Measurements of the Λ_b lifetime at DØ

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for the DØ Collaboration

Layout

Λ_b Lifetime Measurements

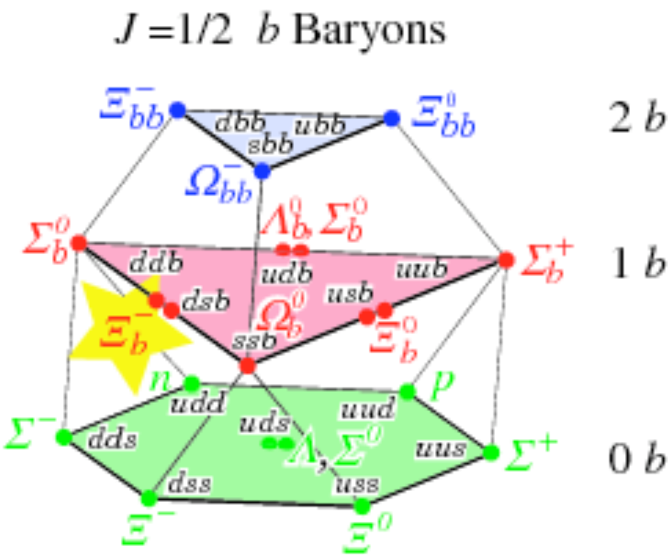
- Motivation (status)
- Lifetime measurement using semi-reconstructed

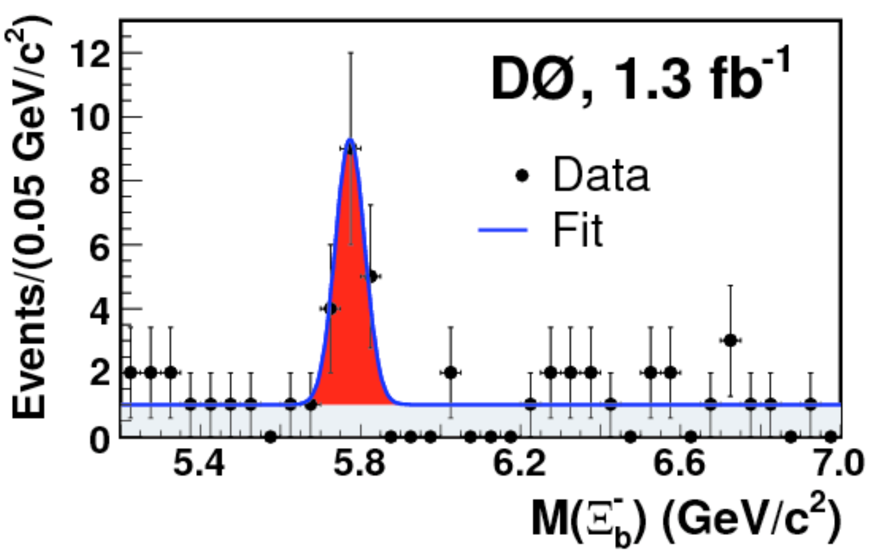
  $\Lambda_b \rightarrow \Lambda_c^+ \mu^- \nu$ hep-ex/0706.2358
- Lifetime measurement using fully-reconstructed

  $\Lambda_b \rightarrow J/\psi \Lambda$ hep-ex/0704.3909
- Combined/Final result

Credits: The analyses presented today were performed by: Marcus Lewin and Guennadi Borissov (U. Lancaster); and Natalia Panikashvili and Eduard De La Cruz Burelo (U. Michigan)

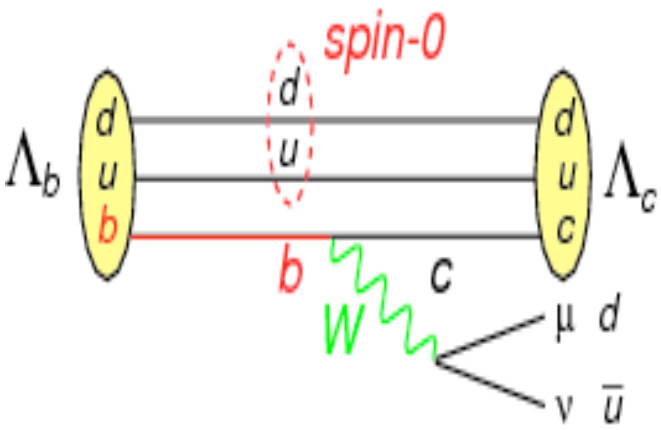
Remember: Few weeks ago

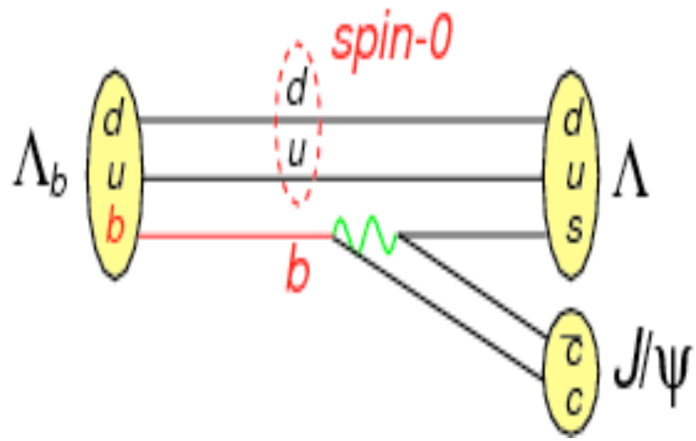




Motivation: Lifetime

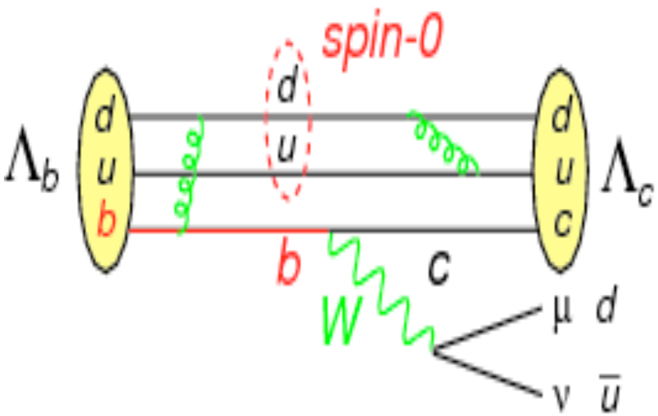
- Pattern of lifetime differences between B hadrons predicted by Heavy Quark Expansion, Spectator model

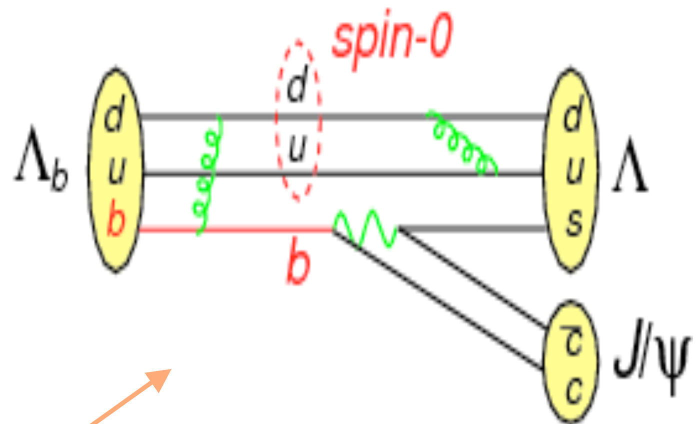




Motivation: Lifetime

- Pattern of lifetime differences between B hadrons predicted by Heavy Quark Expansion, Spectator model messep up by interactions between quarks





- HQE: no leading order corrections a $1/m_q$
  General feature of QCD gauge structure

$$\delta\tau_{H_b} \sim O\left(\frac{\Lambda_{QCD}^2}{m_b^2}\right) + O\left(\frac{\Lambda_{QCD}^3}{m_b^3}\right) + \ldots$$

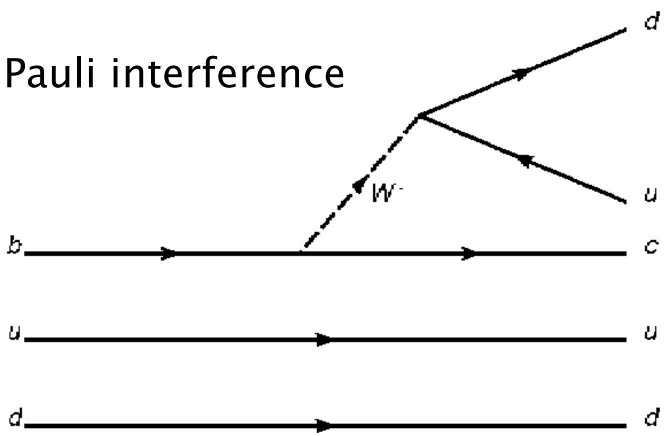
$$-\frac{1}{2}\frac{\mu_\pi^2}{m_b^2} - c_G\frac{\mu_G^2}{2m_b^2}$$

$$\langle B|\bar{b}\Gamma q \cdot \bar{q}\Gamma' b|B\rangle$$

e.g., Voloshin, Uraltsev, Kohze, Shifman

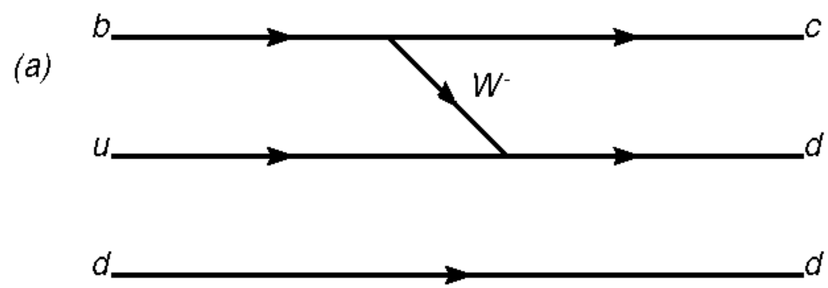
Motivation: Lifetime differences

Pauli interference



$O(\frac{\Lambda^3_{QCD}}{m_b^3})$ enhanced by phase space

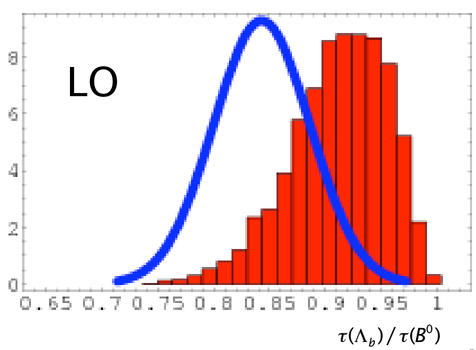
Weak scattering

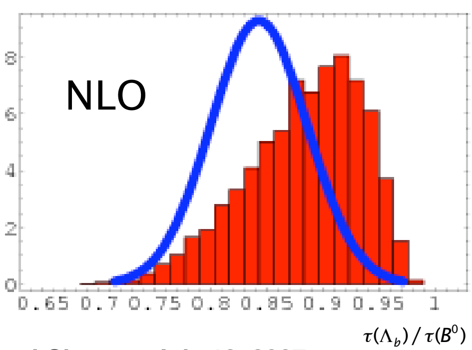


A lot of theoretical work:
Lattice, QCD-NLO, etc.

NLO calculations: Tarantino, Franco, Lubicz, Mescia, Gabbiani, Onishchenko, Petrov among others.

experiment
theory





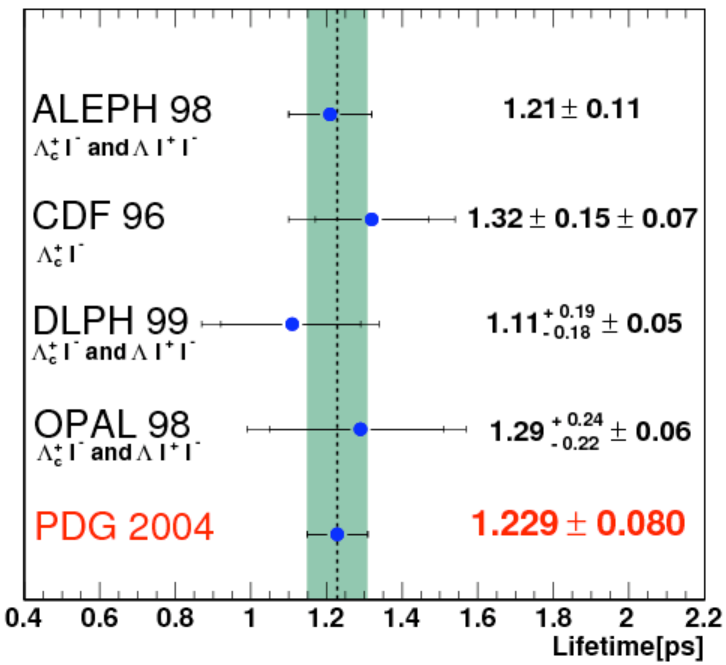
$$\frac{\tau(\Lambda_b)}{\tau(B^0)} = 0.88 \pm 0.05$$

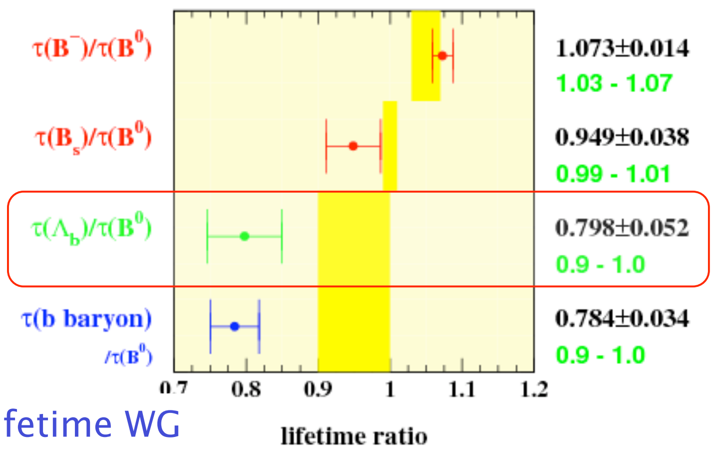
Motivation: Λ_b Lifetime Puzzle

- Before RunII, theory and experiment did not agree

  "Λ_b lifetime puzzle"

- World average was dominated by LEP semileptonic measurements





B Lifetime WG 2002

- Significant improvement since then, theory has included NLO calculations, but experiments still have large uncertainties

- important to revisit this with data sets now available at the Tevatron

Motivation: What is the status?

First Λ_b lifetime measurement in *exclusive* decay channel was done at D0 (250 pb^{-1}):

$$\tau(\Lambda_b) = 1.22^{+0.22}_{-0.18}(stat) \pm 0.04(syst)\,ps$$

$$\frac{\tau(\Lambda_b)}{\tau(B^0)} = 0.87^{+0.17}_{-0.04}(stat) \pm 0.03(syst)$$

PRL 94,102001 (2005)

CDF latest result using 1fb^{-1}

$$\tau(\Lambda_b) = 1.593^{+0.083}_{-0.078}\,(stat) \pm 0.033\,(syst)\,ps$$

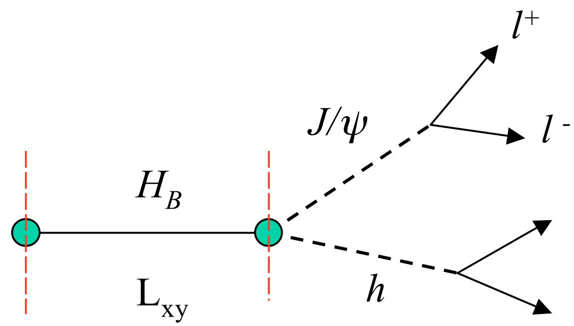
$$\frac{\tau(\Lambda_b)}{\tau(B^0)} = 1.041 \pm 0.057$$

hep-ex/0609021, accepted by PRL

PDG 2006:

$$\frac{\tau(\Lambda_b)}{\tau(B^0)} = 0.803 \pm 0.049$$

Measuring the lifetime: hadronic channels



decay length

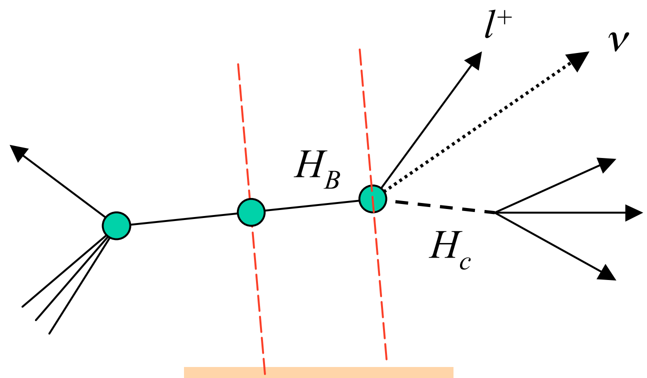
Proper decay time

$$ct = L_{xy} \cdot M / p_T$$

Pros: Full reconstructed, easy to trigger, know the boost

Cons: Low statistics

Measuring the lifetime: Semileptonic channels

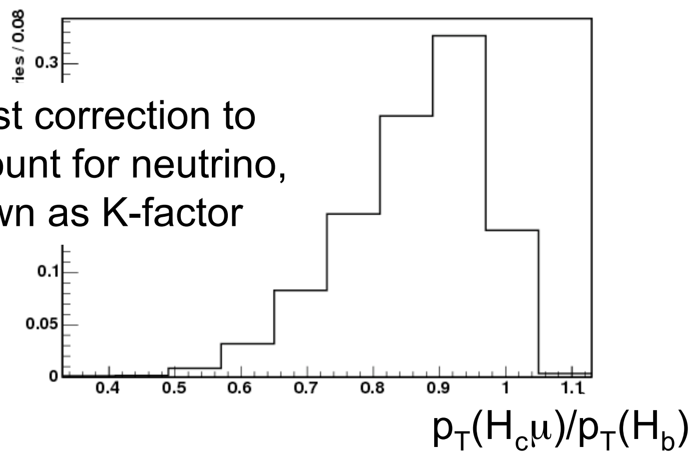


decay length

Proper decay time

$$ct = L_{xy} \cdot M / p_T$$

p_T approx.



Boost correction to account for neutrino, known as K-factor

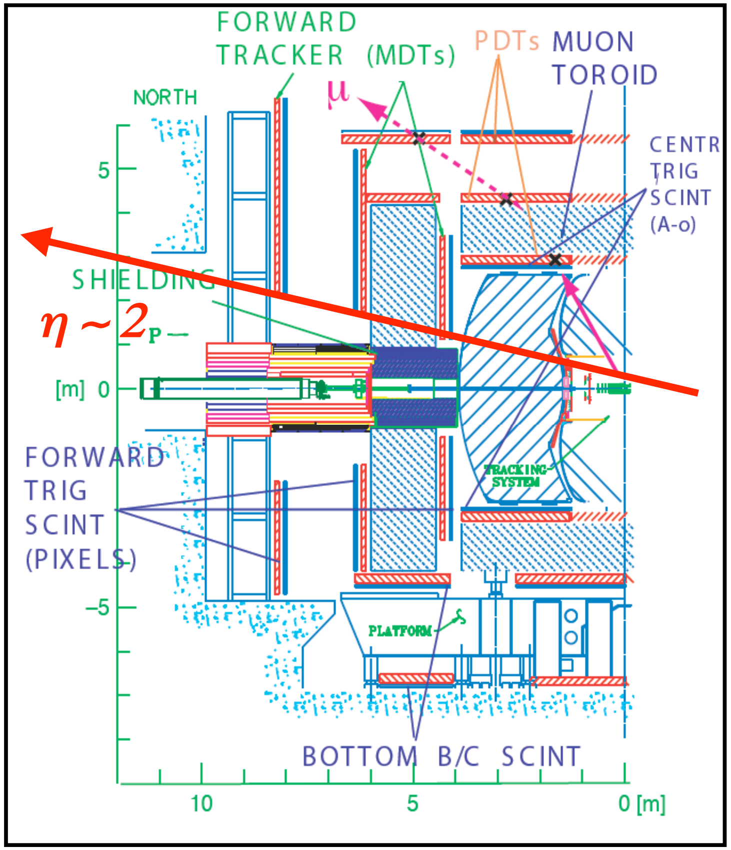
Pros: large statistics

Cons: more ambiguities, need to correct for missing neutrino

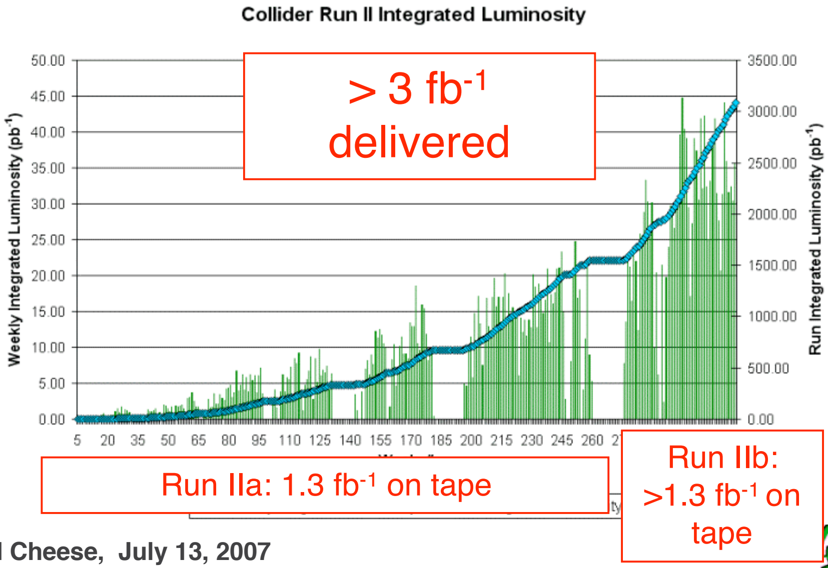
DØ Detector and Dataset

Excellent, large angular acceptance, muon spectrometer and trigger

Large $H_B \to \mu$ semileptonic and $H_B \to J/\psi$ samples



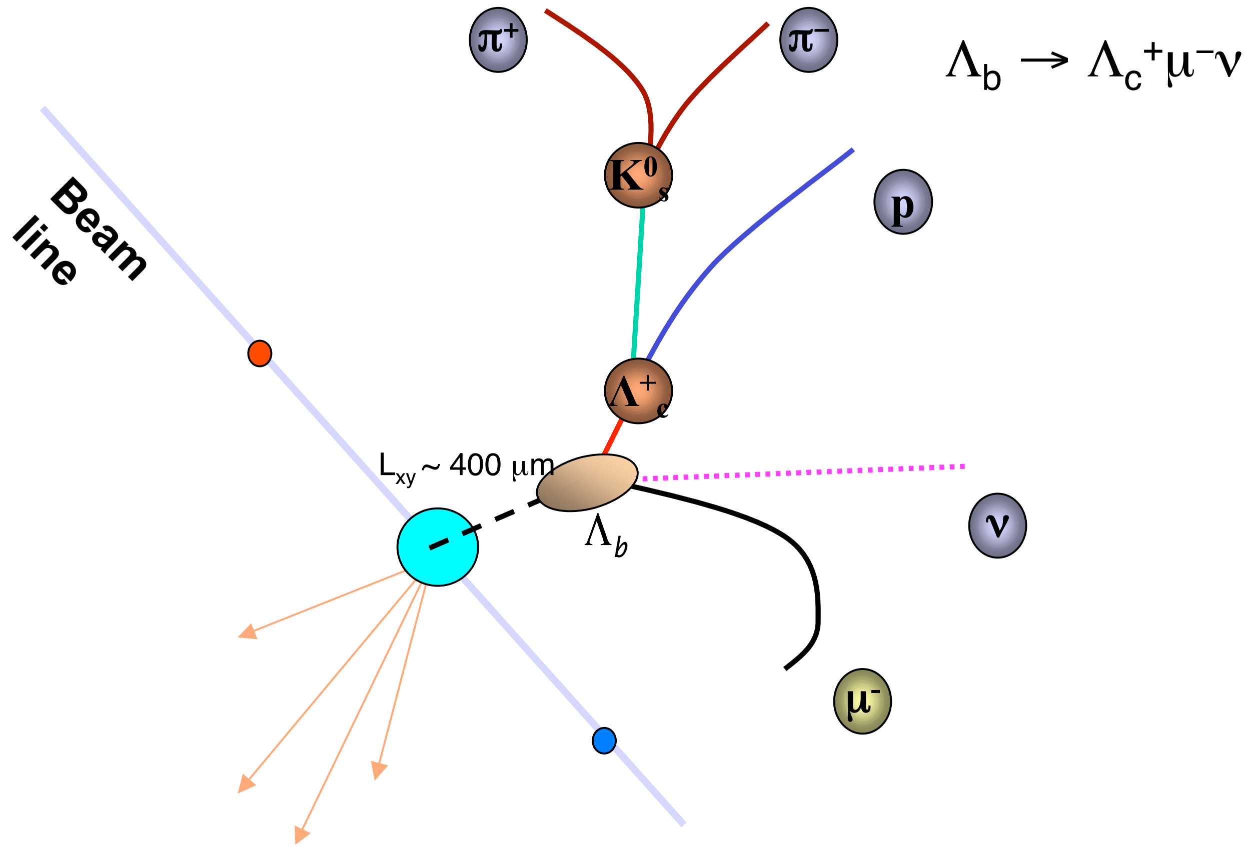
	$\lvert\eta\rvert$	$\lvert\theta\rvert$
Muon ID	~2	~15°
Tracking	~3	~5°
EM and Hadronic calorimetry	~4	~2°



Lifetime measurement with $\Lambda_b \to \Lambda_c^+ \mu^- \nu$

Semileptonic Decay channel

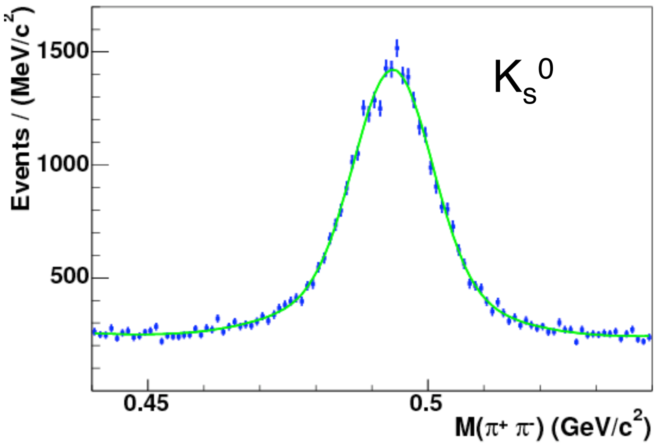
Using a large dataset, but not fully reconstructed



Selection

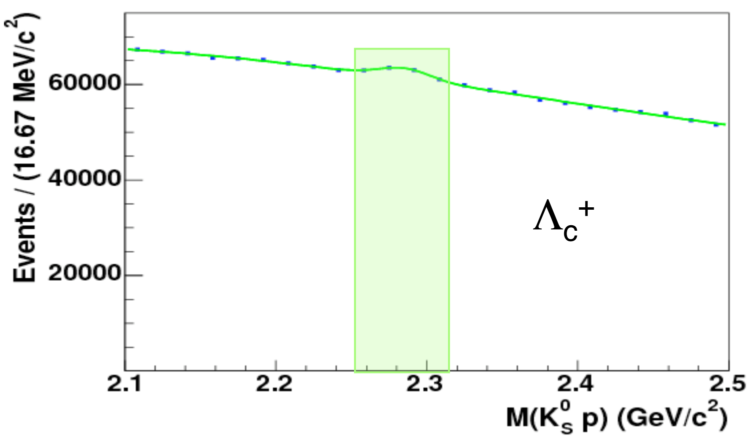
$\Lambda_b \rightarrow \Lambda_c^+ \mu^- \nu$ followed by $\Lambda_c^+ \rightarrow p K_s^0$

- Select events which fire a lifetime unbiased trigger

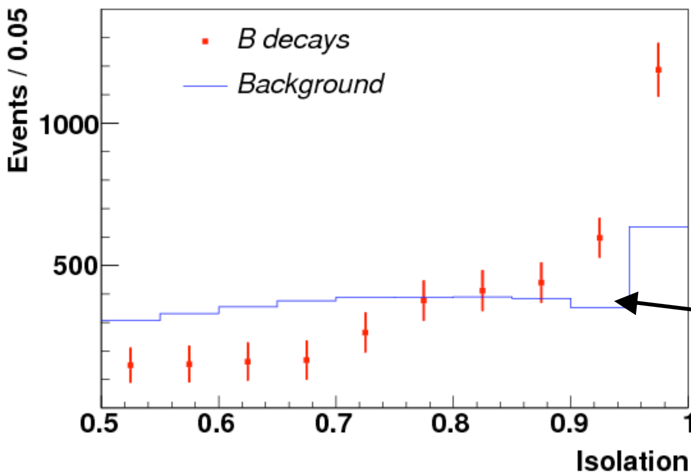


- $p_T(\mu) > 2.0$ GeV
- $p_T(K^0_s) > 0.7$ GeV
- $p_T(p) > 1.0$ GeV
- $3.4 < M(\Lambda_c^+\mu) < 5.4$ GeV

Background still very high, we use a likelihood ratio method to suppress it.

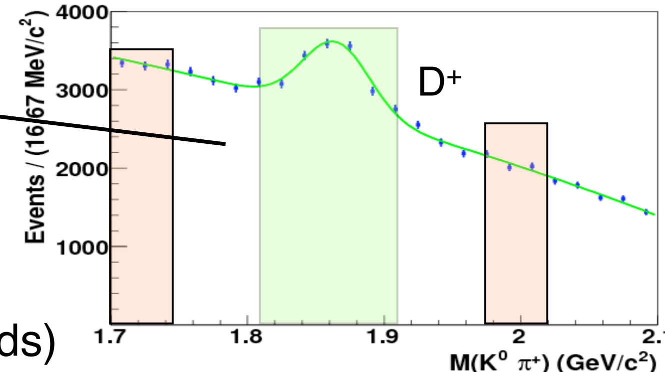


Likelihood Ratios



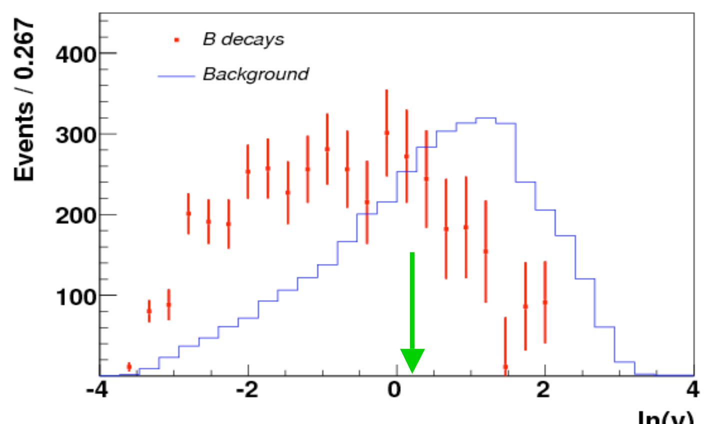
Use similar topological-kinematic decays:

$\Lambda_b \to \Lambda_c \mu\nu X$ where $\Lambda_c \to K_s p$
$B^0 \to D\mu\nu X$ where $D \to K_s\pi$
$B_s \to D_s\mu\nu X$ where $D_s \to K_s K$

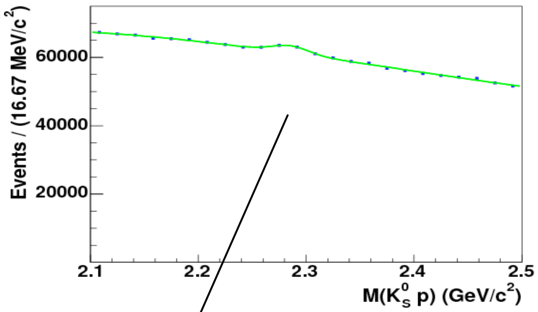


PDF(signal) = PDF(signal band) - PDF(sidebands)
Discriminanting variables: $p_T(K_s^0)$, $p_T(p/\pi)$, isolation (Λ_b/B), M(μ+Λ_c/D), p_T(Λ_c/D)

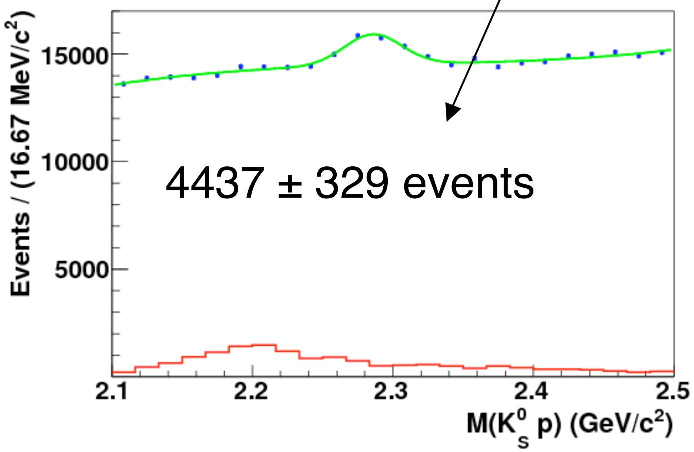
Cut on combined ln(y), for the maximum Λ_c signal significance: < 0.1



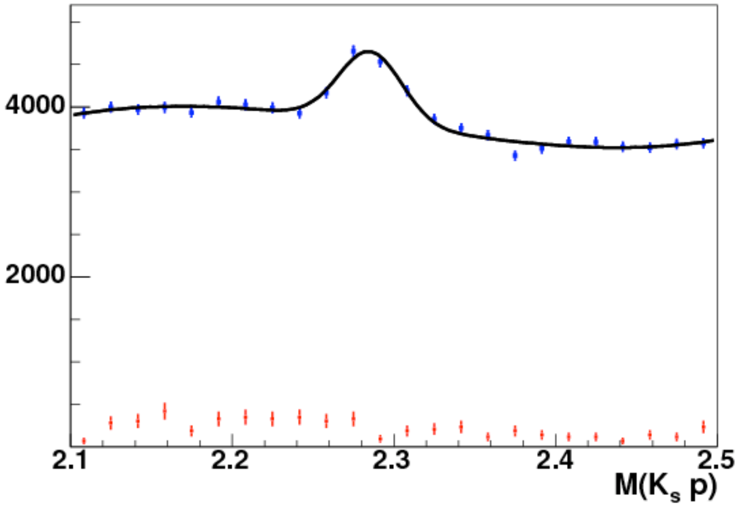
Final Selection



Final sample: Λ_c + μ



Final sample with VPDL > 200 μm



$B^0/B^+/B_s \rightarrow D^+\mu^-\nu$ ($D^+ \rightarrow K_s^0\,\pi$) reflections evaluated with MC (red)

Lifetime fit

- Measure the transverse decay length L_{xy} and calculate the visible proper decay length (VPDL) λ

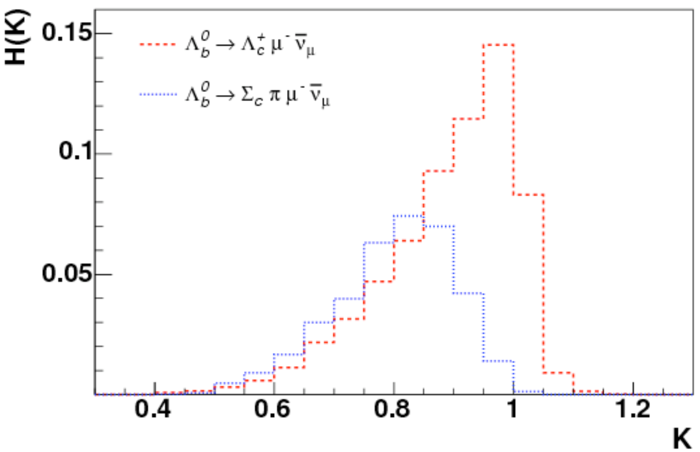
$$\lambda = L_{xy} \frac{M}{p_T(\Lambda_c \mu)} = \frac{c\tau(\Lambda_b)}{K} \qquad L_{xy} = \frac{\vec{X} \bullet \vec{p}_T(\Lambda_c \mu)}{p_T(\Lambda_c \mu)}$$

- Λ_b not fully reconstructed so include a "K factor"

$$K = \frac{p_T(\Lambda_c \mu)}{p_T(\Lambda_b)}$$

- Distributions of K factors from MC

$$\Lambda_b \to \Lambda_c \mu \nu$$
$$\Lambda_b \to \Sigma_c \mu \pi \nu$$

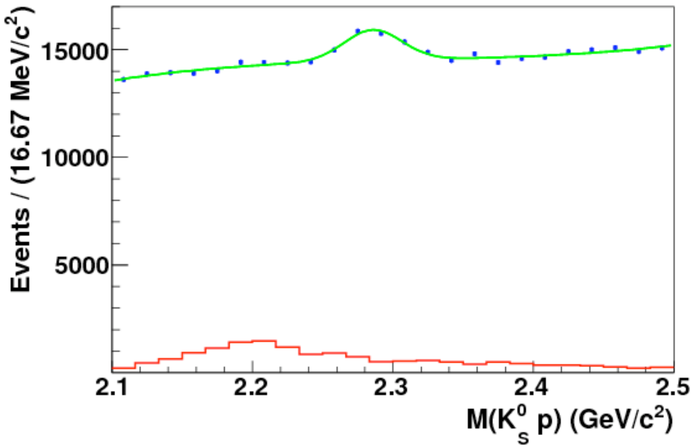


We found that other contributions such as: $\Lambda_b \to \Lambda_c^+ D_s^{(*)-}$, $\Xi_b \to \mu\nu\Lambda_c X$ and $\Lambda_b \to \tau\nu\Lambda_c X$ are very suppressed (small Br and low eff.)

systematics include very large variation in the Σ_c fraction

Lifetime Fit

- To get the lifetime we usually use an unbinned maximum likelihood fit; however, here the result would be completely dominated by uncertainties in the background model due to the small S/N, therefore we pursue a differe procedure

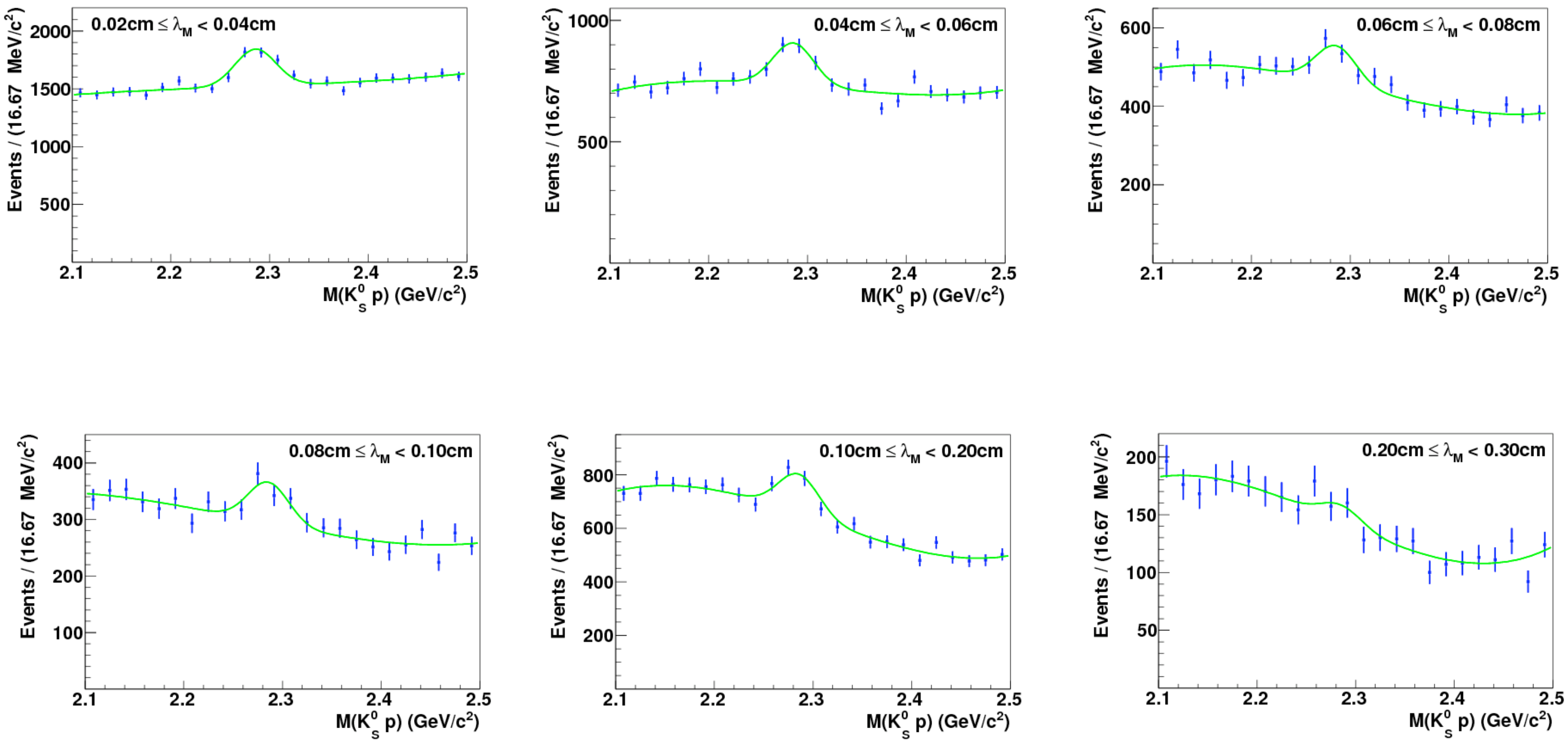


- We use a binned χ^2 fit
  - Split the sample into bins of visible proper decay length and fit the invariant mass distribution in each bin to obtain the yields n_i and their errors, σ_i
  - Use signal PDF, $F(\lambda_M)$ to calculate the expected numbers in each bin
  - Minimize χ^2, N_{TOT} is the total number of signal events

$$\chi^2 = \sum_{i=1}^{N_{bin}} \frac{\left(n_i - N_{TOT} * \int_{bini} F(\lambda_M)\, d\lambda_M\right)^2}{\sigma_i^2}$$

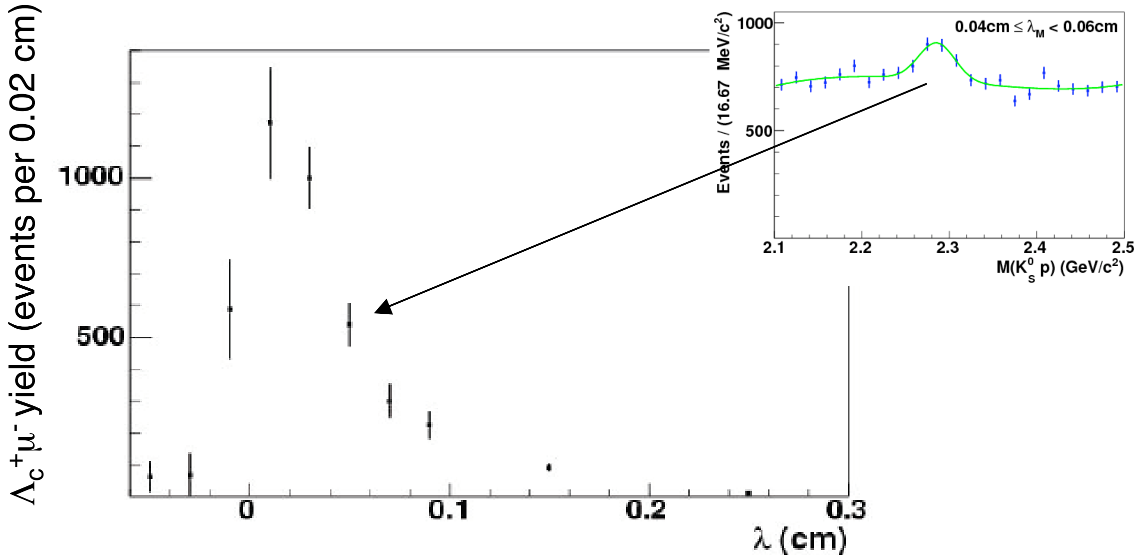
Bins of Visual Proper Decay Length

Mass and width are fixed to values found in the full sample, background is modeled by a 4th-degree polynomial



Systematic uncertainty will be dominated by this fitting procedure

Lifetime Fit



- Distribution of measured VPDL for signal

$$F_s(\lambda_M) = \int d(K)H(K)\left[\frac{K}{c\tau(\Lambda_b)} e^{-K\lambda/c\tau(\Lambda_b)} \otimes R_1(\lambda_M - \lambda, s)\right]$$

- Resolution function

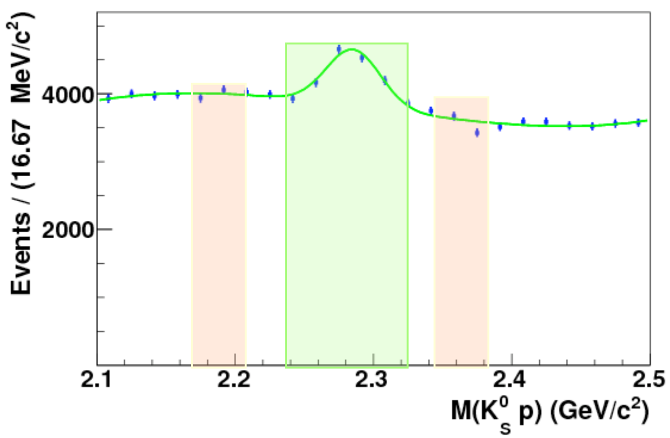
$$R(\lambda_M - \lambda, s) = \int P(\sigma)G(\lambda_M - \lambda, \sigma, s)d\sigma$$

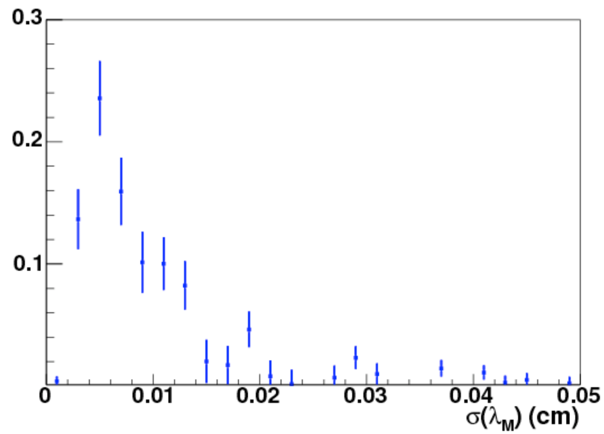
- Scale factor s to take into account misestimate of error on VPDL

Error Distribution

- Following a lifetime cut
- Use signal band and sidebands to estimate the signal error

  PDF(signal) = PDF(signal-band) - PDF(sidebands)

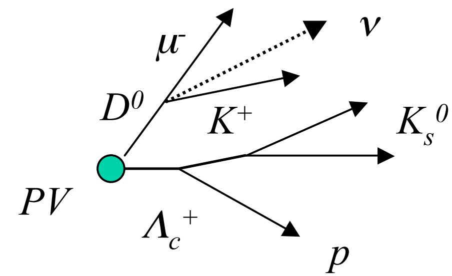




- We sum over the bins of normalized signal error distribution to do the integral

Prompt/Direct ccbar Background

- The signal peak contains contributions from the signal as well as Λ_c produced at the primary vertex with muons from another charm decay - the ccbar background



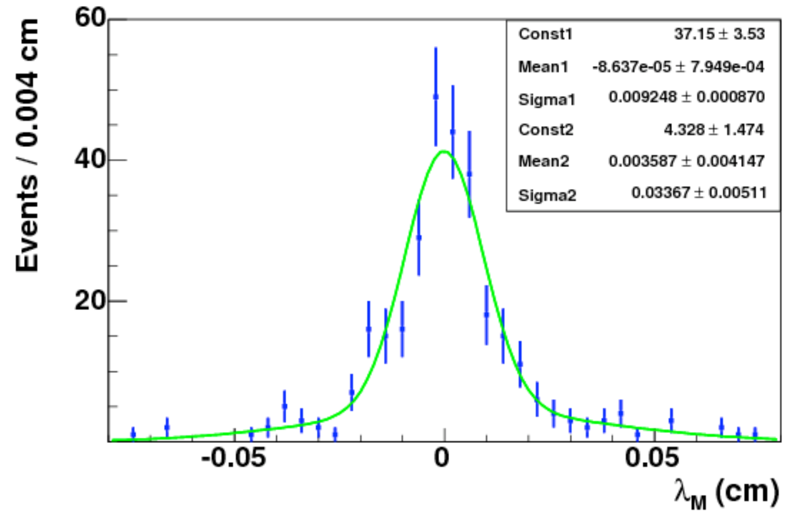
- VPDL distribution centered at zero

- Then the full PDF for the signal peak is

$$F_{TOT}(\lambda_M) = (1 - f_{CC})F_s(\lambda_M) + f_{CC}G(\lambda_M)$$

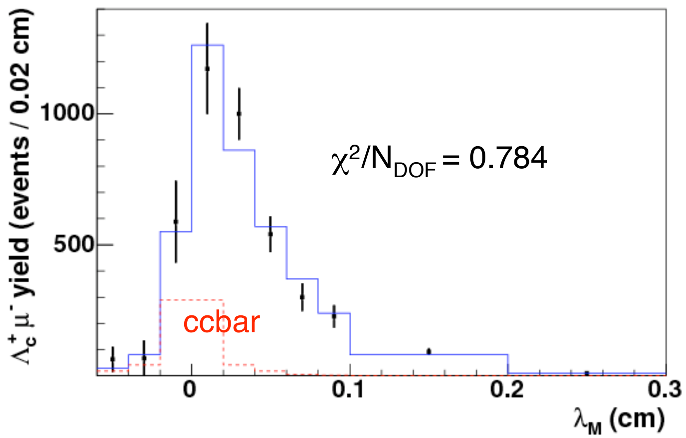
- We float the f_{cc} fraction of ccbar in the signal peak
- MC is used to get the distribution
- To parameterize it, we use a double Gaussian centered at zero with the widths and relative fractions from the fit to MC distribution

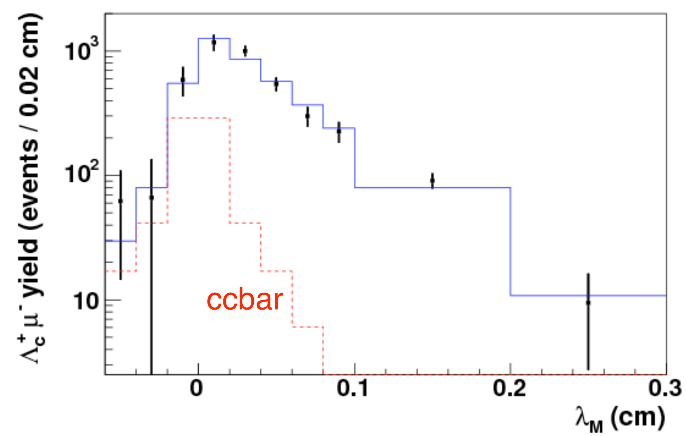
VPDL distribution for ccbar MC



Lifetime Fit

- 3 parameters go into the fit: N_{TOT}, $c\tau$, and f_{cc}
- Resolution scale factor, s, is fixed, it was found in another study to be 1.19 ± 0.06





Parameter	Fitted value	stat. error	units
N_{TOT}	4471	296	
f_{cc}	0.160	$^{+0.068}_{-0.074}$	
$c\tau(\Lambda_b)$	387.0	$^{+35.6}_{-33.0}$	μm

hep-ex/0706.2358

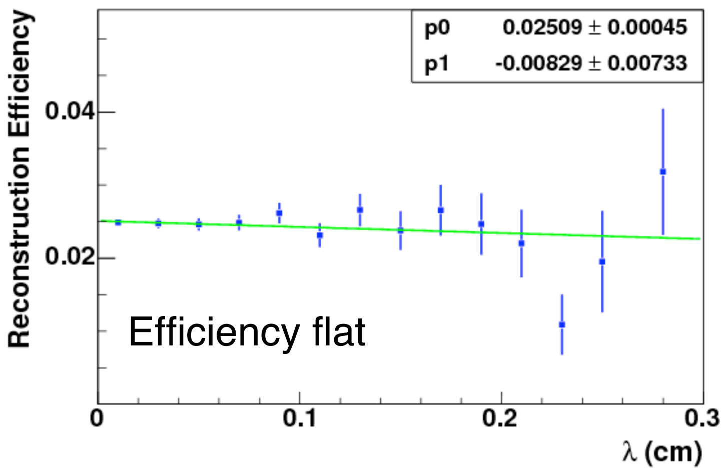
- Consistent with world average: 369 ± 22 μm (PDG2006)

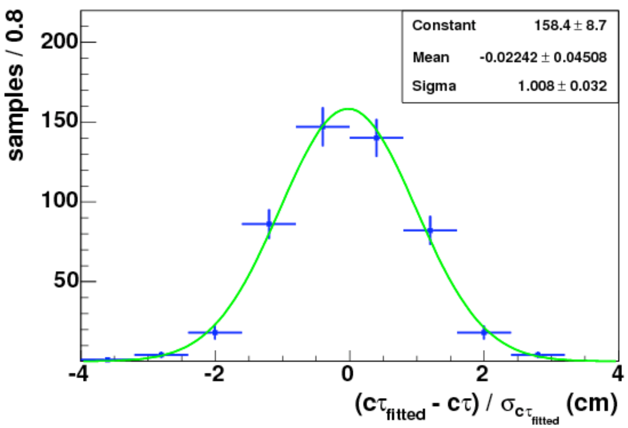
Consistency Checks

We test our fitting procedure and selection using MC signal events $\Lambda_b \rightarrow \Lambda_c^+ \mu^- \nu$:

- get 369.3 ± 5.5 μm when input 368 μm
- fitted scale factor, 0.976 ± 0.054

Toy MC studies indicate no significant bias



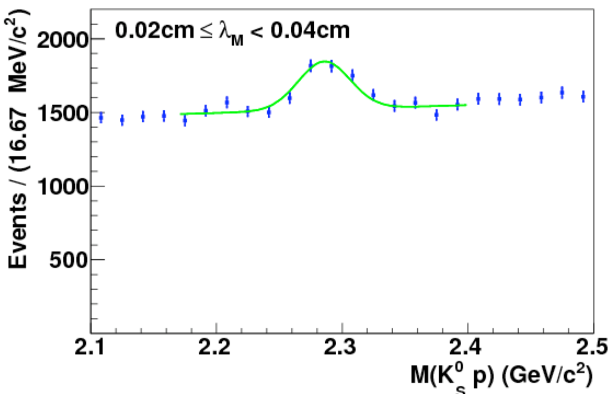


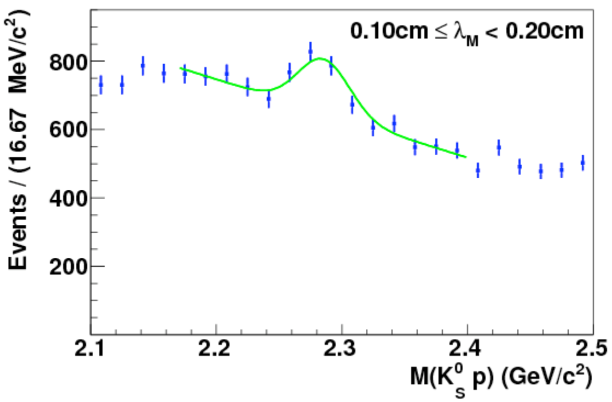
Split sample tests, consistent

Sample	$c\tau$ (μm)
Run $<$ 196000	419 ± 54
Run $>$ 196000	358 ± 57
$\eta(\mu) > 0$	381 ± 48
$\eta(\mu) < 0$	406 ± 56
$q(\mu) > 0$	381 ± 50
$q(\mu) < 0$	378 ± 49

Systematic Uncertainties

- Mass fitting
  - Redo the mass fits with different background model, over small range
  - shift bins by half bin width, remove end bins, half width bins
  - Largest observed shift of 20 μm





- Prompt/Direct ccbar
  - Vary widths and fractions by errors
  - Increase widths by 20% for resolution underestimates
- K-factor distributions
  - vary branching fractions over wide range, pT cut, differences due to kinematics/decay model estimated from previous studies - 2% change to K-factors
- Scale factor - vary by 20% to take into account errors from the study and its value when it is allowed to float
- Alignment

Systematic Uncertainty

- Possible background $B \rightarrow \Lambda_c \mu \nu X$
  - Decay has not yet been observed
  - Measured upper limit:

    $Br(B \rightarrow \Lambda_c e \nu X) < 3.2 \times 10^{-3}$ (90% CL)

  - This channel would reduce the measured lifetime since we overestimate the boost
  - Should be suppressed by branching ratio and low mass of $(\mu\Lambda_c)$ system (another baryon must be present)
  - The upper 90% CL limit on the fraction of this decay translates to a 5% contamination in this sample
  - This would reduce the Λ_b lifetime by 0.027 ps

Systematic Uncertainties

Source	Uncertainty in $\tau(\Lambda_b)$ [ps]
Detector alignment	0.018
Mass fitting	0.067
K-factor	0.036
peaking background	0.012
resolution scale factor	0.036
$B \to \mu\nu\Lambda_c X$	$^{+0.000}_{-0.027}$
Total	$^{+0.087}_{-0.091}$

Semileptonic Lifetime Result

- We measure the lifetime in the $\Lambda_b \rightarrow \Lambda_c \mu \nu X$ decay channel to be:

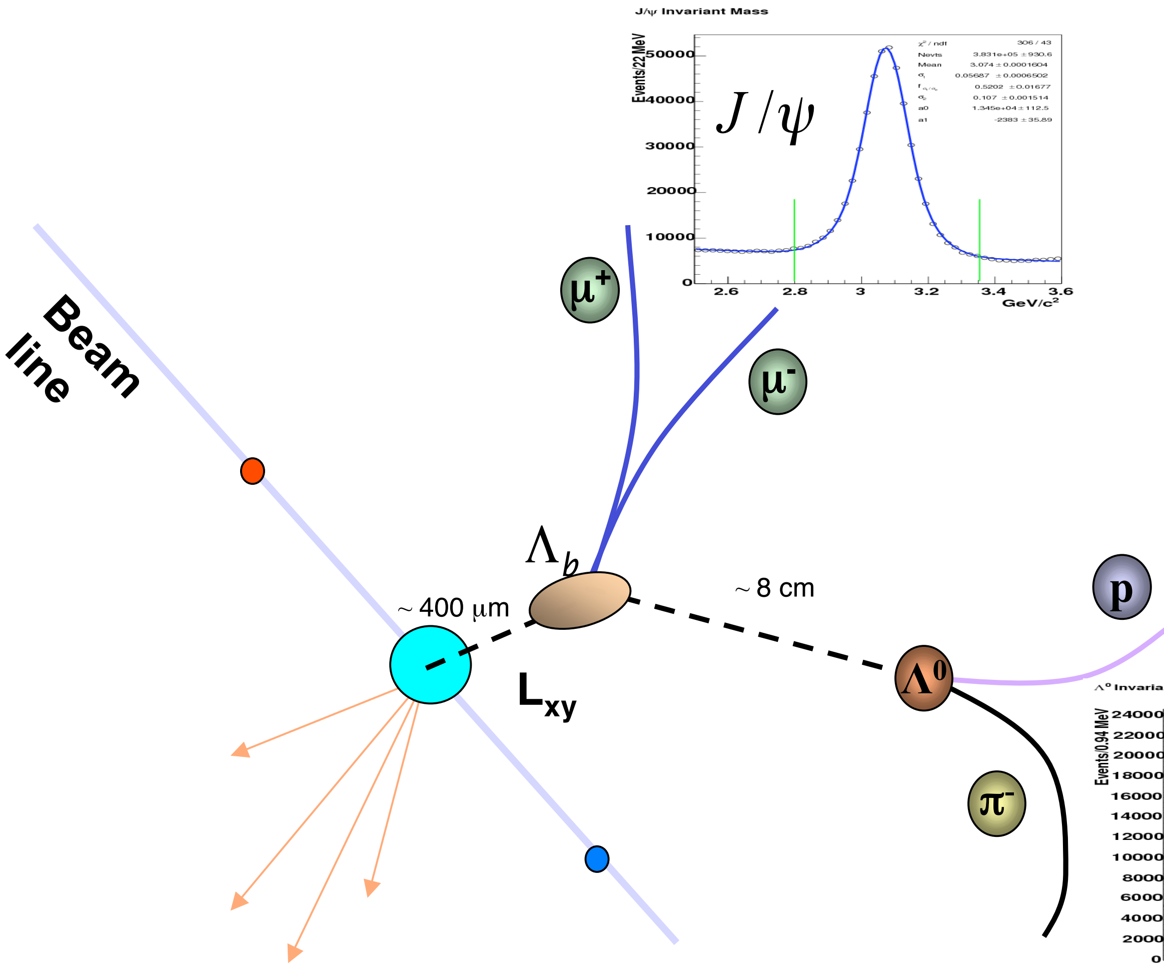
$$\tau(\Lambda_b) = 1.290^{+0.119}_{-0.110}(stat)^{+0.087}_{-0.091}(syst)\, ps$$

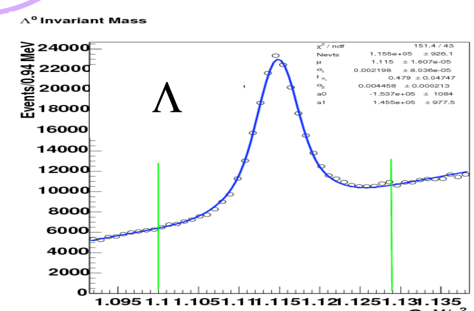
hep-ex/0706.2358

Lifetime measurement with $\Lambda_b \rightarrow J/\psi \Lambda$

$\Lambda_b \to J/\psi\Lambda$ Reconstruction

- we reconstruct $\Lambda_b \to J/\psi\Lambda$ optimizing the ratio $S/\sqrt{S+B}$





$$L_{xy} = \frac{\vec{L}_{xy} \bullet \vec{p}_T^{\,B}}{\left|\vec{p}_T^{\,B}\right|}$$

$$\lambda = \frac{L_{xy}}{(\beta\gamma)_T} = L_{xy}\frac{M_B}{p_T^B}$$

Strategy

Fitting Procedure

Signal selection:
b-hadron

λ and mass distributions

Propose models (PDFs) for λ and mass to describe data

Build likelihood function

Unbinned maximum likelihood fit

Likelihood function:

$$L = N_s S_M S_\lambda S_E + N_b \left(f_P B_{M(sh)} B_{\lambda(sh)} + (1 - f_P) B_{M(lg)} B_{\lambda(lg)} \right) B_E$$

Mass PDF

S_M – single Gaussian distribution

$$S_M(M_j) = \left(\frac{1}{\sqrt{2\pi\sigma}}\right) e^{\frac{-(M_j-\mu)^2}{2\sigma^2}}$$

$B_{M(sh)}$ – flat distribution for prompt background

$$B_{M[sh]}(M_j) = 1/(M_{\max} - M_{\min})$$

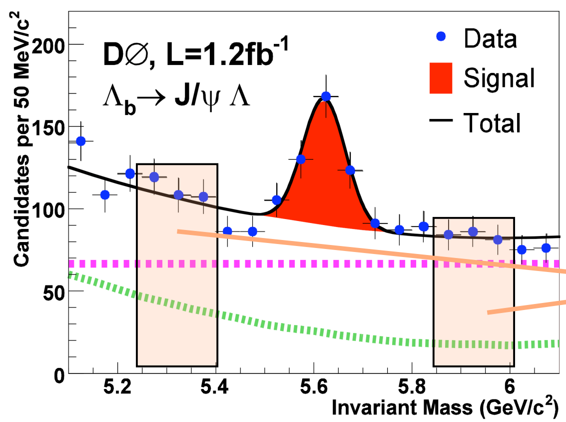
$B_{M[lg]}$ – second-order polynomial function for non-prompt background

$$B_{M[\lg]}(M_j) = \frac{1}{M_{\max} - M_{\min}}\left(1 - \frac{1}{2}A_1(M^2_{\max} - M^2_{\min}) - \frac{1}{3}A_2(M^3_{\max} - M^3_{\min})\right) + A_1 M_j + A_2 M_j^2$$

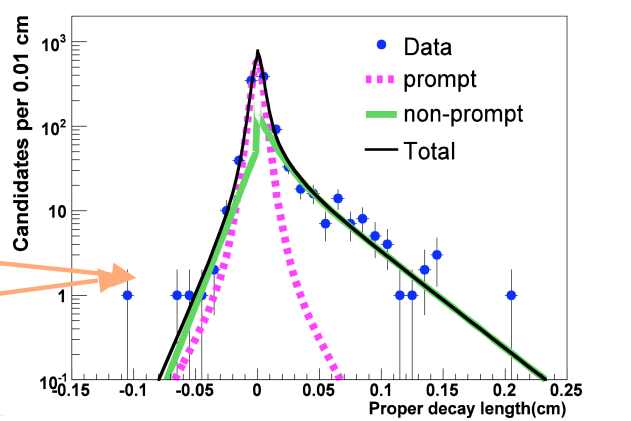
Where m, s, A_1, A_2 are free parameters of the fit;

--- Prompt component of the background, J/ψ direct production

--- Non-prompt component of the background (partial reco heavy hadrons)



Lifetime of the sidebands



Proper Decay Length PDF

- S_λ – Convolution of exponential decay and resolution function

$$S_{LF}(\lambda_j, \sigma_{\lambda_j}) = \frac{1}{\lambda_B \sqrt{2\pi} s \sigma_j} \int_0^\infty Exp\left(-\frac{(x-\lambda_j)^2}{2(s\sigma_j)^2}\right) Exp\left(-\frac{x}{\lambda_B}\right) dx$$

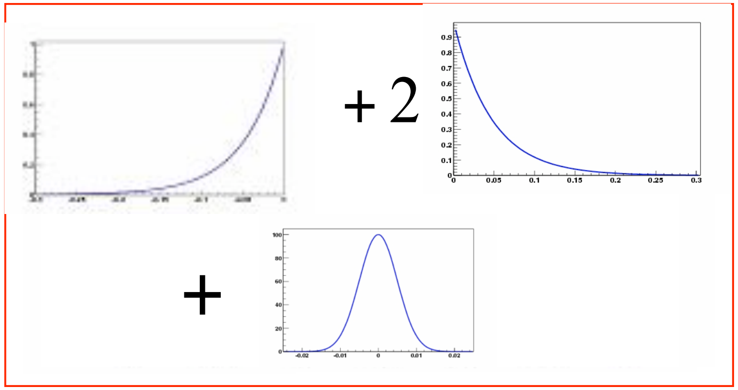
Where $\lambda_B = c\tau(\Lambda_b)$, s-scale factor, σ_j is event-per-event uncertainty

- B_λ – Prompt component
- Resolution function

Non-prompt component

- Short - lived component
  - Negative and Positive exp. Decay
- Long - lived component
  - Positive exp. decay

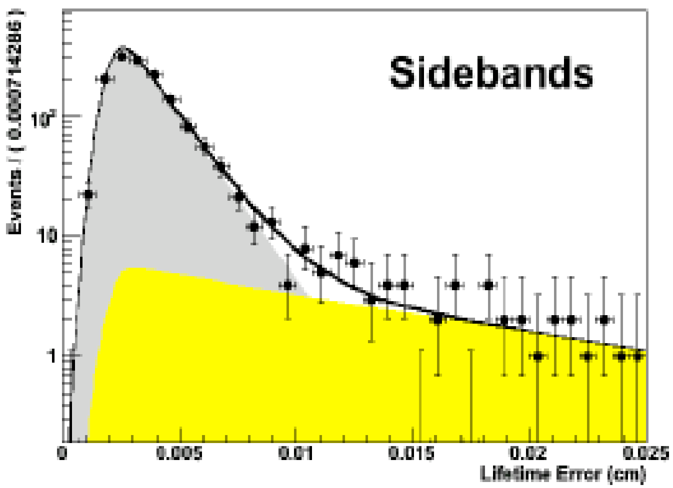
Models:

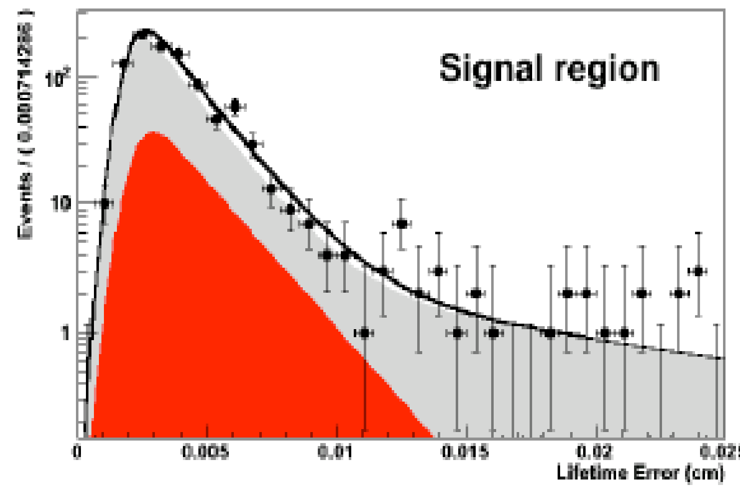


$$B_{\lambda[\mathrm{lg}]}(\lambda_j, \sigma_j) = \begin{cases} \frac{f_1^+}{\lambda_1^+} e^{-\frac{\lambda_j}{\lambda_1^+}} + \frac{f_2^+}{\lambda_2^+} e^{-\frac{\lambda_j}{\lambda_2^+}} & (\lambda_j \geq 0) \\ \frac{(1 - f_0 - f_1^+ - f_2^+)}{\lambda_2^+} e^{-\frac{\lambda_j}{\lambda^-}} & (\lambda_j < 0) \end{cases}$$

PDF of $\sigma(\lambda)$ uncertainty

- Distribution of uncertainty of λ for Signal and Background looks different



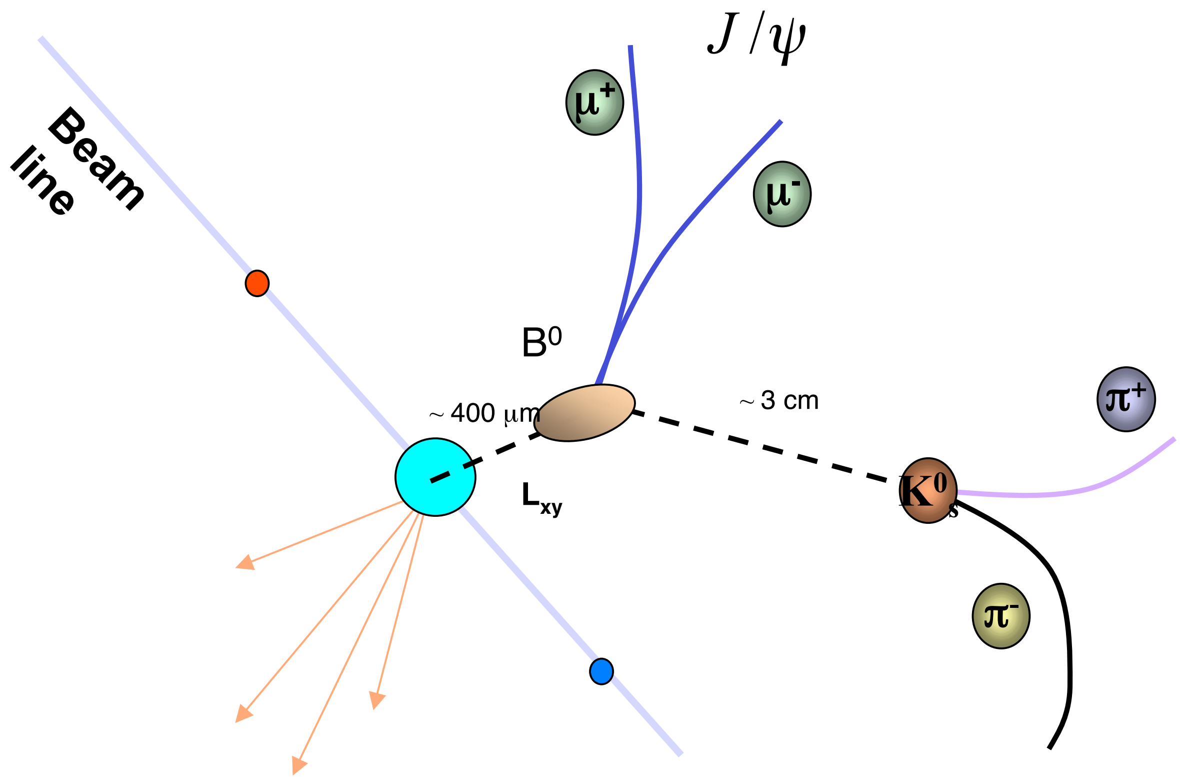


- First, the $\sigma(\lambda)$ uncertainty distribution of the background region is fitted $\rightarrow$ fix all parameters and fit signal region (Ns – from the fit of mass distribution) $\rightarrow$ fix all parameters to fit data

Lifetime of B^0

Similar topology: $B^0 \rightarrow J/\psi(\mu^+\mu^-)\ K^0_s(\pi^+\pi^-)$

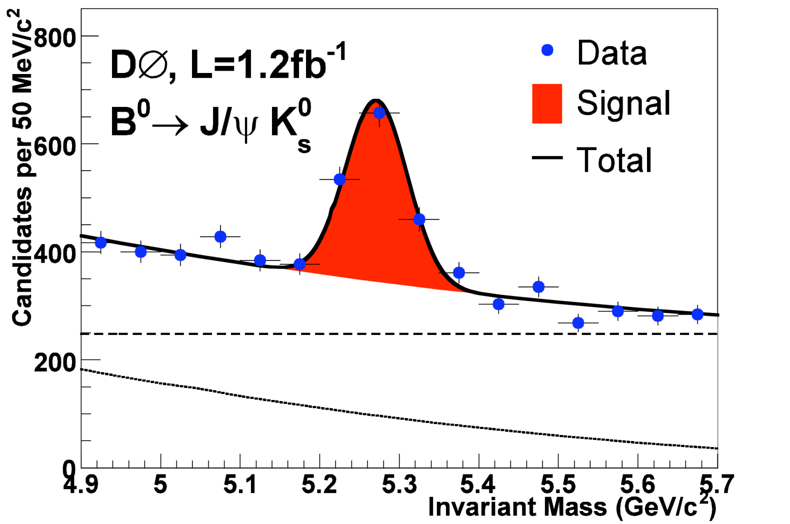
just replace Λ with K_s^0

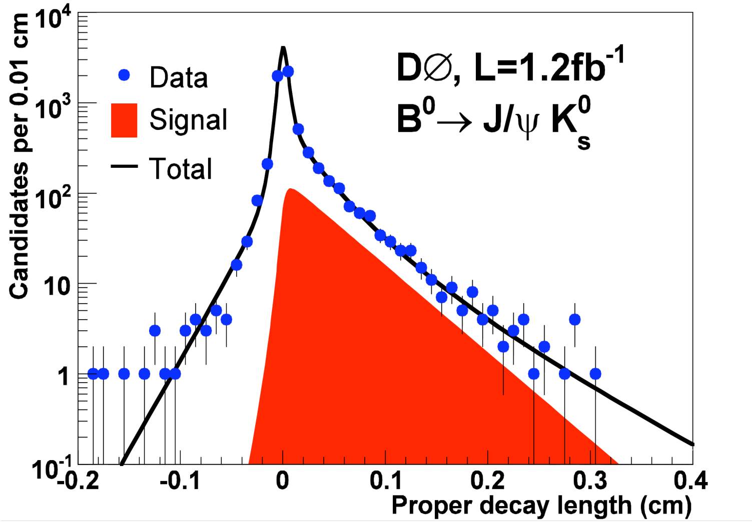


Used as control sample

Lifetime of B^0

Similar topology: $B^0 \to J/\psi(\mu^+\mu^-)\, K^0_s(\pi^+\pi^-)$





For B^0 in the decay channel $B^0 \to J/\psi K^0_s$: $N_s = 717.1 \pm 37.7$

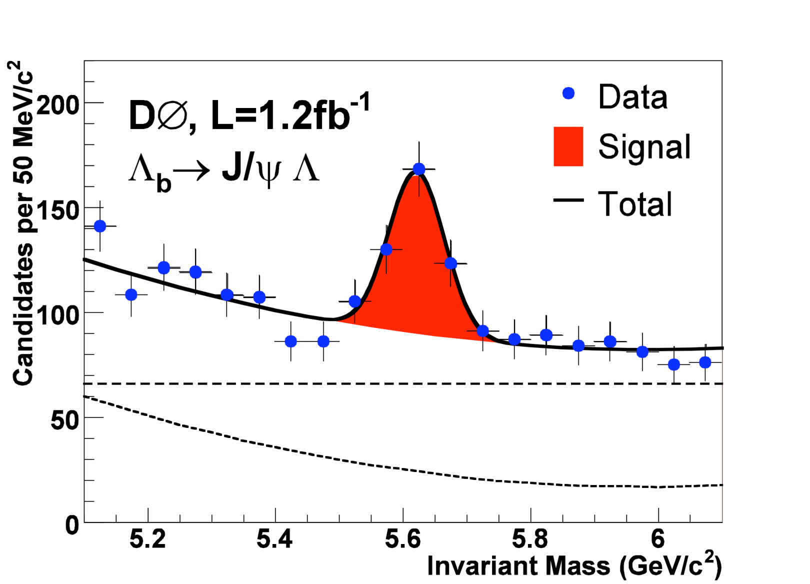
$$c\tau(B^0) = 450.0^{+23.5}_{-22.1}(stat) \pm 14.9(syst)\,\mu m$$

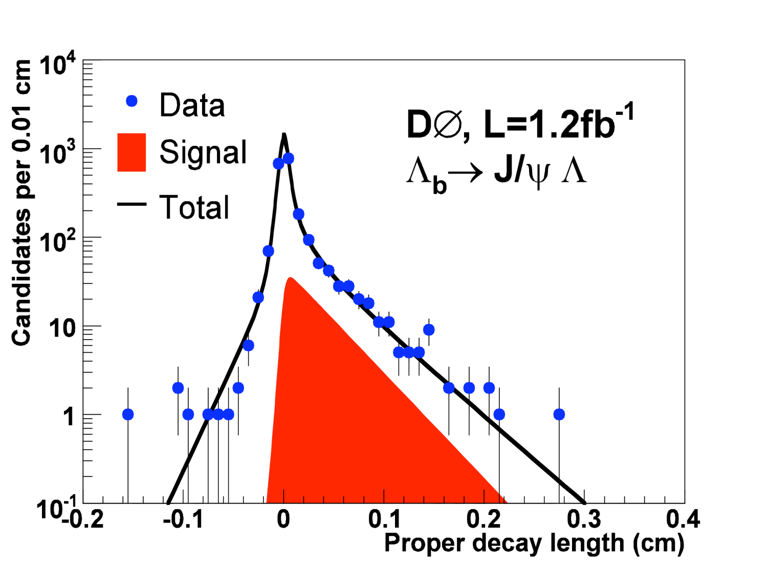
$$\tau(B^0) = 1.501^{+0.078}_{-0.074}(stat) \pm 0.050(syst)\,ps$$

hep-ex/0704.3909

PDG 2006: $\tau(B^0) = 1.530 \pm 0.009\,ps$

Exclusive Λ_b Lifetime





For Λ_b in the decay channel $\Lambda_b \rightarrow J/\psi\Lambda$: $N_s = 171.3 \pm 20.0$

$$c\tau(\Lambda_b) = 365.1^{+39.1}_{-34.7}(stat) \pm 12.7(syst)\,\mu m$$

$$\tau(\Lambda_b) = 1.218^{+0.130}_{-0.115}(stat) \pm 0.042(syst)\,ps$$

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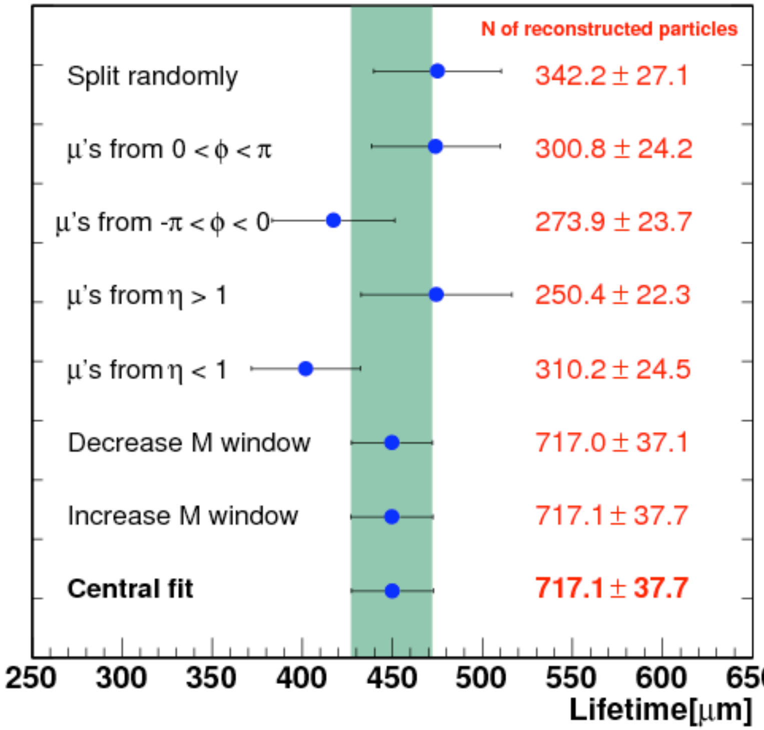
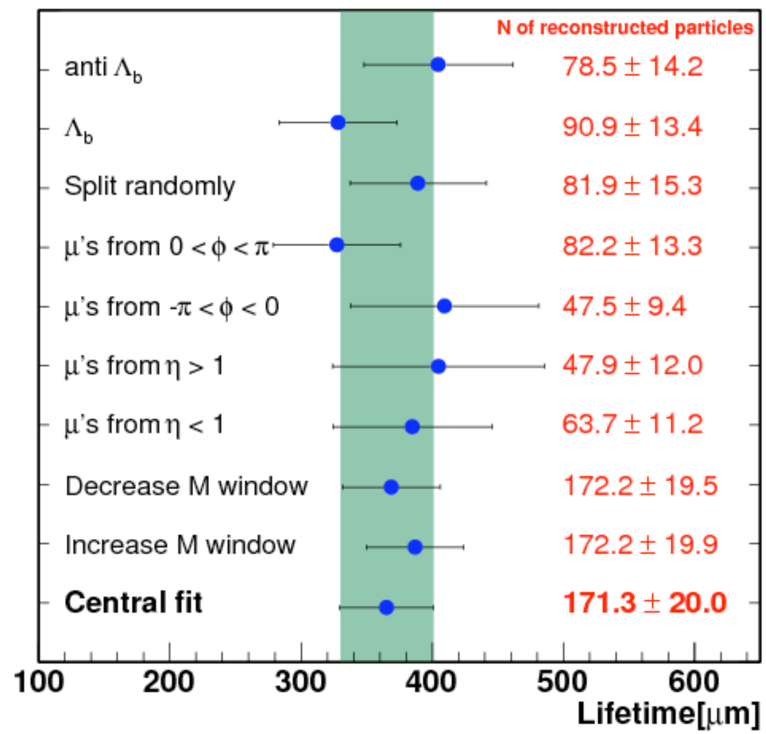
PDG 2006: $\tau(\Lambda_b) = 1.230 \pm 0.074\,ps$

Consistency Checks



Split sample technique, all tests are consistent



Systematic Uncertainties

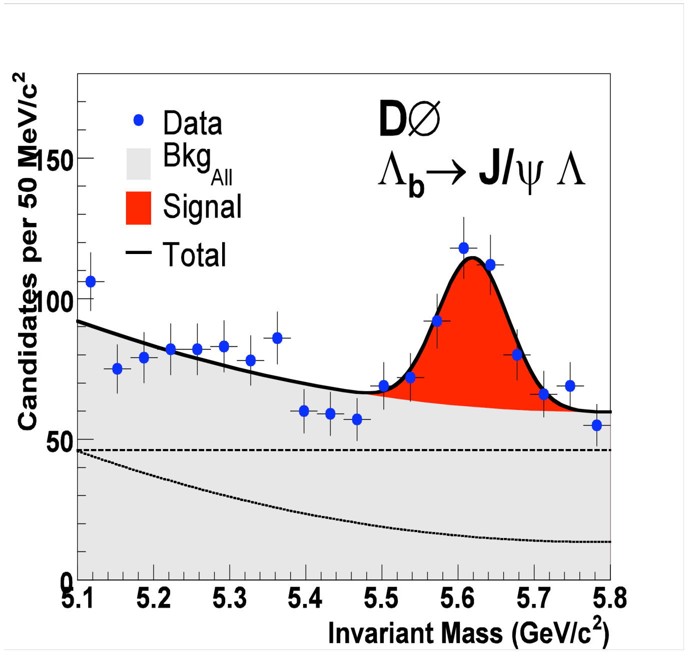
Sources	B^0 (μm)	Λ_b (μm)	Ratio
Alignment	5.4	5.4	0.002
Distribution models	2.8	6.6	0.020
Long-lived components	13.6	6.0	0.022
Contamination	-	7.2	0.016
Total syst.	14.9	12.7	0.034
Stat.	$^{+23.5}_{-22.1}$	$^{+39.1}_{-34.7}$	$^{+0.096}_{-0.087}$

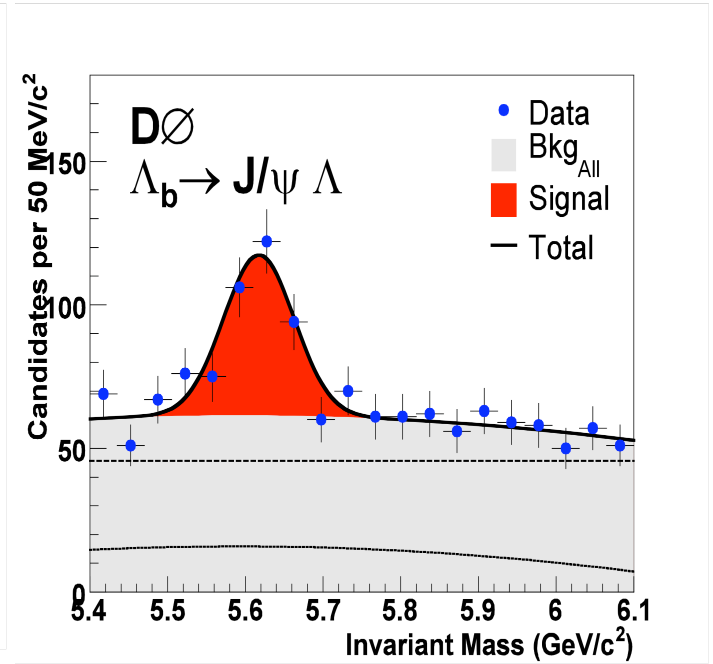
Lifetime ratio $\tau(\Lambda_b)/\tau(B^0)$ is also evaluated since very similar topology, many systematic uncertainties will tend to cancel out

Uncertainties on the lifetime ratio $\tau(\Lambda_b)/\tau(B^0)$ are propagated using standard methods

Long-lived Background Composition

- Difference between the events in the low and high mass background regions:
  - Separate fit to each mass regions of 5.1-5.8 and 5.4-6.1 GeV (Λ_b)





Mass regions (GeV/c^2)	Value (μm)
5.1-5.8	359.1 ± 34.2
5.4-6.1	365.8 ± 37.2

- As systematic uncertainty, take the largest difference to the central fit in absolute value

Λ_b/B^0 lifetime measurement

B^0 and Λ_b measurement using full reconstructed decay channels are:

$$\tau(\Lambda_b) = 1.218^{+0.130}_{-0.115}(stat) \pm 0.042(syst)\, ps$$

$$\tau(B^0) = 1.501^{+0.078}_{-0.074}(stat) \pm 0.050(syst)\, ps$$

While the lifetime ratio is:

$$\frac{\tau(\Lambda_b)}{\tau(B^0)} = 0.811^{+0.096}_{-0.087}(stat) \pm 0.034(syst)$$

hep-ex/0704.3909

Combined DØ Measurements and Comparisons

Lifetime results

- We measured the lifetime in the $\Lambda_b \to \Lambda\, J/\psi$ decay channel to be: hep-ex/0704.3909

$$\tau(\Lambda_b) = 1.218^{+0.130}_{-0.115}\,(stat) \pm 0.042\,(syst)\,ps$$

- Consistent with the Dzero measurement in the $\Lambda_b \to \Lambda_c \mu\nu X$ decay channel

$$\tau(\Lambda_b) = 1.290^{+0.119}_{-0.110}\,(stat)^{+0.087}_{-0.091}\,(syst)\,ps$$

- The two measurements of the Λ_b lifetime presented are statistically independent and the correlation of systematics between them is very small, combine:

$$\tau(\Lambda_b) = 1.251^{+0.102}_{-0.096}\,ps$$

hep-ex/0706.2358

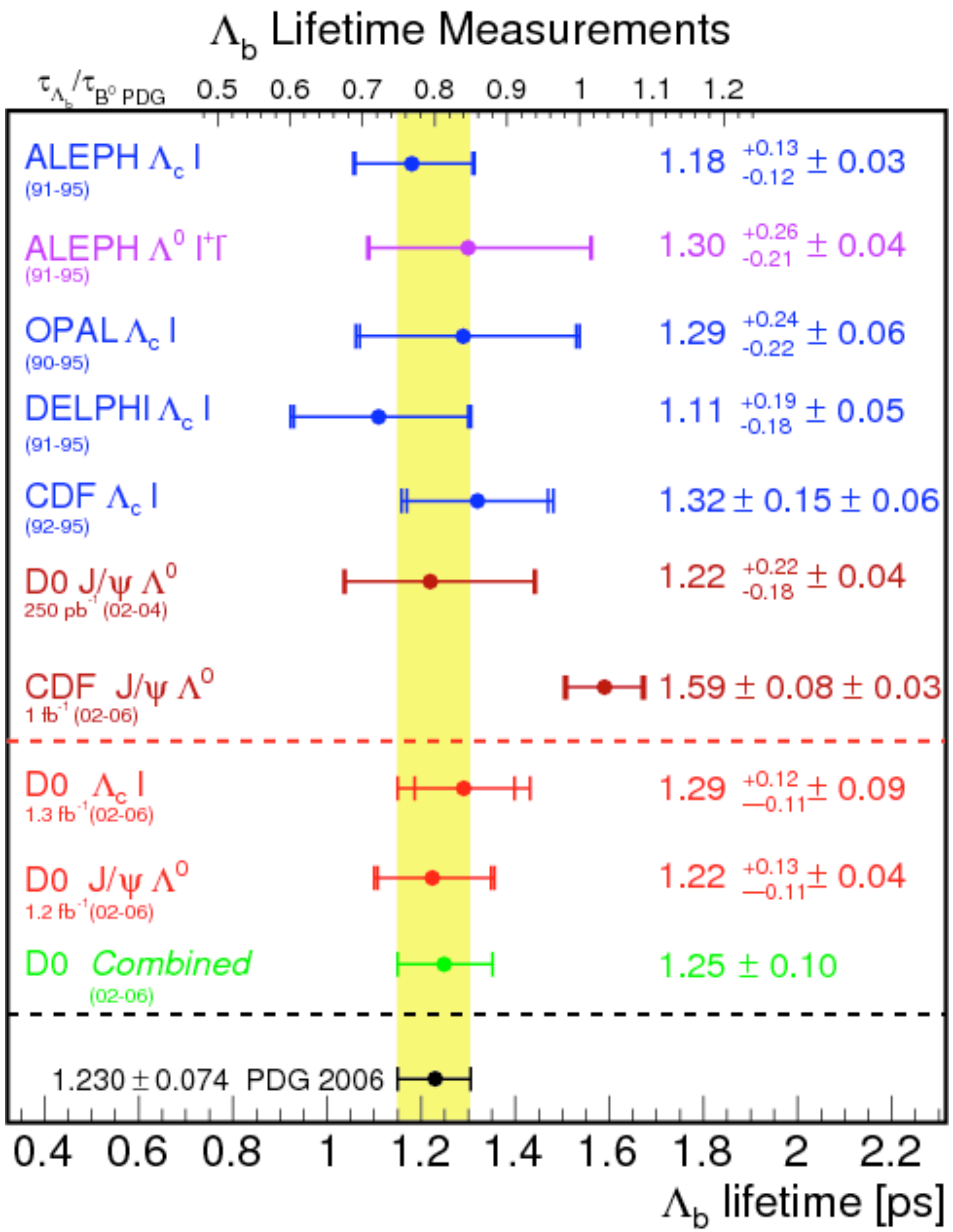
- Consistent with world average (PDG 2006):

$$\tau(\Lambda_b) = 1.230 \pm 0.074\,ps$$

- CDF 1fb^{-1} result: hep-ex/0609021 accepted by PRL

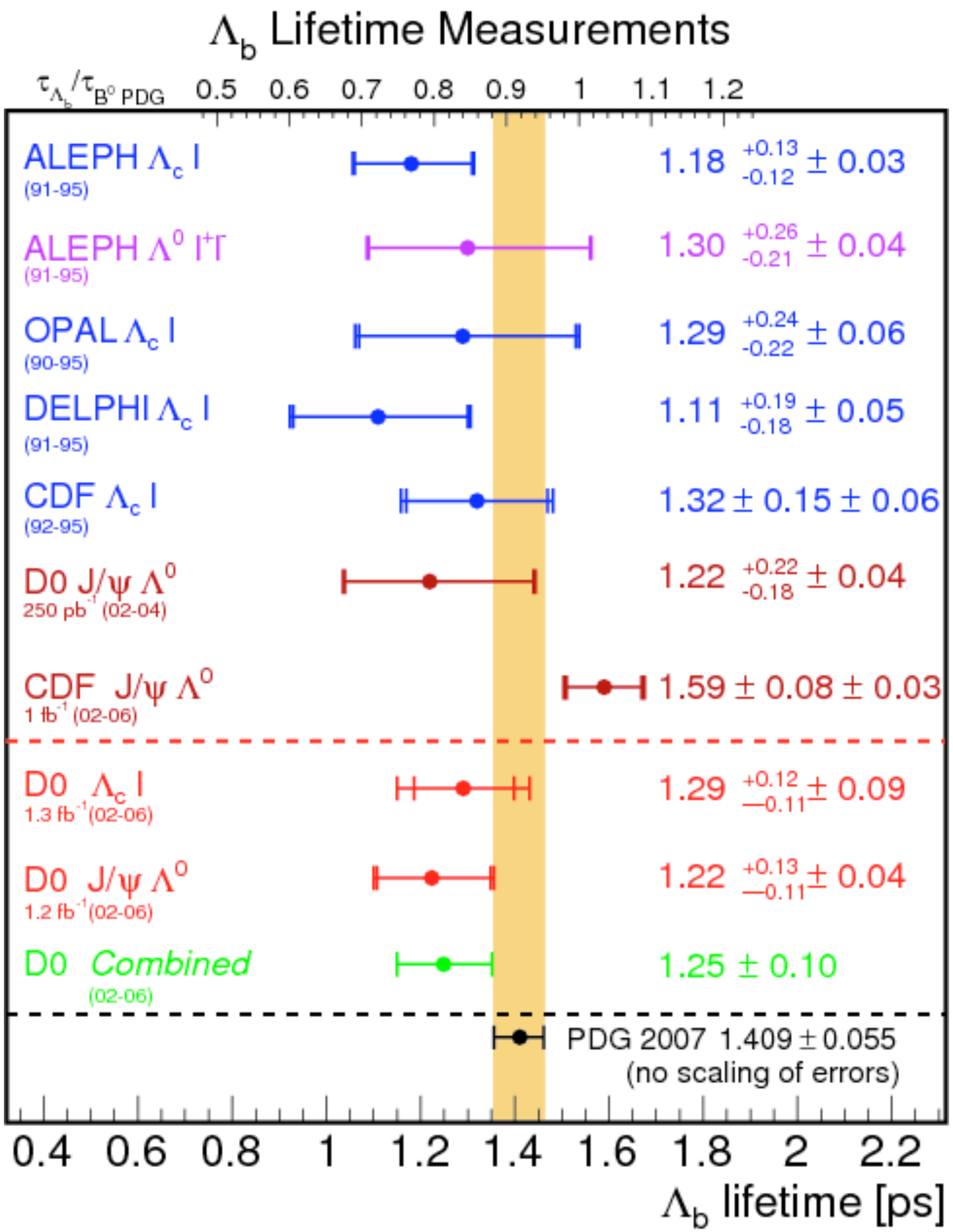
$$\tau(\Lambda_b) = 1.593^{+0.083}_{-0.078}\,(stat) \pm 0.033\,(syst)\,ps$$

2.6σ above our combined measurement



Not in PDG averages

Not in
PDG
averages



Summary

- We have measured the lifetime of the Λ_b baryon using two different decay channels

hep-ex/0704.3909

  - $J/\psi\Lambda$

$$\tau(\Lambda_b) = 1.218^{+0.130}_{-0.115}(stat) \pm 0.042(syst)\,ps$$

  - $\Lambda_c\mu\nu$

$$\tau(\Lambda_b) = 1.290^{+0.119}_{-0.110}(stat)^{+0.087}_{-0.091}(syst)\,ps$$

hep-ex/0706.2358

- combined Dzero result

$$\tau(\Lambda_b) = 1.251^{+0.102}_{-0.096}\,ps$$

- Consistent with World average measurement (PDG 2006)

$$\tau(\Lambda_b) = 1.230 \pm 0.074\,ps$$