

1 LEVERAGING MULTI-MESSENGER ASTROPHYSICS FOR DARK MATTER SEARCHES

By

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Today

ABSTRACT

3 I did Dark Matter with HAWC and IceCube. I also used Graph Neural Networks

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⁶ Today

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8 I love my friends. Thanks to everyone that helped me figure this out. Amazing thanks to the people
9 at LANL who supported me. Eames, etc Dinner Parties Jenny and her child Kaydince Kirsten, Pat,
10 Andrea Family. You're so far but so critical to my formation. Unconditional love. Roommate

TABLE OF CONTENTS

12	LIST OF TABLES	vii
13	LIST OF FIGURES	ix
14	LIST OF ABBREVIATIONS	xx
15	CHAPTER 1 INTRODUCTION	1
16	CHAPTER 2 DARK MATTER IN THE COSMOS	2
17	2.1 Introduction	2
18	2.2 Dark Matter Basics	3
19	2.3 Evidence for Dark Matter	4
20	2.4 Searching for Dark Matter: Particle DM	11
21	2.5 Sources for Indirect Dark Matter Searches	16
22	2.6 Multi-Messenger Dark Matter	18
23	CHAPTER 3 HIGH ALTITUDE WATER CHERENKOV (HAWC) OBSERVATORY	21
24	3.1 The Detector	21
25	3.2 Event Reconstruction	26
26	3.3 Background Estimation: Direct Integration	34
27	CHAPTER 4 ICECUBE NEUTRINO OBSERVATORY	36
28	4.1 The Detector	36
29	4.2 Events Reconstruction and Data Acquisition	36
30	4.3 Northern Test Site	36
31	CHAPTER 5 GLORY DUCK: MULTI-WAVELENGTH SEARCH FOR DARK MATTER ANNIHILATION TOWARDS DWARF SPHEROIDAL GALAXIES	37
32	5.1 Introduction	37
33	5.2 Dataset and Background	39
34	5.3 Analysis	41
35	5.4 Likelihood Methods	45
36	5.5 HAWC Results	52
37	5.6 Glory Duck Combined Results	54
38	5.7 HAWC Systematics	59
39	5.8 J -factor distributions	61
40	5.9 Discussion and Conclusions	67
43	CHAPTER 6 MULTITHREADING HAWC ANALYSES FOR DARK MATTER SEARCHES	71
44	6.1 Introduction	71
45	6.2 Dataset and Background	71
46	6.3 Analysis	73

48	6.4	Likelihood Methods	77
49	6.5	Computational Methods: Multithreading	77
50	6.6	Analysis Results	83
51	6.7	Systematics	88
52	6.8	Conclusion and Discussion	88
53	CHAPTER 7	HEAVY DARK MATTER ANNIHILATION SEARCH WITH ICE-CUBE'S NORTH SKY TRACK DATA	90
54	7.1	Introduction	90
55	7.2	Dataset and Background	90
56	7.3	Analysis	92
57	7.4	Likelihood Methods	101
58	7.5	Background Simulation	101
59	7.6	Signal Recovery	119
60	7.7	Systematics	122
61	7.8	Conclusions	125
63	CHAPTER 8	NU DUCK: CONCLUSIONS AND FUTURE DIRECTIONS	127
64	8.1	Conclusions	127
65	8.2	Future Directions: Multi-Messenger Dark Matter Search	128
66	APPENDIX A	MULTI-EXPERIMENT SUPPLEMENTARY FIGURES	130
67	APPENDIX B	MULTITHREADING DARK MATTER ANALYSES SUPPLEMENTARY MATERIAL	131
68	B.1	Remaining Spectral Models	131
69	B.2	<code>mpu_analysis.py</code>	132
70	B.3	Comparison with Glory Duck	141
72	APPENDIX C	ICECUBE HEAVY DARK MATTER ANALYSIS SUPPLEMENTARY MATERIAL	144
73	C.1	Docker Image for Oscillating Neutrino Spectra	144
74	C.2	Spline Fitting Statuses	147
75	C.3	Neutrino Composite Spectra	148
76	C.4	Segue 1 And Ursa Major II Signal Recovery	149
77	C.5	n_s Sensitivities	155
79	BIBLIOGRAPHY		157

LIST OF TABLES

<p>81 Table 3.1 TODO: copied. Definitions of the fhit bins, given by the fraction of available 82 PMTs that are triggered during an air shower event. The angular resolution, 83 denoted Ψ_{68} as the bin containing 68% of the events, improves with larger 84 events [34]</p> <p>85 Table 5.1 Summary of the relevant properties of the dSphs used in the present work. 86 Column 1 lists the dSphs. Columns 2 and 3 present their heliocentric distance 87 and galactic coordinates, respectively. Columns 4 and 5 report the J-factors of 88 each source given from the \mathcal{GS} and \mathcal{B} independent studies and their estimated 89 $\pm 1\sigma$ uncertainties. The values $\log_{10} J$ (\mathcal{GS} set) [59] correspond to the mean 90 J-factor values for a source extension truncated at the outermost observed star. 91 The values $\log_{10} J$ (\mathcal{B} set) [63] are provided for a source extension at the tidal 92 radius of each dSph. Bolded sources are within HAWC's field of view and 93 provided to the Glory Duck analysis.</p> <p>94 Table 5.2 Summary of dSph observations by each experiment used in this work. A 95 ‘-’ indicates the experiment did not observe the dSph for this study. For 96 Fermi-LAT, the exposure at 1 GeV is given. For HAWC, $\Delta\theta$ is the absolute 97 difference between the source declination and HAWC latitude. HAWC is more 98 sensitive to sources with smaller $\Delta\theta$. For IACTs, we show the zenith angle 99 range, the total exposure, the energy range, the angular radius θ of the signal or 100 ON region, the ratio of exposures between the background-control (OFF) and 101 signal (ON) regions (τ), and the significance of gamma-ray excess in standard 102 deviations, σ.</p> <p>103 Table 6.1 Summary of the relevant properties of the dSphs used in the present work. 104 Column 1 lists the dSphs. Columns 2 and 3 present their heliocentric distance 105 and galactic coordinates, respectively. Column 4 reports the J-factors of each 106 source given from the \mathcal{LS} studies and estimated $\pm 1\sigma$ uncertainties. The 107 values $\log_{10} J$ (\mathcal{LS} set) [80] correspond to the mean J-factor values for a 108 source extension truncated at 0.5°.</p> <p>109 Table 6.2 Timing summaries for analyses for serial and multithreaded processes. M 110 tasks is the number of functional-parallel tasks ran for the computation. $T_{p,c}$ 111 is a single run time in hours:minutes:seconds for runs utilizing p nodes and 112 c threads. Runs are run interactively on the same computer to maximize 113 consistency. Empty entries are indicated with ‘-’. (·) entries are estimated 114 entries extrapolated from data earlier in the column.</p> <p>115 Table 6.3 Speed up summaries for analyses for serial and multithreaded processes. M 116 tasks is the number of functional-parallel tasks ran for the computation. $S_{p,c}$ 117 is a single speedup comparison for runs utilizing p nodes and c threads. [·] 118 are the estimated speedups calculated from Tab. 6.2, Eq. (6.7), and Eq. (6.4). 119 Empty entries are indicated with ‘-’</p>	<p>31</p> <p>46</p> <p>47</p> <p>77</p> <p>81</p> <p>83</p>
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120	Table 7.1 Spline err tolerances used for input in particle physics component to Eq. (5.1).	
121	Column 1 is the DM annihilation channel being fit. Columns 2, 3, and 4	
122	are the tolerances for "GOOD" (pass), "OK" requires inspection, and "FAIL"	
123	(tune and refit) respectively. Column 5 has the X ranges over which the error	
124	is evaluated. MAX/MIN [·,·] takes the maximum or minimum of the two	
125	enclosed values.	98
126	Proof I know how to include	

LIST OF FIGURES

128	Figure 2.1	Rotation curve fit to NGC 6503 from [7]. Dashed line is the contribution 129 from visible matter. Dotted curves are from gas. Dash-dot curves are from 130 dark matter (DM). Solid line is the composite contribution from all matter 131 and DM sources. Data are indicated with bold dots with error bars. Data 132 agree strongly with a matter + DM composite prediction.	5
133	Figure 2.2	Light from distant galaxy is bent in unique ways depending on the distribution 134 of mass between the galaxy and Earth. Yellow dashed lines indicate where 135 the light would have gone if the matter were not present [8].	7
136	Figure 2.3	(left) Optical image of galactic cluster 1E0657-558. (right) X-ray image of the 137 cluster with redder meaning hotter and higher baryon density. (both) Green 138 contours are reconstruction of gravity contours from weak lensing. White 139 rings are the best fit mass maxima at 68.3%, 95.5%, and 99.7% confidence. 140 The matter maxima of the clusters are clearly separated from x-ray maxima. [9]	8
141	Figure 2.4	Plank CMB sky. Sky map features small variations in temperature in primor- 142 dial light. These anisotropies are used to make inferences about the universe's 143 energy budget and developmental history. [10]	9
144	Figure 2.5	Observed Cosmic Microwave Background power spectrum as a function of 145 multipole moment from Plank [10]. Blue line is best fit model from Λ CDM. 146 Red points and lines are data and error, respectively.	10
147	Figure 2.6	Predicted power spectra of CMB for different $\Omega_m h^2$ values for fixed baryon 148 density from [11]. (left) Low $\Omega_m h^2$ increases the prominence of first and 149 second peaks. (middle) $\Omega_m h^2$ is most similar to the observed power spectrum. 150 The second and third peaks are similar in height. (right) $\Omega_m h^2$ is large which 151 suppresses the first peak and raises the prominence of the third peak.	10
152	Figure 2.7	The Standard Model (SM) of particle physics. Figure taken from http://www.quantumdiaries.org/2014/03/14/the-standard-model-a-beautiful-but-flawed-theory/	12
155	Figure 2.8	Simplified Feynman diagram demonstrating with different ways DM can 156 interact with SM particles. The 'X's refer to the DM particles whereas the 157 SM refer to fundamental particles in the SM. The large circle in the center 158 indicates the vertex of interaction and is purposely left vague. The colored 159 arrows refer to different directions of time as well as their respective labels. 160 The arrows indicate the initial and final state of the DM -SM interaction in time.	13

161	Figure 2.9 A single jet event in ATLAS detector from 2017 [16]. Jet momentum was 162 observed to be 1.9 TeV. Missing transverse momentum was observed to be 163 1.9 TeV compared to the initial transverse momentum of the event was 0. 164 Implied MET is traced by a red dashed line in event display.	14
165	Figure 2.10 More detailed pseudo-Feynman diagram of particle cascade from dark matter 166 annihilation into 2 quarks. The quarks hadronize and down to stable particles 167 like γ or the anti-proton (p^-). Diagram pulled from ICRC 2021 presentation 168 on DM annihilation search [17].	15
169	Figure 2.11 Dark Matter (DM) decay spectrum for $b\bar{b}$ initial state and γ final state. Redder 170 spectra are for larger DM masses. Bluer spectra are light DM masses. x is a 171 unitless factor defined as the ratio of the mass of DM, m_χ , and the final state 172 particle energy E_γ . Figure from [19].	17
173	Figure 2.12 Different dark matter density profiles compared. Some models produce ex- 174 ceptionally large densities at small r [20].	18
175	Figure 2.13 The Milky Way Galaxy in photons (γ) and neutrinos (ν) [22]. The Galactic 176 center is at $l=0^\circ$ and is the brightest region in all panels. (top) An Optical 177 color image of the Milky Way galaxy seen from Earth. Clouds of gas and dust 178 obscure some light from stars. (2nd down) Integrated flux of γ -rays observed 179 by the Fermi-LAT telescope [23]. (middle) Expected neutrino emission 180 that corresponds with Fermi-LAT observations. (2nd up) Expected neutrino 181 emission profile after considering detector systematics of IceCube. (bottom) 182 Observed neutrino emission from region of the galactic plane. Substantial 183 neutrino emission was detected.	19
184	Figure 2.14 Dark Matter annihilation spectra for different final state particle and standard 185 model annihilation channels [24]. Photons (red), e^\pm (green), \bar{p} (blue), ν (black).	20
186	Figure 3.1 Photo of the HAWC detector that I took on May 17, 2023. Main array is 187 centered in the photo and comprised of the larger tanks. Outriggers are the 188 smaller tanks around the main array.	21
189	Figure 3.2 A particle physics illustration of high energy particle showers. Left shower is 190 an electromagnetic shower from a high energy gamma-ray. Most particles in 191 the shower will be a combination of photons and charged leptons, in this case 192 electrons (e). Right figure shows a cosmic ray particle shower. The cosmic 193 ray will produce many more types of particles including pions (π), neutrinos, 194 and charged leptons. Figure pulled from [26].	22
195	Figure 3.3 The WCDs. Left image features several WCDs looking from within the main 196 array of HAWC. Right image shows a schematic of a WCD pulled from [25].	23

197	Figure 3.4	TODO: copied from nim. Top-level diagram of the HAWC electronics showing a summary of the critical subsystems and the interconnections, including HV and optical fiber cabling. NMEA refers to the National Marine Electric Association format in which GPS presents data [66,67]; CLR, TRG and RST are control signals for the TDC system. The LoToT andHiToT time over threshold signals are discussed in Section 4.1	24
203	Figure 3.5	TODO: copied from NIM. Schematic overview [68] of the HAWC data acquisition and online processing system, as described in the text of Section 4	24
206	Figure 3.6	TODO: text copied from nim. The analog PMT signals are split and passed through two paths. In each path, there is an amplifier and discriminator circuit. The ratio of the amplifier gains is 7 to 1. The higher gain circuit has an effectively lower threshold (Low Th). There is a time (T) delay in the high threshold (High Th) path. The 2-edge event is related with the Low Th, while the 4 edge event is related to the High Th.	25
212	Figure 3.7	TODO: copied from A's thesis. An illustration of the angle reconstruction of the original particle. The secondary particles of an air shower travel in a plane perpendicular to the direction of the original particle, allowing for the reconstruction of the initial angle after corrections due to the curvature of the plane. Figure from [33].	27
217	Figure 3.8	TODO: pulled for thesis. Charge deposited in each PMT for a reconstructed gamma-ray event. Each large circle represents a WCD and each of the 4 smaller circles within represent a PMT. The color scale represents the amount of charge deposited in each PMT. The red star in the center of the dashed circle shows the location of the shower core fit by the SFCF algorithm. [34] . .	28
222	Figure 3.9	TODO: coped from paper. Normalized histogram of the energy distribution of each fhit bin defined in Table 2.1. This figure was made using Monte Carlo simulations assuming a spectral distribution E about 2.63 at a declination of 20°. Figure from [34].	30
226	Figure 3.10	TODO: copiedNN (right) energy estimators. The dotted line is the identity line; events that fall along this line are reconstructed perfectly. Gamma/hadron separation cuts have been applied. The first energy bin starts at , and the last energy bin ends at , which accounts for the sharp features in the figures. Figure pulled from [37]	32
231	Figure 3.11	TODO: copied Lateral distribution functions of an obvious cosmic ray (left) and a photon candidate from the Crab Nebula (right).The cosmic ray has isolated high-charge hits far from the shower core due to penetrating particles in the hadronic air shower. These features are absent in the gamma-ray shower .	33

235	Figure 5.1	Sensitivities of five gamma-ray experiments compared to percentages of the Crab nebula's emission and dark matter annihilation. Solid lines present estimated sensitivities to power law spectra [FACT CHECK THIS]for each experiment. Green lines are Fermi-LAT sensitivities where lighter green is the sensitivity to the galactic center and dark green is its sensitivity to higher declinations. Orange, red, and purple solid lines represent the MAGIC, HESS, and VERITAS 50 hour sensitivities respectively. The maroon and brown lines are the HAWC 1 year and 5 year sensitivities. Across four decades of gamma-ray energy, these experiments have similar sensitivities on the order 10^{-12} erg cm $^{-2}$ s $^{-1}$. The dotted lines are estimated dark matter fluxes assuming $m_\chi = 5$ TeV DM annihilating to bottom quarks (red), tau leptons (blue), and W bosons (green). Faded gray lines outline percentage flux of the Crab nebula. Figure is an augmented version of [40]	38
248	Figure 5.2	Effect of Electroweak (EW) corrections on expected DM annihilation spectrum for $\chi\chi \rightarrow W^-W^+$. Solid lines are spectral models that consider EW corrections. Dash-dot lines are spectral models without EW corrections. Red lines are models for $M_\chi = 1$ TeV. Blue lines represent models for $M_\chi = 100$ TeV. All models are sourced from the PPPC4DMID [58].	42
253	Figure 5.3	$\frac{dJ}{d\Omega}$ maps for Segue1 (top) and Coma Berenices (bottom). Origin is centered on the specific dwarf spheroidal galaxies (dSph). X and Y axes are the angular separation from the center of the dwarf. Profile is truncated at the scale radius. Plots of the remaining 11 dSph HAWC studied are linked in Fig. A.1.	44
257	Figure 5.4	Illustration of the combination technique showing a comparison between $-2 \ln \lambda$ provided by four instruments (colored lines) from the observation of the same dSph without any J nuisance and their sum, <i>i.e.</i> the resulting combined likelihood (thin black line). According to the test statistics of Equation (5.7), the intersection of the likelihood profiles with the line $-2 \ln \lambda = 2.71$ indicates the 95% C.L. upper limit on $\langle \sigma v \rangle$. The combined likelihood (thin black line) shows a smaller value of upper limit on $\langle \sigma v \rangle$ than those derived by individual instruments. We also show how the uncertainties on the J factor effects the combined likelihood and degrade the upper limit on $\langle \sigma v \rangle$ (thick black line). All likelihood profiles are normalized so that the global minimum $\widehat{\langle \sigma v \rangle}$ is 0. We note that each profile depends on the observational conditions in which a target object was observed. The sensitivity of a given instrument can be degraded and the upper limits less constraining if the observations are performed in non-optimal conditions such as a high zenith angle or a short exposure time.	50
272	Figure 5.5	53

273	Figure 5.6 HAWC TS values for best fit $\langle\sigma v\rangle$ versus m_χ for seven SM annihilation channels with J factors from \mathcal{GS} . The solid black line shows the combined best fit TS values. The colored, dashed lines are the TS values for each of the 13 sources HAWC studied.	54
277	Figure 5.7 HAWC Brazil bands at 95% confidence level on $\langle\sigma v\rangle$ versus DM mass for seven annihilation channels with J -factors from \mathcal{GS} [69]. The solid line represents the combined limit from 13 dSphs. The dashed line is the expected limit. The green band is the 68% containment. The yellow band is the 95% containment.	55
282	Figure 5.8 Upper limits at 95% confidence level on $\langle\sigma v\rangle$ in function of the DM mass for eight annihilation channels, using the set of J factors from Ref. [69] (\mathcal{GS} set in Table 5.1). The black solid line represents the observed combined limit, the black dashed line is the median of the null hypothesis corresponding to the expected limit, while the green and yellow bands show the 68% and 95% containment bands. Combined upper limits for each individual detector are also indicated as solid, colored lines. The value of the thermal relic cross-section in function of the DM mass is given as the red dotted-dashed line [70].	56
291	Figure 5.9 Same as Fig. 5.8, using the set of J factors from Ref. [63, 71] (\mathcal{B} set in Table 5.1).	57
292	Figure 5.10 Comparisons of the combined limits at 95% confidence level for each of the eight annihilation channels when using the J factors from Ref. [69] (\mathcal{GS} set in Table 5.1), plain lines, and the J factor from Ref. [63, 71] (\mathcal{B} set in Table 5.1), dashed lines. The cross-section given by the thermal relic is also indicated [70].	59
296	Figure 5.11 Comparisons of the combined limits at 95% confidence level for a point source analysis and extended source using [69] \mathcal{GS} J-factor distributions and PPPC [58] annihilation spectra. Shown are the limits for Segue1 which will have the most significant impact on the combined limit. 6 of the 7 DM annihilation channels are shown. Solid lines are extended source studies. Dashed lines are point source studies. Overall, the extended source analysis improves the limit by a factor of 2.	61
303	Figure 5.12 Same as Fig. 5.11 on Coma Berenices. This dSph also contributes significantly to the limit. The limits are identical in this case.	62
305	Figure 5.13 Comparison of combined limits when correcting for HAWC's pointing systematic. All DM annihilation channels are shown. The solid black line is the ratio between published limit to the declination corrected limit. The blue solid line or "Combined_og" represented the limits computed for Glory Duck. The solid orange line or "Combined_ad" represented the limits computed after correcting for the pointing systematic.	63

311	Figure 5.14 Differential map of dJ/Ω from model built in Section 5.8.1 and profiles 312 provided directly from authors. (Top) Differential from Segue1. (bottom) 313 Differential from Coma Berenices. Note that their scales are not the same. 314 Segue1 shows the deepest discrepancies which is congruent with its large 315 uncertainties. Both models show anuli where unique models become apparent.	64
316	Figure 5.15 HAWC limits for Coma Berenices (top) and Segue1 (bottom) for two different 317 map sets. Blue lines are limits calculated on maps with poor model repre- 318 sentation. Orange lines are limits calculated on spatial profiles provided by 319 the authors of [59]. Black line is the ratio of the poor spatial model limits to 320 the corrected spatial models. The left y-axis measures $\langle\sigma v\rangle$ for the blue and 321 orange lines. The right y-axis measures the ratio and is unitless.	65
322	Figure 5.16 Comparisons between the J -factors versus the angular radius for the com- 323 putation of J factors from Ref. [69] (\mathcal{GS} set in Table 5.1) in blue and for 324 the computation from Ref. [63, 71] (\mathcal{B} set in Tab. 5.1) in orange. The solid 325 lines represent the central value of the J -factors while the shaded regions 326 correspond to the 1σ standard deviation.	67
327	Figure 5.17 Comparisons between the J -factors versus the angular radius for the com- 328 putation of J factors from Ref. [69] (\mathcal{GS} set in Tab. 5.1) in blue and for the 329 computation from Ref. [63, 71] (\mathcal{B} set in Tab. 5.1) in orange. The solid 330 lines represent the central value of the J -factors while the shaded regions 331 correspond to the 1σ standard deviation.	68
332	Figure 6.1 Spectral hypotheses from PPPC [58] and HDM [79] for DM annihilation: 333 $\chi\chi \rightarrow W^-W^+$. Solid lines are spectral models with EW corrections from the 334 PPPC. Dash-dot lines are spectral models from HDM. Red lines are models 335 for $M_\chi = 1$ TeV. Blue lines represent models for $M_\chi = 100$ TeV.	73
336	Figure 6.2 Photon spectra for $\chi\chi \rightarrow \gamma\gamma$ (left) and $\chi\chi \rightarrow ZZ$ (right) after Gaussian 337 convolution of line features. Both spectra have δ -features at photon energies 338 equal to the DM mass. Bluer lines are annihilation spectra with lower DM 339 mass. Redder lines are spectra from larger DM mass. All spectral models are 340 sourced from the Heavy Dark Matter models [79]. Axes are drawn roughly 341 according to the energy sensitivity of HAWC.	74
342	Figure 6.3 $\frac{dJ}{d\Omega}$ maps for Coma Berenices, Draco, Segue1, and Sextans. Columns are 343 divided for the $\pm 1\sigma$ uncertainties in $dJ/d\Omega$ around the mean value from \mathcal{LS} 344 [80]. Origin is centered on the specific dwarf spheroidal galaxies (dSph). θ 345 and ϕ axes are the angular separation from the center of the dwarf. Profiles 346 are truncated at 1° and flattened beyond.	76

347	Figure 6.4	Infographic on how jobs and DM computation was organized in Section 5.3. Jobs were built for each permutation of CHANS and SOURCES shown by the left block in the figure. Each job, which took on the order 2 hrs to compute, had the following work flow: 1. Import HAWC analysis software, 2 min to run. 2. Load HAWC count maps, 5 min to run. 3. Load HAWC energy and spatial resolutions, 4 min. 5. Load DM spatial source templates and spectral models, less than 1 s. 6. Perform likelihood fit on data and model, about 8 min per DM mass. 7. Write results to file, less than 1s.	78
355	Figure 6.5	Graphic of Gustafson parallel coding pattern. f_s is the fraction of a program, in time, spent on serial computation. f_p is the fraction of computing time that is parallelizable. T_p is the total time for a parallel program to run. T_1 is the total time for a parallel program to run if only 1 processor is allocated. P_N is the N -th processor where it's row is the computation the processor performs. The Gustafson pattern is most similar to what is implemented for this analysis. Figure is pulled from [82].	79
362	Figure 6.6	Task chart for one multithreaded job developed for this project. Green blocks indicate a shared resource across the threads AND computation performed serially. Red blocks indicate functional parallel processing within each thread. 3 threads are represented here, yet many more can be employed during the full analysis. Jobs are defined by the SOURCE as these require unique maps to be loaded into the likelihood estimator. The m_χ , CHAN, and $\langle\sigma v\rangle$ variables are entered into the thread pool and allocated as evenly as possible across the threads.	81
370	Figure 6.7	HAWC upper limits at 95% confidence level on $\langle\sigma v\rangle$ versus m_χ for $\chi\chi \rightarrow b\bar{b}, t\bar{t}, u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}, gg, W^+W^-$, and hh . Limits are with \mathcal{LS} J -factors [80]. The solid line represents the observed combined limit. Dashed lines represent limits from individual dSphs.	84
374	Figure 6.8	HAWC upper limits at 95% confidence level on $\langle\sigma v\rangle$ versus m_χ for $\chi\chi \rightarrow \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, e\bar{e}, \mu\bar{\mu}, \tau\bar{\tau}, \gamma\gamma$ and ZZ . Limits use \mathcal{LS} J -factors [80]. The solid line represents the observed combined limit. Dashed lines represent limits from individual dSphs.	85
378	Figure 6.9	HAWC TS values for best fit $\langle\sigma v\rangle$ versus m_χ for SM annihilation channels: $\chi\chi \rightarrow b\bar{b}, t\bar{t}, u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}, gg, W^+W^-$, and hh . Limits use \mathcal{LS} J -factors. The solid black line shows the combined best fit TS values. The colored, dashed lines are the TS values from each dSph.	86
382	Figure 6.10	HAWC TS values for best fit $\langle\sigma v\rangle$ versus m_χ for SM annihilation channels: $\chi\chi \rightarrow \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, e\bar{e}, \mu\bar{\mu}, \tau\bar{\tau}, \gamma\gamma$ and ZZ . Limits use \mathcal{LS} J -factors. The solid black line shows the combined best fit TS values. The colored, dashed lines are the TS values from each dSph.	87

386	Figure 6.11 Comparison of HAWC limits from this analysis to Glory Duck (Fig. 5.5) for 3 dSphs and 3 DM annihilation channels: $b\bar{b}$, $\tau\bar{\tau}$, and $e\bar{e}$. Each sector shows the 95% confidence limit from Glory Duck (blue line) and this analysis (orange line) in the top plot. The lower plot features the ratio in log scale of Glory Duck to this analysis in a red solid line. Horizontal dashed lines are for ratios of 1.0 (black) and $\sqrt{2}$ (blue). Ratios larger than 1.0 are for limits smaller, or stricter, than Glory Duck. Ratios larger than $\sqrt{2}$ indicates limits are stricter than a simple doubling of the Glory Duck data.	89
394	Figure 7.1 Neutrino spectra at production (left panels) and after oscillation at Earth (right panels). Blue, orange, and green lines are the ν_e , ν_μ , and ν_τ spectra respectively. Top panels show the spectra in $\frac{dN}{dE}$. Lower panels plot the flavor ratio to $\nu_e + \nu_\mu + \nu_\tau$. SM annihilation channels $b\bar{b}$, $\tau\bar{\tau}$, and $\nu_\mu\bar{\nu}_\mu$ are shown for $M_\chi = 1$ PeV, TeV, and EeV.	94
399	Figure 7.2 Signal recovery for 100 TeV DM annihilation into $\nu_\mu\bar{\nu}_\mu$ for a source at Dec = 16.06° . n_{inj} is the number of injected signal events in simulation. n_s is the number of reconstructed signal events from the simulation data. Although the uncertainties are small and tight, the reconstructed n_s are systematically underestimated.	95
404	Figure 7.3 Left panel shows the two kernels overlaying the original spectrum from χ arony after propagation to Earth [85]. The vertical red line indicates where the original neutrino line is maximized. Blue line is the output from χ aroy. Green line is the spectrum after convolution with a flat kernel. Orange line is the spectrum after Gaussian convolution. Right panel shows the signal recovery of the spectral model using the Gaussian kernel with parameters enumerated above.	96
411	Figure 7.4 Example spline that failed the fit. Failed splined are corrected on a case by case basis unless the SM channel has a systematic problem fitting the splines. In this case, I made a bookkeeping error and loaded the incorrect spectral model	98
414	Figure 7.5 Summary of input spectral models that were smoothed with Gaussian kernels. Spectral models are for $\chi\chi \rightarrow e\bar{e}, \mu\bar{\mu}, \tau\bar{\tau}, \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu$, and $\nu_\tau\bar{\nu}_\tau$. These spectra are the composite ($\nu_\mu + \nu_\tau$) of neutrino flavors. Every spectral model used for this analysis is featured as a colored solid line. Bluer lines are for low m_χ models. m_χ ranges from 681 GeV to 100 PeV. HDM [79], χ aroy [85], and Photospline [89] are used to generate these spectra. Energy (x-axis) was chosen to roughly represent the energy sensitivity of NST.	99

421	Figure 7.6 Test statistic (TS) distributions for Segue 1 and $\chi\chi \rightarrow b\bar{b}$. Each subplot, 422 except the final, is the TS distribution for a specific DM mass listed in the 423 subplot. Orange dashed lines are the traces for a χ^2 distribution with 1 degree 424 of freedom. $\epsilon[\cdot]$ is the fraction of trials smaller than the bracketed value. The 425 final subplot features the all DM spectral models, similar to Fig. 7.5, used as 426 input for the TS distributions.	102
427	Figure 7.7 Same as Fig. 7.6 for Segue 1 $\chi\chi \rightarrow \tau\bar{\tau}$	103
428	Figure 7.8 Same as Fig. 7.6 for Segue 1 $\chi\chi \rightarrow \nu_\mu\bar{\nu}_\mu$	104
429	Figure 7.9 Same as Fig. 7.6 for Ursa Major II 1 $\chi\chi \rightarrow b\bar{b}$	105
430	Figure 7.10 Same as Fig. 7.6 for Ursa Major II 1 $\chi\chi \rightarrow \tau\bar{\tau}$	106
431	Figure 7.11 Same as Fig. 7.6 for Ursa Major II 1 $\chi\chi \rightarrow \nu_\mu\bar{\nu}_\mu$	107
432	Figure 7.12 Same as Fig. 7.6 for 15, GS J-factor, stacked sources and $\chi\chi \rightarrow b\bar{b}$	108
433	Figure 7.13 Same as Fig. 7.6 for 15, GS J-factor, stacked sources and $\chi\chi \rightarrow t\bar{t}$	109
434	Figure 7.14 Same as Fig. 7.6 for 15, GS J-factor, stacked sources and $\chi\chi \rightarrow u\bar{u}$	110
435	Figure 7.15 Same as Fig. 7.6 for 15, GS J-factor, stacked sources and $\chi\chi \rightarrow d\bar{d}$	111
436	Figure 7.16 Same as Fig. 7.6 for 15, GS J-factor, stacked sources and $\chi\chi \rightarrow e\bar{e}$	112
437	Figure 7.17 Same as Fig. 7.6 for 15, GS J-factor, stacked sources and $\chi\chi \rightarrow \mu\bar{\mu}$	113
438	Figure 7.18 Same as Fig. 7.6 for 15, GS J-factor, stacked sources and $\chi\chi \rightarrow \tau\bar{\tau}$	114
439	Figure 7.19 Same as Fig. 7.6 for 15, GS J-factor, stacked sources and $\chi\chi \rightarrow W^+W^-$	115
440	Figure 7.20 Same as Fig. 7.6 for 15, GS J-factor, stacked sources and $\chi\chi \rightarrow ZZ$	116
441	Figure 7.21 Same as Fig. 7.6 for 15, GS J-factor, stacked sources and $\chi\chi \rightarrow \nu_e\bar{\nu}_e$	117
442	Figure 7.22 Same as Fig. 7.6 for 15, GS J-factor, stacked sources and $\chi\chi \rightarrow \nu_\mu\bar{\nu}_\mu$	118

443	Figure 7.23 Signal Recovery study for an analysis with 15 stacked sources using the \mathcal{GS}	120
444	J -factors [59]. Above shows 14 studies for DM mass ranging between 1	
445	TeV and 20 PeV for $\chi\chi \rightarrow \mu_\mu\overline{\mu_\mu}$. The bottom right subplot features every	
446	spectral model used as input for the remaining subplots. The remaining	
447	subplots show n_{inj} as the number of signal events injected into background	
448	simulation. Whereas, n_s is the number of signal events recovered from	
449	analyzing the injected simulation. Blue line represents the median values of	
450	100 simulations. Light blue bands show the 1σ statistical uncertainty around	
451	the median.	
452	Figure 7.24 Same as Fig. 7.23 but for $\chi\chi \rightarrow t\bar{t}$ (top) and $b\bar{b}$ (bottom).	121
453	Figure 7.25 IceCube North Sky Track Sensitivities. Each panel shows sensitivity curves	
454	for various DM annihilation channels. Sensitivities are for the velocity-	
455	weighted cross-section $\langle\sigma v\rangle$ versus m_χ . Dotted, colored lines are sensitivities	
456	for individual sources. Solid white lines are for the combined sensitivity of	
457	all 15 \mathcal{GS} sources used in this study.	123
458	Figure 7.26 Same as Fig. 7.25 for three additional DM annihilation channels.	124
459	Figure 7.27 Panel A: Neutrino's from the Northern sky and incident on the IceCube	
460	detector will travel through the Earth. How much of the Earth these neutrinos	
461	travels is a function of zenith from the vertical axis. Panel B: SM prediction of	
462	neutrino transmission probabilities for neutrinos arriving at $90^\circ - 180^\circ$ zenith	
463	and with 100 GeV to 100 PeV energies. High-energy neutrinos traversing	
464	the whole Earth are completely absorbed, whereas low-energy neutrinos pass	
465	through unimpeded. Neutrinos coming from above the horizon will arrive	
466	unimpeded for all neutrino energies. Figure pulled from [92].	125
467	Figure 7.28 $\langle\sigma v\rangle$ sensitivities for 5 imaginary sources with $\log_{10} J = 19.42 \log_{10}(\text{GeV}^2\text{cm}^{-5})$.	
468	Each imaginary source shares a declination with a source in Tab. 5.1	126
469	Figure 8.1 The prompt electron neutrino and photon spectrum resulting from the decay	
470	of a 2EeV DM particle to $\nu_e\overline{\nu}_e$, as currently being searched for at IceCube	
471	[5]. Solid curves represent the results of this work, and predict orders of	
472	magnitude more flux at certain energies than the dashed results of Pythia 8.2,	
473	one of the only existing methods to generate spectra at these masses. In both	
474	cases energy conservation is satisfied: there is a considerable contribution to	
475	a δ -function at $x = 1$, associated with events where an initial W or Z was never	
476	emitted and thus no subsequent shower developed. Large disagreements are	
477	generically observed at these masses for electroweak dominated channels,	
478	while the agreement is better for colored initial SM states.	128
479	Figure 8.2 TODO: neutrino and bb plot with nu Sensitivities[NEEDS A SOURCE][FACT	
480	CHECK THIS]	129

481	Figure A.1	Sister figure to Figure 5.3. Sources in the first row from left to right: Bootes I, Canes Venatici I, II. In second row: Draco, Hercules, Leo I. In the first row: Leo II, Leo IV, Sextans. In the final row: Ursa Major I, Ursa Major II.	130
484	Figure B.1	Sister figure to Figure 6.2 for remaining SM primary annihilation channels studied for this thesis. These did not require any post generation smoothing and so are directly pulled from [79] with a binning scheme most helpful for a HAWC analysis.	131
488	Figure B.2	Comparison of HAWC limits from this analysis to Glory Duck (Fig. 5.5) for Coma Berenices and 7 DM annihilation channels.	141
490	Figure B.3	Same as Fig. B.2 but for Segue 1.	142
491	Figure B.4	Same as Fig. B.2 but for Sextans.	143
492	Figure C.1	Current status of spline tables according to constraints defined by Tab. 7.1. Green splines are splines that passed under the GOOD tolerance. Yellow are splines that are OK. Red are splines that FAIL. All yellow splines were inspected individually before running the analysis. Splines were made for the μ (PID 14; top panel) flavor and τ (PID 16; bottom panel) neutrino flavors.	147
497	Figure C.2	Sister figure to Fig. 7.5 for annihilation channels that did not require kernel smoothing. These spectra are the composite ($\nu_\mu + \nu_\tau$) of neutrino flavors. Every spectral model used for this analysis is featured as a colored solid line. Bluer lines are for lower DM mass spectral models. DM masses range from 681 GeV to 100 PeV.	148
502	Figure C.3	Same as Fig. 7.23 but for Segue 1 and $\chi\chi \rightarrow b\bar{b}$	149
503	Figure C.4	Same as Fig. 7.23 but for Segue 1 and $\chi\chi \rightarrow t\bar{t}$	150
504	Figure C.5	Same as Fig. 7.23 but for Segue 1 and $\chi\chi \rightarrow \nu_\mu\bar{\nu}_\mu$	151
505	Figure C.6	Same as Fig. 7.23 but for Ursa Major II and $\chi\chi \rightarrow b\bar{b}$	152
506	Figure C.7	Same as Fig. 7.23 but for Ursa Major II and $\chi\chi \rightarrow t\bar{t}$	153
507	Figure C.8	Same as Fig. 7.23 but for Ursa Major II and $\chi\chi \rightarrow \nu_\mu\bar{\nu}_\mu$	154
508	Figure C.9	IceCube North Sky Track Sensitivities for $n_s/\langle N \rangle$. n_s values are the counts fed into Eq. (7.8) to produce Fig. 7.26 and Fig. 7.25.	155
510	Figure C.10	Same as Fig. C.9 for three additional DM annihilation channels.	156

511

LIST OF ABBREVIATIONS

- 512 **MSU** Michigan State University
513 **LANL** Los Alamos National Laboratory
514 **DM** Dark Matter
515 **SM** Standard Model
516 **HAWC** High Altitude Water Cherenkov Observatory
517 **dSph** Dwarf Spheroidal Galaxy

CHAPTER 1

INTRODUCTION

519 Is the text not rendering right? Ah ok it knows im basically drafting the doc still

CHAPTER 2

520

DARK MATTER IN THE COSMOS

521 **2.1 Introduction**

522 The dark matter problem can be summarized in part by the following thought experiment.

523 Let us say you are the teacher for an elementary school classroom. You take them on a field
524 trip to your local science museum and among the exhibits is one for mass and weight. The exhibit
525 has a gigantic scale, and you come up with a fun problem for your class.

526 You ask your class, "What is the total weight of the classroom? Give your best estimation to
527 me in 30 minutes, and then we'll check your guess on the scale. If your guess is within 10% of the
528 right answer, we will stop for ice cream on the way back."

529 The students are ecstatic to hear this, and they get to work. The solution is some variation of
530 the following strategy. The students should give each other their weight or best guess if they do
531 not know. Then, all they must do is add each student's weight and get a grand total for the class.

532 The measurement on the giant scale should show the true weight of the class. When comparing
533 the measured weight to your estimation, multiply the measurement by 1.0 ± 0.1 to get the $\pm 10\%$
534 tolerances for your estimation.

535 Two of your students, Sandra and Mario, return to you with a solution.

536 They say, "We weren't sure of everyone's weight. We used 65 lbs. for the people we didn't
537 know and added everyone who does know. There are 30 of us, and we got 2,000 lbs.! That's a ton!"

538 You estimated 1,900 lbs. assuming the average weight of a student in your class was 60 lbs.
539 So, you are pleased with Sandra's and Mario's answer. You instruct your students to all gather on
540 the giant scale and read off the weight together. To all your surprise, the scale reads *10,000 lbs.*!
541 10,000 is significantly more than a 10% error from 2,000. In fact, it is approximately 5 times more
542 massive than either your or your students' estimates. You think to yourself and conclude there
543 must be something wrong with the scale. You ask an employee to check the scale and verify it is
544 well calibrated. They confirm that the scale is in working order. You weigh a couple of students
545 individually to assess that the scale is well calibrated. Sandra weighs 59 lbs., and Mario weighs

546 62 lbs., typical weights for their age. You then weigh each student individually and see that their
547 weights individually do not deviate greatly from 60 lbs. So, where does all the extra weight come
548 from?

549 This thought experiment serves as an analogy to the Dark Matter problem. The important
550 substitution to make however is to replace the students with stars and the classroom with a galaxy,
551 say the Milky Way. Individually the mass of stars is well measured and defined with the Sun as our
552 nearest test case. However, when we set out to measure the mass of a collection of stars as large as
553 galaxies, our well-motivated estimation is wildly incorrect. There simply is no way to account for
554 this discrepancy except without some unseen, or dark, contribution to mass and matter in galaxies.
555 I set out in my thesis to narrow the possibilities of what this Dark Matter could be.

556 This chapter is organized like the following... **TODO: Text should look like ... Chapter x has**
557 **blah blah blah.**

558 2.2 Dark Matter Basics

559 Presently, a more compelling theory of cosmology that includes Dark Matter (DM) in order
560 to explain a variety of observations is Λ Cold Dark Matter, or Λ CDM. I present the evidence
561 supporting Λ CDM in Section 2.3 yet discuss the conclusions of the Λ CDM model here. According
562 to Λ CDM fit to observations on the Cosmic Microwave Background (CMB), DM is 26.8% of the
563 universe's current energy budget. Baryonic matter, stuff like atoms, gas, and stars, contributes to
564 4.9% of the universe's current energy budget [1, 2, 3].

565 DM is dark; it does not interact readily with light at any wavelength. DM also does not interact
566 noticeably with the other standard model forces (Strong and Weak) at a rate that is readily observed
567 [3]. DM is cold, which is to say that the average velocity of DM is below relativistic speeds [1].
568 'Hot' DM would not likely manifest the dense structures we observe like galaxies, and instead
569 would produce much more diffuse galaxies than what is observed [3, 1]. DM is old; it played a
570 critical role in the formation of the universe and the structures within it [1, 2].

571 Observations of DM have so far been only gravitational. The parameter space available to what
572 DM could be therefore is extremely broad. The broad DM parameter space is iteratively tested in

573 DM searches by supposing a hypothesis that has not yet been ruled out and performing observations
574 to test them. When the observations yield a null result, the parameter space is constrained further.
575 I present some approaches for DM searches in Section 2.4.

576 **2.3 Evidence for Dark Matter**

577 Dark Matter (DM) has been a looming problem in physics for almost 100 years. Anomalies
578 have been observed by astrophysicists in galactic dynamics as early as 1933 when Fritz Zwicky
579 noticed unusually large velocity dispersion in the Coma cluster. Zwicky's measurement was the
580 first recorded to use the Virial theorem to measure the mass fraction of visible and invisible matter
581 in celestial bodies [4]. From Zwicky in [5], "*If this would be confirmed, we would get the surprising*
582 *result that dark matter is present in much greater amount than luminous matter.*" Zwicky's and
583 others' observation did not instigate a crisis in astrophysics because the measurements did not
584 entirely conflict with their understanding of galaxies [4]. In 1978, Rubin, Ford, and Norbert
585 measured rotation curves for ten spiral galaxies [6]. Rubin et al.'s 1978 publication presented a
586 major challenge to the conventional understanding of galaxies that could no longer be dismissed by
587 measurement uncertainties. Evidence has been mounting ever since for this exotic form of matter.
588 The following subsections provide three compelling pieces of evidence in support of the existence
589 of DM.

590 **2.3.1 First Clues: Stellar Velocities**

591 Zwicky, and later Rubin, measured the stellar velocities of various galaxies to estimate their
592 virial mass. The Virial Theorem upon which these observations are interpreted is written as

$$2T + V = 0. \quad (2.1)$$

593 Where T is the kinetic energy and V is the potential energy in a self-gravitating system. The
594 classical Newton's law of gravity from stars and gas was used for gravitational potential modeled in
595 the observed galaxies:

$$V = -\frac{1}{2} \sum_i \sum_{j \neq i} \frac{m_i m_j}{r_{ij}}. \quad (2.2)$$

596 Zwicky et al. measured just the velocities of stars apparent in optical wavelengths [5]. Rubin et al.
 597 added by measuring the velocity of the hydrogen gas via the 21 cm emission line of Hydrogen [6].
 598 The velocities of the stars and gas are used to infer the total mass of galaxies and galaxy clusters
 599 via Equation (2.1). An inferred mass is obtained from the luminosity of the selected sources. The
 600 two inferences are compared to each other as a luminosity to mass ratio which typically yielded [1]

$$\frac{M}{L} \sim 400 \frac{M_{\odot}}{L_{\odot}} \quad (2.3)$$

601 M_{\odot} and L_{\odot} referring to stellar mass and stellar luminosity, respectively. These ratios clearly indicate
 602 a discrepancy in apparent light and mass from stars and gas and their velocities.

603 Rubin et al. [6] demonstrated that the discrepancy was unlikely to be an underestimation of
 604 the mass of the stars and gas. The inferred "dark" mass was up to 5 times more than the luminous
 605 mass. This dark mass also needed to extend well beyond the extent of the luminous matter.

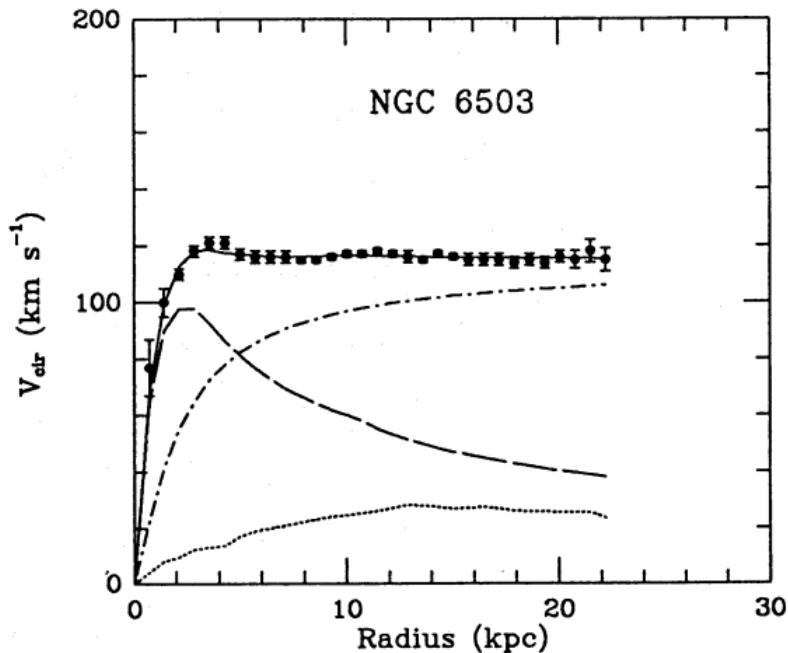


Figure 2.1 Rotation curve fit to NGC 6503 from [7]. Dashed line is the contribution from visible matter. Dotted curves are from gas. Dash-dot curves are from dark matter (DM). Solid line is the composite contribution from all matter and DM sources. Data are indicated with bold dots with error bars. Data agree strongly with a matter + DM composite prediction.

606 Figure 2.1 features one of many rotation curves plotted from the stellar velocities within galaxies.

607 The measured rotation curves mostly feature a flattening of velocities at higher radius which is not
608 expected if the gravity was only coming from gas and luminous matter. The extension of the
609 flat velocity region also indicates that the DM is distributed far from the center of the galaxy.
610 Modern velocity measurements include significantly larger objects, galactic clusters, and smaller
611 objects, dwarf galaxies. Yet, measurements along this regime are leveraging the Virial theorem
612 with Newtonian potential energies. We know Newtonian gravity is not a comprehensive description
613 of gravity. New observational techniques have been developed since 1978, and those are discussed
614 in the following sections.

615 **2.3.2 Evidence for Dark Matter: Gravitational Lensing**

616 Modern evidence for dark matter comes from new avenues beyond stellar velocities. Grav-
617 itational lensing from DM is a new channel from general relativity. General relativity predicts
618 aberrations in light caused by massive objects. In recent decades we have been able to measure the
619 lensing effects from compact objects and DM halos. Figure 2.2 shows how different massive ob-
620 jects change the final image of a faraway galaxy resulting from gravitational lensing. Gravitational
621 lensing developed our understanding of dark matter in two important ways.

622 Gravitational lensing provides additional compelling evidence for DM. The observation of two
623 merging galactic clusters in 2006, shown in Figure 2.3, provided a compelling argument for DM
624 outside the Standard Model. These clusters merged recently in astrophysical time scales. Galaxies
625 and star cluster have mostly passed by each other as the likelihood of their collision is low. Therefore,
626 these massive objects will mostly track the highest mass, dark and/or baryonic, density. Yet, the
627 intergalactic gas is responsible for the majority of the baryonic mass in the systems [4]. These gas
628 bodies will not phase through and will heat up as they collide together. The hot gas is located via
629 x-ray emission from the cluster. Two observations of the clusters were performed independently of
630 each other.

631 The first was the lensing of light around the galaxies due to their gravitational influences.
632 When celestial bodies are large enough, the gravity they exert bends space and time itself. The
633 warped space-time lenses light and will deflect in an analogous way to how glass lenses will bend

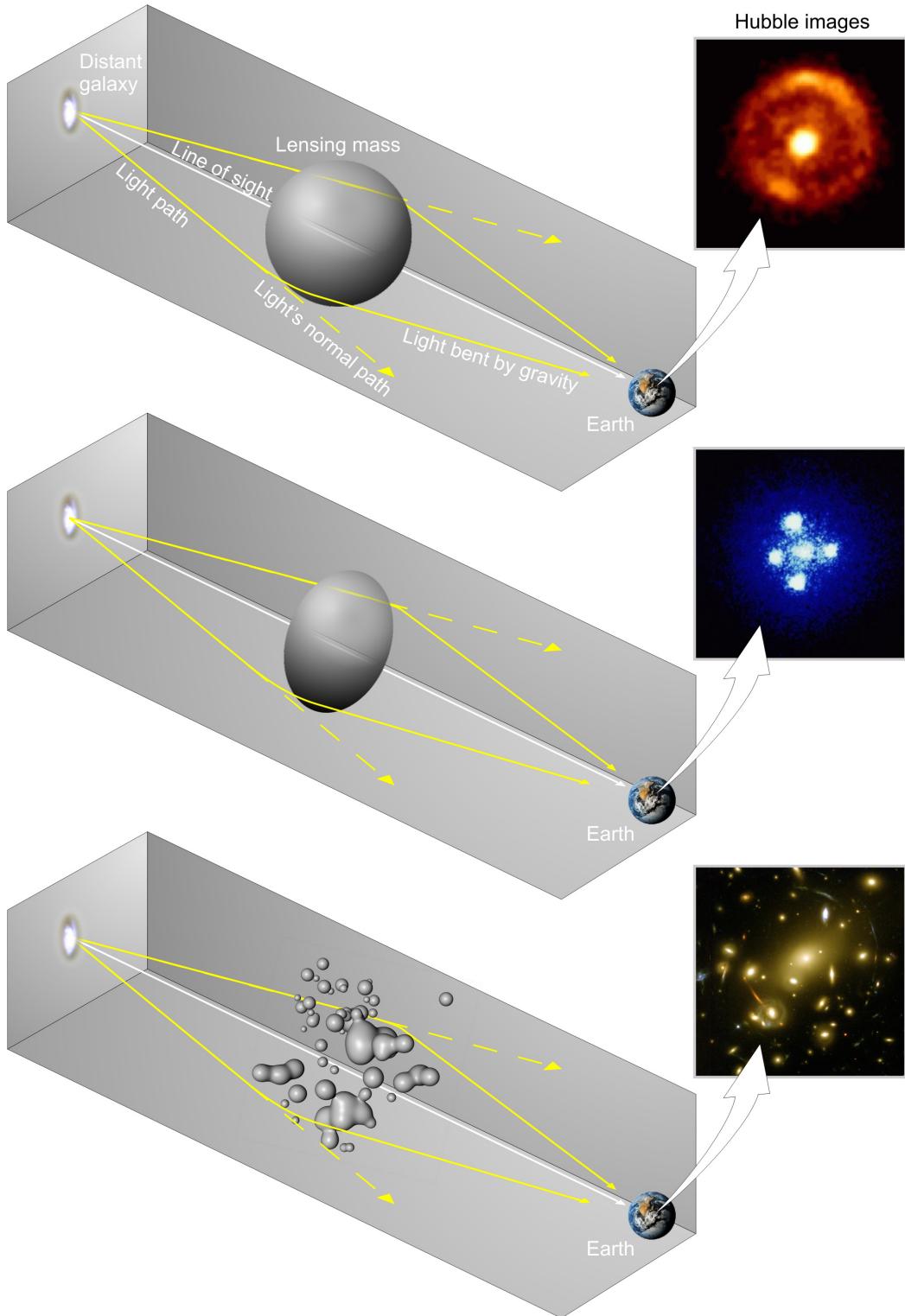


Figure 2.2 Light from distant galaxy is bent in unique ways depending on the distribution of mass between the galaxy and Earth. Yellow dashed lines indicate where the light would have gone if the matter were not present [8].

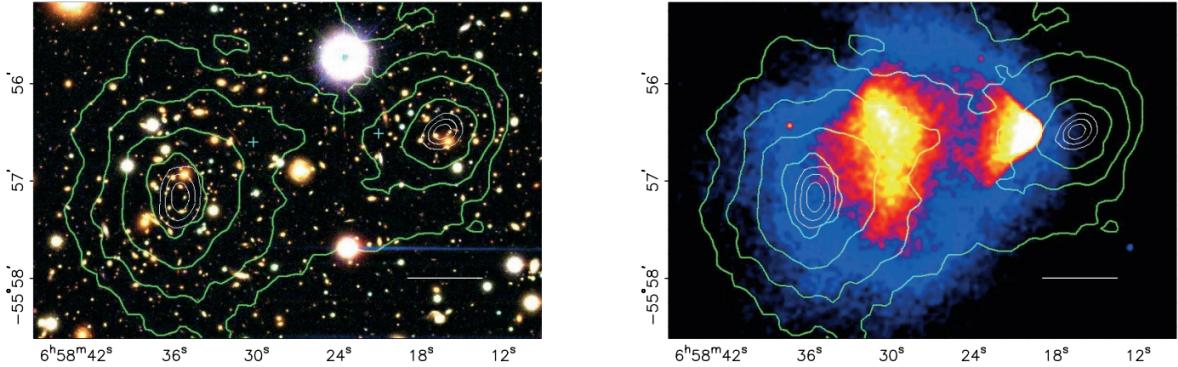


Figure 2.3 (left) Optical image of galactic cluster 1E0657-558. (right) X-ray image of the cluster with redder meaning hotter and higher baryon density. (both) Green contours are reconstruction of gravity contours from weak lensing. White rings are the best fit mass maxima at 68.3%, 95.5%, and 99.7% confidence. The matter maxima of the clusters are clearly separated from x-ray maxima. [9]

634 light, see Figure 2.2. With a sufficient understanding of light sources behind a massive object, we
 635 can reconstruct the contours of the gravitational lenses. The gradient of the contours shown in
 636 Figure 2.3 then indicates how dense the matter is and where it is.

637 The x-ray emission can then be observed from the clusters. Since these galaxies are mostly gas
 638 and are merging, then the gas should be getting hotter. If they are merging, the x-ray emissions
 639 should be the strongest where the gas is mostly moving through each other. Hence, X-ray emission
 640 maps out where the gas is in the merging galaxy cluster.

641 The lensing and x-ray observations were done on the Bullet cluster featured on Figure 2.3.
 642 The x-ray emissions do not align with the gravitational contours from lensing. The incongruence
 643 in mass density and baryon density suggests that there is a lot of matter somewhere that does
 644 not interact with light. Moreover, this dark matter cannot be baryonic [9]. The Bullet Cluster
 645 measurement did not really tell us what DM is exactly, but it did give the clue that DM also does
 646 not interact with itself very strongly. If DM did interact strongly with itself, then it would have been
 647 more aligned with the x-ray emission [9]. There have been follow-up studies of galaxy clusters with
 648 similar results. The Bullet Cluster and others like it provide a persuasive case against something
 649 possibly amiss in our gravitational theories.

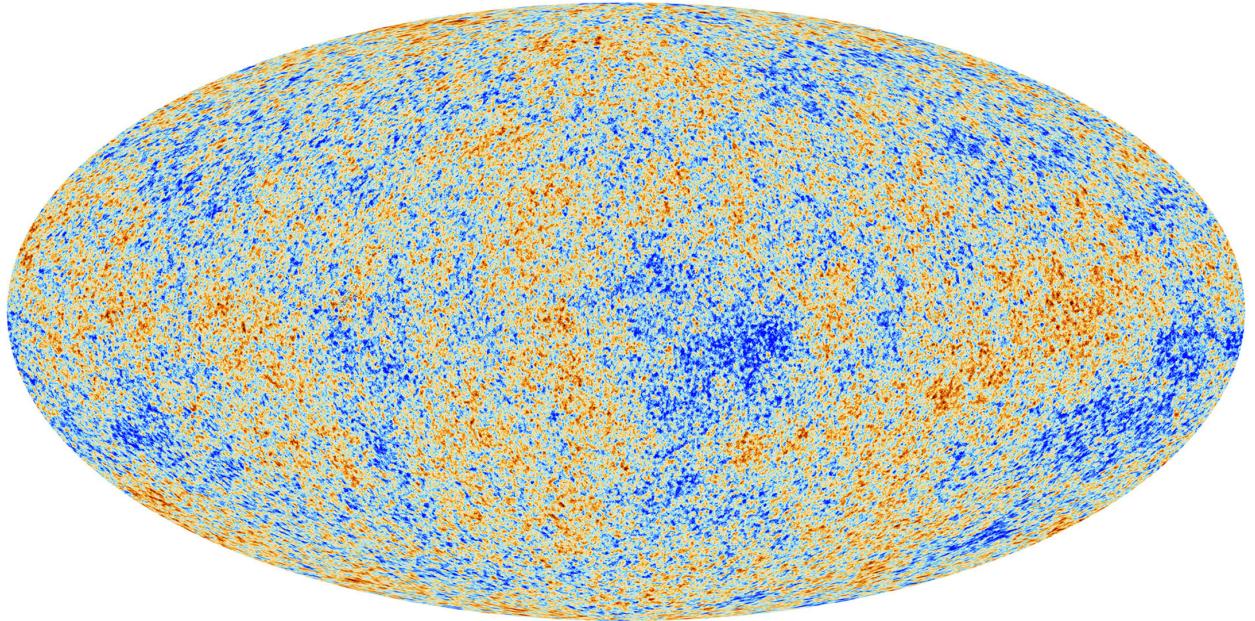


Figure 2.4 Plank CMB sky. Sky map features small variations in temperature in primordial light. These anisotropies are used to make inferences about the universe’s energy budget and developmental history. [10]

650 **2.3.3 Evidence for Dark Matter: Cosmic Microwave Background**

651 The Cosmic Microwave Background (CMB) is the primordial light from the early universe
652 when Hydrogen atoms formed from the free electron and proton soup in the early universe. The
653 CMB is the earliest light we can observe; released when the universe was about 380,000 years old.
654 Then we look at how the simulated universes look like compared to what we see. Figure 2.4 is the
655 most recent CMB image from the Plank satellite after subtracting the average value and masking the
656 galactic plane [10]. Redder regions indicate a slightly hotter region in the CMB, and blue indicates
657 colder. The intensity variations are on the order of 1 in 1000 with respect to the average value.

658 The Cosmic Microwave Background shows that the universe had DM in it from an incredibly
659 early stage. To measure the DM, Dark Energy, and matter fractions of the universe from the CMB,
660 the image is analyzed into a power spectrum, which shows the amplitude of the fluctuations as
661 a function of spherical multipole moments. Λ CDM provides the best fit to the power spectra of
662 the CMB as shown in Figure 2.5. The CMB power spectrum is quite sensitive to the fraction
663 of each energy contribution in the early universe. Low l modes are dominated by variations
664 in gravitational potential. Intermediate l emerge from oscillations in photon-baryon fluid from

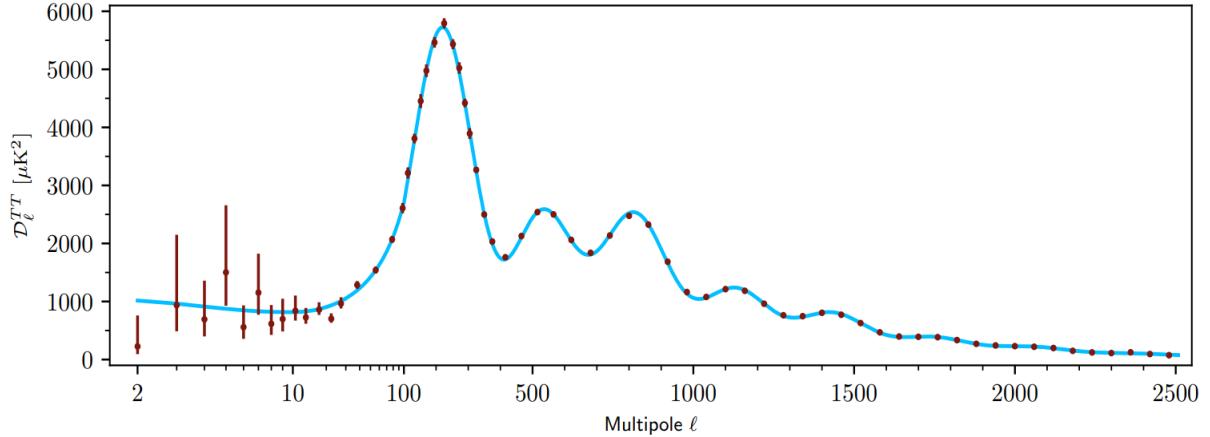


Figure 2.5 Observed Cosmic Microwave Background power spectrum as a function of multipole moment from Plank [10]. Blue line is best fit model from Λ CDM. Red points and lines are data and error, respectively.

665 competing baryon pressures and gravity. High l is a damped region from the diffusion of photons
 666 during electron-proton recombination. [1]

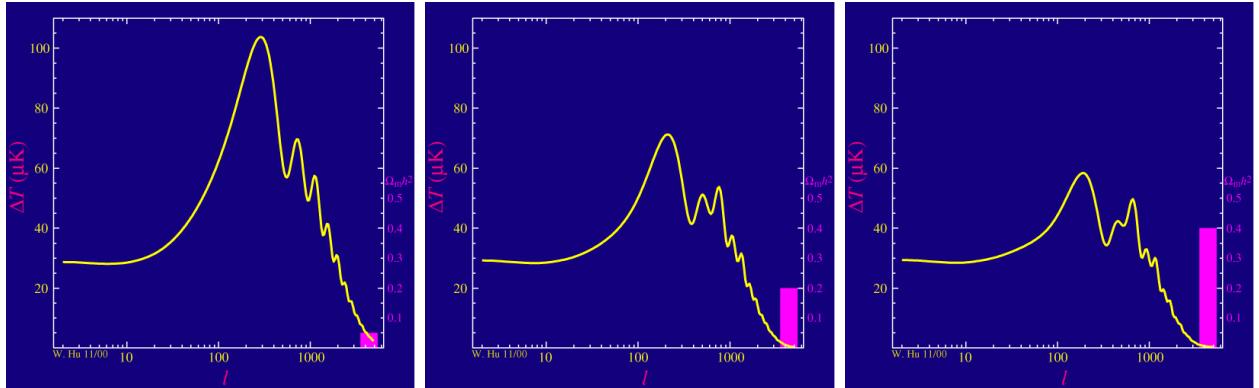


Figure 2.6 Predicted power spectra of CMB for different $\Omega_m h^2$ values for fixed baryon density from [11]. (left) Low $\Omega_m h^2$ increases the prominence of first and second peaks. (middle) $\Omega_m h^2$ is most similar to the observed power spectrum. The second and third peaks are similar in height. (right) $\Omega_m h^2$ is large which suppresses the first peak and raises the prominence of the third peak.

667 The harmonics would look quite different for a universe with less DM. Figure 2.6 demonstrates
 668 the effect $\Omega_m h^2$ has on the expected power spectrum for fixed baryon matter density. [11] Sweeping
 669 $\Omega_m h^2$ in this way clearly shows the effect dark matter has on the CMB power spectrum. The
 670 observations fit well with the Λ CDM model, and the derived fractions are as follows. The matter
 671 fraction: $\Omega_m = 0.3153$; and the baryon fraction: $\Omega_b = 0.04936$ [10]. Plank's observations also
 672 provide a measure of the Hubble constant, H_0 . H_0 especially has seen a growing tension in the

673 past decade that continues to deepened with observations from instruments like the James Webb
674 Telescope [12, 13]. As Hubble tensions deepen, we may find that perhaps Λ **CDM**, despite its
675 successes, is missing some critical physics.

676 Overall, the Newtonian motion of stars in galaxies, weak lensing from galactic clusters, and
677 power spectra from primordial light form a compelling body of research in favor of dark matter.
678 It takes another leap of theory and experimentation to make observations of DM that are non-
679 gravitational in nature. In Section 2.3, the evidence for DM implies strongly that the DM is matter
680 and not a lost parameter in the gravitational fields between massive objects. Finally, if we take one
681 axiom: that this matter has quantum behavior, such as being described by some Bohr wavelength
682 and abiding by some fermion or boson statistics; then we arrive at particle dark matter. One particle
683 DM hypothesis is the Weakly Interacting Massive Particle (WIMP). This DM candidate theory is
684 discussed further in the next section and is the focus of this thesis.

685 **2.4 Searching for Dark Matter: Particle DM**

686 Section 2.4 shows the Standard Model of particle physics and is currently the most accurate
687 model for the dynamics of fundamental particles like electrons and photons. The current status
688 of the SM does not have a viable DM candidate. When looking at the standard model, we can
689 immediately exclude any charged particle because charged particles interact strongly with light.
690 Specifically, this will rule out the following charged, fundamental particles: $e, \mu, \tau, W, u, d, s, c, t, b$
691 and their corresponding antiparticles. Recalling from Section 2.2 that DM must be long-lived and
692 stable over the age of the universe which excludes all SM particles with decay half-lives at or shorter
693 than the age of the universe. The lifetime constraint additionally eliminates the Z and H bosons.
694 Finally, the candidate DM needs to be somewhat massive. Recall from Section 2.2 that DM is cold
695 or not relativistic through the universe. This eliminates the remaining SM particles: $\nu_{e,\mu,\tau}, g, \gamma$ as
696 DM candidates. Because there are no DM candidates within the SM, the DM problem strongly
697 hints to physics beyond the SM (BSM).

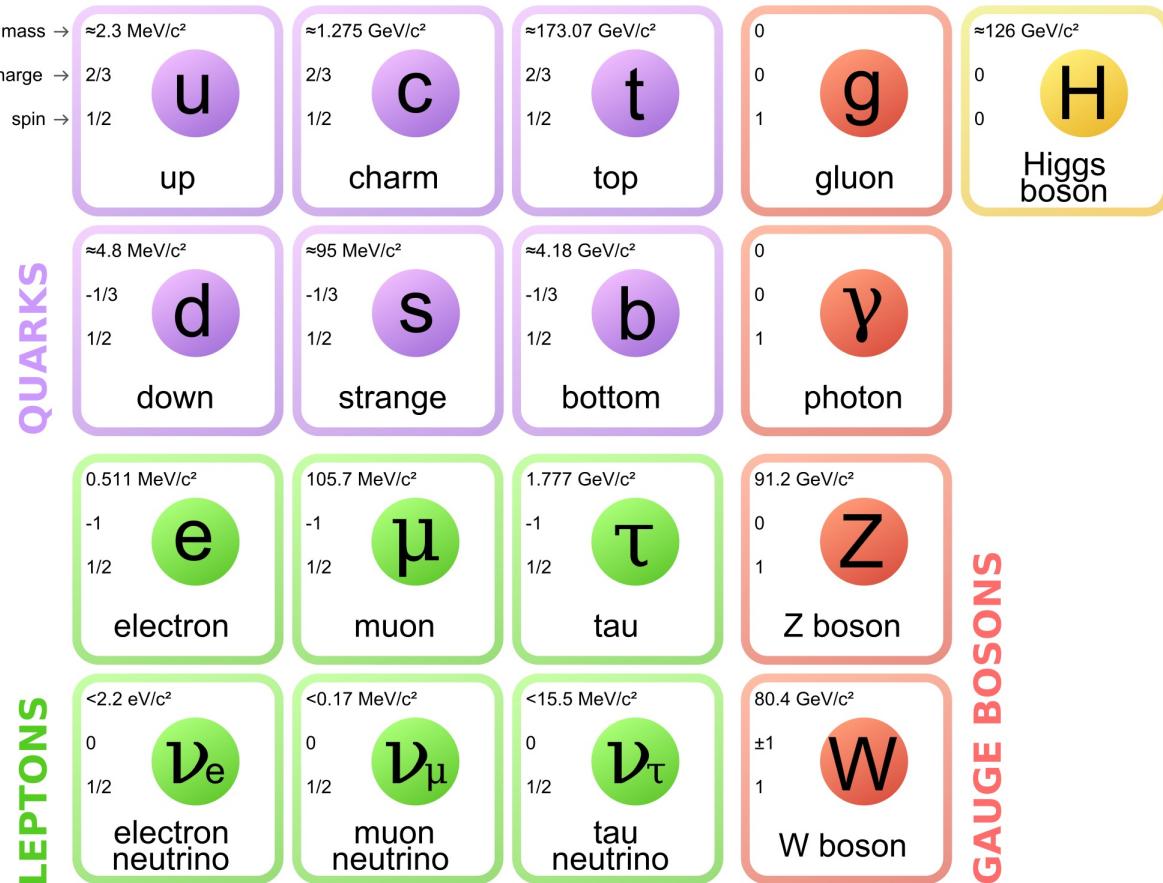


Figure 2.7 The Standard Model (SM) of particle physics. Figure taken from <http://www.quantumdiaries.org/2014/03/14/the-standard-model-a-beautiful-but-flawed-theory/>

698 2.4.1 Shake it, Break it, Make it

699 When considering DM that couples in some way with the SM, the interactions are roughly
 700 demonstrated by interaction demonstrated in Figure 2.8. The figure is a simplified Feynman
 701 diagram where the arrow of time represents the interaction modes of: **Shake it, Break it, Make it**.

702 **Shake it** refers to the direct detection of dark matter. Direct detection interactions start with
 703 a free DM particle and an SM particle. The DM and SM interact via elastic or inelastic collision
 704 and recoil away from each other. The DM remains in the dark sector and imparts some momentum
 705 onto the SM particle. The hope is that the momentum imparted onto the SM particle is sufficiently
 706 high enough to pick up with extremely sensitive instruments. Because we cannot create the DM in
 707 the lab, a direct detection experiment must wait until DM is incident on the detector. Most direct
 708 detection experiments are therefore placed in low-background environments with inert detection

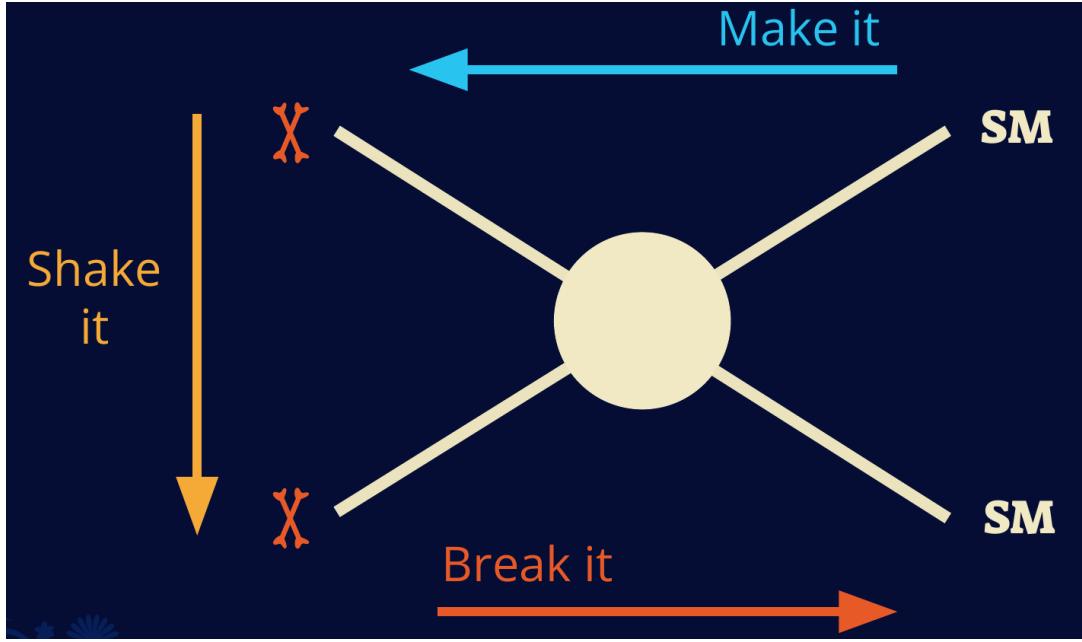


Figure 2.8 Simplified Feynman diagram demonstrating different ways DM can interact with SM particles. The 'X's refer to the DM particles whereas the SM refer to fundamental particles in the SM. The large circle in the center indicates the vertex of interaction and is purposely left vague. The colored arrows refer to different directions of time as well as their respective labels. The arrows indicate the initial and final state of the DM -SM interaction in time.

709 media like the noble gas Xenon. [14]

710 **Make it** refers to the production of DM from SM initial states. The experiment starts with
 711 particles in the SM. These SM particles are accelerated to incredibly high energies and then collide
 712 with each other. In the confluence of energy, DM hopefully emerges as a byproduct of the SM
 713 annihilation. Often it is the collider experiments that are energetic enough to hypothetically produce
 714 DM. These experiments include the world-wide collaborations ATLAS and CMS at CERN where
 715 proton collide together at extreme energies. The DM searches, however, are complex. DM likely
 716 does not interact with the detectors and lives long enough to escape the detection apparatus of
 717 CERN's colliders. This means any DM production experiment searches for an excess of events
 718 with missing momentum or energy in the events. An example event with missing transverse
 719 momentum is shown in Figure 2.9. The missing momentum with no particle tracks implies a
 720 neutral particle carried the energy out of the detector. However, there are other neutral particles
 721 in the SM, like neutrons or neutrinos, so any analysis has to account for SM signatures of missing

722 momentum. [15]

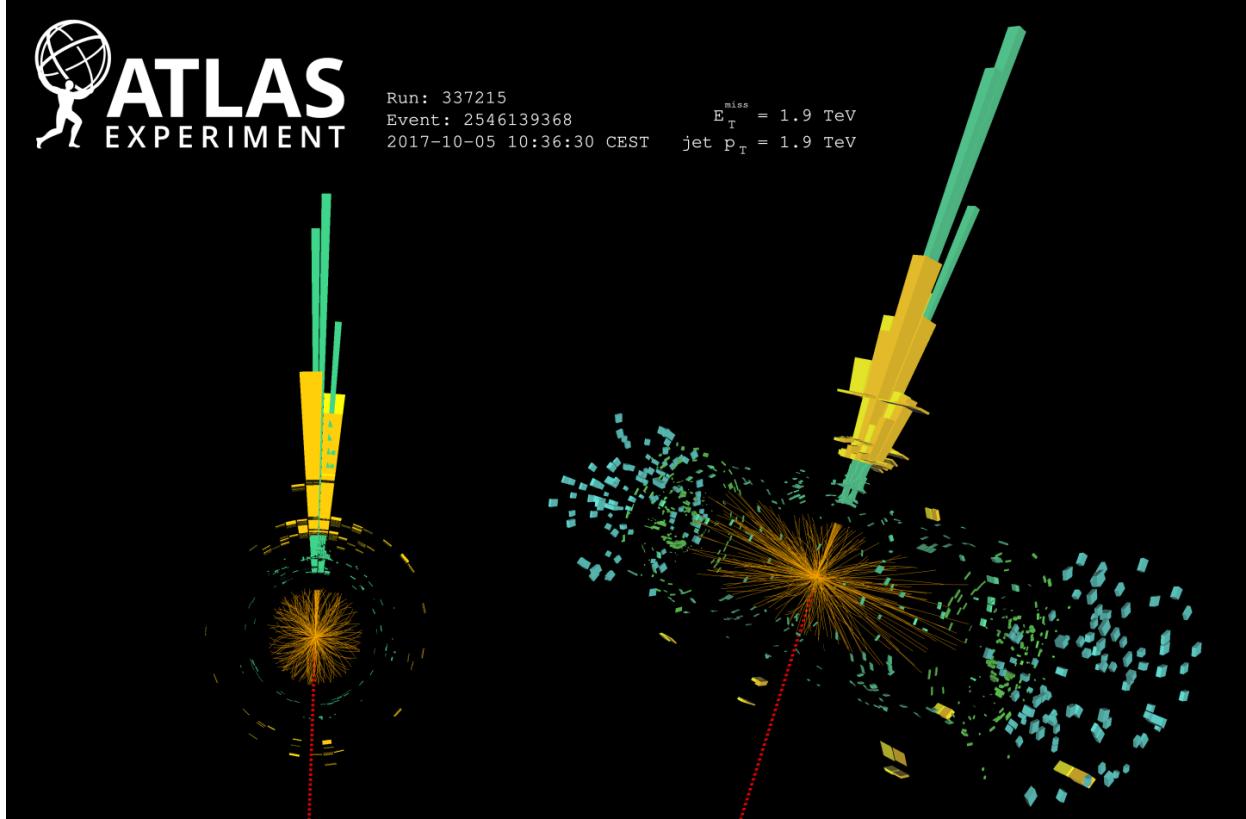


Figure 2.9 A single jet event in ATLAS detector from 2017 [16]. Jet momentum was observed to be 1.9 TeV. Missing transverse momentum was observed to be 1.9 TeV compared to the initial transverse momentum of the event was 0. Implied MET is traced by a red dashed line in event display.

723 2.4.2 Break it: Standard Model Signatures of Dark Matter through Indirect Searches

724 **Break it** refers to the creation of SM particles from the dark sector, and it is the primary focus
725 of this thesis. The interaction begins with DM or in the dark sector. The hypothesis is that this
726 DM will either annihilate with itself or decay and produce an SM byproduct. This method is
727 often referred to as the Indirect Detection of DM because we have no lab to directly control or
728 manipulate the DM. Therefore, most indirect DM searches are performed using observations of
729 known DM densities among the astrophysical sources. The strength is that we have the whole of the
730 universe and its 13.6-billion-year lifespan to use as a detector and particle accelerator. Additionally,
731 locations of dark matter are well cataloged since it was astrophysical observations that presented

732 the problem of DM in the first place.

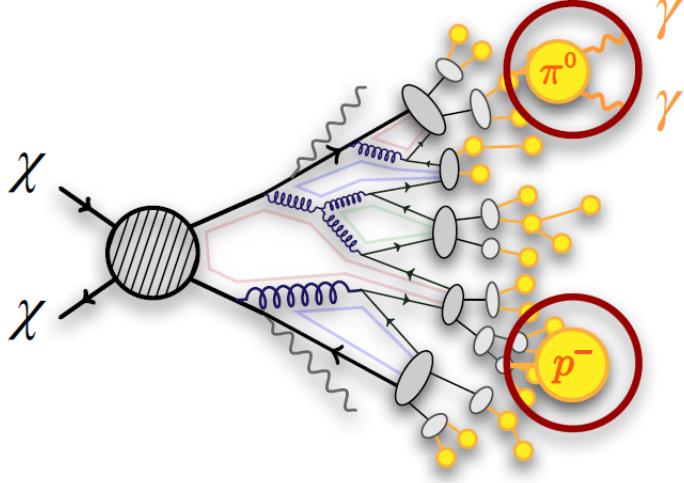


Figure 2.10 More detailed pseudo-Feynman diagram of particle cascade from dark matter annihilation into 2 quarks. The quarks hadronize and down to stable particles like γ or the anti-proton (p^-). Diagram pulled from ICRC 2021 presentation on DM annihilation search [17].

733 However, anything can happen in the universe. There are many difficult to deconvolve back-
734 grounds when searching for DM. One prominent example is the galactic center. We know the
735 galactic center has a large DM content because of stellar kinematics in our Milky Way and DM halo
736 simulations. Yet, any signal from the galactic center is challenging to parse apart from the extreme
737 environment of our supermassive black hole, unresolved sources, and diffuse emission from the
738 interstellar medium [18]. Despite the challenges, any DM model that yields evidence in the other
739 two observation methods, **Shake it or Make it** must be corroborated with indirect observations of
740 the known DM sources. Without corroborating evidence, DM observation in the lab is hard-pressed
741 to demonstrate that it is the model contributing to the DM seen at the universal scale.

742 In the case of WIMP DM, signals are described in terms of primary SM particles produced
743 from DM decay or annihilation. The SM initial state particles are then simulated down to stable
744 final states such as the γ , ν , p , or e which can traverse galactic lengths to reach Earth.

745 Figure 2.10 shows the quagmire of SM particles that emerges from SM initial states that are not
746 stable [17]. There are many SM particles with varying energies that can be produced in such an

747 interaction. For any arbitrary DM source and stable SM particle, the SM flux from DM annihilating
 748 to a neutral particle in the SM, ϕ , from a region in the sky is described by the following.

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE_\gamma} \times \int_{\text{source}} d\Omega \int_{l.o.s} \rho_\chi^2 dl(r, \theta') \quad (2.4)$$

749 In Equation (5.1), $\langle\sigma v\rangle$ is the velocity-weighted annihilation cross-section of DM to the SM. m_χ
 750 refers to the mass of DM, noted with Greek letter χ . $\frac{dN_\phi}{dE_\phi}$ is the N particle flux weighted by the
 751 particle energy. An example is provided in Figure 2.11 for the γ final state. The integrated terms
 752 are performed over the solid angle, $d\Omega$, and line of sight, l.o.s. ρ is the density of DM for a
 753 location (r, θ') in the sky. The terms left of the '×' are often referred to as the particle physics
 754 component. The terms on the right are referred to as the astrophysical component. For decaying
 755 DM, the equation changes to...

$$\frac{d\Phi_\phi}{dE_\phi} = \frac{1}{4\pi\tau m_\chi} \frac{dN_\phi}{dE_\phi} \times \int_{\text{source}} d\Omega \int_{l.o.s} \rho_\chi dl(r, \theta') \quad (2.5)$$

756 In Equation (2.5), τ is the decay lifetime of the DM. Just as in Equation (5.1), the left and right
 757 terms are the particle physics and the astrophysical components respectively. The integrated
 758 astrophysical component of Equation (5.1) is often called the J-Factor. Whereas the integrated
 759 astrophysical component of Equation (2.5) is often called the D-Factor.

760 Exact DM $\text{DM} \rightarrow \text{SM SM}$ branching ratios are not known, so it is usually assumed to go 100%
 761 into an SM particle/anti-particle. Additionally, when a DM annihilation or decay produces one of
 762 the neutral, long-lived SM particles (ν or γ), the particle is traced back to a DM source. For DM
 763 above GeV energies, there are very few SM processes that can produce particles with such a high
 764 energy. Seeing such a signal would almost certainly be an indication of the presence of dark matter.
 765 Fortunately, the universe provides us with the largest volume and lifetime ever for a particle physics
 766 experiment.

767 2.5 Sources for Indirect Dark Matter Searches

768 The first detection of DM relied on optical observations. Since then, we have developed new
 769 techniques to find DM dense regions. As described in Section 2.3.1, many DM dense regions were
 770 through observing galactic rotation curves. Our Milky Way galaxy is among DM dense regions

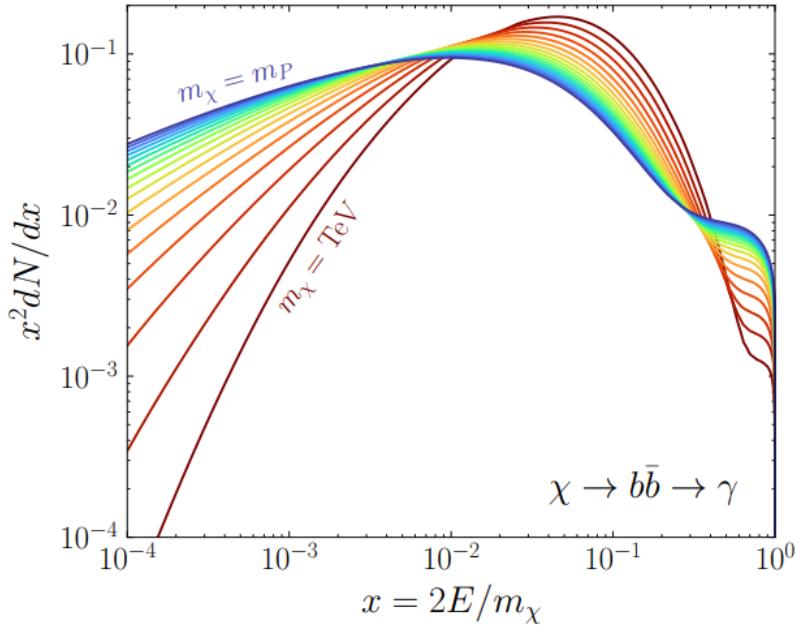


Figure 2.11 Dark Matter (DM) decay spectrum for $b\bar{b}$ initial state and γ final state. Redder spectra are for larger DM masses. Bluer spectra are light DM masses. x is a unitless factor defined as the ratio of the mass of DM, m_χ , and the final state particle energy E_γ . Figure from [19].

discovered, and it is the largest nearby DM dense region to look at. Additionally, the DM halo surrounding the Milky Way is clumpy [18]. There are regions in the DM halo of the Milky Way that have more DM than others that have captured gas over time. These sub-halos were dense enough to collapse gas and form stars. These apparent sub galaxies are known as dwarf spheroidal galaxies and are the main sources studied in this thesis. Each source type comes with different trade-offs. Galactic Center studies will be very sensitive to the assumed distribution of DM. The central DM density can vary substantially as demonstrated in Figure 2.12. At distances close to the center of the galaxy, or small r , the differences in DM densities can be 3-4 orders of magnitude. Searches toward the galactic center will therefore be quite sensitive to the assumed DM distribution.

Searches toward Dwarf Spheroidal Galaxies (dSph's) suffer from uncertainties in the DM density less than the galactic center studies. This is mostly from their diminutive size being smaller than the angular resolution of most γ -ray observatories [18]. The DM content dSph's are typically determined with the Virial theorem, Equation (2.1), and are usually majority DM [18] in mass. DSph's tend to be ideal sources to look at for DM searches. Their environments are quiet with little

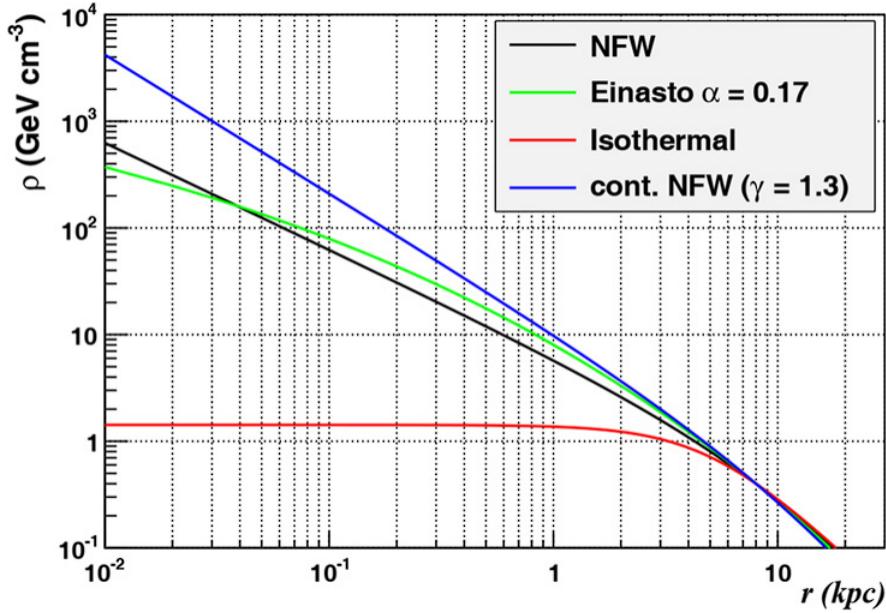


Figure 2.12 Different dark matter density profiles compared. Some models produce exceptionally large densities at small r [20].

785 astrophysical background. Unlike the galactic center, the most active components of dSph's are the
 786 stars within them versus a violent accretion disc around a black hole. All this together means that
 787 dSph's are among the best sources to look at for indirect DM searches. dSph's are the targets of
 788 focus for this thesis.

789 **2.6 Multi-Messenger Dark Matter**

790 Astrophysics entered a new phase in the past few decades that leverages our increasing sensitivity
 791 to SM channels and general relativity (GR). Up until the 21st century, astrophysical observations
 792 were performed with photons (γ) only. Astrophysics with this 'messenger' is fairly mature now.
 793 Novel observations of the universe have since only adjusted the sensitivity of the wavelength of
 794 light that is observed except at MeV energies. Gems like the CMB [10], and more have ultimately
 795 been observations of different wavelengths of light. Multi-messenger astrophysics proposes using
 796 other SM particles such the p^{+-} , or ν or gravitation waves predicted by general relativity.

797 The experiment LIGO had a revolutionary discovery in 2016 with the first detection of a binary
 798 black hole merger [21]. This opened the collective imagination to observing the universe through
 799 gravitational waves. There has also been a surge of interest in the neutrino (ν) sector. IceCube

800 demonstrated that we are sensitive to neutrinos in regions that correlate with significant photon
 801 emission like the galactic plane [22]. Neutrinos, like gravitational waves and light, travel mostly
 802 unimpeded from their source to our observatories. This makes pointing to the originating source
 803 of these messengers much easier than it is for cosmic rays which are deflected from their source by
 804 magnetic fields.

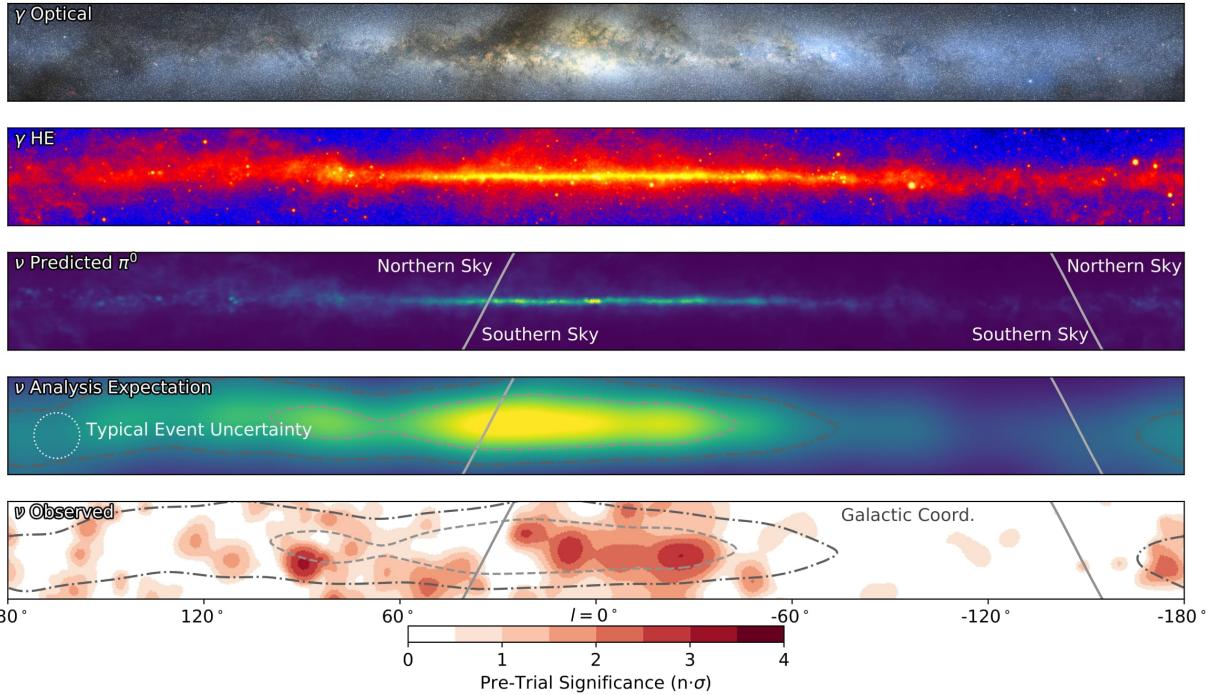


Figure 2.13 The Milky Way Galaxy in photons (γ) and neutrinos (ν) [22]. The Galactic center is at $l=0^\circ$ and is the brightest region in all panels. (top) An Optical color image of the Milky Way galaxy seen from Earth. Clouds of gas and dust obscure some light from stars. (2nd down) Integrated flux of γ -rays observed by the Fermi-LAT telescope [23]. (middle) Expected neutrino emission that corresponds with Fermi-LAT observations. (2nd up) Expected neutrino emission profile after considering detector systematics of IceCube. (bottom) Observed neutrino emission from region of the galactic plane. Substantial neutrino emission was detected.

805 The IceCube collaboration recently published a groundbreaking result of the Milky Way in
 806 neutrinos. The recent result from IceCube, shown in Figure 2.13, proves that we can make
 807 observations under different messenger regimes. The top two panels show the appearance of the
 808 galactic plane to different wavelengths of light. Some sources are more apparent in some panels,
 809 while others are not. This new channel is powerful because neutrinos are readily able to penetrate
 810 through gas and dust in the Milky Way. This new image also refines our understanding of how high

811 energy particles are produced. For example, the fit to IceCube data prefers neutrino production
 812 from the decay of π^0 [22].

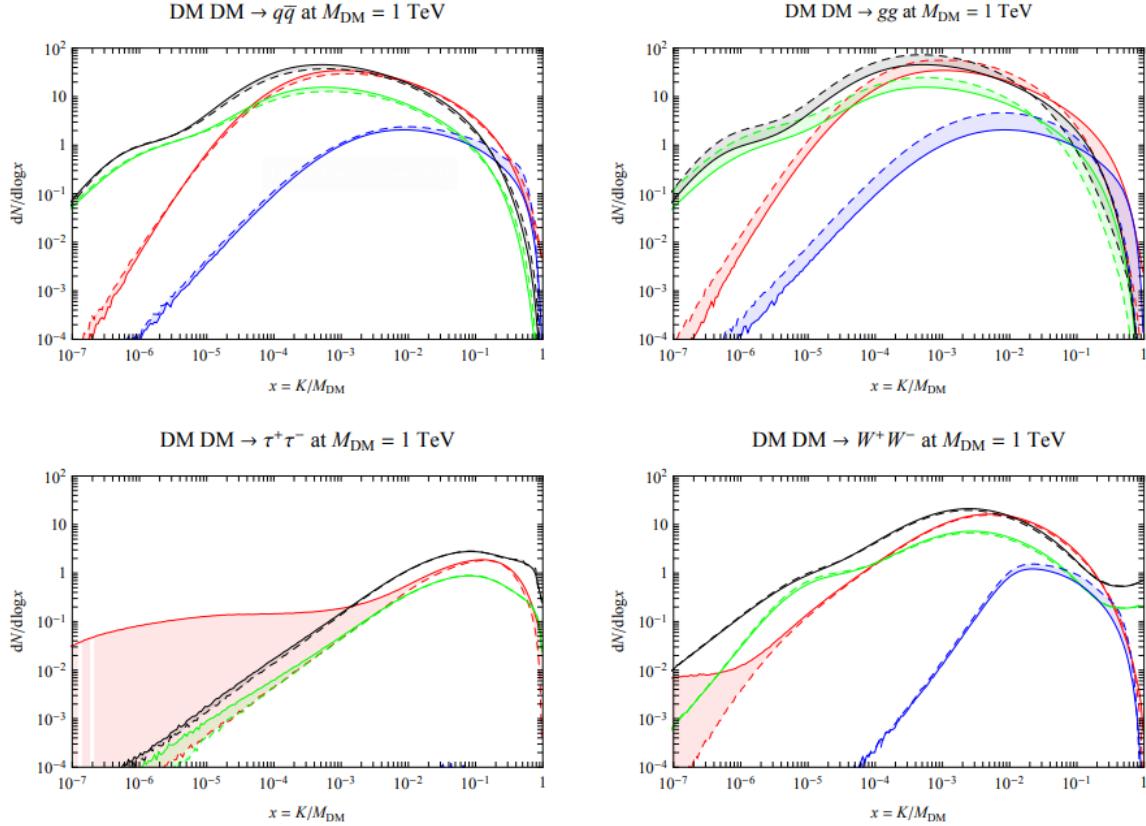


Figure 2.14 Dark Matter annihilation spectra for different final state particle and standard model annihilation channels [24]. Photons (red), e^\pm (green), \bar{p} (blue), ν (black).

813 Exposing our observations to more cosmic messengers greatly increases our sensitivity to
 814 rare processes. In the case of DM, Figure 2.14, there are many SM particles produced in DM
 815 annihilation. Among the final state fluxes are gammas and neutrinos. Charged particles are also
 816 produced however they would not likely make it to Earth since they will be deflected by magnetic
 817 fields between the source and Earth. This means observatories that can see the neutral messengers
 818 are especially good for DM searches and for combining data for a multi-messenger DM search.

CHAPTER 3

819

HIGH ALTITUDE WATER CHERENKOV (HAWC) OBSERVATORY

820 **3.1 The Detector**



Figure 3.1 Photo of the HAWC detector that I took on May 17, 2023. Main array is centered in the photo and comprised of the larger tanks. Outriggers are the smaller tanks around the main array.

821 The High Altitude Water Cherenkov (HAWC) Observatory is a specialized instrument designed
822 for the observation of high energy gamma-rays and cosmic rays [25]. Located on the Sierra
823 Negra volcano in Mexico, HAWC observes gamma rays and cosmic rays in the energy range of
824 approximately 100 GeV to 100's of TeV. HAWC is strategically situated to maximize observational
825 efficiency due to its high altitude. At an elevation of 4,100 meters, it monitors about two-thirds of
826 the sky every day with an uptime above 90%. This capability is essential for studying high-energy
827 astronomical phenomena.

828 HAWC comprises of 300 water Cherenkov detectors (WCDs) spread over 22,000 square meters.
829 Each main array detector is filled with purified water and equipped with four, upward-facing
830 photomultiplier tubes (PMTs). These PMTs detect Cherenkov radiation from charged particles
831 passing through the tanks. These charged particles are generated when a high energy gamma or

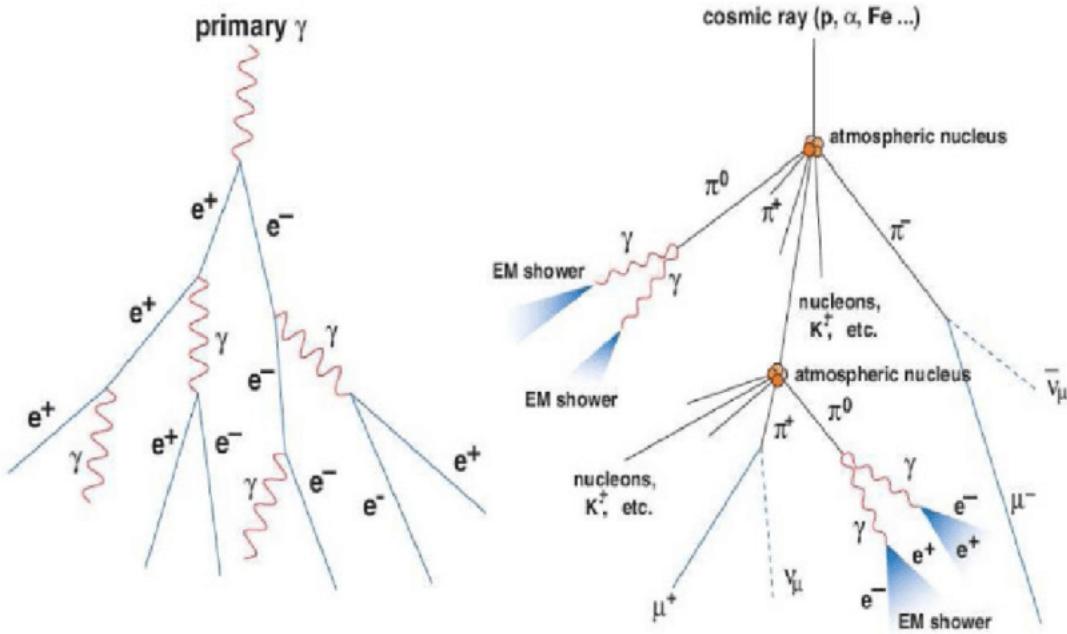


Figure 3.2 A particle physics illustration of high energy particle showers. Left shower is an electromagnetic shower from a high energy gamma-ray. Most particles in the shower will be a combination of photons and charged leptons, in this case electrons (e). Right figure shows a cosmic ray particle shower. The cosmic ray will produce many more types of particles including pions (π), neutrinos, and charged leptons. Figured pulled from [26].

832 cosmic ray collides with gas in the atmosphere to create a charged particle shower, see Fig. 3.2.
 833 The observatory includes a separate tank configuration which are referred to as the outriggers. They
 834 are a secondary array of 345 smaller WCD's. Surrounding the main array, each outrigger tank
 835 measures 1.55 meters in diameter and height and contain a single upward-facing eight-inch PMT.
 836 This expansion increases the instrumented footprint fourfold. It improves the reconstruction of
 837 showers extending beyond the main array, especially for events above 10 TeV. However, at the time
 838 of writing this thesis, the outriggers have not been fully integrated into HAWC's reconstruction
 839 software.

840 3.1.1 Construction and Hardware

841 **TODO: fact check the content below. GPT may have hallucinated** Each main array WCD is a
 842 cylindrical tank with dimensions of 7.3 m in diameter and 5.4 m in height and filled with 180,000
 843 liters of water [25]. The metal shell of these tanks is made from bolted together, corrugated,

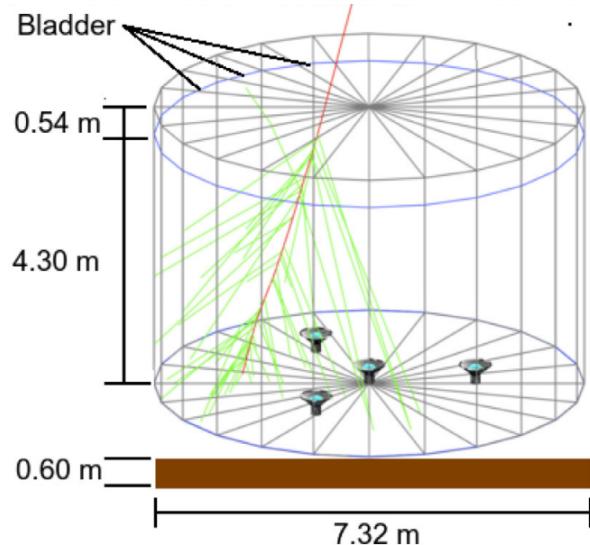


Figure 3.3 The WCDs. Left image features several WCDs looking from within the main array of HAWC. Right image shows a schematic of a WCD pulled from [25].

galvanized steel panels. The tanks are placed into 0.6 m deep trenches filled with rammed earth to secure it against seismic activity. The interior of each tank is lined with a black, low-density polyethylene bladder, designed to be impermeable to external light and to prevent reflection of Cherenkov light within the tank. This bladder is approximately 0.4 mm thick and composed of two layers of three-substrate film. To further minimize light penetration, a black agricultural foil covers the bladder. The ground and walls inside the tank are protected with felt and sand to safeguard against punctures. The tanks are filled 4.5 m deep of purified water, achieving a photon attenuation length for Cherenkov photons that exceeds the tank's dimensions. This purification level ensures the optimal detection environment for the photons generated by traversing charged particles.

At the base of each tank, four photomultiplier tubes (PMTs) are installed to detect the Cherenkov radiation emitted by charged particles. Three 8-inch diameter PMTs surround a larger 10 inch PMT from Hamamatsu [27]. The variation in PMT response is carefully accounted for in event reconstruction algorithms. Signals from the PMTs travel 610 ft cables to the counting house, where they are processed by Front-End Boards (FEBs). These FEBs, along with Time to Digital Converters (TDCs), digitize the signals and manage the high voltage supply to the PMTs.

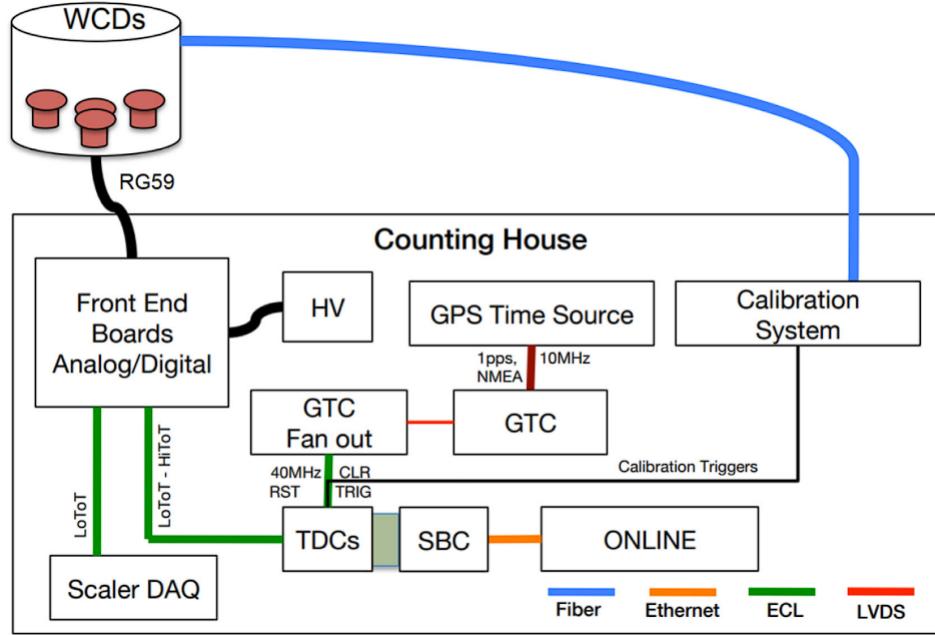


Figure 3.4 TODO: copied from nim. Top-level diagram of the HAWC electronics showing a summary of the critical subsystems and the interconnections, including HV and optical fiber cabling. NMEA refers to the National Marine Electric Association format in which GPS presents data [66,67]; CLR, TRG and RST are control signals for the TDC system. The LoToT andHiToT time over threshold signals are discussed in Section 4.1

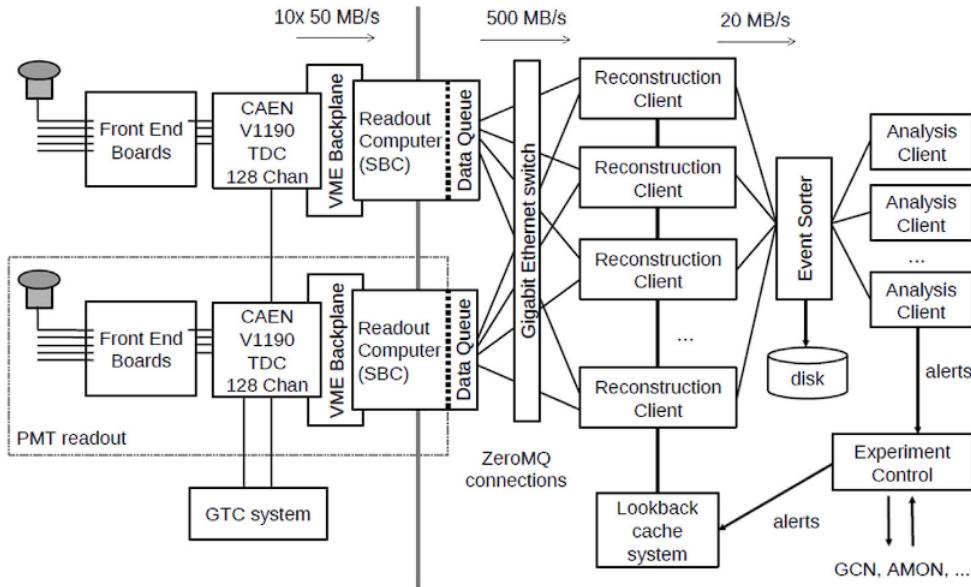


Figure 3.5 TODO: copied from NIM. Schematic overview [68] of the HAWC data acquisition and online processing system, as described in the text of Section 4

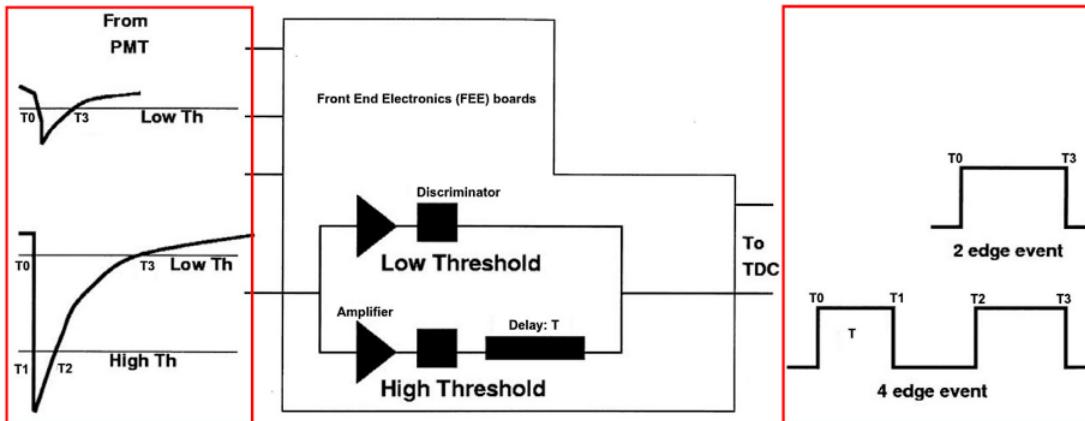


Figure 3.6 TODO: text copied from nim. The analog PMT signals are split and passed through two paths. In each path, there is an amplifier and discriminator circuit. The ratio of the amplifier gains is 7 to 1. The higher gain circuit has an effectively lower threshold (Low Th). There is a time (T) delay in the high threshold (High Th) path. The 2-edge event is related with the Low Th, while the 4 edge event is related to the High Th.

859 3.1.2 Data Acquisition and Signal Processing

860 The HAWC data acquisition (DAQ) and signal processing systems convert the physical detection
 861 of particles into analyzable data. This process involves a series of steps from initial signal detection
 862 by PMTs to digital conversion and preliminary analysis, see Fig. 3.4 and Fig. 3.5.

863 Once the signal from the PMTs arrive at the counting house, they enter the Front-End Boards
 864 (FEBs). The FEBs are responsible for the initial processing of these signals, which includes
 865 amplification and integration [28]. Each PMT signal is compared against preset LOW/HIGH
 866 voltage thresholds in the FEBs Fig. 3.6, identifying signals that correspond to about 1/4 and
 867 4 photoelectrons, respectively. This differentiation allows the system to gauge the strength of
 868 the detected Cherenkov radiation. The processed signals are then digitized by Time to Digital
 869 Converters (TDCs). These converters measure the time over threshold (ToT) for each signal, a
 870 parameter that reflects both the duration and amplitude of the signal. This digitization facilitates
 871 reconstruction of the original event for translating the physical interactions within the detectors into
 872 data [29, 30, 28].

873 Synchronization across the HAWC observatory is maintained by a central GPS Timing and
 874 Control (GTC) system, which achieves a timing resolution of 98 ps. This high-resolution timing

875 is vital for accurately reconstructing the timing and location of air showers initiated by cosmic
876 and gamma rays. The GTC system ensures that all components of the DAQ operate in unison to
877 preserve the temporal integrity of the detected events [29, 31].

878 Once digitized, the data are transferred to an online event reconstruction system. This system
879 runs the Reconstruction Client, which utilizes the raw PMT data to reconstruct the characteristics
880 of the air showers, such as their direction and energy [30]. The capacity for real-time analysis
881 allows HAWC to promptly respond to astrophysical phenomena like Gamma Ray Bursts (GRBs)
882 and to participate in multi-messenger astronomy by following up on alerts from other observatories.
883 This real-time processing system is designed to handle high data throughput, using ZeroMQ [32]
884 for efficient data transfer between software components. Analysis Clients perform specific online
885 analyses that require immediate data, including monitoring for GRBs, solar flare activity, and
886 participation in global efforts to track gravitational waves and neutrinos [29].

887 The DAQ system is overseen by an Experiment Control system and crew that manage the
888 operational aspects of data collection. This includes initiating and terminating data collection
889 runs and monitoring the experiment for errors. In the event of a system crash, often caused by
890 environmental factors such as lightning, the Experiment Control system is designed to automatically
891 restart the experiment and minimize downtime [29, 30].

892 **3.2 Event Reconstruction**

893 Event reconstruction at the HAWC Observatory is a critical procedure that converts the raw data
894 from the observatory’s WCDs into a coherent framework for understanding cosmic and gamma-
895 ray events. This process includes several distinct steps. Core Fitting determines the geometric
896 center of the air shower on the detector plane. Angle Reconstruction assesses the trajectory of the
897 incoming particle, revealing its origin in the sky. Energy Estimation is performed using both f -hit
898 and Neural Network (NN) methods to quantify the energy of the detected events. Gamma-hadron
899 (\tilde{G}) discrimination differentiates between gamma-ray and hadronic cosmic ray initiated showers,
900 a vital step for astrophysical interpretations. Each of these steps is integral to the observatory’s
901 objective of investigating the high-energy universe and enable the transformation of signals into

902 detailed insights about high energy cosmic phenomena.

903 **3.2.1 Core Fitting**

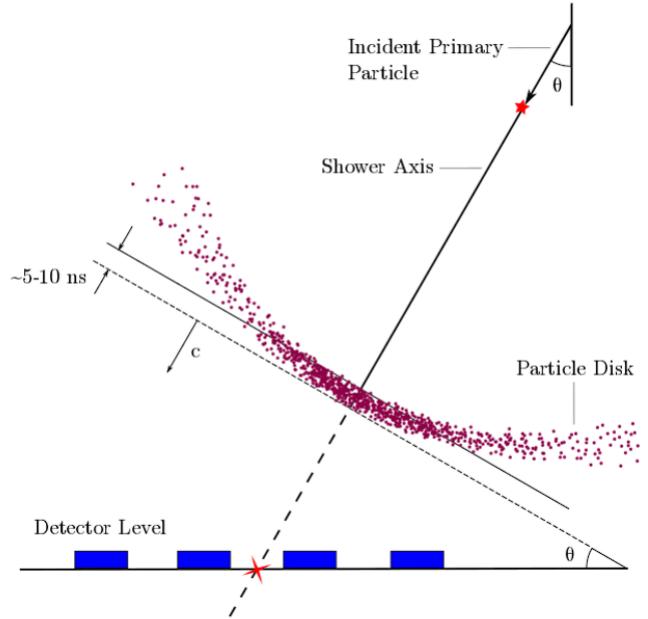


Figure 3.7 TODO: copied from A's thesis. An illustration of the angle reconstruction of the original particle. The secondary particles of an air shower travel in a plane perpendicular to the direction of the original particle, allowing for the reconstruction of the initial angle after corrections due to the curvature of the plane. Figure from [33].

904 In the study of air showers, accurately determining the location of the air shower core on the
905 ground is crucial for reconstructing the direction of the originating primary particle. An illustration
906 of this can be seen in a HAWC event plot, where the lateral charge distribution across the array is
907 displayed. The core is identified and marked with a red star, reconstructed using a predetermined
908 functional form.

909 The signal S_i from the i th PMT is given by the following equation:

$$S_i = S(A, \tilde{x}, \tilde{x}_i) = A \left(\frac{1}{2\pi\sigma^2} e^{-\frac{|\vec{x}_i - \vec{x}|^2}{2\sigma^2}} + \frac{N}{(0.5 + |\vec{x}_i - \vec{x}|/R_m)^3} \right) \quad (3.1)$$

910 In this model, \tilde{x} represents the core location and \tilde{x}_i is the position of the i th PMT. R_m stands for
911 the Molière radius, which is approximately 120 meters at the altitude of HAWC, while σ , is the
912 standard deviation of the Gaussian distribution. The equation incorporates fixed values of $\sigma = 10$

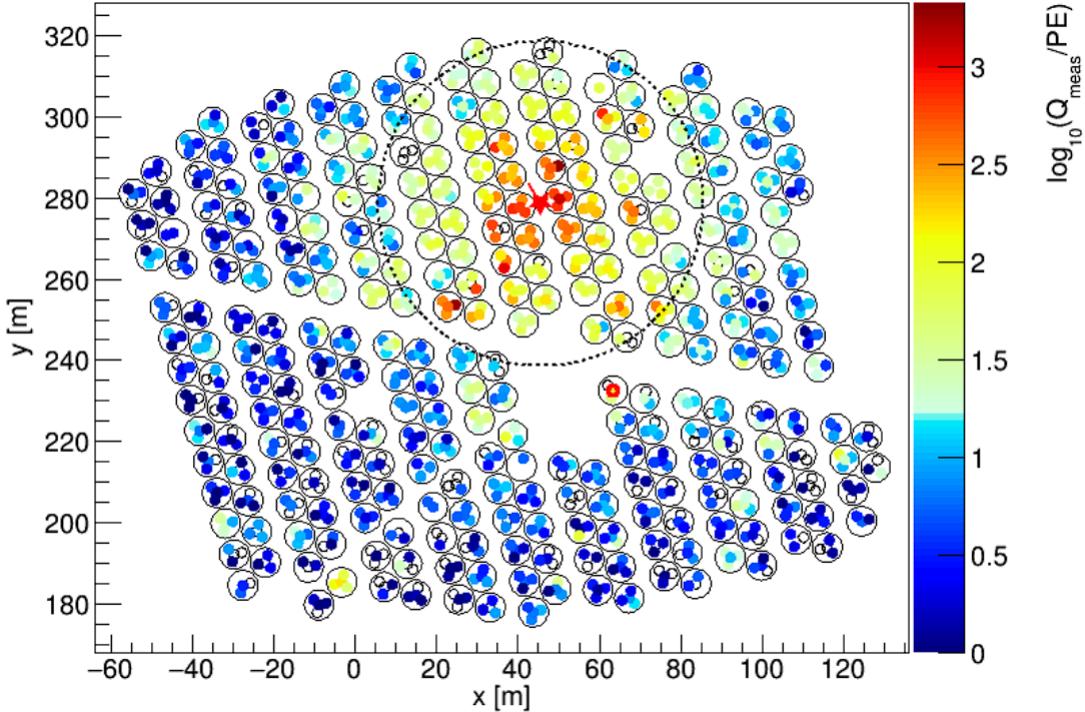


Figure 3.8 TODO: pulled for thesis. Charge deposited in each PMT for a reconstructed gamma-ray event. Each large circle represents a WCD and each of the 4 smaller circles within represent a PMT. The color scale represents the amount of charge deposited in each PMT. The red star in the center of the dashed circle shows the location of the shower core fit by the SFCF algorithm. [34]

913 m and $N = 5.10^{-5}$. N is the normalization factor for the tail of the distribution. This leaves the
 914 core location and overall amplitude A as the free parameters to be determined during fitting.

915 The chosen functional form for the Super Fast Core Fit (SFCF) algorithm is a simplified version
 916 of a modified Nishimura-Kamata-Greisen (NKG) function [35], selected for its computational
 917 efficiency which is essential for rapid fitting of air shower cores. The SFCF form allows numerical
 918 minimization to converge more quickly due to the function's simplicity, the analytical computation
 919 of its derivatives, and the absence of a pole at the core location. Figure 2 provides a visualization
 920 of a recorded event, with the plot depicting the charge recorded by each PMT as a function of the
 921 distance to the reconstructed shower core. Through the application of the SFCF, core locations can
 922 be identified with a median error of approximately 2 meters for large events and about 4 meters for
 923 smaller ones, assuming the gamma-ray event core impacts directly upon the HAWC detector array
 924 [34]. It is noted that as the core's distance from the array increases, the precision in locating the

925 core diminishes, highlighting the importance of proximity in the accuracy of core reconstruction.

926 **3.2.2 Angle Reconstruction**

927 After establishing the core position, the next step is angle reconstruction. This process deter-
928 mines the primary particle's trajectory. The angle of arrival is indicative of the originating gamma
929 ray's direction. It correlates to the cosmic source of the gamma-ray. We deduce this angle using
930 the timing of PMT hits [34].

931 The air shower's front is conically shaped, not flat. This shape arises from the travel patterns
932 of secondary particles. An event example is illustrated in Fig. 3.7. Far from the core, secondary
933 particles undergo multiple scattering. They also travel longer distances [36]. Particle sampling
934 decreases with distance from the core. This decrease results in measurable delays in arrival times
935 [36, 34]. Simulations provide a corrective measure for these effects. The correction is a function of
936 shower parameters [34]. It adjusts both curvature and sampling. The distance from the shower core
937 and the charge recorded by PMTs are crucial to this correction. A function based on simulation and
938 Crab Nebula observations is used for this purpose [34]. This correction is essential for accurate
939 reconstruction.

940 Corrections lead to the χ^2 minimization step. This technique fits a plane to the timing data of
941 the PMTs. It then calculates the shower's angle of arrival. The zenith and azimuth angles are the
942 result of this fitting [36]. The local angles are converted to celestial coordinates. These coordinates
943 allow correlation with gamma-ray sources. Right ascension (RA) and declination (Dec) are used
944 for this purpose. RA is akin to longitude, and Dec to latitude.

945 The reconstructed angle's resolution ranges from 0.1° to 1° . This range depends on the incoming
946 particle's energy and zenith angle [36]. The analysis uses a curvature/sampling correction. This
947 correction applies a quadratic function based on distance from the core [34]. The adjustment
948 improves angular resolution. However, discrepancies between simulation and observation persist.
949 These discrepancies introduce systematic errors into the analysis [34].

950 Angle reconstruction is vital for the HAWC Observatory. It accurately traces primary particles
951 back to their cosmic sources. This tracing allows for exact correlations with known gamma-ray

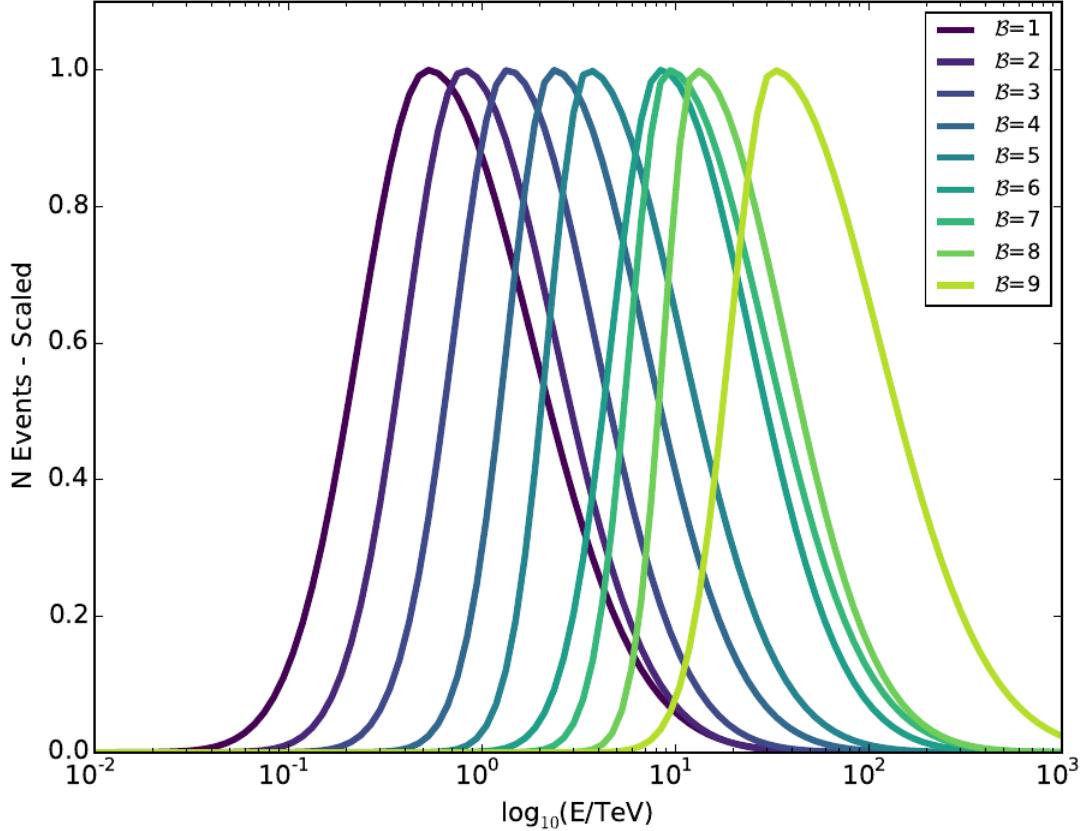


Figure 3.9 TODO: coped from paper. Normalized histogram of the energy distribution of each fhit bin defined in Table 2.1. This figure was made using Monte Carlo simulations assuming a spectral distribution E about 2.63 at a declination of 20° . Figure from [34].

952 sources.

953 3.2.3 f_{hit} Energy Estimation

954 The HAWC Observatory quantifies the primary particle energy of air showers using a metric
 955 known as f_{hit} . This ratio compares the count of PMTs involved in the event reconstruction to the
 956 total number of functional PMTs at the time [34]. The main array consists of about 1200 PMTs,
 957 but the count may vary due to maintenance or other operational factors.

958 Events are stratified into several f_{hit} bins. Each bin corresponds to a specific range of angular
 959 resolutions, enabling a structured approach to event analysis based on the extent of the shower
 960 footprint, Fig. 3.8. The f_{hit} metric, while effective, has several limitations. It is dependent on
 961 the zenith angle and the spectral characteristics presumed for the observed source. The variable
 962 also reaches a saturation point around 10 TeV, after which the detector's ability to discriminate

Bin	Lower Edge %	Upper Edge %	Θ_{68} ($^{\circ}$)
1	6.7	10.5	1.05
2	10.5	16.2	0.69
3	16.2	24.7	0.50
4	24.7	35.6	0.39
5	35.6	48.5	0.30
6	48.5	61.8	0.28
7	61.8	74.0	0.22
8	74.0	84.0	0.20
9	84.0	100	0.17

Table 3.1 **TODO: copied.** Definitions of the fhit bins, given by the fraction of available PMTs that are triggered during an air shower event. The angular resolution, denoted Ψ_{68} as the bin containing 68% of the events, improves with larger events [34]

963 between higher energy levels diminishes [34]. Furthermore, the energy distribution for each f_{hit}
964 bin is notably broad, see Fig. 3.9. In response to these limitations, HAWC has developed more
965 intricate algorithms for energy estimation. These algorithms incorporate the zenith angle and
966 the distribution of charge around the shower core for a more accurate assessment of the primary
967 particle’s energy, particularly at energies surpassing 10 TeV [36].

968 The relationship between f_{hit} and primary energy is complex. Atmospheric attenuation can
969 cause high-energy showers to present a smaller footprint, misrepresenting their energy in the f_{hit}
970 metric. This effect is captured in simulations that chart the actual energy distribution across f_{hit}
971 categories [36]. Such distributions vary with the declination of the source and the theoretical
972 energy spectrum used in the model.

973 3.2.4 Neural Network Energy Estimation

974 The energy estimation for photon events at the HAWC Observatory is refined through an
975 artificial neural network (NN) algorithm. This method, based on the Toolkit for Multivariate
976 Analysis NN, adopts a multilayer-perceptron model with logistic activation functions across its
977 layers. The structure includes two hidden layers, the first with 15 nodes and the second with 14,
978 designed to process input variables through a framework optimized to closely estimate primary
979 energies [38].

980 The NN is trained to minimize a specific error function that measures discrepancies between the

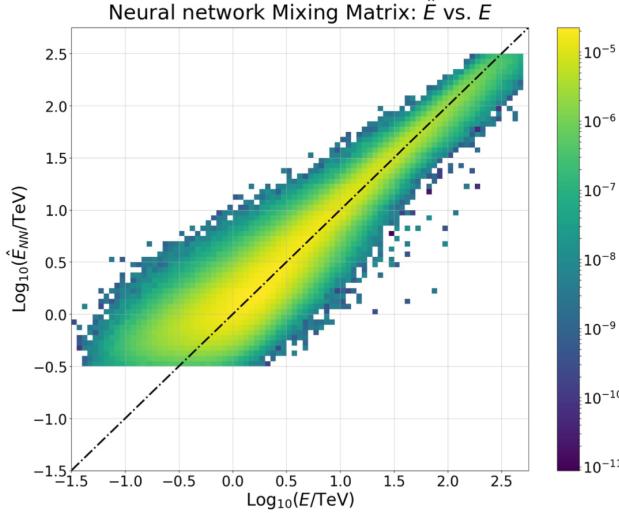


Figure 3.10 TODO: copiedNN (right) energy estimators. The dotted line is the identity line; events that fall along this line are reconstructed perfectly. Gamma/hadron separation cuts have been applied. The first energy bin starts at , and the last energy bin ends at , which accounts for the sharp features in the figures. Figure pulled from [37]

981 NN’s energy predictions and the actual energies from Monte Carlo simulations. This minimization
 982 targets an error function that incorporates the relative importance of each event, weighting the
 983 importance to mimic an E-2 power law spectrum. This approach helps achieve a uniform error
 984 rate across energies ranging from 1 to 100 TeV. The optimization process leverages the Broyden-
 985 Fletcher-Goldfarb-Shanno algorithm, ensuring a precise calibration of the NN’s 479 weights [37].

986 The spectral analysis employs a binned likelihood method, using a forward-folding technique to
 987 accommodate the energy estimate’s bias and resolution. This analysis benefits from a 2D binning
 988 scheme that categorizes events by both their f_{hit} value and estimated energy. The decision to use
 989 this scheme over a simple energy-based binning lies in the correlation between gamma/hadron
 990 separation parameters and the angular resolution with both the size and energy of the event. The
 991 spectrum of interest is dissected into nine f_{hit} bins, each further divided into 12 energy bins,
 992 spanning from 0.316 TeV to 316 TeV, encompassing a total of 108 bins [37]. However, not all
 993 bins contribute to the final analysis—those with low probability of event population or insufficient
 994 Monte Carlo simulation accuracy are excluded. This selective approach focuses on the central 99%
 995 of events by estimated energy within each f_{hit} category, effectively removing outliers and ensuring
 996 a robust fit [37].

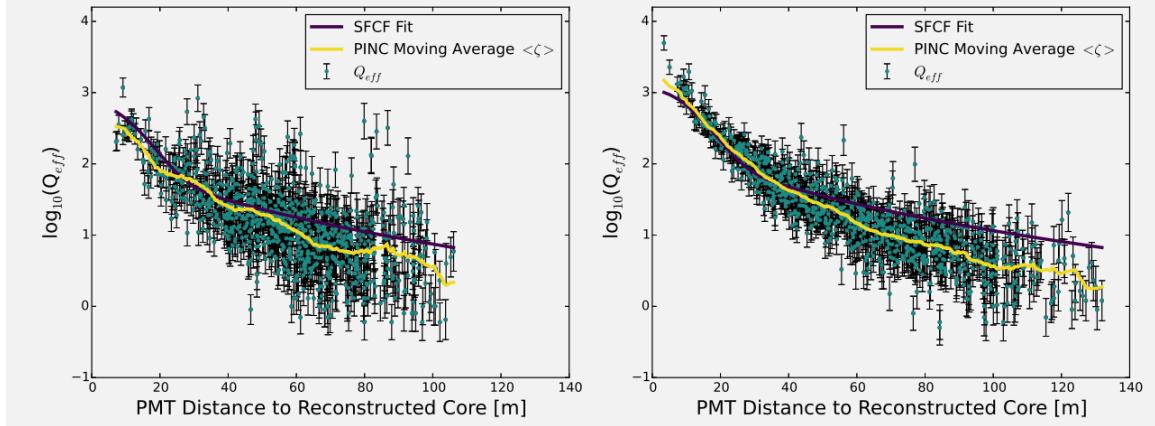


Figure 3.11 TODO: copied Lateral distribution functions of an obvious cosmic ray (left) and a photon candidate from the Crab Nebula (right). The cosmic ray has isolated high-charge hits far from the shower core due to penetrating particles in the hadronic air shower. These features are absent in the gamma-ray shower

997 Input variables for the NN are selected to capture key characteristics of the air shower: energy
 998 deposition, containment, and atmospheric attenuation. The algorithm calculates energy deposition
 999 using the fraction of PMTs and tanks activated, alongside the logarithm of the normalization from
 1000 the lateral distribution fit. Containment is inferred from the distance between the shower core and
 1001 the array's center, while atmospheric attenuation is evaluated using the reconstructed zenith angle
 1002 and a detailed analysis of the shower's lateral charge distribution [38, 37].

1003 This refined NN energy estimation methodology is an integral component of HAWC's toolkit,
 1004 enabling precise analysis of high-energy gamma-ray events. It represents a significant advancement
 1005 in the field, offering deeper insights into cosmic phenomena by accurately mapping observed shower
 1006 characteristics to primary particle energies.

1007 3.2.5 G/H Discrimination

1008 At the HAWC Observatory, distinguishing between air showers initiated by gamma rays and
 1009 those by hadronic cosmic rays is fundamental for astrophysical data purity. The separation process
 1010 leverages differences in shower characteristics: electromagnetic showers from gamma rays typically
 1011 display fewer muons and a smoother distribution, whereas hadronic showers are more chaotic due
 1012 to the abundance of muons and hadronic sub-showers.

1013 Discrimination Parameters Two primary parameters facilitate the identification of cosmic-ray

1014 events [34]:

1015 Compactness (C): This parameter evaluates the charge captured by PMTs, particularly focusing
1016 on the PMT with the highest effective charge beyond a 40-meter radius from the shower core.
1017 Compactness is inversely proportional to this effective charge, as higher charges at extended
1018 distances from the core are indicative of hadronic showers. It is mathematically expressed as:

$$C = \frac{N_{\text{hit}}}{CxPE_{40}} \quad (3.2)$$

1019 PINCness (P): PINCness quantifies the "clumpiness" of a shower using the charges recorded by
1020 PMTs. It is computed from the logarithm of the effective charge of each PMT hit, compared to an
1021 expected average for that annular region. A higher PINCness suggests a less smooth distribution,
1022 typical of hadronic showers. The formula is:

$$P = \frac{1}{N} \sum_{i=0}^N \frac{(\zeta_i - \langle \zeta_i \rangle)^2}{\sigma_{\zeta_i}^2} \quad (3.3)$$

1023 These parameters are accurately modeled in simulations, aligning well with observational data near
1024 gamma-ray sources like the Crab Nebula. Figures illustrating the lateral distributions for represen-
1025 tative cosmic-ray and photon candidate showers, as well as the distribution of these discrimination
1026 parameters, affirm their efficacy [34].

1027 Optimization and Application The discrimination technique has remained consistent, but cut
1028 values have been reoptimized in each 2D bin based on f_{hit} and estimated energy. This refinement
1029 enhances the selection of high-energy events. Each bin ensures at least 50% efficiency for gamma-
1030 ray detection, with efficiencies extending up to nearly 100% in certain bins [34, 37].

1031 **3.3 Background Estimation: Direct Integration**

1032 The ratio of cosmic rays to gamma rays can be as high as 10,000 to 1, depending on the energy.
1033 At HAWC, we confront a significant challenge even after gamma/hadron cuts: our gamma-ray data
1034 is still inundated with cosmic-ray events. To tackle this, we rely on the direct integration method
1035 developed by Milagro [39]. This method capitalizes on the cosmic rays' isotropic nature resulting
1036 from their deflection by interstellar magnetic fields.

1037 The direct integration method estimates background events by integrating over a stable two-
1038 hour period of detector operation. The expected number of background events at a particular sky
1039 location (ϕ, θ) is determined by integrating the normalized detector's efficiency with the all-sky
1040 event rate:

$$N_{\text{exp}}(\phi, \theta) = \int \int E(\text{ha}, \theta) \cdot R(t) dt dt \quad (3.4)$$

1041 Here, $E(\text{ha}, \theta)$, represents the detector's efficiency, which varies with local coordinates (hour angle
1042 and declination). $R(t)$ is the event rate as a function of time [39].

1043 Our background estimation is expected to falter in high-energy ranges where cosmic-ray events
1044 are less frequent due to enhanced gamma/hadron discrimination. Sparsity in our background and
1045 data also arise at the limits of HAWC's sensitivity and during short-term analyses of transient
1046 events. HAWC addresses these issues by using a pixel size of 0.5° in our background calculations
1047 to maintain robustness in our estimation [34, 36]. In constructing the background model, it's crucial
1048 to exclude areas of the sky with known gamma-ray sources. Regions containing the Crab Nebula,
1049 Mrk 421, Mrk 501, and the Galactic Plane are masked to prevent their significant gamma-ray
1050 signals from biasing our background estimate [34].

1051

CHAPTER 4

ICECUBE NEUTRINO OBSERVATORY

1052 **4.1 The Detector**

1053 **4.2 Events Reconstruction and Data Acquisition**

1054 **4.2.1 Angle**

1055 **4.2.2 Energy**

1056 **4.3 Northern Test Site**

1057 **4.3.1 PIgeon remote dark rate testing**

1058 **4.3.2 Bulkhead Construction**

CHAPTER 5

1059 **GLORY DUCK: MULTI-WAVELENGTH SEARCH FOR DARK MATTTER** 1060 **ANNIHILATION TOWARDS DWARF SPHEROIDAL GALAXIES**

1061 **5.1 Introduction**

1062 The field of astrophysics now has several instruments and observatories sensitive to high energy
1063 gamma-rays. The energy sensitivity for the modern gamma-ray program spans many orders of
1064 magnitude. Figure 5.1 demonstrates these comparable sensitivities across energies for the five
1065 experiments: Fermi-LAT, HAWC, HESS, MAGIC, and VERITAS.

1066 Each of the five experiments featured in Figure 5.1 have independently searched for DM
1067 annihilation from dwarf spheroidal galaxies (dSph) and set limits on annihilation cross-section of
1068 WIMPs. Intriguingly, there are regions of substantial overlap in their energy sensitivities. This
1069 clearly motivates an analysis that combines data from these five. Each experiment has unique
1070 gamma-ray detection methods and their weaknesses and strengths can be leveraged with each other.
1071 The HAWC gamma-ray observatory is extensively introduced in chapter 3, so it is not introduced
1072 here. A brief description of the remaining experiments are in the following paragraphs.

1073 The Large Area Telescope (LAT) is a pair conversion telescope mounted on the NASA Fermi
1074 satellite in orbit \sim 550 km above the Earth [41]. LAT's field of view covers about 20% of the
1075 whole sky, and it sweeps the whole sky approximately every 3 hours. LAT's gamma-ray energy
1076 sensitivity ranges from 20 MeV up to 1 TeV. Previous DM searches towards dSphs using Fermi-LAT
1077 are published in [42] and [43].

1078 The High Energy Spectroscopic System (HESS), Major Atmospheric Gamma Imaging
1079 Cherenkov (MAGIC), and Very Energetic Radiation Imaging Telescope Array System (VERI-
1080 TAS) are arrays of Imaging Atmospheric Cherenkov Telescopes (IACT). These telescopes observe
1081 the Cherenkov light emitted from gamma-ray showers in the Earth's atmosphere. The field of
1082 view for these telescopes is no larger than 5° with energy sensitivities ranging from 30 GeV up
1083 to 100 TeV [44, 45, 46]. IACTs are able to make precise observations in selected regions of the
1084 sky, however can only be operated in ideal dark conditions. HESS's observations of the dwarves

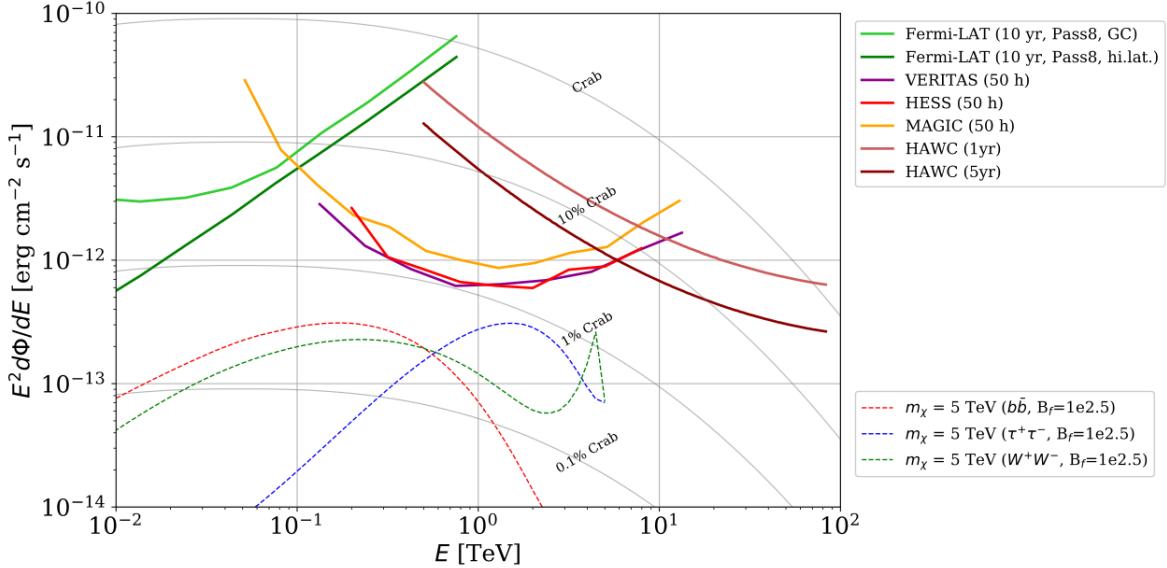


Figure 5.1 Sensitivities of five gamma-ray experiments compared to percentages of the Crab nebula’s emission and dark matter annihilation. Solid lines present estimated sensitivities to power law spectra [FACT CHECK THIS] for each experiment. Green lines are Fermi-LAT sensitivities where lighter green is the sensitivity to the galactic center and dark green is its sensitivity to higher declinations. Orange, red, and purple solid lines represent the MAGIC, HESS, and VERITAS 50 hour sensitivities respectively. The maroon and brown lines are the HAWC 1 year and 5 year sensitivities. Across four decades of gamma-ray energy, these experiments have similar sensitivities on the order 10^{-12} erg $\text{cm}^{-2}\text{s}^{-1}$. The dotted lines are estimated dark matter fluxes assuming $m_\chi = 5$ TeV DM annihilating to bottom quarks (red), tau leptons (blue), and W bosons (green). Faded gray lines outline percentage flux of the Crab nebula. Figure is an augmented version of [40]

1085 Sculptor and Carina were between January 2008 and December 2009. HESS’s observations of
 1086 Coma Berenices were taken from 2010 to 2013, and Fornax was observed in 2010 [47, 48, 49].
 1087 MAGIC provided deep observations of Segue1 between 2011 and 2013 [50]. MAGIC also provides
 1088 data for three additional dwarves: Coma Berenices, Draco, and Ursa Major II where observations
 1089 were made in: January - June 2019 [51], March - September 2018 [51], and 2014 - 2016 [52]
 1090 respectively. VERITAS provided data for Boötes I, Draco, Segue 1, and Ursa Minor from 2009 to
 1091 2016 [53].

1092 This chapter presents the Glory Duck analysis, the name given for the search for dark matter
 1093 annihilation from dSph by combining data from the five gamma-ray observatories: Fermi-LAT,
 1094 HAWC, HESS, MAGIC, and VERITAS. Specifically, the methods in analysis and modeling are
 1095 presented for the HAWC gamma-ray observatory. This work will be published in the Journal of

1096 Cosmology and Astroparticle Physics and presented at the International Cosmic Ray Conference
1097 in 2019, 2021, and 2023 [54, 55, 56] and others.

1098 **5.2 Dataset and Background**

1099 This section enumerates the data analysis and background estimation methods used for HAWC's
1100 study of dSphs. Section 5.2.1 and Section 5.2.2 are most useful for fellow HAWC collaborators
1101 looking to replicate the Glory Duck analysis.

1102 **5.2.1 Itemized HAWC files**

1103 These files are only available withing HAWC's internal documentation and collaborators. They
1104 are not meant for public access, and are presented here so that HAWC collaborators can reproduce
1105 results accurately.

- 1106 • Detector Response: `response_aerie_svn_27754_systematics_best_mc_test_noBr`
1107 `oadpulse\10pctlogchargesmearing_0.63qe_25kHzNoise_run5481_curvature`
1108 `0_index3.root`
- 1109 • Data Map: `maps-20180119/liff/maptree_1024.root`
- 1110 • Spectral Dictionary: `DM_CirrelliSpectrum_dict_gammas.npy`
- 1111 • Analysis wiki: https://private.hawc-observatory.org/wiki/index.php/Glory_Duck_Multi-Experiment_Dark_Matter_Search

1113 **5.2.2 Software Tools and Development**

1114 This analysis was performed using HAL and 3ML [34, 57] in Python version 2. I built software
1115 to implement the *A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection* (PPPC)
1116 [58] DM spectral model and dSphs spatial model from [59] for HAWC analysis. A NumPy version
1117 of this dictionary was made for both Py2 and Py3. The code base for creating this dictionary is
1118 linked on my GitLab sandbox:

- 1119 • Py2: [Dictionary Generator \(Deprecated\)](#)

- 1120 • Py3: [PPPC2Dict](#)

1121 The analysis was performed using the f_{hit} framework as used and described in the HAWC Crab
1122 paper [34]. The Python2 NumPy dictionary file for gamma-ray final states is `dmCirSpecDict.npy`.
1123 The corresponding Python3 file is `DM_CirrelliSpectrum_dict_gammas.npy`. These files can
1124 also be used for decay channels and the PPPC describes how [58]. All other software used for data
1125 analysis, DM profile generation, and job submission to SLURM are also kept in my sandbox for
1126 [the Glory Duck](#) project.

1127 **5.2.3 Data Set and Background Description**

1128 The HAWC data maps used for this analysis contain 1017 days of data between runs 2104
1129 (2014-11-26) and 7476 (2017-12-20). They were generated from pass 4.0 reconstruction. The
1130 analysis is performed using the f_{hit} energy binning scheme with bins (1-9) similar to what was done
1131 for the Crab and previous HAWC dSph analysis [34, 60]. Bin 0 was excluded as it has substantial
1132 hadronic contamination and poor angular resolution.

1133 This analysis was done on dSphs because of their large DM mass content relative to baryonic
1134 mass. We consider the following to estimate the background to this study.

- 1135 • The dSphs' angular extent are small relative to HAWC's spatial resolution, so the analysis is
1136 not sensitive to large or small scale anisotropies.
- 1137 • The dSphs used in this analysis are off the galactic plane and therefore not contaminated by
1138 diffuse emission from the galaxy.
- 1139 • The dSphs are baryonically faint relative to their expected dark matter content and are not
1140 expected to contain high energy gamma-ray sources.

1141 Therefor we make no additional assumptions on the background from our sources and use
1142 HAWC's standard direct integration method for background estimation [34]. The largest background
1143 under this consideration is from an isotropic flux of cosmic rays. The contamination of this hadronic
1144 flux is worse at lower energies where HAWC's gamma/hadron discrimination worse. It is possible

1145 for gamma rays from DM annihilation to scatter in transit to HAWC via Inverse Compton Scattering
1146 (ICS). This was investigated and its impact on the flux is negligible. Supporting information on
1147 this is in Section 5.7.1

1148 **5.3 Analysis**

1149 The expected differential photon flux from DM-DM annihilation to standard model particles,
1150 $d\Phi_\gamma/dE_\gamma$, over solid angle, Ω , is described by the familiar equation.

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE_\gamma} \times \int_{\text{source}} d\Omega \int_{l.o.s} dl \rho_\chi^2 J(r, \theta') \quad (5.1)$$

1151 Where $\langle\sigma v\rangle$ is the velocity weighted annihilation cross-section. $\frac{dN}{dE}$ is the expected differential
1152 number of photons produced at each energy per annihilation. m_χ is the rest mass of the supposed
1153 DM particle. ρ_χ is the DM density. J is the astrophysical J-factor and is defined as

$$J = \int d\Omega \int_{l.o.s} dl \rho_\chi^2(r, \theta') \quad (5.2)$$

1154 l is the distance to the source from Earth. r is the radial distance from the center of the source. θ' is
1155 the half angle defining a cone containing the DM source. How each component is synthesized and
1156 considered for HAWC's analysis is presented in the following sections. Section 5.3.1 presents the
1157 particle physics model for DM annihilation. Section 5.3.2 presents the spatial distributions built
1158 for each dSph.

1159 **5.3.1 $\frac{dN_\gamma}{dE_\gamma}$ - Particle Physics Component**

1160 For these spectra, we import the PPPC with Electroweak (EW) corrections [58]. Public versions
1161 of the imported tables are provided by the [authors online](#). The spectrum is implemented as a model
1162 script in astromodels for 3ML. The EW corrections were previously not considered for HAWC and
1163 are significant for DM annihilating to EW coupled SM particles such as all leptons, and the γ ,
1164 Z , and W bosons [60]. Figure 5.2 demonstrates the significance of EW corrections for W boson
1165 annihilation. Across EW SM channels, the gamma-ray spectra become harder than spectra without
1166 EW corrections. Tables from the PPPC were reformatted into Python NumPy dictionaries for
1167 collaboration-wide use. A class in astromodels was developed to include the EW correction from
1168 the PPPC and is aptly named `PPPCSpectra` within `DM_models.py`.

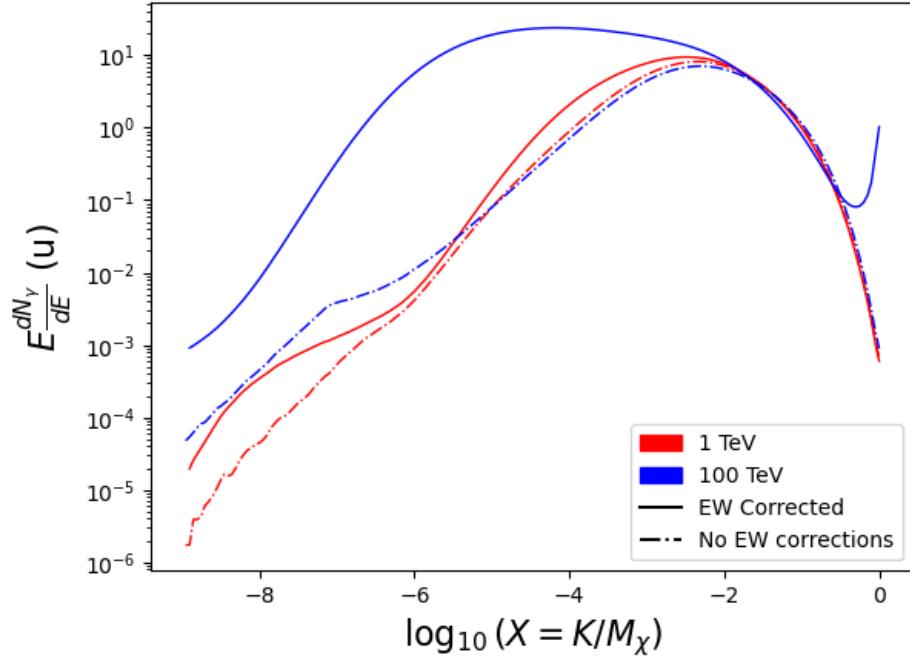


Figure 5.2 Effect of Electroweak (EW) corrections on expected DM annihilation spectrum for $\chi\chi \rightarrow W^-W^+$. Solid lines are spectral models that consider EW corrections. Dash-dot lines are spectral models without EW corrections. Red lines are models for $M_\chi = 1$ TeV. Blue lines represent models for $M_\chi = 100$ TeV. All models are sourced from the PPPC4DMID [58].

1169 5.3.2 J- Astrophysical Component

1170 The J-factor profiles for each source are imported from Geringer-Sameth (referred to with \mathcal{GS})
 1171 [59]. \mathcal{GS} fits the Zhao DM profile to the dSphs which has a DM density described as [61]

$$\rho(r) = \frac{\rho_0}{(r/R_s)^\gamma (1 + (r/R_s)^\alpha)^{(\beta-\gamma)}}. \quad (5.3)$$

1172 R_s is the scale radius and free parameter in the model. γ is the logarithmic slope in the region
 1173 $r \ll R_s$. β is the logarithmic slope in the region $r \gg R_s$. α is known as the sharpness of transition
 1174 where $r \approx R_s$. The classic Navarro-Frenk-White [62] (NFW) can be retrieved from Zhao by fixing
 1175 $(\alpha, \beta, \gamma) = (1, 3, 1)$.

1176 \mathcal{GS} best fits were pulled from the publication as $J(\theta)$, where θ is the angular separation from
 1177 the center of the source. HAWC requires maps in terms of $\frac{dJ}{d\Omega}$, so the conversion from the maps
 1178 was done in the following way...

1179 First, convert the angular distances to solid angles

$$\Omega = 2 \cdot \pi(1 - \cos(\theta)) \quad (5.4)$$

1180 which reduces with a small angle approximation to $\pi\theta^2$. Next, the central difference for both the
1181 ΔJ and $\Delta\Omega$ value were calculated from the discretized $J(\theta)$ with the central difference stencil:

$$\Delta\phi_i = \phi_{i+1} - \phi_{i-1} \quad (5.5)$$

1182 Where ϕ is either Ω or J . These were done separately in case the grid spacing in θ was not uniform.
1183 Finally, these lists are divided so that we are left with an approximation of the $dJ/d\Omega$ profile that
1184 is a function of θ . Admittedly, this is an approximation method for the map which introduces small
1185 errors compared to the true profile estimate. This was checked as a systematic against the author's
1186 profiling of the spatial distribution and is documented in Section 5.8.1.

1187 With $\frac{dJ}{d\Omega}(\theta)$, a map is generated, first by filling in the north-east quadrant of the map. This
1188 quadrant is then reflected twice, vertically then horizontally, to fill the full map. Maps are then
1189 normalized by dividing the discrete 2D integral of the map. The 2D integral was a simple height
1190 of bins, Newton's integral:

$$p^2 \cdot \sum_{i,j=0}^{N,M} \frac{dJ}{d\Omega}(\theta_{i,j}, \phi_{i,j}) \quad (5.6)$$

1191 These maps are HEALpix maps with NSIDE 16384 and saved in the .fits format. The hyper fine
1192 resolution was selected to better preserve the total expected counts after integrating Eq. (5.1) with
1193 the detector response.

1194 Another DM spatial distribution model from Bonnivard (\mathcal{B}) [63] was used for the Glory Duck
1195 study. However, to save computational time, limits from \mathcal{GS} were scaled to \mathcal{B} instead of each
1196 experiment performing a full study a second time. How these models compare is demonstrated
1197 for each dSph in Figure 5.16 and Figure 5.17 Plots of these maps are provided for each source
1198 in chapter A Examples of the two most impactful dSphs derived from \mathcal{GS} , Segue1 and Coma
1199 Berenices are featured in Figure 5.3

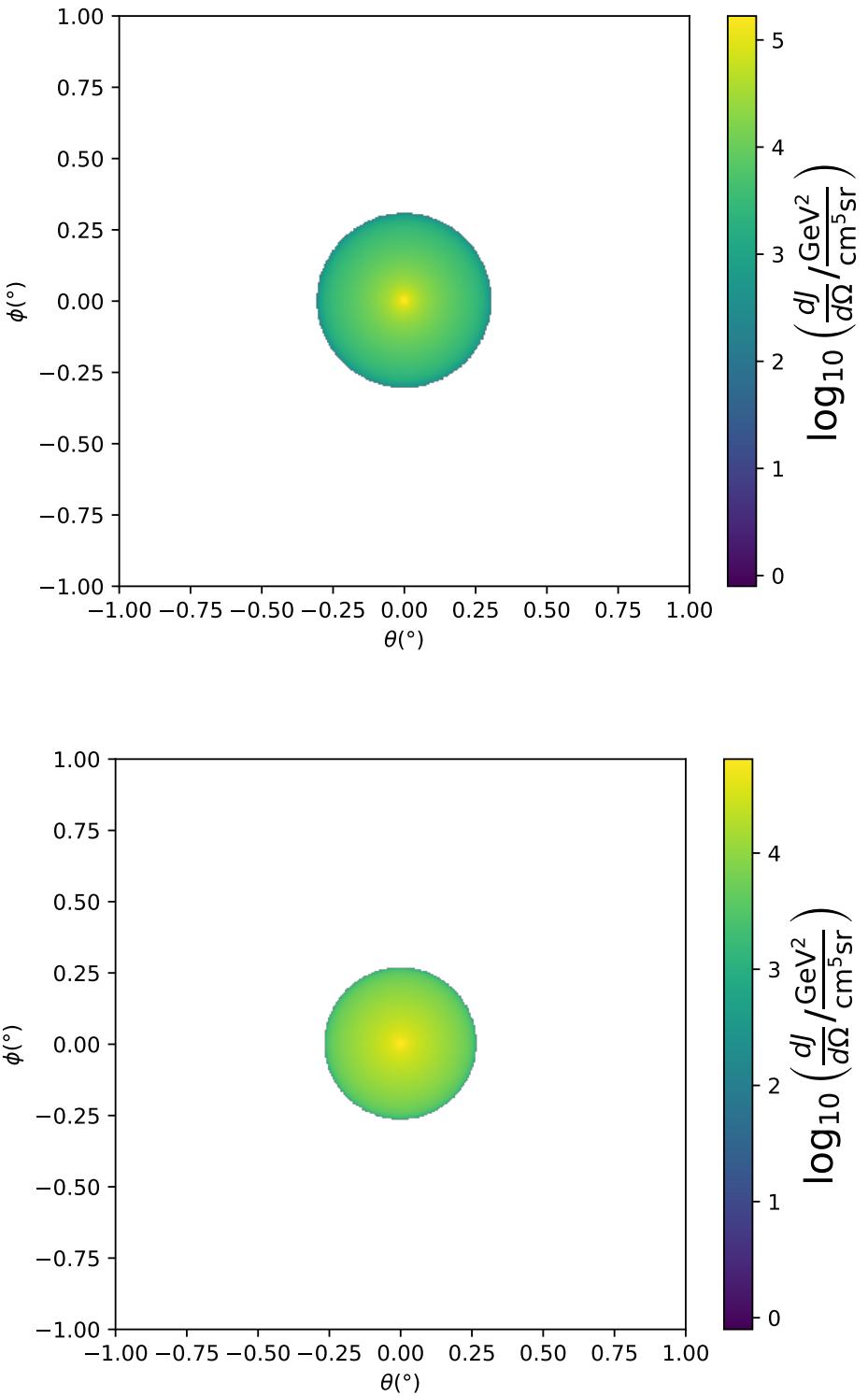


Figure 5.3 $\frac{dJ}{d\Omega}$ maps for Segue1 (top) and Coma Berenices (bottom). Origin is centered on the specific dwarf spheroidal galaxies (dSph). X and Y axes are the angular separation from the center of the dwarf. Profile is truncated at the scale radius. Plots of the remaining 11 dSph HAWC studied are linked in Fig. A.1.

1200 **5.3.3 Source Selection and Annihilation Channels**

1201 We use many of the dSphs presented in HAWC’s previous dSph DM search [60]. HAWC’s
1202 sources for Glory Duck include Boötes I, Coma Berenices, Canes Venatici I + II, Draco, Hercules,
1203 Leo I, II, + IV, Segue 1, Sextans, and Ursa Major I + II. A full description of all sources used
1204 in Glory Duck is found in Table 5.1. Triangulum II was excluded from the Glory Duck analysis
1205 because of large uncertainties in its J factor. Ursa Minor was excluded from HAWC’s contribution
1206 to the combination because the source extension model extended Ursa Minor beyond HAWC’s field
1207 of view. Ursa Minor was not expected to contribute significantly to the combined limit, so work
1208 was not invested in a solution to include Ursa Minor.

1209 This analysis improves on the previous HAWC dSph paper [60] in the following ways. Pre-
1210 viously, the dSphs were treated and implemented as point sources. For this analysis, dSphs are
1211 modeled and treated as extended source. The impact of this change with respect to the upper limit
1212 is source dependent and is explored in Section 5.7.2. Previously, the particle physics model used for
1213 gamma-ray spectra from DM annihilation did not have EW corrections where the PPPC includes
1214 them. Finally, the gamma-ray ray dataset is much larger. The study performed here analyzes over
1215 1000 days of data compared to 507.

1216 The SM annihilation channels probed for the Glory Duck combination include $b\bar{b}$, $e\bar{e}$, $\mu\bar{\mu}$, $\tau\bar{\tau}$,
1217 $t\bar{t}$, W^+W^- , and ZZ . A summary of all sources, with a description of each experiments’ sensitivity
1218 to the source, is provided in Table 5.2.

1219 **5.4 Likelihood Methods**

1220 **5.4.1 HAWC Likelihood**

1221 For every analysis bin in energy, f_{hit} bins (1-9), and location, we can expect N signal events and
1222 B background events. The expected number of excess signal events from dark matter annihilation,
1223 S , is estimated by convolving Equation (5.1) with HAWC’s energy response and pixel point spread
1224 functions. I then compute the test statistic (TS) with the log-likelihood ratio test,

$$TS_{\max} = -2 \ln \left(\frac{\mathcal{L}_0}{\mathcal{L}_{\max}} \right) \quad (5.7)$$

Table 5.1 Summary of the relevant properties of the dSphs used in the present work. Column 1 lists the dSphs. Columns 2 and 3 present their heliocentric distance and galactic coordinates, respectively. Columns 4 and 5 report the J -factors of each source given from the \mathcal{GS} and \mathcal{B} independent studies and their estimated $\pm 1\sigma$ uncertainties. The values $\log_{10} J$ (\mathcal{GS} set) [59] correspond to the mean J -factor values for a source extension truncated at the outermost observed star. The values $\log_{10} J$ (\mathcal{B} set) [63] are provided for a source extension at the tidal radius of each dSph. **Bolded sources are within HAWC’s field of view and provided to the Glory Duck analysis.**

Name	Distance (kpc)	l, b ($^{\circ}$)	$\log_{10} J$ (\mathcal{GS} set) $\log_{10}(\text{GeV}^2\text{cm}^{-5}\text{sr})$	$\log_{10} J$ (\mathcal{B} set) $\log_{10}(\text{GeV}^2\text{cm}^{-5}\text{sr})$
Boötes I	66	358.08, 69.62	$18.24^{+0.40}_{-0.37}$	$18.85^{+1.10}_{-0.61}$
Canes Venatici I	218	74.31, 79.82	$17.44^{+0.37}_{-0.28}$	$17.63^{+0.50}_{-0.20}$
Canes Venatici II	160	113.58, 82.70	$17.65^{+0.45}_{-0.43}$	$18.67^{+1.54}_{-0.97}$
Carina	105	260.11, -22.22	$17.92^{+0.19}_{-0.11}$	$18.02^{+0.36}_{-0.15}$
Coma Berenices	44	241.89, 83.61	$19.02^{+0.37}_{-0.41}$	$20.13^{+1.56}_{-1.08}$
Draco	76	86.37, 34.72	$19.05^{+0.22}_{-0.21}$	$19.42^{+0.92}_{-0.47}$
Fornax	147	237.10, -65.65	$17.84^{+0.11}_{-0.06}$	$17.85^{+0.11}_{-0.08}$
Hercules	132	28.73, 36.87	$16.86^{+0.74}_{-0.68}$	$17.70^{+1.08}_{-0.73}$
Leo I	254	225.99, 49.11	$17.84^{+0.20}_{-0.16}$	$17.93^{+0.65}_{-0.25}$
Leo II	233	220.17, 67.23	$17.97^{+0.20}_{-0.18}$	$18.11^{+0.71}_{-0.25}$
Leo IV	154	265.44, 56.51	$16.32^{+1.06}_{-1.70}$	$16.36^{+1.44}_{-1.65}$
Leo V	178	261.86, 58.54	$16.37^{+0.94}_{-0.87}$	$16.30^{+1.33}_{-1.16}$
Leo T	417	214.85, 43.66	$17.11^{+0.44}_{-0.39}$	$17.67^{+1.01}_{-0.56}$
Sculptor	86	287.53, -83.16	$18.57^{+0.07}_{-0.05}$	$18.63^{+0.14}_{-0.08}$
Segue I	23	220.48, 50.43	$19.36^{+0.32}_{-0.35}$	$17.52^{+2.54}_{-2.65}$
Segue II	35	149.43, -38.14	$16.21^{+1.06}_{-0.98}$	$19.50^{+1.82}_{-1.48}$
Sextans	86	243.50, 42.27	$17.92^{+0.35}_{-0.29}$	$18.04^{+0.50}_{-0.28}$
Ursa Major I	97	159.43, 54.41	$17.87^{+0.56}_{-0.33}$	$18.84^{+0.97}_{-0.43}$
Ursa Major II	32	152.46, 37.44	$19.42^{+0.44}_{-0.42}$	$20.60^{+1.46}_{-0.95}$
Ursa Minor	76	104.97, 44.80	$18.95^{+0.26}_{-0.18}$	$19.08^{+0.21}_{-0.13}$

Table 5.2 Summary of dSph observations by each experiment used in this work. A ‘-’ indicates the experiment did not observe the dSph for this study. For Fermi-LAT, the exposure at 1 GeV is given. For HAWC, $|\Delta\theta|$ is the absolute difference between the source declination and HAWC latitude. HAWC is more sensitive to sources with smaller $|\Delta\theta|$. For IACTs, we show the zenith angle range, the total exposure, the energy range, the angular radius θ of the signal or ON region, the ratio of exposures between the background-control (OFF) and signal (ON) regions (τ), and the significance of gamma-ray excess in standard deviations, σ .

Source name	Fermi-LAT	HAWC	H.E.S.S, MAGIC, VERITAS						
	Exposure (10^{11} s m 2)	$ \Delta\theta $ ($^\circ$)	IACT	Zenith ($^\circ$)	Exposure (h)	Energy range (GeV)	θ ($^\circ$)	τ	S (σ)
Boötes I	2.6	4.5	VERITAS	15 – 30	14.0	100–41000	0.10	8.6	-1.0
Canes Venatici I	2.9	14.6	–	–	–	–	–	–	–
Canes Venatici II	2.9	15.3	–	–	–	–	–	–	–
Carina	3.1	–	H.E.S.S.	27 – 46	23.7	310 – 70000	0.10	18.0	-0.3
Coma Berenices	2.7	4.9	H.E.S.S.	47 – 49	11.4	550 – 70000	0.10	14.4	-0.4
			MAGIC	5 – 37	49.5	60 – 10000	0.17	1.0	–
			MAGIC	29 – 45	52.1	70 – 10000	0.22	1.0	–
Draco	3.8	38.1	VERITAS	25 – 40	49.8	120 – 70000	0.10	9.0	-1.0
Fornax	2.7	–	H.E.S.S.	11 – 25	6.8	230 – 70000	0.10	45.5	-1.5
Hercules	2.8	6.3	–	–	–	–	–	–	–
Leo I	2.5	6.7	–	–	–	–	–	–	–
Leo II	2.6	3.1	–	–	–	–	–	–	–
Leo IV	2.4	19.5	–	–	–	–	–	–	–
Leo V	2.4	–	–	–	–	–	–	–	–
Leo T	2.6	–	–	–	–	–	–	–	–
Sculptor	2.7	–	H.E.S.S.	10 – 46	11.8	200 – 70000	0.10	19.8	-2.2
Segue I	2.5	2.9	MAGIC	13 – 37	158.0	60 – 10000	0.12	1.0	-0.5
			VERITAS	15 – 35	92.0	80 – 50000	0.10	7.6	0.7
Segue II	2.7	–	–	–	–	–	–	–	–
Sextans	2.4	20.6	–	–	–	–	–	–	–
Ursa Major I	3.4	32.9	–	–	–	–	–	–	–
Ursa Major II	4.0	44.1	MAGIC	35 – 45	94.8	120 – 10000	0.30	1.0	-2.1
Ursa Minor	4.1	–	VERITAS	35 – 45	60.4	160 – 93000	0.10	8.4	-0.1

1225 where \mathcal{L}_0 is the null hypothesis, or no DM emission, likelihood. \mathcal{L}^{\max} is the best fit signal
 1226 hypothesis where $\langle\sigma v\rangle$ maximizes the likelihood. We calculate the likelihood of each source and
 1228 model, assuming events are Poisson distributed, with

$$\mathcal{L} = \prod_i \frac{(B_i + S_i)^{N_i} e^{-(B_i + S_i)}}{N_i!} \quad (5.8)$$

1229 where S_i is the sum of expected number of signal counts. B_i is the number of background counts
 1230 observed. N_i is the total number of counts.

1231 I also calculate an upper limit on $\langle\sigma v\rangle$ by calculating the 95% confidence level (CL). For the
 1232 CL, we define a parameter, TS_{95} , as

$$TS_{95} \equiv \sum_{\text{bins}} \left[2N \ln \left(1 + \frac{\epsilon S_{\text{ref}}}{B} \right) - 2\epsilon S_{\text{ref}} \right] \quad (5.9)$$

1233 where the expected signal counts from a dSph is scaled by ϵ . S_{ref} is the expected number of excess
 1234 counts in a bin from DM emission from a dSph with a corresponding annihilation cross-section,
 1235 $\langle\sigma v\rangle$. We scan ϵ such that

$$2.71 = TS_{\max} - TS_{95} \quad (5.10)$$

1236 HAWC's exclusive results are provided in Section 5.5.

1237 5.4.2 Glory Duck Joint Likelihood

1238 The joint likelihood for the 5-experiment combination was done similarly as Section 5.4.1. We
 1239 calculate upper limits on $\langle\sigma v\rangle$ from the TS, Eq. (5.7), and define the likelihood ratio more generally

$$\lambda(\langle\sigma v\rangle | \mathcal{D}_{\text{dSphs}}) = \frac{\mathcal{L}(\langle\sigma v\rangle; \hat{\nu} | \mathcal{D}_{\text{dSphs}})}{\mathcal{L}(\widehat{\langle\sigma v\rangle}; \hat{\nu} | \mathcal{D}_{\text{dSphs}})} \quad (5.11)$$

1240 $\mathcal{D}_{\text{dSphs}}$ is the totality of observations across experiments and dSphs. ν are the nuisance parameters
 1241 which are the J factors in this study. $\widehat{\langle\sigma v\rangle}$ and $\hat{\nu}$ are the respective estimate that maximize \mathcal{L}
 1242 globally. Finally, $\hat{\nu}$ is the set of nuisance parameters that maximize \mathcal{L} for a fixed value of $\langle\sigma v\rangle$.

1243 The *complete* joint likelihood, \mathcal{L} that encompasses all observations from all instruments and
 1244 dSphs can be factorized into *partial* functions for each dSph l (with $\mathcal{L}_{\text{dSph},l}$) and its J factor (\mathcal{J}_l):

$$\mathcal{L}(\langle\sigma v\rangle; \nu | \mathcal{D}_{\text{dSphs}}) = \prod_{l=1}^{N_{\text{dSphs}}} \mathcal{L}_{\text{dSph},l}(\langle\sigma v\rangle; J_l, \nu_l | \mathcal{D}_l) \times \mathcal{J}_l(J_l | J_{l,\text{obs}}, \sigma_{\log J_l}). \quad (5.12)$$

1245 For this study, $N_{\text{dSphs}} = 20$ is the number of dSphs studied. \mathcal{D}_l are the gamma-ray observations
 1246 of dSph, l . ν_l are the nuisance parameters modifying the gamma-ray observations of dSph, l ,
 1247 but excludes \mathcal{J}_l . \mathcal{J}_l is the J factor for dSph, l , as defined in Equation (5.2), and it is a nuisance
 1248 parameter whose value is unknown. $\log_{10} J_{l,\text{obs}}$ and $\sigma_{\log J_l}$ are obtained by fitting a log-normal
 1249 function of $J_{l,\text{obs}}$ to the posterior distribution of J_l [64]. $\log_{10} J_{l,\text{obs}}$ and $\sigma_{\log J_l}$ values are provided
 1250 in Table 5.1. The term \mathcal{J}_l constraining J_l is written as:

$$\mathcal{J}_l(J_l | J_{l,\text{obs}}, \sigma_{\log J_l}) = \frac{1}{\ln(10)J_{l,\text{obs}}\sqrt{2\pi}\sigma_{\log J_l}} \exp\left(-\frac{(\log_{10} J_l - \log_{10} J_{l,\text{obs}})^2}{2\sigma_{\log J_l}^2}\right). \quad (5.13)$$

1251 Both the \mathcal{GS} and \mathcal{B} , displayed in Table 5.1, sets of J factors are used in this analysis. Equation (5.13)
 1252 is also normalized, so it can also be interpreted as a probability density function (PDF) for $J_{l,\text{obs}}$.
 1253 From Equation (5.1), we can also see that $\langle\sigma v\rangle$ and J_l are degenerate when computing $\mathcal{L}_{\text{dSph},l}$.
 1254 Therefore, as noted in [65], it is sufficient to compute $\mathcal{L}_{\text{dSph},l}$ versus $\langle\sigma v\rangle$ for a fixed value of J_l .
 1255 We used $J_{l,\text{obs}}(\mathcal{GS})$ reported in Tab. 5.1, in order to perform the profile of \mathcal{L} with respect to J_l .
 1256 The degeneracy implies that for any $J'_l \neq J_{l,\text{obs}}$ (in practice in our case we used $J'_l = J_{l,\text{obs}}(\mathcal{B})$ to
 1257 compute results from a different set of J factors):

$$\mathcal{L}_{\text{dSph},l}(\langle\sigma v\rangle; J'_l, \nu_l | \mathcal{D}_l) = \mathcal{L}_{\text{dSph},l}\left(\frac{J'_l}{J_{l,\text{obs}}} \langle\sigma v\rangle; J_{l,\text{obs}}, \nu_l | \mathcal{D}_l\right), \quad (5.14)$$

1258 which is a straightforward rescaling operation that reduces the computational needs of the profiling
 1259 operation since:

$$\mathcal{L}(\langle\sigma v\rangle; \hat{\nu} | \mathcal{D}_{\text{dSphs}}) = \prod_{l=1}^{N_{\text{dSphs}}} \max_{J_l} \left[\mathcal{L}_{\text{dSph},l}(\langle\sigma v\rangle; J_l, \hat{\nu}_l | \mathcal{D}_l) \times \mathcal{J}_l(J_l | J_{l,\text{obs}}, \sigma_{\log J_l}) \right]. \quad (5.15)$$

1260 In addition, Eq. (5.14) enables the combination of data from different gamma-ray instruments and
 1261 observed dSphs via tabulated values of $\mathcal{L}_{\text{dSph},l}$, or equivalently of λ from Eq. (5.11) as was done in
 1262 this work, versus $\langle\sigma v\rangle$. $\mathcal{L}_{\text{dSph},l}$ is computed for a fixed value of J_l and profiled with respect to all
 1263 instrumental nuisance parameters ν_l , these nuisance parameters are discussed in more detail below.
 1264 These values are produced by each detector independently and therefore there is no need to share
 1265 sensitive low-level information used to produce them, such as event lists. Figure 5.4 illustrates the
 1266 multi-instrument combination technique used in this study with a comparison of the upper limit

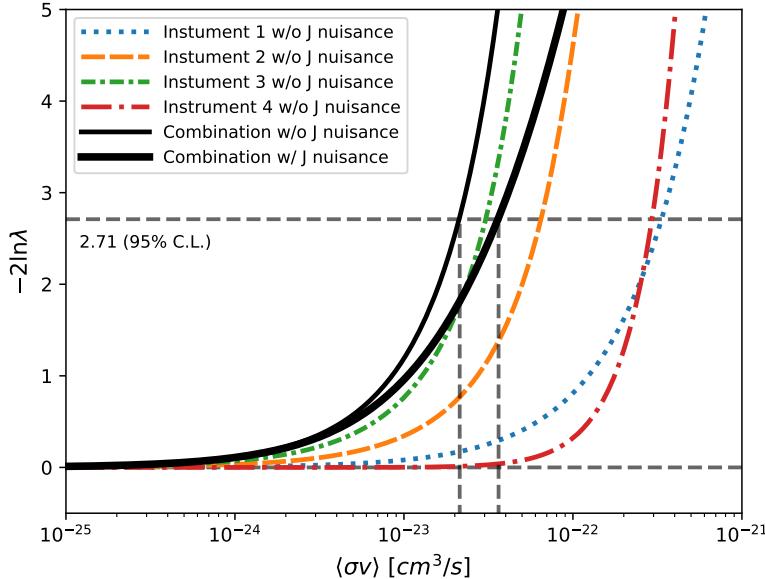


Figure 5.4 Illustration of the combination technique showing a comparison between $-2 \ln \lambda$ provided by four instruments (colored lines) from the observation of the same dSph without any J nuisance and their sum, *i.e.* the resulting combined likelihood (thin black line). According to the test statistics of Equation (5.7), the intersection of the likelihood profiles with the line $-2 \ln \lambda = 2.71$ indicates the 95% C.L. upper limit on $\langle\sigma v\rangle$. The combined likelihood (thin black line) shows a smaller value of upper limit on $\langle\sigma v\rangle$ than those derived by individual instruments. We also show how the uncertainties on the J factor effects the combined likelihood and degrade the upper limit on $\langle\sigma v\rangle$ (thick black line). All likelihood profiles are normalized so that the global minimum $\widehat{\langle\sigma v\rangle}$ is 0. We note that each profile depends on the observational conditions in which a target object was observed. The sensitivity of a given instrument can be degraded and the upper limits less constraining if the observations are performed in non-optimal conditions such as a high zenith angle or a short exposure time.

1267 on $\langle\sigma v\rangle$ obtained from the combination of the observations of four experiments towards one dSph
 1268 versus the upper limit from individual instruments. It also shows graphically the effect of the
 1269 J -factor uncertainty on the combined observations.

1270 The *partial* joint likelihood function for gamma-ray observations of each dSph ($\mathcal{L}_{\text{dSph},l}$) is
 1271 written as the product of the likelihood terms describing the $N_{\text{exp},l}$ observations performed with
 1272 any of our observatories:

$$\mathcal{L}_{\text{dSph},l} (\langle\sigma v\rangle; J_l, \nu_l | \mathcal{D}_l) = \prod_{k=1}^{N_{\text{exp},l}} \mathcal{L}_{lk} (\langle\sigma v\rangle; J_l, \nu_{lk} | \mathcal{D}_{lk}), \quad (5.16)$$

1273 where each \mathcal{L}_{lk} term refers to an observation of the l -th dSph with associated k -th instrument

1274 responses. $N_{\text{exp},l}$ varies from dSph to dSph and can be inferred from Table 5.2.

1275 Each collaboration separately analyzes their data for \mathcal{D}_{lk} corresponding to dSph l and gamma-
 1276 ray detector k , using as many common assumptions as possible in the analysis. HAWC's treatment
 1277 was described earlier in Section 5.4.1 whereas the specifics of the remaining experiments is left to
 1278 the publication. We compute the values for the likelihood functions \mathcal{L}_{lk} (see Eq. (5.16)) for a fixed
 1279 value of J_l and profile over the rest of the nuisance parameters ν_{lk} . Then, values of λ from Eq. (5.11)
 1280 are computed as a function of $\langle \sigma v \rangle$, and shared using a common format. Results are computed for
 1281 seven annihilation channels, W^+W^- , ZZ , $b\bar{b}$, $t\bar{t}$, e^+e^- , $\mu^+\mu^-$, and $\tau^+\tau^-$ over 62 m_χ values between
 1282 5 GeV and 100 TeV provided in [58]. The $\langle \sigma v \rangle$ range is defined between 10^{-28} and $10^{-18} \text{cm}^3 \cdot \text{s}^{-1}$,
 1283 with 1001 logarithmically spaced values. The likelihood combination, i.e. Equation (5.12), and
 1284 profile over the J -factor to compute the profile likelihood ratio λ , Equation (5.11), are carried out
 1285 with two different public analysis software packages, namely `gLike` [66] and `LklCom` [67], that
 1286 provide the same results [68].

1287 As mentioned previously, each experiment computes the \mathcal{L}_{lk} from Equation (5.11) differently.
 1288 The remainder of this section highlights the differences in this calculation across the experiments.
 1289 Four experiments, namely *Fermi*-LAT, H.E.S.S., HAWC and MAGIC, use a binned likelihood to
 1290 compute the \mathcal{L}_{lk} . For these experiments, for each observation \mathcal{D}_{lk} of a given dSph l carried out
 1291 using a given gamma-ray detector k , the binned likelihood function is:

$$\mathcal{L}_{lk} (\langle \sigma v \rangle; J_l, \nu_{lk} | \mathcal{D}_{lk}) = \prod_{i=1}^{N_E} \prod_{j=1}^{N_P} \left[\mathcal{P}(s_{lk,ij}(\langle \sigma v \rangle, J_l, \nu_{lk}) + b_{lk,ij}(\nu_{lk}) | N_{lk,ij}) \right] \times \mathcal{L}_{lk,\nu} (\nu_{lk} | \mathcal{D}_{\nu_{lk}}) \quad (5.17)$$

1292 where N_E and N_P are the number of considered bins in reconstructed energy and arrival direction,
 1293 respectively; \mathcal{P} represents a Poisson PDF for the number of gamma-ray candidate events $N_{lk,ij}$
 1294 observed in the i -th bin in energy and j -th bin in arrival direction, when the expected number is
 1295 the sum of the expected mean number of signal events s_{ij} (produced by DM annihilation) and of
 1296 background events b_{ij} ; $\mathcal{L}_{lk,\nu}$ is the likelihood term for the extra ν_{lk} nuisance parameters that vary
 1297 from one instrument k to another. The expected counts for signal events s_{ij} for a given dSph l and

1298 detector k is given by:

$$s_{ij}(\langle\sigma\nu\rangle, J) = \int_{E'_{\min,i}}^{E'_{\max,i}} dE' \int_{P'_{\min,j}}^{P'_{\max,j}} d\Omega' \int_0^\infty dE \int_{\Delta\Omega_{tot}} d\Omega \int_0^{T_{\text{obs}}} dt \frac{d^2\Phi(\langle\sigma\nu\rangle, J)}{dEd\Omega} \text{IRF}(E', P' | E, P, t) \quad (5.18)$$

1299 where E' and E are the reconstructed and true energies, P' and P the reconstructed and true
1300 arrival directions; $E'_{\min,i}$, $P'_{\min,j}$, $E'_{\max,i}$, and $P'_{\max,j}$ are their lower and upper limits of the i -th
1301 energy bin and the j -th arrival direction bin; T_{obs} is the (dead-time corrected) total observation
1302 time; t is the time along the observations; $d^2\Phi/dEd\Omega$ is the DM flux in the source region (see
1303 Equation (5.1)); and $\text{IRF}(E', P' | E, P, t)$ is the IRF, which can be factorized as the product of the
1304 effective collection area of the detector $A_{\text{eff}}(E, P, t)$, the PDFs for the energy estimator $f_E(E' | E, t)$,
1305 and arrival direction $f_P(P' | E, P, t)$ estimators. Note that for Fermi-LAT, HAWC, MAGIC, and
1306 VERITAS the effect of the finite angular resolution is taken into account through the convolution
1307 of $d\Phi/dEd\Omega$ with f_P in Equation (5.18), whereas in the cases of H.E.S.S. f_P is approximated by a
1308 delta function. This approximation has been made in order to maintain compatibility of the result
1309 with what has been previously published. The difference introduced by this approximation is $< 5\%$
1310 for all considered dSphs. A more comprehensive review of the differences between the analyses of
1311 different instruments can be found in [40].

1312 5.5 HAWC Results

1313 13 of the 20 dSphs considered for the Glory Duck analysis are within HAWC's field of view.
1314 These dSph are analyzed for emission from DM annihilation according to the likelihood method
1315 described in Section 5.4. The 13 likelihood profiles are then stacked to synthesize a combined
1316 limit on the dark matter cross-section, $\langle\sigma\nu\rangle$. This combination is done for the 7 SM annihilation
1317 channels used in the Glory Duck analysis. Figure 5.5 shows the combined limit for all annihilation
1318 channels with HAWC only observations. We also perform 300 studies of Poisson trials on the
1319 background. These trials are used to produce HAWC sensitivities with $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty
1320 bands which were shared with the other collaborators for combination. The results on fitting to
1321 HAWC's Poisson trials of the DM hypothesis is shown in Figure 5.7 for all the DM annihilation
1322 channels studied for Glory Duck.

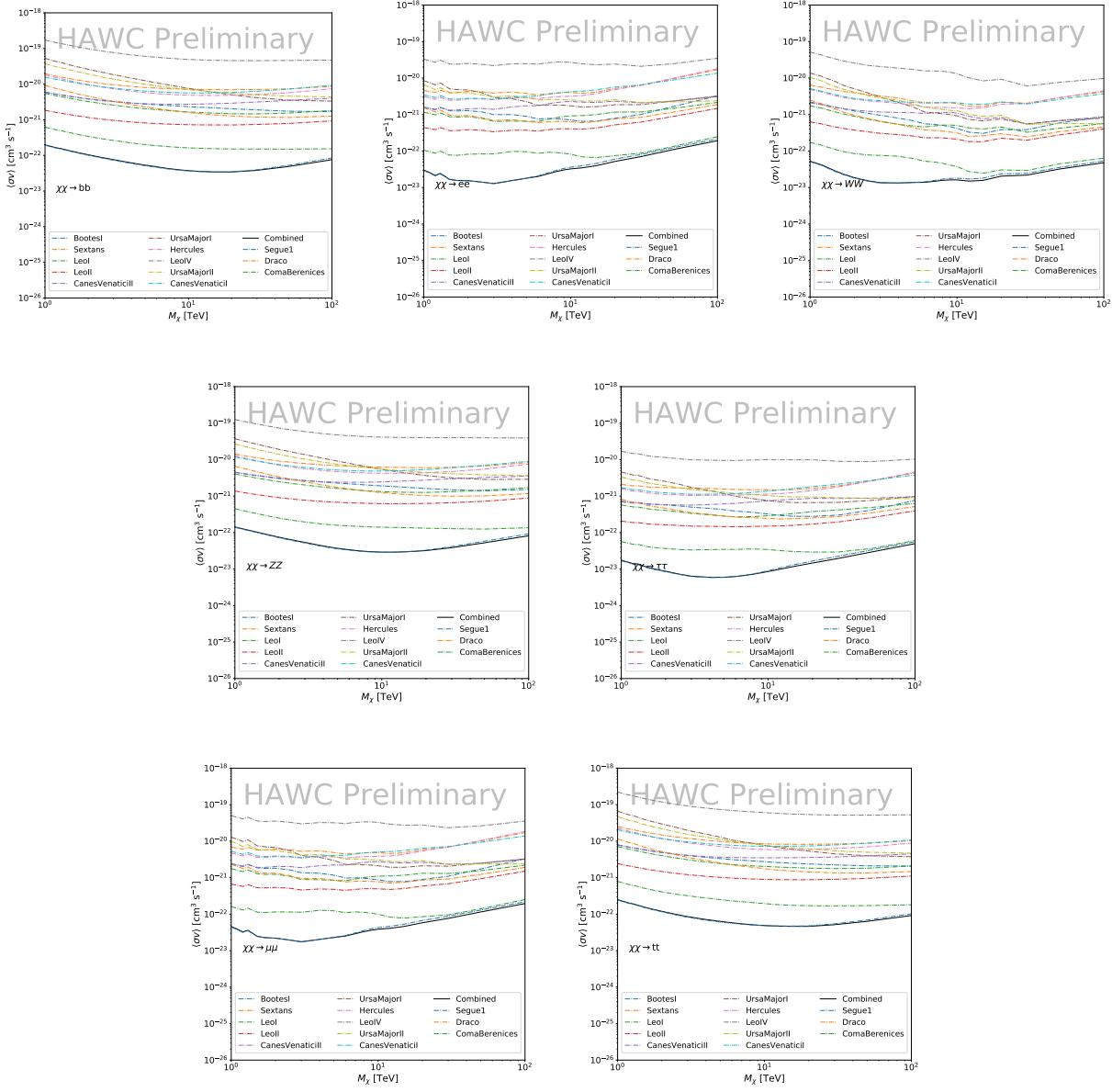


Figure 5.5

1323 No DM was found in HAWC observations. HAWC's limits are dominated by the dSphs Segue1
 1324 and Coma Berenices. The remaining 11 dSphs do not contribute significantly to the limit because
 1325 they are at high zenith and/or have much smaller J factors. Even though some remaining dSphs
 1326 have large J factors, they are towards the edge of HAWC's field of view where HAWC analysis is
 1327 less sensitive.

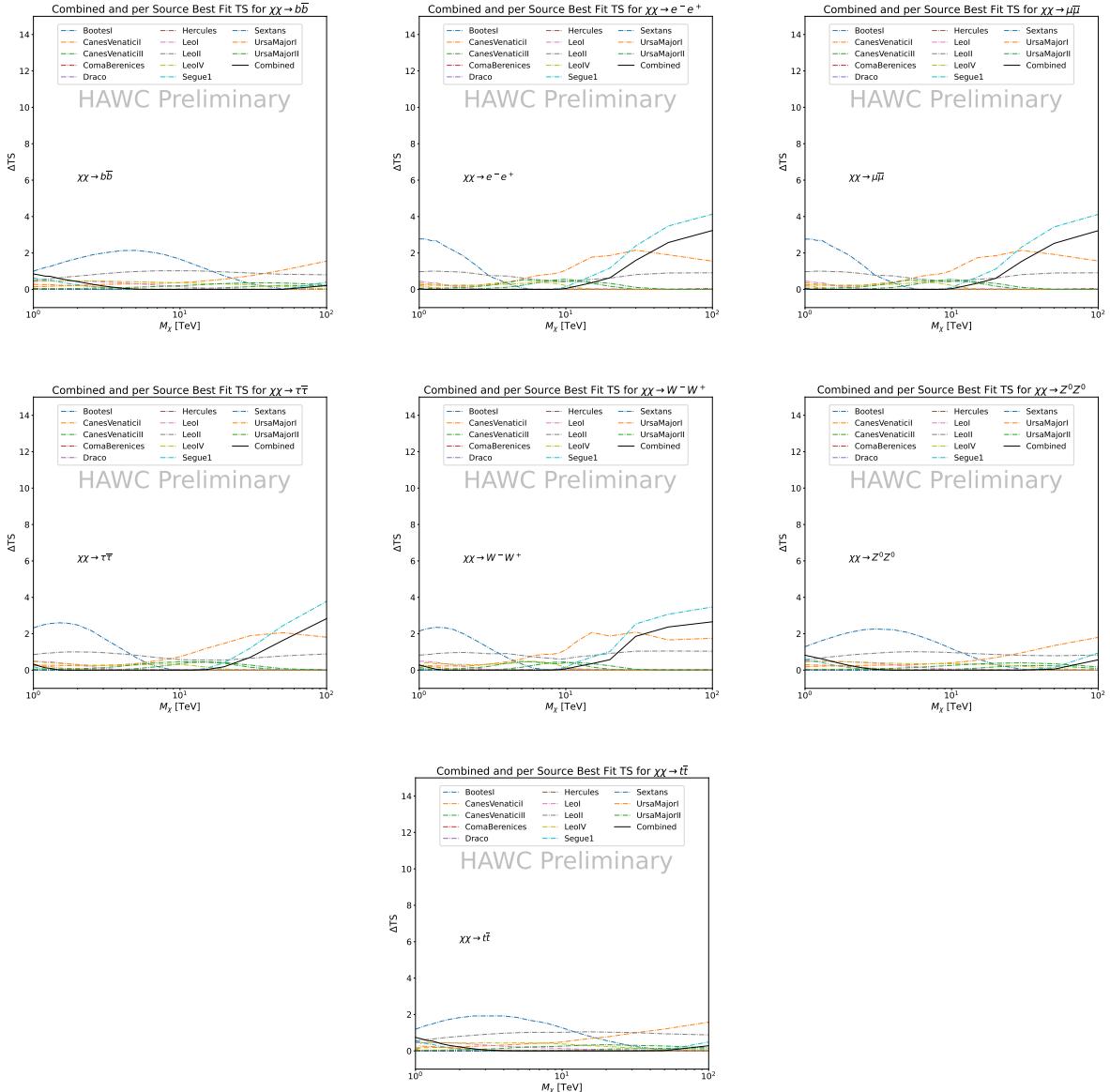


Figure 5.6 HAWC TS values for best fit $\langle\sigma v\rangle$ versus m_χ for seven SM annihilation channels with J factors from \mathcal{GS} . The solid black line shows the combined best fit TS values. The colored, dashed lines are the TS values for each of the 13 sources HAWC studied.

1328 5.6 Glory Duck Combined Results

1329 The crux of this analysis is that HAWC's results are combined with 4 other gamma-ray observa-
 1330 tories: Fermi-LAT, H.E.S.S., MAGIC, and VERITAS. No significant DM emission was observed
 1331 by any of the five instruments. We present the upper limits on $\langle\sigma v\rangle$ assuming seven independent
 1332 DM self annihilation channels, namely W^+W^- , Z^+Z^- , $b\bar{b}$, $t\bar{t}$, e^+e^- , $\mu^+\mu^-$, and $\tau^+\tau^-$. The 68%

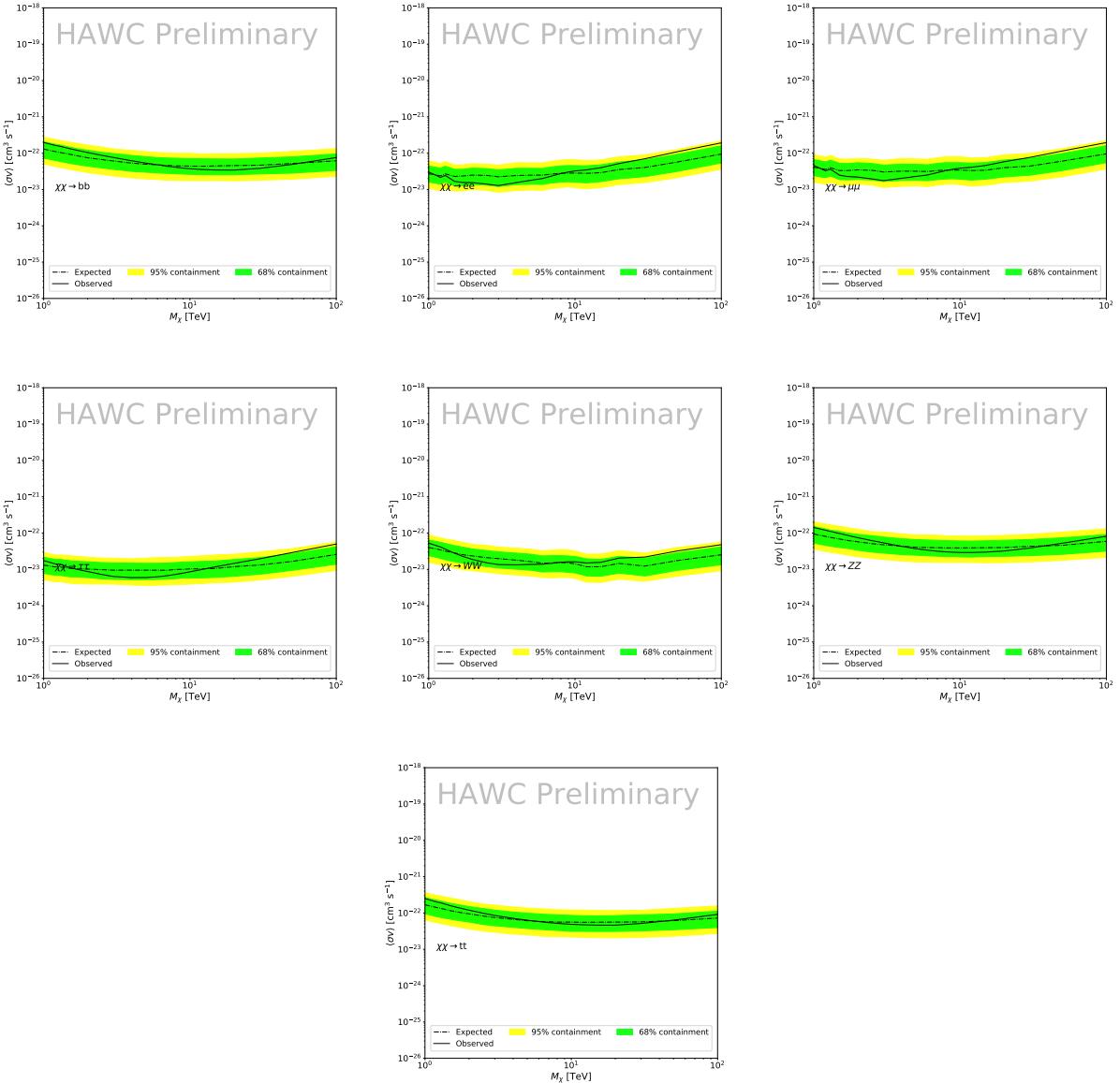


Figure 5.7 HAWC Brazil bands at 95% confidence level on $\langle\sigma v\rangle$ versus DM mass for seven annihilation channels with J -factors from GS [69]. The solid line represents the combined limit from 13 dSphs. The dashed line is the expected limit. The green band is the 68% containment. The yellow band is the 95% containment.

1333 and 95% containment bands are produced from 300 Poisson realizations of the null hypothesis
 1334 corresponding to each of the combined datasets. These 300 realizations are combined identically
 1335 to dSph observations. The containment bands and the median are extracted from the distribution
 1336 of resulting limits on the null hypothesis. These 300 realizations are obtained either by fast simu-
 1337 lations of the OFF observations, for H.E.S.S., MAGIC, VERITAS, and HAWC, or taken from real

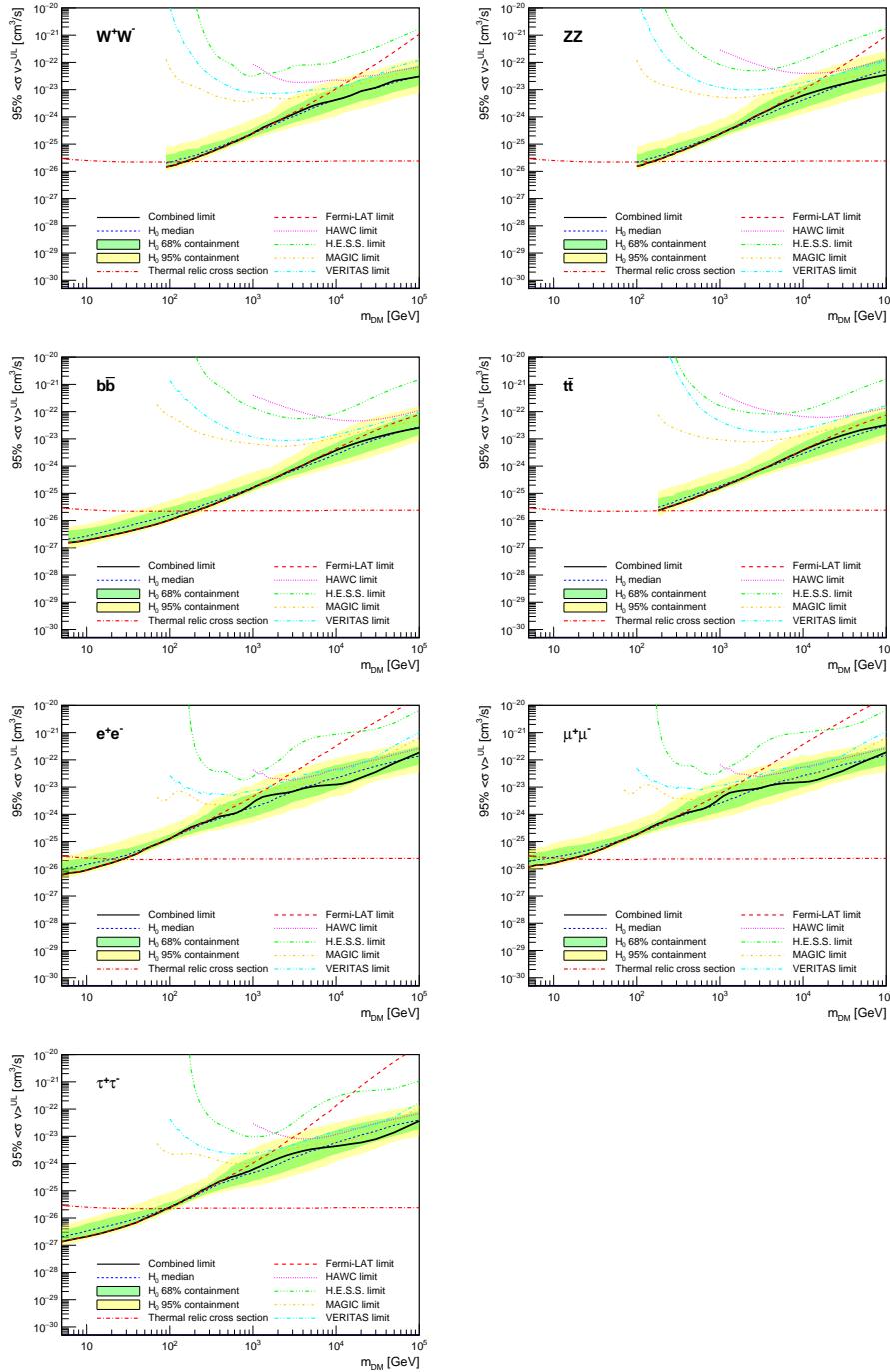


Figure 5.8 Upper limits at 95% confidence level on $\langle\sigma v\rangle$ in function of the DM mass for eight annihilation channels, using the set of J factors from Ref. [69] (\mathcal{GS} set in Table 5.1). The black solid line represents the observed combined limit, the black dashed line is the median of the null hypothesis corresponding to the expected limit, while the green and yellow bands show the 68% and 95% containment bands. Combined upper limits for each individual detector are also indicated as solid, colored lines. The value of the thermal relic cross-section in function of the DM mass is given as the red dotted-dashed line [70].

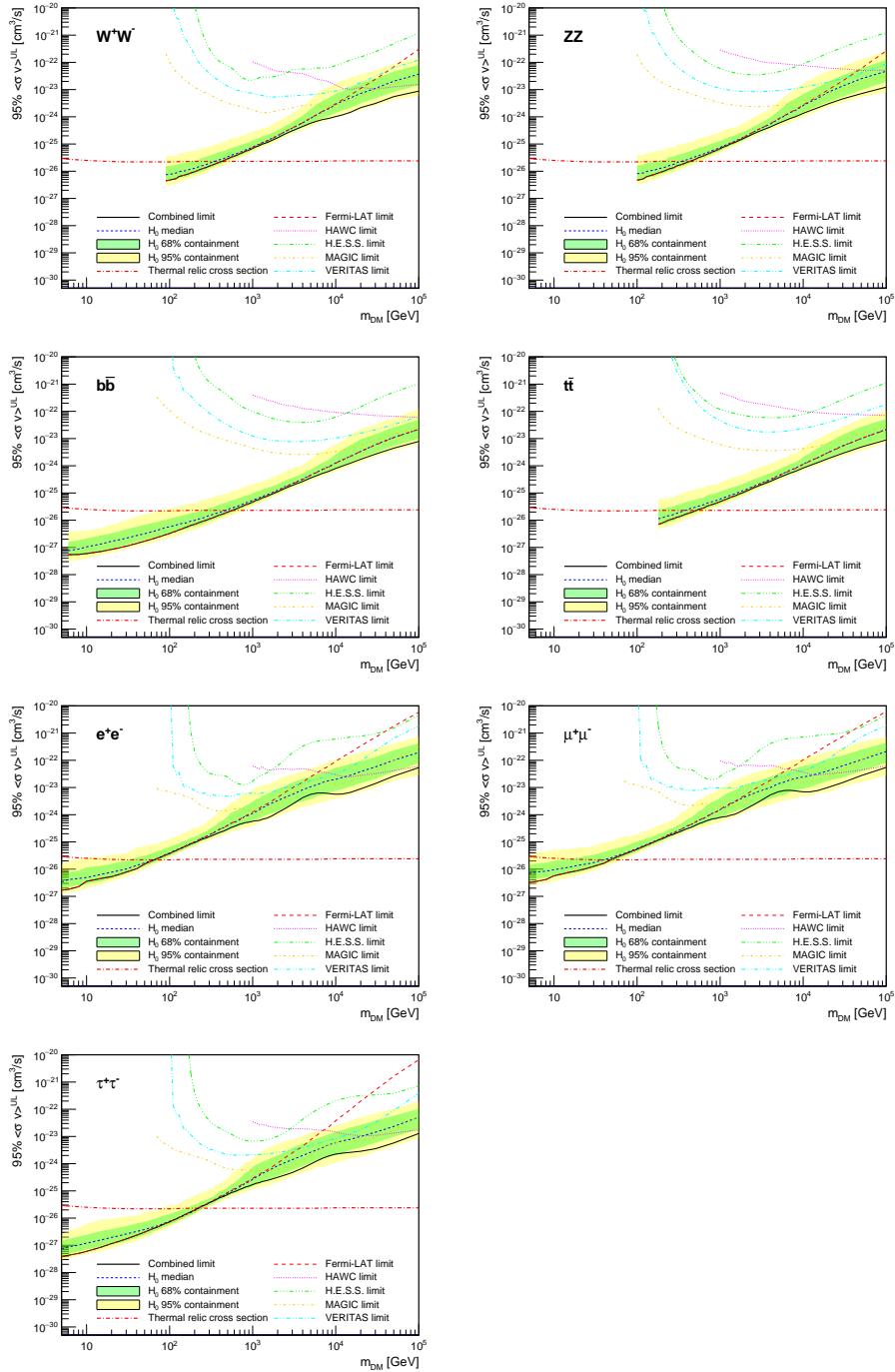


Figure 5.9 Same as Fig. 5.8, using the set of J factors from Ref. [63, 71] (\mathcal{B} set in Table 5.1).

1338 observations of empty fields of view in the case of Fermi-LAT [64, 72, 73].

1339 The obtained limits are shown in Figure 5.8 for the \mathcal{GS} set of J -factors [69] and in Figure 5.9
1340 for the \mathcal{B} set of J -factors [63, 71]. The combined limits are presented with their 68% and 95%
1341 containment bands, and are expected to be close to the median limit when no signal is present.

1342 We observe agreement with the null hypothesis for all channels, within 2σ standard deviations,
1343 between the observed limits and the expectations given by the median limits. Limits obtained from
1344 each detector are also indicated in the figures, where limits for all dSphs observed by the specific
1345 instrument have been combined.

1346 Below ~ 300 GeV, the *Fermi*-LAT dominates the DM limits for all annihilation channels. From
1347 ~ 300 GeV to ~ 2 TeV, *Fermi*-LAT continues to dominate for the hadronic and bosonic DM channels,
1348 yet the IACTs (H.E.S.S., MAGIC, and VERITAS) and *Fermi*-LAT all contribute to the limit for
1349 leptonic DM channels. For DM masses between ~ 2 TeV to ~ 10 TeV, the IACTs dominate leptonic
1350 DM annihilation channels, whereas both the *Fermi*-LAT and the IACTs dominate bosonic and
1351 hadronic DM annihilation channels. From ~ 10 TeV to ~ 100 TeV, both the IACTs and HAWC
1352 contribute significantly to the leptonic DM limit. For hadronic and bosonic DM, the IACTs and
1353 *Fermi*-LAT both contribute strongly.

1354 We notice that the limits computed using the \mathcal{B} set of J -factor are always better compared to the
1355 ones calculated with the \mathcal{GS} set. For the W^+W^- , Z^+Z^- , $b\bar{b}$, and $t\bar{t}$ channels, the ratio between the
1356 limits computed with the two sets of J -factor is varying between a factor of ~ 3 and ~ 5 depending
1357 on the energy, with the largest ratio around 10 TeV. For the channels e^+e^- , $\mu^+\mu^-$, and $\tau^+\tau^-$, the
1358 ratio lies between ~ 2 to ~ 6 , being maximum around 1 TeV. Examining Figure 5.16 and Figure 5.17
1359 in Section 5.8, these differences are explained by the fact that the \mathcal{B} set provides higher J -factors
1360 for the majority of the studied dSphs, with the notable exception of Segue I. The variation on the
1361 ratio of the limits for the two sets is due to different dSph dominating the limits depending on the
1362 energy. One set, \mathcal{B} , pushes the range of which thermal cross-section which can be excluded to
1363 higher mass. This comparison demonstrates the magnitude of systematic uncertainties associated
1364 with the choice of the J -factor calculation. The \mathcal{GS} and \mathcal{B} sets present a difference in the limits for
1365 all channels of about This difference is explained, see Figure 5.16 and Figure 5.17, by the fact that
1366 the \mathcal{B} set provides higher J -factors for all dSph except for Segue I.

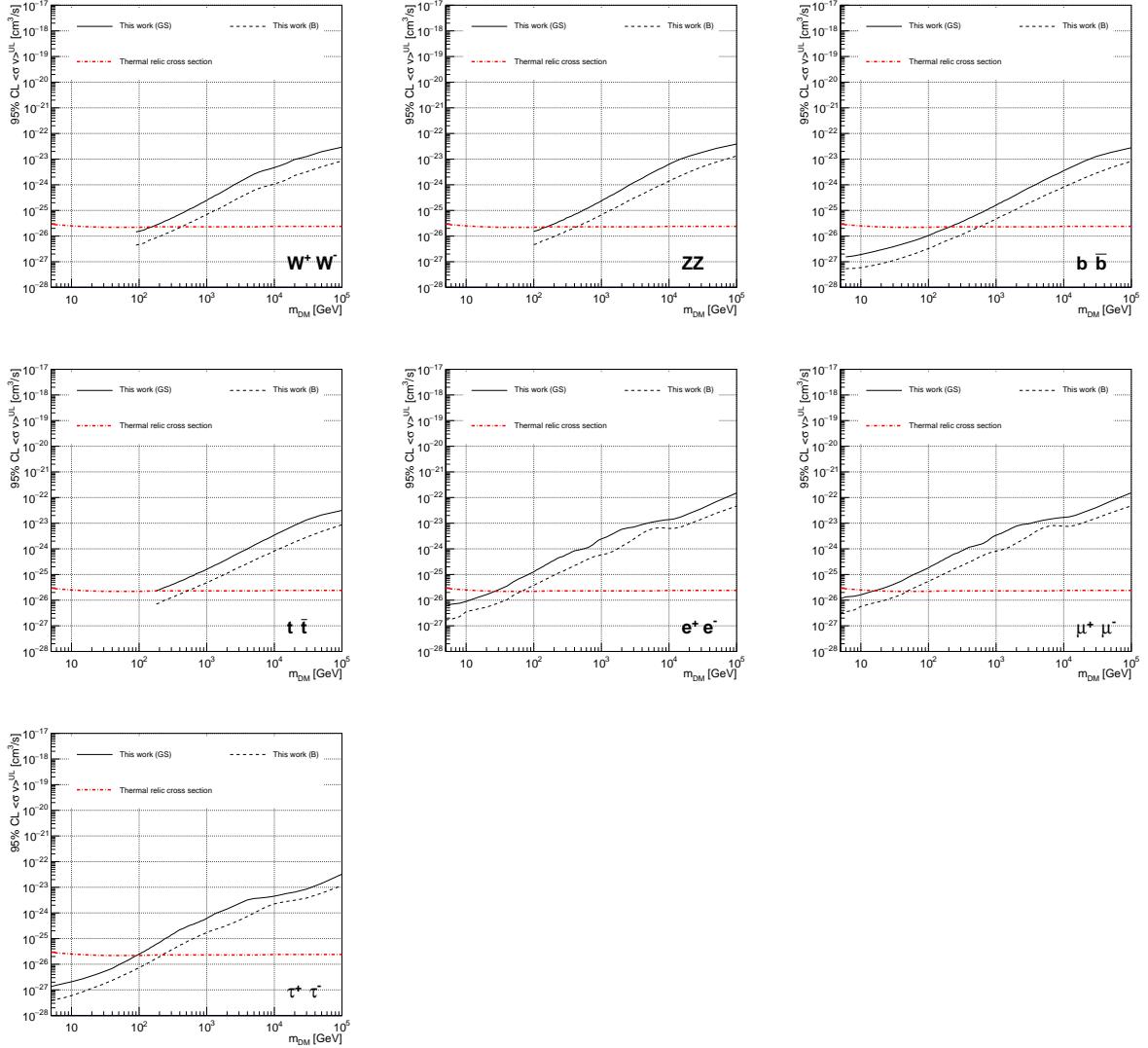


Figure 5.10 Comparisons of the combined limits at 95% confidence level for each of the eight annihilation channels when using the J factors from Ref. [69] (\mathcal{GS} set in Table 5.1), plain lines, and the J factor from Ref. [63, 71] (\mathcal{B} set in Table 5.1), dashed lines. The cross-section given by the thermal relic is also indicated [70].

1367 5.7 HAWC Systematics

1368 5.7.1 Inverse Compton Scattering

1369 The DM-DM annihilation channels produce many high energy electrons regardless of the
 1370 primary annihilation channel. These high energy electrons can produce high energy gamma-rays
 1371 through Inverse Compton Scattering (ICS). If this effect is strong, it would change the morphology
 1372 of the source and increase the total expected gamma-ray counts from any source. The PPPC [58]

1373 provides tools in Mathematica for calculating the impact of ICS for an arbitrary location in the
1374 sky for a specified annihilation channel. We calculated the change in gamma-ray counts for DM
1375 annihilation to primary $e\bar{e}$ for RA and Dec corresponding to Segue1 and Coma Berenices. These
1376 dSphs were chosen because they are the strongest contributors to the limit. $e\bar{e}$ was selected because
1377 it would have the largest number of high energy electrons. The effect was found to be on the order
1378 of 10^{-7} on the gamma-ray spectrum. As a result, this systematic is not considered in our analysis.

1379 **5.7.2 Point Source Versus Extended Source Limits**

1380 The previous DM search toward dSph approximated the dSphs as point sources [60]. In
1381 this analysis, the dSphs are implemented as extended with J-factor distributions following those
1382 produced by [69]. The resolution of the cited map is much finer than HAWC's angular resolution.
1383 The vast majority of the J-factor distribution is represented on the central HAWC pixel of the dSph
1384 spatial map. However, the neighboring 8 pixels are not negligible and contribute to our limit.

1385 Figure 5.11 shows a substantial improvement to the limit for Segue1. Fig. 5.12 however showed
1386 identical limits. These disparities are best explained by the relative difference in their J-Factors.
1387 Both dSphs pass almost overhead the HAWC detector, however Segue1 has the larger J-Factor
1388 between the two. Adjacent pixels to the central pixel will therefore contribute to the limits. This is
1389 the case for other dSph that are closer to the zenith of the HAWC detector.

1390 Comparison plots for all sources and the combined limit can be found in the sandbox for the
1391 Glory Duck project.

1392 **5.7.3 Impact of Pointing Systematic**

1393 During the analysis it was discovered that directional reconstruction of gamma-rays had a
1394 systematic bias at large zenith angles. Slides describing this systematic can be found [here](#). Shown
1395 on the presentation is dependence on the pointing systematic on declination. New spatial profiles
1396 were generated for every dSph and limits were computed for the adjusted declination.

1397 Section 5.7.3 demonstrates the impact of this systematic for all DM annihilation channels
1398 studied by HAWC. The impact is a tiny improvement, yet mostly identical, to the combined limits.

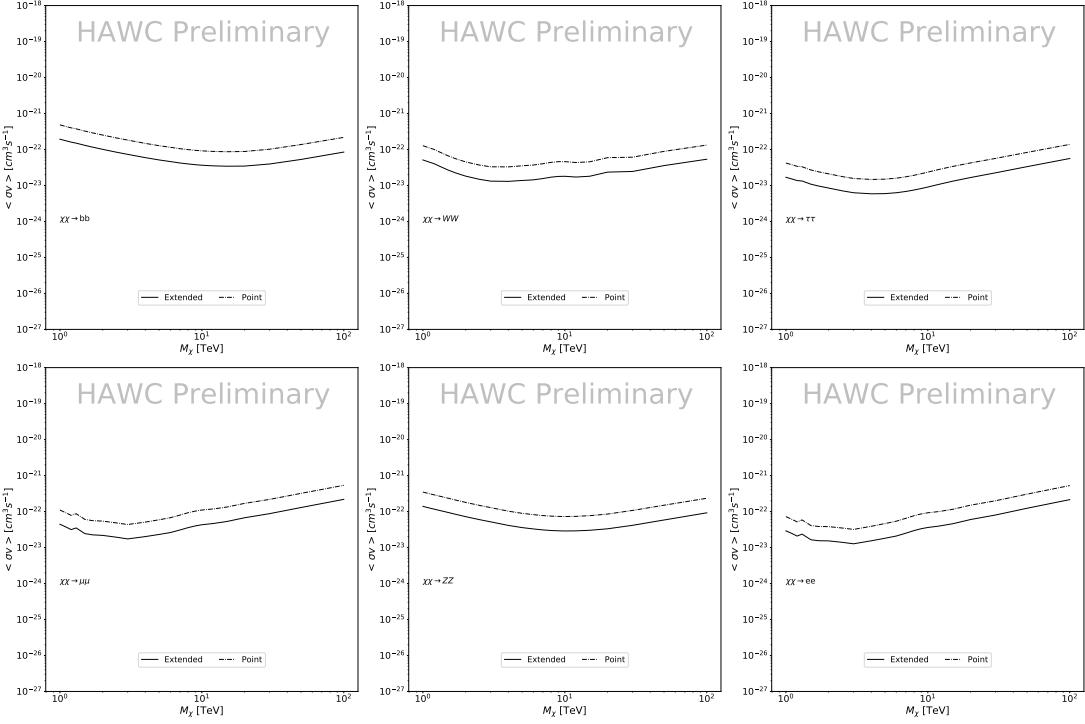


Figure 5.11 Comparisons of the combined limits at 95% confidence level for a point source analysis and extended source using [69] \mathcal{GS} J-factor distributions and PPPC [58] annihilation spectra. Shown are the limits for Segue1 which will have the most significant impact on the combined limit. 6 of the 7 DM annihilation channels are shown. Solid lines are extended source studies. Dashed lines are point source studies. Overall, the extended source analysis improves the limit by a factor of 2.

1399 5.8 J-factor distributions

1400 5.8.1 Numerical integration of \mathcal{GS} maps

1401 It was discovered well after the HAWC analysis was completed that the published tables from
 1402 \mathcal{GS} [59] quoted median J -factors were computed in a non-trivial manner. The assumption myself
 1403 and collaborators had been that the published tables represented the J -factor as a function of θ for
 1404 the best global fit model on a per-source basis. However, this is not the case. Instead, what is
 1405 published are the best fit model for each dwarf that only considers stars up to the angular separation
 1406 θ . Therefore, the model is changing for each value of θ for each dwarf. Yet, the introduced features
 1407 from unique models at each θ are much smaller than the angular resolution of HAWC. It is not
 1408 expected for these effects to impact the limits and TS greatly as a result.

1409 Median J -factor model profiles were provided by the authors. New maps were generated

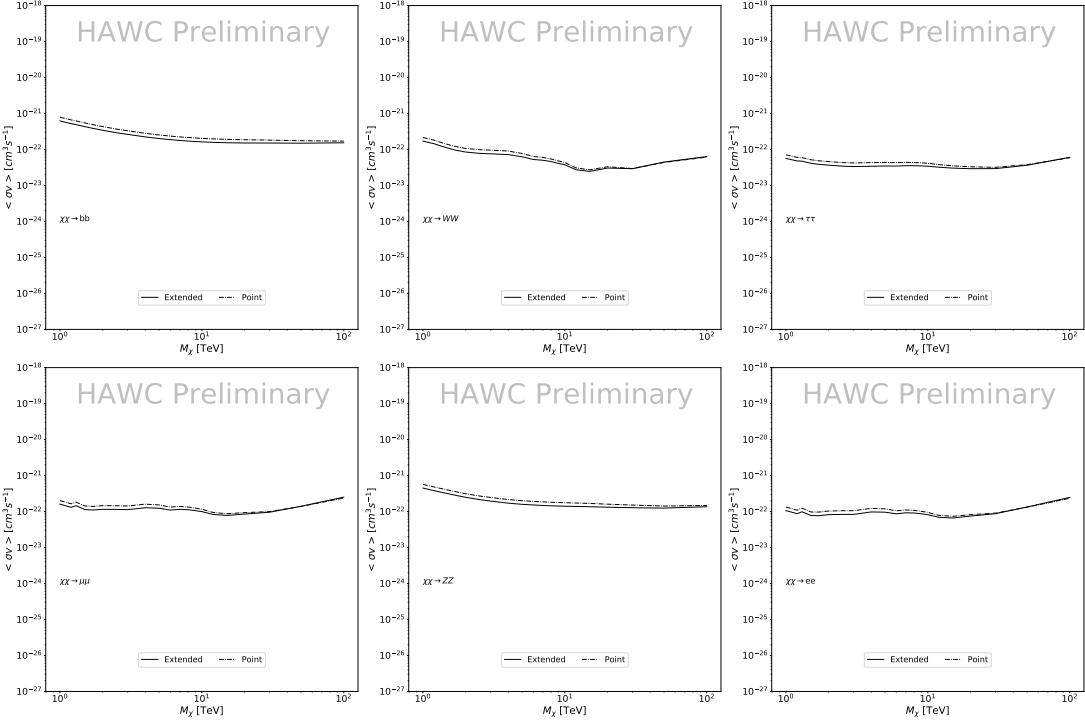


Figure 5.12 Same as Fig. 5.11 on Coma Berenices. This dSph also contributes significantly to the limit. The limits are identical in this case.

and analyzed for Segue1 and Coma Berenices. Figure 5.14 shows the differential between maps generated with the method from Section 5.8.1 and from the authors of [59]. These maps were reanalyzed for all SM DM annihilation channels. Upper limits for these channels are shown in Figure 5.15

From Figure 5.15, we can see that the impact of these model difference was no substantial. The observed impact was a fractional effect which is much smaller than the impact from selecting another DM spatial distribution model as was shown in Figure 5.10.

5.8.2 \mathcal{GS} Versus \mathcal{B} spatial models

We show in this appendix a comparison between the J -factors computed by Geringer-Sameth *et al.* [69] (the \mathcal{GS} set) and the ones computed by Bonnivard *et al.* [63, 71] (the \mathcal{B} set). The \mathcal{GS} J -factors are computed through a Jeans analysis of the kinematic stellar data of the selected dSphs, assuming a dynamic equilibrium and a spherical symmetry for the dSphs. They adopted the generalized DM density distribution, known as Zhao-Hernquist, introduced by [61], carrying

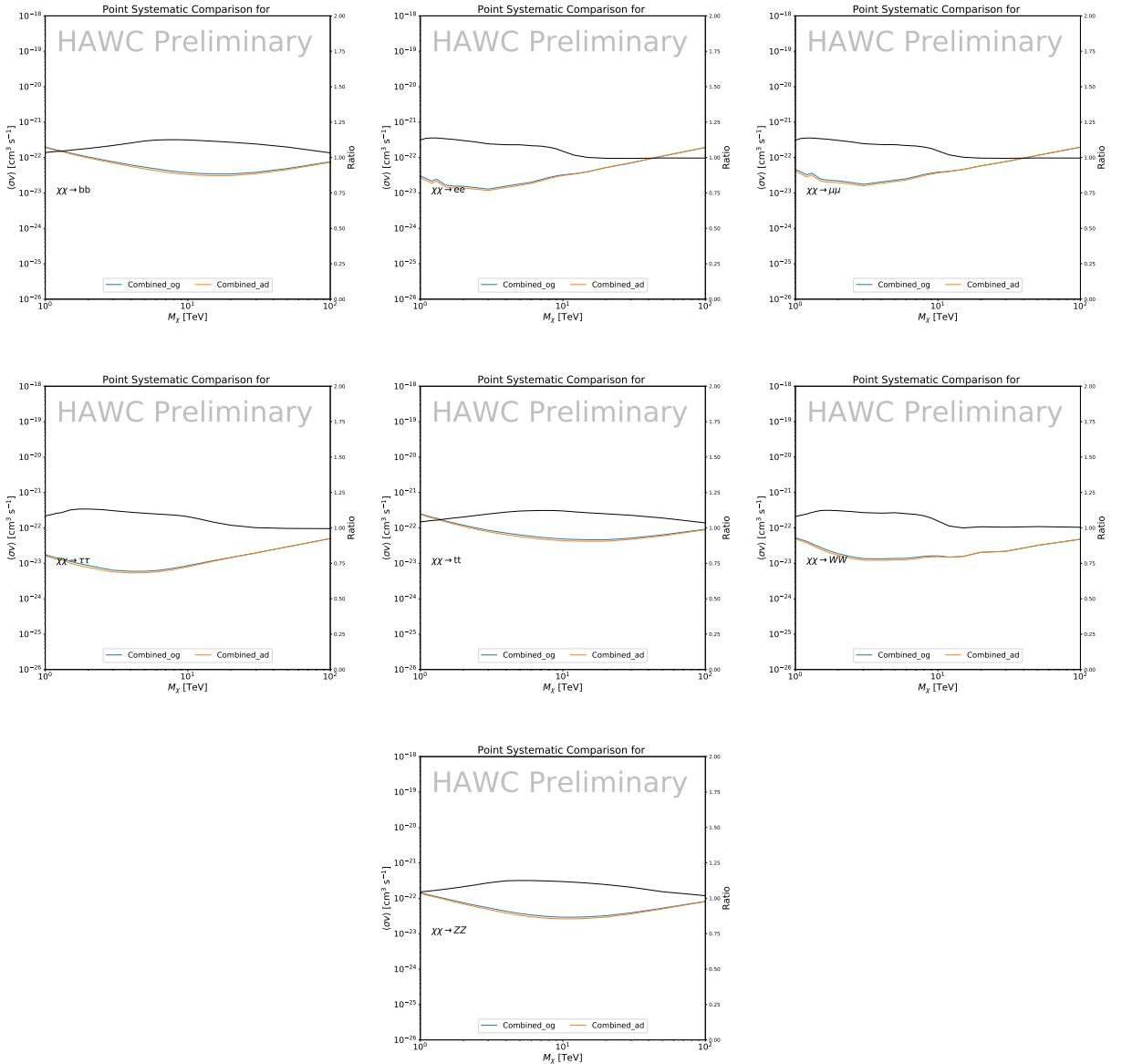


Figure 5.13 Comparison of combined limits when correcting for HAWC's pointing systematic. All DM annihilation channels are shown. The solid black line is the ratio between published limit to the declination corrected limit. The blue solid line or "Combined_og" represented the limits computed for Glory Duck. The solid orange line or "Combined_ad" represented the limits computed after correcting for the pointing systematic.

1423 three additional index parameters to describe the inner and outer slopes, and the break of the
 1424 density profile. Such a profile parametrization allows the reduction of the theoretical bias from
 1425 the choice of a specific radial dependency on the kinematic data. In other words, the increase of
 1426 free parameters with the use of the Zhao-Hernquist profile allows a better description of the mass

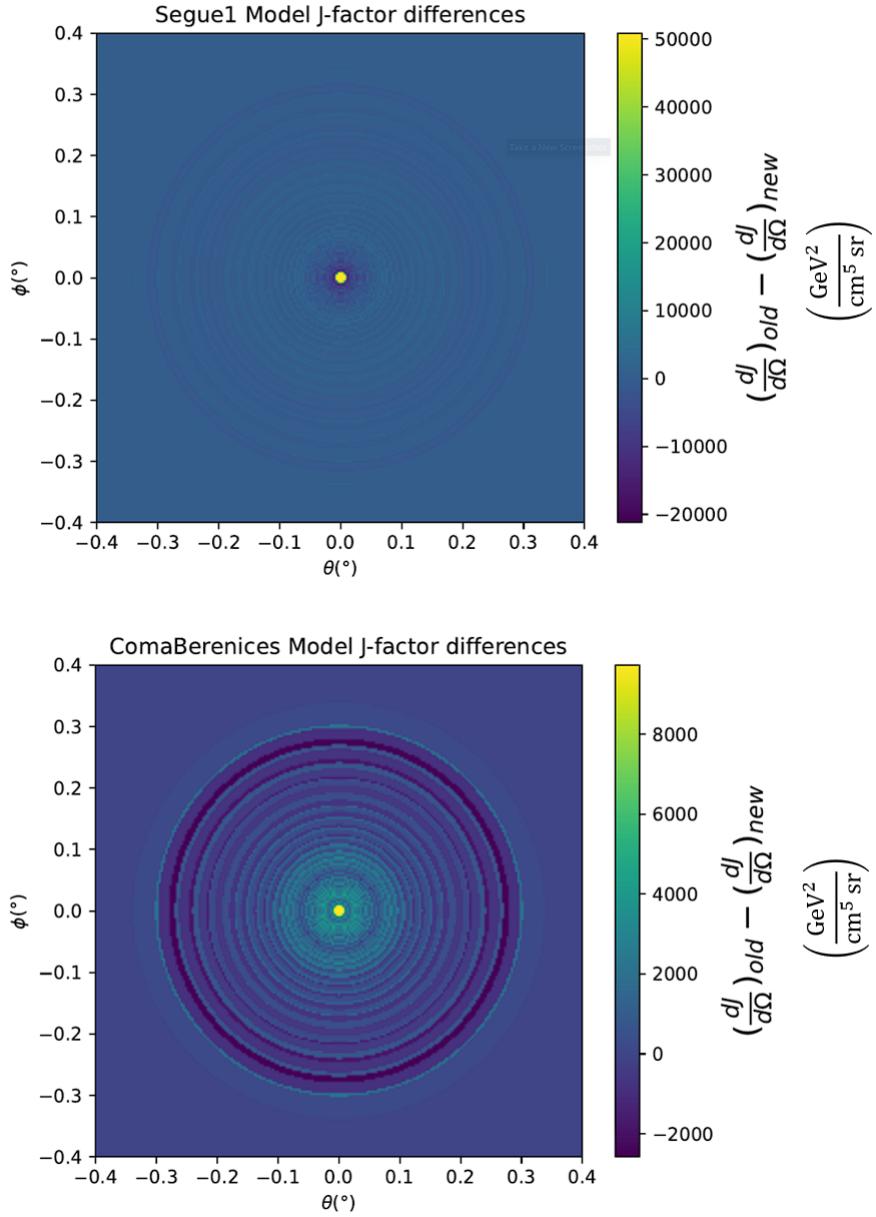


Figure 5.14 Differential map of dJ/Ω from model built in Section 5.8.1 and profiles provided directly from authors. (Top) Differential from Segue1. (bottom) Differential from Coma Berenices. Note that their scales are not the same. Segue1 shows the deepest discrepancies which is congruent with its large uncertainties. Both models show anuli where unique models become apparent.

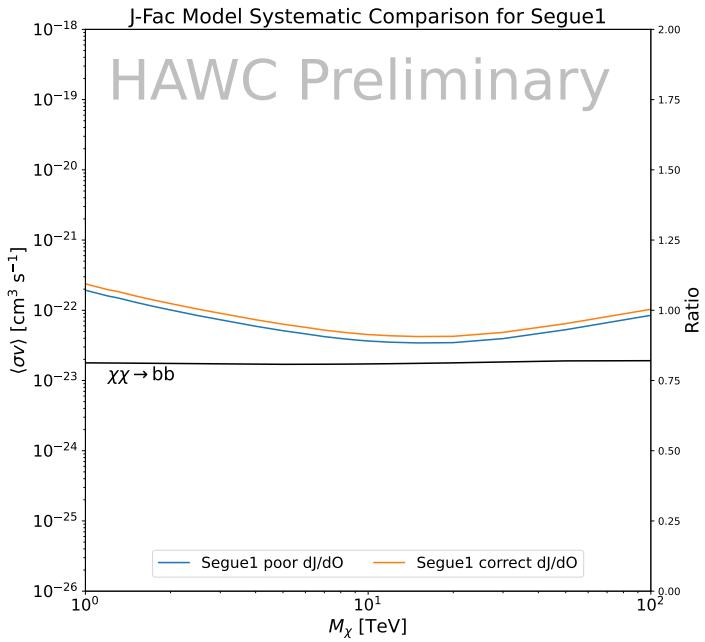
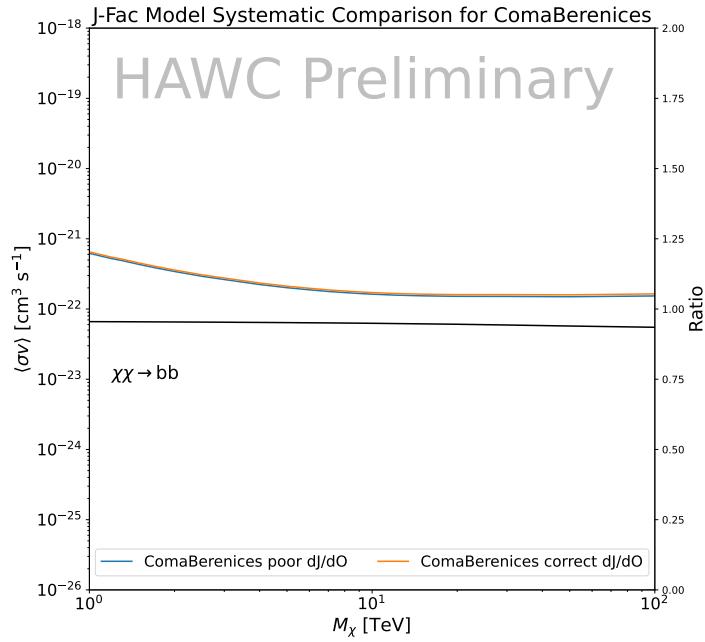


Figure 5.15 HAWC limits for Coma Berenices (top) and Segue1 (bottom) for two different map sets. Blue lines are limits calculated on maps with poor model representation. Orange lines are limits calculated on spatial profiles provided by the authors of [59]. Black line is the ratio of the poor spatial model limits to the corrected spatial models. The left y-axis measures $\langle \sigma v \rangle$ for the blue and orange lines. The right y-axis measures the ratio and is unitless.

1427 density distribution of dark matter.

1428 In addition, a constant velocity anisotropy profile and a Plummer light profile [74] for the stellar
1429 distribution were assumed. The velocity anisotropy profile depends on the radial and tangential
1430 velocity dispersion. However, its determination remains challenging since only the line-of-sight
1431 velocity dispersion can be derived from velocity measurements. Therefore, the parametrization of
1432 the anisotropy profile is obtained from simulated halos (see [75] for more details). They provide the
1433 values of the J -factors of regions extending to various angular radius up to the outermost member
1434 star.

1435 The \mathcal{B} J -factors were computed through a Jeans analysis taking into account the systematic
1436 uncertainties induced by the DM profile parametrization, the radial velocity anisotropy profile, and
1437 the triaxiality of the halo of the dwarf galaxies. They performed a more complete study of the dSph
1438 kinematics and dynamics than \mathcal{GS} for the determination of the J -factor. Conservative values of the
1439 J -factors where obtained using an Einasto DM density profile [76], a realistic anisotropy profile
1440 known as the Baes & Van Hese profile [77] which takes into account that the inner regions can be
1441 significantly non-isotropic, and a Zhao-Hernquist light profile [61].

1442 For both sets, J -factor values are provided for all dSphs as a function of the radius of the
1443 integration region [69, 63, 71]. Table 5.1 shows the heliocentric distance and Galactic coordinates
1444 of the twenty dSphs, together with the two sets of J -factor values integrated up to the outermost
1445 observed star for \mathcal{GS} and the tidal radius for \mathcal{B} . Both J -factor sets were derived through a Jeans
1446 analysis based on the same kinematic data, except for Draco where the measurements of [78] have
1447 been adopted in the computation of the \mathcal{B} value. The computations for producing the \mathcal{GS} and \mathcal{B}
1448 samples differ in the choice of the DM density, velocity anisotropy, and light profiles, for which the
1449 set \mathcal{B} takes into account some sources of systematic uncertainties.

1450 Figure 5.16 and Figure 5.17 show the comparisons for the J -factor versus the angular radius
1451 for each of the 20 dSphs used in this study. The uncertainties provided by the authors are also
1452 indicated in the figures. For the \mathcal{GS} set, the computation stops at the angular radius corresponding
1453 to the outermost observed star, while for the \mathcal{B} set, the computation stops at the angular radius

1454 corresponding to the tidal radius.

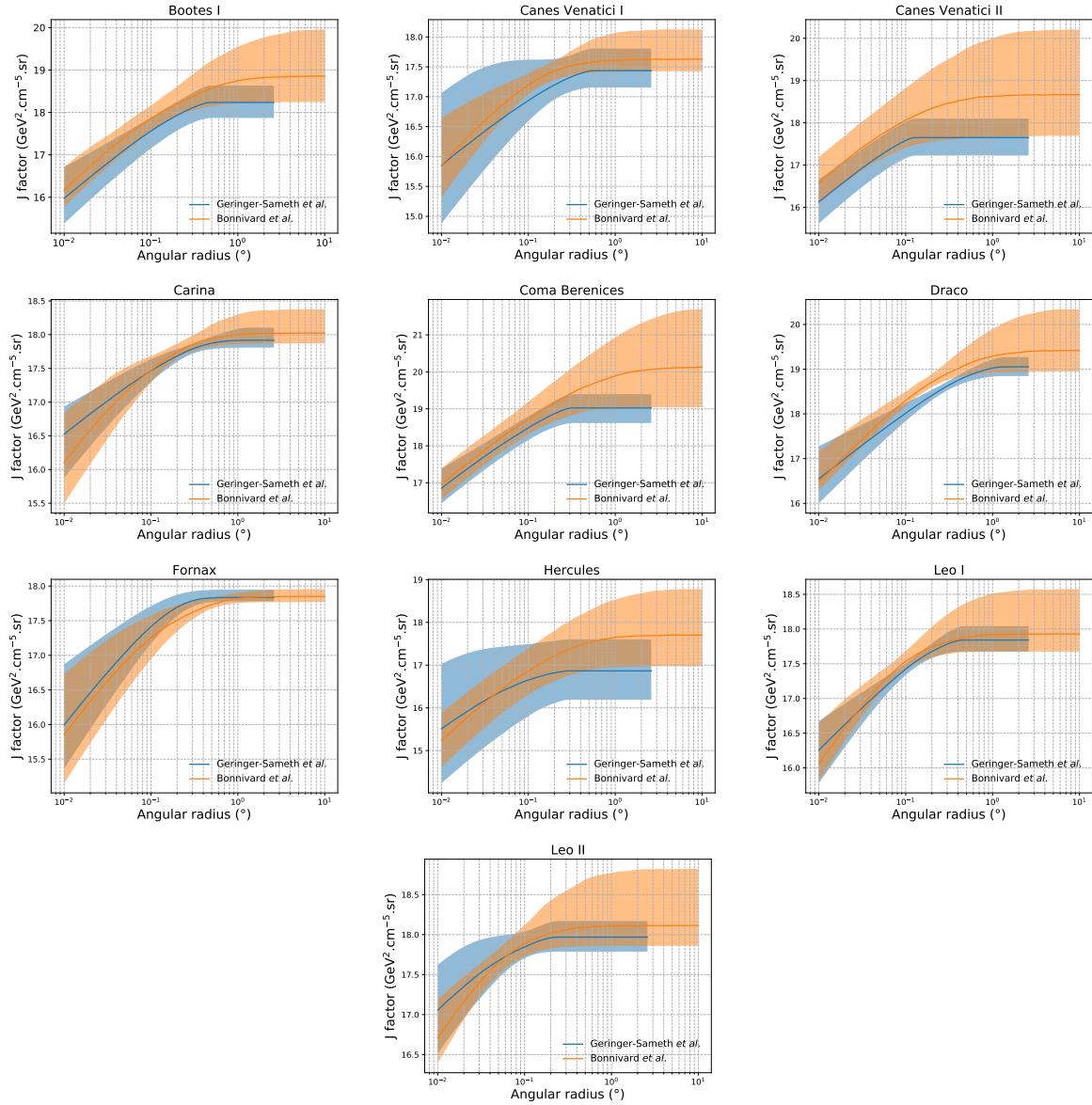


Figure 5.16 Comparisons between the J -factors versus the angular radius for the computation of J factors from Ref. [69] (\mathcal{GS} set in Table 5.1) in blue and for the computation from Ref. [63, 71] (\mathcal{B} set in Tab. 5.1) in orange. The solid lines represent the central value of the J -factors while the shaded regions correspond to the 1σ standard deviation.

1455 5.9 Discussion and Conclusions

1456 In this multi-instrument analysis, we have used observations of 20 dSphs from the gamma-ray
 1457 telescopes Fermi-LAT, H.E.S.S., MAGIC, VERITAS, and HAWC to perform a collective DM
 1458 search annihilation signals. The data were combined across sources and detectors to significantly

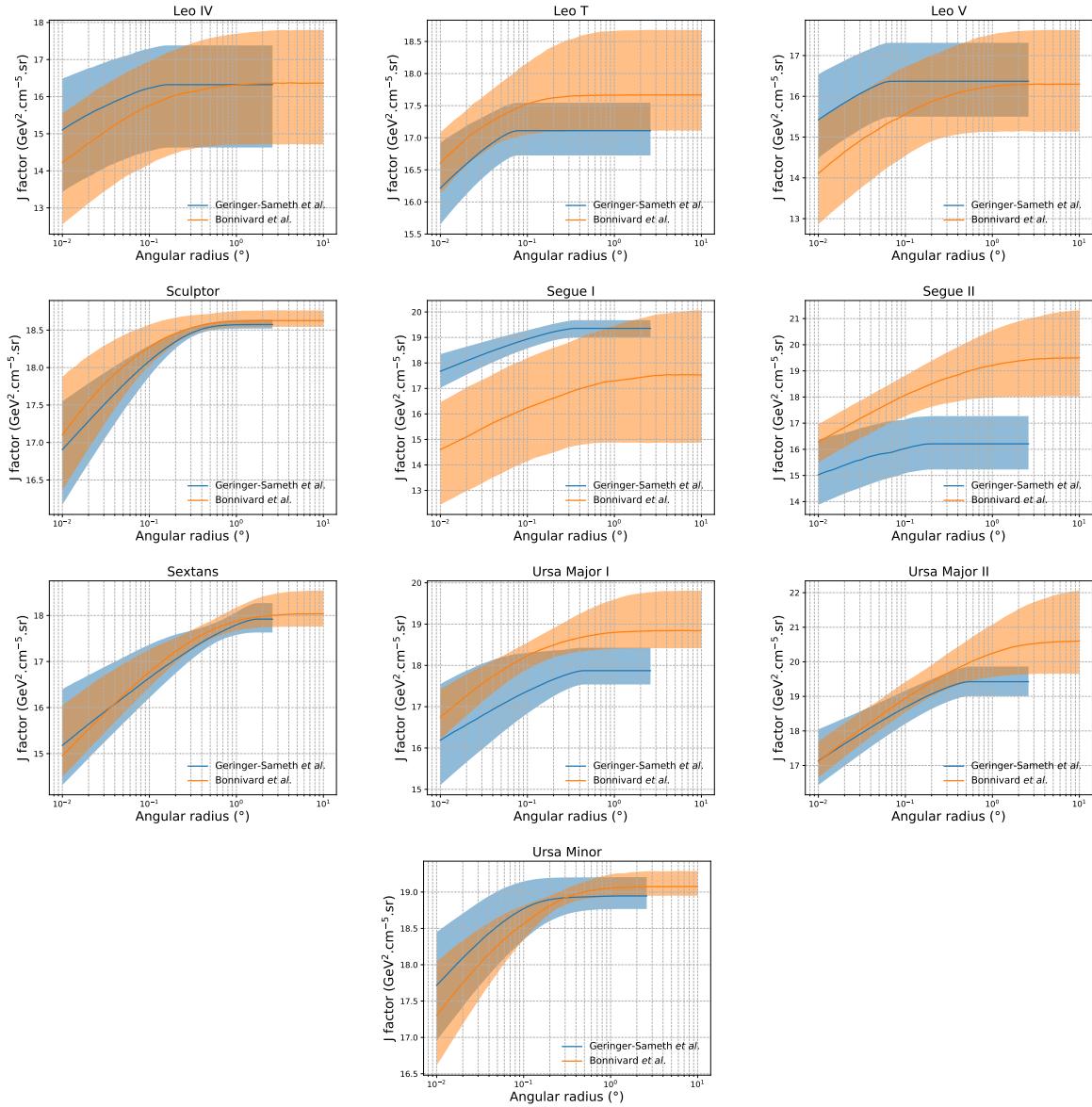


Figure 5.17 Comparisons between the J -factors versus the angular radius for the computation of J factors from Ref. [69] (\mathcal{GS} set in Tab. 5.1) in blue and for the computation from Ref. [63, 71] (\mathcal{B} set in Tab. 5.1) in orange. The solid lines represent the central value of the J -factors while the shaded regions correspond to the 1σ standard deviation.

1459 increase the sensitivity of the search. We have observed no significant deviation from the null, no
 1460 DM hypothesis, and so present our results in terms of upper limits on the annihilation cross-section
 1461 for seven potential DM annihilation channels.
 1462 Fermi-LAT brings the most stringent constraints for continuum channels below approximately
 1463 1 TeV. The remaining detectors dominate at higher energies. Overall, for multi-TeV DM mass,

1464 the combined DM constraints from all five telescopes are 2-3 times stronger than any individual
1465 telescope for multi-TeV DM.

1466 Derived from observations of many dSphs, our results produce robust limits given the DM
1467 content of the dSphs is relatively well constrained. The obtained limits span the largest mass
1468 range of any WIMP DM search. Our combined analysis improves the sensitivity over previously
1469 published results from each detector which produces the most stringent limits on DM annihilation
1470 from dSphs. These results are based on deep exposures of the most promising known dSphs with
1471 the currently most sensitive gamma-ray instruments. Therefore, our results constitute a legacy of
1472 a generation of gamma-ray instruments on WIMP DM searches towards dSphs. Our results will
1473 remain the reference in the field until a new generation of more sensitive gamma-ray instruments
1474 begin operations, or until new dSphs with higher J -factors are discovered.

1475 This analysis serves as a proof of concept for future multi-instrument and multi-messenger
1476 combination analyses. With this collaborative effort, we have managed to sample over four orders
1477 in magnitude in gamma-ray energies with distinct observational techniques. Determining the nature
1478 of DM continues to be an elusive and difficult problem. Larger datasets with diverse measurement
1479 techniques could be essential to tackling the DM problem. A future collaboration using similar
1480 techniques as the ones described in this paper could grow even beyond gamma rays. The models we
1481 used for this study include annihilation channels with neutrinos in the final state. Advanced studies
1482 could aim to merge our results with those from neutrino observatories with large data sets. Efforts
1483 are already underway to add data from the IceCube, ANTARES, and KM3NeT observatories to
1484 these gamma-ray results.

1485 From this work, a selection of the best candidates for observations, according to the latest
1486 knowledge on stellar dynamics and modelling techniques for the derivation of the J -factors on
1487 the potential dSphs targets, is highly desirable at the time that new experiments are starting their
1488 dark matter programs using dSphs. Given the systematic uncertainty inherent to the derivation of
1489 the J -factors, an informed observational strategy would be to select both objects with the highest
1490 J -factors that could lead to DM signal detection, and objects with robust J -factor predictions, i.e.

1491 with kinematic measurements on many bright stars, which would strengthen the DM interpretation
1492 reliability of the observation outcome.

1493 This analysis combines data from multiple telescopes to produce strong constraints on astro-
1494 physical objects. From this perspective, these methods can be applied beyond just DM searches.
1495 Almost every astrophysical study can benefit from multi-telescope, multi-wavelength gamma-ray
1496 studies. We have enabled these telescopes to study the cosmos with greater precision and detail.
1497 Many astrophysical searches can benefit from multi-instrument gamma-ray studies, for which our
1498 analysis lays the foundation.

CHAPTER 6

1499 MULTITHREADING HAWC ANALYSES FOR DARK MATTER SEARCHES

1500 6.1 Introduction

1501 HAWC’s current software suite, plugins to 3ML and HAL [68, 34], do not fully utilize compu-
1502 tational advancements of recent decades. Said advancements include the proliferation of Graphical
1503 Processing Units (GPUs), and multithreading on multicore processors. The analysis described in
1504 chapter 5 took up to 3 months of wall time waiting for the full gambit of data analysis and simulation
1505 of background to compute. Additionally, with the updated 2D energy binning scheme, f_{hit} and
1506 Neural Network (NN), the time needed to compute expected to grow. Although excessive comput-
1507 ing time was, in part, from an intense use of a shared computing cluster, it was evident that there
1508 was room for improvement. In HAWC’s next generation dSph DM search, I decided to develop
1509 codes that would utilize the multicore processors on modern high performance computing clusters.
1510 The results of this work are featured in this chapter and brought a human timing improvement to
1511 computation that scales approximately as $1/N$ where N is the number of threads.

1512 6.2 Dataset and Background

1513 This section enumerates the data and background methods used for HAWC’s multithreaded
1514 study of dSphs. Section 6.2.1 and Section 6.2.2 are most useful for fellow HAWC collaborators
1515 looking to replicate a multithreaded dSph DM search.

1516 6.2.1 Itemized HAWC files

1517 These files are only available withing HAWC’s internal documentation and collaborators. They
1518 are not meant for public access, and are presented here so that HAWC collaborators can reproduce
1519 results accurately.

- 1520 • Detector Resolution: `refit-Pass5-Final-NN-detRes-zenith-dependent.root`
- 1521 • Data Map: `Pass5-Final-NN-maptree-ch103-ch1349-zenith-dependent.root`
- 1522 • Spectral Dictionary: `HDMspectra_dict_gamma.npy`

1523 **6.2.2 Software Tools and Development**

1524 This analysis was performed using HAL and 3ML [34, 57] in Python3. I built software
1525 in collaboration with Michael Martin and Letrell Harris to implement the *Dark Matter Spectra*
1526 *from the Electroweak to the Planck Scale* (HDM) [79] and dSphs spatial model from [80] for
1527 HAWC analysis. A NumPy dictionary of HDM, `HDMspectra_dict_gamma.npy`, was made for
1528 portability within the collaboration. These dictionaries were generated from the [git repository](#) [79].
1529 The analysis was performed using the Neural Network energy estimator for Pass 5.F. A description
1530 of this estimator was provided in chapter 3. [TODO: Define a subsection when it's written](#), and its
1531 key, relevant improvements are an improved energy estimation and improved sensitivities at higher
1532 zenith angles. All other software used for data analysis, DM profile generation, and job submission
1533 to SLURM are also kept in my sandbox in the [Dark Matter HAWC](#) project. The above repository
1534 also incorporates the model inputs used previously in Glory Duck, described in chapter 5, so Glory
1535 Duck remains compatible with modern software.

1536 **6.2.3 Data Set and Background Description**

1537 The HAWC data maps used for this analysis contain 2565 days of data between runs 2104 and
1538 7476. They were generated from pass 5.f reconstruction. The analysis is performed using the NN
1539 energy estimator with bin list:

1540 `B1C0Ea, B1C0Eb, B1C0Ec, B1C0Ed, B1C0Ee, B2C0Ea, B2C0Eb, B2C0Ec, B2C0Ed, B2C0Ee,`
1541 `B3C0Ea, B3C0Eb, B3C0Ec, B3C0Ed, B3C0Ee, B3C0Ef, B4C0Eb, B4C0Ec, B4C0Ed, B4C0Ee,`
1542 `B4C0Ef, B5C0Ec, B5C0Ed, B5C0Ee, B5C0Ef, B5C0Eg, B6C0Ed, B6C0Ee, B6C0Ef, B6C0Eg,`
1543 `B6C0Eh, B7C0Ee, B7C0Ef, B7C0Eg, B7C0Eh, B7C0Ei, B8C0Ee, B8C0Ef, B8C0Eg, B8C0Eh,`
1544 `B8C0Ei, B8C0Ej, B9C0Ef, B9C0Eg, B9C0Eh, B9C0Ei, B9C0Ej, B10C0Eg, B10C0Eh,`
1545 `B10C0Ei, B10C0Ej, B10C0Ek, B10C0El`

1546 Bin 0 was excluded as it has substantial hadronic contamination and poor angular resolution.

1547 Background considerations and source selection was identical to Section 5.2.3, and no additional
1548 arguments are provided here. Many of the HAWC systematics explored in Section 5.7 also apply

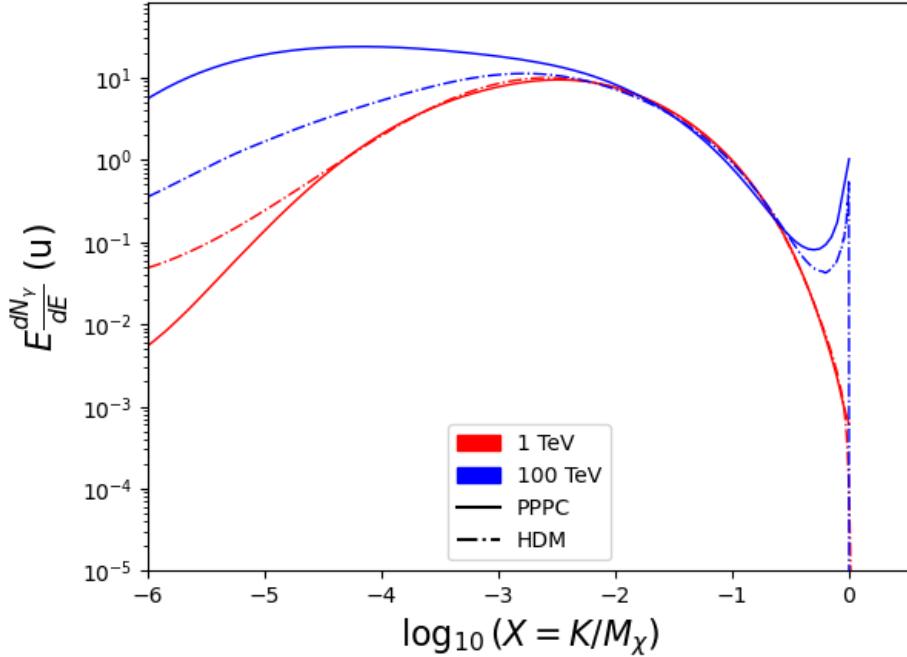


Figure 6.1 Spectral hypotheses from PPPC [58] and HDM [79] for DM annihilation: $\chi\chi \rightarrow W^-W^+$. Solid lines are spectral models with EW corrections from the PPPC. Dash-dot lines are spectral models from HDM. Red lines are models for $M_\chi = 1$ TeV. Blue lines represent models for $M_\chi = 100$ TeV.

1549 for this DM search and are not added upon here.

1550 **6.3 Analysis**

1551 The analysis and its systematics are almost identical to Section 5.3. Importantly, we use the
 1552 same **TODO: fix this ref** Equation (5.1) and Equation (5.2) for estimating the gamma-ray flux at
 1553 HAWC from our sources.

1554 **6.3.1 $\frac{dN_\gamma}{dE_\gamma}$ - Particle Physics Component**

1555 For these spectra, we import HDM with Electroweak (EW) corrections and additional correc-
 1556 tions for neutrinos above the EW scale [79]. The spectra are implemented as a model script in
 1557 astromodels for 3ML. A comprehensive description of EW corrections and neutrino considerations
 1558 are provided later in Sec. 8.

1559 Figure 6.1 demonstrates the impact of changes implemented in HDM on DM annihilation to W
 1560 bosons. A class in astromodels was developed to include HDM and is aptly named **HDMspectra**
 1561 within `DM_models.py`. The SM DM annihilation channels studied here are $\chi\chi \rightarrow$:

1562 e^+e^- , $\mu^+\mu^-$, $\tau^+\tau^-$, $b\bar{b}$, $t\bar{t}$, gg , W^+W^- , ZZ , $c\bar{c}$, $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, $\nu_e\bar{\nu}_e$, $\nu_\mu\bar{\nu}_\mu$, $\nu_\tau\bar{\nu}_\tau$, $\gamma\gamma$, hh .

1563 For $\gamma\gamma$ and ZZ , a substantial fraction of the signal photons are expected to have $E_\gamma = m_\chi$ [79].
 1564 This introduces δ -function that is much narrower than the energy resolution of the HAWC detector.
 1565 To ensure that this feature is not lost in the likelihood fits, the 'line' feature is convolved with a
 1566 Gaussian kernel with a 1σ width of $0.05 \cdot m_\chi$ and total kernel window of $\pm 4\sigma$. This differs from
 1567 HAWC's previous line study where 30% of HAWC's energy resolution was used for the kernel [81].
 1568 The NN energy estimator's strength compared to f_{hit} at low gamma-ray energy enables narrower
 1569 kernels [79]. $\chi\chi \rightarrow \gamma\gamma$ and ZZ spectral hypotheses are shown in Figure 6.2. We did not explore
 1570 how well we reconstruct injected signal events for various kernels widths. This is a systematic
 1571 that should be tested before publication to journal. Spectral models for the remaining annihilation
 1572 channels are plotted for each m_χ in Figure B.1.

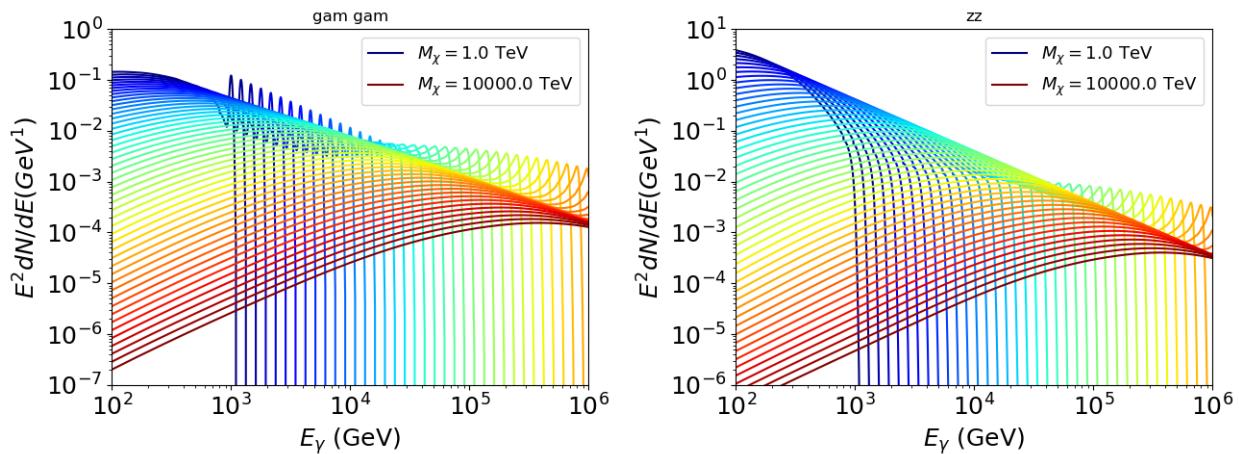


Figure 6.2 Photon spectra for $\chi\chi \rightarrow \gamma\gamma$ (left) and $\chi\chi \rightarrow ZZ$ (right) after Gaussian convolution of line features. Both spectra have δ -features at photon energies equal to the DM mass. Bluer lines are annihilation spectra with lower DM mass. Redder lines are spectra from larger DM mass. All spectral models are sourced from the Heavy Dark Matter models [79]. Axes are drawn roughly according to the energy sensitivity of HAWC.

1573 **6.3.2 J Astrophysical Components**

1574 The J-factor profiles for each source are imported from Louis Strigari et al. (referred to with
 1575 \mathcal{LS}) [80]. The \mathcal{LS} catalog fits a Navarro–Frenk–White (NFW) [62] spatial DM distributions to

1576 the dSphs which has a DM density of

$$\rho(r) = \frac{\rho_0}{\frac{r}{R_s} \left(1 + \frac{r}{R_s}\right)^2}. \quad (6.1)$$

1577 ρ_0 and the scale radius, R_s are free parameters fit for each dSph. r is the distance from the center
1578 of the dSph.

1579 Profiles in $\frac{dJ}{d\Omega}(\theta)$ up to an angular separation $\theta = 0.5^\circ$ were provided directly from the authors.
1580 Map generation from these profiles were almost identical to Section 5.3.2 except that a higher order
1581 trapezoidal integral was used for the normalization of the square, uniformly-spaced map:

$$p^2 \cdot \sum_{i=0}^N \sum_{j=0}^M w_{i,j} \frac{dJ}{d\Omega}(\theta_{i,j}, \phi_{i,j}) \quad (6.2)$$

1582 p is the angular side of one pixel in the map. $w_{i,j}$ is a weight assigned the following ways:

1583 $w_{i,j} = 1$ if $(\theta_{i,j}, \phi_{i,j})$ is fully within the region of integration

1584 $w_{i,j} = 1/2$ if $(\theta_{i,j}, \phi_{i,j})$ is on an edge of the region of integration

1585 $w_{i,j} = 1/4$ if $(\theta_{i,j}, \phi_{i,j})$ is on a corner of the region of integration

1586 Figure 6.3 shows the median and $\pm 1\sigma$ maps used as input for this DM annihilation study.

1587 6.3.3 Source Selection and Annihilation Channels

1588 HAWC's sources for this multithreaded analysis include Coma Berenices, Draco, Segue 1, and
1589 Sextans. \mathcal{LS} observed up to 43 sources in its publication, however only 4 of the best fit profiles
1590 were provided at the time this thesis was written. A full description of each source used in this
1591 analysis is found in Table 6.1.

1592 This analysis improves on chapter 5 in the following ways. Previously, the particle physics
1593 model used for gamma-ray spectra from DM annihilation was from the PPPC [58] which missed
1594 important considerations relevant for the neutrino sector. HDM is used to account for this shortfall
1595 [79]. HDM also models DM to the Planck scale which permits HAWC to probe PeV scale DM. For
1596 this study, we sample DM masses: 1 TeV - 10 PeV with 6 mass bins per decade in DM mass. In

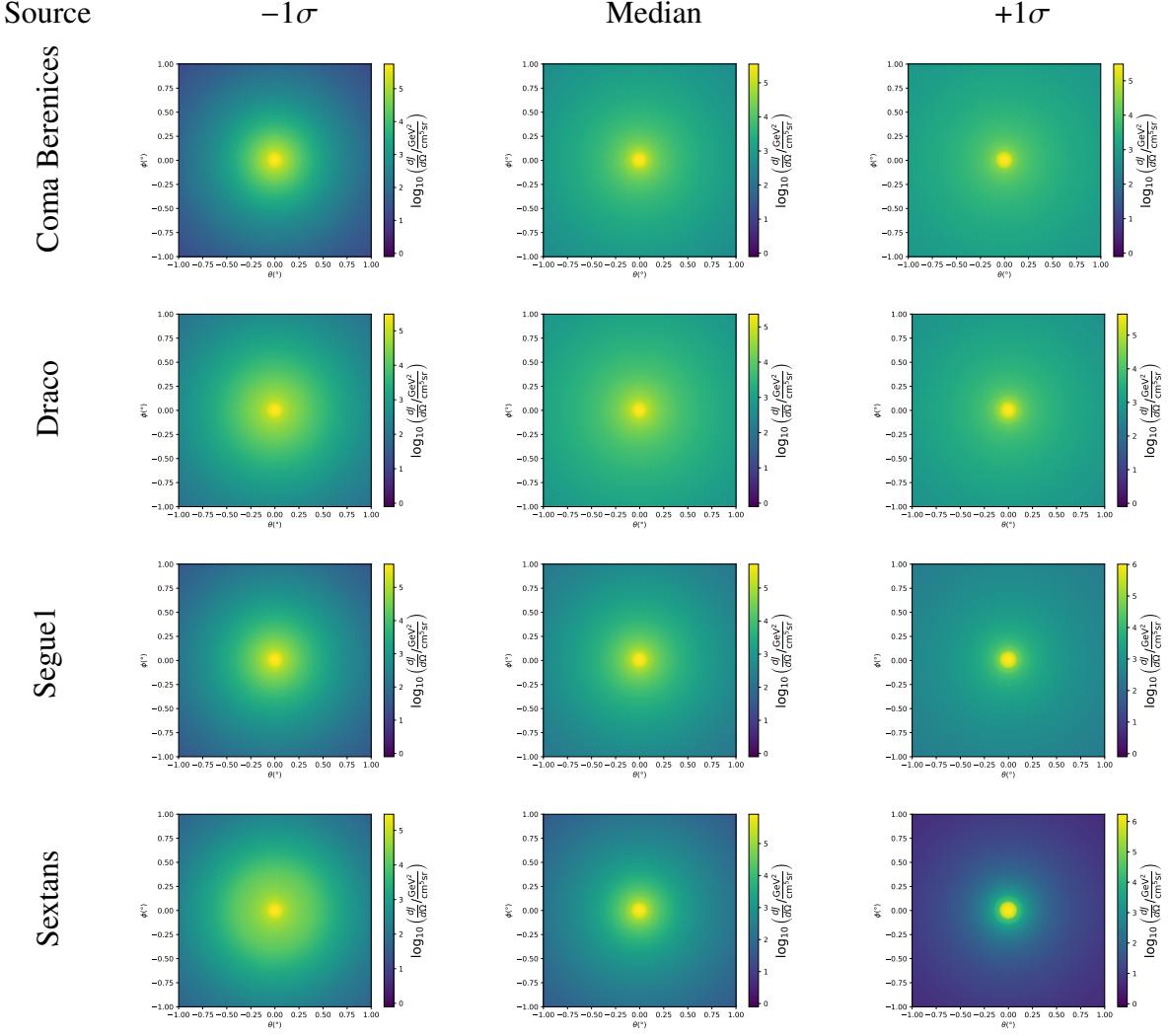


Figure 6.3 $\frac{dJ}{d\Omega}$ maps for Coma Berenices, Draco, Segue1, and Sextans. Columns are divided for the $\pm 1\sigma$ uncertainties in $dJ/d\Omega$ around the mean value from \mathcal{LS} [80]. Origin is centered on the specific dwarf spheroidal galaxies (dSph). θ and ϕ axes are the angular separation from the center of the dwarf. Profiles are truncated at 1° and flattened beyond.

1597 the case of line spectra ($\chi\chi \rightarrow \gamma\gamma$, or ZZ), we double the mass binning to 12 DM mass bins per
 1598 decade in DM mass.

1599 \mathcal{LS} provides 25 sources within HAWC's field of view. Additionally, NFW [62] DM distributions
 1600 have fewer parameters than Zhao [61], so \mathcal{LS} fits ultra-faint dwarves which expands the number of
 1601 sources. However, all sources were not provided by the authors in time for the completion of this
 1602 dissertation. Finally, the gamma-ray ray dataset is much larger. The study performed here analyzes
 1603 2565 days of data compared to 1017 days analyzed in chapter 5.

1604 **6.4 Likelihood Methods**

1605 These are identical to Section 5.4.1 and no additional changes are made to the likelihood. Bins
 1606 in this analysis are expanded to include HAWC’s NN energy estimator.

1607 **6.5 Computational Methods: Multithreading**

1608 Previously, as in Section 5.3, the likelihood was minimized for one model at a time. One model
 1609 in this case representing a DM annihilation channel (CHAN), DM mass (m_χ), and dSph ((SOURCE)).
 1610 In an effort to conserve human and CPU time, jobs submitted for high performance computing
 1611 contained a list of m_χ to iterate over for likelihood fitting. Jobs were then trivially parallelized
 1612 for each permutation of the two lists: CHANS and SOURCES. The lists for CHANS and SOURCES are
 1613 found in Section 6.3.1 and Table 6.1, respectively. Initially, 11 m_χ were serially sampled for one
 1614 job defined by a [CHAN, SOURCE] tuple. Computing the likelihoods would take between 1.5 to 2 hrs,
 1615 stochastically, for a job. We expect to compute likelihoods for data and 300 Poisson background
 1616 trials. The estimated CPU time based on the above for all CHAN (N = 17) and SOURCE (M = 25)
 1617 was estimated to 127,925 jobs. In total, 1,407,175 likelihood fits and profiles would be computed
 1618 for the 11 mass bins we wished to study. The estimated CPU time ranged between 8k CPU days
 1619 to 10k CPU days. Human time is more challenging to estimate as job allocation is stochastic and
 1620 highly dependent on what other users are submitting. Yet, it is unlikely that all jobs would run
 1621 simultaneously. Therefore, we can expect human time to be about as long as was seen in chapter 5

Name	Distance (kpc)	l, b ($^\circ$)	$\log_{10} J$ (\mathcal{LS} set) $\log_{10}(\text{GeV}^2 \text{cm}^{-5} \text{sr})$
Coma Berenices	44	241.89, 83.61	$19.00^{+0.36}_{-0.35}$
Draco	76	86.37, 34.72	$18.83^{+0.12}_{-0.12}$
Segue I	23	220.48, 50.43	$19.12^{+0.49}_{-0.58}$
Sextans	86	243.50, 42.27	$17.73^{+0.13}_{-0.12}$

Table 6.1 Summary of the relevant properties of the dSphs used in the present work. Column 1 lists the dSphs. Columns 2 and 3 present their heliocentric distance and galactic coordinates, respectively. Column 4 reports the J -factors of each source given from the \mathcal{LS} studies and estimated $\pm 1\sigma$ uncertainties. The values $\log_{10} J$ (\mathcal{LS} set) [80] correspond to the mean J -factor values for a source extension truncated at 0.5° .

1622 which was on the order of months to fully compute on a smaller analysis. A visual aid to describe
 1623 how jobs were organized is provided in Figure 6.4.

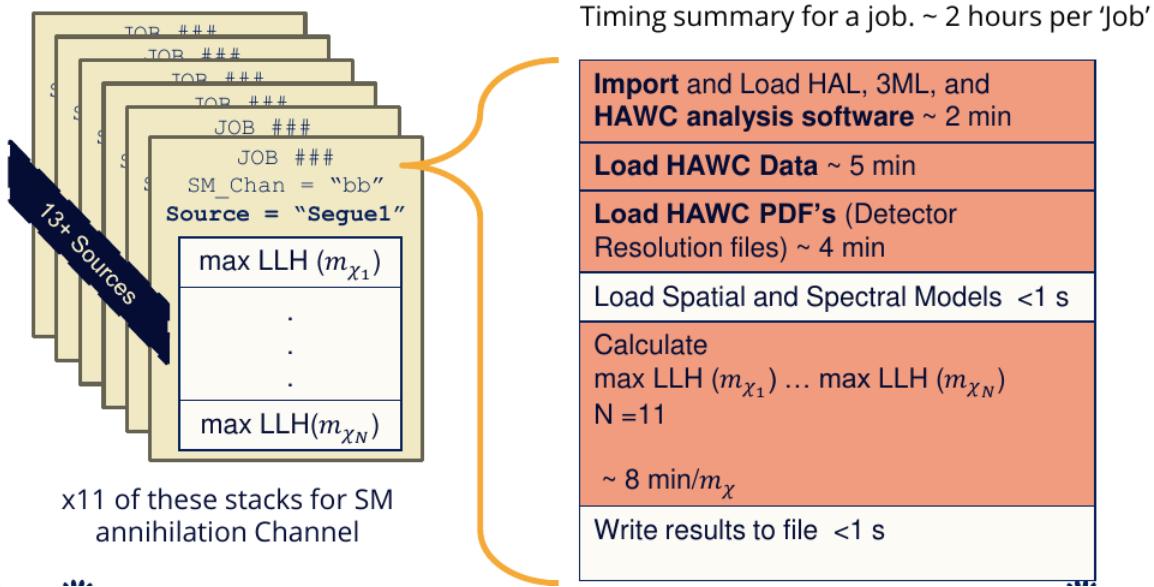


Figure 6.4 Infographic on how jobs and DM computation was organized in Section 5.3. Jobs were built for each permutation of CHANS and SOURCES shown by the left block in the figure. Each job, which took on the order 2 hrs to compute, had the following work flow: 1. Import HAWC analysis software, 2 min to run. 2. Load HAWC count maps, 5 min to run. 3. Load HAWC energy and spatial resolutions, 4 min. 4. Load DM spatial source templates and spectral models, less than 1 s. 6. Perform likelihood fit on data and model, about 8 min per DM mass. 7. Write results to file, less than 1s.

1624 The computational needs for this next generation DM analysis are extreme and is unlike other
 1625 analyses performed on HAWC. It became clear that there was a lot to gain from optimizing how
 1626 the likelihoods are computed. This section discusses how multi-threading was applied to solve and
 1627 reduce HAWC's computing of likelihoods for large parameter spaces like in DM searches.

1628 6.5.1 Relevant Foundational Information

1629 The profiling of the likelihood for HAWC is done via gradient descent where the normalization
 1630 of Equation (5.1) (linearly correlated with $\langle \sigma v \rangle$) is rescaled in the descent. Additionally, we sample
 1631 the likelihood space for a defined list of $\langle \sigma v \rangle$'s described in Section 5.4.2. The time to compute
 1632 these values is not predictable or consistent because many variables can change across the full
 1633 model-space. Comprehensively, these variables are:

1634 • m_χ : DM rest mass
 1635 • CHAN : DM annihilation channel in SM.
 1636 • SOURCE : dSph. Involves a spatial template AND coordinate in HAWC data.
 1637 • $\langle\sigma v\rangle$: Effectively the flux normalization and free parameter in the likelihood fit.
 1638 Therefore, we develop an asynchronous, functional-parallel coding pattern. Asynchronous meaning
 1639 the instructions within a function are independent and permitted to be out of sync with sibling
 1640 computations. Functional-parallel meaning that instructions are the subject of parallelization
 1641 rather than threading the likelihood computation. This is close to trivial parallelization seen in
 1642 Figure 6.4 except that we seek to consolidate the loading stages (software, data, and detector
 1643 resolution loading). Multiple asynchronous threads are expected to reduce total serial processing
 1644 time and total overhead across the entire project in addition to saving human time.

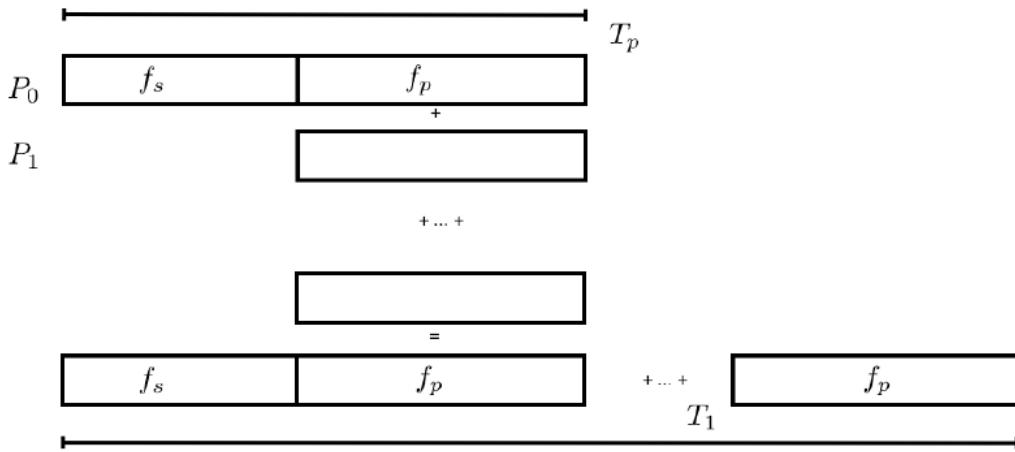


Figure 6.5 Graphic of Gustafson parallel coding pattern. f_s is the fraction of a program, in time, spent on serial computation. f_p is the fraction of computing time that is parallelizable. T_p is the total time for a parallel program to run. T_1 is the total time for a parallel program to run if only 1 processor is allocated. P_N is the N -th processor where its row is the computation the processor performs. The Gustafson pattern is most similar to what is implemented for this analysis. Figure is pulled from [82].

1645 We need a way to measure and compare the expected speedup and efficiency gain for this
 1646 asynchronous coding pattern. I pull inspiration for timing measurement from [82] and use *Amdahl's*

1647 law with hybrid programming. Hybrid programming meaning that the computation is a mix of
 1648 distributed and shared memory programming. If we assume the code is fully parallelizable over p
 1649 processors and c threads, the ideal speedup is simply pc , and ideal run-time is $T_1/(pc)$. T_1 is the
 1650 total time for a parallel program to run if only 1 processor is allocated. However, the coding pattern
 1651 contains some amount of unavoidable serial computation, as shown in Figure 6.5. In our case, the
 1652 run time, $T_{p,c}$, is estimated to be

$$T_{p,c} = \frac{T_1}{pc} (1 + F_s(c - 1)). \quad (6.3)$$

1653 F_s is the fraction of CPU time dedicated to serial computation. The expected speedup, $S_{p,c}$, is

$$S_{p,c} \equiv \frac{T_1}{T_{p,c}} = \frac{pc}{1 + F_s(c - 1)}. \quad (6.4)$$

1654 From Equation (6.4), we can see that the speed-up scales with p/F_s . We are free to minimize F_s
 1655 asymptotically by enlarging the total models that are submitted to the thread pool, thereby shrinking
 1656 the CPU fraction dedicated to serial operation. We are also free to define exactly how many threads
 1657 and processors we utilize, yet eventually hit a hard cap at the hardware available on our computing
 1658 cluster. HAWC uses Intel Xeon™processors with 48 cores and 96 threads. We see that a successful
 1659 code will scale well as the expected speedup is inversely correlated with F_s . As the total number
 1660 of models sampled grows, the speedup will also.

1661 6.5.2 Implementation

1662 The multithreaded code was written in Python3 and is documented in the `dark_matter_hawc`
 1663 [repository](#) within the script named `mpu_analysis.py`. A version of the script as of April 25
 1664 **TODO: make sure to update on this date** is also provided in Section B.2. It has many dependencies
 1665 including the HAWC analysis software. Figure 6.6 displays the workflow of a job with 3 threads.
 1666 Within a job, SOURCE is kept fixed and CHANS remains 17 elements long. More m_χ are sampled
 1667 from 11 bins up to 49 (for $\gamma\gamma$ and ZZ) and 25 (for remaining CHANS) which amounts to 12 or 6
 1668 mass bins per decade. m_χ and CHANS are permuted into a 473 element list which is split evenly
 1669 across N threads where N is [2, 8, 16]. For each m_χ -CHAN tuple, 1001 $\langle\sigma v\rangle$ values are sampled in

Timing summary for a multi-threaded job.

Import and Load HAL, 3ML, and HAWC analysis software ~ 2 min		
Load HAWC Data ~ 5 min		
Load HAWC PDF's (Detector Resolution files) ~ 4 min		
Load Spatial Model < 1s		
Load Spectra Models <1 s	Load Spectra Models <1 s	Load Spectra Models <1 s
Calculate max LLH (Chan_0, m_{χ_1}) ... max LLH (Chan_?, m_{χ_N}) N = TOTAL/N_THREADS ~ 8 min/Spec_model	Calculate max LLH (Chan_?, m_{χ_1}) ... max LLH (Chan_?, m_{χ_N}) N = TOTAL/N_THREADS ~ 8 min/Spec_model	Calculate max LLH (Chan_?, m_{χ_1}) ... max LLH (Chan_?, m_{χ_N}) N = TOTAL/N_THREADS ~ 8 min/Spec_model
Write results to file <1 s	Write results to file <1 s	Write results to file <1 s
Join Threads and terminate < 1s		

Figure 6.6 Task chart for one multithreaded job developed for this project. Green blocks indicate a shared resource across the threads AND computation performed serially. Red blocks indicate functional parallel processing within each thread. 3 threads are represented here, yet many more can be employed during the full analysis. Jobs are defined by the SOURCE as these require unique maps to be loaded into the likelihood estimator. The m_{χ} , CHAN, and $\langle \sigma v \rangle$ variables are entered into the thread pool and allocated as evenly as possible across the threads.

- 1670 the likelihood, and the value of $\langle \sigma v \rangle$ that maximizes the likelihood is found. Although rare, fits
1671 that failed are handled on a case by case basis.

1672 6.5.3 Performance

M Tasks	$T_{p,c}$ (hr:min:s)			
	$T_{1,1}$	$T_{1,2}$	$T_{1,8}$	$T_{1,16}$
50	1:40:37.5	0:52:43.7	0:19:13.8	0:13:44.0
74	2:22:30.0	1:15:00.6	0:25:21.3	0:15:49.8
100	(3:07:51.9)	1:40:10.5	0:30:44.4	0:20:01.4
200	(6:02:20.6)	-	1:00:32.0	0:30:35.0
473	(13:58:40.3)	-	2:01:41.4	1:07:53.2

Table 6.2 Timing summaries for analyses for serial and multithreaded processes. M tasks is the number of functional-parallel tasks ran for the computation. $T_{p,c}$ is a single run time in hours:minutes:seconds for runs utilizing p nodes and c threads. Runs are run interactively on the same computer to maximize consistency. Empty entries are indicated with '-'. (·) entries are estimated entries extrapolated from data earlier in the column.

- 1673 We see a significant reduction to wall time needed for our dSph analyses to run. Table 6.2

1674 shows the timing summaries for analyses of different sizes and thread counts. Additionally, the
 1675 efficiency gained when consolidating the serial loading of data is also apparent in our ability to
 1676 study many more tasks in about the same amount of wall time as a smaller serial computation. Trials
 1677 represented in the table were run on an AMD Opteron® processor 6344 with 48 cores, 2 threads per
 1678 core; 2.6 GHz clock. This is not the same architecture used for analysis on the HAWC computing
 1679 cluster however they are similar enough that results shown here are reasonably representative of
 1680 computing on the HAWC computing cluster. I use Tab. 6.2 for the inferences and conclusions in
 1681 the following paragraphs.

1682 First, we want to find T_s , the time of serial computation. From Fig. 6.5, the timing for our
 1683 coding pattern can be written as

$$T_s + Mt_p = T_{1,1}^M. \quad (6.5)$$

1684 M is the number of functional-parallel tasks (represented as column 1 of Tab. 6.2), and t_p is the
 1685 average time to complete a single parallel task. $T_{1,1}^M$ is the total time for a parallel program to run if
 1686 only 1 processor is allocated for M parallel task. With two runs of different M (M_1 and M_2), we
 1687 can use a system of equations to compute

$$T_s = 803.1\text{s} \text{ and } t_p = 104.6\text{s} \quad (6.6)$$

1688 Now, we have specific estimation for the fraction of serial computing time, F_s :

$$F_s = \frac{803.1}{803.1 + 104.6 \cdot M}. \quad (6.7)$$

1689 The maximum M for this study is 473 which evaluates to: $F_s = 0.016$ or 1.6% of computing time.
 1690 Table 6.3 shows the resulting speedups.

1691 We see a speedup that generally exceeds expectations from Eq. (6.4) for real trail runs. We also
 1692 see that there are diminishing returns as the number of threads increases. For small jobs with large c ,
 1693 both the expected and observed speedup are significantly smaller than c . One thing not considered
 1694 in Eq. (6.4) is the time incurred via communication latency. Communication latency increases
 1695 with the number of threads and contributes to diminishing returns. Additionally, these values are

M Tasks	F_s	$S_{1,2}$	$S_{1,8}$	$S_{1,16}$
50	1.33 E-1	1.90 [1.76]	5.23 [4.14]	6.35 [5.34]
74	9.40 E-2	1.90 [1.83]	5.62 [4.82]	9.00 [6.64]
100	7.13 E-2	1.88 [1.87]	6.11 [5.34]	9.38 [7.73]
200	3.70 E-2	- [1.93]	5.98 [6.36]	11.85 [10.29]
473	1.60 E-2	- [1.97]	6.89 [7.20]	12.35 [12.91]

Table 6.3 Speed up summaries for analyses for serial and multithreaded processes. M tasks is the number of functional-parallel tasks ran for the computation. $S_{p,c}$ is a single speedup comparison for runs utilizing p nodes and c threads. [·] are the estimated speedups calculated from Tab. 6.2, Eq. (6.7), and Eq. (6.4). Empty entries are indicated with '-'.

1696 for single runs and do not consider the stochastic variation expected in a shared high performance
 1697 computing resource. Therefor, these results are not strictly conclusive, yet demonstrate the merits
 1698 of multi-threading. We see very clearly that there is a lot to gain, and this new coding pattern will
 1699 expand HAWC's analysis capabilities.

1700 6.6 Analysis Results

1701 3 of the 43 $\mathcal{L}\mathcal{S}$ dSphs considered for the multithreaded analysis. These dSph are analyzed
 1702 for emission from DM annihilation according to the likelihood method described in Section 5.4.
 1703 The three likelihood profiles are then stacked to synthesize a combined limit on the dark matter
 1704 annihilation cross-section, $\langle\sigma v\rangle$. This combination is done each of the 17 SM annihilation channels.
 1705 Figure 6.7 and Fig. 6.8 show the combined limits for all annihilation channels with HAWC's
 1706 observations. Test statistics of the best fit $\langle\sigma v\rangle$ values for each m_χ and CHAN are shown in Fig. 6.9
 1707 and Fig. 6.10. We also compare these limits to HAWC's Glory Duck limits shown in Section 5.5.
 1708 The comparison to Glory Duck are featured in Fig. 6.11 for all the DM annihilation channels studied
 1709 for Glory Duck. A full comparison is provided in the appendix in Fig. B.2, Fig. B.3, and Fig. B.4.
 1710 Here, we show updated limits for $\chi\chi \rightarrow b\bar{b}, e\bar{e}, \mu\bar{\mu}, \tau\bar{\tau}, t\bar{t}, W^+W^-$, $\gamma\gamma$ and ZZ . For the first time
 1711 ever, we show limits for $\chi\chi \rightarrow c\bar{c}, s\bar{s}, u\bar{u}, d\bar{d}, \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, gg$, and hh .

1712 No DM was found in HAWC observations. The largest excess found in HAWC data was for DM
 1713 annihilating to W -bosons or $\nu_e\bar{\nu}_e$ for $m_\chi = 10$ TeV at significance 2.11σ and 2.14σ respectively.
 1714 HAWC's limits and excesses are dominated by Segue1. Coma Berenices shows excesses at higher
 1715 DM mass, yet no similar excesses were observed in Segue1 or Sextans. Sextans did not contribute

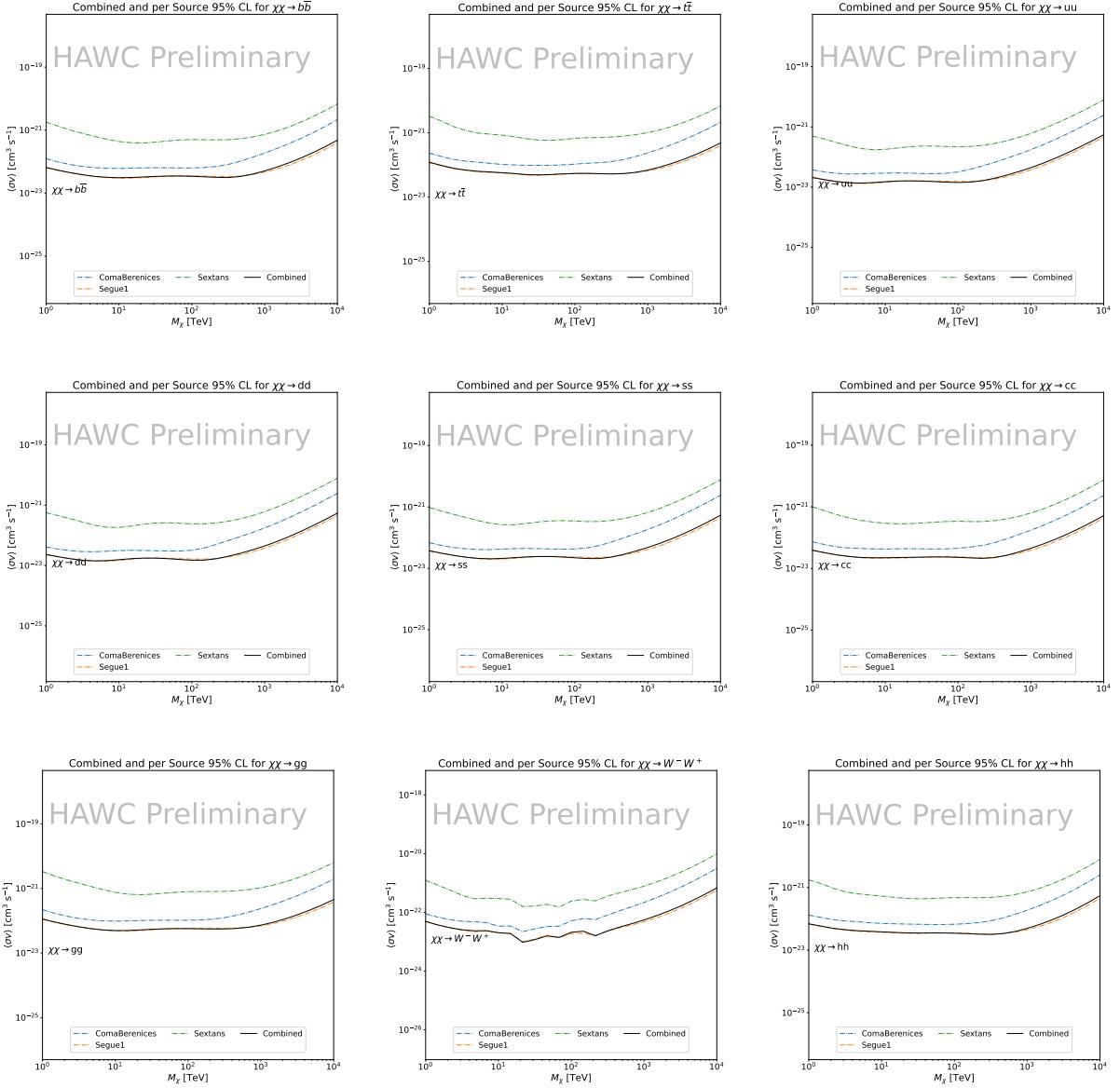


Figure 6.7 HAWC upper limits at 95% confidence level on $\langle\sigma v\rangle$ versus m_χ for $\chi\chi \rightarrow b\bar{b}$, $t\bar{t}$, $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, $c\bar{c}$, gg , W^+W^- , and hh . Limits are with $\mathcal{L}\mathcal{S}$ J -factors [80]. The solid line represents the observed combined limit. Dashed lines represent limits from individual dSphs.

1716 significantly to signal excesses or the combined limit as it is at high zenith. Draco was not included
 1717 as the PDF of some of our analysis bins were wider than what is reasonable for a point source
 1718 analysis. Draco is at a high zenith for HAWC, so the effort required to include it was not justified
 1719 by the benefits.

1720 We did not generate background trials in time of writing this thesis. These are not shown and

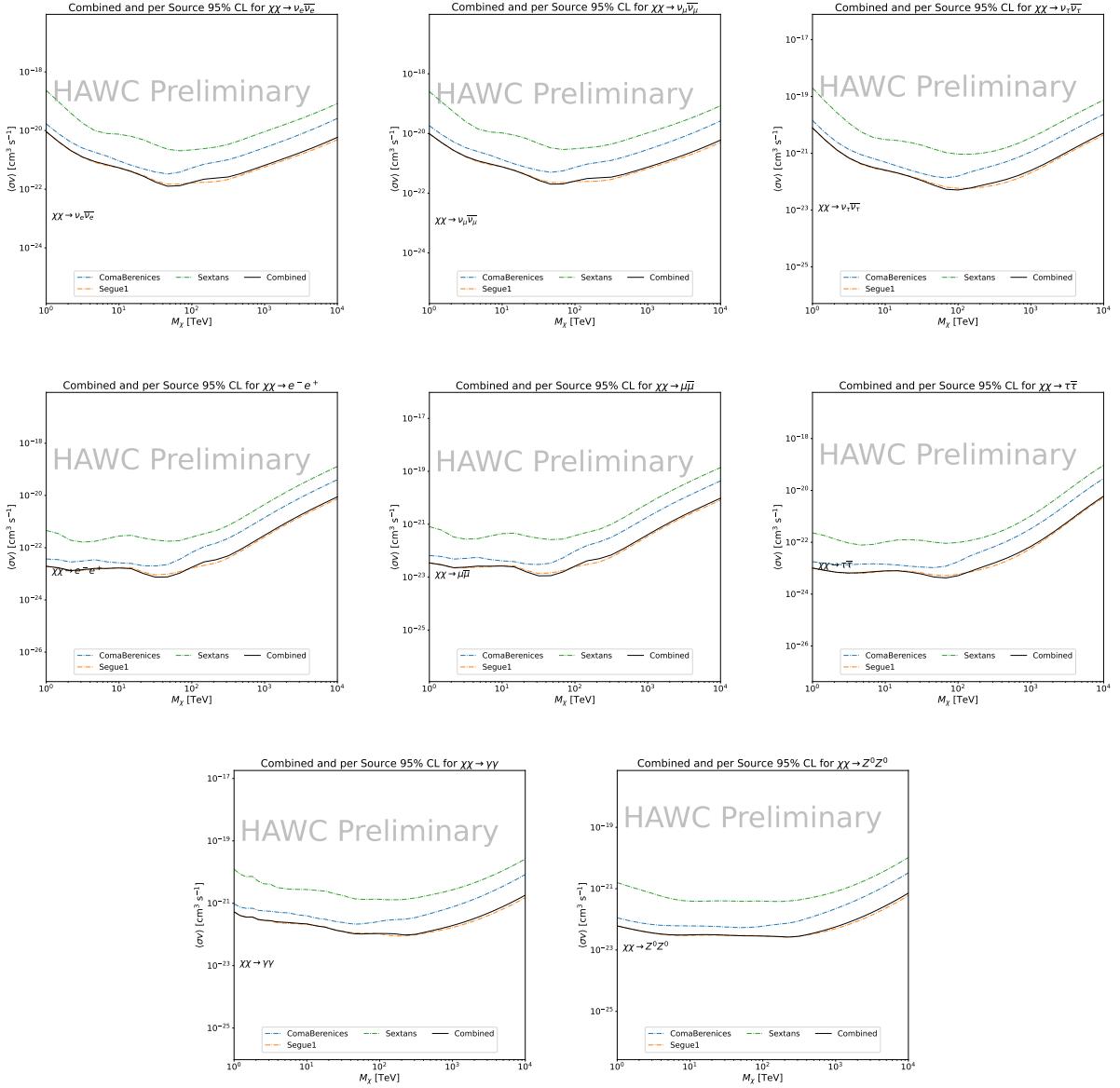


Figure 6.8 HAWC upper limits at 95% confidence level on $\langle\sigma v\rangle$ versus m_χ for $\chi\chi \rightarrow \nu_e \bar{\nu}_e$, $\nu_\mu \bar{\nu}_\mu$, $\nu_\tau \bar{\nu}_\tau$, $e \bar{e}$, $\mu \bar{\mu}$, $\tau \bar{\tau}$, $\gamma\gamma$ and ZZ . Limits use $\mathcal{L}S$ J -factors [80]. The solid line represents the observed combined limit. Dashed lines represent limits from individual dSphs.

1721 are an immediate next step for this analysis before publication.

1722 When comparing these results to Section 5.5, we see an overall decrease to the confidence limit
 1723 therefore improvement to HAWC's expected sensitivity. This improvement is generally stronger
 1724 than a doubling of data, or a factor $\sqrt{2}$ decrease. The comparison is somewhat complex and
 1725 dependent on the dSph and SM annihilation channel. Figure 6.11 shows the comparisons of limits

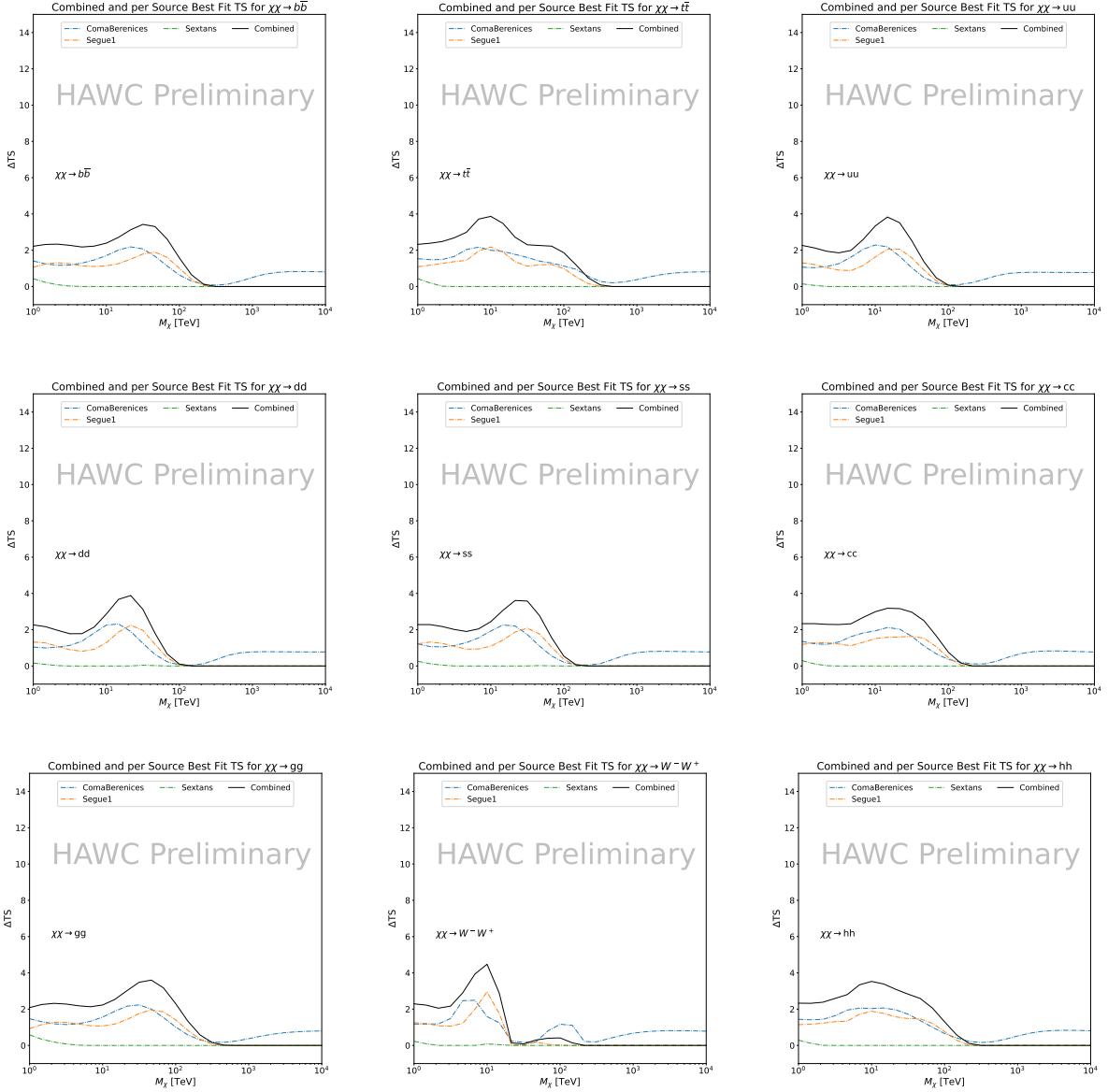


Figure 6.9 HAWC TS values for best fit $\langle\sigma v\rangle$ versus m_χ for SM annihilation channels: $\chi\chi \rightarrow b\bar{b}$, $t\bar{t}$, $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, $c\bar{c}$, gg , W^-W^+ , and hh . Limits use \mathcal{LS} J -factors. The solid black line shows the combined best fit TS values. The colored, dashed lines are the TS values from each dSph.

1726 calculated for this analysis and Glory Duck (Section 5.5). Segue 1 and Coma Berenices are low
 1727 zenith where improvements to HAWC's analysis come only from energy estimation. Differences
 1728 between these two are dominantly from their differences in J -factor, half-light radii of the dSphs,
 1729 and the particle physics inputs. Substantial gains in HAWC's analysis methods (pass 5.F) were
 1730 made at high zenith which is important for sources like Sextans. The HDM particle physics model

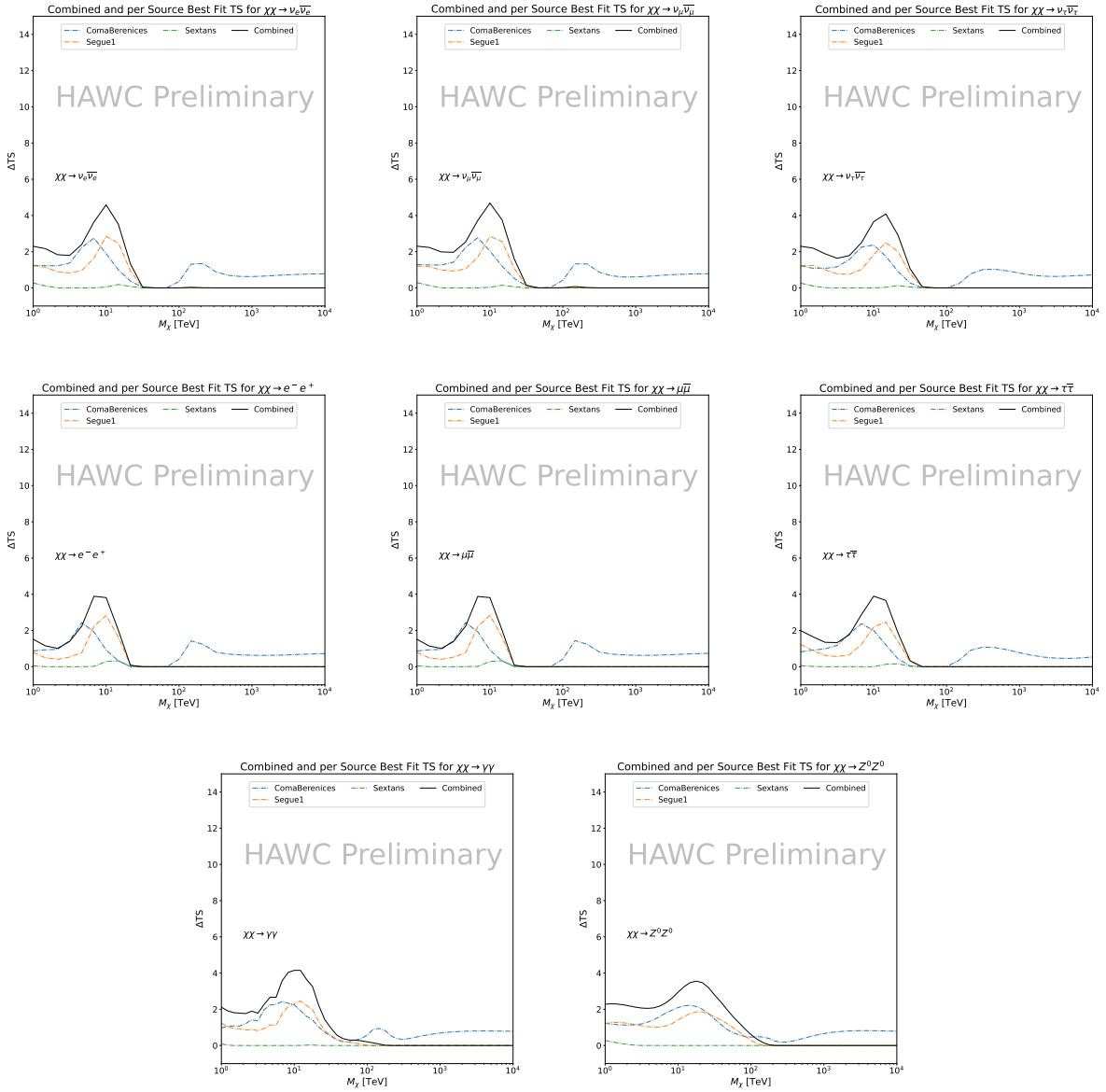


Figure 6.10 HAWC TS values for best fit $\langle\sigma v\rangle$ versus m_χ for SM annihilation channels: $\chi\chi \rightarrow \nu_e \bar{\nu}_e$, $\nu_\mu \bar{\nu}_\mu$, $\nu_\tau \bar{\nu}_\tau$, $e^- e^+$, $\mu \bar{\mu}$, $\tau \bar{\tau}$, $\gamma\gamma$ and ZZ . Limits use \mathcal{LS} J -factors. The solid black line shows the combined best fit TS values. The colored, dashed lines are the TS values from each dSph.

1731 produces almost identical spectra to the PPPC for $\chi\chi \rightarrow e^- e^+$. This channel can be used to
 1732 compare limits between dSph spatial models. Overhead sources see minimal improvement to the
 1733 limits, while high zenith sources see an order of magnitude improvement for all DM masses. Softer
 1734 SM annihilation channels see broad improvements to the limit compared to harder channels.

1735 **6.7 Systematics**

1736 Systematics to this analysis are identical to what was performed earlier in Glory Duck, Sec-
1737 tion 5.7. We are also sensitive to the choice in spatial template, and this was explored in Section 5.7.2
1738 and Section 5.8.2.

1739 **6.8 Conclusion and Discussion**

1740 In this multithreaded analysis, we have used observations of 3 dSphs from HAWC to perform
1741 a collective DM annihilation search towards dSphs. The data were combined across sources
1742 to significantly increase the sensitivity of the search. Advanced computational techniques were
1743 deployed to accelerate wall-time spent analyzing by an order of magnitude. We have observed
1744 no significant deviation from the null, no DM hypothesis, and so present our results in terms of
1745 upper limits on the velocity-weighted cross-section, $\langle\sigma v\rangle$, for seventeen potential DM annihilation
1746 channels across four decades of DM mass.

1747 This analysis serves as a proof of concept for multithreaded HAWC analyses with large parameter
1748 spaces. Larger datasets with fast techniques will be essential to tackling the DM problem. The
1749 models we used for this study include annihilation channels with neutrinos in the final state.
1750 Advanced studies could aim to merge our results with those from neutrino observatories with large
1751 data sets.

1752 A full HAWC analysis will include systematic studies of the J -factor distributions. Additionally,
1753 because of the timing reduction, the study can be doubled in size to include DM decay. We have not
1754 yet received the remaining spatial profiles to the \mathcal{LS} catalog, and limits can be quickly computed
1755 once these are received. Finally, statistical studies with Poisson variation of HAWC's background
1756 are essential to a comprehensive understanding of our observed excesses.

Segue1

Coma Berenices

Sextans

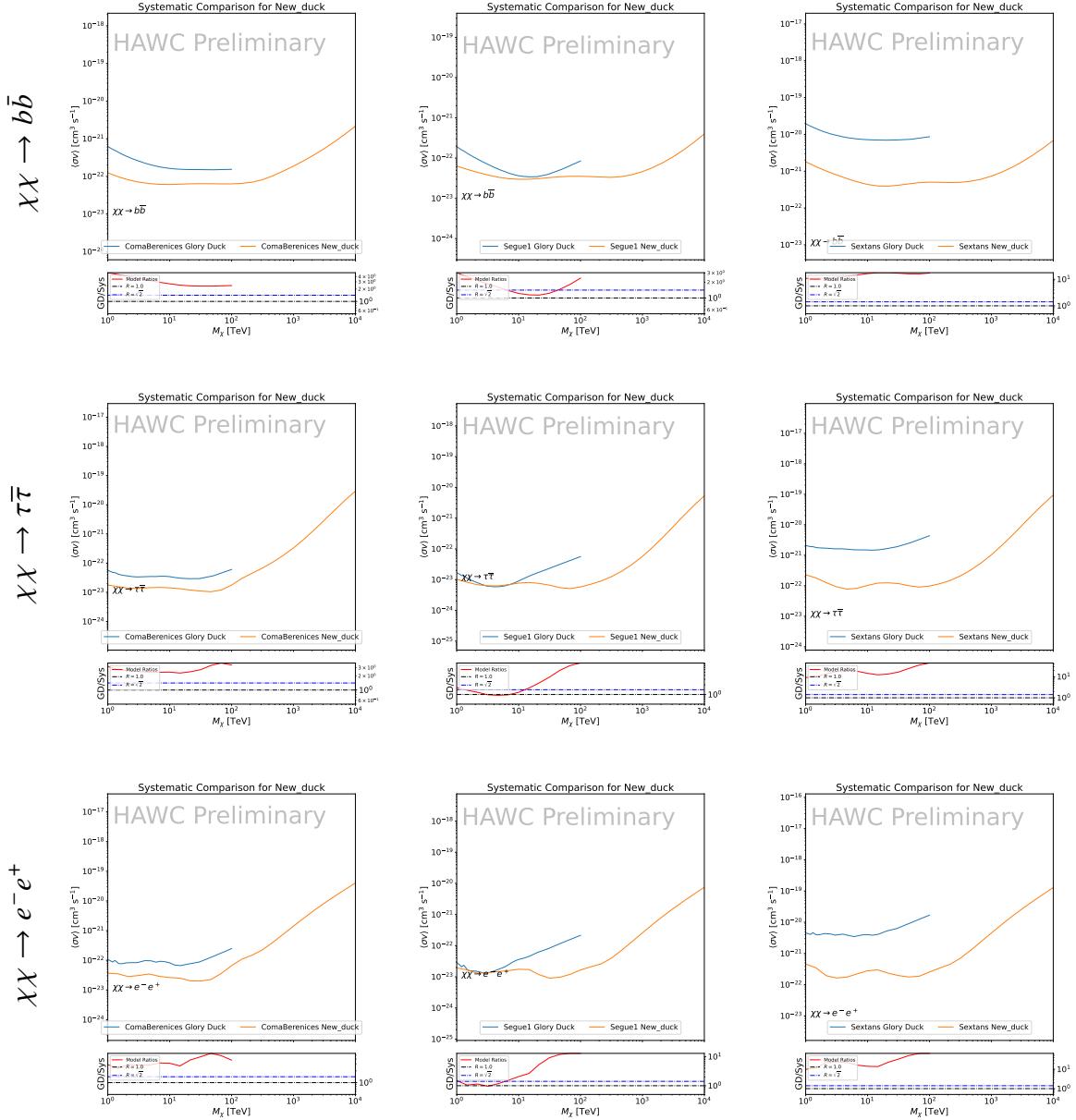


Figure 6.11 Comparison of HAWC limits from this analysis to Glory Duck (Fig. 5.5) for 3 dSphs and 3 DM annihilation channels: $b\bar{b}$, $\tau\bar{\tau}$, and $e\bar{e}$. Each sector shows the 95% confidence limit from Glory Duck (blue line) and this analysis (orange line) in the top plot. The lower plot features the ratio in log scale of Glory Duck to this analysis in a red solid line. Horizontal dashed lines are for ratios of 1.0 (black) and $\sqrt{2}$ (blue). Ratios larger than 1.0 are for limits smaller, or stricter, than Glory Duck. Ratios larger than $\sqrt{2}$ indicates limits are stricter than a simple doubling of the Glory Duck data.

CHAPTER 7

HEAVY DARK MATTER ANNIHILATION SEARCH WITH ICECUBE'S NORTH SKY TRACK DATA

7.1 Introduction

Neutrinos are another astrophysical messenger than can travel long distances without significant attenuation or deflection. Additionally, Neutrinos come in three flavors which triples the multiplicity of the particles we are searching for. Uniquely, they interact less readily than photons especially above PeV energies. Neutrinos therefore provide another window through which we can perform dark matter searches.

The previous IceCube DM annihilation analysis towards dwarf galaxies was performed in 2013 [83] which, in technical terms, is more than a minute ago. This is in spite of IceCube's crucial sensitivity afforded from neutrino spectral lines [84]. A lot has changed in IceCube since its previous DM annihilation search such as, additional strings, more sophisticated analysis methods, and more accurate theory modeling. It has come time for IceCube to make a DM dSph contribution.

IceCube is sensitive to annihilating DM for DM masses above 1 TeV. Additionally, IceCube's sensitivity is comparable gamma-ray observatories in spectral models that produce hard neutrino features. The goal of this analysis is to perform a DM annihilation search using the Northern Sky Tracks datasets. The search will only be towards dwarf spheroidal galaxies (dSph) for the strengths mentioned in Section 5.3.3. These sources are treated as point sources for IceCube with little loss to sensitivity or model dependence on how the DM is distributed. DM masses from 500 GeV to 100 PeV are considered for this analysis. Several DM annihilation channels available from the HDMspectra [79] are studied in this analysis. This chapter presents the analysis work for IceCube to update our DM searches toward dSphs.

7.2 Dataset and Background

This section enumerates the data and background methods used for IceCube's study of dSphs. Section 7.2.1 and Section 7.2.2 are most useful for fellow IceCube collaborators looking to replicate this analysis.

1783 **7.2.1 Itemized IceCube files**

1784 These files are only available within IceCube’s internal documentation and wikis. They are not
1785 meant for public access, and are presented here so that IceCube collaborators can reproduce results
1786 accurately.

1787 • Software Environment: CVMFS Py3-v4.1.1

1788 • Data Sample: Northern Tracks NY86v5p1

1789 • Analysis Software: csky ([nu_dark_matter](#))

1790 • Analysis wiki: https://wiki.icecube.wisc.edu/index.php/Dark_Matter_Annihilation_Search_towards_dwarf_spheroidals_with_NST_and_DNN_Cascades
1791

1792 • Project repository

1793 **7.2.2 Software Tools and Development**

1794 This analysis was performed inside IceCube’s CVMFS (3.4.1.1) software environment using
1795 csky for likelihood calculations. Csky at first did not come with dark matter spectral models nor
1796 could accommodate custom flux models. We developed these capacities for single source and
1797 stacked source studies for this analysis. The analysis code is held in a separate repository from
1798 csky. The [nu_dark_matter branch of csky](#) manages the input of custom dark matter spectra and
1799 accompanied DM astrophysical source. Csky also enables the use of multithreading which was
1800 shown to be crucial for DM searches (see Sec. 6). Csky then calculates likelihoods with a selected
1801 data sample. The [IceCube Dark Matter dSph repository](#) manages the generation of spectral models
1802 for neutrinos, physics parameter extraction from n_{sig} , J -factor per source inputs, and bookkeeping
1803 for the large parameter space. The project repository required a secondary software environment
1804 for neutrino oscillations. How to launch and run those calculations are documented in the project
1805 repository and the Docker image is additionally saved in Section C.1.

1806 **7.2.3 Data Set and Background Description**

1807 For this analysis, I use the Northern Sky Tracks (NST) Sample (Version V005-P01). The sample
1808 contains up-going track-like events, usually from ν_μ and ν_τ , with a superior angular resolution
1809 compared to the cascade dataset. This sample covers 10.4 years of data (IC86_2011-2021). The
1810 accepted neutrino energy range used for the analysis is unique from most other IceCube searches
1811 because DM spectra are hard with large contributions close to $E_\nu = m_\chi$. Therefore, the sampled
1812 energy range is $1 < \log(E_\nu/\text{GeV}) < 9.51$ with step size 0.125.

1813 The strengths of a dwarf analysis is that there are no additional background considerations
1814 beyond nominal, baseline background estimations (see Section 5.2.3). For NST, the nominal
1815 contributions come from atmospheric neutrinos and isotropic astrophysical neutrinos. We estimate
1816 the background by scrambling NST data along Right Ascension.

1817 **7.3 Analysis**

1818 The expected differential neutrino flux from DM-DM annihilation to standard model particles,
1819 $d\Phi_\nu/dE_\nu$, over solid angle, Ω is described by the familiar equation.

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\langle\sigma\nu\rangle}{8\pi m_\chi^2} \frac{dN_\nu}{dE_\nu} \times \int_{\text{source}} d\Omega \int_{l.o.s} \rho_\chi^2 dl(r, \theta') \quad (7.1)$$

1820 This is identical to Eq. (5.1) except that there are 3 neutrino flavors, so there are a corresponding
1821 3 flux equations. Section 5.3 has a complete description of each term in Eq. (7.1). Additionally,
1822 neutrinos oscillate between flavors which needs to be considered for the expected neutrino flux
1823 at Earth. Section 7.3.1 presents the particle physics model and processing for DM annihilation.
1824 Section 7.3.2 presents the spatial distributions built for each dSph.

1825 **7.3.1 $\frac{dN_\nu}{dE_\nu}$ - Particle Physics Component**

1826 Neutrino spectra from heavy DM annihilation were generated using HDMspectra [79] and
1827 χ arov [85]. HDMspectra has tables for the decay and annihilation of heavy DM for different
1828 dark DM and SM primary annihilation channels. The simulation includes electroweak or gluon
1829 radiative corrections and higher order loop corrections from the W and Z bosons (WWZ and $WW\gamma$).
1830 These corrections are especially important for accurately estimating the prompt neutrino flux. This

1831 publication also pushes the simulated DM mass to the Plank scale (1 EeV), however this study will
1832 not explore that high.

1833 An important feature in the spectra is that neutrino line channels will be accompanied by a low
1834 energy tail [79], see Fig. 7.1. Thus, the Earth will not fully attenuate a heavy neutrino line-like
1835 signal from high declination sources where the neutrino flux must first traverse through the Earth.
1836 The DM annihilation channels that feature lines include all leptonic channels: $\nu_{e,\mu,\tau}$, e , μ , and τ . We
1837 use the `xarov` software to propagate and oscillate the neutrinos from the source to Earth. Because
1838 these sources are quite large in absolute terms, and also far (order 10 kpc or more), the resulting
1839 flavor spectra are the averages of the transition probabilities [85]:

$$P(\nu_\alpha \rightarrow \nu_\beta) \approx \begin{bmatrix} 0.55 & 0.18 & 0.27 \\ 0.18 & 0.44 & 0.38 \\ 0.27 & 0.38 & 0.35 \end{bmatrix} \quad (7.2)$$

1840 Examples of the spectra before and after propagation are shown in Fig. 7.1.

1841 When calculating the expected contribution to n_s , only ν_μ and ν_τ are considered as NST's
1842 effective area to ν_e is negligible [86]. Therefore, the expected composite neutrino spectrum is the
1843 sum of the two flavors: $\frac{dN\nu_\mu}{dE\nu_\mu} + \frac{dN\nu_\tau}{dE\nu_\tau}$. The spectral tables are then converted to splines to condense
1844 information, enable random sampling of the spectra, and reduce computing times. The spectral
1845 splines are finally implemented as a DM class in csky.

1846 7.3.1.1 Treatment of Neutrino Line Features

1847 All DM annihilation channels into leptons $\chi\chi \rightarrow [\nu_{e,\mu,\tau}, e, \mu, \tau]$ develop a prominent and
1848 narrow spectral line feature. For all neutrino flavors, this line is visible and prominent in all m_χ
1849 studied in this analysis. For charged leptons, the feature typically manifests at $m_{ch} > 10$ TeV, yet
1850 its prominence varies slightly between the flavors. Examples for lines in the annihilation spectra
1851 with neutrinos or charged leptons are provided in Fig. 7.1.

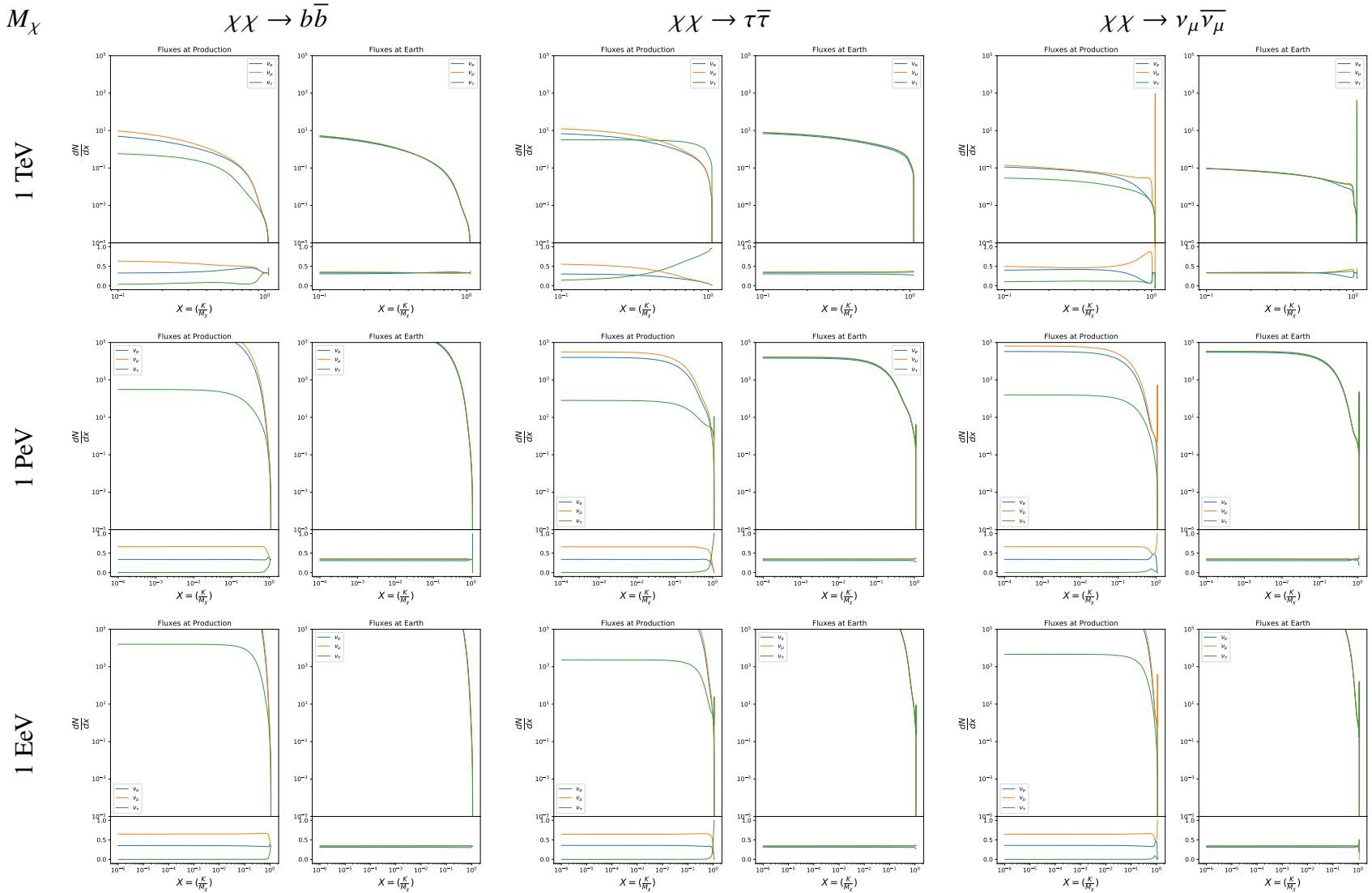


Figure 7.1 Neutrino spectra at production (left panels) and after oscillation at Earth (right panels). Blue, orange, and green lines are the ν_e , ν_μ , and ν_τ spectra respectively. Top panels show the spectra in $\frac{dN}{dE}$. Lower panels plot the flavor ratio to $\nu_e + \nu_\mu + \nu_\tau$. SM annihilation channels $b\bar{b}$, $\tau\bar{\tau}$, and $\nu_\mu\bar{\nu}_\mu$ are shown for $M_\chi = 1 \text{ PeV}$, 1 TeV , and 1 EeV .

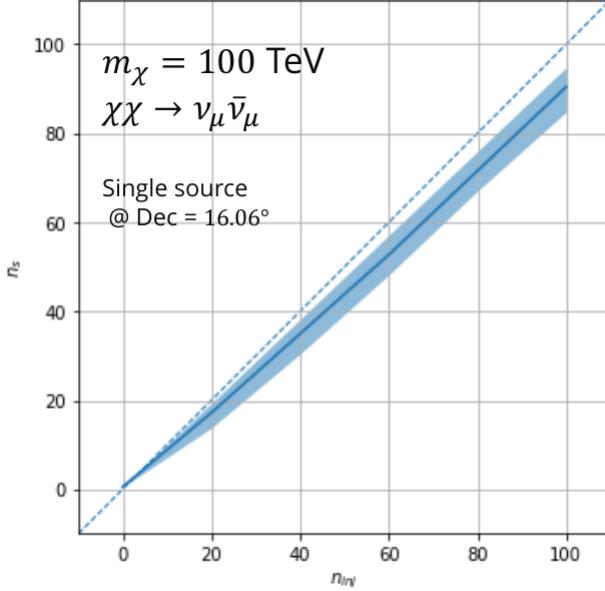


Figure 7.2 Signal recovery for 100 TeV DM annihilation into $\nu_\mu \bar{\nu}_\mu$ for a source at Dec = 16.06°. n_{inj} is the number of injected signal events in simulation. n_s is the number of reconstructed signal events from the simulation data. Although the uncertainties are small and tight, the reconstructed n_s are systematically underestimated.

1852 The neutrino line feature is so narrow relative the sampled energy range that the random
 1853 sampling of the spectra and likelihood fitting rarely capture the line in computation. As a result,
 1854 often the best fit to simulation of background will always floor to TS = 0 and the signal recovery
 1855 systematically underestimates the signal (see Fig. 7.2).

1856 To remedy this, we take a similar approach to the IceCube’s decay analysis [87] and the previous
 1857 gamma-ray study in Section 6.3.1. Two smoothing kernels were tested (Gaussian and uniform)
 1858 to widen the line feature. The widths were tuned such that the signal recovery approached unity
 1859 for DM mass 100 TeV to 1 PeV for a source at Segue 1’s declination, 16.06°. Near horizon
 1860 was chosen in order to isolate loss in signal recovery away from Earth’s attenuation of very high
 1861 energy neutrinos and atmospheric backgrounds. The kernel convolution needed closely preserve
 1862 the integrated counts of neutrinos. The optimized kernel parameters for all lines are summarized
 1863 as:

- 1864 • Gaussian kernel with 1σ width = $1.75E-3 \cdot m_\chi$
 1865 • Minimum energy included in convolution = $\text{MIN}[0.995 \cdot m_\chi, E(\nu_{\text{line}}) - 4\sigma]$

1866

- Maximum energy included in convolution = $\text{MAX}[1.005 \cdot m_\chi, E(\nu_{\text{line}}) + 4\sigma]$

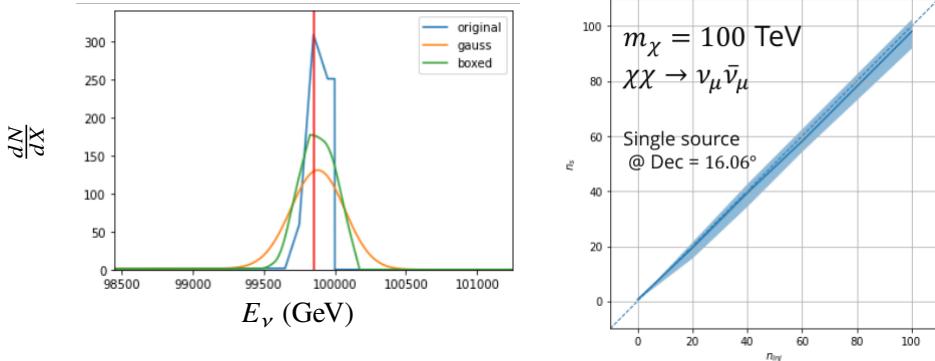
1867 where $E(\nu_{\text{line}})$ is the neutrino energy where the neutrino line is at the maximum.

Figure 7.3 Left panel shows the two kernels overlaying the original spectrum from $\chi\text{aron}\nu$ after propagation to Earth [85]. The vertical red line indicates where the original neutrino line is maximized. Blue line is the output from $\chi\text{aron}\nu$. Green line is the spectrum after convolution with a flat kernel. Orange line is the spectrum after Gaussian convolution. Right panel shows the signal recovery of the spectral model using the Gaussian kernel with parameters enumerated above.

1868

These parameters broadly improved the signal recovery of the line spectra. An example is in

1869 Fig. 7.3. Analysis level signal recovery studies are expanded upon in Section 7.6.

1870

7.3.1.2 Spline Fitting

1871 In an effort to reduce computational work, memory burden, and align with point source methods
 1872 used for NGC1068 [88], spectral splines were created and adopted for estimating the neutrino flux
 1873 for the different spectral models. Software was written to generate, book keep, and calculate values
 1874 on the splines.

1875 When using splines, one has to be careful of the goodness to fit. The spline software used
 1876 here, Photospline [89], uses the penalized spline technique [90]. Through the penalized technique,
 1877 poor fits are penalized according to the accuracy of the nominal value, and the smoothness of the
 1878 first and second derivatives. However, this construction does not penalize on the integral of the
 1879 fit distribution which is critical in low signal studies, such as DM searches. There are additional
 1880 caveats when testing the goodness to fit to the MC generated above for all DM annihilation channels.

- 1881 • The splines must be Log10(*) in Energy and dN/dX to account for the exponential nature of
 1882 the flux.
- 1883 • The fidelity of the fit matters more at $E_\nu \approx m_\chi$ where the model uncertainties are minimal
 1884 and physical considerations (like the cut-off) are most important.
- 1885 • The fidelity of the fit matters less at low E_ν as the model uncertainties are large AND
 1886 IceCube's sensitivity diminishes significantly below 500 GeV.
- 1887 • Total integrated counts should be well-preserved.

1888 The resulting cost function was built to evaluate the goodness of spline fits to account for the above
 1889 considerations.

$$e_i = x_i \cdot \left(\frac{dN_i}{dX_i} - 10^{\hat{e}_i} \right) \quad (7.3)$$

1890 Where \hat{e}_i is the spline estimator's value for x_i . $x_i = E_{\nu_i}/m_\chi$. $\frac{dN_i}{dX_i}$ is the flux value from MC. I then
 1891 take the RMS of the error distribution and the resulting value, err, is used to evaluate the fidelity of
 1892 the spectral spline.

$$\text{err} = \sqrt{\frac{1}{x_{\max} - x_{\min}} \int_{x_{\min}}^{x_{\max}} e^2 dx} \quad (7.4)$$

1893 x_{\min} and x_{\max} are the scope of the error evaluation and are provided in Tab. 7.1.

1894 Each SM channel had unique tolerances for 'err'. Channels with very hard cut-offs had looser
 1895 tolerance for err because a significant error would be generated from single counts over/underes-
 1896 timated at the cut-off. Soft channels do not share this issue, so the tolerance is much stricter. All
 1897 annihilation channels from HDM are modeled well below IceCube's NST sensitivity which falls
 1898 off substantially below 100 GeV [86]. We do not think it is necessary to evaluate the spline fits
 1899 below 100 GeV and use this value as the default lower cut-off. Yet, HDM's model uncertainties
 1900 at $E_\nu < 10^{-6} \cdot m_\chi$ span an order of magnitude [79]. We also choose not to evaluate the splines
 1901 below this critical value if it is within IceCube's sensitivity. Finally, the smoothing of the spectral
 1902 lines in leptonic annihilation channels are ignored for evaluating the fit. We used the lower limit of

$\chi\chi \rightarrow$	GOOD	OK	FAIL	Limits of err calc [X_{min}, X_{max}]
$Z^0 Z^0, W^+ W^-$	1.0E-3	1.0E-3, 1.0E-2	1.0E-2	MAX[100GeV/ m_χ , 10^{-6}], 1.0
$t\bar{t}, hh$	1.0E-5	1.0E-5, 1.0E-4	1.0E-4	MAX[100GeV/ m_χ , 10^{-6}], 1.0
$b\bar{b}, d\bar{d}, u\bar{u}$	9.0E-7	9.0E-7, 9.0E-6	9.0E-6	MAX[100GeV/ m_χ , 10^{-6}], 1.0
$\nu\bar{\nu}_{e,\mu,\tau}$	1.0E-3	1.0E-3, 1.0E-2	1.0E-2	MAX[100GeV/ m_χ , 10^{-6}], MIN[0.995, ($E_n(\nu_{line}) - 4\sigma$)/ M_χ]
$e\bar{e}, \mu\bar{\mu}, \tau\bar{\tau}$	1.0E-3	1.0E-3, 1.0E-2	1.0E-2	MAX[100GeV/ m_χ , 10^{-6}], MIN[0.995, ($E_n(\nu_{line}) - 4\sigma$)/ M_χ]

Table 7.1 Spline err tolerances used for input in particle physics component to Eq. (5.1). Column 1 is the DM annihilation channel being fit. Columns 2, 3, and 4 are the tolerances for "GOOD" (pass), "OK" requires inspection, and "FAIL" (tune and refit) respectively. Column 5 has the X ranges over which the error is evaluated. MAX/MIN [\cdot, \cdot] takes the maximum or minimum of the two enclosed values.

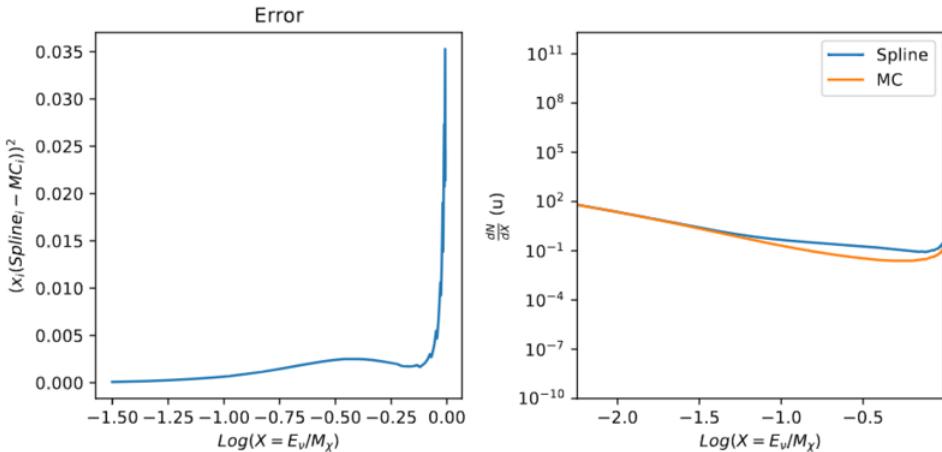


Figure 7.4 Example spline that failed the fit. Failed splines are corrected on a case by case basis unless the SM channel has a systematic problem fitting the splines. In this case, I made a bookkeeping error and loaded the incorrect spectral model

1903 the kernel mask as the upper limit of evaluation. Table 7.1 summarizes the tolerances for the DM
 1904 annihilation channels used for this analysis.

1905 The errors are then assesed in two ways. First, FAIL and OK are directly plotted with e_i as a
 1906 function of x with the full spline and MC. An example of a single failure is provided in Fig. 7.4.
 1907 Second, a summary plot of all the splines is plotted and colors coded. Figure C.1 are the spline
 1908 summaries as of writing this thesis. The goal broadly is to eliminate all red and inspect yellow
 1909 statuses.

1910 The ν_e spectra at Earth are not considered in this analysis, so no work was done to refine the

1911 spline fits for this flavor. Finally, I perform a visual inspection of the splines to verify that the spline
 1912 fitting did not introduce spurious features that would corrupt the likelihood fitting.

1913 7.3.1.3 Composite Neutrino Spectra

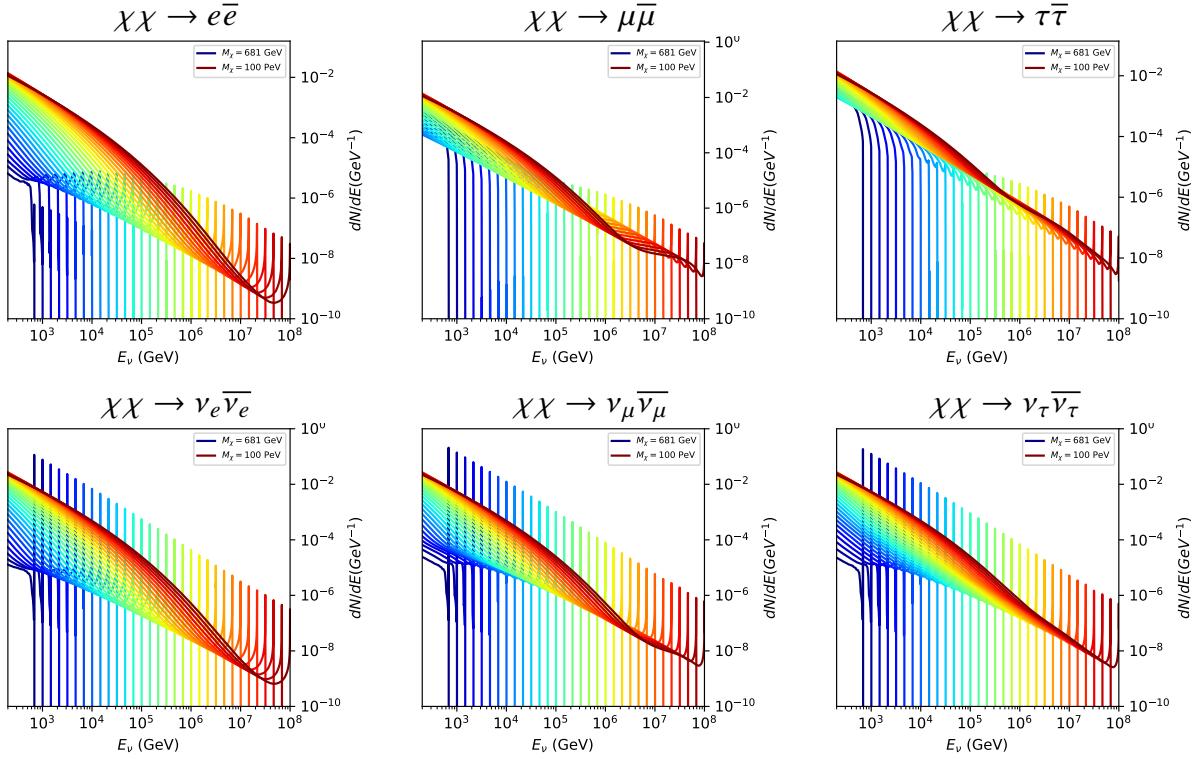


Figure 7.5 Summary of input spectral models that were smoothed with Gaussian kernels. Spectral models are for $\chi\chi \rightarrow e\bar{e}$, $\mu\bar{\mu}$, $\tau\bar{\tau}$, $\nu_e\bar{\nu}_e$, $\nu_\mu\bar{\nu}_\mu$, and $\nu_\tau\bar{\nu}_\tau$. These spectra are the composite ($\nu_\mu + \nu_\tau$) of neutrino flavors. Every spectral model used for this analysis is featured as a colored solid line. Bluer lines are for low m_χ models. m_χ ranges from 681 GeV to 100 PeV. HDM [79], χ arov [85], and Photospline [89] are used to generate these spectra. Energy (x-axis) was chosen to roughly represent the energy sensitivity of NST.

1914 With all the previously mentioned pieces, we are ready to fully assemble a comprehensive
 1915 description of the particle physics term dN/dE in Eq. (7.1).

$$\frac{dN_\nu}{dE_\nu} = \left(\frac{dN_{\nu_e}}{dE_{\nu_e}} + \frac{dN_{\nu_\mu}}{dE_{\nu_\mu}} + \frac{dN_{\nu_\tau}}{dE_{\nu_\tau}} \right)_{\text{src}} \cdot \mathbf{P}(\nu_\alpha \rightarrow \nu_\beta) \quad (7.5)$$

1916 Figure 7.5 shows the spectral models that required Gaussian smoothing, the leptonic annihilation
 1917 channels. The remaining models where the only processing were spline fitting and neutrino
 1918 oscillation are documented in Section C.3. Notice that the different neutrino flavors are unique,

especially in their low energy tails. Therefore, this analysis will be sensitive to DM annihilating to the distinct neutrino flavors.

7.3.2 *J*- Astrophysical Component

For this analysis, we re-adopt the \mathcal{GS} model [59] used in Sec. 5 for dSphs. These models are based on a modified Navarro-Frenk-White (NFW) profile where the indices of the NFW (traditionally 1,3,1) are allowed to float. The angular width of these sources is much smaller than the angular resolution of IceCube NST [88]. We therefore treat these sources as point sources in this analysis, and forgo generating maps. These sources and the \mathcal{GS} model have already been discussed at length in Section 5.3.2 and is not repeated here. IceCube uses identical sources to Tab. 5.1 except we analyze source with declinations above 0.0° .

7.3.3 Source Selection and Annihilation Channels

We use all the dSphs presented in IceCube’s previous dSph DM search [83] and expand beyond it. IceCube’s sources for this analysis studies include Boötes I, Canes Venatici I, Canes Venatici II, Coma Berenices, Draco, Hercules, Leo I, Leo II, Leo V, Leo T, Segue 1, Segue 2, Ursa Major I, Ursa Major II, and Ursa Minor. A full description of all sources used is in Table 5.1. Sources with declinations less than 0.0 are excluded from this analysis.

This analysis improves on the previous IceCube dSph paper [83] in the following ways. Previously, the IceCube detector was not yet completed to the 86 string configuration. Many more dSphs will be observed, from 4 to 15. Previously, the particle physics model used for neutrino spectra from DM annihilation did not have EW corrections where they are now included [79]. The spectral models also predict substantial differences between the neutrino flavors, so this analysis will be the first DM dwarf analysis to discriminate between primary neutrino flavors. The study performed here studies 10.4 years of data.

The SM annihilation channels probed for this study include $\chi\chi \rightarrow$

$b\bar{b}, t\bar{t}, u\bar{u}, d\bar{d}, e\bar{e}, \mu\bar{\mu}, \tau\bar{\tau}, ZZ, W^+W^-, \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu$, and $\nu_\tau\bar{\nu}_\tau$

1944 **7.4 Likelihood Methods**

1945 I use the Point-Source search likelihood which is widely used in IceCube analyses. The
1946 likelihood function is defined as the following:

$$L(n_s) = \prod_{i=1}^N \left[\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right] \quad (7.6)$$

1947 where i is an event index, S and B are the signal PDF and background PDF respectively. For a joint
1948 analysis where the sources are stacked the likelihood is expanded in the simplified way:

$$L(n_s) = \prod_{i=1}^{N_{\text{sources}}} L_i(n_s) \quad (7.7)$$

1949 Where L_i is the likelihood from the i -th source in the stacked analysis. The Test Statistic (TS)
1950 definition remains the same as Eq. (5.7)

1951 **7.5 Background Simulation**

1952 Before we look at data, we must first analyze background and signal injection to validate our
1953 analysis. We set out to characterize the TS distributions for each source, annihilation channel, and
1954 m_χ . Previous IceCube DM searches [87, 91] showed TS distributions that did not behave according
1955 to a χ^2 distribution with 1 degree of freedom. TS distributions can also vary significantly between
1956 DM mass and annihilation models. Therefore, Wilk's theorem may not be applicable to the analysis.
1957 Instead, a critical value is defined from many background trials. We study the TS distributions
1958 first for each source, then for the stacked analysis. The following sections show the results of the
1959 likelihood fitting for a suite of background trials.

1960 I assume that TS values are physical: $TS \geq 0$. $\epsilon[x]$ indicate the fraction of events where $TS < x$.
1961 For TS plots shown here, the decimal values of x are 1.0e-2 and 1.0e-3. Each subplot represents
1962 a simulation of 100,000 data-scrambled background trials. Section 7.5.1 show the background TS
1963 distributions obtained from Segue 1, a source with little Earth attenuation and large J -factor, and
1964 Ursa Major II, which has similarly large J -factor but significantly more Earth attenuation, assuming
1965 DM annihilation into $b\bar{b}$, $\tau\bar{\tau}$, and $\nu_\mu\bar{\nu}_\mu$. I show the TS distributions of a stacked study of 15 sources
1966 for all DM annihilation channels.

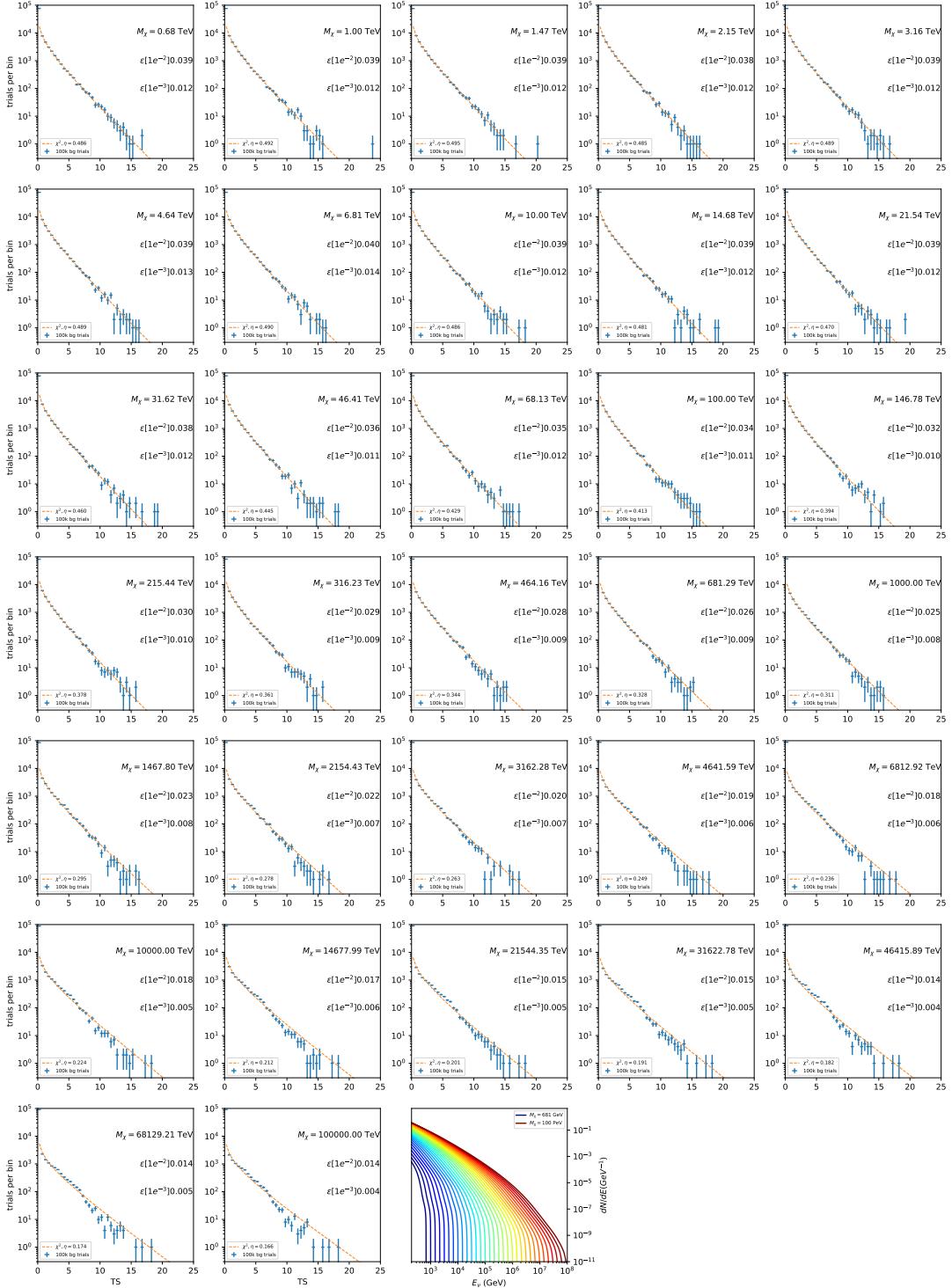


Figure 7.6 Test statistic (TS) distributions for Segue 1 and $\chi\chi \rightarrow b\bar{b}$. Each subplot, except the final, is the TS distribution for a specific DM mass listed in the subplot. Orange dashed lines are the traces for a χ^2 distribution with 1 degree of freedom. $\epsilon[\cdot]$ is the fraction of trials smaller than the bracketed value. The final subplot features the all DM spectral models, similar to Fig. 7.5, used as input for the TS distributions.

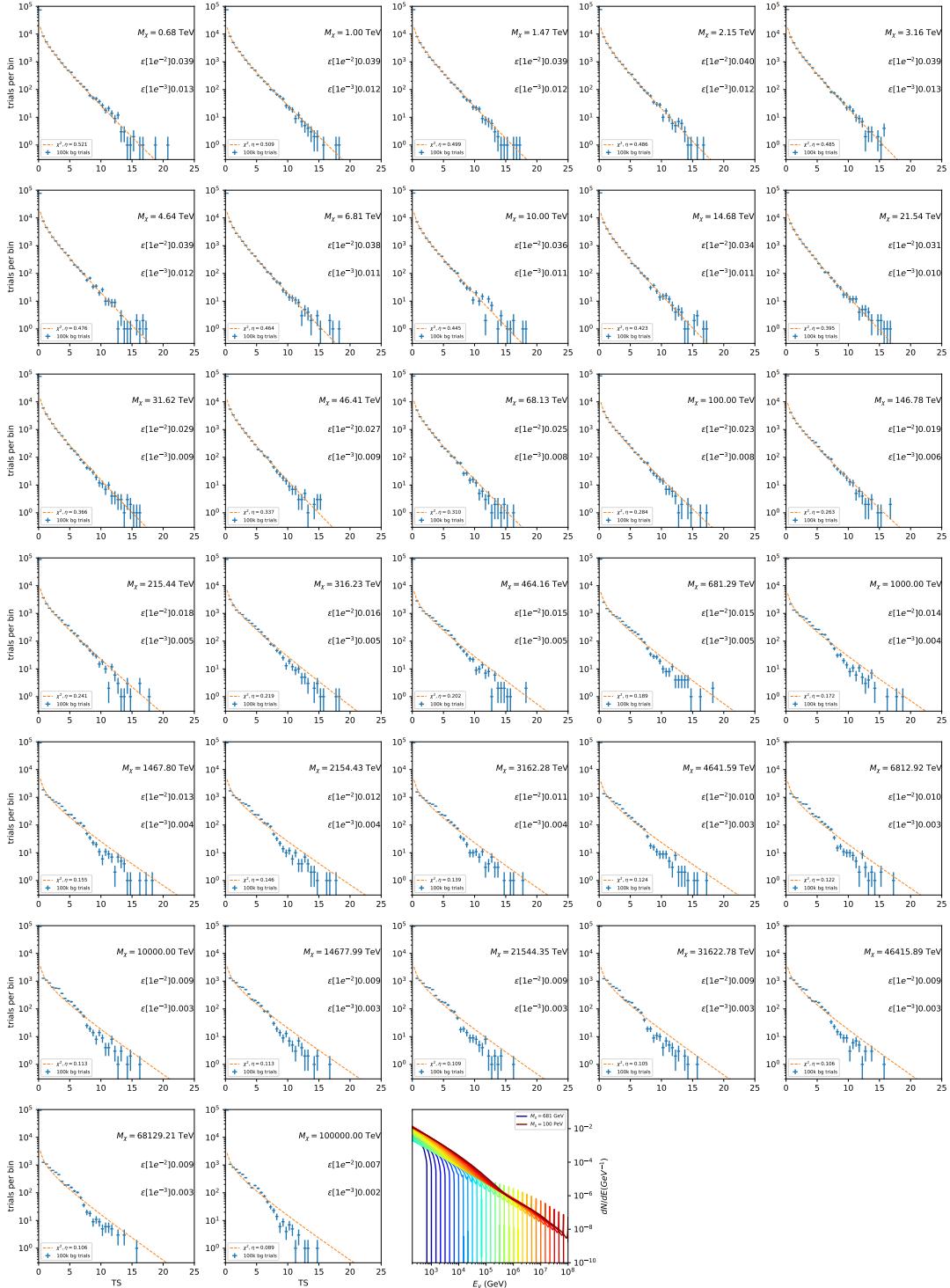


Figure 7.7 Same as Fig. 7.6 for Segue 1 $\chi\chi \rightarrow \tau\bar{\tau}$.

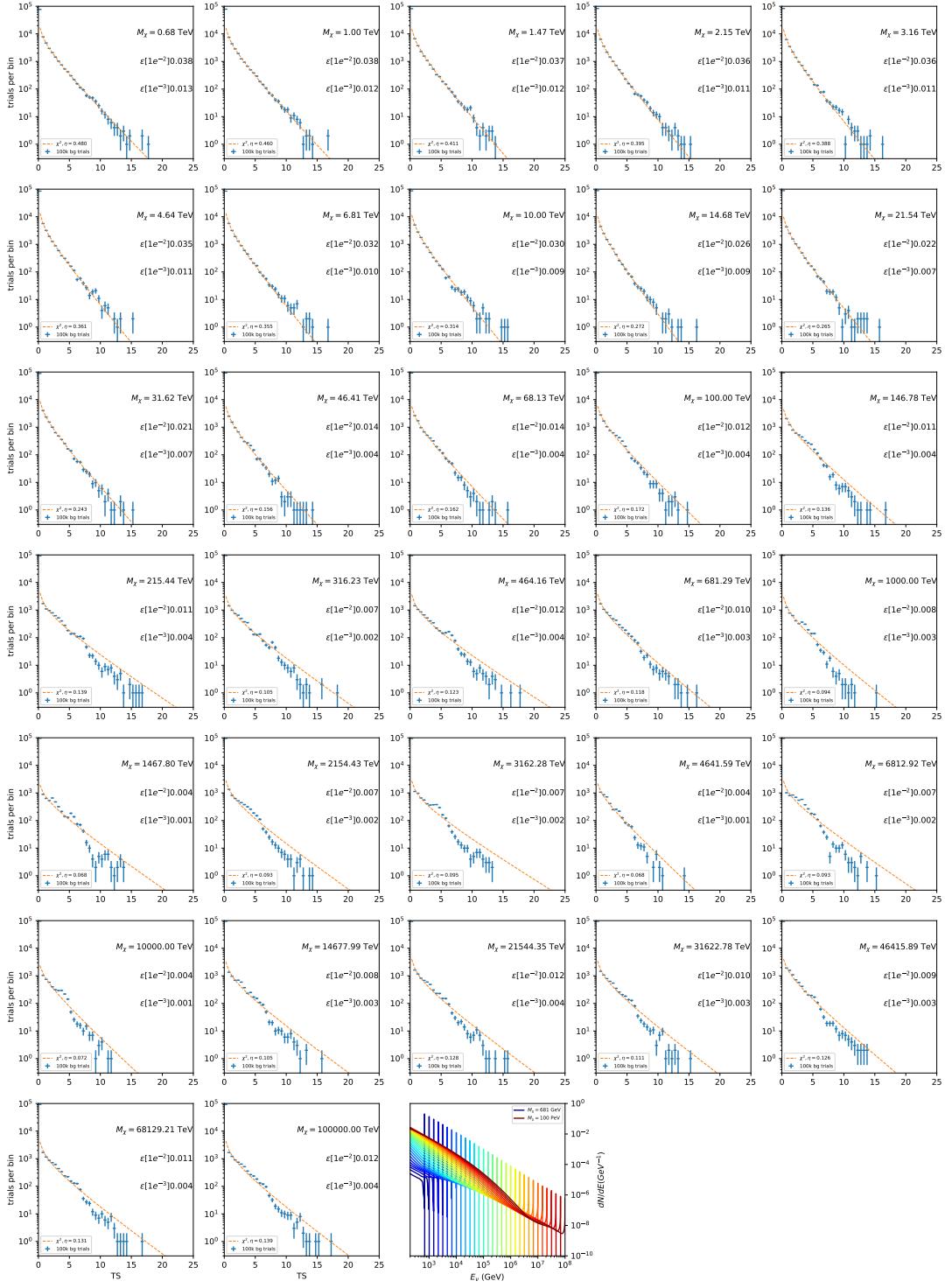


Figure 7.8 Same as Fig. 7.6 for Segue 1 $\chi\chi \rightarrow \nu_\mu\bar{\nu}_\mu$.

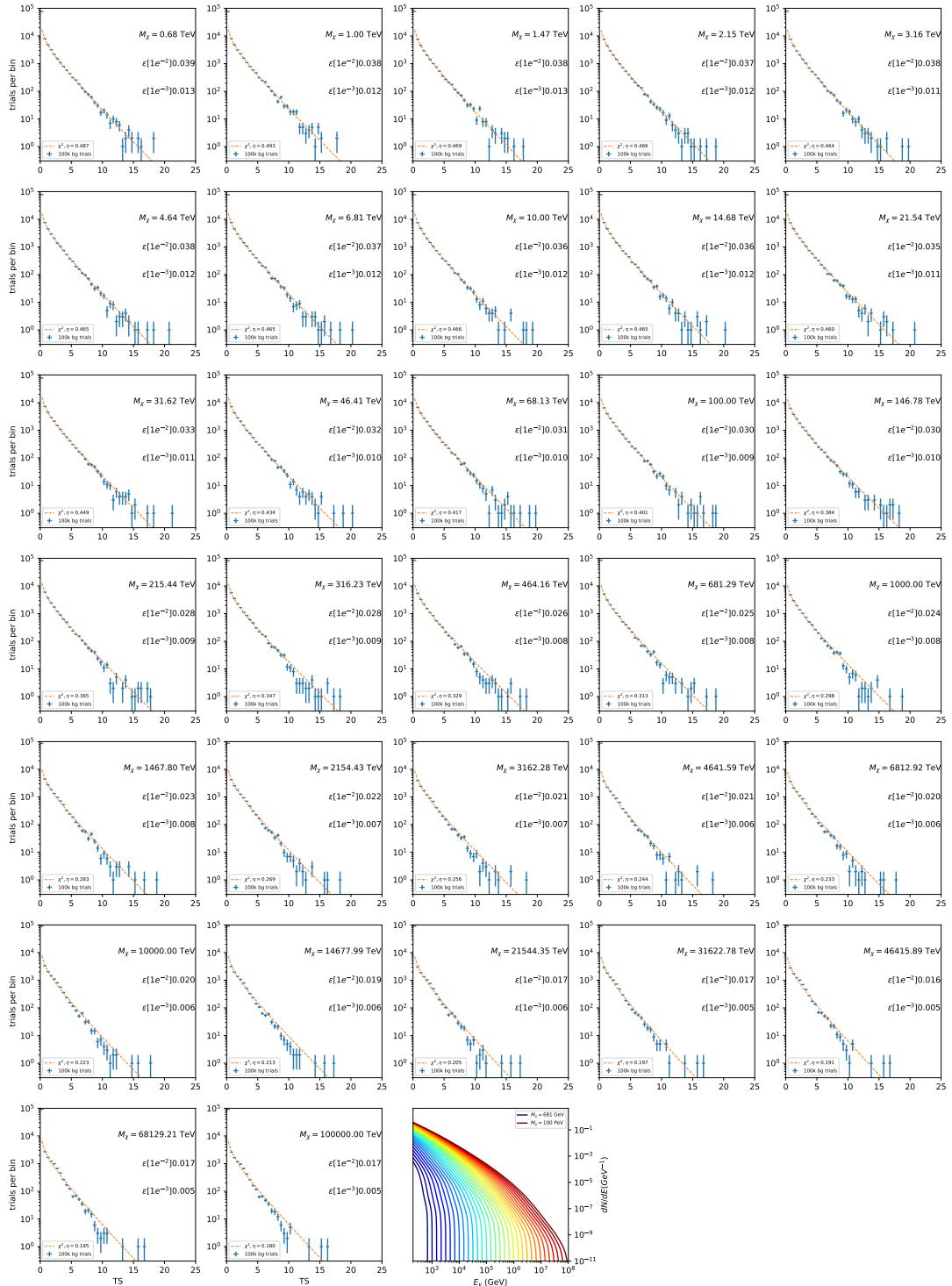


Figure 7.9 Same as Fig. 7.6 for Ursa Major II 1 $\chi\chi \rightarrow b\bar{b}$.

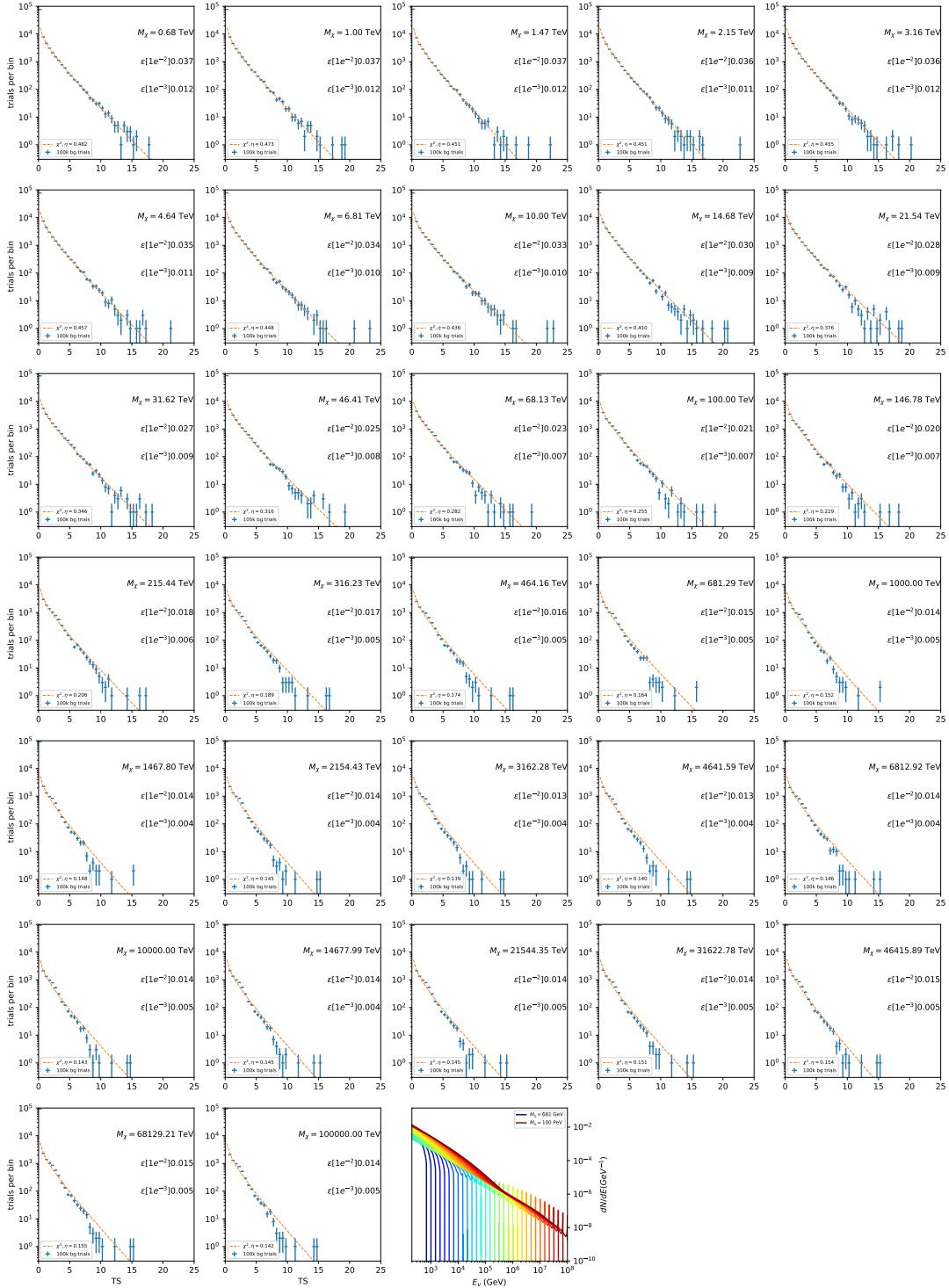


Figure 7.10 Same as Fig. 7.6 for Ursa Major II 1 $\chi\chi \rightarrow \tau\bar{\tau}$.

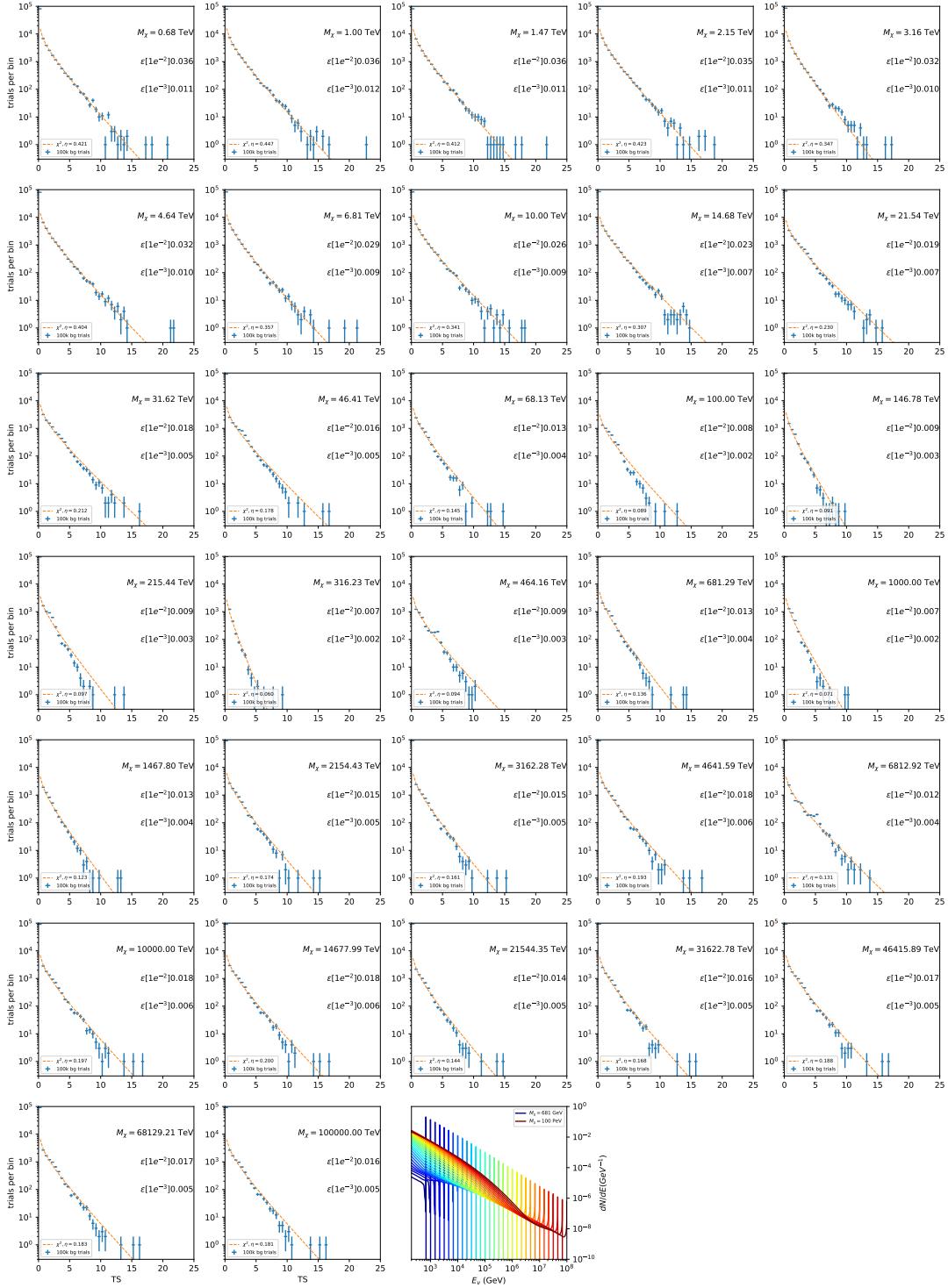


Figure 7.11 Same as Fig. 7.6 for Ursus Major II 1 $\chi\chi \rightarrow \nu_\mu\bar{\nu}_\mu$.

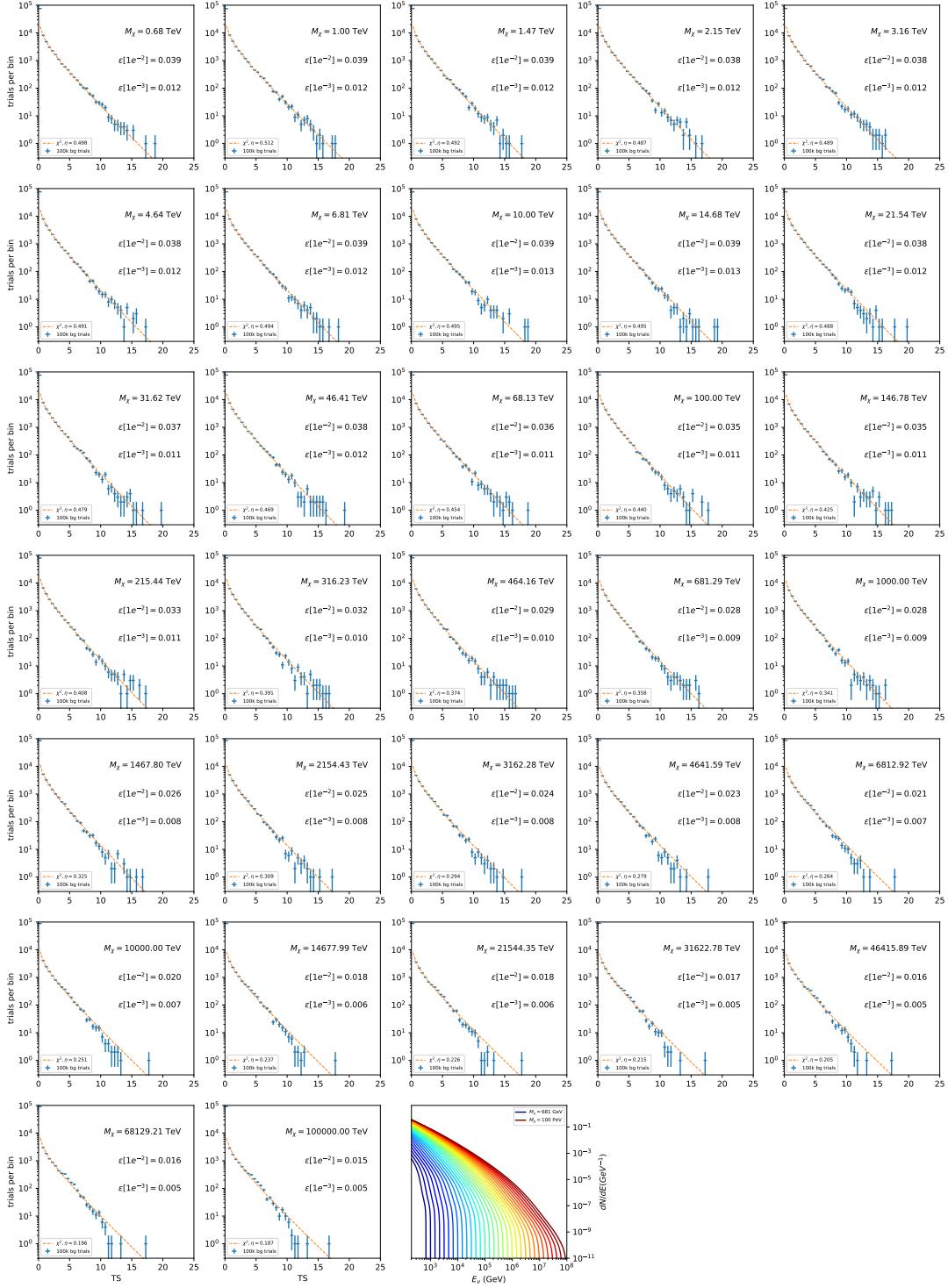


Figure 7.12 Same as Fig. 7.6 for 15, \mathcal{GS} J -factor, stacked sources and $\chi\chi \rightarrow b\bar{b}$.

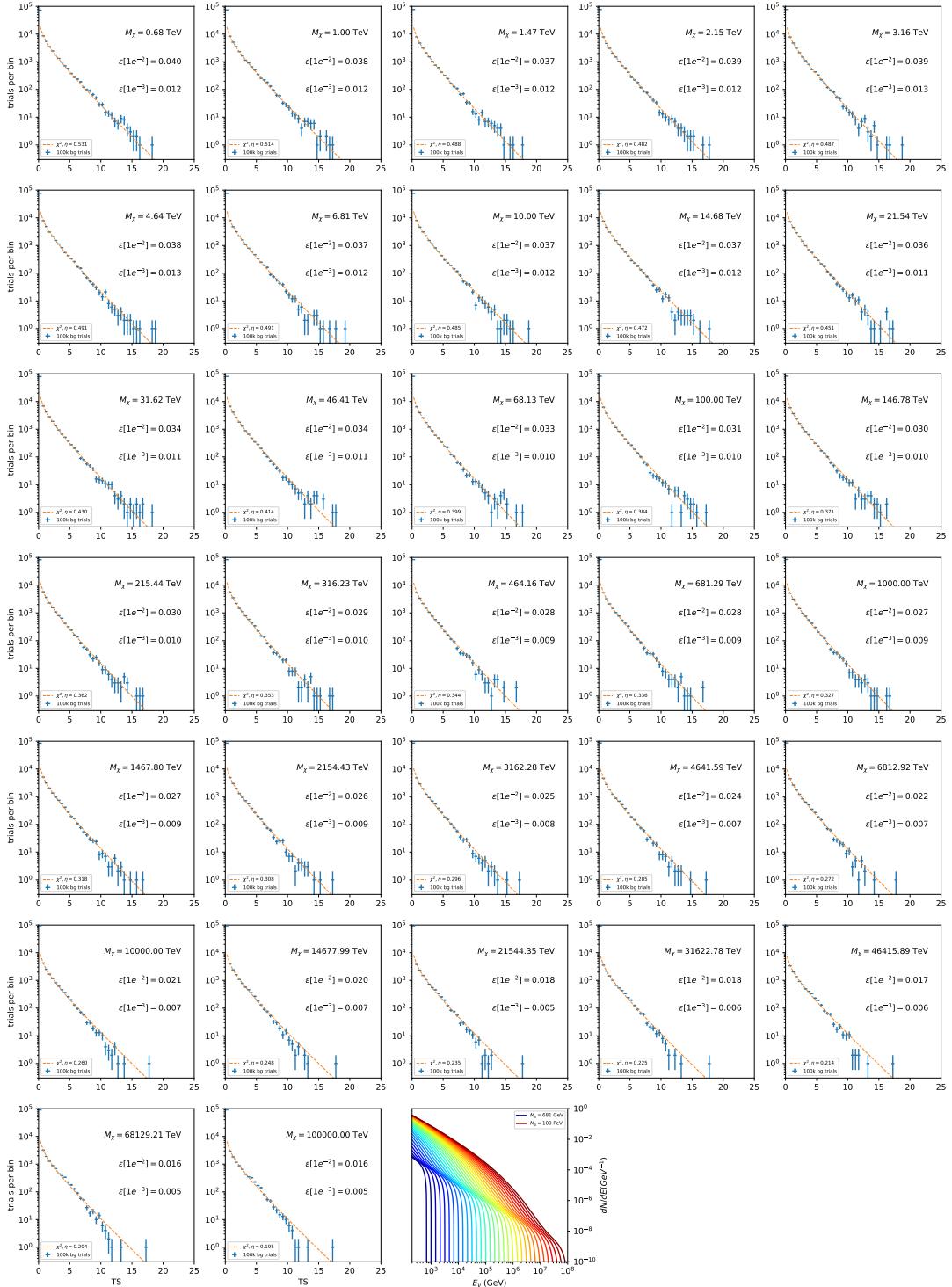


Figure 7.13 Same as Fig. 7.6 for 15, \mathcal{GS} J-factor, stacked sources and $\chi\chi \rightarrow t\bar{t}$.

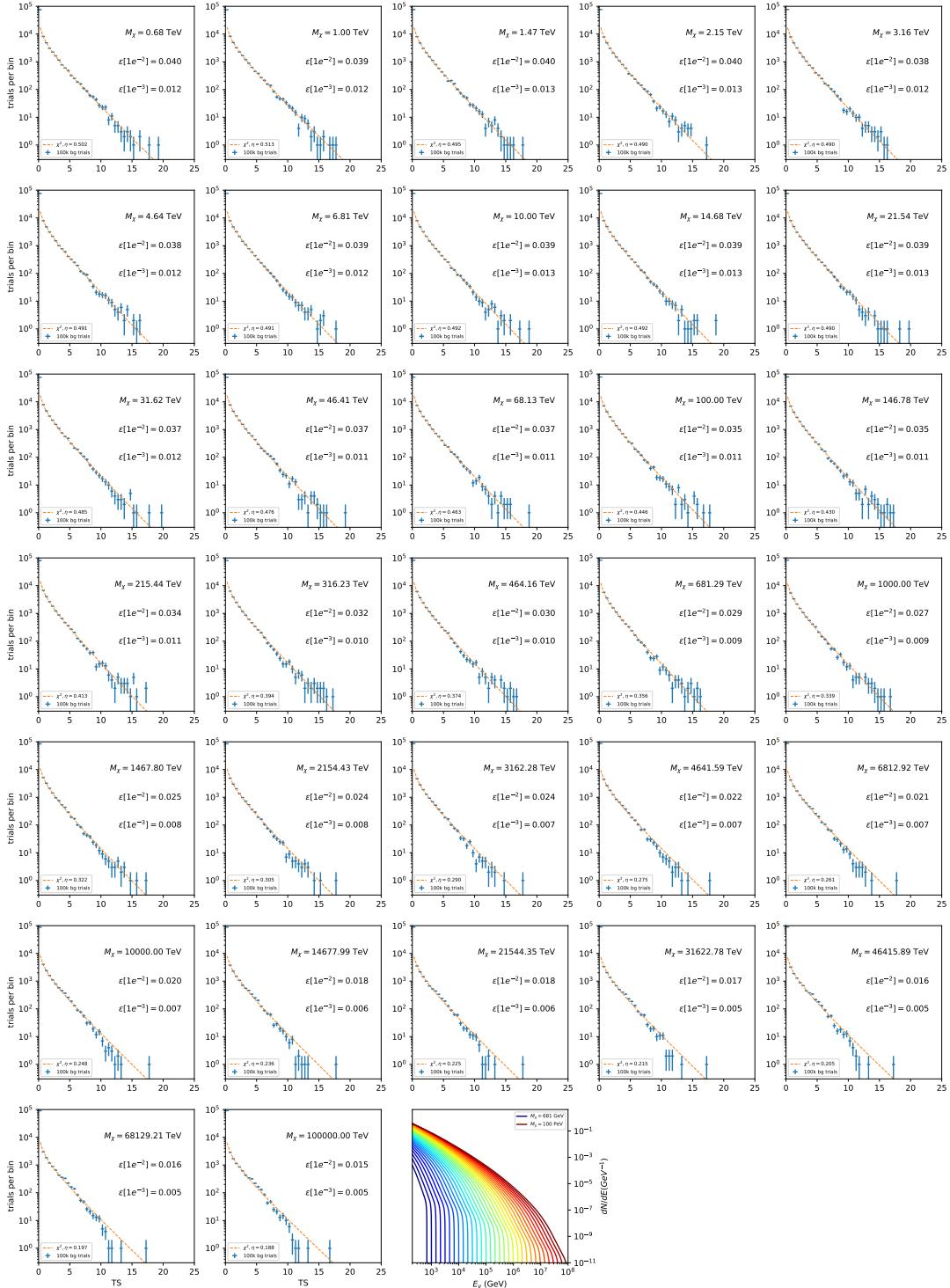


Figure 7.14 Same as Fig. 7.6 for 15, \mathcal{GS} J -factor, stacked sources and $\chi\chi \rightarrow u\bar{u}$.

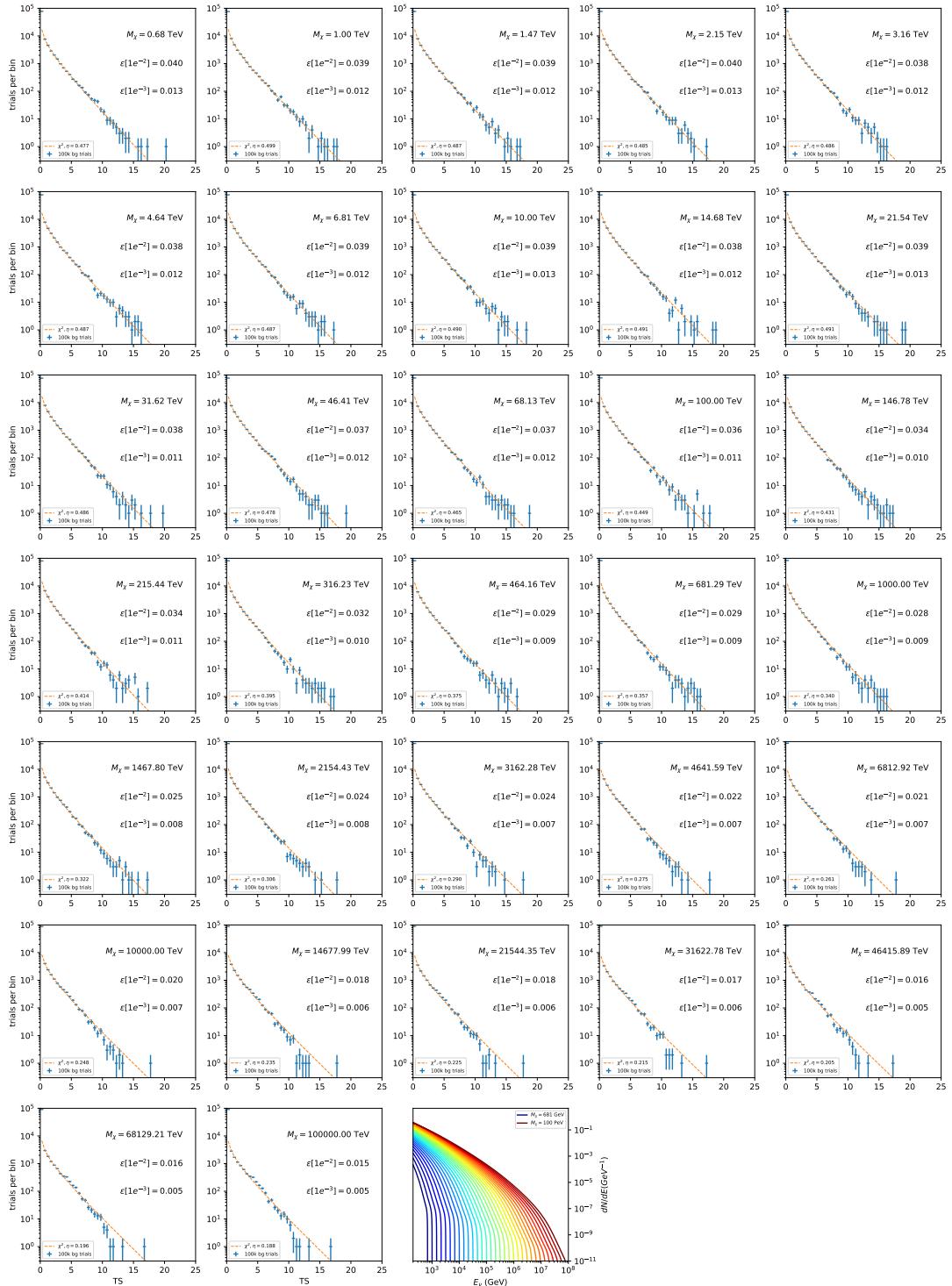


Figure 7.15 Same as Fig. 7.6 for 15, \mathcal{GS} J-factor, stacked sources and $\chi\chi \rightarrow d\bar{d}$.

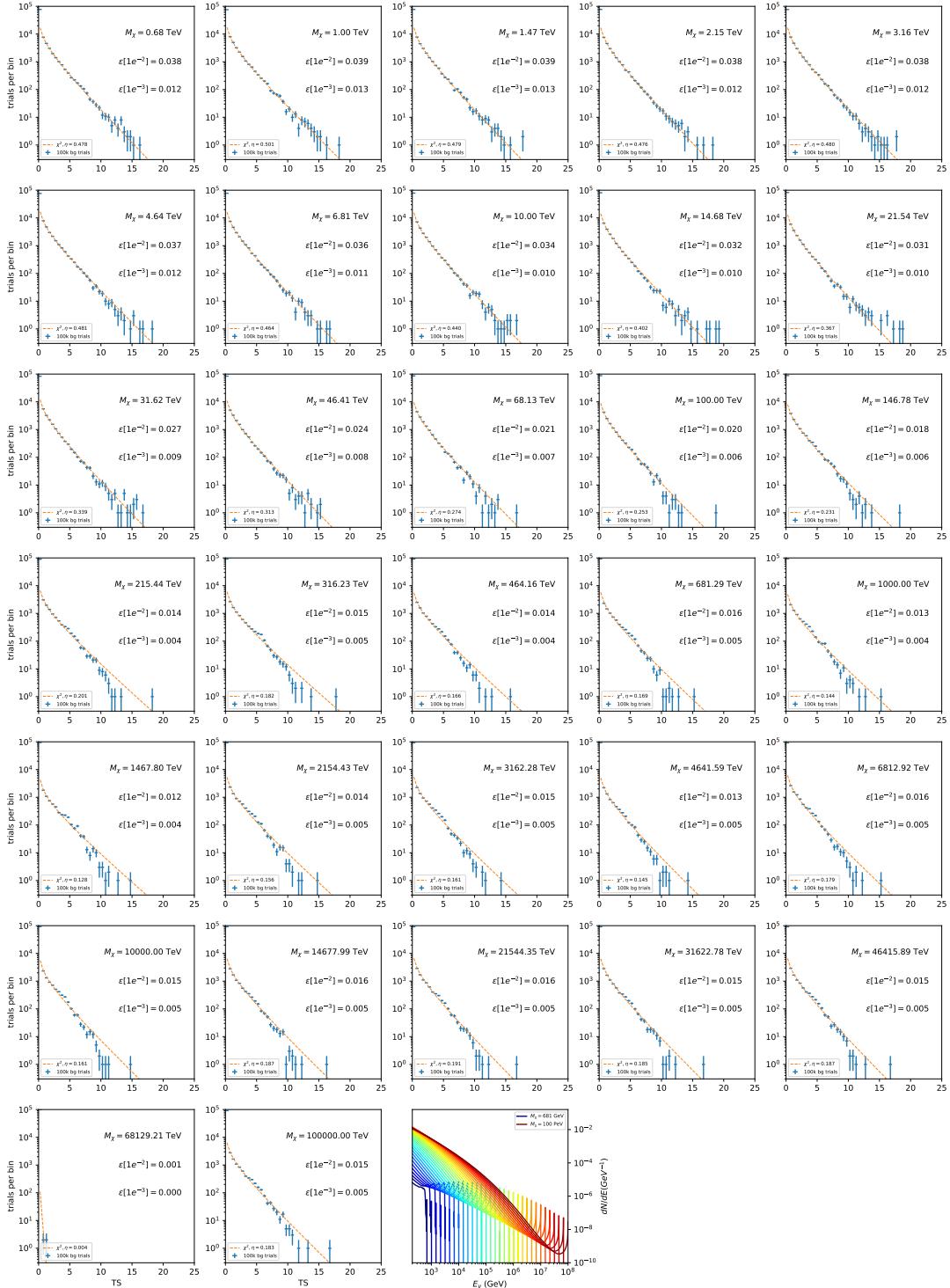


Figure 7.16 Same as Fig. 7.6 for 15, $\mathcal{G}\mathcal{S}$ J-factor, stacked sources and $\chi\chi \rightarrow e\bar{e}$.

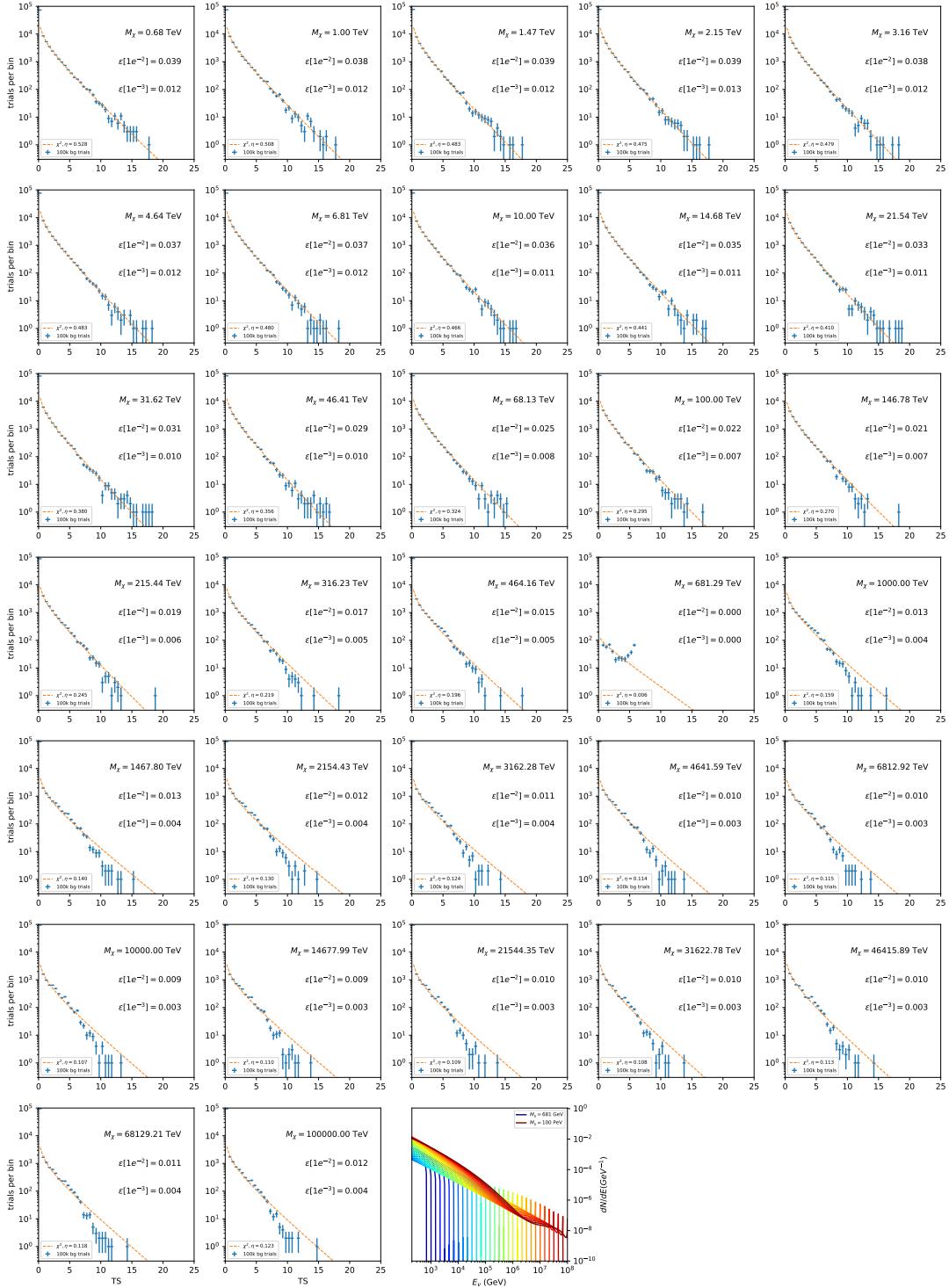


Figure 7.17 Same as Fig. 7.6 for 15, \mathcal{GS} J -factor, stacked sources and $\chi\chi \rightarrow \mu\bar{\mu}$.

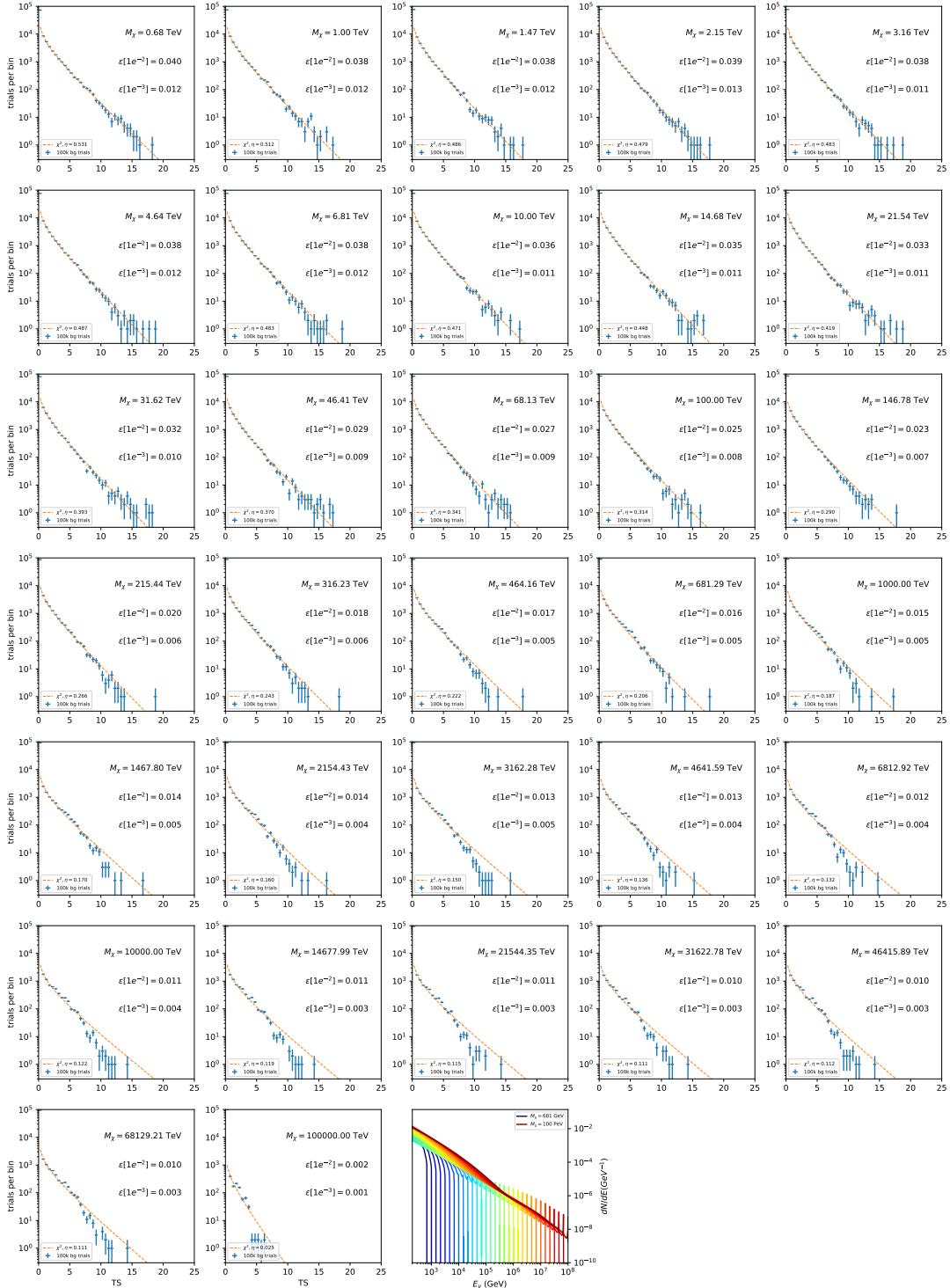


Figure 7.18 Same as Fig. 7.6 for 15, \mathcal{GS} J -factor, stacked sources and $\chi\chi \rightarrow \tau\bar{\tau}$.

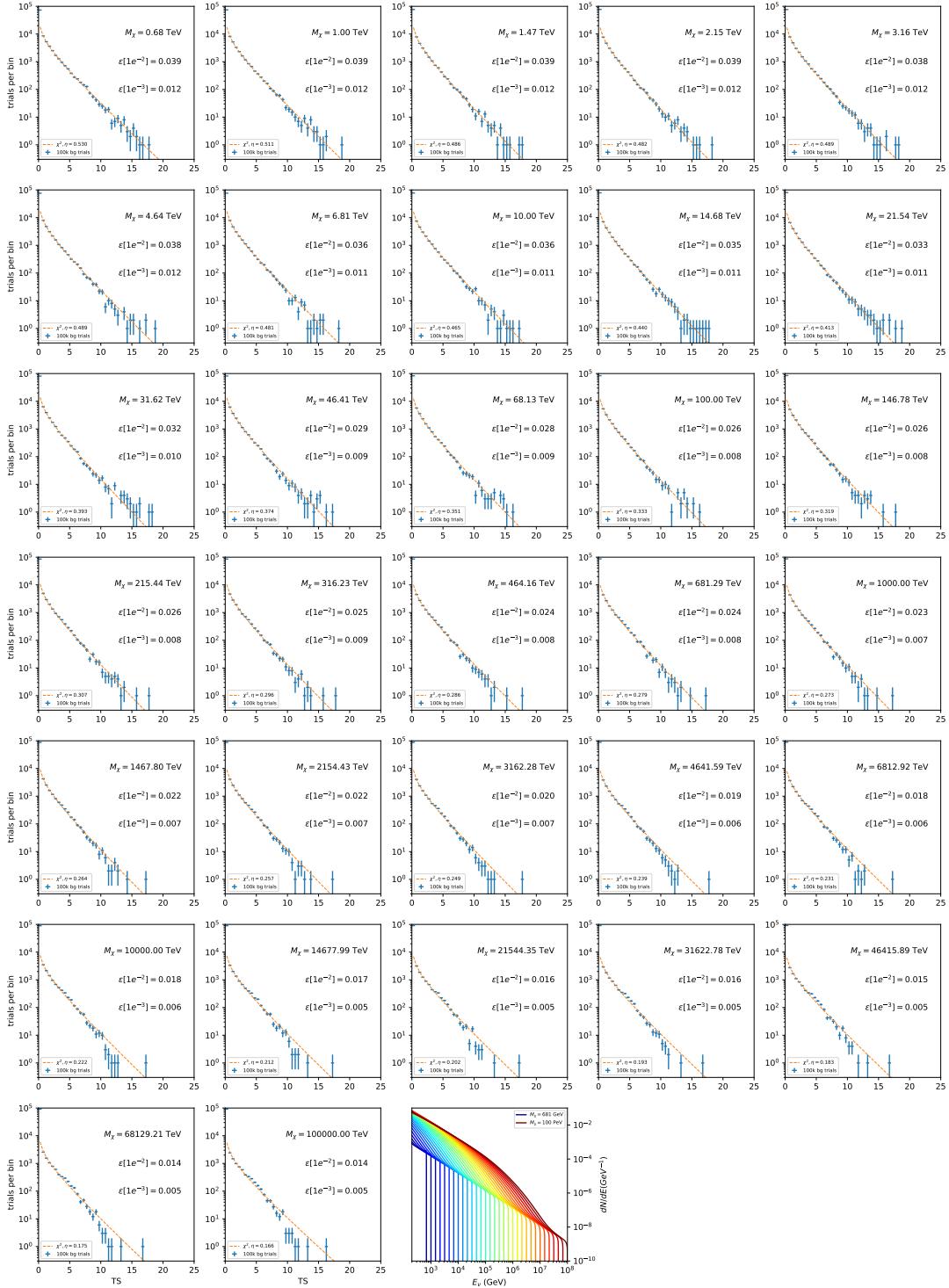


Figure 7.19 Same as Fig. 7.6 for 15, \mathcal{GS} J-factor, stacked sources and $\chi\chi \rightarrow W^+W^-$.

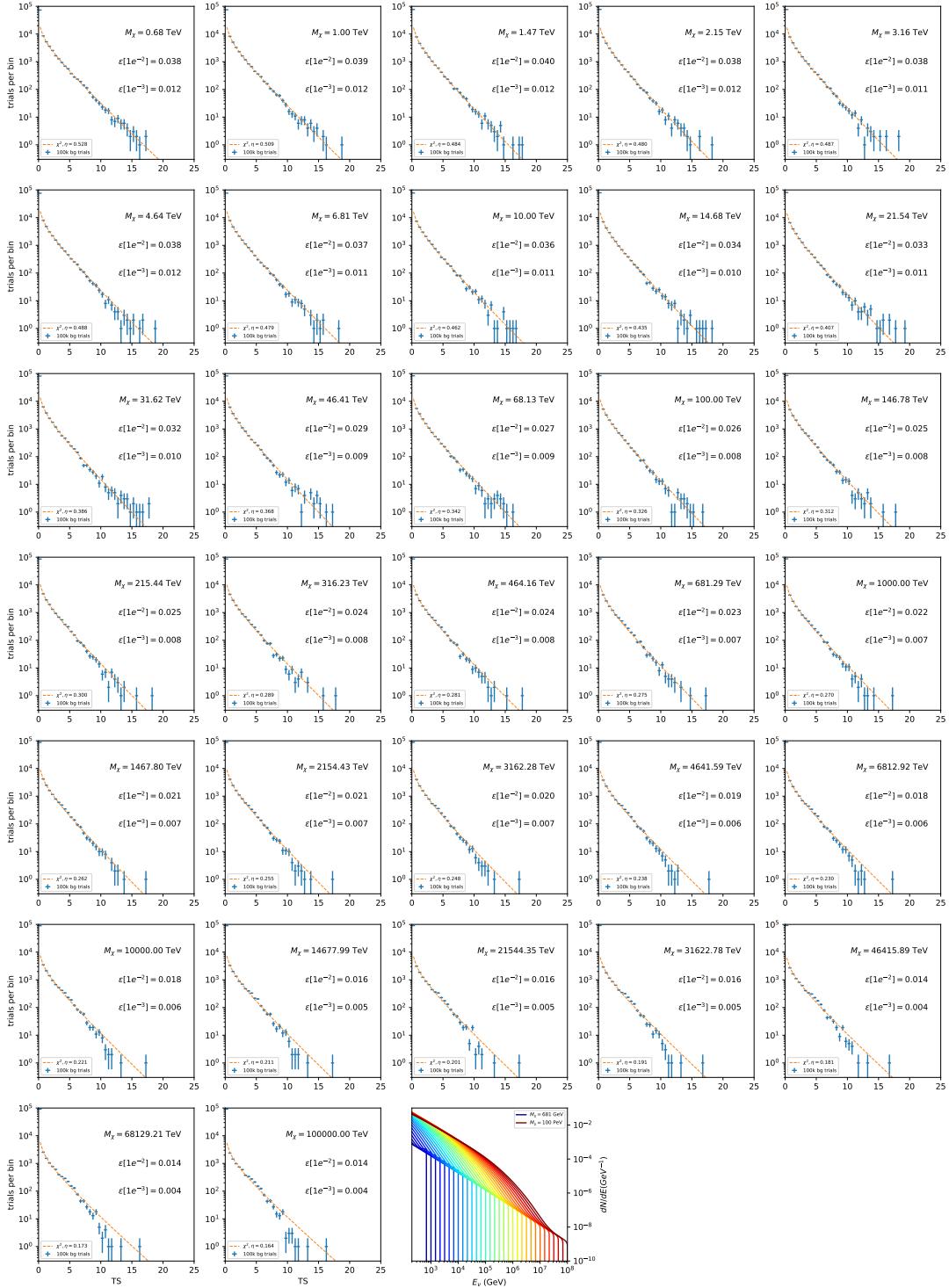


Figure 7.20 Same as Fig. 7.6 for 15, \mathcal{GS} J-factor, stacked sources and $\chi\chi \rightarrow ZZ$.

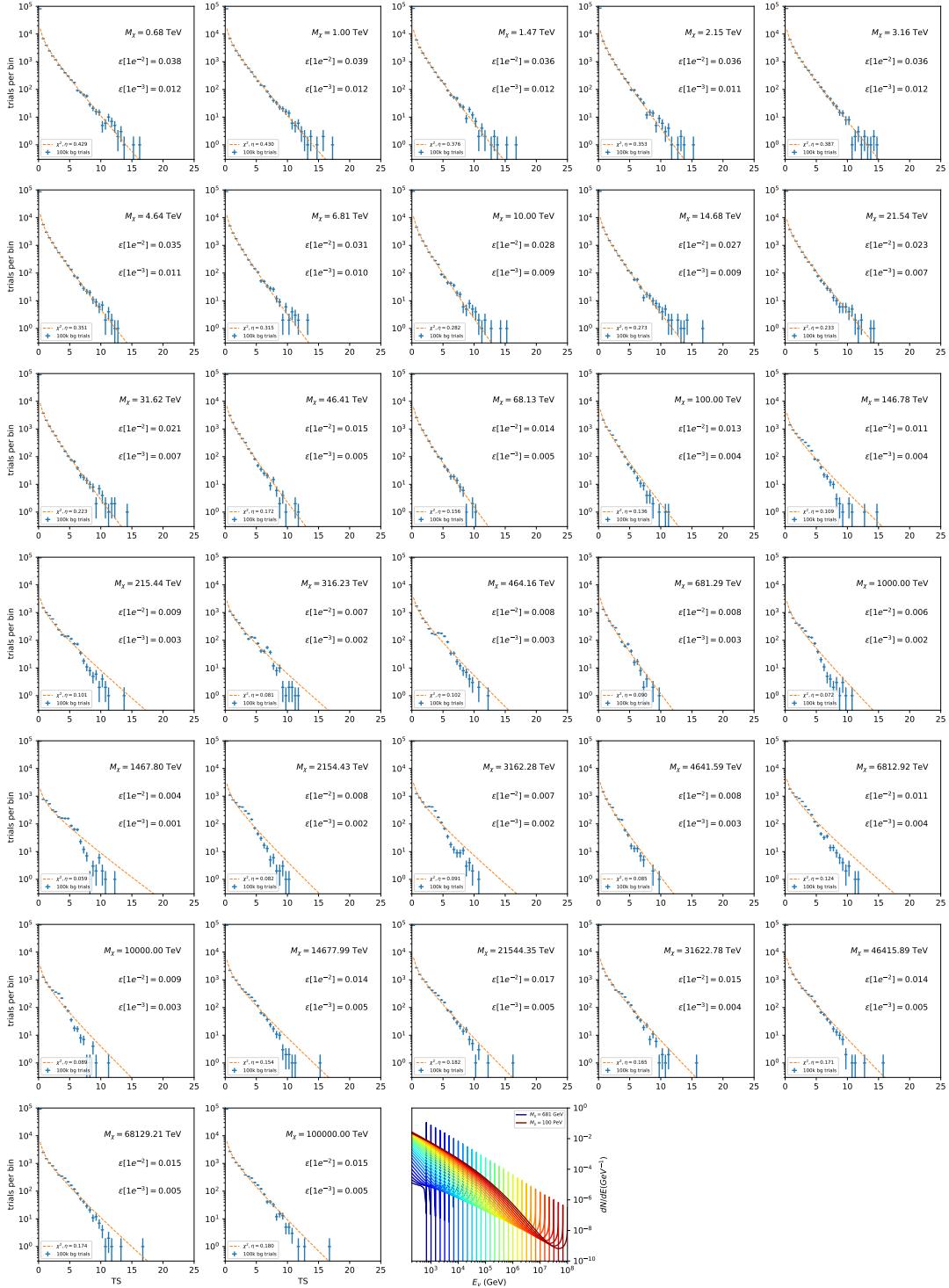


Figure 7.21 Same as Fig. 7.6 for 15, \mathcal{GS} J-factor, stacked sources and $\chi\chi \rightarrow \nu_e \bar{\nu}_e$.

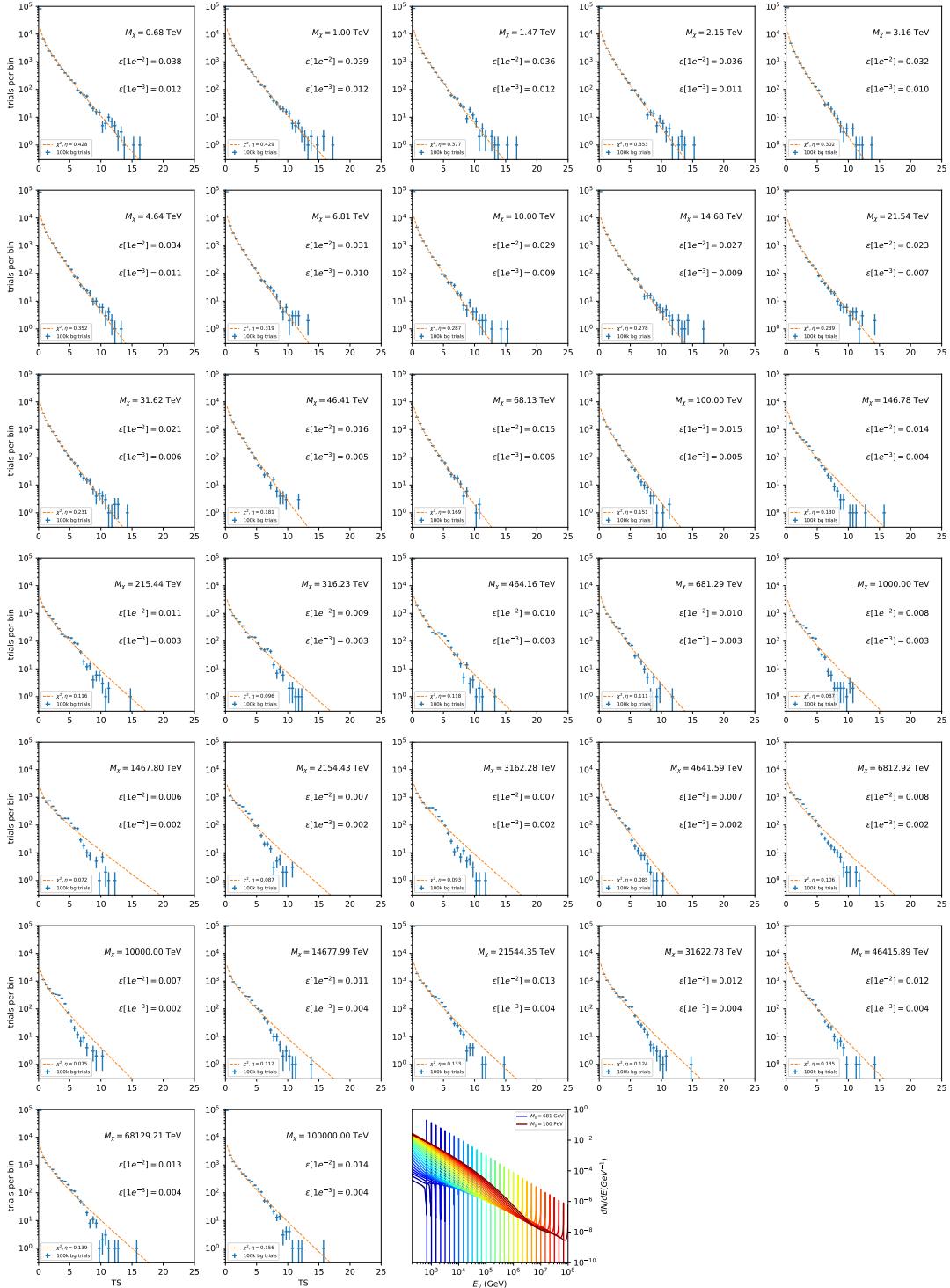


Figure 7.22 Same as Fig. 7.6 for 15, GS J-factor, stacked sources and $\chi\chi \rightarrow \nu_\mu \bar{\nu}_\mu$.

1967 **7.5.1 TS per Source**

1968 Figure 7.6 to Figure 7.11 present the TS distributions for Segue 1 and Ursa Major II for 100,000
1969 trials. More studies for all annihilation channels and remaining 13 sources were also performed
1970 and are documented in IceCube’s internal wiki.

1971 Almost every distribution produced follows a χ^2 distribution with 1 degree of freedom. This is
1972 more true for low m_χ than high m_χ models. These observations are important for future assumptions
1973 made in Sec. 8 and may justify statistical calculations assuming our test statistics follow a χ^2 with
1974 1 degree of freedom.

1975 **7.5.2 Stacked TS**

1976 Figure 7.12 to Figure 7.22 present the TS distributions for a stacked study of 15 sources with
1977 \mathcal{GS} J -factors on 100,000 trials. The presentation of these plots are identical to the single source
1978 distributions in Section 7.5.1. We see similar behaviour in the stacked TS distributions compared
1979 to the single source studies.

1980 **7.6 Signal Recovery**

1981 We also wish to understand how well the analysis is able to reconstruct signal neutrinos. In
1982 order to test this, we inject neutrinos from our spectral models randomly then attempt to discern
1983 the number of signal neutrinos in the simulated data. Figure 7.23 and Figure 7.24 show this study
1984 for $\chi\chi \rightarrow b\bar{b}$, $t\bar{t}$, and $\nu_\mu\bar{\nu}_\mu$ for a stacked analysis of 15 sources. Figure C.3 to Figure C.8 show
1985 identical studies for Segue 1 and Ursa Major II. We see that the analysis is conservative at smaller
1986 m_χ , yet improves at larger m_χ . We also see that the uncertainty is small for the neutrino annihilation
1987 spectra, and the uncertainty is larger for softer channels like $b\bar{b}$.

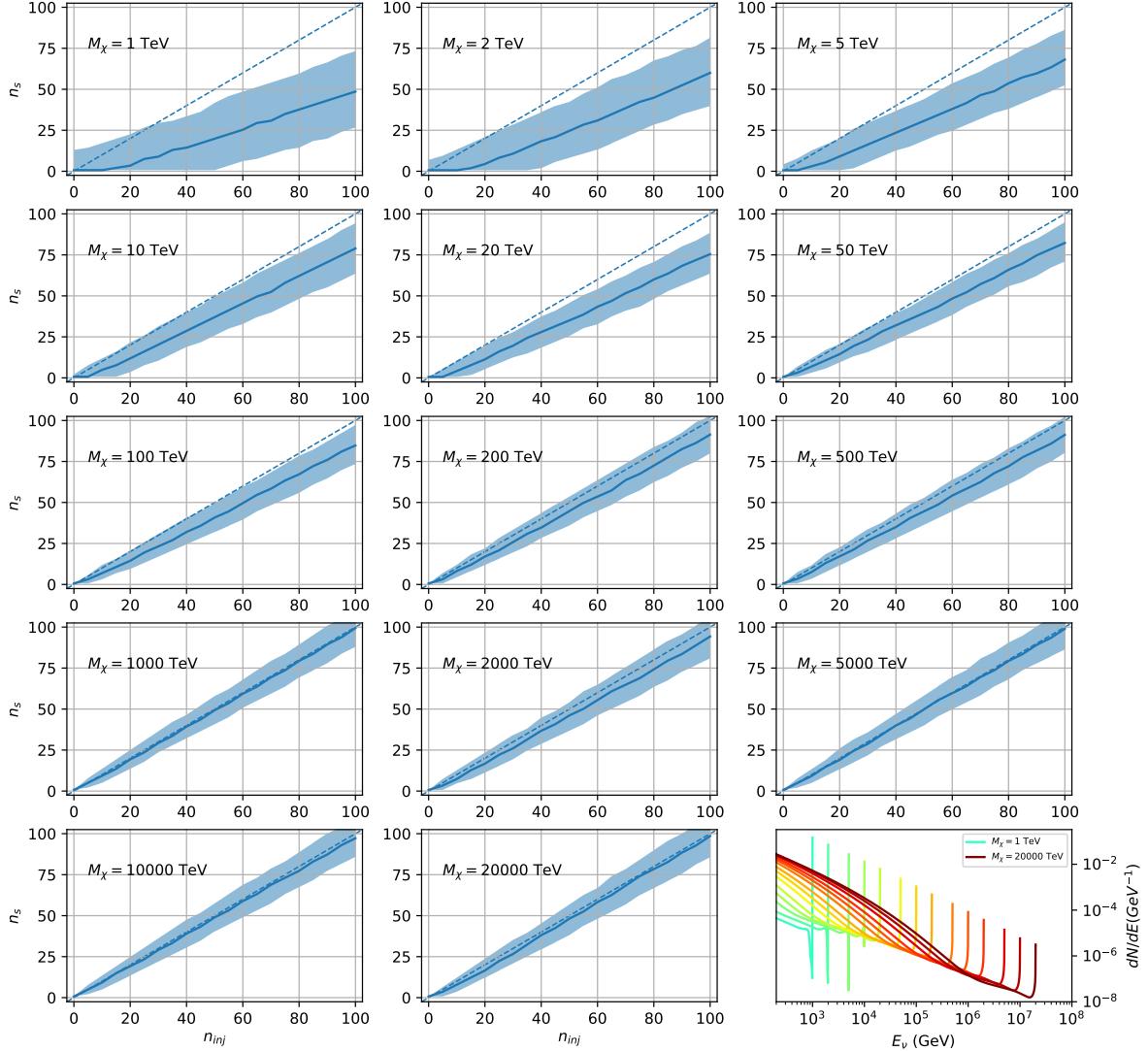


Figure 7.23 Signal Recovery study for an analysis with 15 stacked sources using the \mathcal{GS} J -factors [59]. Above shows 14 studies for DM mass ranging between 1 TeV and 20 PeV for $\chi\chi \rightarrow \mu_\mu\bar{\mu}_\mu$. The bottom right subplot features every spectral model used as input for the remaining subplots. The remaining subplots show n_{inj} as the number of signal events injected into background simulation. Whereas, n_s is the number of signal events recovered from analyzing the injected simulation. Blue line represents the median values of 100 simulations. Light blue bands show the 1σ statistical uncertainty around the median.

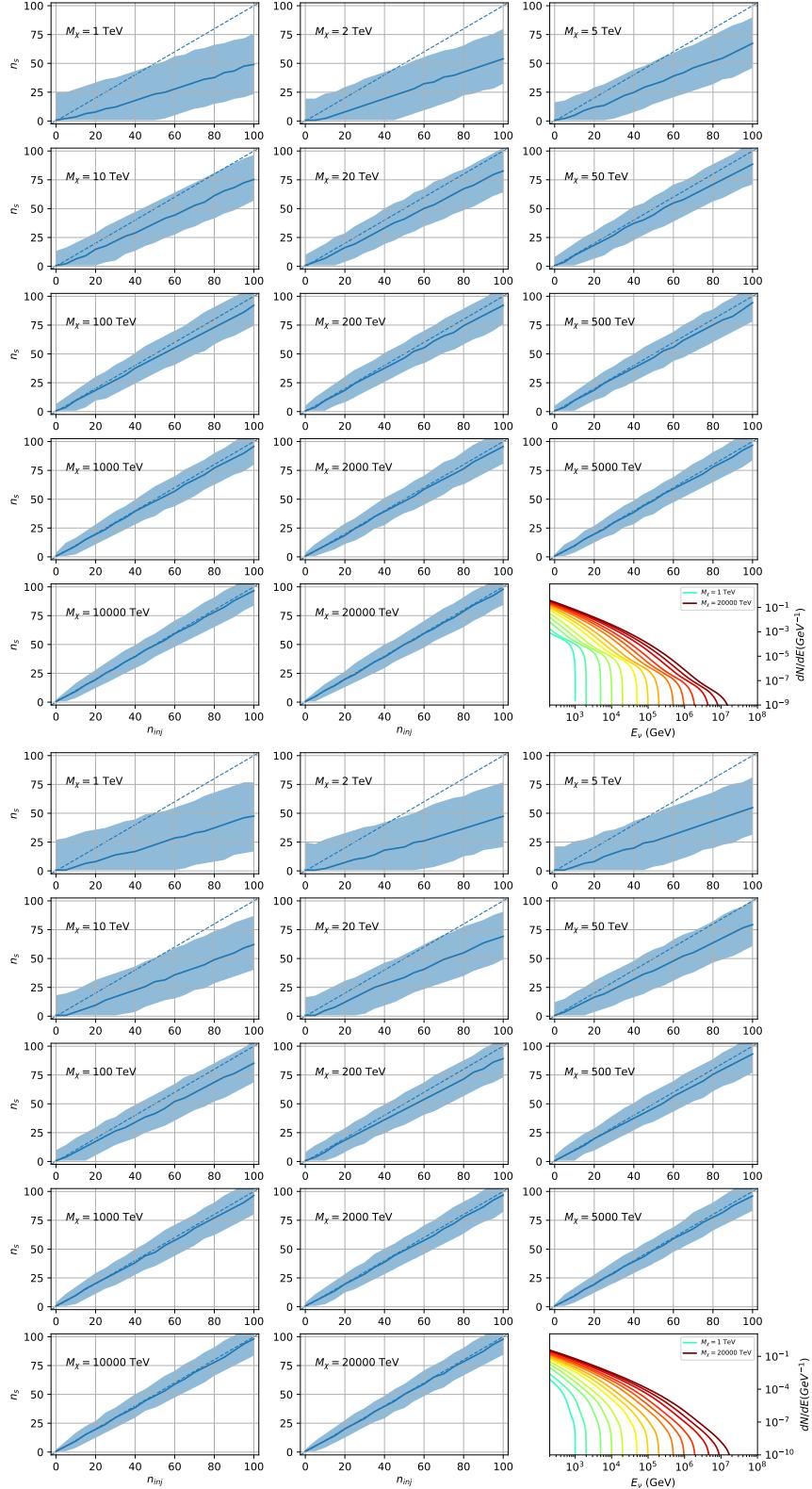


Figure 7.24 Same as Fig. 7.23 but for $\chi\chi \rightarrow t\bar{t}$ (top) and $b\bar{b}$ (bottom).

1988 **7.6.1 Sensitivities**

1989 In IceCube, we usually define the 90% confidence level (CL), as the minimum number of signal
1990 events (n_s) required to have a Type I error rate smaller than 0.5 and Type II error rate of 0.1. We
1991 compute n_s from the following equation

$$n_s = T_{\text{live}} \int_0^{\Delta\Omega} d\Omega \int_{E_{\min}}^{E_{\max}} dE_\nu A_{\text{eff}}(\hat{n}, E_\nu) \frac{d\Phi_\nu}{d\Omega dE_\nu}(\hat{n}, E_\nu), \quad (7.8)$$

1992 to extract the sensitivity on the dark matter velocity-weighted annihilation cross-section, $\langle\sigma v\rangle$. T_{live}
1993 is the detector live time, A_{eff} is the effective area of the detector, and E_{\min} , E_{\max} are the minimum,
1994 maximum energies of the expected neutrinos, respectively.

1995 Sensitivities are calculated for each source individually as if they were the only source and as a
1996 stack over 1000 trials. From Eq. (7.8) and Eq. (7.1) we can compute the $\langle\sigma v\rangle$ at a 90% confidence
1997 level. Figure 7.26 and Fig. 7.25 show the sensitivities for some DM annihilation channels. Not
1998 all channels computed successfully in time for the writing of this dissertation. Among channels
1999 missing include the charged leptons: e and τ .

2000 **7.7 Systematics**

2001 The current analysis plan is to compare these sensitivities to another J -factor catalog such as
2002 \mathcal{LS} [80] although this was not completed in time for this dissertation. Additionally, we set out to
2003 perform a standard suite of IceCube systematic studies which include: DOM efficiency, Hole ice,
2004 ice absorption, and photon scattering. We do study Earth attenuation, and Section 7.7.1 enumerates
2005 the impact of the Earth on our hardest neutrino spectra.

2006 **7.7.1 Earth Effects**

2007 We look to quantify the impact of the Earth on our sensitivity to $\chi\chi \rightarrow \nu_\mu \bar{\nu}_\mu$. This channel is
2008 expected to be among the significantly impacted annihilation channels because it has a significant
2009 contribution at PeV energies for $m_\chi \geq 1\text{PeV}$. The Earth is expected to attenuate these higher energy
2010 neutrinos. However, these neutrino spectra have significant low energy contributions, so we do not
2011 expect to entirely lose our sensitivity. This motivated a study examining our $\langle\sigma v\rangle$ sensitivity over
2012 all DM masses sampled for a selection of declinations.

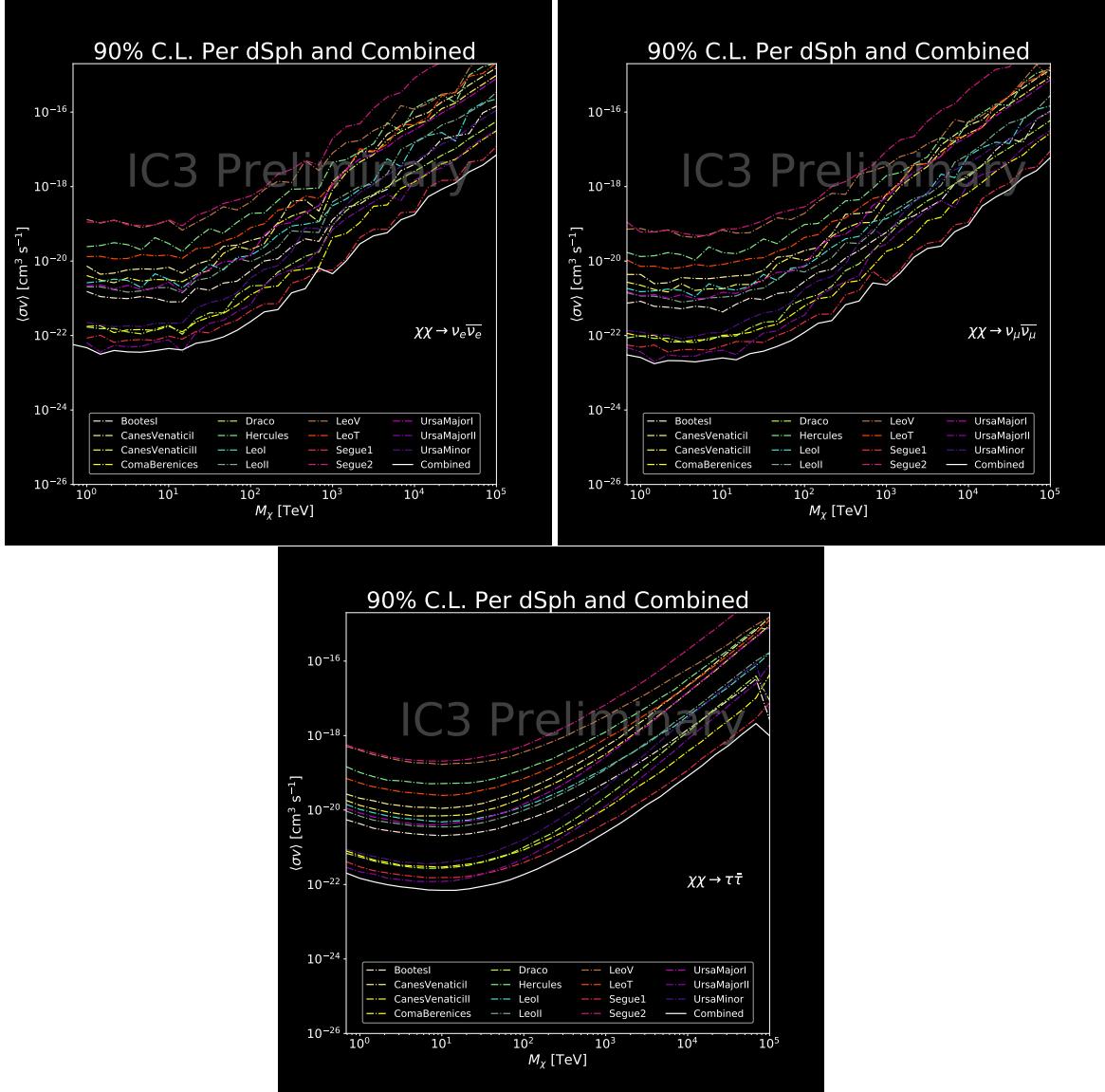


Figure 7.25 IceCube North Sky Track Sensitivities. Each panel shows sensitivity curves for various DM annihilation channels. Sensitivities are for the velocity-weighted cross-section $\langle\sigma v\rangle$ versus m_χ . Dotted, colored lines are sensitivities for individual sources. Solid white lines are for the combined sensitivity of all 15 \mathcal{GS} sources used in this study.

2013 For this systematic study, I sample 6 DM masses per decade from 681 GeV to 100 PeV. I select
 2014 declinations that are shared with sources in the \mathcal{GS} catalog: Boötes I, Canes Venatici II, Leo V,
 2015 Ursa Major I, and Ursa Minor. I study a fake source who's J -factor is shared with Ursa Major II,
 2016 but who's coordinates belong to the aforementioned list. The sensitivity studies performed for each
 2017 source (Fig. 7.25 and Section C.5) provided n_s for 1000 trials which we extracted from Eq. (7.8).
 2018 We derive $\langle\sigma v\rangle$ using $\log_{10} J = 19.42 \log_{10}(\text{GeV}^2 \text{cm}^{-5})$. Figure 7.28 shows the results.

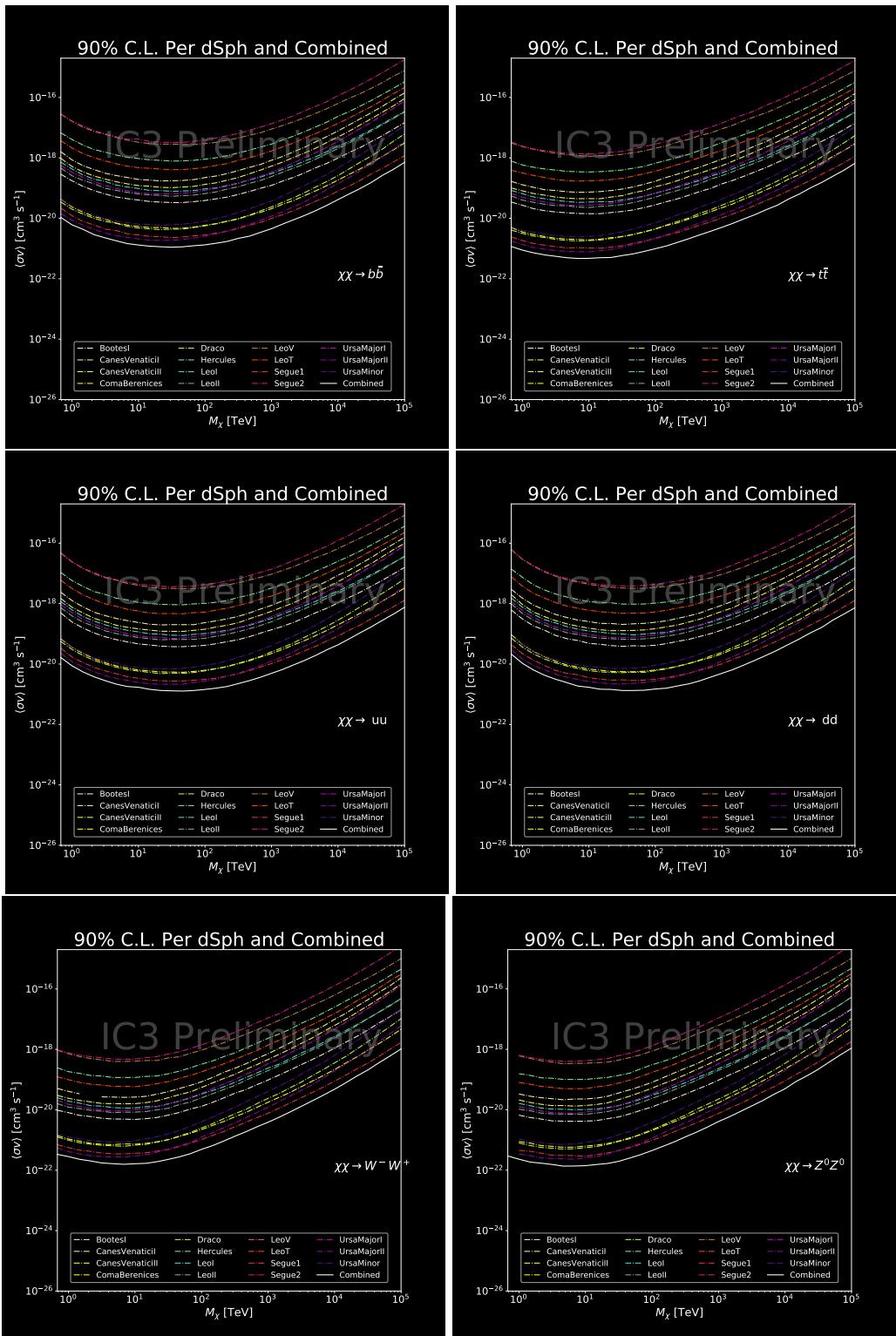


Figure 7.26 Same as Fig. 7.25 for three additional DM annihilation channels.

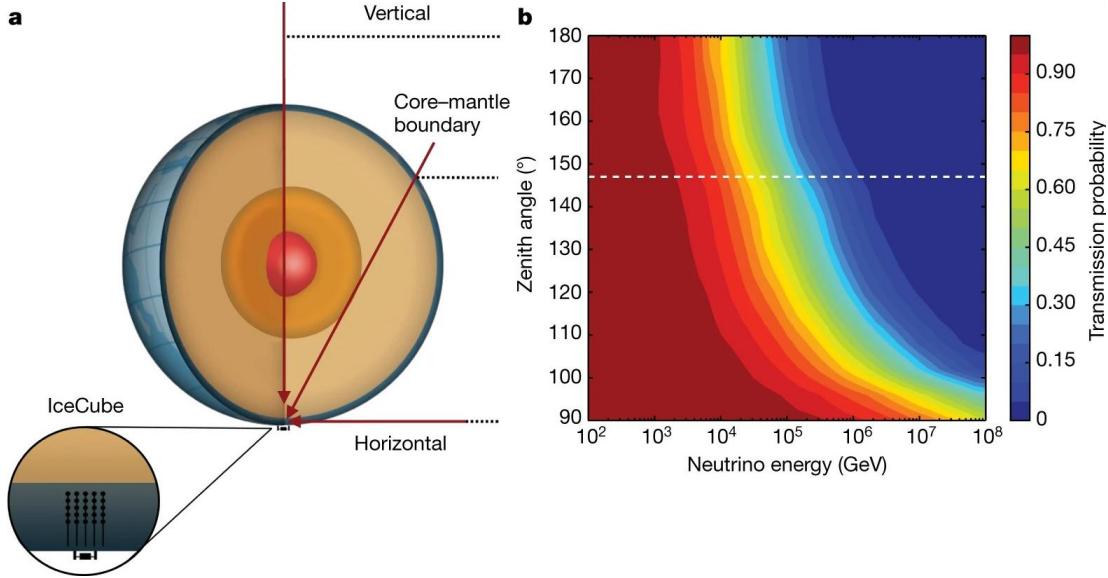


Figure 7.27 Panel A: Neutrino's from the Northern sky and incident on the IceCube detector will travel through the Earth. How much of the Earth these neutrinos travels is a function of zenith from the vertical axis. Panel B: SM prediction of neutrino transmission probabilities for neutrinos arriving at $90^\circ - 180^\circ$ zenith and with 100 GeV to 100 PeV energies. High-energy neutrinos traversing the whole Earth are completely absorbed, whereas low-energy neutrinos pass through unimpeded. Neutrinos coming from above the horizon will arrive unimpeded for all neutrino energies. Figure pulled from [92].

2019 Figure 7.28 shows that we have significant but diminishing sensitivity to sources at high
 2020 declination. We see in the worse case, the sensitivity at high declination is up to an order of
 2021 magnitude worse than at low declination. However, for $m_\chi < 1$ PeV, the sensitivities are very
 2022 similar. The comparable sensitivities imply that a stacking analysis with IceCube is most powerful
 2023 in the 500 GeV to 1 PeV region. Above 1 PeV, our limits and sensitivities are dominated by sources
 2024 near the horizon. When we additionally consider the J -factors, we expect Segue 1 to dominate
 2025 contributions to sensitivity and limits where $m_\chi > 1$ PeV.

2026 7.8 Conclusions

2027 We utilized advanced computing techniques like parallel programming and spline fitting of
 2028 particle physics Monte Carlo to greatly expand and refine IceCube's sensitivity to DM annihilation
 2029 from dSphs. Furthermore, we imported updated astrophysical and particle physics models that
 2030 better represent what we believe neutrino signals from DM annihilation should look like. We, for
 2031 the first time, build an analysis that is sensitive to PeV DM annihilation.

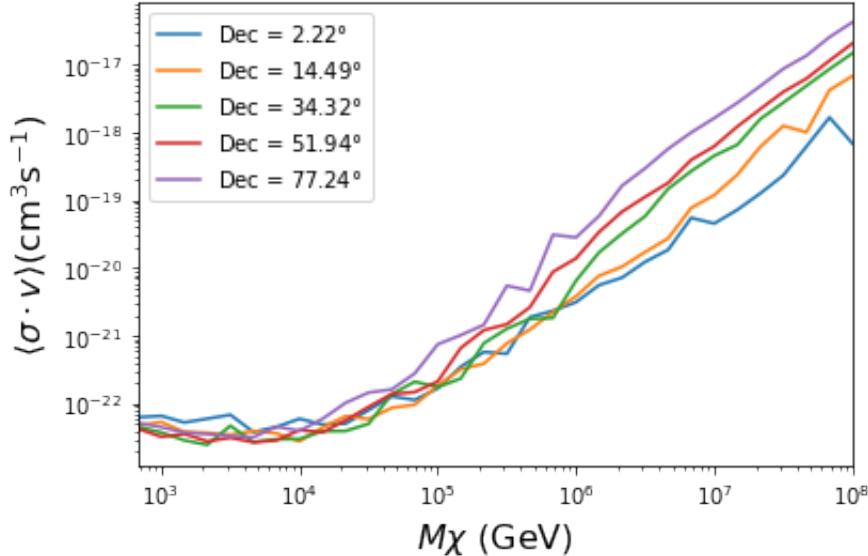


Figure 7.28 $\langle \sigma v \rangle$ sensitivities for 5 imaginary sources with $\log_{10} J = 19.42$ $\log_{10}(\text{GeV}^2 \text{cm}^{-5})$. Each imaginary source shares a declination with a source in Tab. 5.1

When we compare to previous IceCube publications of dSphs [83], we see an order of magnitude improvement to our sensitivity. This analysis has been working group approved within IceCube and is currently under collaboration review before unblinding. These processes did not complete in time for this dissertation. Therefore we do not show data for this thesis and is the clear next step.

The test statistic distributions in this analysis also demonstrate more characteristic behavior compared to previous DM analyses [87, 91]. With a 10-year dataset, we finally have enough statistics to almost trivially combine with other photon observatories, such as HAWC. The first groundwork for a multi-messenger DM search is provided with concluding remarks in chapter 8.

CHAPTER 8

2040 NU DUCK: CONCLUSIONS AND FUTURE DIRECTIONS

2041 8.1 Conclusions

2042 **TODO: Chat GPT the shit of everything below** In this work, three analyses were performed
2043 with data from the HAWC and IceCube observatories in order to explore some of the fundamental
2044 questions in particle astrophysics. The goal was to contribute to the understanding of the sources of
2045 cosmic rays, their acceleration mechanisms, and the nature of dark matter. The detection techniques
2046 and reconstruction methods for both observatories were described, along with the properties that
2047 make them ideal instruments to perform such searches.

2048 This dissertation used data from the HAWC detector to probe cutting-edge physics beyond
2049 the Standard Model. The techniques by which HAWC is able to detect cosmic gamma rays were
2050 demonstrated and the many advantages of HAWC in probing ultra-high energy gamma-ray physics
2051 were detailed. It was shown how HAWC data can be used to explore unanswered questions such as
2052 the nature of dark matter and the limits of Lorentz invariance. In particular, a search for evidence of
2053 WIMP dark matter in the Milky Way Galactic Halo was performed. To accomplish this, simulations
2054 of the dark matter density profile were combined with estimates of the HAWC sensitivity to dark
2055 matter-like energy spectra. This allowed strong constraints on dark matter annihilation and decay
2056 from the Galactic Halo to be derived that are insensitive to the large uncertainties arising from
2057 systematics in the dark matter spatial distribution. Multi-hundred TeV photon spectra were also
2058 significantly detected from HAWC sources within the Galactic Plane. These results lead to the
2059 strongest constraints on Lorentz invariance violation to be published at the time of writing.

2060 The work of this dissertation was made possible by the ongoing development of new algorithms
2061 and reconstruction techniques within the HAWC collaboration. Probing the Galactic Halo required
2062 the creation of a novel background estimation technique that relied on HAWC's wide field of view
2063 and strong ability to discriminate between gamma rays and cosmic rays. Meanwhile, the constraints
2064 on Lorentz invariance violation were enabled by the improved energy resolution from a machine
2065 learning technique. HAWC has recently completed a reprocessing of all archival data using an

2066 updated set of algorithms that can lead to compelling follow-up work on these results. Combining
 2067 the new background technique with the re-optimized energy estimators will allow for Galactic
 2068 dark matter to be probed at even higher masses, as well as for analyses that require precise energy
 2069 resolution such as gamma-ray line searches.

2070 **8.2 Future Directions: Multi-Messenger Dark Matter Search**

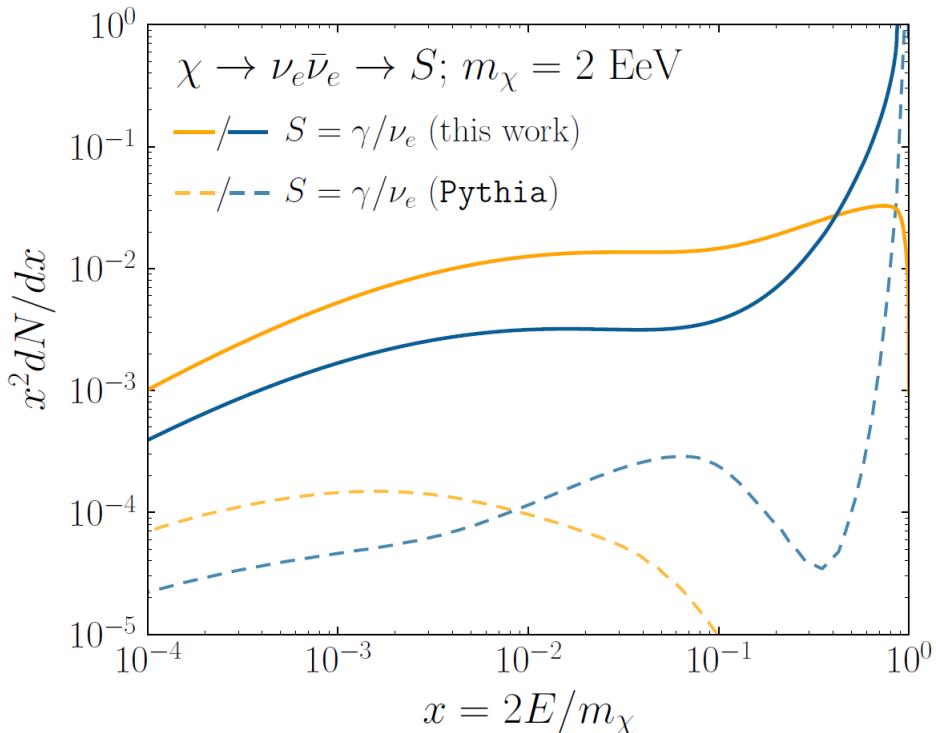


Figure 8.1 The prompt electron neutrino and photon spectrum resulting from the decay of a 2EeV DM particle to $\nu_e \bar{\nu}_e$, as currently being searched for at IceCube [5]. Solid curves represent the results of this work, and predict orders of magnitude more flux at certain energies than the dashed results of Pythia 8.2, one of the only existing methods to generate spectra at these masses. In both cases energy conservation is satisfied: there is a considerable contribution to a δ -function at $x = 1$, associated with events where an initial W or Z was never emitted and thus no subsequent shower developed. Large disagreements are generically observed at these masses for electroweak dominated channels, while the agreement is better for colored initial SM states.

2071 As I have shown previously in Sec. 5 and Sec. 6, we can build a fast and robust analysis
 2072 that shares tools with the field. The hope being that IceCube can eventually combine data with
 2073 gamma-ray observatories.



Figure 8.2 TODO: neutrino and bb plot with nu Sensitivities[NEEDS A SOURCE][FACT CHECK THIS]

MULTI-EXPERIMENT SUPPLEMENTARY FIGURES

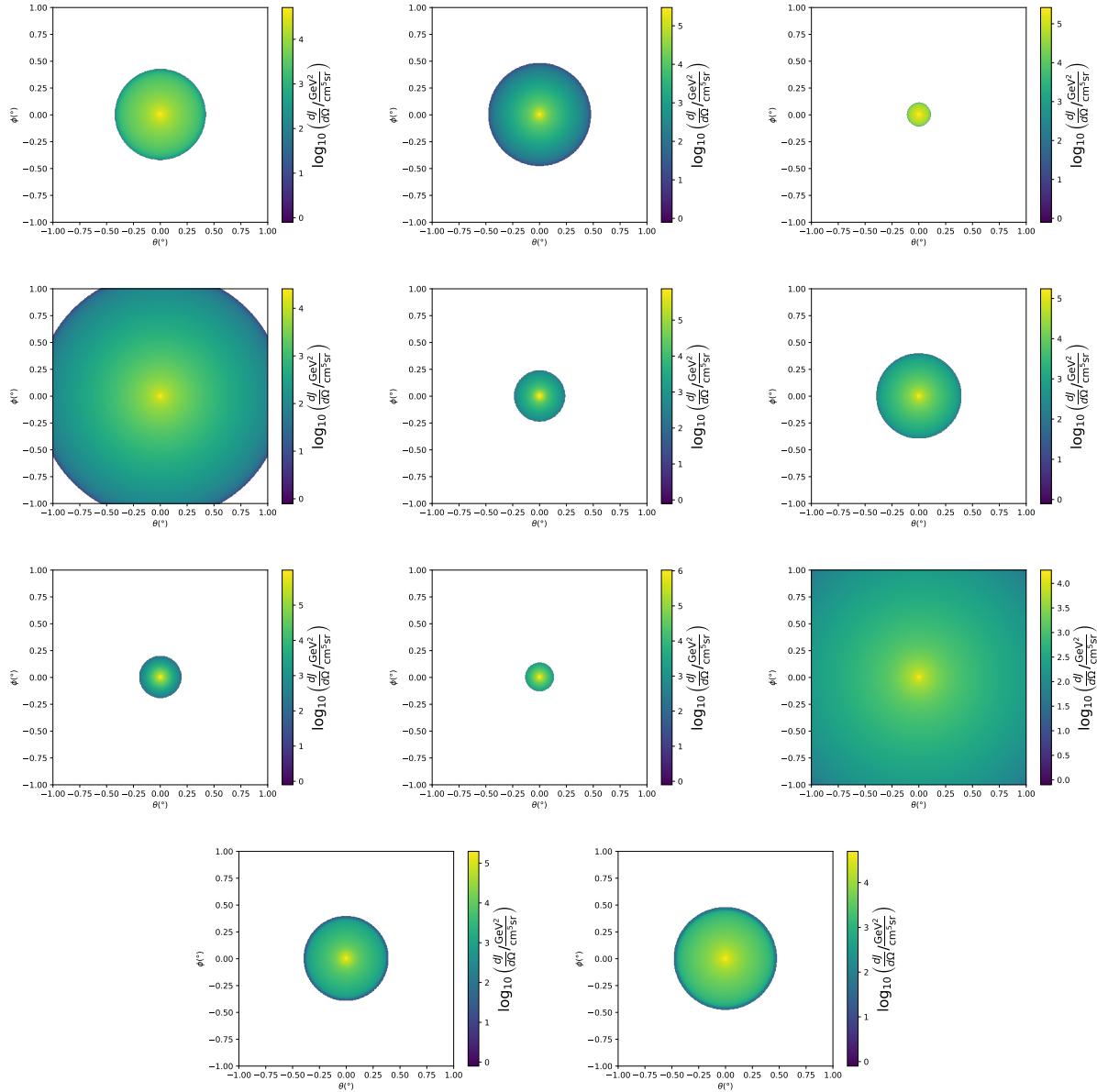


Figure A.1 Sister figure to Figure 5.3. Sources in the first row from left to right: Bootes I, Canes Venatici I, II. In second row: Draco, Hercules, Leo I. In the first row: Leo II, Leo IV, Sextans. In the final row: Ursa Major I, Ursa Major II.

APPENDIX B

2075 MULTITHREADING DARK MATTER ANALYSES SUPPLEMENTARY MATERIAL

2076 B.1 Remaining Spectral Models

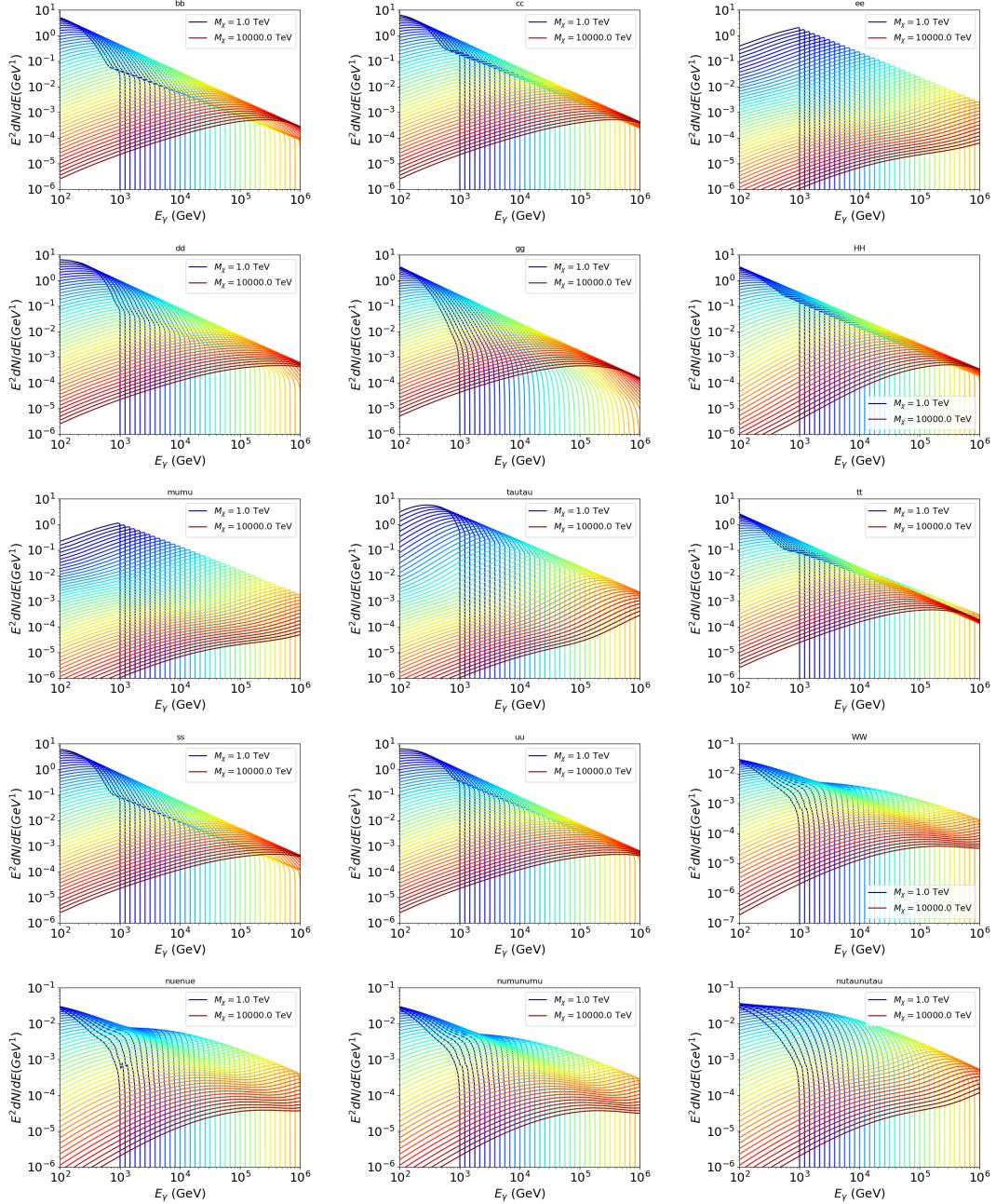


Figure B.1 Sister figure to Figure 6.2 for remaining SM primary annihilation channels studied for this thesis. These did not require any post generation smoothing and so are directly pulled from [79] with a binning scheme most helpful for a HAWC analysis.

2077 **B.2 mpu_analysis.py**

```
20781 import warnings
20792 with warnings.catch_warnings():
20803     warnings.simplefilter("ignore")
20814 # Python base libraries
20825 import os
20836 import sys
20847 import time
20858 # Import general libraries with namespace
20869 import matplotlib
20870 # Necessary for computing on cluster
20881 matplotlib.use("agg")
20892 import numpy as np
20903 import multiprocessing as mp
20914 # Import HAWC software
20925 sys.path.insert(1, os.path.join(os.environ['HOME'], 'hawc_software', 'threeML-
2093     analysis-scripts', 'fitModel'))
20946 from analysis_modules import *
20957 from threeML import *
20968 from hawc_hal import HAL, HealpixConeROI
20979 from threeML.minimizer.minimization import FitFailed
20980 # Import Dark Matter HAWC Libraries
20991 import analysis_utils as au
21002 import spectra as spec
21013 import sources as srcs
21024
21035 #* READ ONLY PATHS This block will change eventually
21046 MASS_LIST = './plotting/studies/nd/masses.txt'
21057 CHAN_LIST = './plotting/studies/nd/chans.txt'
21068
21079 #* WRITE PATHS, default location is to scratch
21080 OUT_PATH = os.path.join(os.environ["SCRATCH"], os.environ["USER"], 'New_duck')
```

```

21091 print('Our out path is going to be {}'.format(OUT_PATH))
21102
21113 # Define parallel Function. Can also be run serially
21124 def some_mass_fit(sigVs, datalist, shape, dSph, jfactor, mass_chan,
21135                 progress=None, log_file='', queue=None, i_job=0):
21146
21157     if progress is None:
21168         progress = [0]
21179     else: # Create log files for each thread
21180         log_file = log_file.replace('.log', '_ThreadNo_')
21191         log_file = log_file + str(i_job) + ".log"
21202         sys.stdout = open(log_file, "w")
21213
21224     fits = []
21235
21246     try:
21257         for m_c in mass_chan:
21268             print(f'Mass chan tuple: {m_c}')
21279             mass = int(m_c[0])
21280             ch = m_c[1]
21291             # Build path to output files
21302             outPath = os.path.join(OUT_PATH, ch, dSph)
21313             au.ut.ensure_dir(outPath)
21324
21335             if progress[i_job] < 0:
21346                 # If the master gets a Keyboard interrupt, commit suicide.
21357                 break
21368
21379                 ### Start Model Building for DM mass and SM channel #####
21380                 spectrum = spec.DM_models.HDMSpectra()
21391                 spectrum.set_channel(ch)
21402
21413                 myDwarf = ExtendedSource(dSph, spatial_shape=shape,

```

```

21424                     spectral_shape=spectrum)
21435
21446             spectrum.J = jfactor * u.GeV**2 / u.cm**5
21457             spectrum.sigmav = 1e-24 * u.cm**3 / u.s
21468             spectrum.set_dm_mass(mass * u.GeV)
21479
21480             spectrum.sigmav.bounds = (1e-30, 1e-12)
21491             model = Model(myDwarf)
21502             ##### End model Building #####
21513
21524             jl = JointLikelihood(model, datalist, verbose=False)
21535
21546             try:
21557                 result, lhdf = jl.fit(compute_covariance=False)
21568                 ts = -2.* (jl.minus_log_like_profile(1e-30) - jl.
2157 _current_minimum)
21589                 # Also profile the LLH vs sv
21590                 ll = jl.get_contours(spectrum.sigmav, sigVs[0],
21601                                 sigVs[-1], len(sigVs),
21612                                 progress=False, log=['False'])
21623
21634                 sigv_ll = au.ut.calc_95_from_profile(ll[0], ll[2])
21645                 # Write results to file
21656                 outFileLL = outPath+f"/LL_{dSph}_{ch}_mass{int(mass)}_GD.txt"
21667                 np.savetxt(outFileLL, (sigVs, ll[2]),
21678                               delimiter='\t', header='sigV\tLL\n')
21689
21690                 with open(outPath+f"/results_{dSph}_{ch}_mass{int(mass)}_GD.
2170 txt", "w") as results_file:
21711                     results_file.write("mDM [GeV]\tsigV_95\tsigV_B.F.\n")
21722
21733                     results_file.write("%i\t%.5E\t%.5E\t%.5E"%(mass, sigv_ll,
21744                                         ts, result.value[0]))

```

```

21755         # End write to file
21766     except FitFailed: # Don't kill all threads if a fit fails
21777         print("Fit failed. Go back and calculate this spectral model
2178 later")
21798         fits.append((ch, mass, -1, -1))
21809         with open(log_file+'.fail', 'w') as f_file:
21810             f_file.write(f'{ch}, {mass}\n')
21821
21832             progress[i_job] += 1
21843             matplotlib.pyplot.close() # Prevent leaky memory
21854
21865             fits.append((ch, mass, result.value[0], ts))
21876             progress[i_job] += 1
21887             matplotlib.pyplot.close()
21898     except KeyboardInterrupt:
21909         progress[i_job] = -1
21910
21921     fits = np.array(fits)
21932     if queue is None:
21943         return fits
21954     else:
21965         queue.put((i_job, fits))
21976
21987 def main(args):
21998     masses = np.loadtxt(MASS_LIST, dtype=int)
22009     chans = np.loadtxt(CHAN_LIST, delimiter=',', dtype=str)
22010     mass_chan = au.ut.permute_lists(chans, masses)
22021
22032     print(f"DM masses for this study are: {masses}")
22043     print(f"SM Channels for this study are XX -> {chans}")
22054     print(mass_chan)
22065
22076     # extract information from input argument

```

```

22087 dSph = args.dSph
22098 data_mngr = au.ut.Data_Selector('P5_NN_2D')
22109 dm_profile = srcts.Spatial_DM(args.catalog, dSph, args.sigma, args.decay)
22110
22111     ### Extract Source Information ####
22112 if dm_profile.get_dec() < -22.0 or dm_profile.get_dec() > 62.0:
22113     raise ValueError("HAWC can't see this source D: Exitting now...")
22114
22115     print(f'{dSph} information')
22116     print(f'jfac: {dm_profile.get_factor()}\tRA: {dm_profile.get_ra()}\tDec: {dm_profile.get_dec()}\n')
22117
22118 shape = SpatialTemplate_2D(fits_file=dm_profile.get_src_fits())
22119     ### Finish Extract Source Information ####
22120
22121     ### LOAD HAWC DATA ####
22122 roi = HealpixConeROI(data_radius=2.0, model_radius=8.0,
22123                         ra=dm_profile.get_ra(), dec=dm_profile.get_dec())
22124 bins = choose_bins.analysis_bins(args, dec=dm_profile.get_dec())
22125
22126 hawc = HAL(dSph, data_mngr.get_datmap(), data_mngr.get_detres(), roi)
22127 hawc.set_active_measurements(bin_list=bins)
22128 datalist = DataList(hawc)
22129     ### FINISH LOAD HAWC DATA ####
22130
22131 # set up SigV sampling. This sample is somewhat standardized
22132 sigVs = np.logspace(-28,-18, 1001, endpoint=True) # NOTE This will change
22133 whith HDM
22134
22135 if args.n_threads == 1:
22136     # No need to start || programming just iterate over the masses
22137     kw_arg = dict(sigVs=sigVs, datalist=datalist, shape=shape, dSph=dSph,
22138                     jfactor=dm_profile.get_factor(), mass_chan=mass_chan,

```

```

22418                 log_file=args.log)
22419         some_mass_fit(**kw_arg)
22420     else:
22421         # I Really want to suppress TQMD output
22422         from tqdm import tqdm
22423         from functools import partialmethod
22424         tqdm.__init__ = partialmethod(tqdm.__init__, disable=True)
22425
22426         x = np.array_split(mass_chan, args.n_threads)
22427         n_jobs = len(x)
22428
22429         print("Thread jobs summary by mass and SM channel")
22430         for xi in x:
22431             print(f'{xi}')
22432
22433         queue = mp.Queue()
22434         progress = mp.Array('i', np.zeros(n_jobs, dtype=int))
22435
22436         # Define task pool that will be split amongsts threads
22437         kw_args = [dict(sigVs=sigVs, datalist=datalist, shape=shape,
22438                         dSph=dSph, jfactor=dm_profile.get_factor(),
22439                         mass_chan=mass_chan, progress=progress,
22440                         queue=queue, i_job=i, log_file=args.log)
22441             for i, mass_chan in enumerate(x)]
22442
22443         # Define each process
22444         procs = [mp.Process(target=some_mass_fit, kwargs=kw_args[i]) \
22445             for i in range(n_jobs)]
22446
22447         ### Start MASTER Thread only code block ###
22448         # Begin running all child threads
22449         for proc in procs: proc.start()
22450

```

```

22741     try:
22752         # In this case, the master does nothing except monitor progress of
2276         # the threads
22773         # In an ideal world, the master thread also does some computation.
22784         n_complete = np.sum(progress)
22795         while_count = 0
22806
22817         while n_complete < len(mass_chan):
22828
22839             if np.any(np.asarray(progress) < 0):
22840                 # This was no threads are stranded when killing the script
22851                 raise KeyboardInterrupt()
22862             if while_count%1000 == 0:
22873                 print(f"{np.sum(progress)} of {len(mass_chan)} finished")
22884
22895             n_complete = np.sum(progress)
22906             time.sleep(.25)
22917             while_count += 1
22928
22939         except KeyboardInterrupt:
22940             # signal to jobs that it's time to stop
22951                 for i in range(n_jobs):
22962                     progress[i] = -2
22973                     print('\nKeyboardInterrupt: terminating early.')
22984             ### End MASTER Thread only code block ###
22995
23006             fitss = [queue.get() for proc in procs]
23017             print(fitss)
23028             print(f'Thread statuses: {progress[:]}')
23039
23040             # putting results in a file
23051
23062             print("QUACK! All Done!")

```

```

23073
23084
23095 if __name__ == '__main__':
23106     import argparse
23117
23128     p = argparse.ArgumentParser(description="Run a DM annihilation analysis on
2313         a dwarf spheroidal for a specific SM channel for DM masses [1 TeV to 10
2314         PeV]")
23159
23160     # Dwarf spatial modeling arguements
23171     p.add_argument("-ds", "--dSph", type=str,
23182                     help="dwarf spheroidal galaxy to be studied", required=
2319 True)
23203     p.add_argument("-cat", "--catalog", type=str, choices=['GS15', 'LS20'],
23214                     default='LS20', help="source catalog used")
23225     p.add_argument("-sig", "--sigma", type=int, choices=[-1, 0, 1], default=0,
23236                     help="Spatial model uncertainty. 0 corresponds to the
2324 median. +/-1 correspond to the +/-1sigma uncertainty respectively.")
23257
23268     # Arguements for the energy estimators
23279     p.add_argument("-e", "--estimator", type=str,
23280                     choices=['P5_NHIT', 'P5_NN_2D'],
23291                     default="P5_NN_2D", required=False,
23302                     help="The energy estimator choice. Options are: P5_NHIT,
2331 P5_NN_2D. GP not supported (yet).")
23323     p.add_argument("--use-bins", default=None, nargs="*",
23334                     help="Bins to use for the analysis", dest="use_bins")
23345     p.add_argument('--select_bins_by_energy', default=None, nargs="*",
23356                     help="Does nothing. May fill in later once better
2336 understood")
23377     p.add_argument('--select_bins_by_fhit', default=None, nargs="*",
23388                     help="Also does nothing see above")
23399     p.add_argument( '-ex', "--exclude", default=None, nargs="*",

```

```

23400         help="Exclude Bins", dest="exclude")
2341
23422     # Computing and logging arguements.
23433     p.add_argument('-nt', '--n_threads', type=int, default=1,
23444                     help='Maximum number of threads spawned by script. Default
23455                     is 4')
23465     p.add_argument('-log', '--log', type=str, required=True,
23476                     help='Name for log files. Especially needed for threads')
23487
23498     p.add_argument('--decay', action="store_true",
23509                     help='Set spectral DM hypothesis to decay')
23510
23521     args = p.parse_args()
23532     print(args.decay)
23543     if args.exclude is None: # default exclude bins 0 and 1
23554         args.exclude = ['B0C0Ea', 'B0C0Eb', 'B0C0Ec', 'B0C0Ed', 'B0C0Ee']
23565
23576     if args.decay: OUT_PATH += '_dec'
23587     else: OUT_PATH += '_ann'
23598
23609     OUT_PATH = OUT_PATH + '_' + args.catalog
23610     if args.sigma != 0: OUT_PATH += f'_{args.sigma}sig'
23621
23632     main(args)

```

2364 B.3 Comparison with Glory Duck

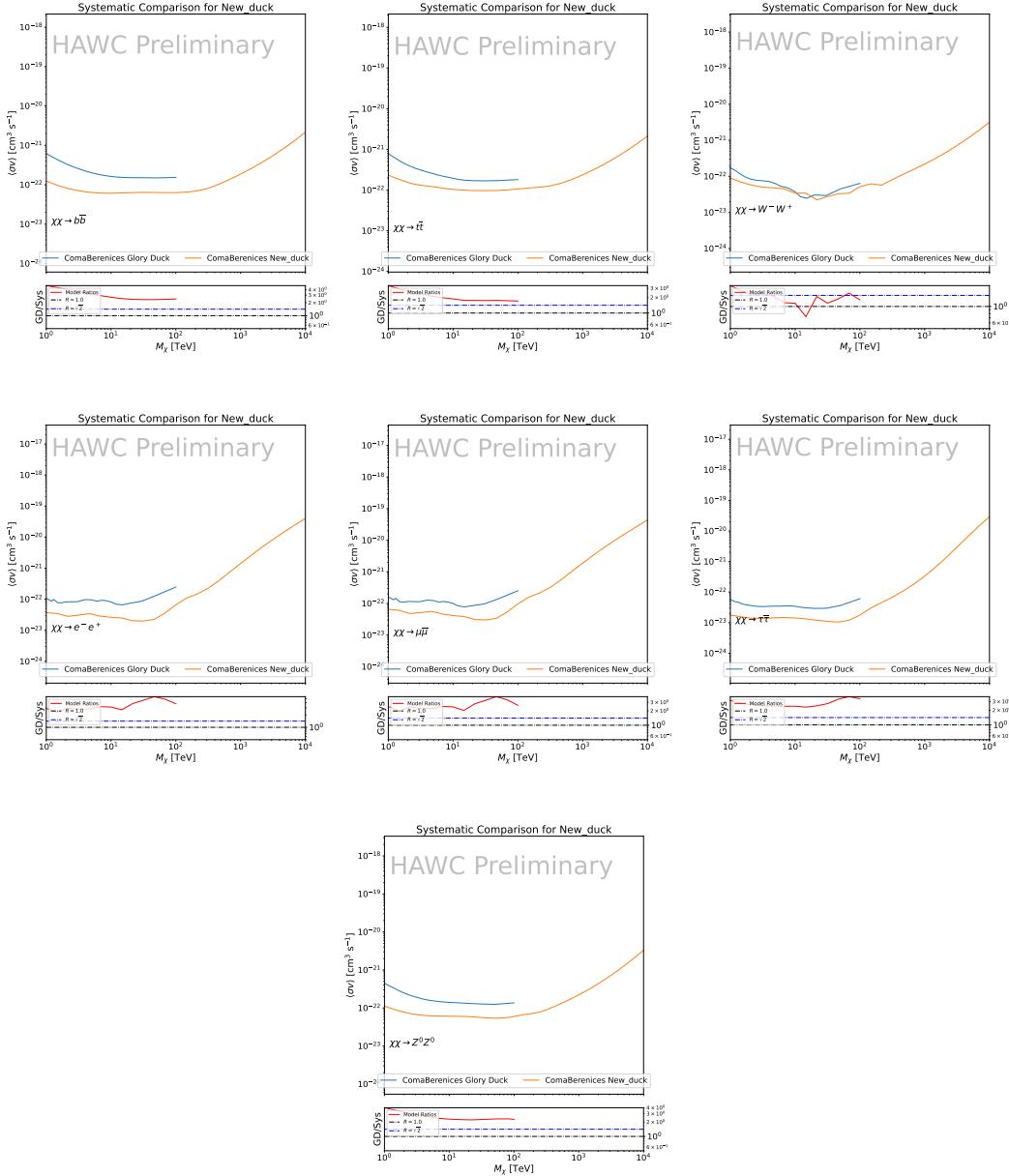


Figure B.2 Comparison of HAWC limits from this analysis to Glory Duck (Fig. 5.5) for Coma Berenices and 7 DM annihilation channels.

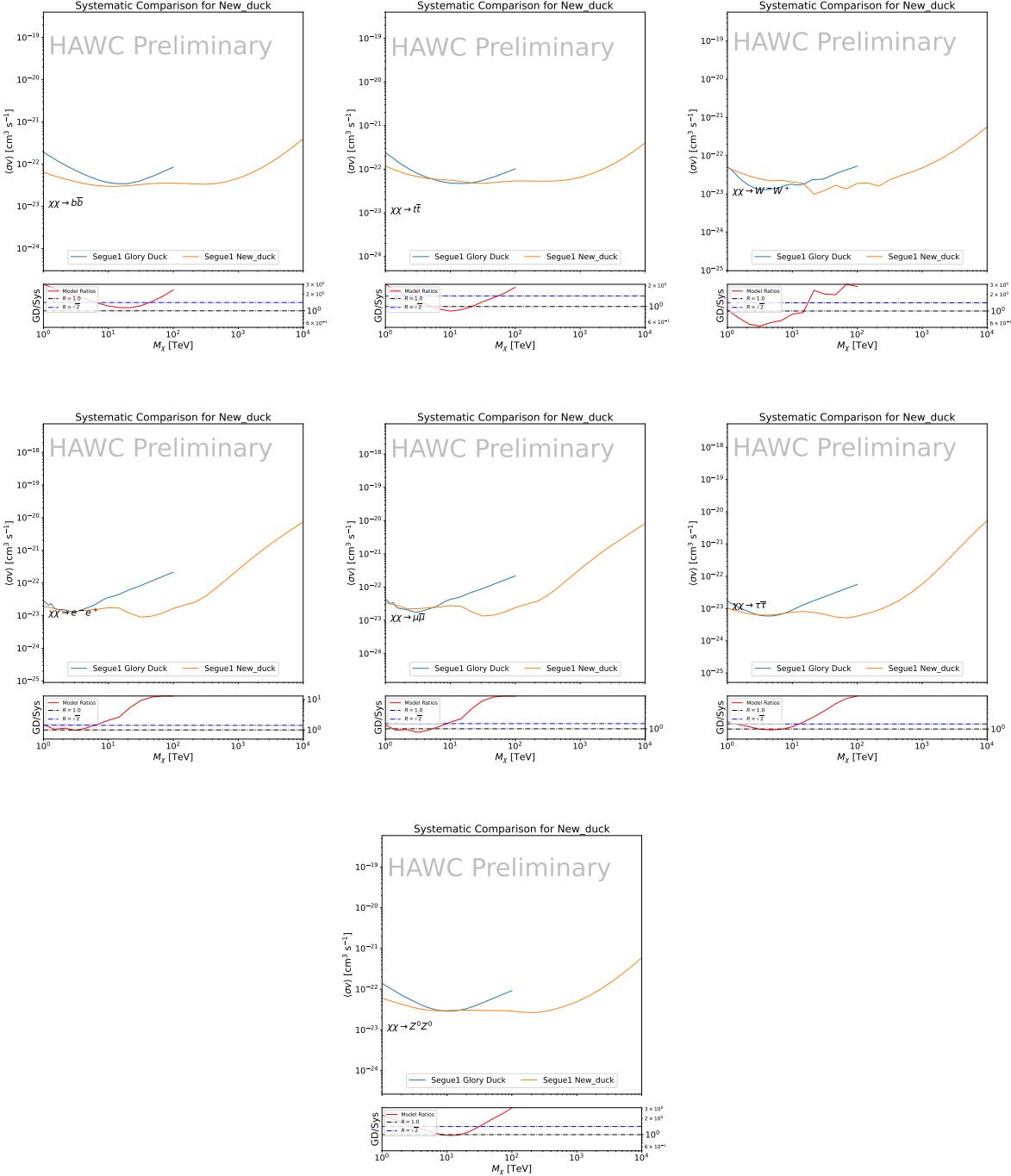


Figure B.3 Same as Fig. B.2 but for Segue 1.

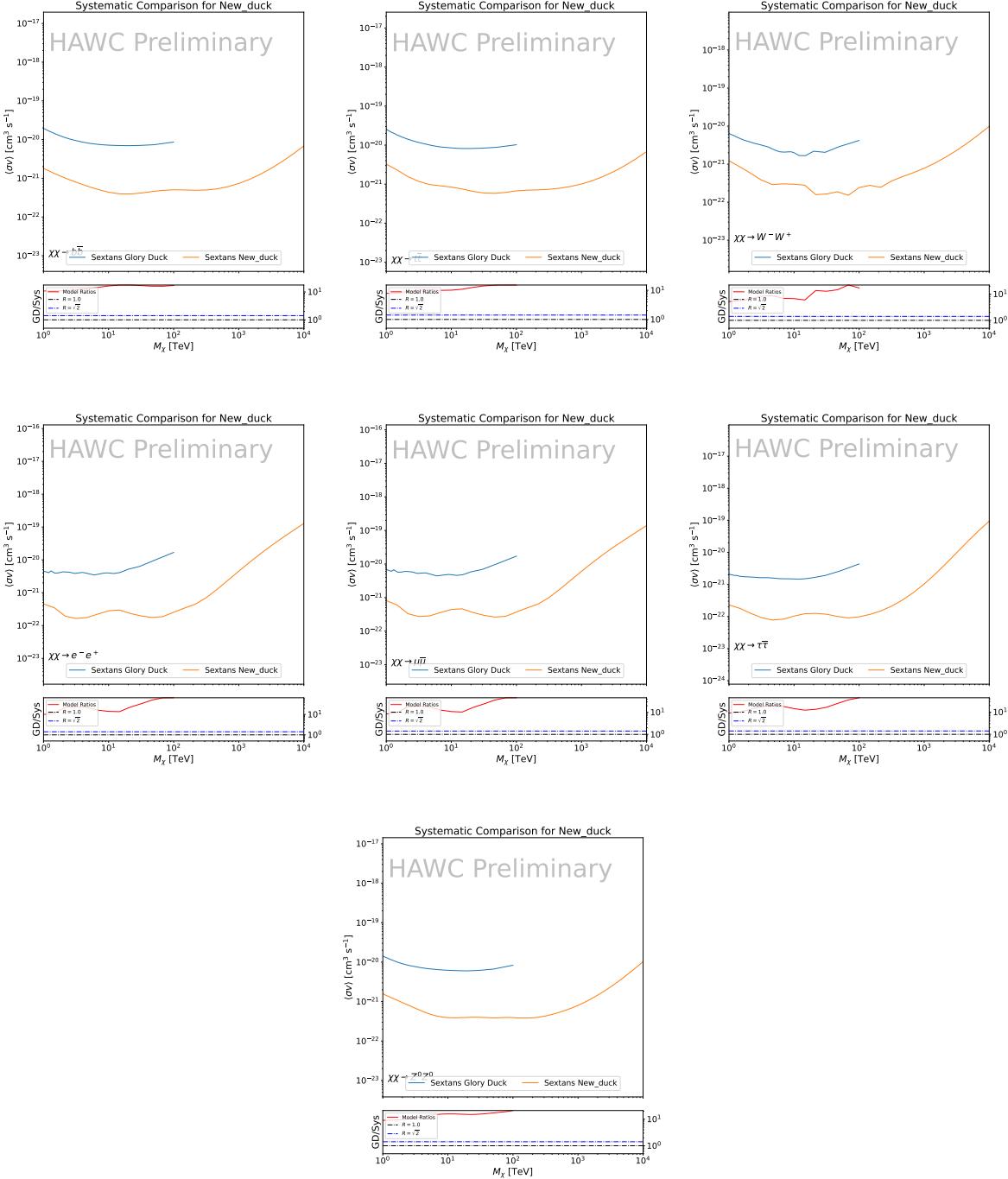


Figure B.4 Same as Fig. B.2 but for Sextans.

APPENDIX C

2365 ICECUBE HEAVY DARK MATTER ANALYSIS SUPPLEMENTARY MATERIAL

2366 C.1 Docker Image for Oscillating Neutrino Spectra

```
23671 FROM ubuntu:18.04
23682
23693 # Execute commands to install software packages
23704 RUN apt -y update
23715
23726     # Install utility programs
23737 RUN apt -y install vim wget git cmake
23748
23759 ARG DEBIAN_FRONTEND=noninteractive
23760
23771     # Install python
23782 RUN apt -y install python python-dev python-pip libjpeg-dev zlib1g-dev
23793
23804     # We need Python2 for installing Charon.
23815 RUN apt -y install python-numpy python-sympy python-matplotlib \
23826             python-sympy python-h5py python-astropy python-ipython
23837
23848     # Install dependencies of Charon : SQuIDS, NuSQuIDS
23859 RUN apt -y install libgsl-dev libgslcblas0 libgsl23 gsl-bin pkg-config
23860     # Install SQuIDS
23871 RUN mkdir /home/SQuIDS /home/SQuIDS_install
23882 WORKDIR /home/SQuIDS
23893 RUN git clone https://github.com/jsalvado/SQuIDS.git
23904 WORKDIR /home/SQuIDS/SQuIDS
23915 RUN git checkout 7ad9ba7c6ad06d1f0fa8418f937ebf1a403fef90
23926     # Before executing "make install" an environmental variable has to be set.
23937 ENV PKG_CONFIG_PATH=/home/SQuIDS/SQuIDS/lib
23948 RUN ./configure --prefix=../SQuIDS_install \
```

```

23959     && make
23960 RUN make install
23971
23982     # Set up an environmental variable that is required to install nuSQuIDS..
23993 ENV SQuIDS=/home/SQuIDS/SQuIDS
24004 ENV LD_LIBRARY_PATH=$SQuIDS/lib:$LD_LIBRARY_PATH
24015
24026     # Install NuSQuIDS
24037 RUN mkdir /home/nuSQuIDS
24048 WORKDIR /home/nuSQuIDS
24059 RUN git clone https://github.com/qrliu/nuSQuIDS.git
24060 WORKDIR /home/nuSQuIDS/nuSQuIDS
24071 RUN git checkout 072d8ef740e2fc7330f1fabaea94f0f4540c46f9
24082 RUN apt -y install libhdf5-dev hdf5-tools
24093 RUN apt -y install libboost1.65-all-dev
24104 RUN ./configure --with-squids=$SQuIDS --with-python-bindings --prefix=../
2411     nuSQuIDS_install \
24125     && make \
24136     && make install
24147
24158     # Set up an environmental variable for nuSQuIDS.
24169 ENV nuSQuIDS=/home/nuSQuIDS/nuSQuIDS
24170 ENV LD_LIBRARY_PATH=$nuSQuIDS/lib:$LD_LIBRARY_PATH
24181
24192     # Build the python bindings
24203 WORKDIR /home/nuSQuIDS/nuSQuIDS/resources/python/src
24214 RUN make
24225
24236     # Set up an environmental variable for the python bindings.
24247 ENV PYTHONPATH=$nuSQuIDS/resources/python/bindings/:$PYTHONPATH
24258
24269     # Install Charon in the /home/Charon/charon directory.
24270 RUN mkdir /home/Charon

```

```
24281 WORKDIR /home/Charon
24292 RUN git clone https://github.com/icecube/charon.git \
24303     && apt -y install unzip python-scipy
24314 WORKDIR charon
24325 RUN git checkout c531efe4e01dc364a60d1c83f950f04526ccd771
24336 RUN unzip ./charon/xsec/xsec.zip -d charon/xsec/ \
24347
24358 # Download neutrino spectra tables in the /home/Charon/charon/data directory
2436 .
24379 && mkdir ./charon/data
24380 WORKDIR ./charon/data
24391 RUN wget --no-check-certificate https://icecube.wisc.edu/~qliu/charon/
2440     SpectraEW.hdf5 \
24412 && wget --no-check-certificate https://icecube.wisc.edu/~qliu/charon/
2442     Spectra_PYTHIA.hdf5 \
24433 && wget --no-check-certificate https://icecube.wisc.edu/~qliu/charon/
2444     Spectra_noEW.hdf5
24454
24465 WORKDIR ../..
24476 RUN python setup.py install
24487 WORKDIR /home
```

2449 C.2 Spline Fitting Statuses

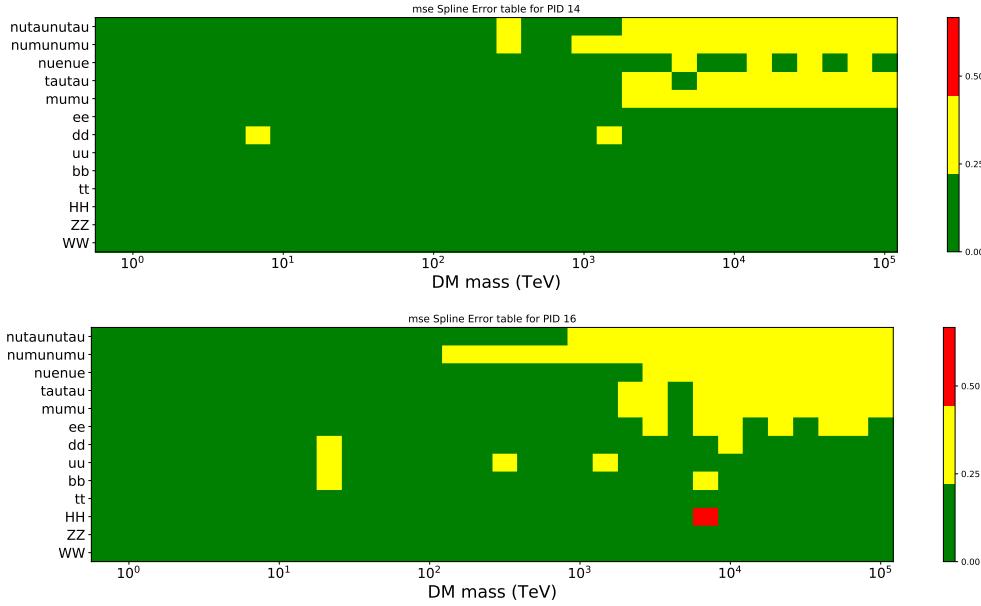


Figure C.1 Current status of spline tables according to constraints defined by Tab. 7.1. Green splines are splines that passed under the GOOD tolerance. Yellow are splines that are OK. Red are splines that FAIL. All yellow splines were inspected individually before running the analysis. Splines were made for the μ (PID 14; top panel) flavor and τ (PID 16; bottom panel) neutrino flavors.

2450 C.3 Neutrino Composite Spectra

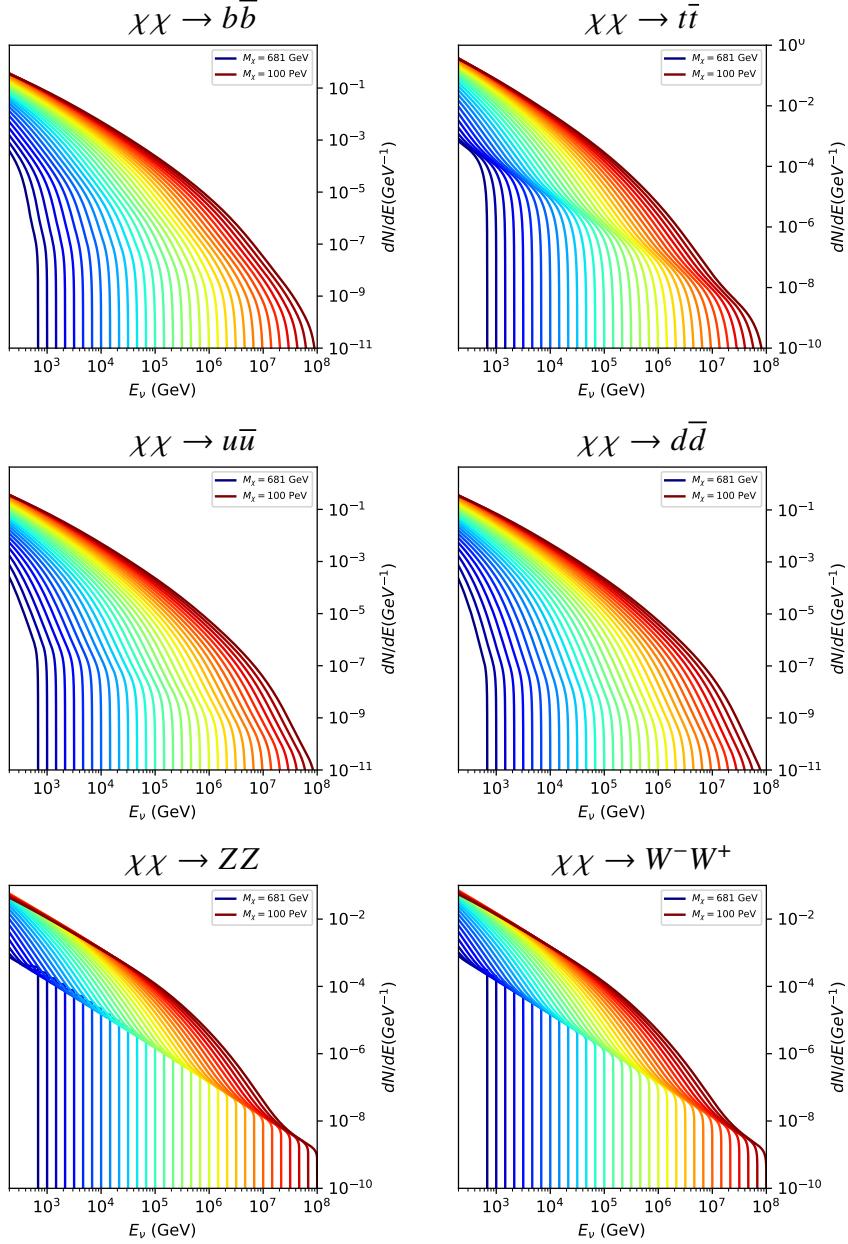


Figure C.2 Sister figure to Fig. 7.5 for annihilation channels that did not require kernel smoothing. These spectra are the composite ($\nu_\mu + \nu_\tau$) of neutrino flavors. Every spectral model used for this analysis is featured as a colored solid line. Bluer lines are for lower DM mass spectral models. DM masses range from 681 GeV to 100 PeV.

2451 C.4 Segue 1 And Ursa Major II Signal Recovery

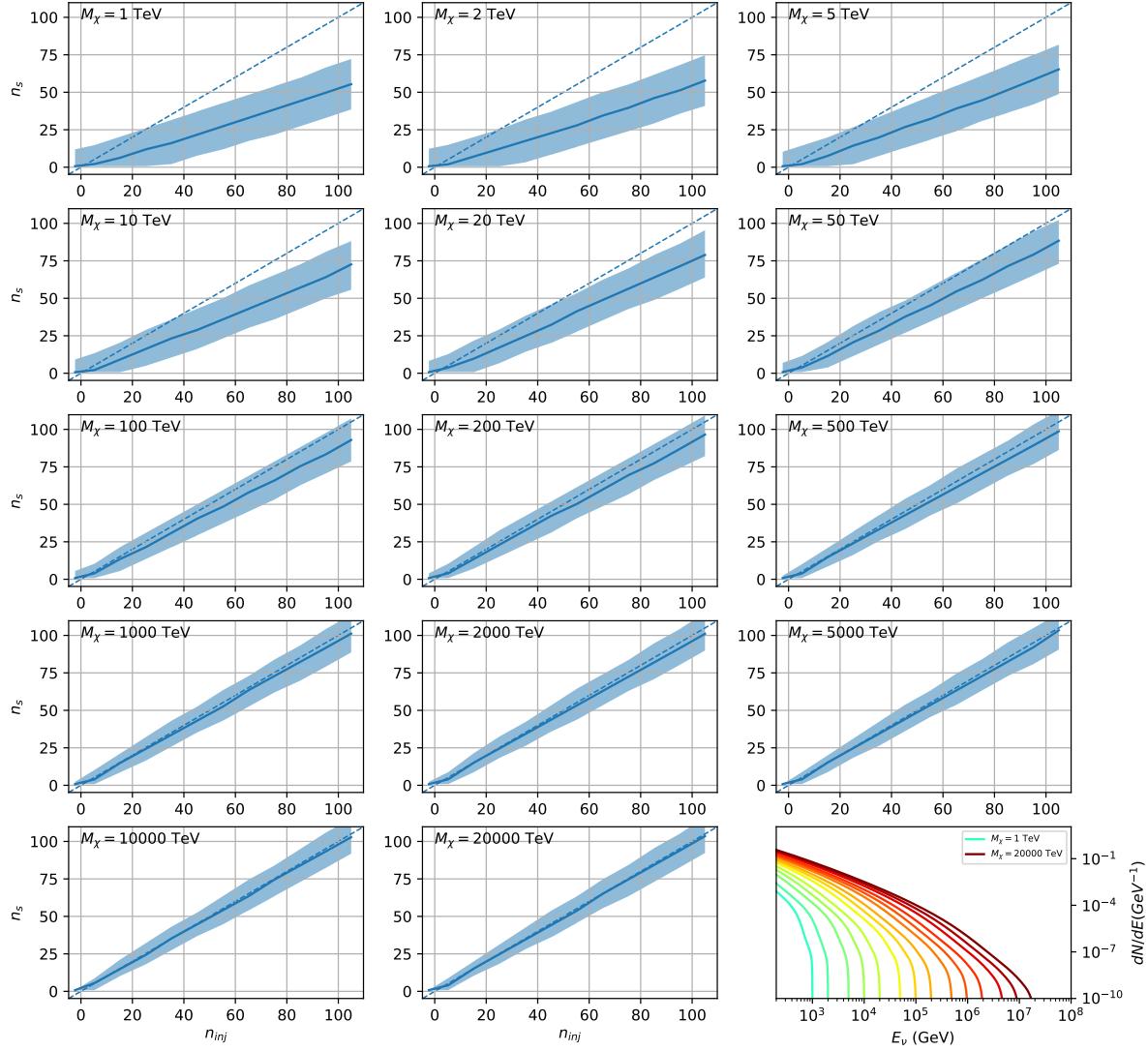


Figure C.3 Same as Fig. 7.23 but for Segue 1 and $\chi\chi \rightarrow b\bar{b}$.

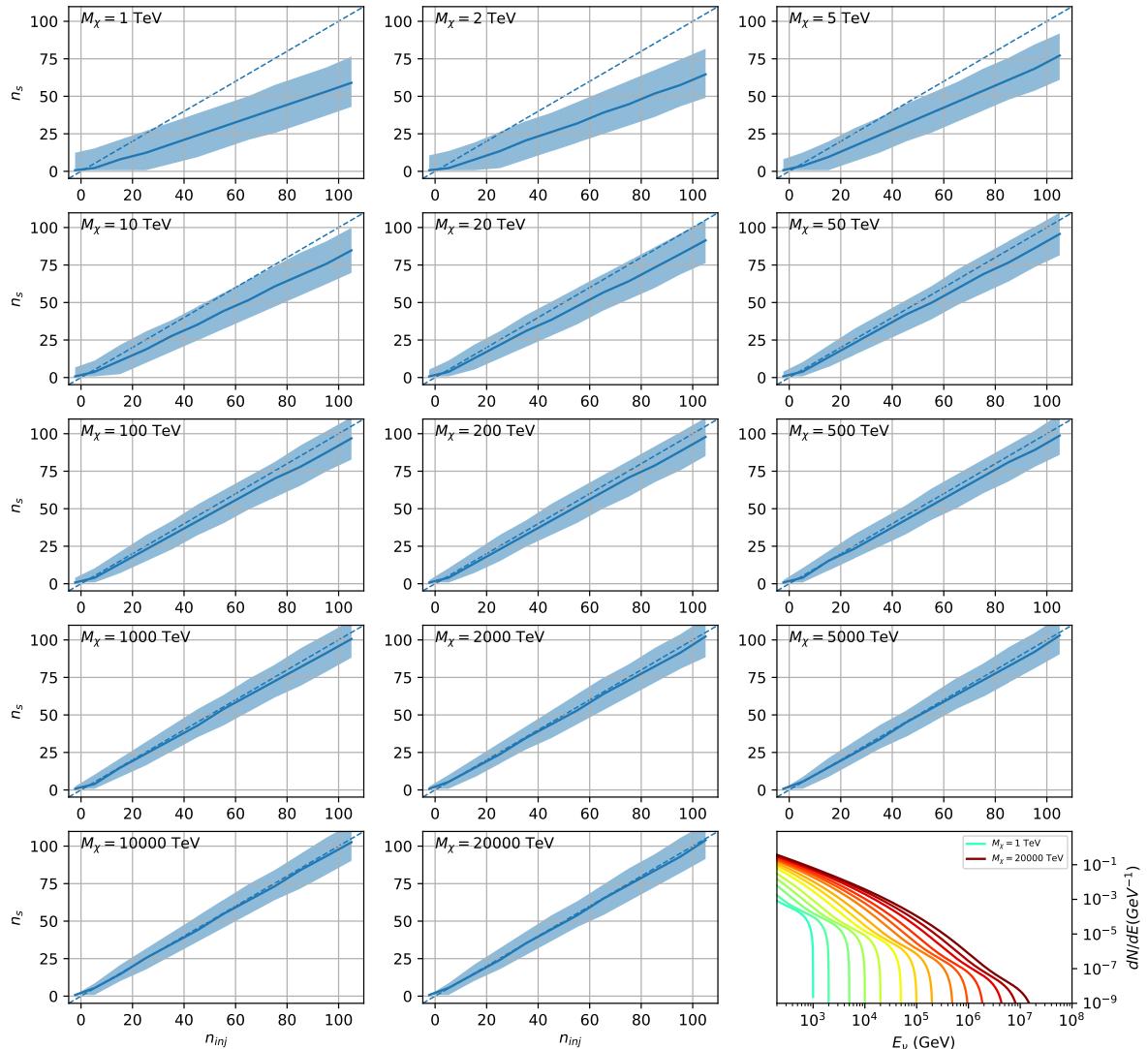


Figure C.4 Same as Fig. 7.23 but for Segue 1 and $\chi\chi \rightarrow t\bar{t}$.

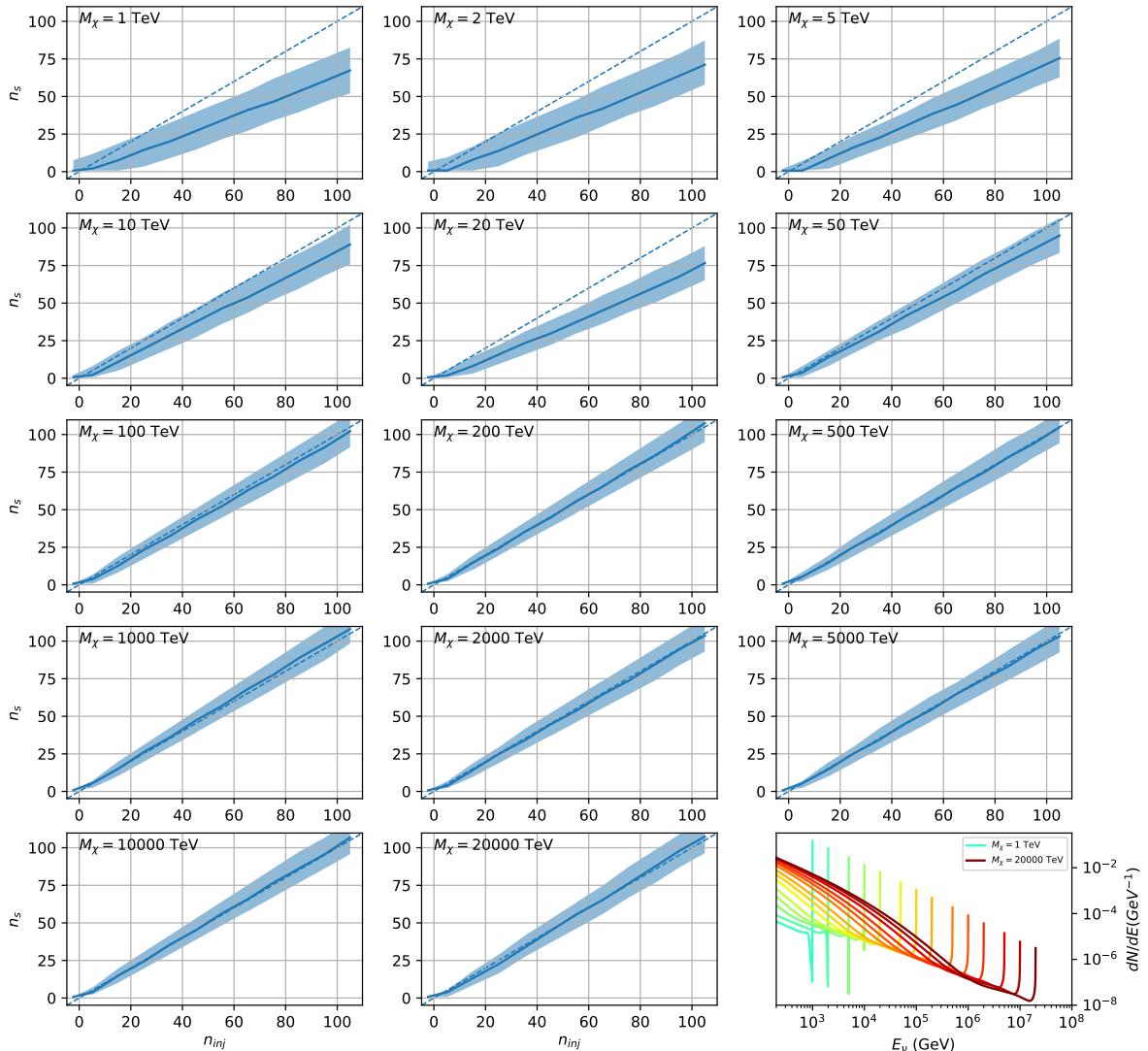


Figure C.5 Same as Fig. 7.23 but for Segue 1 and $\chi\chi \rightarrow \nu_\mu \bar{\nu}_\mu$.

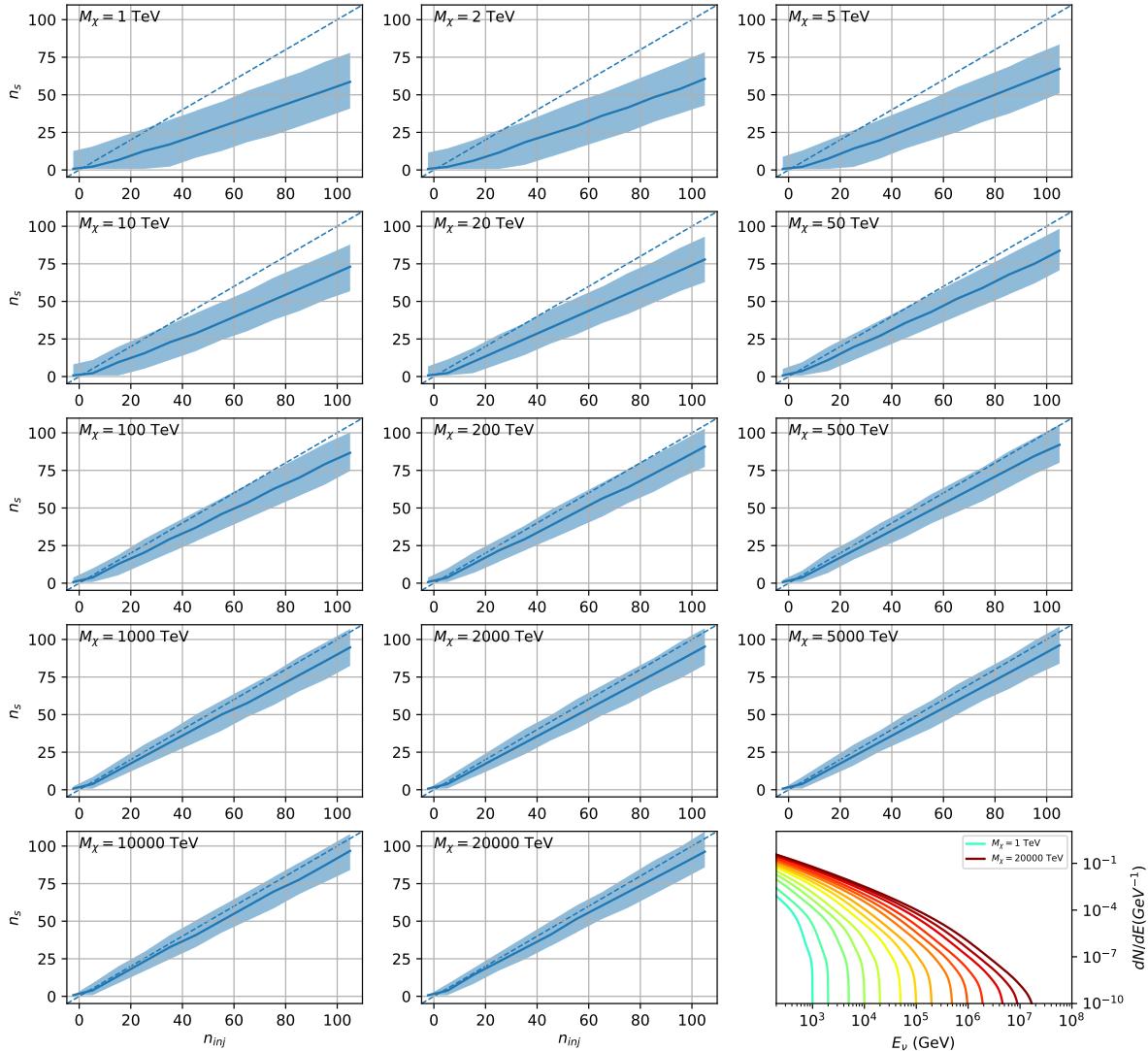


Figure C.6 Same as Fig. 7.23 but for Ursa Major II and $\chi\chi \rightarrow b\bar{b}$.

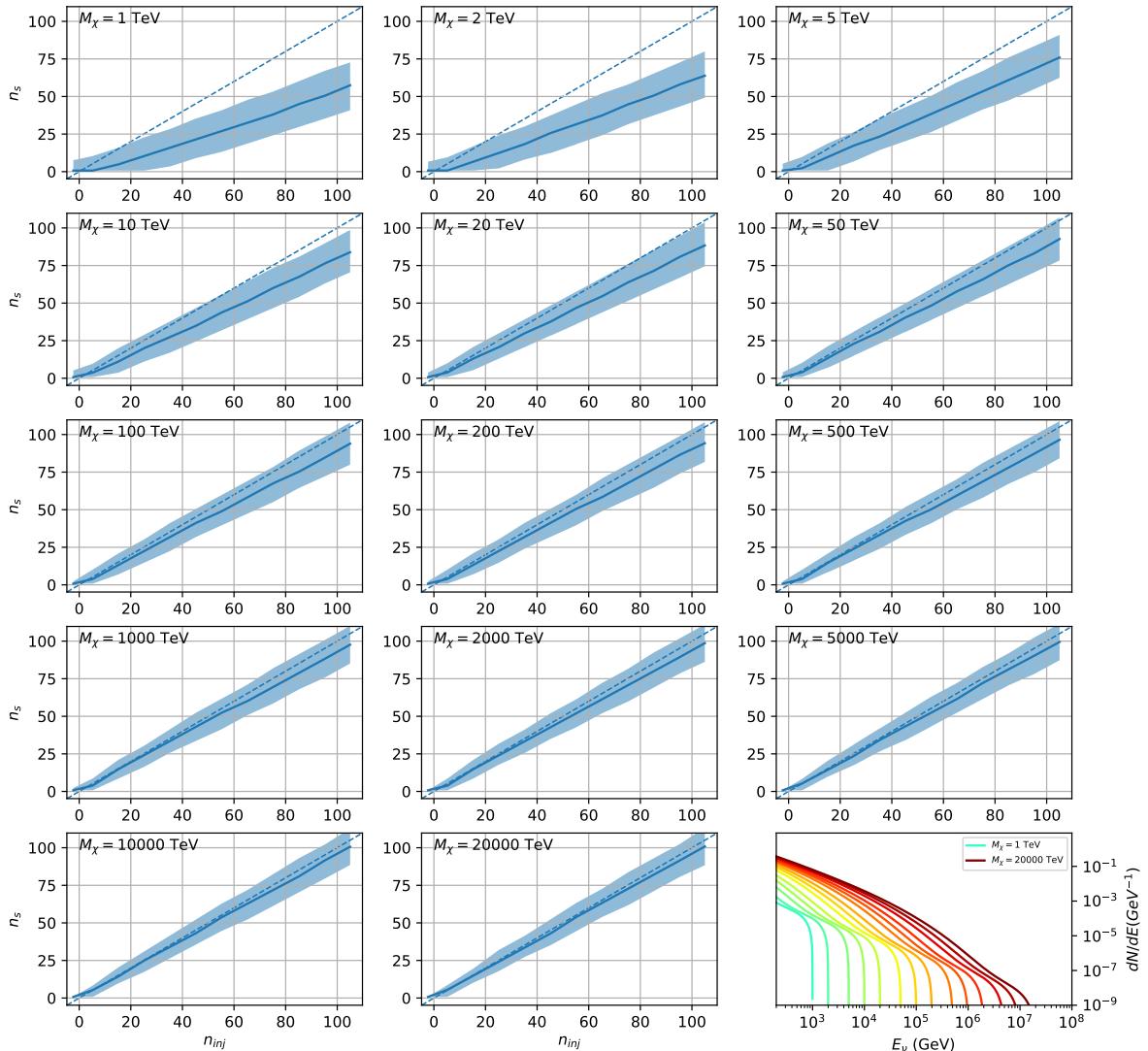


Figure C.7 Same as Fig. 7.23 but for Ursa Major II and $\chi\chi \rightarrow t\bar{t}$.

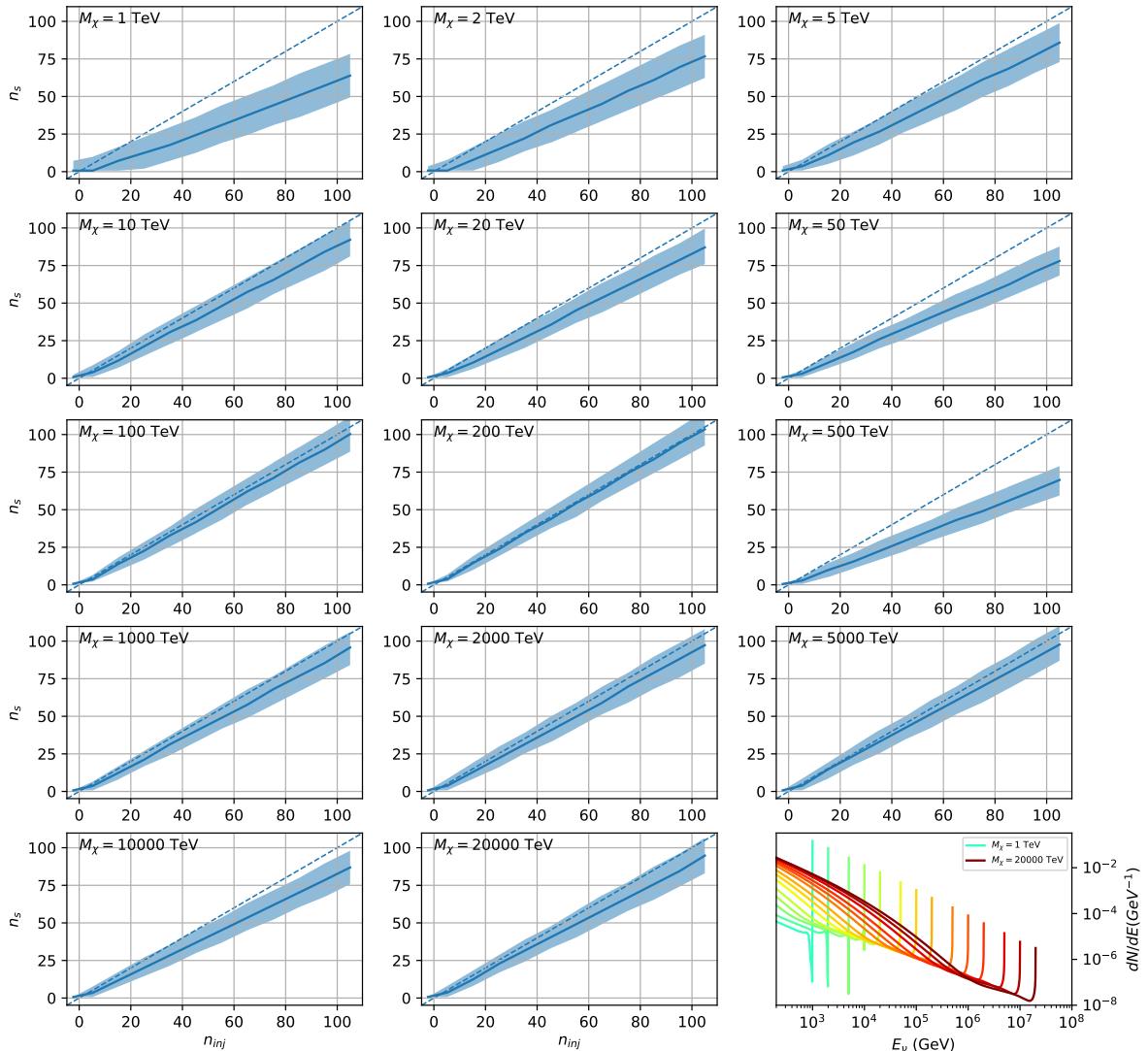


Figure C.8 Same as Fig. 7.23 but for Ursa Major II and $\chi\chi \rightarrow \nu_\mu \bar{\nu}_\mu$.

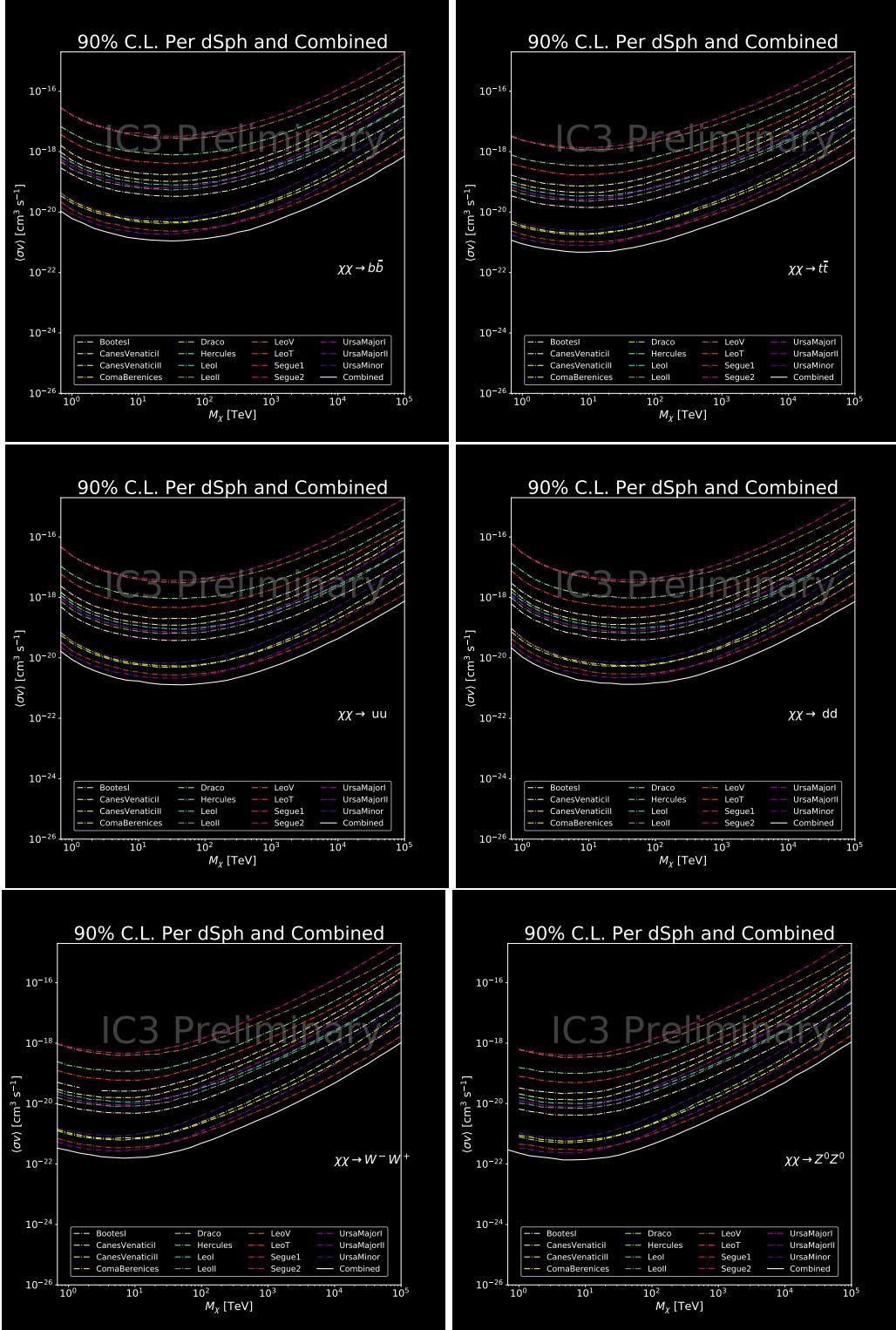


Figure C.9 IceCube North Sky Track Sensitivities for $n_s/\langle N \rangle$. n_s values are the counts fed into Eq. (7.8) to produce Fig. 7.26 and Fig. 7.25.

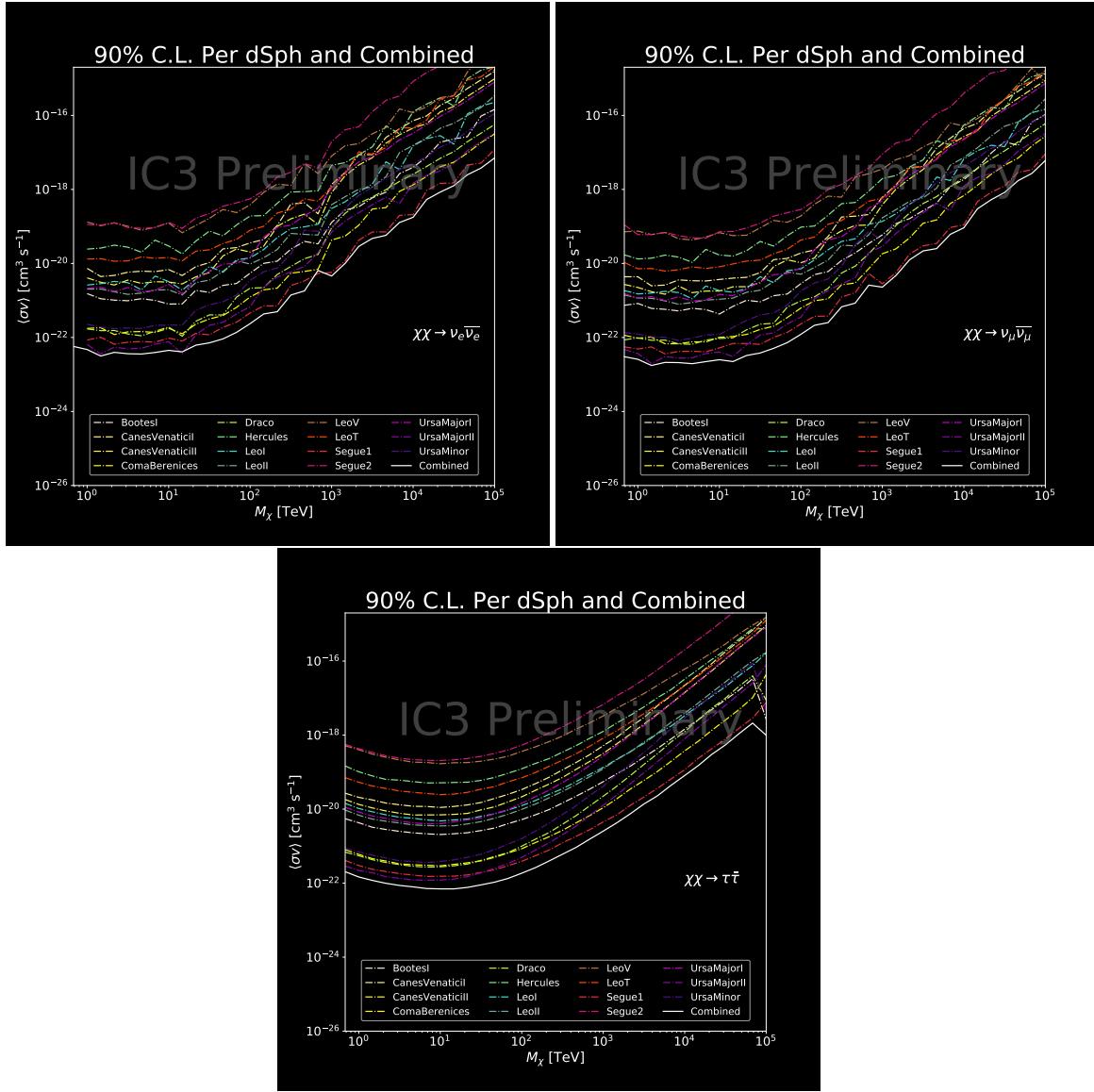


Figure C.10 Same as Fig. C.9 for three additional DM annihilation channels.

2453

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