

All-sky search for long-duration gravitational-wave transients in the second Advanced LIGO observing run

THE LIGO SCIENTIFIC COLLABORATION AND THE VIRGO COLLABORATION

ABSTRACT

We present the results of a search for long-duration gravitational-wave transients in the data from the Advanced LIGO second observation run; we search for gravitational-wave transients of 2 – 500 s duration in the 24 – 2048 Hz frequency band with minimal assumptions about signal properties such as waveform morphologies, polarization, sky location or time of occurrence. Signal families covered by these search algorithms include fallback accretion onto neutron stars, broadband chirps from innermost stable circular orbit waves around rotating black holes, eccentric inspiral-merger-ringdown compact binary coalescence waveforms, and other models. The second observation run totals about 118.3 days of coincident data between November 2016 and August 2017. We find no significant events within the parameter space that we searched, apart from the already-reported binary neutron star merger GW170817. We thus report sensitivity limits on the root-sum-square strain amplitude  $h_{\text{rss}}$  at 50% efficiency. These sensitivity estimates are an improvement relative to the first observing run and also done with an enlarged set of gravitational-wave transient waveforms. Overall, the best search sensitivity is  $h_{\text{rss}}^{50\%} = 2.7 \times 10^{-22} \text{ Hz}^{-1/2}$  for a millisecond magnetar model. For eccentric compact binary coalescence signals, the search sensitivity reaches  $h_{\text{rss}}^{50\%} = 9.6 \times 10^{-22} \text{ Hz}^{-1/2}$ .

1. INTRODUCTION

The second observation run of the Advanced LIGO (Aasi et al. 2015) and Advanced Virgo (Acernese et al. 2015) detectors ushered in the era of multi-messenger astronomy. In addition to the detection of further binary black hole systems (Abbott et al. 2017a,b,c), the first binary neutron star system GW170817 (Abbott et al. 2017d), associated with GRB 170817A (Abbott et al. 2017e) and corresponding electromagnetic radiation AT 2017gfo (Abbott et al. 2017f), were jointly detected. This led to searches for a post-merger signal from the binary neutron star event, including on the timescales presented in this paper (Abbott et al. 2017; Abbott et al. 2018a). In this paper, we update the results of the unmodeled long-duration transient search from the first Advanced LIGO observing run (Abbott et al. 2018b) with the data from the second observing run.

We use four pipelines, described below, with different responses across the parameter space, providing complementary coverage of the signal models we are interested in. The search was motivated by a wide range of poorly understood astrophysical phenomena for which predictive models are not readily available; these include fallback accretion, accretion disk instabilities and non-axisymmetric deformations in magnetars. Fallback accretion of ejected mass in newborn neutron stars can lead to deformation, causing the emission of gravitational waves until the star collapses into a black hole (Lai & Shapiro 1995; Piro & Ott 2011; Piro & Thrane 2012).

Accretion disk instabilities and fragmentation can cause stellar material to spiral in a black hole, emitting relatively long-lived gravitational waves (Piro & Pfahl 2007; van Putten 2001, 2008). Non-axisymmetric deformations in magnetars, proposed as progenitors of long and short gamma-ray bursts (Metzger et al. 2011; Rowlinson et al. 2013), can also emit gravitational waves (Corsi & Mészáros 2009). Moreover, we introduce new waveform families based on astrophysical phenomena such as fallback accretion down to the innermost stable circular orbit of a rapidly rotating black hole (van Putten 2016), highly eccentric binary black hole coalescences (Huerta et al. 2018), and gamma-ray burst & X-ray events (Corsi & Mészáros 2009).

Although this analysis targets sources for which the gravitational waveform is not well-described, it is possible for the long-duration searches to detect low-mass compact binary coalescences, typically searched for with matched filtering techniques. As discussed in other publications (Abbott et al. 2017d), the data containing the gravitational-wave signal resulting from GW170817 is corrupted by the presence of a short-duration (less than 5 ms), powerful transient noise event in one of the detectors (Abbott et al. 2017d). Using a data set where this short transient has been subtracted from the LIGO-Livingston data stream, the GW170817 signal is the most significant event of the search. As the searches reported in this paper does not add significantly to the many other studies carried out for this event (Abbott et al. 2017d; Abbott et al. 2018a,b, 2017), it has been

76 decided to keep the original data set, veto the large  
77 transient noise and focus on any other long duration  
78 gravitational-wave signals.

79 The paper is organized as follows. We describe the  
80 data used in the analysis in Section 2. The algorithms  
81 used to analyze the data are outlined in Section 3. The  
82 results of the analysis and their implications are dis-  
83 cussed in Section 4. Section 5 provides our conclusions  
84 and avenues for future research.

## 85 2. DATA

86 The second observation run lasted from November 25,  
87 2016 to August 25, 2017. Between the first and second  
88 observing runs, a series of fixes and upgrades of the two  
89 LIGO detectors in Hanford, WA and Livingston, LA,  
90 allowed the run to begin with LIGO detectors' sensitiv-  
91 ity reaching a binary neutron star range of  $\sim 80$  Mpc  
92 – please see [Abbott et al. \(2018c\)](#) for a discussion of  
93 the range metric. Thanks to commissioning break pe-  
94 riods, Livingston's sensitivity increased steadily during  
95 the second observation run, finally reaching 100 Mpc.  
96 LIGO Hanford suffered from a 5.8 magnitude earth-  
97 quake in Montana on July 6<sup>th</sup> 2017, which induced a  
98 10 Mpc drop in sensitivity, and this was not recovered  
99 during the science run. On August 1<sup>st</sup>, the Virgo detec-  
100 tor joined the run with a binary neutron star range of  
101 26 Mpc. It has been shown that adding the one-month  
102 Virgo data set does not improve the search sensitivity  
103 mainly because of the sensitivity difference between the  
104 detectors. We thus report the results of a two LIGO de-  
105 tector coincident search. The overlap in time when both  
106 detectors are taking data in suitable for analysis was ap-  
107 proximately 118.3 days. The effective coincident time  
108 analyzed by each pipeline depends on the data segmen-  
109 tation choice and lies in the range 114.7 to 118.3 days.

110 Coincident data contains a large number of non-  
111 Gaussian transient noise events (glitches) of instrumen-  
112 tal or environmental origin that mimic the characteristic  
113 of the targeted signals. For the first time, well identified  
114 sources of noise have been subtracted from the LIGO  
115 data ([Davis et al. 2018](#)). Yet, some glitches, typically  
116 lasting from a few milliseconds up to few seconds and  
117 varying widely in frequency, remain. Their presence,  
118 even the very short ones, may negatively impact the  
119 sensitivity of the searches ([Abbott et al. 2018c](#)). Time  
120 varying spectral lines are also a source of noise events  
121 for the long-duration transient searches. To veto these  
122 transient noise events, each pipeline implements spe-  
123 cific glitch rejection criteria; because the search targets  
124 long-duration signals, short-duration glitches, which are  
125 usually the most problematic sources of noise, are eas-  
126 ily suppressed. The next section provides more details

127 about the noise rejection procedures that also may in-  
128 clude data quality vetoes based on correlations with aux-  
129 iliary channels ([Aasi et al. 2012](#); [Abbott et al. 2016](#)).

## 130 3. SEARCHES

131 As in the previous analysis, we use four pipelines to  
132 search for transients that last between 2 – 500 s and  
133 span a frequency band of 24 – 2048 Hz. The use of  
134 multiple pipelines provides redundancy, and due to the  
135 differences in the clustering algorithms, lead to differ-  
136 ent sensitivities to different waveform morphologies or  
137 parts of the parameter space. Unmodeled searches for  
138 gravitational waves typically cast the analysis as pattern  
139 recognition problems. Gravitational-wave time-series  
140 are Fourier transformed in chunks of time, and spec-  
141 trograms are created based on statistics derived from  
142 these Fourier transforms. Then pattern recognition al-  
143 gorithms are used to search for patterns, corresponding  
144 to gravitational waves, within spectrograms. In gen-  
145 eral, these consist of two classes. The first is seed-  
146 based ([Khan & Chatterji 2009](#); [Prestegard 2016](#)), where  
147 thresholds are placed on pixel values in the spectrograms  
148 and pixels above this threshold are clustered together.  
149 The second is seedless ([Thrane & Coughlin 2013, 2014](#)),  
150 where tracks are constructed from a generic model and  
151 integrated across the spectrograms; in this analysis, we  
152 use Bézier curves ([Farin 1996](#); [Thrane & Coughlin 2013,](#)  
153 [2014](#); [Coughlin et al. 2015](#); [Thrane & Coughlin 2015](#)).

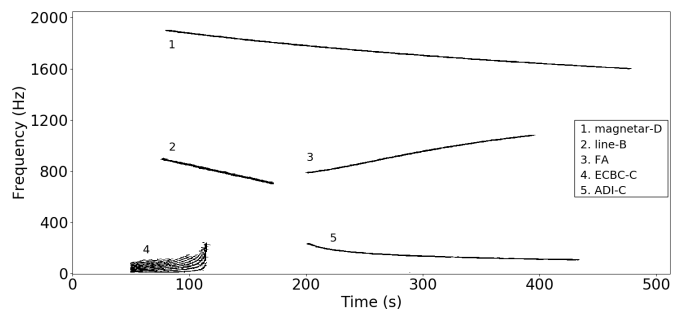
154 The pipelines used are the long-duration configura-  
155 tion of Coherent WaveBurst (cWB) ([Klimenko et al.](#)  
156 [2016](#)), two different versions of the Stochastic Transient  
157 Analysis Multi-detector Pipeline - all sky (STAMP-  
158 AS) pipeline ([Prestegard 2016](#); [Thrane & Coughlin](#)  
159 [2015](#)), and the X-pipeline Spherical Radiometer (X-  
160 SphRad) ([Fays 2017](#)). These pipelines are the same, or  
161 slightly updated versions, of those used in the search for  
162 long-duration transients in the first observation run and  
163 fully described in ([Abbott et al. 2017g](#)). cWB is based  
164 on a maximum-likelihood-ratio statistic, built as a sum  
165 of excess power coherent between multiple detectors in  
166 the time-frequency representation of the interferometer  
167 responses ([Klimenko et al. 2016](#)). The search is per-  
168 formed in the frequency range 24 – 2048 Hz, on data  
169 where all poor quality periods have been discarded. The  
170 trigger events surviving the selection criteria to reject  
171 glitches are ranked according to their detection statistic  
172  $\eta_c$ , which is related to the coherent signal-to-noise ra-  
173 tio (SNR). The selection criteria require the coherence  
174 coefficient  $c_c$  to be larger than 0.6, and the weighted  
175 duration of the candidate to be larger than 1.5 s. The  
176 first measures the degree of correlation between the de-  
177 tectors, while the latter measures the duration weighted

by the excess power amplitude of the pixel on the time-frequency likelihood map. The trigger events are then divided in two samples according to their estimated mean frequency: 24-200 Hz and 200-2048 Hz. This allows for the isolation of the unexpected higher rate of glitches at low frequency during the first half of the O2 observation run. STAMP-AS uses the cross-correlation of data from two detectors to create coherent time-frequency maps of cross-power SNR with a pixel size of  $1\text{ s} \times 1\text{ Hz}$  covering 24 – 2000 Hz in combination with a seed-based (ZebraGard) and seedless (Lonetrack) clustering algorithm. Significant spectral features, including wandering lines, are masked in the creation of the spectrograms. As in the search during the first observing run, ZebraGard eliminates the short duration glitches by requesting that the fraction of SNR in each time bin be smaller than 0.5 and that the SNR ratio between the two detectors be smaller than 3. The X-pipeline Spherical Radiometer (X-SphRad) uses an X-pipeline (Sutton et al. 2010) back end in combination with a fast cross-correlator in the spherical harmonic domain (Cannon 2007) to search for gravitational-wave transients in the 24 – 1000 Hz frequency range. The method allows for the data to be processed independently of sky position and avoids redundant computations. A next-nearest-neighbor clustering algorithm is applied on a time-frequency representation of the data with a resolution of  $1\text{ s} \times 1\text{ Hz}$  to form trigger events, which are then ranked by the ratio of the sum of power in all the  $l > 0$  spherical harmonic modes to that in the  $l = 0$  mode. Significant spectral features such as standing power lines are removed using a zero-phase linear predictor filter that estimates the power spectrum and whitens the data (Chatterji 2005). Finally, X-SphRad eliminates triggers that coincide with poor quality data periods that have been identified using auxiliary channels. These periods are excluded from the analysis time by cWB, and STAMP-AS ZebraGard analysis selects a subset of them according to a procedure described in (Frey 2018).

The false alarm rate of each search is estimated as a function of the pipeline’s ranking statistic. Each use the data to perform this estimate, as opposed to a Gaussian approximation, because of the significant non-Gaussianity of the data, transient noise, and the non-stationarity of some of the spectral features. These glitches have a variety of causes, both environmentally driven such as from seismic events (MacLeod et al. 2012; Coughlin et al. 2017) or magnetic fields (Kowalska-Leszczynska et al. 2017; Coughlin et al. 2016), and instrumental effects, such as test mass suspension glitches (Walker et al. 2017) and other sources of spec-

tral features (Coughlin 2010). For all of the pipelines in this analysis, the correlation of data in different detectors is used to exclude data transients which are unlikely to be of astrophysical origin. To estimate the background for all pipelines used in this analysis, the time-slides methodology is applied (Was et al. 2010a,b), each one implementing its own version. The fundamental idea is to shift the detector data with non-physical relative time delays to eliminate any correlation from gravitational waves and re-analyze the data. The procedure is repeated until a total of 50 years coincident detector time has been analyzed, allowing us to estimate false alarm rates at the level of 1 event in 50 years.

#### 4. RESULTS



**Figure 1.** Time-frequency representations of a few model signals used in the search, showing a mix of chirp-up (FA, ECBC) & chirp-down (Magnetar, ADI) astrophysical waveforms as well as a linearly decreasing ad-hoc waveform (LINE). Descriptions of these waveforms and others are given in Section 4. The harmonics of ECBC are also visible. The full set of waveforms ( $\sim 70$ ) chosen for this analysis fully covers the search frequency band of 24-2000 Hz. The waveforms are shifted in time to show how they cover the parameter space in this axis as well.

Pipeline	FAR [Hz]	p-value	Frequency [Hz]	Duration [s]
cWB	$1.4 \times 10^{-7}$	0.75	53–69	11
ZebraGard	$2.5 \times 10^{-7}$	0.92	1649–1753	29
Lonetrack	$7.9 \times 10^{-8}$	0.80	608–1344	463
X-SphRad	$9.7 \times 10^{-8}$	0.60	435–443	3

**Table 1.** Properties of the most significant coincident triggers found by each of the long-duration transient search pipelines during the second observation run. FAR stands for false alarm rate, while the p-value is the probability of observing at least 1 noise trigger at higher significance than the most significant coincident trigger.

None of the pipelines find a significant excess of coincident events. The most significant events found by each

pipeline are reported in Table 1. Their false alarm rate is in agreement with the expected background estimation. Given the absence of a detection, we can derive upper limits on long-duration gravitational-wave transients’ strain amplitude. A usual measure of gravitational-wave amplitude is the root-sum-square strain amplitude at the Earth,  $h_{\text{rss}}$ ,

$$h_{\text{rss}} = \sqrt{\int_{-\infty}^{\infty} (h_{+}^2(t) + h_{\times}^2(t)) dt}, \quad (1)$$

where  $h_{+}$  and  $h_{\times}$  are signal polarizations at Earth’s center expressed in the source frame. We can relate this quantity to the gravitational-wave energy radiated by a source emitting isotropically at a given central frequency  $f_0$  (Sutton 2013)

$$\begin{aligned} E_{\text{gw}}^{\text{iso}} &= \frac{\pi c^3}{G} \mathcal{D}^2 \int df f^2 (|\tilde{h}_{+}(f)|^2 + |\tilde{h}_{\times}(f)|^2) \\ &\approx \frac{\pi^2 c^3}{G} \mathcal{D}^2 f_0^2 h_{\text{rss}}^2, \end{aligned} \quad (2)$$

where  $\mathcal{D}$  is the distance to the source and  $\tilde{h}$  indicates a Fourier transform. To estimate the  $h_{\text{rss}}$  at 50% detection efficiency, we add simulated waveforms coherently to detector data, uniformly distributed in time and over sky locations. The waveform polarization angle and the cosine of the inclination are also varied uniformly. Waveforms are generated at a variety of distances (or equivalently  $h_{\text{rss}}$ ) such that the 50% detection efficiency is well-measured. The events reconstructed are then “detected” if their false alarm rate is lower than the chosen value of 1/50 years.

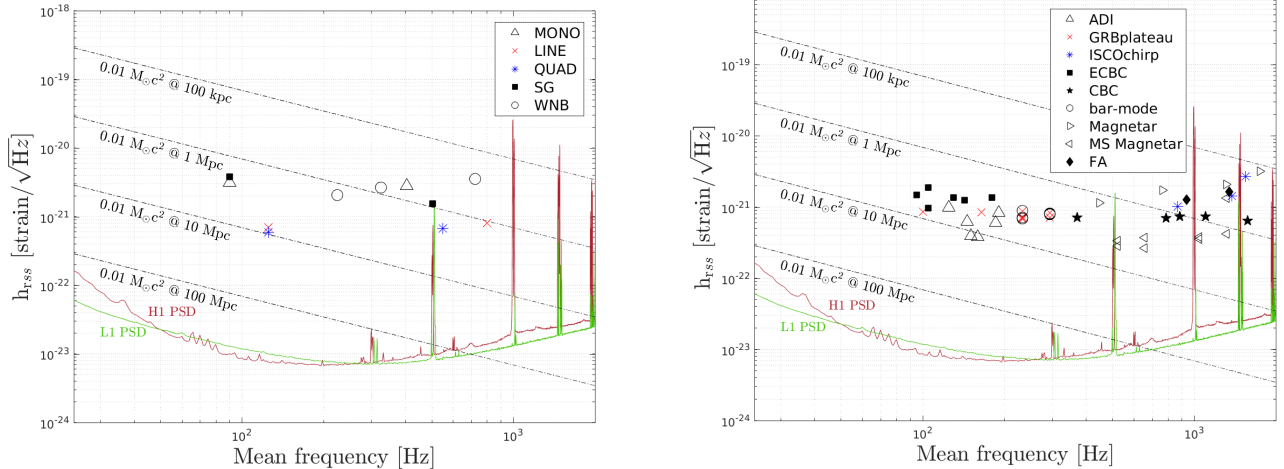
We use 13 families of simulated gravitational-wave signals to estimate the sensitivity of each pipeline. The waveform families include a variety of astrophysically motivated waveforms and ad-hoc waveform models. For the astrophysical models, we include fallback accretion onto neutron stars (FA) (Piro & Thrane 2012), broadband chirps from innermost stable circular orbit waves around rotating black holes (ISCOchirp) (van Putten 2016), inspiral-only compact binary coalescence waveforms up to 2nd post-Newtonian order (Blanchet et al. 1996) (CBC), eccentric inspiral-merger-ringdown compact binary coalescence waveforms (ECBC) (Huerta et al. 2018), secular bar-mode instabilities in post-merger remnants (Lai & Shapiro 1995; Corsi & Mészáros 2009), newly formed magnetar powering a gamma-ray burst plateau (GRBplateau) (Corsi & Mészáros 2009), black hole accretion disk instabilities (ADI) (van Putten 2001), post-merger magnetars (magnetar) (Dall’Osso et al. 2015), and neutron star spin down waveforms (MSmagnetar) (Lasky et al. 2017; Sarin et al. 2018).

For the ad-hoc waveforms, we include monochromatic waveforms (MONO), waveforms with a linear (LINE), quadratic (QUAD) frequency evolution, white noise band-limited (WNB) and sine-Gaussian bursts (SG). The waveforms are designed to span a range of astrophysical models, as well as a wide duration and frequency parameter space to test the response of the algorithms across the parameter space. Figure 1 shows the coverage of a representative sample of the simulation set in the time-frequency space. The frequency band 10-300 Hz are well covered with the GRBplateau and ADI families. Astrophysical waveform families such as ISCOchirp and magnetar are characterised by a wide frequency coverage and populate the higher frequency band 700-2000 Hz. Ad-hoc waveform families such as MONO, LINE, QUAD, WNB and SG span a wide frequency range and covers the band 50-800 Hz, filling in any potential gap in coverage from the other models.

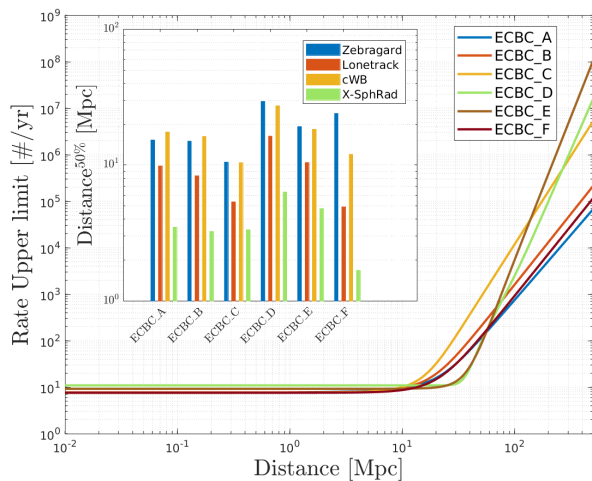
In Figure 2, we show the best results among all pipelines for almost all waveforms. We also compute the 90% confidence level limit on the rate of long-duration gravitational-wave transients assuming a Poissonian distribution of sources. To do so, we use the loudest event statistic method (Brady et al. 2004). We fold in the systematic uncertainty that arises from the strain amplitude calibration, which is 7% in amplitude and 3 degrees in phase, a conservative number used for both instruments in the frequency band analyzed here (Cahillane et al. 2017).

Figure 3 shows the rate as a function of distance for the eccentric compact binary coalescence signals considered in this analysis. For a 1.4 – 1.4 solar mass binary with an eccentricity of 0.4, the 50% efficiency distance is 30 Mpc. For comparison, this is more than a factor 2 lower than what matched filter searches could reach for 1.4 – 1.4 solar mass binaries with no eccentricity during the second observation run (Abbott et al. 2017d). Due to the improved sensitivity and greater duration of the second observation run above and beyond the first observation run, the rate limits for models used in previous analyses improved by a factor of  $\sim 30\%$ . The detection distances vary significantly from one signal to another. For example, the ADI waveforms have distance limits of tens of megaparsecs, while the magnetar waveforms have limits of tens of kiloparsecs. The difference in ranges is due mainly to the energy budget of the system, but also due to the overall signal morphologies, which can be more or less difficult for the pipeline clustering techniques to recover entirely.

## 5. CONCLUSIONS



**Figure 2.** Upper limits on gravitational-wave strain versus frequency for sources detected with 50% efficiency and a false alarm rate of 1 event in 50 years. The lowest value among all 4 pipelines is represented on the plots. The left figure shows the “ad-hoc” waveforms’ results while the “physical” waveforms are represented on the right. The average amplitude spectral density curves for both Hanford and Livingston are also shown.



**Figure 3.** Upper limits (marginalizing over the second observation run amplitude calibration errors) on eccentric compact binary coalescences as a function of the distance at a 90% confidence level considering the best results for each waveform. The inset shows the distance at 50% detection efficiency for the pipelines in this analysis for comparison. ECBC\_A, ECBC\_B, and ECBC\_C are 1.4 – 1.4 solar mass binaries with eccentricities of 0.2, 0.4, and 0.6 respectively, while ECBC\_D, ECBC\_E, and ECBC\_F are 3.0 – 3.0 solar mass binaries with eccentricities of 0.2, 0.4, and 0.6 respectively, where the masses are quoted in the detector frame.

325 We have performed an all-sky search for unmodeled  
 326 long-duration gravitational-wave transients in the sec-  
 327 ond observing run. This search did not lead to the de-  
 328 tection of any new gravitational waves. In addition to  
 329 the intrinsic gain due to detectors’ sensitivity improve-

330 ment and the length of the observing run, we have in-  
 331 creased significantly the number of waveforms used to  
 332 estimate the pipelines’ sensitivity. The theoretical un-  
 333 certainties of the models used are rather large, including  
 334 the mechanisms, their amplitudes, and their potential  
 335 rates, although it is likely we are sensitive to relatively  
 336 small amplitude emissions within the Local Group.

337 With the recent arrival of Advanced Virgo to the ad-  
 338 vanced gravitational-wave detector network, its future  
 339 improvements will merit its inclusion in analyses in the  
 340 next observing runs. Overall, the expectation is that the  
 341 design sensitivities for the gravitational-wave networks  
 342 will yield gains of up to a factor of 10, depending on the  
 343 frequency range considered (Abbott et al. 2018c).

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 552 B. R. IYER,<sup>18</sup> T. JACQMIN,<sup>72</sup> S. J. JADHAV,<sup>143</sup> K. JANI,<sup>77</sup> N. N. JANTHALUR,<sup>143</sup> P. JARANOWSKI,<sup>144</sup> D. JARIWALA,<sup>30</sup>  
 553 A. C. JENKINS,<sup>145</sup> J. JIANG,<sup>30</sup> D. S. JOHNSON,<sup>19</sup> A. W. JONES,<sup>13</sup> D. I. JONES,<sup>146</sup> J. D. JONES,<sup>46</sup> R. JONES,<sup>45</sup>  
 554 R. J. G. JONKER,<sup>36</sup> L. JU,<sup>65</sup> J. JUNKER,<sup>9,10</sup> C. V. KALAGHATGI,<sup>105</sup> V. KALOGERA,<sup>57</sup> B. KAMAI,<sup>1</sup> S. KANDHASAMY,<sup>3</sup>  
 555 G. KANG,<sup>37</sup> J. B. KANNER,<sup>1</sup> S. J. KAPADIA,<sup>24</sup> S. KARKI,<sup>71</sup> R. KASHYAP,<sup>18</sup> M. KASPRZACK,<sup>1</sup> S. KATSANEVAS,<sup>29</sup>  
 556 E. KATSAVOUNIDIS,<sup>14</sup> W. KATZMAN,<sup>7</sup> S. KAUFER,<sup>10</sup> K. KAWABE,<sup>46</sup> N. V. KEERTHANA,<sup>3</sup> F. KÉFÉLIAN,<sup>64</sup> D. KEITEL,<sup>139</sup>  
 557 R. KENNEDY,<sup>111</sup> J. S. KEY,<sup>147</sup> F. Y. KHALILI,<sup>60</sup> I. KHAN,<sup>16,31</sup> S. KHAN,<sup>9,10</sup> E. A. KHAZANOV,<sup>148</sup> N. KHETAN,<sup>16,17</sup>  
 558 M. KHURSHED,<sup>59</sup> N. KIJUNCHOO,<sup>8</sup> CHUNGLEE KIM,<sup>149</sup> J. C. KIM,<sup>150</sup> K. KIM,<sup>92</sup> W. KIM,<sup>56</sup> W. S. KIM,<sup>151</sup> Y.-M. KIM,<sup>152</sup>  
 559 C. KIMBALL,<sup>57</sup> P. J. KING,<sup>46</sup> M. KINLEY-HANLON,<sup>45</sup> R. KIRCHHOFF,<sup>9,10</sup> J. S. KISSEL,<sup>46</sup> L. KLEYBOLTE,<sup>133</sup> J. H. KLIKA,<sup>24</sup>  
 560 S. KLIMENKO,<sup>30</sup> T. D. KNOWLES,<sup>38</sup> P. KOCH,<sup>9,10</sup> S. M. KOEHLLENBECK,<sup>9,10</sup> G. KOEKOEK,<sup>36,153</sup> S. KOLEY,<sup>36</sup>  
 561 V. KONDRASHOV,<sup>1</sup> A. KONTOS,<sup>154</sup> N. KOPER,<sup>9,10</sup> M. KOROBKO,<sup>133</sup> W. Z. KORTH,<sup>1</sup> M. KOVALAM,<sup>65</sup> D. B. KOZAK,<sup>1</sup>  
 562 C. KRÄMER,<sup>9,10</sup> V. KRINGEL,<sup>9,10</sup> N. KRISHNENDU,<sup>155</sup> A. KRŮLÁK,<sup>156,157</sup> N. KRUPINSKI,<sup>24</sup> G. KUEHN,<sup>9,10</sup> A. KUMAR,<sup>143</sup>  
 563 P. KUMAR,<sup>158</sup> RAHUL KUMAR,<sup>46</sup> RAKESH KUMAR,<sup>110</sup> L. KUO,<sup>89</sup> A. KUTYNIA,<sup>156</sup> S. KWANG,<sup>24</sup> B. D. LACKEY,<sup>75</sup>  
 564 D. LAGHI,<sup>20,21</sup> K. H. LAI,<sup>92</sup> T. L. LAM,<sup>92</sup> M. LANDRY,<sup>46</sup> B. B. LANE,<sup>14</sup> R. N. LANG,<sup>159</sup> J. LANGE,<sup>61</sup> B. LANTZ,<sup>50</sup>  
 565 R. K. LANZA,<sup>14</sup> A. LARTAUX-VOLLARD,<sup>28</sup> P. D. LASKY,<sup>6</sup> M. LAXEN,<sup>7</sup> A. LAZZARINI,<sup>1</sup> C. LAZZARO,<sup>53</sup> P. LEACI,<sup>118,32</sup>  
 566 S. LEAVEY,<sup>9,10</sup> Y. K. LECOEUICHE,<sup>46</sup> C. H. LEE,<sup>95</sup> H. K. LEE,<sup>160</sup> H. M. LEE,<sup>161</sup> H. W. LEE,<sup>150</sup> J. LEE,<sup>94</sup> K. LEE,<sup>45</sup>  
 567 J. LEHMANN,<sup>9,10</sup> A. K. LENON,<sup>38</sup> N. LEROY,<sup>28</sup> N. LETENDRE,<sup>33</sup> Y. LEVIN,<sup>6</sup> A. LI,<sup>92</sup> J. LI,<sup>82</sup> K. J. L. LI,<sup>92</sup> T. G. F. LI,<sup>92</sup>  
 568 X. LI,<sup>47</sup> F. LIN,<sup>6</sup> F. LINDE,<sup>162,36</sup> S. D. LINKER,<sup>132</sup> T. B. LITTENBERG,<sup>163</sup> J. LIU,<sup>65</sup> X. LIU,<sup>24</sup> M. LLORENS-MONTEAGUDO,<sup>22</sup>  
 569 R. K. L. LO,<sup>92,1</sup> L. T. LONDON,<sup>14</sup> A. LONGO,<sup>164,165</sup> M. LORENZINI,<sup>16,17</sup> V. LORIETTE,<sup>166</sup> M. LORMAND,<sup>7</sup> G. LOSURDO,<sup>21</sup>  
 570 J. D. LOUGH,<sup>9,10</sup> C. O. LOUSTO,<sup>61</sup> G. LOVELACE,<sup>27</sup> M. E. LOWER,<sup>167</sup> H. LÜCK,<sup>10,9</sup> D. LUMACA,<sup>84,31</sup> A. P. LUNDGREN,<sup>139</sup>  
 571 R. LYNCH,<sup>14</sup> Y. MA,<sup>47</sup> R. MACAS,<sup>105</sup> S. MACFOY,<sup>25</sup> M. MACINNIS,<sup>14</sup> D. M. MACLEOD,<sup>105</sup> A. MACQUET,<sup>64</sup>  
 572 I. MAGAÑA HERNANDEZ,<sup>24</sup> F. MAGAÑA-SANDEVAL,<sup>30</sup> R. M. MAGEE,<sup>88</sup> E. MAJORANA,<sup>32</sup> I. MAKSIMOVIC,<sup>166</sup> A. MALIK,<sup>59</sup>  
 573 N. MAN,<sup>64</sup> V. MANDIC,<sup>42</sup> V. MANGANO,<sup>45,118,32</sup> G. L. MANSELL,<sup>46,14</sup> M. MANSKE,<sup>24</sup> M. MANTOVANI,<sup>29</sup> M. MAPELLI,<sup>52,53</sup>  
 574 F. MARCHESONI,<sup>51,40</sup> F. MARION,<sup>33</sup> S. MÁRKA,<sup>104</sup> Z. MÁRKA,<sup>104</sup> C. MARKAKIS,<sup>19</sup> A. S. MARKOSYAN,<sup>50</sup> A. MARKOWITZ,<sup>1</sup>  
 575 E. MAROS,<sup>1</sup> A. MARQUINA,<sup>103</sup> S. MARSAT,<sup>26</sup> F. MARTELLI,<sup>62,63</sup> I. W. MARTIN,<sup>45</sup> R. M. MARTIN,<sup>35</sup> V. MARTINEZ,<sup>78</sup>  
 576 D. V. MARTYNOV,<sup>13</sup> H. MASALEHDAN,<sup>133</sup> K. MASON,<sup>14</sup> E. MASSERA,<sup>111</sup> A. MASSEROT,<sup>33</sup> T. J. MASSINGER,<sup>1</sup>  
 577 M. MASSO-REID,<sup>45</sup> S. MASTROGIOVANNI,<sup>26</sup> A. MATAS,<sup>75</sup> F. MATICHARD,<sup>1,14</sup> L. MATONE,<sup>104</sup> N. MAVALVALA,<sup>14</sup>  
 578 J. J. McCANN,<sup>65</sup> R. MCCARTHY,<sup>46</sup> D. E. McCLELLAND,<sup>8</sup> S. MCCORMICK,<sup>7</sup> L. McCULLER,<sup>14</sup> S. C. McGUIRE,<sup>168</sup>  
 579 C. McISAAC,<sup>139</sup> J. McIVER,<sup>1</sup> D. J. McMANUS,<sup>8</sup> T. McRAE,<sup>8</sup> S. T. McWILLIAMS,<sup>38</sup> D. MEACHER,<sup>24</sup> G. D. MEADORS,<sup>6</sup>  
 580 M. MEHMET,<sup>9,10</sup> A. K. MEHTA,<sup>18</sup> J. MEIDAM,<sup>36</sup> E. MEJUTO VILLA,<sup>115,68</sup> A. MELATOS,<sup>99</sup> G. MENDELL,<sup>46</sup> R. A. MERCER,<sup>24</sup>  
 581 L. MERENI,<sup>23</sup> K. MERFELD,<sup>71</sup> E. L. MERILH,<sup>46</sup> M. MERZOGUIG,<sup>64</sup> S. MESHKOV,<sup>1</sup> C. MESSENGER,<sup>45</sup> C. MESSICH,<sup>88</sup>  
 582 F. MESSINA,<sup>43,44</sup> R. METZDORFF,<sup>72</sup> P. M. MEYERS,<sup>99</sup> F. MEYLAHN,<sup>9,10</sup> A. MIANI,<sup>116,117</sup> H. MIAO,<sup>13</sup> C. MICHEL,<sup>23</sup>  
 583 H. MIDDLETON,<sup>99</sup> L. MILANO,<sup>79,5</sup> A. L. MILLER,<sup>30,118,32</sup> M. MILLHOUSE,<sup>99</sup> J. C. MILLS,<sup>105</sup> M. C. MILOVICH-GOFF,<sup>132</sup>  
 584 O. MINAZZOLI,<sup>64,169</sup> Y. MINENKOV,<sup>31</sup> A. MISHKIN,<sup>30</sup> C. MISHRA,<sup>170</sup> T. MISTRY,<sup>111</sup> S. MITRA,<sup>3</sup> V. P. MITROFANOV,<sup>60</sup>  
 585 G. MITSELMAKHER,<sup>30</sup> R. MITTLEMAN,<sup>14</sup> G. MO,<sup>96</sup> D. MOFFA,<sup>120</sup> K. MOGUSHI,<sup>85</sup> S. R. P. MOHAPATRA,<sup>14</sup>  
 586 M. MOLINA-RUIZ,<sup>140</sup> M. MONDIN,<sup>132</sup> M. MONTANI,<sup>62,63</sup> C. J. MOORE,<sup>13</sup> D. MORARU,<sup>46</sup> F. MORAWSKI,<sup>55</sup> G. MORENO,<sup>46</sup>  
 587 S. MORISAKI,<sup>81</sup> B. MOURS,<sup>33</sup> C. M. MOW-LOWRY,<sup>13</sup> F. MUCIACCIA,<sup>118,32</sup> ARUNAVA MUKHERJEE,<sup>9,10</sup> D. MUKHERJEE,<sup>24</sup>  
 588 S. MUKHERJEE,<sup>107</sup> SUBROTO MUKHERJEE,<sup>110</sup> N. MUKUND,<sup>9,10,3</sup> A. MULLAVEY,<sup>7</sup> J. MUNCH,<sup>56</sup> E. A. MUÑIZ,<sup>41</sup>  
 589 M. MURATORE,<sup>34</sup> P. G. MURRAY,<sup>45</sup> A. NAGAR,<sup>87,126,171</sup> I. NARDECCHIA,<sup>84,31</sup> L. NATICCHIONI,<sup>118,32</sup> R. K. NAYAK,<sup>172</sup>  
 590 B. F. NEIL,<sup>65</sup> J. NEILSON,<sup>115,68</sup> G. NELEMANS,<sup>66,36</sup> T. J. N. NELSON,<sup>7</sup> M. NERY,<sup>9,10</sup> A. NEUNZERT,<sup>136</sup> L. NEVIN,<sup>1</sup>  
 591 K. Y. NG,<sup>14</sup> S. NG,<sup>56</sup> C. NGUYEN,<sup>26</sup> P. NGUYEN,<sup>71</sup> D. NICHOLS,<sup>141,36</sup> S. A. NICHOLS,<sup>2</sup> S. NISSANKE,<sup>141,36</sup> F. NOCERA,<sup>29</sup>  
 592 C. NORTH,<sup>105</sup> L. K. NUTTALL,<sup>139</sup> M. OBERGAULINGER,<sup>22,173</sup> J. OBERLING,<sup>46</sup> B. D. O'BRIEN,<sup>30</sup> G. OGANESYAN,<sup>16,17</sup>  
 593 G. H. OGIN,<sup>174</sup> J. J. OH,<sup>151</sup> S. H. OH,<sup>151</sup> F. OHME,<sup>9,10</sup> H. OHTA,<sup>81</sup> M. A. OKADA,<sup>15</sup> M. OLIVER,<sup>100</sup> P. OPPERMANN,<sup>9,10</sup>  
 594 RICHARD J. ORAM,<sup>7</sup> B. O'REILLY,<sup>7</sup> R. G. ORMISTON,<sup>42</sup> L. F. ORTEGA,<sup>30</sup> R. O'SHAUGHNESSY,<sup>61</sup> S. OSSOKINE,<sup>75</sup>  
 595 D. J. OTTAWAY,<sup>56</sup> H. OVERMIER,<sup>7</sup> B. J. OWEN,<sup>83</sup> A. E. PACE,<sup>88</sup> G. PAGANO,<sup>20,21</sup> M. A. PAGE,<sup>65</sup> G. PAGLIAROLI,<sup>16,17</sup>  
 596 A. PAI,<sup>129</sup> S. A. PAI,<sup>59</sup> J. R. PALAMOS,<sup>71</sup> O. PALASHOV,<sup>148</sup> C. PALOMBA,<sup>32</sup> H. PAN,<sup>89</sup> P. K. PANDA,<sup>143</sup> P. T. H. PANG,<sup>92,36</sup>  
 597 C. PANKOW,<sup>57</sup> F. PANNARALE,<sup>118,32</sup> B. C. PANT,<sup>59</sup> F. PAOLETTI,<sup>21</sup> A. PAOLI,<sup>29</sup> A. PARIDA,<sup>3</sup> W. PARKER,<sup>7,168</sup>  
 598 D. PASCUCCI,<sup>45,36</sup> A. PASQUALETTI,<sup>29</sup> R. PASSAQUIETI,<sup>20,21</sup> D. PASSUELLO,<sup>21</sup> M. PATIL,<sup>157</sup> B. PATRICELLI,<sup>20,21</sup> E. PAYNE,<sup>6</sup>  
 599 B. L. PEARLSTONE,<sup>45</sup> T. C. PECHSIRI,<sup>30</sup> A. J. PEDERSEN,<sup>41</sup> M. PEDRAZA,<sup>1</sup> R. PEDURAND,<sup>23,175</sup> A. PELE,<sup>7</sup> S. PENN,<sup>176</sup>  
 600 A. PEREGO,<sup>116,117</sup> C. J. PEREZ,<sup>46</sup> C. PÉRIGOS,<sup>33</sup> A. PERRECA,<sup>116,117</sup> J. PETERMANN,<sup>133</sup> H. P. PFEIFFER,<sup>75</sup> M. PHELPS,<sup>9,10</sup>  
 601 K. S. PHUKON,<sup>3</sup> O. J. PICCINI,<sup>118,32</sup> M. PICHOT,<sup>64</sup> F. PIERGIOVANNI,<sup>62,63</sup> V. PIERRO,<sup>115,68</sup> G. PILLANT,<sup>29</sup> L. PINARD,<sup>23</sup>  
 602 I. M. PINTO,<sup>115,68,87</sup> M. PIRELLO,<sup>46</sup> M. PITKIN,<sup>45</sup> W. PLASTINO,<sup>164,165</sup> R. POGGIANI,<sup>20,21</sup> D. Y. T. PONG,<sup>92</sup>  
 603 S. PONRATHNAM,<sup>3</sup> P. POPOLIZIO,<sup>29</sup> E. K. PORTER,<sup>26</sup> J. POWELL,<sup>167</sup> A. K. PRAJAPATI,<sup>110</sup> J. PRASAD,<sup>3</sup> K. PRASAI,<sup>50</sup>

604 R. PRASANNA,<sup>143</sup> G. PRATTEN,<sup>100</sup> T. PRESTEGARD,<sup>24</sup> M. PRINCIPE,<sup>115,87,68</sup> G. A. PRODI,<sup>116,117</sup> L. PROKHOROV,<sup>13</sup>  
 605 M. PUNTURO,<sup>40</sup> P. PUPPO,<sup>32</sup> M. PÜRRER,<sup>75</sup> H. QI,<sup>105</sup> V. QUETSCHKE,<sup>107</sup> P. J. QUINONEZ,<sup>34</sup> F. J. RAAB,<sup>46</sup>  
 606 G. RAAIJMAKERS,<sup>141,36</sup> H. RADKINS,<sup>46</sup> N. RADULESCO,<sup>64</sup> P. RAFFAI,<sup>109</sup> S. RAJA,<sup>59</sup> C. RAJAN,<sup>59</sup> B. RAJBHANDARI,<sup>83</sup>  
 607 M. RAKHMANOV,<sup>107</sup> K. E. RAMIREZ,<sup>107</sup> A. RAMOS-BUADES,<sup>100</sup> JAVED RANA,<sup>3</sup> K. RAO,<sup>57</sup> P. RAPAGNANI,<sup>118,32</sup>  
 608 V. RAYMOND,<sup>105</sup> M. RAZZANO,<sup>20,21</sup> J. READ,<sup>27</sup> T. REGIMBAU,<sup>33</sup> L. REI,<sup>58</sup> S. REID,<sup>25</sup> D. H. REITZE,<sup>1,30</sup> P. RETTEGNO,<sup>126,177</sup>  
 609 F. RICCI,<sup>118,32</sup> C. J. RICHARDSON,<sup>34</sup> J. W. RICHARDSON,<sup>1</sup> P. M. RICKER,<sup>19</sup> G. RIEMENSCHNEIDER,<sup>177,126</sup> K. RILES,<sup>136</sup>  
 610 M. RIZZO,<sup>57</sup> N. A. ROBERTSON,<sup>1,45</sup> F. ROBINET,<sup>28</sup> A. ROCCHI,<sup>31</sup> L. ROLLAND,<sup>33</sup> J. G. ROLLINS,<sup>1</sup> V. J. ROMA,<sup>71</sup>  
 611 M. ROMANELLI,<sup>70</sup> R. ROMANO,<sup>4,5</sup> C. L. ROMEL,<sup>46</sup> J. H. ROMIE,<sup>7</sup> C. A. ROSE,<sup>24</sup> D. ROSE,<sup>27</sup> K. ROSE,<sup>120</sup> D. ROSIŃSKA,<sup>73</sup>  
 612 S. G. ROSOFSKY,<sup>19</sup> M. P. ROSS,<sup>178</sup> S. ROWAN,<sup>45</sup> A. RÜDIGER,<sup>9,10,\*</sup> P. RUGGI,<sup>29</sup> G. RUTINS,<sup>131</sup> K. RYAN,<sup>46</sup> S. SACHDEV,<sup>88</sup>  
 613 T. SADECKI,<sup>46</sup> M. SAKELLARIADOU,<sup>145</sup> O. S. SALAFIA,<sup>179,43,44</sup> L. SALCONI,<sup>29</sup> M. SALEEM,<sup>155</sup> A. SAMAJDAR,<sup>36</sup> L. SAMMUT,<sup>6</sup>  
 614 E. J. SANCHEZ,<sup>1</sup> L. E. SANCHEZ,<sup>1</sup> N. SANCHIS-GUAL,<sup>180</sup> J. R. SANDERS,<sup>181</sup> K. A. SANTIAGO,<sup>35</sup> E. SANTOS,<sup>64</sup> N. SARIN,<sup>6</sup>  
 615 B. SASSOLAS,<sup>23</sup> P. R. SAULSON,<sup>41</sup> O. SAUTER,<sup>136,33</sup> R. L. SAVAGE,<sup>46</sup> P. SCHALE,<sup>71</sup> M. SCHEEL,<sup>47</sup> J. SCHEUER,<sup>57</sup>  
 616 P. SCHMIDT,<sup>13,66</sup> R. SCHNABEL,<sup>133</sup> R. M. S. SCHOFIELD,<sup>71</sup> A. SCHÖNBECK,<sup>133</sup> E. SCHREIBER,<sup>9,10</sup> B. W. SCHULTE,<sup>9,10</sup>  
 617 B. F. SCHUTZ,<sup>105</sup> J. SCOTT,<sup>45</sup> S. M. SCOTT,<sup>8</sup> E. SEIDEL,<sup>19</sup> D. SELLERS,<sup>7</sup> A. S. SENGUPTA,<sup>182</sup> N. SENNETT,<sup>75</sup>  
 618 D. SENTENAC,<sup>29</sup> V. SEQUINO,<sup>58</sup> A. SERGEEV,<sup>148</sup> Y. SETYAWATI,<sup>9,10</sup> D. A. SHADDOCK,<sup>8</sup> T. SHAFFER,<sup>46</sup> M. S. SHAHRIAR,<sup>57</sup>  
 619 M. B. SHANER,<sup>132</sup> A. SHARMA,<sup>16,17</sup> P. SHARMA,<sup>59</sup> P. SHAWHAN,<sup>76</sup> H. SHEN,<sup>19</sup> R. SHINK,<sup>183</sup> D. H. SHOEMAKER,<sup>14</sup>  
 620 D. M. SHOEMAKER,<sup>77</sup> K. SHUKLA,<sup>140</sup> S. SHYAMSUNDRAR,<sup>59</sup> K. SIELLEZ,<sup>77</sup> M. SIENIAWSKA,<sup>55</sup> D. SIGG,<sup>46</sup> L. P. SINGER,<sup>80</sup>  
 621 D. SINGH,<sup>88</sup> N. SINGH,<sup>73</sup> A. SINGHAL,<sup>16,32</sup> A. M. SINTES,<sup>100</sup> S. SITMUKHAMBETOV,<sup>107</sup> V. SKLIRIS,<sup>105</sup> B. J. J. SLAGMOLEN,<sup>8</sup>  
 622 T. J. SLAVEN-BLAIR,<sup>65</sup> J. R. SMITH,<sup>27</sup> R. J. E. SMITH,<sup>6</sup> S. SOMALA,<sup>184</sup> E. J. SON,<sup>151</sup> S. SONI,<sup>2</sup> B. SORAZU,<sup>45</sup>  
 623 F. SORRENTINO,<sup>58</sup> T. SOURADEEP,<sup>3</sup> E. SOWELL,<sup>83</sup> A. P. SPENCER,<sup>45</sup> M. SPERA,<sup>52,53</sup> A. K. SRIVASTAVA,<sup>110</sup> V. SRIVASTAVA,<sup>41</sup>  
 624 K. STAATS,<sup>57</sup> C. STACHIE,<sup>64</sup> M. STANDKE,<sup>9,10</sup> D. A. STEER,<sup>26</sup> M. STEINKE,<sup>9,10</sup> J. STEINLECHNER,<sup>133,45</sup> S. STEINLECHNER,<sup>133</sup>  
 625 D. STEINMEYER,<sup>9,10</sup> S. P. STEVENSON,<sup>167</sup> D. STOCKS,<sup>50</sup> R. STONE,<sup>107</sup> D. J. STOPS,<sup>13</sup> K. A. STRAIN,<sup>45</sup> G. STRATTA,<sup>185,63</sup>  
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