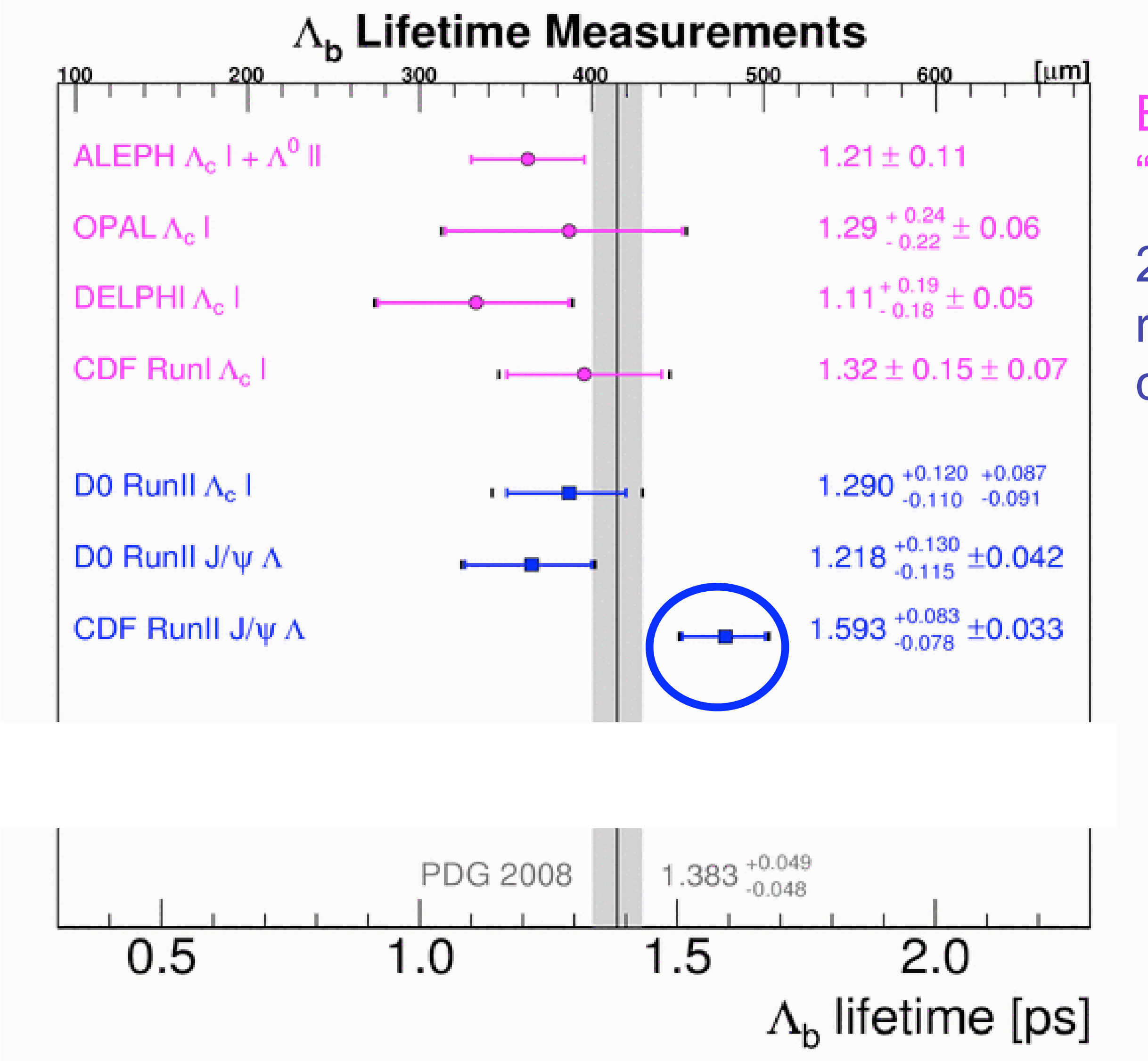
1996:

- World average: 0.78 ± 0.05
- LO + spect. effect: 0.90-0.95 (Bigi et al.)

2004:

- World average: 0.804 ± 0.049
- NLO+ $O(1/m_b^4)$: 0.86 ± 0.05 Gabbiani et al., PRD70 094031

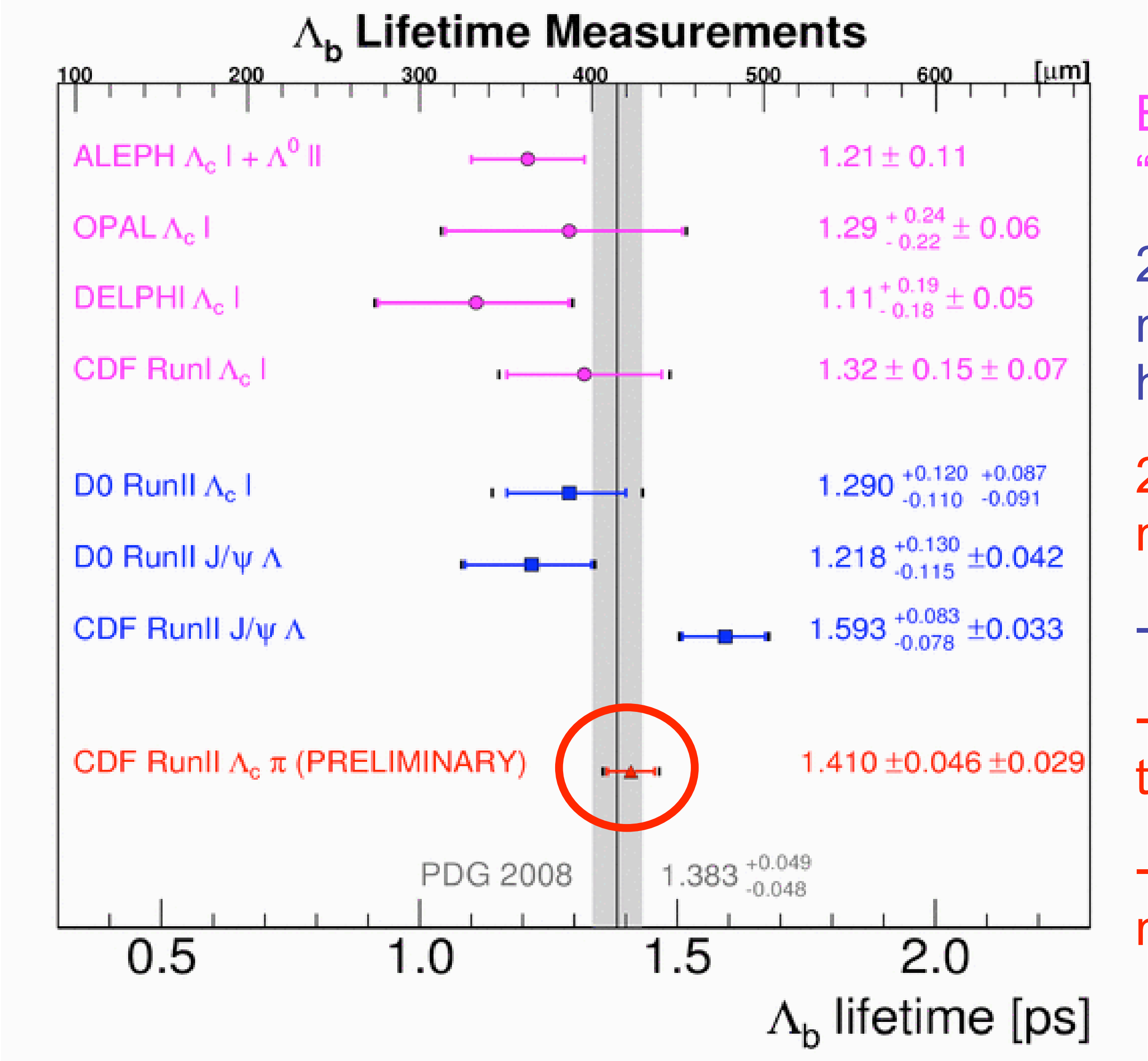
Λ_b " puzzle" - new measurement



Early measurements were "low" cf to theory predictions

2007 CDF Fully reconstructed measurement considerably higher [$J/\psi\Lambda$]

Λ_b " puzzle" 2008 measurement



Early measurements were "low" cf to theory predictions

2007 Fully reconstructed measurement considerably higher [J/ψΛ]

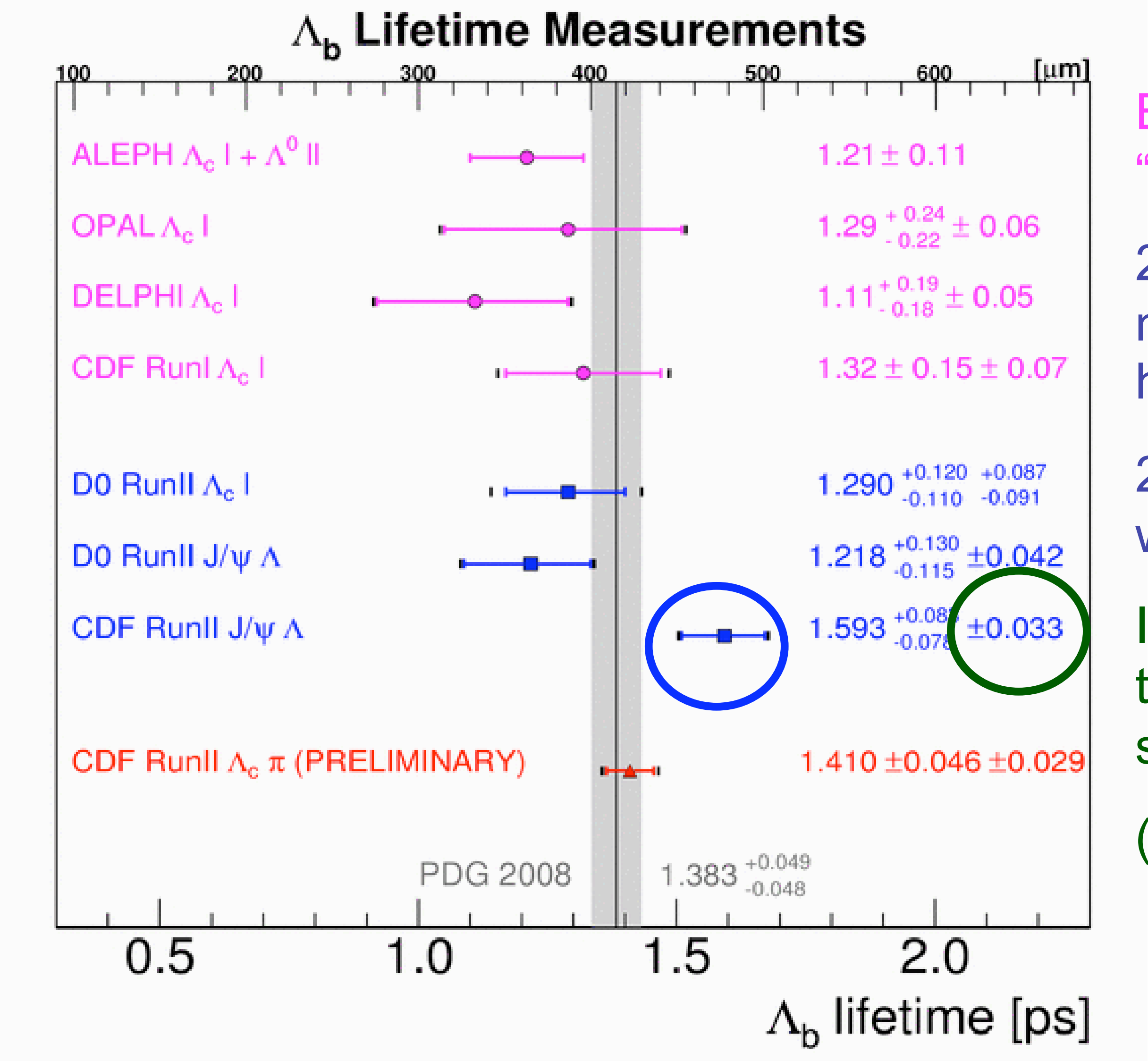
2008 measurement fell in the middle [Λ_c π]

-Different decay channel

-Collected through different trigger

-Systematics between two measurements uncorrelated

Λ_b " puzzle" 2010 update



Early measurements were "low" cf to theory predictions

2007 Fully reconstructed measurement considerably higher [J/ψΛ]

2007 measurement updated with ~x4 data

Improved analysis techniques to reduce systematic uncertainties

(resolution was leading)

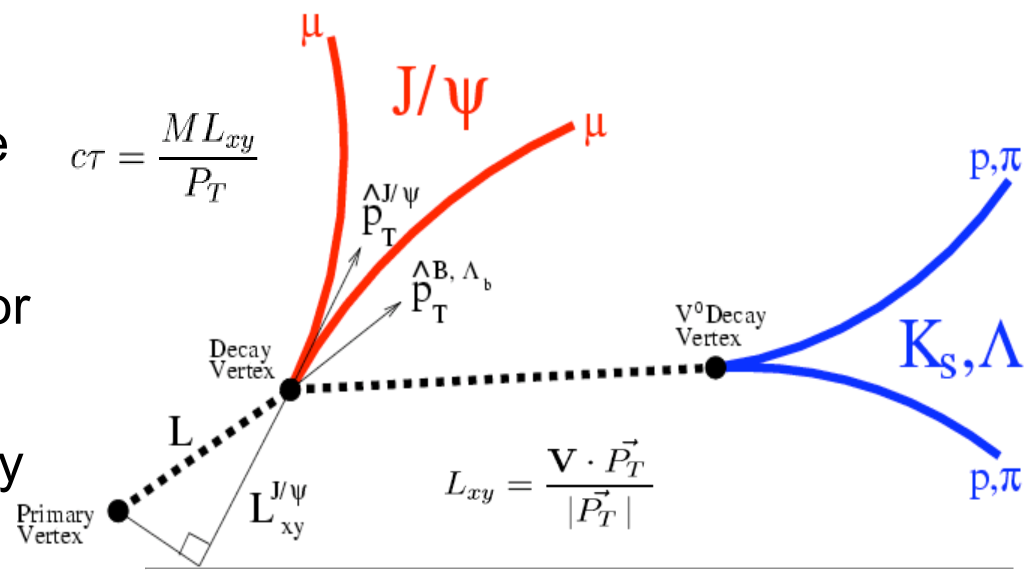
$\Lambda_b \rightarrow J/\psi\Lambda$

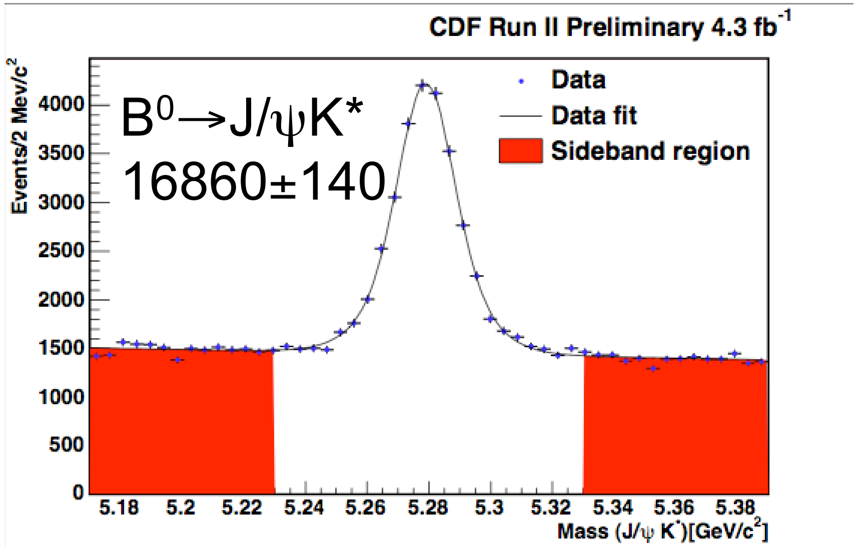
$B^+ \rightarrow J/\psi K^+$ $B^0 \rightarrow J/\psi K^*$, $B^0 \rightarrow J/\psi Ks$ used as control modes.

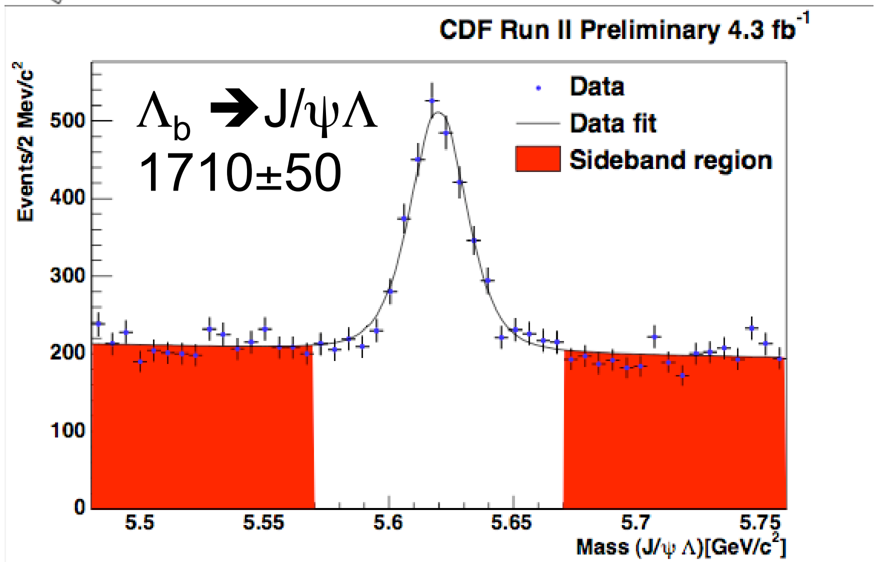
Use the J/ψ vertex to determine the Decay Vertex for all modes

Makes detector resolution similar for all channels

Use the J/ψ sample for further study







Determining the resolution

σ_{ct} measured for each candidate

Detector resolution described Gaussian with width σ_{ct} x scale factor

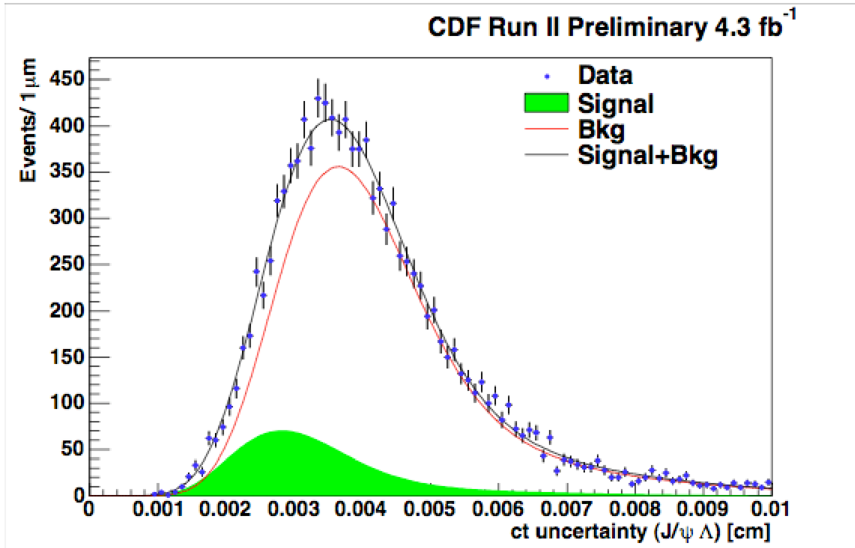
scale factor not reproduced by MC

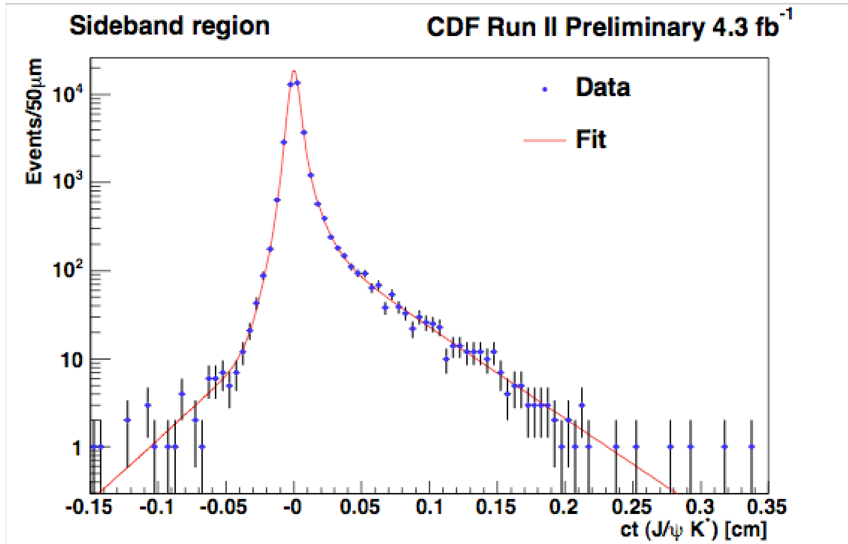
Background is mainly prompt. (80-90)%

Carefully model the mass sideband data ➔extract the parameters that determine the detector resolution.

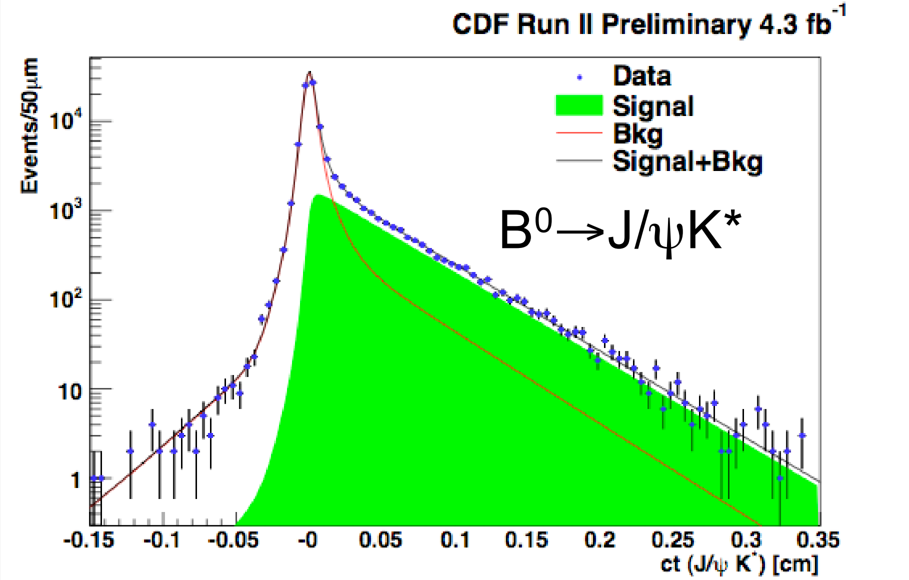
Overall systematic reduction for analysis

0.016 ps ➔ 0.008 ps (B^0)

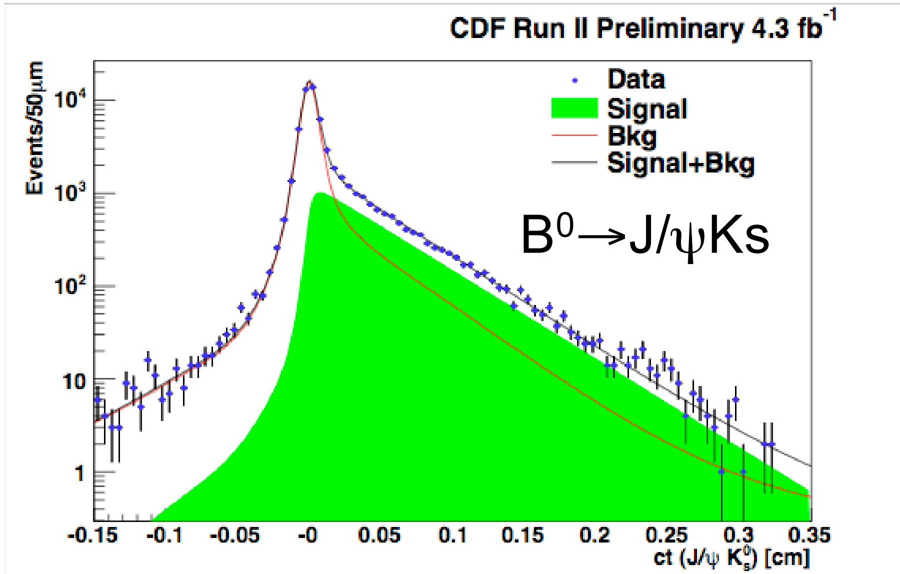


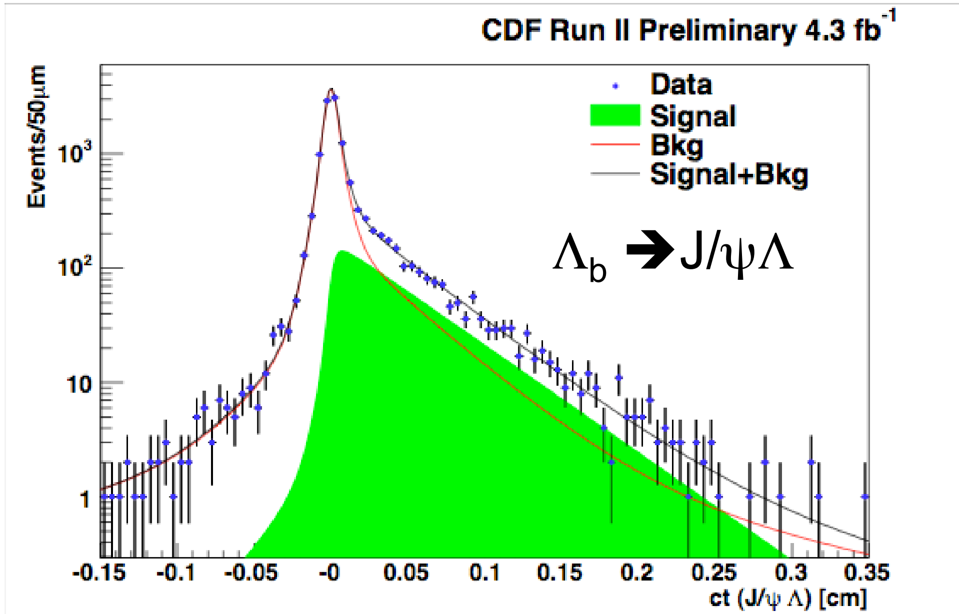


B^0 & Λ_b Lifetime fit projection

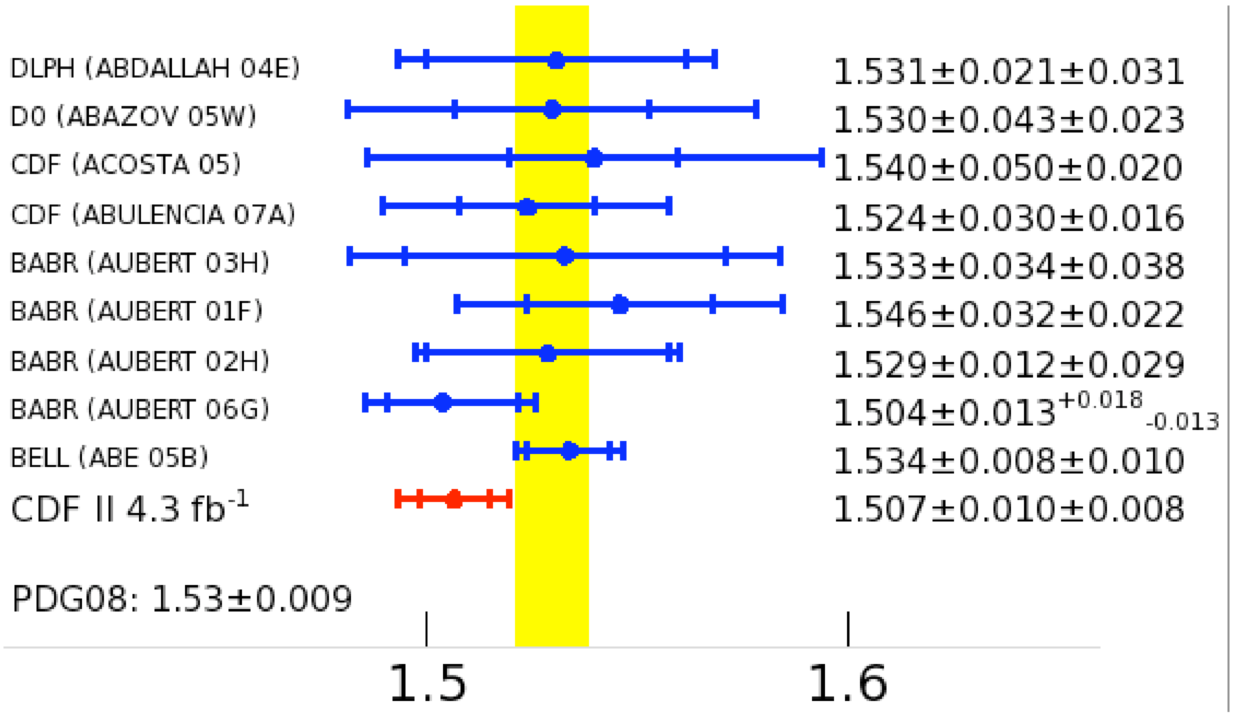


Lifetime extracted from an un-binned likelihood fit, simultaneous in
Mass
Decay time
Decay time error





B^0 Lifetime



Result slightly lower than WA

Competitive with the B factories

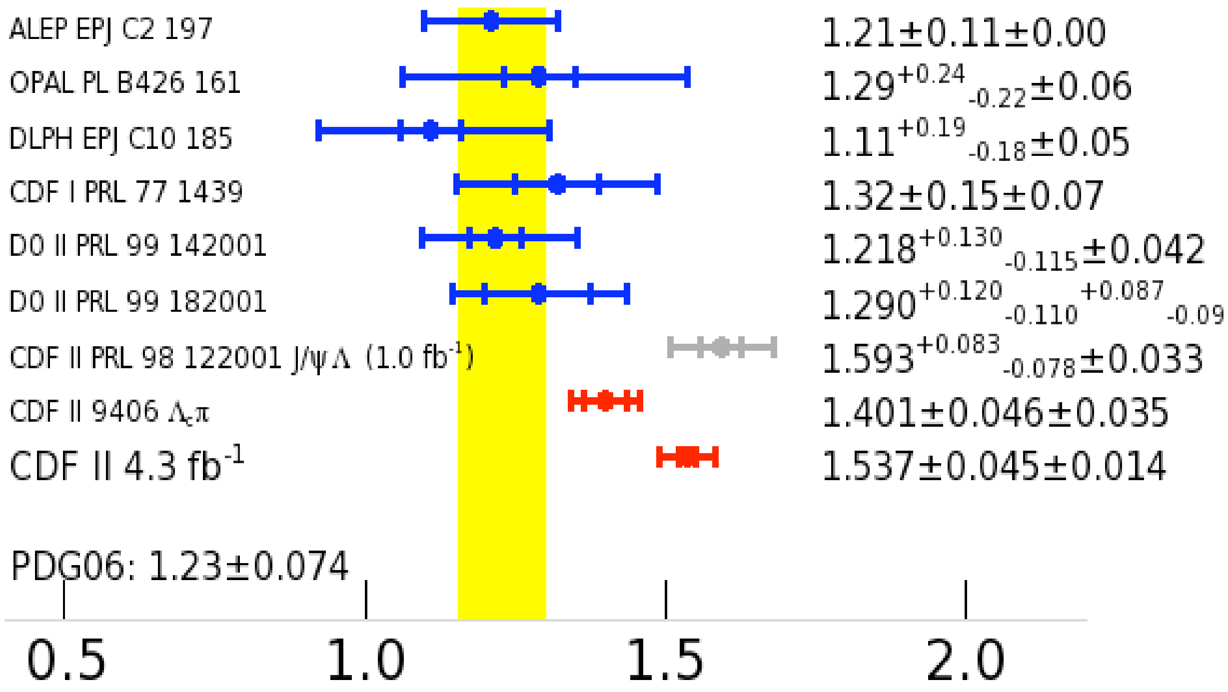
Most precise measurement of the B^+/B^0 ratio

In agreement with theoretical prediction:

$\tau(B^+)=(1.063\pm0.027)\tau(B_d)$ (theory)

$\tau(B^+)=(1.088\pm0.009\pm0.004)\tau(B_d)$ (exp)

Λ_b Lifetime



Lifetime remains high

Systematic uncertainties reduced

$\tau(\Lambda_B)/\tau(B^0) = 1.020 \pm 0.030 \pm 0.008$

Theoretical predictions 0.83 -0.95

Look forward to further inputs both experimental and theoretical

Summary & Prospects

Lifetimes : v. large samples at LHCb

e.g $B_s \rightarrow D_s\pi$ @ $LHCb^{2011}$ ~67K

see V. Gligorov WG V

Expect progress on the lifetimes front: B_s Λ_B particularly interesting. Other B Baryons too.

Mixings and widths:

Results shown today only from past 3-4 years.

B_s oscillation and D^0 mixing established.

Next 3-4 years?

Lifetime difference measurements

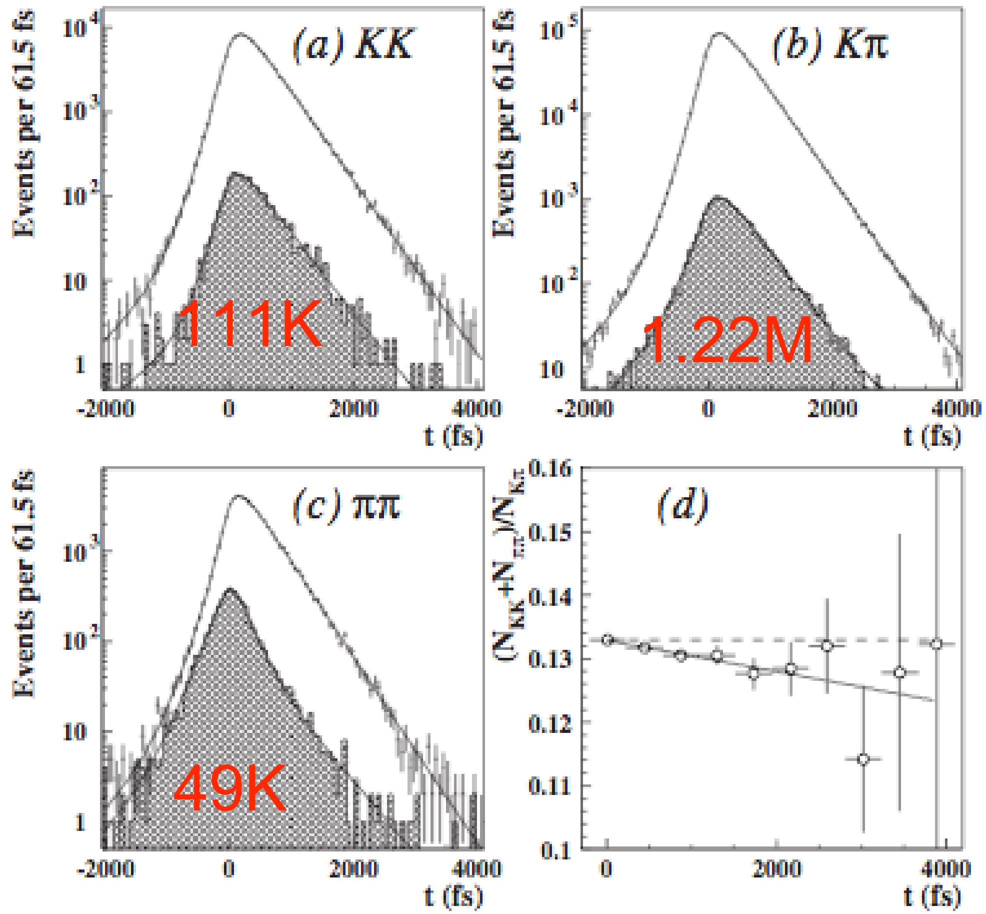
Assuming no CPV, mass eigenstates = CP eigenstates

540 fb^{-1}

Lifetime ratio can determine y

$$y_{cp} \approx y = \frac{\tau(D \to K\pi)}{\tau(D \to hh)} - 1$$

hh = KK, ππ



CP eigenstate

Not CP eigenstate

PRL 98 211803

PRD 80 071103

Lifetime difference measurements

Assuming no CPV, mass eigenstates = CP eigenstates

Lifetime ratio can determine y

$$y_{cp} \approx y = \frac{\tau(D \to K\pi)}{\tau(D \to hh)} - 1$$

hh = KK, ππ

Belle result:

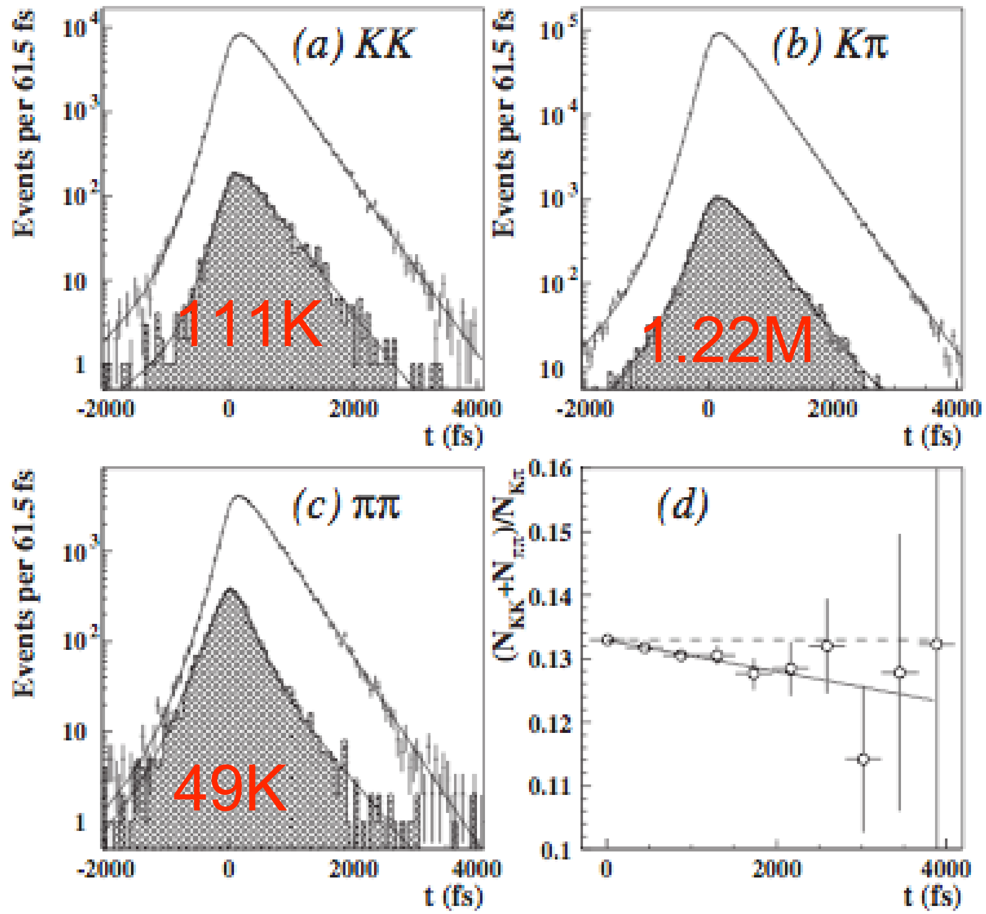
y_{cp} = (1.31±0.32 ±0.25) %

3.2σ evidence

Babar:

y_{cp} = (1.24±0.39 ±0.13)%

3.0σ evidence



Further update using untagged see next talk