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Search for Lepton Flavor Violation in  
Upsilon Decays Forward-Backward  
Asymmetry in Top-Quark Production in  
p(p)over-bar Collisions at  $\sqrt{s}=1.96$   
TeV

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## Search for Lepton Flavor Violation in Upsilon Decays

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In this Letter, we describe a search for lepton flavor violation (LFV) in the bottomonium system. We search for leptonic decays  $Y(nS) \rightarrow \mu\tau$  ( $n = 1, 2,$  and  $3$ ) using the data collected with the CLEO III detector. We identify the  $\tau$  lepton using its leptonic decay  $\nu_\tau \bar{\nu}_e e$  and utilize multidimensional likelihood fitting with probability density function shapes measured from independent data samples. We report our estimates of 95% C.L. upper limits on LFV branching fractions of  $Y$  mesons. We interpret our results in terms of the exclusion plot for the energy scale of a hypothetical new interaction versus its effective LFV coupling in the framework of effective field theory.

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The subject of this Letter is a search for lepton flavor violating (LFV) bottomonium decays  $Y(nS) \rightarrow \mu\tau$  ( $n = 1, 2,$  and  $3$ ). Such decays are predicted by various theoretical models that allow tree-level flavor-changing neutral currents (FCNC), including, e.g.,  $R$ -parity violating

and large  $\tan\beta$  SUSY scenarios, leptoquarks, and other models inspired by the idea of grand unification [1,2]. Our search is motivated by the discovery of large mixing between the second and the third generations in the neutrino sector [3].

The conservation of lepton, lepton flavor, and baryon quantum numbers in the standard model (SM) is due to accidental global symmetries of its Lagrangian. All such symmetries should be violated at higher energies, where we expect the emergence of a gauge group of the higher-order symmetry that presumably describes fundamental interactions at the energy scale of grand unification. The search for beyond the standard model (BSM) physics in low-energy processes is facilitated by parameterizing such BSM physics, without explicitly invoking its unknown dynamics, in the framework of the Wilson operator product expansion (OPE) and effective field theory. The large lepton mass hierarchy and dimensional analysis suggest that the effects of BSM physics are most likely to be observed in transitions that involve heavy quarks, muons, and  $\tau$  leptons. In the OPE, the effects of BSM physics in decays  $Y(nS) \rightarrow \mu\tau$  are expressed by the four-fermion diagonal operators [4,5] that respect the full electroweak SM gauge group  $SU(2)_L \otimes U(1)_Y$  and contribute to the SM Lagrangian as

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{4\pi\alpha_N}{\Lambda^2} (\bar{\mu}\Gamma_\mu\tau)(\bar{b}\gamma^\mu b), \quad (1)$$

where  $\Gamma_\mu$  is a vector ( $\gamma_\mu$ ) or axial-vector ( $\gamma_\mu\gamma_5$ ) current or their combination,  $\Lambda$  is the scale of BSM physics, and  $\alpha_N$  is the effective LFV coupling of the new gauge symmetry associated with BSM.

Previously, we searched for LFV in  $B$  meson decays [6], while the BES experiment searched for LFV in  $J/\psi$  decays [7]. Those two analyses probed the BSM contributions parameterized by the operators  $(\bar{\mu}\Gamma_\mu\tau)(\bar{b}\Gamma d)$  ( $\Gamma = \gamma_5, \gamma_5\gamma_\mu$ ) and  $(\bar{\mu}\Gamma_\mu\tau)(\bar{c}\gamma^\mu c)$ , respectively. In the analysis presented in this Letter, we probe the four-fermion operators  $(\bar{\mu}\Gamma_\mu\tau)(\bar{b}\gamma^\mu b)$ .

The CLEO III detector, centered on the interaction region of the Cornell Electron Storage Ring (CESR), is a versatile multipurpose particle detector [8]. Relevant components of the apparatus include a nearly  $4\pi$  tracking volume surrounded by a Ring Imaging Cherenkov Detector (RICH) [9], an electromagnetic CsI(Tl) crystal calorimeter, and a muon identification system [10] consisting of proportional wire chambers that provide two-dimensional position information. The tracking volume, located inside an axial magnetic field of 1.5 T, is instrumented with a 47-layer wire drift chamber and a four-layer silicon strip detector that allow us to measure the positions, momenta, and specific ionization energy losses ( $dE/dx$ ) of charged particles with momentum resolution of 0.35% (0.86%) at 1 GeV/ $c$  (5 GeV/ $c$ ) and a  $dE/dx$  resolution of 6%. The calorimeter, first installed in the CLEO II detector [11], forms a cylindrical barrel around the tracking volume and has resolution of 2.2% (1.5%) for 1 GeV (5 GeV) photons and electrons. The calorimeter, just inside the magnet coil, is followed by Fe flux-return plates interleaved with three layers of the muon identification system.

We search for non-SM leptonic decays  $Y(nS) \rightarrow \mu\tau$  ( $n = 1, 2$  and  $3$ ) using the data collected with the CLEO III detector. We identify the  $\tau$  lepton using an electron from its leptonic decay  $\nu_\tau\bar{\nu}_e e$ . We use data samples that contain 20.8, 9.3, and 5.9 million  $Y(1S)$ ,  $Y(2S)$ , and  $Y(3S)$  resonant decays, respectively [12,13]. Integrated  $e^+e^-$  luminosities of these signal data samples are  $1.1 \text{ fb}^{-1}$ ,  $1.3 \text{ fb}^{-1}$ , and  $1.4 \text{ fb}^{-1}$ . We use the  $Y(4S)$  ( $6.4 \text{ fb}^{-1}$ ) and hadronic “continuum” [ $2.3 \text{ fb}^{-1}$  collected 60 MeV below the  $Y(4S)$  energy] data to measure the shapes of probability density functions (PDFs) and resolution parameters used in maximum likelihood (ML) signal fits described later in this Letter. We also use the  $Y(4S)$  and continuum data to verify the overall reconstruction and trigger efficiency and to estimate systematic errors.

The signature of our signal is a muon with  $p_\mu/E_{\text{beam}} \approx 0.97$  and an electron from the decay of the  $\tau$  lepton. We select events with two reconstructed tracks of opposite electric charge. One track is identified as a high-quality muon candidate by requiring that it penetrate five hadronic interaction lengths. The other track should satisfy electron identification criteria by requiring a  $\pm 3\sigma$  consistency with the theoretically-predicted  $dE/dx$  contribution and  $0.85 \leq E/p \leq 1.10$ , where  $E$  is the energy reconstructed in the region of the electromagnetic calorimeter matched to the projection of electron’s track of momentum  $p$ . Electron and muon candidates should not also be identified as the candidates of the other lepton species. The beam-energy normalized momenta of the muon and electron candidates,  $x = p_\mu/E_{\text{beam}}$  and  $y = p_e/E_{\text{beam}}$ , are required to be within the ranges  $0.87 \leq x \leq 1.02$  and  $0.10 \leq y \leq 0.85$ .

The geometric acceptance of tracking is  $\approx 86\%$  for two tracks. Track reconstruction efficiency for the signal is 83% in the acceptance region. The muon system coverage is 84% of the solid angle, and the efficiency of muon identification in that region is 92% per muon when its charged track is reconstructed. Electron identification is 95% efficient, due to the calorimeter’s angular acceptance. The trigger for signal events in the fiducial region of the detector is 93% efficient. The efficiency for selecting events in the  $x$  and  $y$  regions (after applying all other criteria) is 95%. Trigger and reconstruction efficiency for the signal is 50%. Its product with the  $\mathcal{B}(\tau \rightarrow \nu_\tau\bar{\nu}_e e) = (17.84 \pm 0.05)\%$  [14] yields an overall efficiency of 8.9%.

We do not expect to find LFV in the  $Y(4S)$  and hadronic continuum data used to calibrate our analysis method. Even if LFV BSM physics, e.g., quantum gravity, becomes strong at a TeV energy scale, LFV would occur in dilepton decays of the  $Y(4S)$  at a much smaller rate than in decays of lower-mass  $b\bar{b}$  resonances, because the products of their production cross sections and SM dilepton partial widths are significantly larger than that for the  $Y(4S)$ . The *BABAR* experiment has recently published an upper limit (UL) for  $\sigma(\tau\mu)/\sigma(\mu\mu)$  at the  $Y(4S)$  energy [15]. Their UL suggests that less than 3 LFV events would be observed in our

calibration data. We show the distribution of  $y$  versus  $x$  for our calibration data in Fig. 1(a) and the projection onto the axis  $x$  in Fig. 1(b).

According to our studies, confirmed by Monte Carlo (MC) simulation for QED processes, three backgrounds arising from  $\mu$  and  $\tau$  pairs contribute to the distributions shown in Fig. 1. The  $\mu$  pairs contribute in two ways, through radiative processes, and, also, when one muon decays to an electron in flight. The first contribution from  $\mu$  pairs includes QED radiation at the vertex and hard bremsstrahlung in the detector. Such events satisfy our selection criteria when a radiative photon matches the muon track's projection to the calorimeter and muon identification fails. Such events cluster around  $y = 0.53$  because of the  $E/p$  requirement, where  $E$ , for such background events, is the energy of radiative photon ( $\approx E_{\text{beam}}/2$ ) combined with a small amount of energy ( $\approx 0.2$  GeV) deposited by the muon in the calorimeter.

The second, and less frequent background from  $\mu$  pairs appears when one muon decays in flight. This results in the actual electron detected in the calorimeter. Such events cluster near  $x = 1$  but scatter in  $y$  between 0.10 and 0.85. Both background contributions from  $\mu$  pairs differ from the hypothetical signal in  $Y(nS)$  ( $n = 1, 2$ , and 3) data. The high-momentum background muon is most often produced at beam energy,  $x = 1$  (though radiative processes introduce a long tail in the  $x$  shape for this background), while the signal muon peaks at  $x = 0.965$ , 0.968, and 0.970 for the  $Y(1S)$ ,  $Y(2S)$ , and  $Y(3S)$ , respectively. Also, when a muon mimics an electron, the  $E/p$  and  $dE/dx$  distributions differ from those we expect for the real electrons. While the  $dE/dx$  measurements do not have sufficient resolution to discriminate between electrons and muons on an event by event basis in the relevant momentum region, namely, around 2.5 GeV, discrimination between the signal and backgrounds on a statistical basis is possible.

The production of  $\tau$  pairs represents an irreducible background to our signal when both  $\tau$  leptons decay leptonically, one to an electron and the other to a muon. The only variable that discriminates our signal from this back-

ground is  $x$ , the beam-energy normalized momentum of the signal muon candidate.

To estimate the number of LFV decays in  $Y(nS)$  ( $n = 1, 2$  and 3) data, we subject the events that pass the selection criteria to four-dimensional unbinned extended ML fits. For each probed data sample, we maximize the likelihood function

$$L = \frac{1}{N!} \exp\left(-\sum_j N_j\right) \prod_i \sum_j N_j \mathcal{P}_j(\{z\}_i, \{\alpha\}_j), \quad (2)$$

where  $N$  is the total number of data events in the fit;  $i$  is the index for these events;  $j$  is the index for fit contributions (the signal and the three backgrounds);  $\{z\}_i$  is the vector of the four variables  $x$ ,  $y$ ,  $dE/dx$ , and  $E/p$  for event  $i$ ;  $N_j$  is the fit parameter that corresponds to the numbers of events for fit contribution  $j$ ; and  $\mathcal{P}_j$  is the four-dimensional PDF with shape parameter vector  $\{\alpha\}_j$  for fit contribution  $j$ .

We utilize calibration data to find approximations for the PDFs, the values of their shape parameters, and respective matrices of systematic errors. The correlations among the variables, especially important for the  $\mu$ -pair backgrounds, are included in the respective PDFs. To take into account initial state radiation, we parameterize the  $x$  shape of the  $\mu$ -pair background using a Crystal Ball function [16] (a power law tail is matched to a Gaussian function below the mean of the Gaussian). The  $E/p$  shape for real electrons is also parameterized by such a function. The  $x$  shape for the  $\tau$ -pair background is parameterized by a first order polynomial smeared by Gaussian detector resolution measured using the data. The  $E/p$  shape for the muon matched with a radiative photon in the calorimeter, therefore misidentified as the signal electron candidate, is approximated by a first order polynomial. The beam-energy normalized electron momentum,  $y$ , is parameterized by a second order polynomial for the signal,  $\tau$  pairs, and  $\mu$  pairs when one muon decays in flight. For radiative  $\mu$  pairs, the shape of  $y$  is approximated by a Crystal Ball function whose Gaussian mean depends on  $E/p$ . We approximate  $dE/dx$  shapes by Gaussians. The signal  $x$  shape is approximated by a Gaussian with the resolution  $\sigma(x) = 0.86\% \pm 0.03\%$ , which we measured using radiative  $\mu$  pairs. We studied the performance of our fitting method by mixing signal toy MC events with calibration data. No biases were observed in these studies. We also verified our results by rejecting events where the signal electron and muon candidates are back to back. Such selection efficiently suppresses the  $\mu$ -pair backgrounds but lowers the sensitivity to the searched-for LFV signal. To further verify the analysis presented in this Letter, we performed a one-dimensional ML fit of the  $x$  distribution for events remaining after this selection, obtaining results consistent with the main analysis but with lower efficiency and reduced significance.

Systematic uncertainties in our analysis arise from several sources. The largest contributions to the error on the efficiency come from the trigger (5%), event selection

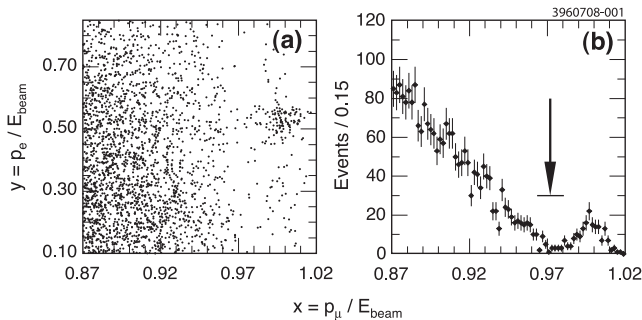


FIG. 1. (a) The scatter plot of  $y$  versus  $x$  and (b) its binned  $x$  projection for calibration data. The location of the hypothetical signal peak is indicated by the arrow, where the width of the horizontal bar at its tip is  $\pm\sigma(x)$ .



TABLE I. Information necessary to interpret our results in terms of BSM physics scale  $\Lambda$  and coupling  $\alpha_N$ . We assume lepton universality and use our results for dielectron partial widths of  $Y$  mesons [17]. Full widths are according to the PDG summary [14].

	Y(1S)	Y(2S)	Y(3S)
Mass (GeV/ $c^2$ )	9.46	10.02	10.36
$N$ decays (millions)	20.8	9.3	5.9
$\Gamma(Y \rightarrow \mu\mu)$ (keV)	1.252	0.581	0.413
$\Gamma(Y)$ (keV)	53.0	43.0	26.3
$\mathcal{B}(\mu\mu)$ ( $\times 10^{-3}$ )	23.6	13.5	15.7
$\mathcal{B}(\mu\tau)$ (95% CL UL, $\times 10^{-6}$ )	6.0	14.4	20.3
$\mathcal{B}(\mu\tau)/\mathcal{B}(\mu\mu)$ (95% CL UL, $\times 10^{-3}$ )	0.25	1.1	1.3
$\Lambda$ (95% CL LL, TeV, $\alpha_N = 1.0$ )	1.30	0.98	0.98

(4%), track reconstruction (3% for two tracks), muon identification (2%), online event preselection (2%), signal MC statistics (2%), software trigger (1%), and electron identification (1%) uncertainties. The overall systematic error on the efficiency is 8%. To verify this error estimate, we measured the partial cross section for  $\tau$ -pair production in the region  $0.65 \leq x \leq 0.95$  using calibration data where no signal and no contamination from  $\mu$  pairs are expected. Properly scaled up to the total cross section for  $\tau$ -pair production at 5 GeV, our measurement agrees with the expected 0.92 nb within 4%, while the statistical uncertainty of this measurement is 5%.

The uncertainty in the  $y$  shape and in the efficiency of  $y$  region selection for the signal are determined by the uncertainty in  $\tau$  polarization. The polarization of  $\tau$  is well defined for QED processes but is model-dependent for BSM contributions. The efficiency of the  $V + A$  ( $V - A$ ) hypothesis, when the electron from  $\tau$  decay is boosted forward (backward), is 3% lower (higher) than in the case of an unpolarized  $\tau$ . We use the unpolarized  $\tau$  efficiency in the analysis and estimate the systematic error in the efficiency of the  $y$  region selection that arises from  $\tau$  polarization uncertainty to be 3%. Significantly larger systematic errors (up to 15%) are associated with the uncertainties in PDF shape parameters in ML fitting. To convert signal yields to LFV branching fractions, we also take into account the 2% uncertainty in  $Y$  statistics.

To determine parametric dependence of the likelihood function on the signal yield (and LFV branching fraction), we integrate the likelihood function over the other three fit parameters, i.e., the numbers of background events. We take the uncertainties in PDF shape parameters into account by performing 1000 ML fits for each data sample using the PDF shape parameters determined from  $Y(4S)$  and continuum data but varied according to Gaussian uncertainties in their values in each fit. In addition, to obtain the likelihood distribution for the LFV branching fraction, we vary the efficiency and the number of  $Y$  mesons in each of these fits according to their Gaussian uncertainties. The

resulting distribution of the likelihood function is the sum of such individual distributions of likelihoods, each obtained with its own set of PDF shape parameters, the efficiency and the number of  $Y$  decays. This technique takes into account the systematic error on the LFV branching fraction arising from the uncertainties in the PDF shape parameters and results in widening the likelihood distribution.

Our largest signal sample with relatively smaller QED background is  $Y(1S)$  data. We show the binned  $x$  projection of the results of our four-dimensional unbinned ML fit to this sample in Fig. 2(a). The final distribution of the likelihood versus LFV branching fraction for leptonic decay  $Y(1S) \rightarrow \mu\tau$  is shown in Fig. 2(b). To estimate the 95% C.L. Bayesian UL on this branching fraction, we integrate the likelihood function for positive (i.e., physical) values of the branching fraction and find the value that correspond to 95% of the area. We apply the same technique to the  $Y(2S)$  and  $Y(3S)$  data and show our results for the 95% CL ULs on the branching fractions for LFV decays of  $Y$  mesons in Table I.

Effective field theory allows one to relate the dilepton and LFV branching fractions of  $Y$  mesons to the scale  $\Lambda$  of LFV BSM physics [4,5] using

$$\frac{\Gamma(Y(nS) \rightarrow \mu\tau)}{\Gamma(Y(nS) \rightarrow \mu\mu)} = \frac{1}{2e_b^2} \left(\frac{\alpha_N}{\alpha}\right)^2 \left(\frac{M[Y(nS)]}{\Lambda}\right)^4, \quad (3)$$

where  $e_b$  is the charge of the  $b$  quark,  $M[Y(nS)]$  is the mass of vector meson  $Y(nS)$ , and  $\alpha$  is the fine structure constant. We show 95% CL lower limits (LL) on the BSM energy scale  $\Lambda$  assuming  $\alpha_N = 1$  in Table I. This table also shows other quantities necessary for estimating  $\Lambda$ .

To estimate the lower limit on the scale of BSM physics and to produce the exclusion plot of  $\Lambda$  versus  $\alpha_N$ , we combine our signal datasets by taking the product of individual likelihood functions obtained for each dataset be-

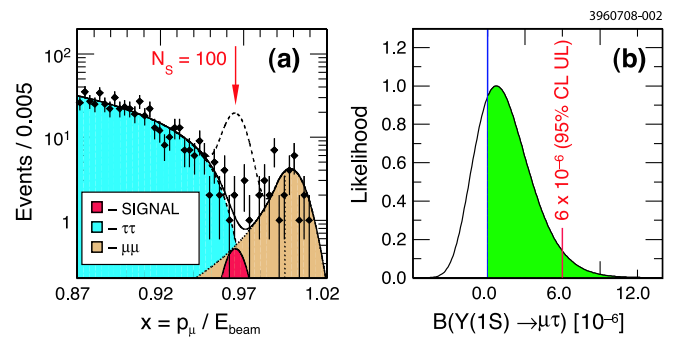


FIG. 2 (color online). (a) The binned  $x$  projection of the results of the ML fit to  $Y(1S)$  data (points with the error bars). Solid line indicates the result of the fit; shaded areas show  $\tau$ -pair,  $\mu$ -pair, and signal contributions to the fit. Dashed line shows the hypothetical signal of 100 LFV events superimposed on the result of the fit. (b) The distribution of the likelihood function versus branching fraction for LFV decay  $Y(1S) \rightarrow \mu\tau$ .



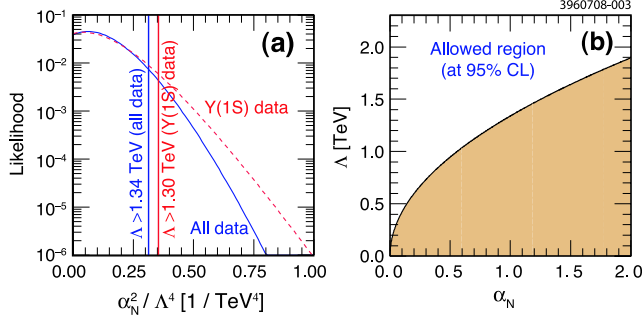


FIG. 3 (color online). (a) The distributions of the likelihood functions versus  $\alpha_N^2/\Lambda^4$  (95% CL ULs are shown assuming  $\alpha_N = 1$ ) and (b) the exclusion plot for  $\Lambda$  versus  $\alpha_N$ .

fore taking into account the systematic errors associated with the uncertainties in the overall reconstruction and trigger efficiency, PDF shape parameters and  $Y$  statistics. In the product of the likelihood distributions, each distribution is represented by

$$\frac{\alpha_N^2}{\Lambda^4} = \frac{\mathcal{B}(Y(nS) \rightarrow \mu\tau)}{\mathcal{B}(Y(nS) \rightarrow \mu\mu)} \frac{2e_b^2\alpha^2}{\{M[Y(nS)]\}^4}. \quad (4)$$

We show the resulting combined likelihood function in Fig. 3(a). We use this figure to estimate the 95% CL LL on the scale of BSM physics and to prepare the exclusion plot shown in Fig. 3(b). In Fig. 3(a), we show the 95% CL LLs obtained separately with  $Y(1S)$  and, also with all three signal data samples combined.

The improvement from combining all signal data samples is small [ $\Lambda > 1.34$  TeV using all data as compared to  $\Lambda > 1.30$  TeV using the  $Y(1S)$  data] because all three samples correspond approximately to the same amount of the integrated  $e^+e^-$  luminosity and contain similar numbers of background QED events. The larger cross section for the production of  $Y(1S)$  makes this sample dominate our results for  $\Lambda$ . The slightly more (less) restrictive limits on LFV branching fractions (by 3%) and  $\Lambda$  (by 1%) could be obtained assuming pure  $V - A$  ( $V + A$ ) BSM interaction for which the efficiency is 9.2% (8.6%). Our interpretation of the LFV results from the BES experiment [7],  $\Lambda > 0.49$  TeV at 95% CL, should not be compared with our results directly because these two analyses probe different operators. Finally, the lower limits on  $\Lambda$  estimated [5] from the decays of  $B$  mesons are much more constraining, of the order of hundreds of TeVs, than the estimate obtained in our analysis. However, such analyses probe nondiagonal operators, where the source of possible BSM contribution is not necessarily the same as in the analysis presented in this Letter.

To conclude, we searched for leptonic decays  $Y(nS) \rightarrow \mu\tau$  ( $n = 1, 2$ , and 3) predicted by various LFV BSM scenarios that would break the accidental lepton flavor

symmetry of the SM. We estimate 95% CL ULs on  $\mathcal{B}[Y(nS) \rightarrow \mu\tau]$  to be 6.0, 14.4, and 20.3 for  $n = 1, 2$ , and 3, respectively, units of  $\times 10^{-6}$ . In the framework of effective field theory, we probed the contribution from the operators  $(\bar{\mu}\Gamma_\mu\tau)(\bar{b}\gamma^\mu b)$  and interpret our results in terms of the exclusion plot for the energy scale  $\Lambda$  of some new BSM interaction and the strength of its effective LFV coupling and, assuming  $\alpha_N = 1$ , estimate the 95% CL LL on  $\Lambda$  to be 1.34 TeV.

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