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Measurement of the  $\Lambda_b^0$  lifetime using semileptonic decays

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We report a measurement of the  $\Lambda_b^0$  lifetime using a sample corresponding to  $1.3 \text{ fb}^{-1}$  of data collected by the D0 experiment in 2002–2006 during Run II of the Fermilab Tevatron collider. The  $\Lambda_b^0$  baryon is reconstructed via the decay  $\Lambda_b^0 \rightarrow \mu\bar{\nu}\Lambda_c^+ X$ . Using  $4437 \pm 329$  signal candidates, we measure the  $\Lambda_b^0$  lifetime to be  $\tau(\Lambda_b^0) = 1.290_{-0.110}^{+0.119} \text{ (stat)}_{-0.091}^{+0.087} \text{ (syst)}$  ps, which is among the most precise measurements in semileptonic  $\Lambda_b^0$  decays. This result is in good agreement with the world average value.

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Lifetimes of  $b$  hadrons provide an important test of models describing quark interaction within bound states. The experimental measurement of the lifetimes are in reasonable agreement with the theoretical predictions [1, 2, 3], but further improvement in the experimental and theoretical precision is essential for the development of non-perturbative quantum chromodynamics.

The lifetime of  $b$  baryons recently attracted a special interest. The current world average  $\Lambda_b^0$  lifetime is  $\tau(\Lambda_b^0) = 1.230 \pm 0.074$  ps, and the ratio of the  $\Lambda_b^0$  baryon and  $B^0$  meson lifetimes is  $\tau(\Lambda_b^0)/\tau(B^0) = 0.80 \pm 0.05$  [4], in good agreement with the theoretical prediction  $\tau(\Lambda_b^0)/\tau(B^0) = 0.86 \pm 0.05$  [3]. However, the recent  $\Lambda_b^0$  lifetime measurement from the CDF collaboration in the  $\Lambda_b^0 \rightarrow J/\psi\Lambda$  decay gives a significantly larger value:  $\tau(\Lambda_b^0) = 1.593_{-0.078}^{+0.083} \pm 0.033$  ps [5], not included in the quoted world average. Additional  $\Lambda_b^0$  lifetime measurements could provide a potential resolution of this inconsistency.

This Letter presents a measurement of the  $\Lambda_b^0$  lifetime using the semileptonic decay  $\Lambda_b^0 \rightarrow \mu\bar{\nu}\Lambda_c^+ X$ , where  $X$  is any other particle. Charge conjugated states are implied throughout this paper. The  $\Lambda_c^+$  baryon is selected in the decay  $\Lambda_c^+ \rightarrow K_S^0 p$ . The sample corresponds to approximately  $1.3 \text{ fb}^{-1}$  of data collected by the D0 experiment in Run II of the Fermilab Tevatron Collider.

The D0 detector is described in detail elsewhere [6]. The components most important to this analysis are the central tracking and muon systems. The central tracking system consists of a silicon microstrip tracker and a central fiber tracker, both located within a 2 T superconducting solenoidal magnet, with designs optimized for tracking and vertexing at pseudorapidities  $|\eta| < 3$  and  $|\eta| < 2.5$  respectively (where  $\eta = -\ln[\tan(\theta/2)]$  and  $\theta$  is the polar angle of the particle with respect to the proton beam direction). The muon system is located outside the calorimeters and has pseudorapidity coverage  $|\eta| < 2$ . It consists of a layer of tracking detectors and scintillation trigger counters in front of 1.8 T iron toroids, followed by two similar layers after the toroids [7]. The trigger system identifies events of interest in a high-luminosity environment based on muon identification and charged tracking. Some triggers require a large impact parameter for the muon. Since this condition biases the lifetime measurement, the events selected exclusively by these triggers are removed from our sample. All processes and decays required for this analysis are simulated using the EVTGEN

[8] generator interfaced to PYTHIA [9] and followed by full modeling of the detector response using GEANT [10] and event reconstruction.

Reconstruction of the  $\Lambda_b^0$  decay starts from the selection of a muon, which must have at least two track segments in the muon chambers associated with a central track, with transverse momentum  $p_T > 2.0 \text{ GeV}/c$ . All charged particles in the event are clustered into jets using the Durham clustering algorithm [11]. The products of the  $\Lambda_c^+$  decay are then searched for among tracks belonging to the jet containing the identified muon.

The primary vertex is determined using the method described in Ref. [12]. The  $K_S^0$  meson is reconstructed as a combination of two oppositely charged tracks that have a common vertex displaced from the  $p\bar{p}$  interaction point by at least four standard deviations of the measured decay length in the plane perpendicular to the beam direction. Both tracks are assigned the pion mass and the mass of the  $\pi^+\pi^-$  system is required to be consistent with the  $K_S^0$  mass to within 1.8 standard deviations. Combinations consistent with the  $\Lambda \rightarrow p\pi$  hypothesis, when either track is assigned the proton mass and the mass of the  $p\pi$  system lies between 1.109 and 1.120  $\text{GeV}/c^2$ , are rejected. Any other charged track in the jet with  $p_T > 1.0 \text{ GeV}/c$  and at least two hits in the silicon detector is assigned the proton mass and combined with the neutral extrapolated  $K_S^0$  candidate to form a  $\Lambda_c^+$  candidate. Their common vertex is required to have a fit  $\chi^2/\text{d.o.f.} < 9/1$ . The  $\Lambda_c^+$  candidate is combined with the muon to make a  $\Lambda_b^0$  candidate, and its invariant mass is required to be between 3.4 and 5.4  $\text{GeV}/c^2$ . A common vertex for the  $\Lambda_c^+$  candidate and muon is required to have a fit  $\chi^2/\text{d.o.f.} < 9/1$ . The transverse distance  $d_T^{bc}$  between the  $\Lambda_b^0$  and  $\Lambda_c^+$  vertices is calculated and is assigned a positive sign if the  $\Lambda_b^0$  vertex is closer to the primary vertex, and a negative sign otherwise. The  $\Lambda_b^0$  candidate is required to have  $-3.0 < d_T^{bc}/\sigma(d_T^{bc}) < 3.3$ , where  $\sigma(d_T^{bc})$  is the uncertainty of the  $d_T^{bc}$  measurement. The upper bound on the distance between  $\Lambda_b^0$  and  $\Lambda_c^+$  vertices reduces the background significantly, since the  $\Lambda_c^+$  lifetime is known to be very small:  $0.200 \pm 0.006$  ps [4].

To further improve the  $\Lambda_b^0$  signal selection, a likelihood ratio method [13] is utilized. This method provides a simple way to combine many discriminating variables into a single variable with an increased power to separate signal and background. The variables chosen for this analysis

are the  $\Lambda_b^0$  isolation, the transverse momentum of the  $K_S^0$ , proton and  $\Lambda_c^+$  candidates, and the mass of the  $\mu\Lambda_c^+$  system. The isolation is defined as the fraction of the total momentum of charged particles within a cone around the  $\mu\Lambda_c^+$  direction carried by the  $\Lambda_b^0$  candidate. The cone is defined by the condition  $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.5$ , where  $\Delta\eta$  and  $\Delta\phi$  are the difference in pseudorapidity and azimuthal angle from the direction of the  $\Lambda_b^0$  candidate.

Figure 1 shows the invariant mass  $M(K_S^0 p)$  for the selected  $\Lambda_b^0$  candidates. The fit to this distribution is performed with a signal Gaussian function and a fourth-order polynomial function for the background. The  $\Lambda_c^+$  signal contains  $4437 \pm 329$  (stat) events at a central mass of  $2285.8 \pm 1.7$  MeV/ $c^2$ . The width of the mass peak is  $\sigma = 20.6 \pm 1.7$  MeV/ $c^2$  consistent with that observed in the simulation.

Simulation shows that the contribution from the  $B_d \rightarrow K_S^0 \pi$  decay when a pion is assigned the proton mass has a broad  $M(K_S^0 p)$  distribution with no excess in the  $\Lambda_c^+$  mass region.

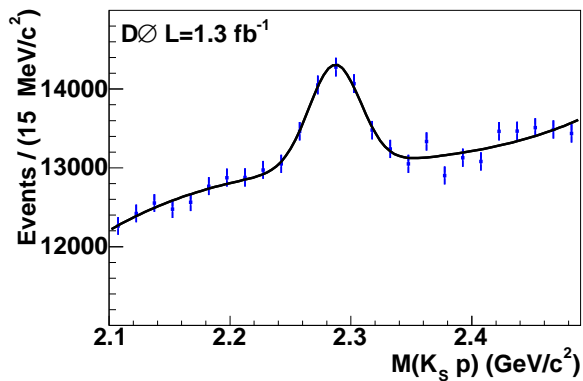


FIG. 1: The  $K_S^0 p$  invariant mass for the selected  $\Lambda_b^0$  candidates and fit overlaid (see text). Notice the suppressed-zero scale of the vertical axis.

Since the final state is not fully reconstructed, the  $\Lambda_b^0$  proper decay length cannot be determined. Instead, a measured visible proper decay length  $\lambda^M$  is computed as  $\lambda^M = mc(\mathbf{L}_T \cdot \mathbf{p}_T(\mu\Lambda_c^+)) / |\mathbf{p}_T(\mu\Lambda_c^+)|^2$ .  $\mathbf{L}_T$  is the vector from the primary vertex to the  $\Lambda_b^0$  vertex in the plane perpendicular to the beams,  $\mathbf{p}_T(\mu\Lambda_c^+)$  is the transverse momentum of the  $\mu\Lambda_c^+$  system and  $m = 5.624$  GeV/ $c^2$  is taken as the  $\Lambda_b^0$  mass [4].

To determine the  $\Lambda_b^0$  lifetime, the selected sample is split into a number of  $\lambda^M$  bins. The mass distribution in each bin is fitted with a signal Gaussian and a fourth degree polynomial background. The position and width of the Gaussian are fixed to the values obtained from the fit of the entire sample (see Fig. 1). The Gaussian normalization and background parameters are allowed to float in the fit. The range of  $\lambda^M$  and the number of signal

events fitted in each bin  $n_i$  together with its statistical uncertainty  $\sigma_i$  are shown in Table I.

TABLE I: Fitted signal yield in different  $\lambda^M$  bins

$\lambda^M$ range(cm)	Number of signal candidates $n_i \pm \sigma_i$ (stat)
[-0.06, -0.04]	$62 \pm 48$
[-0.04, -0.02]	$66 \pm 69$
[-0.02, 0.00]	$587 \pm 156$
[0.00, 0.02]	$1172 \pm 173$
[0.02, 0.04]	$999 \pm 99$
[0.04, 0.06]	$540 \pm 69$
[0.06, 0.08]	$299 \pm 54$
[0.08, 0.10]	$225 \pm 44$
[0.10, 0.20]	$454 \pm 64$
[0.20, 0.30]	$47 \pm 34$

The expected number of signal events in each bin  $n_i^e$  is given by  $n_i^e = N_{tot} \int_i f(\lambda^M) d\lambda^M$ , where  $N_{tot}$  is the total number of  $\mu\Lambda_c^+$  events, and  $f(\lambda^M)$  is the probability density function (*pdf*) for  $\lambda^M$ . The integration is done within the range of a given bin.

In addition to  $\Lambda_b^0 \rightarrow \mu\bar{\nu}\Lambda_c^+ X$  decays, the  $\Lambda_c^+$  baryon can also be created in  $c\bar{c}$  or  $b\bar{b}$  production, along with a muon from the decay of the second  $c$  or  $b$  hadron. In what follows, these processes are referred to as *peaking background*, since they produce a  $\Lambda_c^+$  peak in the  $K_S^0 p$  mass spectrum imitating the signal. Such events are reconstructed as  $\Lambda_b^0$  candidates, and have a fake vertex formed by the intersection of the muon and  $\Lambda_c^+$  trajectories. The simulation shows that the distribution of  $\lambda^M$  for such a fake vertex has a mean of zero and a standard deviation of  $\approx 150$   $\mu\text{m}$ .

The expression for  $f(\lambda^M)$  takes into account the contribution of signal and peaking background:  $f(\lambda^M) = (1 - r_{\text{bck}})f_{\text{sig}}(\lambda^M) + r_{\text{bck}}f_{\text{bck}}(\lambda^M)$ . Here  $r_{\text{bck}}$  is the fraction of peaking background, and  $f_{\text{sig}}(\lambda^M)$  and  $f_{\text{bck}}(\lambda^M)$  are the *pdf*s for signal and background respectively. The background *pdf* is taken from the simulation. The signal *pdf* is expressed as the convolution of the decay probability and the detector resolution:  $f_{\text{sig}}(\lambda^M) = \int dK H(K) [\theta(\lambda)K/(c\tau) \exp(-K\lambda/(c\tau)) \otimes R(\lambda^M - \lambda, s)]$ . Here,  $\tau$  is the  $\Lambda_b^0$  lifetime, and  $\theta(\lambda)$  is the step function. The factor  $K = p_T(\mu\Lambda_c^+)/p_T(\Lambda_b^0)$  is a measure of the difference between the measured  $p_T(\mu\Lambda_c^+)$  and true momentum of the  $\Lambda_b^0$  candidate, and  $H(K)$  is its *pdf*. The  $R(\lambda^M - \lambda, s)$  is a function modeling the detector resolution. A scale factor  $s$  accounts for the difference between the expected and actual  $\lambda^M$  resolution.

The  $H(K)$  distribution is obtained from the simulation. The contribution of decays  $\Lambda_b^0 \rightarrow \mu\bar{\nu}\Lambda_c^+$  and  $\Lambda_b^0 \rightarrow \mu\bar{\nu}\Sigma_c\pi$  with  $\Sigma_c \rightarrow \Lambda_c^+\pi$  is taken into account. The contributions of  $\Lambda_b^0 \rightarrow \Lambda_c^+ D_s^{(*)-}$  with the  $D_s^-$  decaying semileptonically,  $\Xi_b \rightarrow \mu\bar{\nu}\Lambda_c X$  and  $\Lambda_b^0 \rightarrow \tau^-\bar{\nu}\Lambda_c^+$  with  $\tau^- \rightarrow \mu^-\bar{\nu}_\mu\nu_\tau$  are found to be strongly suppressed by the branching fractions and low reconstruction efficiency. To

obtain  $H(K)$ , the  $K$  factor distribution of each process is weighted with its expected fraction in the selected sample. This is computed taking into account both the reconstruction efficiency and the branching fraction of each process. The fraction of  $\ell^- \bar{\nu} \Lambda_c^+$  in semileptonic  $\Lambda_b^0$  decays has been measured recently to be  $0.47_{-0.10}^{+0.12}$  [4]. We use this result in our analysis.

The resolution function is given by  $R(\lambda^M - \lambda, s) = \int f_{\text{res}}(\sigma) G(\lambda^M - \lambda, \sigma, s) d\sigma$ , where  $f_{\text{res}}(\sigma)$  is the *pdf* for the expected resolution of  $\lambda^M$ , and  $G$  is a Gaussian function  $G(\lambda^M - \lambda, \sigma, s) = 1/(\sqrt{2\pi}\sigma s) \exp[-(\lambda^M - \lambda)^2/(2\sigma^2 s^2)]$ . The  $\sigma_s$  is the decay length uncertainty, which is determined for each candidate from the track parameter uncertainties propagated to the vertex uncertainties.

To determine  $f_{\text{res}}(\sigma)$ , signal and background subsamples are defined according to the mass of the  $K_S^0 p$  system. All events with  $2244.7 < M(K_S^0 p) < 2326.9$  MeV/ $c^2$  are included in the signal subsample, and all events with  $2183.9 < M(K_S^0 p) < 2225.0$  MeV/ $c^2$  and  $2346.6 < M(K_S^0 p) < 2387.7$  MeV/ $c^2$  are included in the background subsample. In addition, the events in both subsamples are required to have a measured proper decay length exceeding 200  $\mu\text{m}$ . This cut reduces the background under the  $\Lambda_c^+$  signal and the contribution of peaking background. The  $f_{\text{res}}(\sigma)$  distribution is obtained by subtracting the distribution of expected resolution in the background subsample from the distribution in the signal subsample.

The  $\Lambda_b^0$  lifetime is determined by the minimization of  $\chi^2 = \sum_i^{N_{\text{bins}}} (n_i - n_i^e)^2 / \sigma_i^2$ , where the sum is taken over all bins of measured proper decay length (Table I). The free parameters of the fit are  $N_{\text{tot}}$ ,  $\tau(\Lambda_b^0)$  and  $r_{\text{bck}}$ . A separate study is performed to measure the resolution scale factor using the decay  $D^{*+} \rightarrow D^0 \pi^+$  with  $D^0 \rightarrow \mu^+ \nu K_S^0 \pi^-$ . It has a similar topology to that of the  $\Lambda_b^0 \rightarrow \mu \bar{\nu} \Lambda_c^+$  decay. Since the  $D^{*+}$  meson comes mainly from  $c\bar{c}$  production, its decay vertex coincides with the primary interaction point. The distribution of the  $D^{*+}$  proper decay length is mainly determined by the detector resolution and can be used to measure the resolution scale factor. A value of  $1.19 \pm 0.06$  is found. The scale factor in the lifetime fit is fixed to this value and varied later in a wide range to estimate an associated systematic uncertainty.

The lifetime fit gives  $\tau(\Lambda_b^0) = 1.290_{-0.110}^{+0.119}$  (stat) ps, and the fraction of peaking background  $r_{\text{bck}} = 0.160_{-0.074}^{+0.068}$  (stat). Figure 2 shows the distribution of the number of  $\Lambda_c^+ \mu$  events versus  $\lambda^M$  together with the result of the lifetime fit superimposed. The lifetime model agrees well with data with a  $\chi^2/\text{d.o.f.} = 5.5/7$ . The dashed line shows separately the contribution of the peaking background.

The method used to fit the mass distribution in each of the  $\lambda^M$  bins is the most significant source of systematic uncertainty. The fit sensitivity is tested by refitting each  $\lambda^M$  bin for the mass interval between 2.17 and 2.40 GeV/ $c^2$  with a linear parametrization of the background.

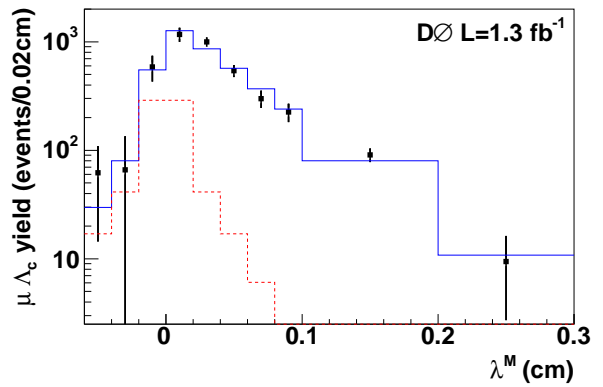


FIG. 2: Measured  $\mu \Lambda_c^+$  yields in the  $\lambda^M$  bins (points) and the result of the lifetime fit (solid histogram). The dashed histogram shows the contribution of peaking background.

Binning effects of the mass histograms are checked by performing fits to the data with bins of half the nominal width and with the lowest and highest bins excluded. The lifetime fit is performed again for each test. The largest deviation of  $\tau(\Lambda_b^0)$  is 0.067 ps, which is given as the systematic uncertainty due to the mass-fitting procedure. The parameters describing the peaking background are varied by their uncertainties. The largest shift in the fitted  $\Lambda_b^0$  lifetime is 0.012 ps.

The selected sample can also contain a contribution from  $B \rightarrow \mu \bar{\nu} \Lambda_c^+ X$  decay. Its branching fraction is unknown; only the upper limit  $\text{Br}(B \rightarrow e \bar{\nu} \Lambda_c^+ X) < 3.2 \times 10^{-3}$  at 90% CL is available [4]. The possible contamination from this decay would reduce the fitted  $\Lambda_b^0$  lifetime, since the  $K$  factor for these events is smaller. The upper 90% CL limit on the fraction of this decay in the selected sample is estimated to be 5%, which would result in the reduction of the  $\Lambda_b^0$  lifetime by 0.027 ps.

The value of the scale factor is varied by  $\pm 20\%$ , and shifts of approximately  $\pm 0.036$  ps are observed in the fitted lifetime. This value is also included in the systematic uncertainty.

The fraction of  $\Lambda_b^0 \rightarrow \mu \bar{\nu} \Lambda_c^+$  decay in the semileptonic  $\Lambda_b^0$  decays is varied between 0.3 and 0.6. The lower bound is selected to be larger than the current uncertainty in this fraction [4] to take into account the possible contribution from decays to  $\tau \bar{\nu} \Lambda_c^+$  and other heavier states with lower mean  $K$  factor. The shift of 0.025 ps in the fitted lifetime is taken as the systematic uncertainty due to the branching fractions in the  $K$  factor. The mean of the  $K$  factor distribution does not change significantly with the  $p_T$  of the muon, however the shape of the distribution is changed. To estimate the possible variation of the  $\Lambda_b^0$  lifetime, the distribution for  $\mu \bar{\nu} \Lambda_c^+$  decays is generated with a cut of  $p_T(\mu) > 6$  GeV/ $c$  and the fit is repeated. A shift of 0.005 ps is observed, which is assumed as the uncertainty due to the momentum dependence of the  $K$  factor.



The change in the  $K$  factor distribution due to the uncertainty in generation and decay of  $B$  hadrons has been estimated in other analyzes to be less than 2% [14, 15]. Therefore we shift all  $K$  factor values by  $\pm 2\%$ , and observe a shift of 0.026 ps in the fitted lifetime. The overall systematic uncertainty due to the  $K$  factor distribution is estimated to be 0.036 ps. The effect on lifetime measurement due to misalignment of elements of the tracking detector is determined by rescaling the geometrical position of all detectors within uncertainties of the alignment procedure. The resulting variation of the  $\Lambda_b^0$  lifetime is estimated to be 0.018 ps.

The systematic uncertainties are summarized and added in quadrature in Table II. Total systematic uncertainty of this measurement is estimated to be 0.09 ps.

In addition, several consistency checks of this analysis are performed. The fitting procedure is applied to the simulated  $\Lambda_b^0 \rightarrow \mu\bar{\nu}\Lambda_c^+$  events that passed the full reconstruction chain and all selection criteria used in data. The fitted lifetime is consistent with the generated value. The simulated events are also used to test that the measured proper decay length is not biased with respect to the generated one, and that the applied selections have the same efficiency for different values of  $\Lambda_b^0$  lifetime.

To test for any bias produced by the fitting procedure, 500 fast, parameterized Monte Carlo samples are generated and analyzed. The average lifetime agrees with the generated one, and the assigned uncertainty corresponds to the statistical spread of fitted values.

Another test consists of splitting the data sample into two roughly equal parts using various criteria and measuring the  $\Lambda_b^0$  lifetime in each sample independently. The sample is split according to the muon charge, the muon direction, the decay length of  $K_S^0$  or the chronological date of data taking. All such tests give statistically consistent values of the  $\Lambda_b^0$  lifetime.

In conclusion, our measurement of the  $\Lambda_b^0$  lifetime using the semileptonic decay  $\Lambda_b^0 \rightarrow \mu\bar{\nu}\Lambda_c^+ X$  results in  $\tau(\Lambda_b^0) = 1.290^{+0.119}_{-0.110}$  (stat) $^{+0.087}_{-0.091}$  (syst) ps. It is consistent with the current world average  $\Lambda_b^0$  lifetime and with our measurement in the exclusive decay  $\Lambda_b^0 \rightarrow J/\psi\Lambda$  [16]. The DØ results are statistically independent and the correlation of systematics between them is very small. Their combination results in  $\tau(\Lambda_b^0) = 1.251^{+0.102}_{-0.096}$  ps. Our new measurements are less consistent with the recent discrepant measured  $\Lambda_b^0$  lifetime [5] than with the current world average [4].

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nology Facilities Council (United Kingdom); MSMT and

TABLE II: Systematic uncertainties in  $\tau(\Lambda_b^0)$

Source	Uncertainty in $\tau(\Lambda_b^0)$
Detector alignment	$\pm 0.018$ ps
Mass-fitting method	$\pm 0.067$ ps
$K$ -factor determination	$\pm 0.036$ ps
Peaking background	$\pm 0.012$ ps
Resolution scale factor	$\pm 0.036$ ps
Contribution of $B \rightarrow \mu\bar{\nu}\Lambda_c X$	$^{+0.000}_{-0.027}$ ps
Total	$^{+0.087}_{-0.091}$ ps

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