

Fermi-LAT 8-year Source List

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ABSTRACT

We distribute a preliminary *Fermi* Large Area Telescope list of sources (FL8Y) initially meant to help in writing 2018 NASA *Fermi* Guest Investigator proposals. Based on the first eight years of science data from the *Fermi Gamma-ray Space Telescope* mission and the 100 MeV–1 TeV range, it is the deepest yet in this energy range. Relative to the 3FGL catalog, the FL8Y source list has twice as much exposure as well as a number of analysis improvements, but is lacking an updated model for Galactic diffuse γ -ray emission. The FL8Y source list includes 5523 sources above 4σ significance, with source location regions and spectral properties. Fifty-eight sources are modeled explicitly as spatially extended, and overall 300 sources are considered as identified based on angular extent or correlated variability (periodic or otherwise) observed at other wavelengths. For 2131 sources we have not found plausible counterparts at other wavelengths. More than 2900 of the identified or associated sources are active galaxies of the blazar class, 218 are pulsars.

This source list is meant to be replaced within a few months by the official 4FGL catalog which will benefit from an improved model of diffuse emission.

1. Introduction

This document presents a preliminary list of high-energy γ -ray sources detected in the first eight years of the *Fermi Gamma-ray Space Telescope* mission by the Large Area Telescope (LAT). It is not yet a full-fledged official catalog; therefore we call it FL8Y (for *Fermi*-LAT 8-Year). As in the Third LAT Source Catalog (hereafter 3FGL, Acero et al. 2015) sources are included based on the statistical significance of their detection considered over the entire time period of the analysis. For this reason the FL8Y source list does not contain transient γ -ray sources which are significant over a short duration (such as γ -ray bursts).

The FL8Y source list benefits from a number of improvements with respect to 3FGL, besides the twice longer exposure:

- 16 1. Pass 8 data¹ are now used (§ 2.2). The principal difference relative to the P7Rep data
17 used for 3FGL is larger acceptance by about 20% at all energies and improved angular
18 resolution above 3 GeV.
- 19 2. We introduce weights in the maximum likelihood analysis (§ 3.2) in order to mitigate
20 the effect of systematic errors due to our imperfect knowledge of the diffuse emission.
- 21 3. We explicitly model 58 sources as extended emission regions (§ 3.4), up from 25 in
22 3FGL.
- 23 4. For studying the associations of LAT sources with counterparts at other wavelengths,
24 we have updated several of the catalogs used for counterpart searches, and correspond-
25 ingly recalibrated the association procedure.

26 The 4FGL catalog will make use of the same methods, but will adopt an improved diffuse
27 emission model. It will also contain, like 3FGL, spectral energy distributions in broad bins
28 and light curves, which are not provided with FL8Y.

29 Section 2 describes the LAT, the data and the models for the diffuse backgrounds,
30 celestial and otherwise. Section 3 describes how the catalog is constructed, with emphasis
31 on what has changed since the analysis for the 3FGL catalog. We provide appendices with
32 technical details of the analysis and of the format of the electronic version of the catalog.

33 2. Instrument & Background

34 2.1. The Large Area Telescope

35 The LAT detects γ rays in the energy range 20 MeV to more than 1 TeV, measuring
36 their arrival times, energies, and directions. The LAT is also an efficient detector of the
37 intense background of charged particles from cosmic rays and trapped radiation at the orbit
38 of the *Fermi* satellite. Accounting for γ rays lost in filtering charged particles from the
39 data, the effective collecting area is ~ 8000 cm² at 1 GeV at normal incidence (for the
40 P8R3_SOURCE_V2 event selection used here; see below). The live time is nearly 76%,
41 limited primarily by interruptions of data taking when *Fermi* is passing through the South
42 Atlantic Anomaly ($\sim 13\%$) and readout dead-time fraction ($\sim 9\%$). The field of view of the
43 LAT is 2.4 sr at 1 GeV. The per-photon angular resolution (point-spread function, PSF,

¹See http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass8_usage.html.

44 68% containment radius) is $\sim 5^\circ$ at 100 MeV, decreasing to 0.8° at 1 GeV (averaged over
 45 the acceptance of the LAT), varying with energy approximately as $E^{-0.8}$ and asymptoting
 46 at $\sim 0.1^\circ$ above 20 GeV. The tracking section of the LAT has 36 layers of silicon strip
 47 detectors interleaved with 16 layers of tungsten foil (12 thin layers, 0.03 radiation length,
 48 at the top or *Front* of the instrument, followed by 4 thick layers, 0.18 radiation length, in
 49 the *Back* section). The silicon strips track charged particles, and the tungsten foils facilitate
 50 conversion of γ rays to positron-electron pairs. Beneath the tracker is a calorimeter composed
 51 of an 8-layer array of CsI crystals (~ 8.5 total radiation lengths) to determine the γ -ray
 52 energy. A segmented charged-particle anticoincidence detector (plastic scintillators read out
 53 by photomultiplier tubes) around the tracker is used to reject charged-particle background
 54 events. More information about the LAT is provided in Atwood et al. (2009), and the in-
 55 flight calibration of the LAT is described in Abdo et al. (2009c), Ackermann et al. (2012a)
 56 and Ackermann et al. (2012b).

57 2.2. The LAT Data

58 The data for the FL8Y source list were taken during the period 2008 August 4 (15:43
 59 UTC) to 2016 August 2 (5:44 UTC) covering close to eight years. Intervals around 30
 60 bright GRBs were excised. Solar flares were excised as well, as for 3FGL. Overall about two
 61 days were excised due to solar flares, and 39 ks due to GRBs. The precise time intervals
 62 corresponding to selected events are recorded in the GTI extension of the FITS file (App. B).
 63 The maximum acceptance (4.5×10^{11} cm² s at 1 GeV) is reached at the North celestial pole.
 64 The minimum acceptance (2.7×10^{11} cm² s at 1 GeV) is reached at the celestial equator.

65 The current version of the LAT data is Pass 8 P302 (Atwood et al. 2013). It offers 20%
 66 more acceptance than P7Rep and a narrower PSF at high energies. Both aspects are very
 67 useful to source detection and localization (Ajello et al. 2017). We used the Source class
 68 event selection. The lower bound of the energy range was left at 100 MeV, but the upper
 69 bound was raised to 1 TeV. This is because as the source-to-background ratio decreases, the
 70 sensitivity curve (Figure 18 of Abdo et al. 2010b, 1FGL) shifts to higher energies.

71 A residual non-isotropic instrumental background component is apparent in the P302
 72 data at all energies, peaking in a broad ring around the ecliptic equator. The LAT collabora-
 73 tion has recently understood that this background was arising from electrons and positrons
 74 leaking through the scintillating ribbons between the anticoincidence tiles. That leakage is
 75 most pronounced perpendicular to the tiles, and the ecliptic axis of symmetry is due to the
 76 orientation of the solar panels toward the Sun. Since we do not have a good model of this
 77 instrumental background, we chose to reduce it to a negligible level ($< 1\%$ of the astrophysi-

78 cal background) by cutting harder on the ribbon-related reconstruction variables. That data
79 set is called P305, and the associated calibration is P8R3_SOURCE_V2. The effective area
80 is within 1% of the official P8R2_SOURCE_V6 at all energies, so the acceptance loss is very
81 small.

82 **2.3. Model for the Diffuse Gamma-Ray Background**

83 *2.3.1. Diffuse emission of the Milky Way*

84 An update to the Galactic diffuse emission model is in preparation and will be used in
85 4FGL, but for FL8Y we used the 3FGL model (Acero et al. 2016a) adapted to the Pass 8
86 data². This is the major limitation of the FL8Y source list.

87 *2.3.2. Isotropic background*

88 The isotropic diffuse background was derived from all-sky fits of the four-year data set
89 using the Galactic diffuse emission model described above and the 3FGL source list. The
90 diffuse background includes charged particles misclassified as γ rays. We implicitly assume
91 that the acceptance for these residual charged particles is the same as for γ rays in treating
92 these diffuse background components together. For the analysis we derived the contributions
93 to the isotropic background separately for all event types.

94 *2.3.3. Solar and lunar template*

95 The quiescent Sun and the Moon are fairly bright γ -ray sources. The Sun moves in
96 the ecliptic but the solar γ -ray emission is extended because of cosmic-ray interactions with
97 the solar radiation field; detectable emission from inverse Compton scattering of cosmic-ray
98 electrons on the radiation field of the Sun extends several degrees from the Sun (Abdo et al.
99 2011). The Moon is not an extended source in this way but the lunar orbit is inclined
100 somewhat relative to the ecliptic and the Moon moves through a larger fraction of the sky
101 than the Sun. Averaged over time, the γ -ray emission from the Sun and Moon trace a region
102 around the ecliptic.

²The model is available as `gll_iem.v06.fit` from the FSSC.

103 The Sun and Moon emission are modulated by the solar magnetic field which deflects
104 cosmic rays more (and therefore reduces γ -ray emission) when the Sun is at maximum
105 activity. For that reason the model used in 3FGL (based on the first 18 months of data
106 when the Sun was near minimum) was not adequate for 8 years. We used the improved
107 model of the Moon (Ackermann et al. 2016a) and a similar model of the solar disk (S. Raino,
108 private communication). We did not change the model of inverse Compton scattering on the
109 solar light.

110 We combined those models with calculations of their motions and of the exposure of
111 the observations by the LAT to make templates for the equivalent diffuse component for the
112 3FGL analysis using *gtsuntemp* (Johannesson et al. 2013). We reduced the pixel size used to
113 compute the emission from the solar and lunar disks to $0^\circ.125$ in order to follow their paths
114 accurately. As for 3FGL those components have no free parameter.

115 *2.3.4. Residual Earth limb template*

116 For 3FGL we reduced the low-energy Earth limb emission by selecting zenith angles
117 less than 100° , and modeled the residual contamination approximately. For FL8Y (except
118 in § 3.1 which used the same approach as 3FGL) we chose to reject it by cutting harder
119 on zenith angle at low energies and selecting event types with the best PSF. The zenith
120 angle cut was set such that the contribution of the Earth limb at that zenith angle was less
121 than 10% of the total background. Integrated over all zenith angles, the residual Earth limb
122 contamination is less than 1%. We kept PSF2 and PSF3 event types with zenith angles less
123 than 90° between 100 and 300 MeV, and PSF1, PSF2 and PSF3 event types with zenith
124 angles less than 100° between 300 MeV and 1 GeV. Above 1 GeV we kept all events with
125 zenith angles less than 105° .

126 Selecting on zenith angle applies a kind of time selection (which depends on direction in
127 the sky). This means that the effective time selection at low energy is not exactly the same as
128 at high energy. That time selection is mostly on time scales (at orbit level) shorter than the
129 variability time scales of astrophysical sources. There remains however a modulation due to
130 the precession of the spacecraft orbit on longer time scales (two months) over which blazars
131 can vary. This is not a problem for a catalog (it can at most appear as a spectral effect, and
132 should average out when considering statistical properties) but it should be kept in mind
133 when extracting spectral parameters of individual variable sources. We used the same zenith
134 angle cut for all event types in a given energy interval in order to reduce systematics due to
135 that time selection.

136 Because the data are limited by systematics at low energies everywhere in the sky
 137 (App. A) rejecting half of the data below 300 MeV does not impact the sensitivity (if we
 138 had kept this data, the weights would have been lower).

139 3. Construction of the Catalog

140 The procedure used to construct the FL8Y source list has a number of improvements rel-
 141 ative to what was implemented for the 3FGL catalog. In this section we review the procedure,
 142 with an emphasis on what is being done differently. The significances (§ 3.2) and spectral
 143 parameters (§ 3.3) of all catalog sources were obtained using the standard *pyLikelihood*
 144 framework (Python analog of *gtlike*) in the LAT Science Tools³ (version v11r7p0). The
 145 localization procedure (§ 3.1), which relies on *pointlike*, provided the source positions, the
 146 starting point for the spectral fitting, and a comparison for estimating the reliability of the
 147 results (§ 3.5.2). Throughout the text we use the Test Statistic $TS = 2\Delta \log \mathcal{L}$ to quantify
 148 how significantly a source emerges from the background, comparing the maximum value of
 149 the likelihood function \mathcal{L} with and without that source.

150 3.1. Detection and Localization

151 This section describes the generation of a list of candidate sources, with locations and
 152 initial spectral fits, for processing by the standard LAT science analysis tools, especially
 153 *gtlike* to compute the likelihood (§ 3.2). This initial stage uses instead *pointlike* (Kerr
 154 2010). Compared with the *gtlike*-based analysis described in § 3.2 to 3.5, it uses the same
 155 data, exposure, and IRFs, but the partitioning of the sky, the computation of the likelihood
 156 function, and its optimization, are independent. Since this version of the computation of
 157 the likelihood function is used for localization, it needs to represent a valid estimate of the
 158 probability of observing a point source with the assumed spectral function.

159 The process started with an initial set of sources from the 3FGL analysis, not just those
 160 reported in that catalog, but also including all candidates failing the significance threshold
 161 (i.e., with $TS < 25$). It also used the same list of 58 spatially extended source (§ 3.4), and the
 162 three-source representation of the Crab (§ 3.3). The same spectral models were considered
 163 for each source as in § 3.3, but the favored model (power law or curved) was not necessarily
 164 the same.

³See <http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/>.

165 Many details of the processing were identical to the 3FGL procedure: using HEALPix⁴
 166 (Górski et al. 2005) with $N_{\text{side}} = 12$, to tile the sky, resulting in 1728 tiles of $\sim 25 \text{ deg}^2$ area;
 167 optimizing spectral parameters for the sources within each tile, for the data in a cone of 5°
 168 radius about the center of the tile; and including the contributions of all sources within 10°
 169 of the center. The tiles are of course discrete, but the regions, which we refer to as RoIs, for
 170 Regions of Interest, are overlapping and not independent. The data were binned in energy
 171 (16 energy bands from 100 MeV to 1 TeV) and position, where the spatial bin size (the bins
 172 also defined using HEALPix) was set to be small compared with the PSF for each energy,
 173 and event type. The parameter optimization was performed by maximizing the logarithm of
 174 the likelihood, expressed as a sum over each energy band and each of the *Front* and *Back*
 175 event types, independently for each RoI. Correlations between sources in neighboring RoIs
 176 were then accounted for by iterating all 1728 fits until the changes in the log likelihoods for
 177 all RoIs were less than 10.

178 After a set of iterations had converged, the localization procedure was applied, and
 179 source positions updated for a new set of iterations. At this stage, new sources were occa-
 180 sionally added using the residual TS procedure described below. The detection and localiza-
 181 tion process resulted in ~ 13300 candidate point sources with $TS > 10$. The fit validation,
 182 Galactic diffuse renormalization and likelihood weighting were done as in 3FGL.

183 3.1.1. Detection of additional sources

184 We used the *pointlike* definition of likelihood itself to detect sources that needed to be
 185 added to the model of the sky. Using HEALPix with $N_{\text{side}} = 512$, we defined 3.2 M pixels in
 186 the sky, separated by $\simeq 0^\circ:15$, then evaluated the improvement in the likelihood from adding
 187 a new point source at the center of each.

188 An improvement with respect to 3FGL is that we considered four different possible
 189 spectral shapes:

- 190 • a power-law spectrum with photon index 2.1
- 191 • a harder power-law spectrum with photon index 1.7
- 192 • a softer power-law spectrum with photon index 2.4
- 193 • a pulsar-like spectrum (Eq. 2) with $\Gamma = 1.7$, $a = 3.33 \times 10^{-4} \text{ MeV}^{-1}$ and $b = 1$.

⁴<http://healpix.sourceforge.net>.

194 The TS value for each attempt, assigned to the pixel, defines a residual TS map of the sky.
 195 Next we performed a cluster analysis for all pixels with $TS > 10$, determining the number
 196 of pixels, the maximum TS , and the TS -weighted centroid. All such clusters with at least
 197 two pixels were added to a list of seeds. Then each seed was reanalyzed, now allowing the
 198 spectral index to vary, with a full optimization in the respective RoI, and then localized.
 199 The last step was to add all such refit seeds, if the fits to the spectrum and the position were
 200 successful, and $TS > 10$, as new sources, for a final optimization of the full sky.

201

3.1.2. Localization

202 The position of each source was determined by maximizing the likelihood with respect
 203 to its position only. That is, all other parameters are kept fixed. The possibility that a
 204 shifted position would affect the spectral models or positions of nearby sources is accounted
 205 for by iteration. Ideally the log likelihood is a quadratic form in any pair of angular variables,
 206 assuming small angular offsets. We define LTS, for Localization Test Statistic, to be twice the
 207 log of the likelihood ratio of any position with respect to the maximum; the LTS evaluated
 208 for a grid of positions is called an LTS map. We fit the distribution of LTS to a quadratic
 209 form to determine the uncertainty ellipse, the major and minor axes and orientation. We
 210 also define a measure, the localization quality (LQ), of how well the actual LTS distribution
 211 matches this expectation by reporting the sum of the squares of the deviations of eight points
 212 evaluated from the fit at a circle of radius corresponding to twice the geometric mean of the
 213 two Gaussian sigmas.

214 We flagged apparently significant sources that do not have good localization fits (LQ
 215 > 8) with Flag 9 (Table 3) and for them estimated the position and uncertainty by per-
 216 forming a moment analysis of the LTS function instead of fitting a quadratic form. Some
 217 sources that did not have a well-defined peak in the likelihood were discarded by hand, on
 218 the consideration that they were most likely related to residual diffuse emission. Another
 219 possibility is that two adjacent sources produce a dumbbell-like shape; for some of these
 220 cases we added a new source by hand.

221 As in 3FGL, we checked the brightest sources spatially associated with likely multiwave-
 222 length counterparts, comparing their localizations with the well-measured positions of the
 223 counterparts. The smaller statistical source localization errors in FL8Y allowed estimating
 224 the absolute precision more accurately to $\sim 0^{\circ}.0075$ at the 95% confidence level, up from
 225 $\sim 0^{\circ}.005$ in 3FGL. The systematic factor was the same 1.05 as in 3FGL. Consequently, we
 226 multiplied all error estimates by 1.05 and added $0^{\circ}.0075$ in quadrature to both 95% ellipse
 227 axes.

228

3.2. Significance and Thresholding

229 The framework for this stage of the analysis is inherited from the 3FGL catalog. It
 230 splits the sky into RoIs, varying typically half a dozen sources near the center of the RoI at
 231 the same time. There were 2363 RoIs for FL8Y, listed in the `ROI`s extension of the catalog
 232 (App. B). The global best fit is reached iteratively, injecting the spectra of sources in the
 233 outer parts of the RoI from the previous step or iteration. In this approach the diffuse
 234 emission model (§ 2.3) is taken from the global templates (including the spectrum, unlike
 235 what is done with *pointlike* in § 3.1) but it is modulated in each RoI by three parameters:
 236 normalization and small corrective slope of the Galactic component and normalization of
 237 the isotropic component.

238 Among more than 13,000 seeds coming from the localization stage, we keep only sources
 239 at $TS > 25$ with the power-law model, corresponding to a significance of just over 4σ evalu-
 240 ated from the χ^2 distribution with 4 degrees of freedom (position and spectral parameters,
 241 Mattox et al. 1996). The model for the current RoI is readjusted after removing each seed
 242 below threshold, so that the final model fits the full data. The low-energy flux of the seeds
 243 below threshold (a fraction of which are real sources) can be absorbed by neighboring sources
 244 closer than the PSF radius.

245 As in 3FGL we manually added known pulsars that could not be localized by the auto-
 246 matic procedure without phase selection. Only one was considered significant and appears
 247 in FL8Y with a fixed position (no error ellipse). This is PSR J1410–6132 at $TS = 30$ inside
 248 the extended source FGES J1409.1–6121 (Ackermann et al. 2017).

249 We introduced a number of improvements with respect to 3FGL (by decreasing order
 250 of importance):

- 251 1. In 3FGL we had already noted that systematic errors due to an imperfect modeling
 252 of diffuse emission were larger than statistical errors in the Galactic plane, and at the
 253 same level over the entire sky. With a twice longer exposure and improved effective area
 254 at low energy with Pass 8, the effect is now dominant. The approach adopted in 3FGL
 255 (comparing runs with different diffuse models) allowed characterizing the effect globally
 256 and flagging the worst offenders, but left purely statistical errors on source parameters.
 257 In FL8Y we introduce weights in the maximum likelihood approach (App. A). This
 258 allows obtaining directly (although in an approximate way) smaller TS and larger
 259 parameter errors, reflecting the level of systematic uncertainties. We estimated the
 260 systematic level from the spatial and spectral residuals in the Galactic plane where the
 261 diffuse emission is strongest. The resulting $\epsilon \sim 3\%$ was used to compute the weights.
 262 This is by far the most important improvement, which avoids reporting many dubious

263 soft sources.

- 264 2. The automatic iteration procedure at the next-to-last step of the process was improved.
 265 There are now two iteration levels. In a standard iteration the sources and source
 266 models are fixed and only the parameters are free. An RoI and all its neighbors are run
 267 again until $\log \mathcal{L}$ does not change by more than 10 from the previous iteration. Around
 268 that we introduce another iteration level (superiterations). At the first iteration of a
 269 given superiteration we reenter all seeds and remove (one by one) those with $TS < 16$.
 270 We also systematically check curvature significance (§ 3.3) at this first iteration, and
 271 allow sources to switch to a curved spectral shape if $TS_{\text{curv}} > 16$ or force them back
 272 to power law if $TS_{\text{curv}} < 16$. At the end of a superiteration an RoI (and its neighbors)
 273 enters the next superiteration until $\log \mathcal{L}$ does not change by more than 10 from the last
 274 iteration of the previous superiteration. This procedure stabilizes the spectral shapes,
 275 particularly in the Galactic plane. Seven superiterations were required to reach full
 276 convergence.
- 277 3. The fits are now performed up to 1 TeV, and the overall significances (`Signif_Avg`) as
 278 well as the spectral parameters refer to the full 100 MeV to 1 TeV band. The photon
 279 and energy fluxes, on the other hand, are still reported up to 100 GeV, because for
 280 hard sources with photon index less than 2 integrating up to 1 TeV results in much
 281 larger uncertainties.
- 282 4. We considered the effect of energy dispersion, in the approximate way implemented in
 283 the Science Tools. The effect of energy dispersion is calculated globally for each source,
 284 and applied to the whole 3D model of that source, rather than accounting for energy
 285 dispersion separately in each pixel. This approximate method captures the main effect
 286 at a very minor computational cost. The effect of energy dispersion on the spectra is
 287 relatively small. It tends to increase the energy flux (by 4% on average), to reduce
 288 the width of the power-law index distribution (by making hard sources softer and soft
 289 sources harder, but changing the index by less than 0.02), and to make spectra more
 290 curved (because energy dispersion acts as a convolution) but increasing β by only 0.01
 291 on average. In evaluating the likelihood function the effects of energy dispersion were
 292 not applied to the diffuse backgrounds whose spectra were obtained from the data
 293 without considering energy dispersion.
- 294 5. We used smaller RoIs at higher energy because we are interested in the core region
 295 only, which contains the sources whose parameters come from that RoI (sources in the
 296 outer parts of the RoI are entered only as background). The core region is the same for
 297 all energy intervals, and the RoI is obtained by adding a ring to that core region, whose
 298 width adapts to the PSF and therefore decreases with energy (Table 1). This does not

Energy interval (GeV)	NBins	ZMax (deg)	Ring width (deg)	Pixel size (deg)				
				PSF0	PSF1	PSF2	PSF3	All
0.1 – 0.3	5	90	7			0.6	0.6	
0.3 – 1	6	100	5		0.4	0.3	0.2	
1 – 3	5	105	4	0.4	0.15	0.1	0.1	
3 – 10	6	105	3	0.25	0.1	0.05	0.04	
10 – 1000	10	105	2					0.04

Table 1: The table describes the 14 components (all in binned mode) of the Summed Likelihood approach used in FL8Y. Components in a given energy interval share the same number of energy bins, the same zenith angle selection and the same RoI size, but have different pixel sizes in order to adapt to the PSF width. Each filled entry under Pixel size corresponds to one component of the summed likelihood. NBins is the number of energy bins in the interval, ZMax is the zenith angle cut, Ring width refers to the difference between the RoI core and the extraction region, as explained in item 5 of § 3.2.

299 affect the result because the outer parts of the RoI would not have been correlated to
 300 the inner sources at high energy anyway, but saves memory and CPU time.

301 6. At the last step of the fitting procedure we tested all spectral shapes described in § 3.3
 302 (including log-normal for pulsars and cutoff power law for other sources), readjusting
 303 the parameters (but not the spectral shapes) of neighboring sources.

304 We used only binned likelihood analysis in FL8Y because unbinned mode is much more
 305 CPU intensive, and does not support weights or energy dispersion. We split the data into
 306 fourteen components, selected according to PSF event type and described in Table 1. As
 307 explained in § 2.3.4 we kept only the best event types at low energy. Each event type
 308 selection has its own isotropic diffuse template (because it includes residual charged-particle
 309 background, which depends on event type).

310 A known inconsistency in acceptance exists between Pass 8 PSF event types. It is easy
 311 to see on bright sources or the entire RoI spectrum and peaks at the level of 10% between
 312 PSF0 (positive residuals, underestimated effective area) and PSF3 (negative residuals, over-
 313 estimated effective area) at a few GeV. In that range all event types were considered so the
 314 effect on source spectra should be minor. Below 1 GeV the PSF0 event type was discarded so
 315 the inconsistency could introduce a downward bias (appearing as slightly too hard spectra)
 316 but the discrepancy is lower at low energy. The bias on power-law index is estimated to be
 317 ~ -0.01 .

318

3.3. Spectral Shapes

319 The spectral representation of sources largely follows what was done in 3FGL, consid-
 320 ering three spectral models (power law, power law with subexponential cutoff, log-normal).
 321 We changed two important things in the way we use the cutoff power law:

- 322 • The cutoff energy was replaced by an exponential factor (a in Eq. 2) which is allowed
 323 to be positive. This makes the simple power law a special case of the cutoff power law
 324 and allows fitting that model to all sources.
- 325 • We set the exponential index (b in Eq. 2) to $2/3$ (instead of 1) for all pulsars that are
 326 too faint for it to be left free. This recognizes the fact that $b < 1$ (subexponential) in
 327 all bright pulsars. Among the six brightest pulsars, three have $b \sim 0.55$ and three have
 328 $b \sim 0.75$). We chose $2/3$ as a simple intermediate value.

329 Therefore the spectral representations which can be found in FL8Y are:

- 330 • a log-normal representation (`LogParabola` in the tables) for all significantly curved
 331 spectra except pulsars and 3C 454.3:

$$\frac{dN}{dE} = K \left(\frac{E}{E_0} \right)^{-\alpha - \beta \log(E/E_0)} \quad (1)$$

332 where \log is the natural logarithm. The reference energy E_0 is set to `Pivot_Energy` in
 333 the tables. The parameters K , α (spectral slope at E_0) and the curvature β appear
 334 as `Flux_Density`, `LP_Index` and `LP_beta` in the tables, respectively. No significantly
 335 negative β (spectrum curved upwards) was found. The maximum allowed β was set
 336 to 1 as in 3FGL.

- 337 • a subexponentially cutoff power law for all significantly curved pulsars (`PLSuperExpCutoff`
 338 in the tables):

$$\frac{dN}{dE} = K \left(\frac{E}{E_0} \right)^{-\Gamma} \exp(a(E_0^b - E^b)) \quad (2)$$

339 where E_0 and E in the exponential are expressed in MeV. The reference energy E_0 is set
 340 to `Pivot_Energy` in the tables and the parameters K , Γ (low-energy spectral slope), a
 341 (exponential factor) and b (exponential index) appear as `Flux_Density`, `PLEC_Index`,
 342 `PLEC_Expfactor` and `PLEC_Exp_Index` in the tables, respectively. Note that in the
 343 Science Tools that spectral shape is called `PLSuperExpCutoff2` and no E_0^b term appears
 344 in the exponential, so the error on K in the tables was obtained from the covariance
 345 matrix. The minimum Γ was set to 0 (in 3FGL it was set to 0.5, but a smaller b results
 346 in a smaller Γ).

- 347 • a simple power-law form (Eq. 2 without the exponential term) for all sources not
348 significantly curved.

349 As in 3FGL, a source is considered significantly curved if $TS_{\text{curv}} > 16$ where $TS_{\text{curv}} =$
350 $2 \log(\mathcal{L}(\text{curved spectrum})/\mathcal{L}(\text{power-law}))$. The curvature significance is reported as `LP_SigCurv`
351 or `PLEC_SigCurv`.

352 One more pulsar (PSR J1057–5226) was fit with a free exponential index, besides
353 the six sources modeled in this way in 3FGL. The Crab was modeled with three spectral
354 components as in 3FGL, but the inverse Compton emission of the nebula was represented
355 as a log-normal law instead of a simple power law. The parameters of that component were
356 fixed to $\alpha = 1.75$, $\beta = 0.08$, $K = 5.5 \times 10^{-13}$ ph/cm²/MeV/s at 10 GeV, mimicking the
357 broken power-law fit by Buehler et al. (2012). They were unstable (too much correlation
358 with the pulsar) without phase selection. Four other sources had fixed parameters in 3FGL.
359 These were freed in FL8Y.

360 Overall in FL8Y seven sources (the six brightest pulsars and 3C 454.3) were fit as
361 `PLSuperExpCutoff` with free b (Eq. 2), 176 pulsars were fit as `PLSuperExpCutoff` with
362 $b = 2/3$, the Small Magellanic Cloud was fit as `PLSuperExpCutoff` with $b = 1$, 660 sources
363 were fit as `LogParabola` (including the fixed inverse Compton component of the Crab and
364 22 extended sources) and the rest were represented as power laws.

365 The way the parameters are reported has changed as well:

- 366 • The spectral shape parameters are now explicitly associated to the spectral model they
367 come from. They are reported as `Shape_Param` where `Shape` is one of `PL` (power law),
368 `PLEC` (exponentially cutoff power law) or `LP` (log-normal) and `Param` is the parameter
369 name. They replace `Spectral_Index` which was ambiguous.
- 370 • All sources were fit with the three spectral shapes, so all fields are filled. The curvature
371 significance is also calculated twice by comparing power law with both log-normal and
372 exponentially cutoff power law (although only one is actually used to switch to the
373 curved shape in the global model, depending on whether the source is a pulsar or not).

374 This representation allows comparing unassociated sources with either pulsars or blazars
375 using the same spectral shape. The preferred spectral shape (reported as `SpectrumType`)
376 remains what is used when the source is part of the background (i.e., when fitting the other
377 sources). It is also what is used to derive the fluxes, their uncertainties and the significance.

3.4. Extended Sources

378

379 As for the 3FGL catalog, we explicitly model as spatially extended those LAT sources
 380 that have been shown in dedicated analyses to be resolved by the LAT. The catalog pro-
 381 cess does not involve looking for new extended sources, testing possible extension of sources
 382 detected as point-like, nor refitting the spatial shapes of known extended sources. Most tem-
 383 plates are geometrical, so they are not perfect matches to the data and the source detection
 384 often finds residuals on top of extended sources, which are then converted into additional
 385 point sources. In FL8Y those additional point sources were left in the model (this differs
 386 from what was done in 3FGL). This can reduce the flux of the extended sources compared
 387 to previous catalogs.

388 The latest compilation is the 55 extended sources entered in the 3FHL catalog (Ajello
 389 et al. 2017), which includes the result of the systematic search for new sources in the Galactic
 390 plane above 10 GeV (FGES, Ackermann et al. 2017). Two of those were not propagated to
 391 FL8Y:

- 392 • FGES J1800.5–2343 was replaced by the W 28 template from 3FGL, and the nearby
 393 excesses (Hanabata et al. 2014) were left to be modeled as point sources.
- 394 • FGES J0537.6+2751 was replaced by the radio template of S 147 used in 3FGL, which
 395 fits better than the disk used in the FGES paper (S 147 is a soft source, so it was
 396 barely detected above 10 GeV).

397 Three sources were added, resulting in 58 extended sources in FL8Y:

- 398 • The Rosette nebula and Monoceros SNR (too soft to be detected above 10 GeV) were
 399 characterized by Katagiri et al. (2016b). We used the same templates.
- 400 • We added back the W 30 SNR on top of FGES J1804.7–2144 (coincident with HESS
 401 J1804–216). The two overlap but the best localization clearly moves with energy from
 402 W 30 to HESS J1804–216.

403 Table 2 lists the source name, origin, spatial template and the reference for the dedicated
 404 analysis. These sources are tabulated with the point sources, with the only distinction
 405 being that no position uncertainties are reported and their names end in **e** (see App. B).
 406 Unidentified point sources inside extended ones are indicated as “xxx field” in the ASSOC
 407 column of the catalog.

Table 2. Extended Sources Modeled in the FL8Y Analysis

FL8Y Name	Extended Source	Origin	Spatial Form	Extent [deg]	Reference
J0058.0–7245e	SMC Galaxy	Updated	Map	1.5	Caputo et al. (2016)
J0221.4+6241e	HB 3	New	Disk	0.8	Katagiri et al. (2016a)
J0222.4+6156e	W 3	New	Map	0.6	Katagiri et al. (2016a)
J0322.6–3712e	Fornax A	3FHL	Map	0.35	Ackermann et al. (2016c)
J0427.2+5533e	SNR G150.3+4.5	3FHL	Disk	1.515	Ackermann et al. (2017)
J0500.3+4639e	HB 9	New	Map	1.0	Araya (2014)
J0500.9–6945e	LMC FarWest	3FHL	Map ^a	0.9	Ackermann et al. (2016d)
J0519.9–6845e	LMC Galaxy	New	Map ^a	3.0	Ackermann et al. (2016d)
J0530.0–6900e	LMC 30DorWest	3FHL	Map ^a	0.9	Ackermann et al. (2016d)
J0531.8–6639e	LMC North	3FHL	Map ^a	0.6	Ackermann et al. (2016d)
J0540.3+2756e	S 147	3FGL	Disk	1.5	Katsuta et al. (2012)
J0617.2+2234e	IC 443	2FGL	Gaussian	0.27	Abdo et al. (2010f)
J0634.2+0436e	Rosette	New	Map	(1.5, 0.875)	Katagiri et al. (2016b)
J0639.4+0655e	Monoceros	New	Gaussian	3.47	Katagiri et al. (2016b)
J0822.1–4253e	Puppis A	3FHL	Disk	0.443	Ackermann et al. (2017)
J0833.1–4511e	Vela X	2FGL	Disk	0.91	Abdo et al. (2010d)
J0851.9–4620e	Vela Junior	3FHL	Disk	0.978	Ackermann et al. (2017)
J1023.3–5747e	Westerlund 2	3FHL	Disk	0.278	Ackermann et al. (2017)
J1036.3–5833e	FGES J1036.3–5833	3FHL	Disk	2.465	Ackermann et al. (2017)
J1109.4–6115e	FGES J1109.4–6115	3FHL	Disk	1.267	Ackermann et al. (2017)
J1208.5–5243e	SNR G296.5+10.0	3FHL	Disk	0.76	Acero et al. (2016b)
J1213.3–6240e	FGES J1213.3–6240	3FHL	Disk	0.332	Ackermann et al. (2017)
J1303.0–6312e	HESS J1303–631	3FGL	Gaussian	0.24	Aharonian et al. (2005)
J1324.0–4330e	Centaurus A (lobes)	2FGL	Map	(2.5, 1.0)	Abdo et al. (2010a)
J1355.1–6420e	HESS J1356–645	3FHL	Disk	0.405	Ackermann et al. (2017)
J1409.1–6121e	FGES J1409.1–6121	3FHL	Disk	0.733	Ackermann et al. (2017)
J1420.3–6046e	HESS J1420–607	3FHL	Disk	0.123	Ackermann et al. (2017)
J1443.0–6227e	RCW 86	3FHL	Map	0.3	Ajello et al. (2016)
J1507.9–6228e	HESS J1507–622	3FHL	Disk	0.362	Ackermann et al. (2017)
J1514.2–5909e	MSH 15–52	3FHL	Disk	0.243	Ackermann et al. (2017)
J1552.7–5611e	MSH 15–56	3FHL	Disk	0.21	Acero et al. (2016b)
J1553.8–5325e	FGES J1553.8–5325	3FHL	Disk	0.523	Ackermann et al. (2017)
J1615.3–5146e	HESS J1614–518	3FGL	Disk	0.42	Lande et al. (2012)
J1616.2–5054e	HESS J1616–508	3FGL	Disk	0.32	Lande et al. (2012)
J1631.6–4756e	FGES J1631.6–4756	3FHL	Disk	0.256	Ackermann et al. (2017)
J1633.0–4746e	FGES J1633.0–4746	3FHL	Disk	0.61	Ackermann et al. (2017)
J1636.3–4731e	SNR G337.0–0.1	3FHL	Disk	0.139	Ackermann et al. (2017)
J1652.2–4633e	FGES J1652.2–4633	3FHL	Disk	0.718	Ackermann et al. (2017)
J1655.5–4737e	FGES J1655.5–4737	3FHL	Disk	0.334	Ackermann et al. (2017)
J1713.5–3945e	RX J1713.7–3946	3FHL	Map	0.56	Abdalla et al. (2017)
J1745.8–3028e	FGES J1745.8–3028	3FHL	Disk	0.528	Ackermann et al. (2017)
J1801.3–2326e	W 28	2FGL	Disk	0.39	Abdo et al. (2010c)
J1804.7–2144e	HESS J1804–216	3FHL	Disk	0.378	Ackermann et al. (2017)
J1805.6–2136e	W 30	2FGL	Disk	0.37	Ajello et al. (2012)
J1824.5–1351e	HESS J1825–137	2FGL	Gaussian	0.75	Grondin et al. (2011)
J1834.1–0706e	SNR G24.7+0.6	3FHL	Disk	0.214	Ackermann et al. (2017)

3.5. Limitations and Systematic Uncertainties

3.5.1. Diffuse emission model

The model of diffuse emission is the main source of uncertainties for faint sources. Contrary to the effective area, it does not affect all sources equally: its effects are smaller outside the Galactic plane where the diffuse emission is fainter and varying on larger angular scales. It is also less of a concern at high energy (> 3 GeV) where the core of the PSF is narrow enough that the sources dominate the background under the PSF. But it is a serious concern inside the Galactic plane at low energy (< 1 GeV) and particularly inside the Galactic ridge ($|l| < 60^\circ$) where the diffuse emission is strongest and very structured, following the molecular cloud distribution. It is not easy to assess precisely how large the uncertainties are, because they relate to uncertainties in the distributions of interstellar gas, the interstellar radiation field, and cosmic rays, which depend in detail on position on the sky.

The FL8Y source list uses the same diffuse emission model as 3FGL. This is a major limitation and the main reason why this source list is not the 4FGL catalog, which will be based on an improved interstellar emission model, making use of better HI data, a *Planck*-based dust map and fitting emissivities over 8 years of Pass 8 data.

We estimate, from the residuals over the entire Galactic plane, that the systematics are at the 3% level. This is already an achievement, but the statistical Poisson errors corresponding to the diffuse emission integrated over the PSF (as described in App. A) are much smaller than this. Integrating all energies above the current one in the Galactic ridge, the statistical precision is 0.2, 0.4, 1, 2, 5% above 100, 200, 500 MeV, 1, 2 GeV respectively.

The weights are able to mitigate the systematic effects globally, but cannot correct the model locally. In particular underestimating the mass of an interstellar cloud will always tend to create spurious sources on top of it, and overestimating diffuse emission at a particular place tends to make the sources on top of it harder than they should be (because the model creates negative residuals there, and those are felt mostly at low energy).

3.5.2. Analysis method

As in 3FGL, we use the *pointlike*-based method described in § 3.1 to estimate systematic errors due to the way the main *gtlike*-based method (§ 3.2) is set up in detail. Many aspects differ between the two methods: the code, the weights implementation, the RoIs, the Earth limb representation. The *pointlike*-based method does not remove faint sources

440 (with $TS < 25$) from the model. The model for diffuse emission is the same spatially but it
441 was rescaled spectrally in each energy bin. Even the data differ, since the *pointlike*-based
442 method uses *Front* and *Back* event types whereas the *gtlike*-based method uses PSF event
443 types with a different zenith angle cut, and rejects a fraction of the events below 1 GeV.

444 Because of all those differences, we expect that comparing the results of the two methods
445 source by source can provide an estimate of the sensitivity of the source list to details of the
446 analysis. In particular we use it to flag sources whose spectral characterization differs a lot
447 with the two methods (Flags 1 and 3 in Table 3).

448 3.5.3. Analysis Flags

449 As in 3FGL we identified a number of conditions that should be considered cautionary
450 regarding the reality of a source or the magnitude of the systematic uncertainties of its
451 measured properties. They are described in Table 3. Because this is a preliminary source
452 list a number of flags are unfilled (4, 5, 6, 7, 11). Flags 1 and 3 account for the comparison
453 with the other analysis method, but not with another diffuse model.

454 In FL8Y 553 sources are flagged (about 10%). No source was flagged with flag 1, 361
455 were flagged with flag 3 (different result with *pointlike*), 119 with flag 9 (bad localization),
456 50 with flag 10 (bad spectral representation) and 52 with flag 12 (highly curved).

457 4. Source Association-Classification

Table 2—Continued

FL8Y Name	Extended Source	Origin	Spatial Form	Extent [deg]	Reference
J1834.5–0846e	W 41	3FHL	Gaussian	0.23	Abramowski et al. (2015)
J1836.5–0651e	FGES J1836.5–0651	3FHL	Disk	0.535	Ackermann et al. (2017)
J1838.9–0704e	FGES J1838.9–0704	3FHL	Disk	0.523	Ackermann et al. (2017)
J1840.9–0532e	HESS J1841–055	3FGL	2D Gaussian	(0.62, 0.38)	Aharonian et al. (2008)
J1855.9+0121e	W 44	2FGL	2D Ring	(0.30, 0.19)	Abdo et al. (2010e)
J1857.7+0246e	HESS J1857+026	3FHL	Disk	0.613	Ackermann et al. (2017)
J1923.2+1408e	W 51C	2FGL	2D Disk	(0.375, 0.26)	Abdo et al. (2009a)
J2021.0+4031e	γ -Cygni	3FGL	Disk	0.63	Lande et al. (2012)
J2028.6+4110e	Cygnus X cocoon	3FGL	Gaussian	3.0	Ackermann et al. (2011a)
J2045.2+5026e	HB 21	3FGL	Disk	1.19	Pivato et al. (2013)
J2051.0+3040e	Cygnus Loop	2FGL	Ring	1.65	Katagiri et al. (2011)
J2301.9+5855e	CTB 109	3FHL	Disk	0.249	Ackermann et al. (2017)

^aEmissivity model.

Note. — List of all sources that have been modeled as spatially extended. The Origin column gives the name of the *Fermi*-LAT catalog in which that spatial template was introduced. The Extent column indicates the radius for Disk (flat disk) sources, the 68% containment radius for Gaussian sources, the outer radius for Ring (flat annulus) sources, and an approximate radius for Map (external template) sources. The 2D shapes are elliptical; each pair of parameters (a, b) represents the semi-major (a) and semi-minor (b) axes.

Table 3. Definitions of the Analysis Flags

Flag ^a	Meaning
1	Source with $TS > 35$ which went to $TS < 25$ when changing the analysis method (§ 3.5.2). Sources with $TS \leq 35$ are not flagged with this bit because normal statistical fluctuations can push them to $TS < 25$.
2	Not used.
3	Flux (> 1 GeV) or energy flux (> 100 MeV) changed by more than 3σ when changing the analysis method. Requires also that the flux change by more than 35% (to not flag strong sources).
4	Not used.
5	Not used.
6	Not used.
7	Not used.
8	Not used.
9	Localization Quality > 8 in <i>pointlike</i> (§ 3.1) or long axis of 95% ellipse $> 0^\circ 25$.
10	Spectral Fit Quality > 30 in <i>pointlike</i> .
11	Not used.
12	Highly curved spectrum; LP_beta fixed to 1 or PLEC_Index fixed to 0 (see § 3.3).

^aIn the FITS version (Table 6 in App. B) the values are encoded as individual bits in a single column, with Flag n having value $2^{(n-1)}$.

Table 4. Catalogs Used for the Automatic Source Association Methods

Name	Objects ^a	Ref.
High \dot{E}/d^2 pulsars	313	Manchester et al. (2005) ^b
Other normal pulsars	2248	Manchester et al. (2005) ^b
Millisecond pulsars	240	Manchester et al. (2005) ^b
Pulsar wind nebulae	69	Collaboration internal
High-mass X-ray binaries	137	Chaty et al. (2018)
Low-mass X-ray binaries	187	Liu et al. (2007)
Point-like SNR	295	Green (2009) ^c
Extended SNR [†]	274	Green (2009) ^c
O stars	378	Maíz-Apellániz et al. (2004)
WR stars	226	van der Hucht (2001)
LBV stars	35	Clark et al. (2005)
Open clusters	2140	Dias et al. (2002)
Globular clusters	160	Harris (1996)
Dwarf galaxies [†]	100	McConnachie (2012)
Nearby galaxies	276	Schmidt et al. (1993)
IRAS bright galaxies	82	Sanders et al. (2003)
BZCAT (Blazars)	3561	Massaro et al. (2009)
Supplement to BZCAT	102	Alvarez-Crespo & Massaro (2017)
BL Lac	1371	Véron-Cetty & Véron (2010)
AGN	10066	Véron-Cetty & Véron (2010)
QSO	129,853	Véron-Cetty & Véron (2010)
Seyfert galaxies	27651	Véron-Cetty & Véron (2010)
Radio loud Seyfert galaxies	29	Collaboration internal
Radio-loud Seyfert galaxies	556	Rakshit et al. (2017)
FRICAT (Radio galaxies)	233	Capetti, A. et al. (2017a)
FRICAT (Radio galaxies)	123	Capetti, A. et al. (2017b)
Giant Radio Sources	1616	Proctor (2016)
2WHSP	1691	Chang et al. (2017)
WISE blazar catalog	12319	D’Abrusco et al. (2014)
Radio Fundamental Catalog	14786	http://astrogeo.org/rfc
CGRaBS	1625	Healey et al. (2008)
CRATES	11499	Healey et al. (2007)
VLBA Calibrator Source List	5776	http://www.vlba.nrao.edu/astro/calib/
ATCA 20 GHz southern sky survey	5890	Murphy et al. (2010)
ATCA follow up of 2FGL unassociated sources	424	Petrov et al. (2013)
70-month BAT catalog	1092	Baumgartner et al. (2013)
IBIS catalog of soft gamma-ray sources	939	Bird et al. (2016)
1st AGILE catalog*	47	Pittori et al. (2009)
3rd EGRET catalog*	271	Hartman et al. (1999)
EGR catalog*	189	Casandjian & Grenier (2008)
0FGL list*	205	Abdo et al. (2009b, 0FGL)
1FGL catalog*	1451	Abdo et al. (2010b, 1FGL)
2FGL catalog*	1873	Nolan et al. (2012, 2FGL)
3FGL catalog*	3033	Acero et al. (2015, 3FGL)
1FHL catalog*	514	Ackermann et al. (2013, 1FHL)
2FHL catalog*	360	Ackermann et al. (2016b, 1FHL)

458 The same association procedure previously used in 3FGL is adopted here. The Bayesian
 459 method (Abdo et al. 2010b) is applied using the set of potential-counterpart catalogs listed in
 460 Table 4. The priors are recalibrated via Monte-Carlo simulations to enable a proper estimate
 461 of the association probabilities and in turn of the false association rates. These rates indeed
 462 depend on the sizes of the error ellipses of the sources. A total of 3392 associations with
 463 posterior probabilities greater than 0.80 are found via this method, with an estimated number
 464 of false positives of ~ 41 . Note that 22 sources have changed associations between 3FGL and
 465 FL8Y. In FL8Y, we did not make use of the Likelihood-Ratio (LR) method (Ackermann
 466 et al. 2011b, 2015), which provided supplementary associations with blazar candidates in
 467 previous LAT catalogs (62 associations in 3FGL). We thus dropped the “unknown” class
 468 introduced in 3FHL, corresponding to associated sources in the ROSAT X-ray survey with
 469 spectral energy distributions not consistent with those expected from blazars.

470 The fraction of associated sources is close to 60%, down from 65% obtained in 3FGL
 471 with the same method. This trend calls for deeper counterpart catalogs and surveys than
 472 those currently available. We list blazar classes in terms of Flat-Spectrum Radio Quasars
 473 (FSRQs), BL Lac type objects (BLL) and blazars of undetermined type (BCU). The BCU
 474 sources represent more than 40% of the blazars. However, note that a thorough search
 475 for optical spectra in the literature has not been completed yet, which will improve the
 476 classification rate in terms of optical classes.

477 The results of the association procedure are summarized in Table 5. Designations shown
 478 in capital letters are firm identifications based on correlated variability (periodic or otherwise)
 479 reported at other wavelengths or angular extent; lower case letters indicate associations.

480 Associations with γ -ray sources reported in earlier LAT catalogs are established by
 481 requiring an overlap of their respective 99.9% error ellipses (assuming axes lengths 1.52
 482 times their 95% values). A total of 3155 FL8Y sources were reported in previous FGL
 483 catalogs. It is found that 292 3FGL sources are missing in FL8Y. The great majority of
 484 them had TS values close to the detection threshold. Some of the missing sources have been
 485 split up in multiple FL8Y sources. Similarly, 21 3FHL sources are missing in FL8Y.

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Table 4—Continued

Name	Objects ^a	Ref.
3FHL catalog*	1556	Ajello et al. (2017, 1FHL)
TeV point-like source catalog*	108	http://tevcat.uchicago.edu/
TeV extended source catalog [†]	72	http://tevcat.uchicago.edu/
LAT pulsars	209	Collaboration internal
LAT identified	143	Collaboration internal

^aNumber of objects in the catalog.

^bversion 1.56, <http://www.atnf.csiro.au/research/pulsar/psrcat>

^cGreen D. A., 2017, ‘A Catalogue of Galactic Supernova Remnants (2017 June version)’, Cavendish Laboratory, Cambridge, United Kingdom (available at “<http://www.mrao.cam.ac.uk/surveys/snrs/>”)

Table 5. LAT FL8Y Source Classes

Description	Identified		Associated	
	Designator	Number	Designator	Number
Pulsar, identified by pulsations	PSR	184	...	...
Pulsar, no pulsations seen in LAT yet	...	...	psr	34
Pulsar wind nebula	PWN	8	pwn	11
Supernova remnant	SNR	22	snr	17
Supernova remnant / Pulsar wind nebula	...	...	spp	96
Globular cluster	GLC	0	glc	28
High-mass binary	HMB	4	hmb	2
Binary	BIN	1	bin	1
Nova	NOV	1	nov	0
Star-forming region	SFR	1	sfr	1
Compact Steep Spectrum Quasar	CSS	0	css	1
BL Lac type of blazar	BLL	22	bll	1008
FSRQ type of blazar	FSRQ	42	fsrq	618
Non-blazar active galaxy	AGN	0	agn	16
Radio galaxy	RDG	5	rdg	16
Seyfert galaxy	SEY	0	sey	1
Blazar candidate of uncertain type	BCU	5	bcu	1229
Normal galaxy (or part)	GAL	2	gal	2
Starburst galaxy	SBG	0	sbg	4
Narrow line Seyfert 1	NLSY1	3	nlsy1	6
Soft spectrum radio quasar	SSRQ	0	ssrq	1
Total	...	300	...	3092
Unassociated	...	...	...	2131

Note. — The designation ‘spp’ indicates potential association with SNR or PWN. Designations shown in capital letters are firm identifications; lower case letters indicate associations. In the case of AGN, many of the associations have high confidence.

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577 **A. Weighted log-likelihood**

578 In 3FGL we introduced a first attempt at accounting for systematic errors in the max-
579 imum likelihood process itself, at the source detection level. It was not used in the source
580 characterization, however, for lack of a suitable framework. The standard way to account for
581 systematic errors (for example in *XSPEC*⁵) is to define them as a fraction ϵ of the signal
582 and add them to the statistical errors in quadrature, in a χ^2 formalism. This can be adapted
583 to the maximum likelihood framework by introducing weights $w_i < 1$ (Hu & Zidek 2002) as

$$\log \mathcal{L} = \sum_i w_i (n_i \log M_i - M_i) \quad (\text{A1})$$

584 where M_i and n_i are the model and observed counts in each bin, and the sum runs over all
585 bins in space and energy. The source significance can then be quantified in the same way,

This preprint was prepared with the AAS L^AT_EX macros v5.2.

⁵<https://heasarc.gsfc.nasa.gov/xanadu/xspec/>

586 via the Test Statistic $TS = 2\log(\mathcal{L}/\mathcal{L}_0)$ in which \mathcal{L} and \mathcal{L}_0 are the (weighted) likelihood
 587 with and without the source of interest, respectively.

588 Since the statistical variance in Poisson statistics is the signal itself, a first guess for the
 589 weights could be

$$w_i = \frac{M_i}{M_i + (\epsilon M_i)^2} = \frac{1}{1 + \epsilon^2 M_i} \quad (\text{A2})$$

590 However, that formulation has a serious flaw, which is that it is not stable to rebinning.
 591 If one splits the bins in half, then M_i is split in half while ϵ stays the same (it is defined
 592 externally). In the limit of very small bins, obviously the weights will all tend to 1 and
 593 the log \mathcal{L} formula will tend to the unweighted one, even though nothing has changed in the
 594 underlying data or the model.

595 The solution we propose, originally presented in Ballet et al. (2015), is to define a
 596 suitable integral over energy (E) and space (\mathbf{r}) $N(\mathbf{r}, E)$ which does not depend on binning.
 597 M_i in the weight formula is then replaced by $N(\mathbf{r}_i, E_i)$ taken at the event’s coordinates. For
 598 the integral over space, since the catalog mostly deals with point sources, the logical solution
 599 is to integrate the background under the PSF, i.e., convolve the model with the PSF $P(\mathbf{r}, E)$,
 600 normalized to 1 at the peak (this is equivalent, for a flat diffuse emission, to multiplying by
 601 the PSF solid angle). Note that the model already contains the PSF, so this amounts to
 602 applying a double convolution to the sky model.

603 For the energy integral the choice is less obvious. The source spectrum is not a narrow
 604 line, so convolving with the energy dispersion (similar to what is done for space) is not
 605 justified. An integral over the full energy range would give the same weight to all energies,
 606 which is clearly not what we want (there is no reason to downplay the few high-energy
 607 events). The option we adopt here is to integrate over all energies above the current one.

$$w_i = \frac{1}{1 + \epsilon^2 N(\mathbf{r}_i, E_i)} \quad (\text{A3})$$

$$N(\mathbf{r}_i, E_i) = \int_{E_i}^{E_{\max}} S(\mathbf{r}_i, E) dE \quad (\text{A4})$$

$$S(\mathbf{r}, E) = \frac{dM}{dE}(\mathbf{r}, E) * P(\mathbf{r}, E) \quad (\text{A5})$$

608 where dM/dE is the differential model. As energy increases, the spectra (in counts) decrease
 609 and the LAT PSF gets narrower so the convolution makes S even steeper than dM/dE . As
 610 a result, the integral giving N is dominated by the lowest energies, so the exact upper bound
 611 E_{\max} is not important.

612 There are two possibilities to define dM/dE . Since the main origin of the systematic
 613 error is the diffuse emission, we can restrict dM/dE to the diffuse emission model only

614 (we call the result model-based weights). On the other hand there are also systematic
 615 uncertainties on sources due to PSF calibration and our imperfect spectral representation,
 616 so another option is to enter the full model (or the data themselves) into dM/dE (we call
 617 the result data-based weights). That second choice limits spurious sources next to bright
 618 sources. There is of course no reason why the level of systematics ϵ should be the same for
 619 the diffuse emission model and the sources, but in practice it is a reasonable approximation.

620 Another important point, for the procedure to be stable, is that the weights should not
 621 change with the model parameters. So dM/dE must be defined beforehand (for example from
 622 a previous fit). In this work we use data-based weights computed from the data themselves,
 623 with a common ϵ . The data are not as smooth as the model, but this is not a problem in
 624 the regime of large counts where weights play a role.

625 We assume here that ϵ is a true constant (it depends neither on space nor on energy).
 626 For a given ϵ the weights are close to 1 at high energy and decrease toward low energy. At
 627 a given energy the weights are smallest where the model is largest (in the Galactic ridge).
 628 Considering all event types (not what we do in FL8Y), for 8 years and $\epsilon = 3\%$, at 100 MeV
 629 the weights are everywhere less than 12%. They reach 50% at high latitude at 250 MeV, and
 630 90% at 500 MeV. In the Galactic ridge, the weights are 0.5% at 100 MeV, 1.5% at 250 MeV,
 631 5% at 500 MeV, 20% at 1 GeV, 60% at 2 GeV and reach 90% at 4.5 GeV.

632 There remains a specific difficulty, due to the fact that at a given energy we split
 633 the data into several components, each corresponding to a particular event type (with a
 634 different PSF). Since the systematics play in the same way on all components, the weights
 635 must be computed globally (i.e., weights must be lower when using PSF2 and PSF3 events
 636 than when using PSF3 alone). On the other hand, the resulting uncertainties with two
 637 components should be smaller than those with a single component (adding a second one
 638 adds information). In this work, we started by computing weights w_k individually for each
 639 component k (the dependence on E and \mathbf{r} is left implicit). Then we assumed that the final
 640 weights are simply proportional to the original ones, with a factor $\alpha < 1$ (α depends on E
 641 and \mathbf{r} as well). A reasonable solution is then

$$N_{\min} = \min_k N_k \tag{A6}$$

$$K_{\text{tot}} = \sum_k \left(\frac{N_{\min}}{N_k} \right)^2 \tag{A7}$$

$$\alpha = \frac{1 + \epsilon^2 N_{\min}}{1 + \epsilon^2 N_{\min} K_{\text{tot}}} \tag{A8}$$

$$w_k = \frac{\alpha}{1 + \epsilon^2 N_k} \tag{A9}$$

642 K_{tot} and α are 1 if one component dominates over the others, and K_{tot} is the number of
 643 components if they are all similar.

644 B. Description of the FITS version of the FL8Y source list

645 The FITS format version of the FL8Y source list has five binary table extensions.
 646 The extension `LAT_Point_Source_Catalog_Extension` has all of the information about the
 647 sources. Its format is described in Table 6.

648 The extension `GTI` is a standard Good-Time Interval listing the precise time intervals
 649 (start and stop in Mission Elapsed Time) included in the data analysis. The number of
 650 intervals is fairly large because on most orbits (~ 95 min) *Fermi* passes through the South
 651 Atlantic Anomaly (SAA), and science data taking is stopped during these times. In addition,
 652 data taking is briefly interrupted on each non-SAA-crossing orbit, as *Fermi* crosses the
 653 ascending node. Filtering of time intervals with large rocking angles, gamma-ray bursts,
 654 solar flares, data gaps, or operation in non-standard configurations introduces some more
 655 entries. The GTI is provided for reference and would be useful, e.g., for reconstructing the
 656 precise data set that was used for the analysis.

657 The extension `ExtendedSources` (format unchanged since 2FGL) contains information
 658 about the 58 spatially extended sources that are modeled in the FL8Y source list, including
 659 locations and shapes. The extended sources are indicated by an e appended to their names
 660 in the main table.

661 The extension `ROIs` contains information about the 2363 RoIs over which the analysis
 662 ran. In particular it reports the best-fit background parameters. Its format is very close to
 663 that in 3FGL, with one exception. The `RADIUS` column is replaced by `CoreRadius` which
 664 reports the radius of the RoI core (in which the sources which belong to the RoI are located).
 665 The RoI radius (half-width in binned mode) depends on the component, and is given by the
 666 core radius plus `RingWidth`, where the latter is given in the `Components` extension.

667 The extension `Components` is new to FL8Y. It reports the settings of each individ-
 668 ual component (14 in all) whose sum forms the entire data set for the SummedLikelihood
 669 approach, as described in Table 1. Its format is given by Table 7.

Table 6. LAT FL8Y FITS Format: LAT_Point_Source_Catalog Extension

Column	Format	Unit	Description
Source_Name	18A	...	Source name FL8Y JHHMM.m+DDMM
RAJ2000	E	deg	Right Ascension
DEJ2000	E	deg	Declination
GLON	E	deg	Galactic Longitude
GLAT	E	deg	Galactic Latitude
Conf_95_SemiMajor	E	deg	Long radius of error ellipse at 95% confidence
Conf_95_SemiMinor	E	deg	Short radius of error ellipse at 95% confidence
Conf_95_PosAng	E	deg	Position angle (eastward) of the long axis from celestial North
ROI_num	I	...	RoI number (cross-reference to ROIs extension)
Extended_Source_Name	18A	...	Cross-reference to the ExtendedSources extension
Signif_Avg	E	...	Source significance in σ units over the 100 MeV to 1 TeV band
Pivot_Energy	E	MeV	Energy at which error on differential flux is minimal
Flux_Density	E	$\text{cm}^{-2} \text{MeV}^{-1} \text{s}^{-1}$	Differential flux at Pivot_Energy
Unc_Flux_Density	E	$\text{cm}^{-2} \text{MeV}^{-1} \text{s}^{-1}$	1σ error on differential flux at Pivot_Energy
Flux1000	E	$\text{cm}^{-2} \text{s}^{-1}$	Integral photon flux from 1 to 100 GeV
Unc_Flux1000	E	$\text{cm}^{-2} \text{s}^{-1}$	1σ error on integral photon flux from 1 to 100 GeV
Energy_Flux100	E	$\text{erg cm}^{-2} \text{s}^{-1}$	Energy flux from 100 MeV to 100 GeV obtained by spectral fitting
Unc_Energy_Flux100	E	$\text{erg cm}^{-2} \text{s}^{-1}$	1σ error on energy flux from 100 MeV to 100 GeV
SpectrumType	18A	...	Spectral type (PowerLaw, LogParabola, PLSuperExpCutoff)
PL_Index	E	...	Photon index when fitting with PowerLaw
Unc_PL_Index	E	...	1σ error on PL_Index
LP_SigCurv	E	...	Significance (in σ units) of the fit improvement between PowerLaw and LogParabola. A value greater than 4 indicates significant curvature
LP_Index	E	...	Photon index at Pivot_Energy (α of Eq. 1) when fitting with LogParabola
Unc_LP_Index	E	...	1σ error on LP_Index
LP_beta	E	...	Curvature parameter (β of Eq. 1) when fitting with LogParabola
Unc_LP_beta	E	...	1σ error on LP_beta
PLEC_SigCurv	E	...	Same as LP_SigCurv for PLSuperExpCutoff model
PLEC_Index	E	...	Low-energy photon index (Γ of Eq. 2) when fitting with PLSuperExpCutoff
Unc_PLEC_Index	E	...	1σ error on PLEC_Index
PLEC_Expfactor	E	...	Exponential factor (a of Eq. 2) when fitting with PLSuperExpCutoff
Unc_PLEC_Expfactor	E	...	1σ error on PLEC_Expfactor
PLEC_Exp_Index	E	...	Exponential index (b of Eq. 2) when fitting with PLSuperExpCutoff
Unc_PLEC_Exp_Index	E	...	1σ error on PLEC_Exp_Index
Npred	E	...	Predicted number of events in the model
ASSOC_GAM	18A	...	Correspondence to previous γ -ray source catalog ^a
TEVCAT_FLAG	A	...	P if positional association with non-extended source in TeVCat, N if no TeV association
ASSOC_TEV	24A	...	Name of likely corresponding TeV source from TeVCat, if any
CLASS	7A	...	Class designation for associated source; see Table 5
ASSOC1	26A	...	Name of identified or likely associated source
ASSOC2	26A	...	Alternate name or indicates whether the source is inside an extended source
ASSOC_PROB_BAY	E	...	Probability of association according to the Bayesian method
Flags	I	...	Source flags (binary coding as in Table 3) ^b

^ain the order 3FHL > 3FGL > 2FHL > 1FHL > 2FGL > 1FGL > 0FGL.

^bEach condition is indicated by one bit among the 16 bits forming **Flags**. The bit is raised (set to 1) in the dubious case, so that sources without any warning sign have **Flags** = 0.

Table 7. LAT FL8Y FITS Format: Components Extension

Column	Format	Unit	Description
Emin	E	MeV	Lower bound of component's energy interval
Emax	E	MeV	Upper bound of component's energy interval
ENumBins	I	...	Number of bins inside energy interval
EvType	I	...	Event type selection for this component
ZenithCut	E	deg	Maximum zenith angle for this component
RingWidth	E	deg	Difference between RoI radius and core radius
PixelSize	E	deg	Pixel size for this component (of exposure map in unbinned mode)
BinnedMode	I	...	0=Unbinned, 1=Binned
Weighted	I	...	1 if weights were applied to this component