Simulations to understand double bump profiles in longitudinal development of extensive air showers in the context of the SKA observatory.

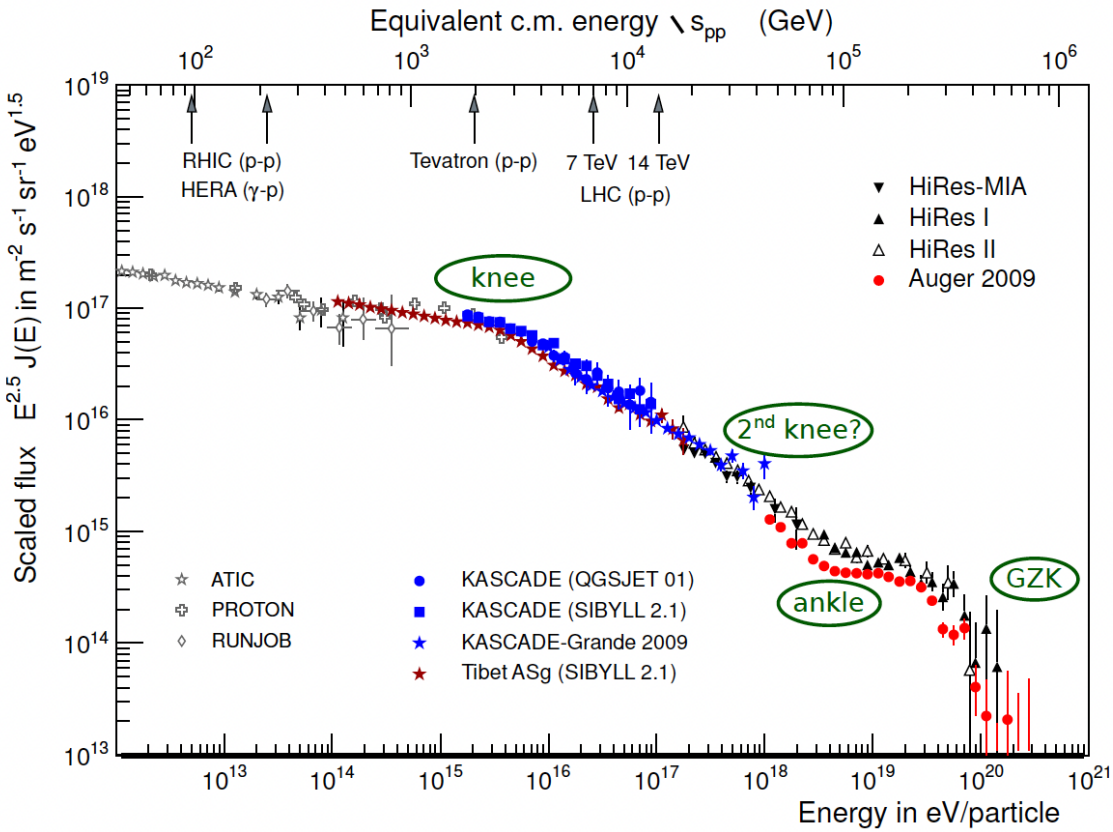
Vital De Henau

April 9, 2024

VRIJE
UNIVERSITEIT
BRUSSEL

COSMIC RAYS

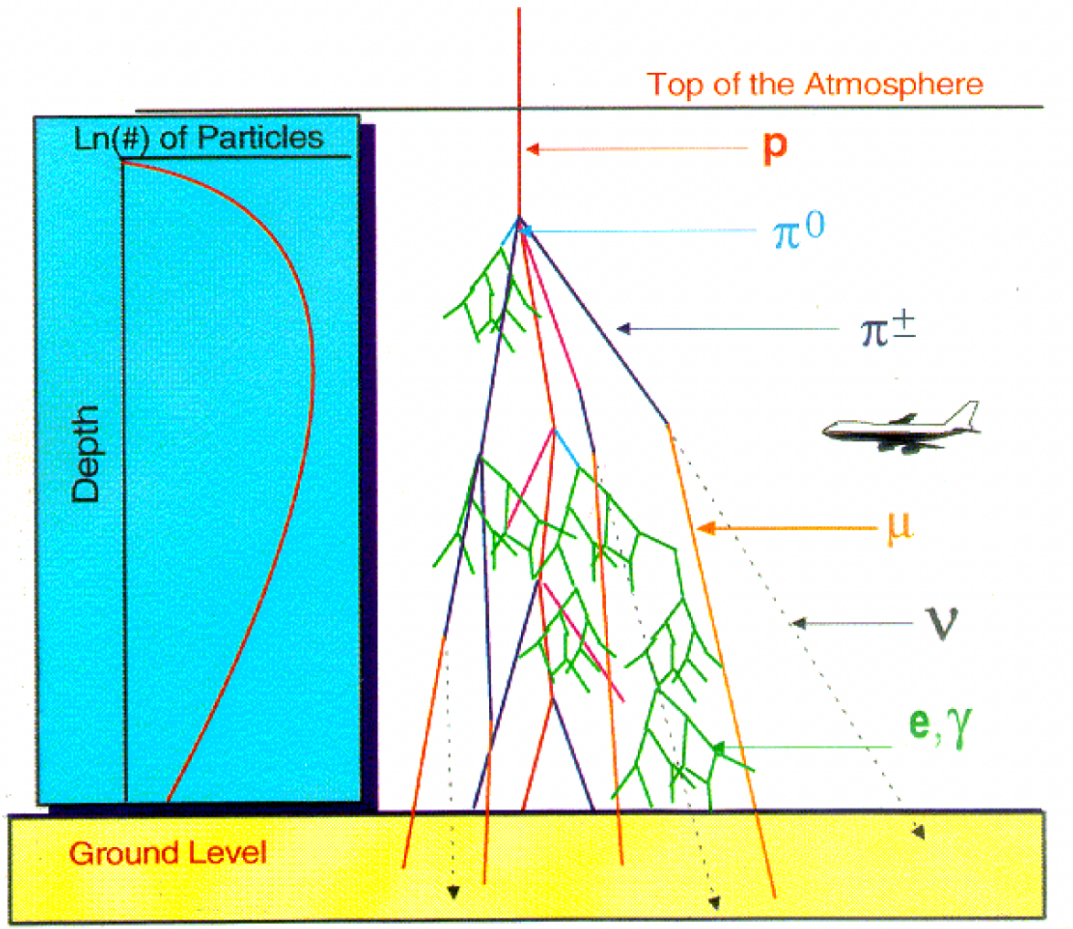
Cosmic rays are highly energetic particles that travel through universe.



SKA 10^{16} – 10^{18} eV transition from galactic to extragalactic cosmic rays

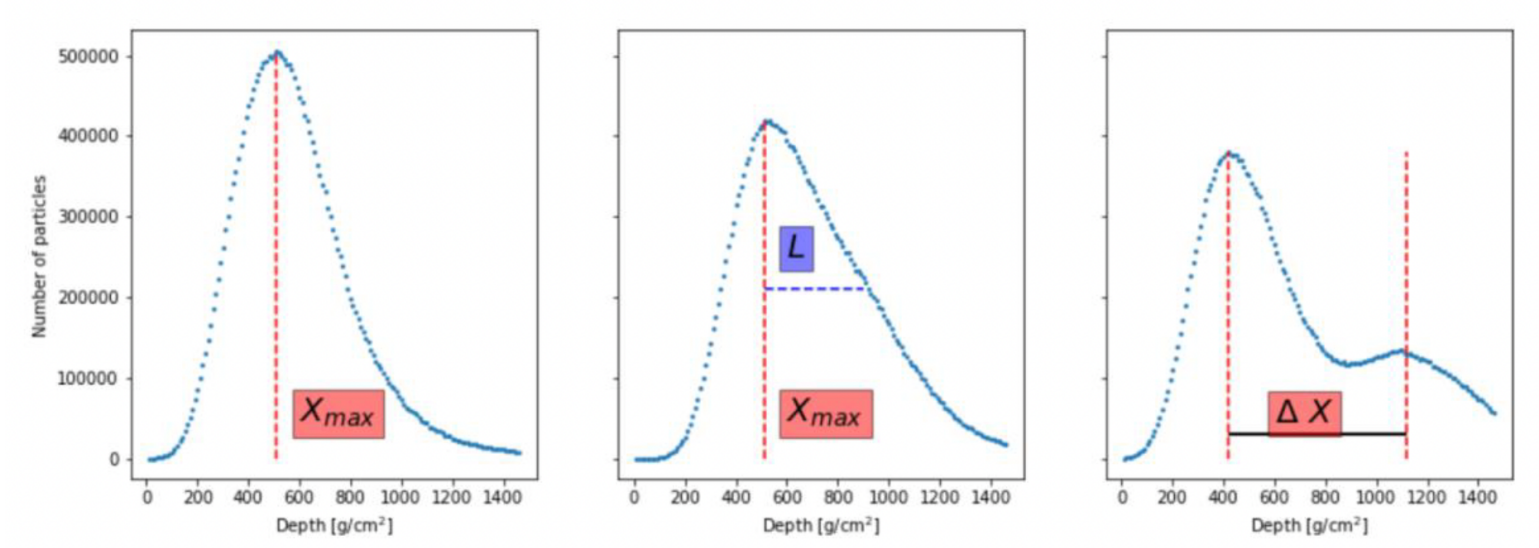
EXTENSIVE AIR SHOWERS

EAS are created when a cosmic ray interacts with an atmospheric particle, which creates a cascade of secondary particles.



DOUBLE BUMPS

A spectator nucleon with a ~quarter of the primary energy penetrates deeply into the atmosphere before it interacts.

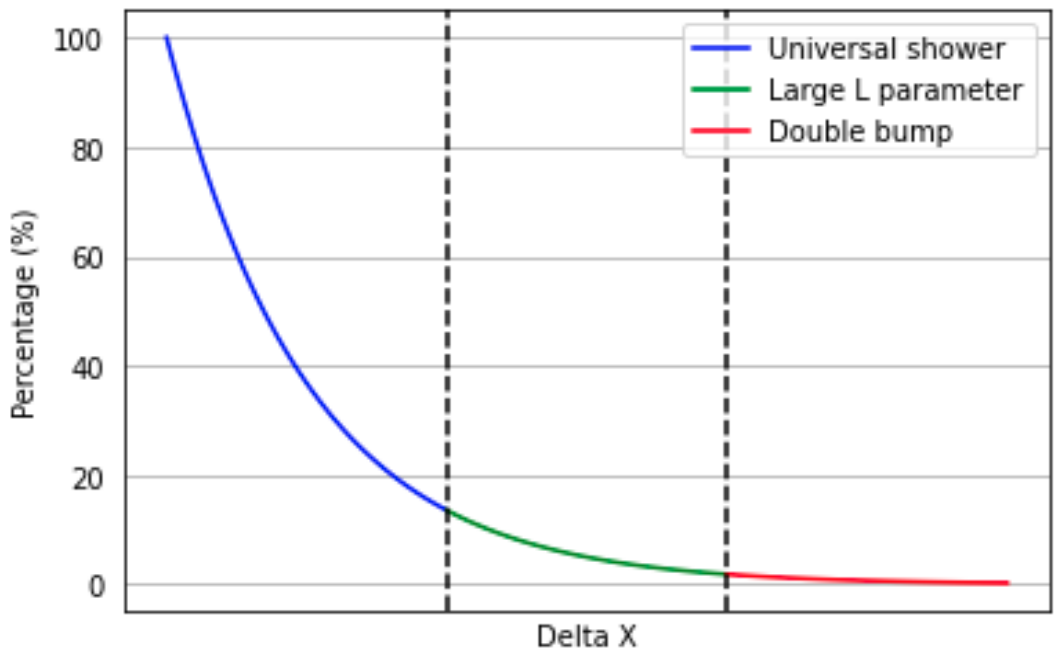


Double bump profiles deviate from the universal profile.

DOUBLE BUMPS AS PROBE OF HADRONIC CROSS-SECTION

$$P(\Delta X) = e^{-\frac{-\Delta X}{\lambda}} \quad (1)$$

λ is the interaction length, which depends on the hadronic cross-section ($\sigma \sim 1/\lambda$).



METHOD OF SIMULATION

Using CORSIKA for:

- primary particle: P, He, C, Si, Fe
- energy: $10^{16} - 10^{21}$ eV
- hadronic model: EPOS, QGSII, SIBYLL

DOUBLE BUMPS

Gaisser–Hillas function:

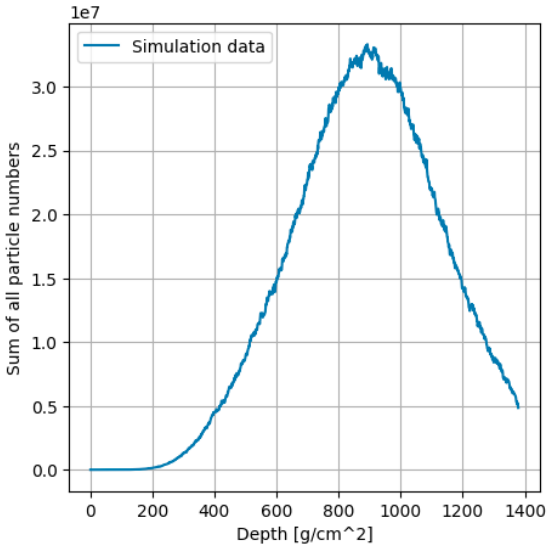
$$N(X) = N_{\max} \left(\frac{X - X_0}{X_{\max} - X_0} \right)^{\frac{X_{\max} - X_0}{\lambda}} \exp\left(\frac{X_{\max} - X}{\lambda} \right) \qquad (2)$$

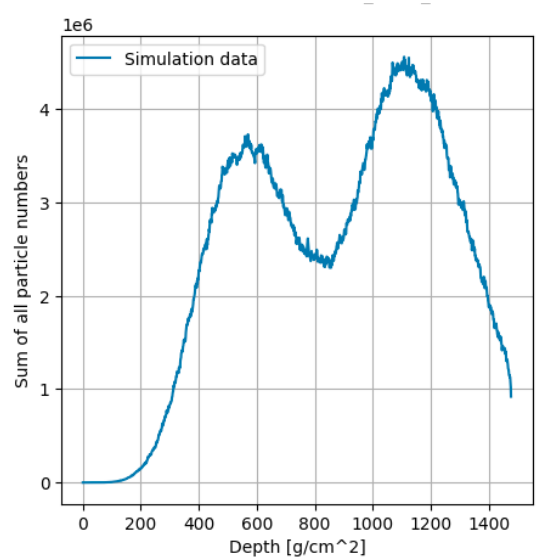
Reduced Gaisser–Hillas function:

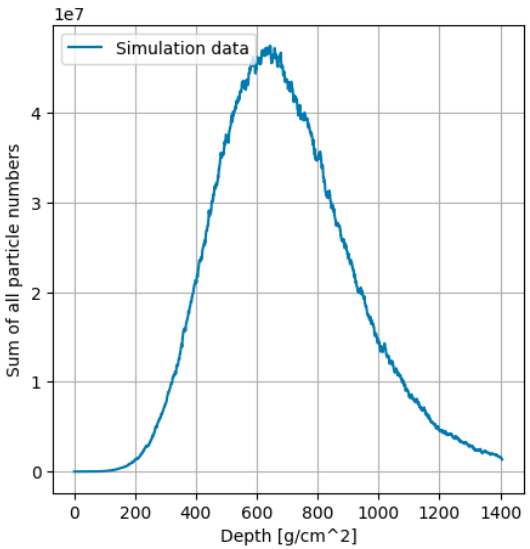
$$N(X) = N_{\max} \left(1 + \frac{R}{L}(X_{\max} - X_0) \right)^{\frac{1}{R^2}} \exp\left(-\frac{X - X_{\max}}{RL} \right) \qquad (3)$$

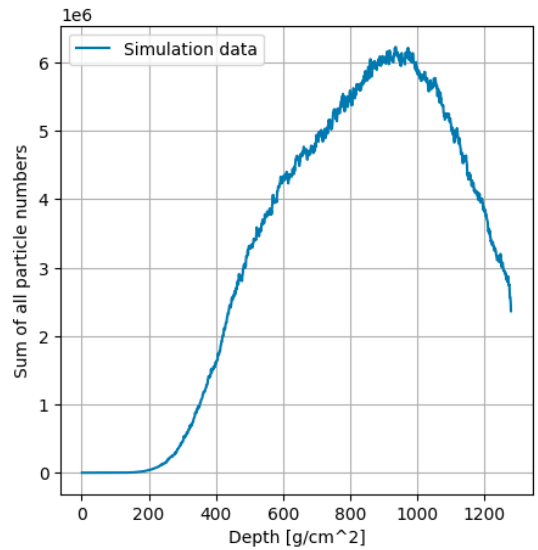
Uncertainties: $V_i = kN_i/E$ and $V_i = \sqrt{\sum V_i} / \sum N_i = 0.006$
Cut-off: $\sqrt{V_i}/N_i > 0.03$

EXAMPLES


1e7
Simulation data
Sum of all particle numbers
Depth [g/cm^2]


1e6
Simulation data
Sum of all particle numbers
Depth [g/cm^2]


1e7
Simulation data
Sum of all particle numbers
Depth [g/cm^2]


1e6
Simulation data
Sum of all particle numbers
Depth [g/cm^2]

WHAT IS A DOUBLE BUMP?

Method 1 [1]

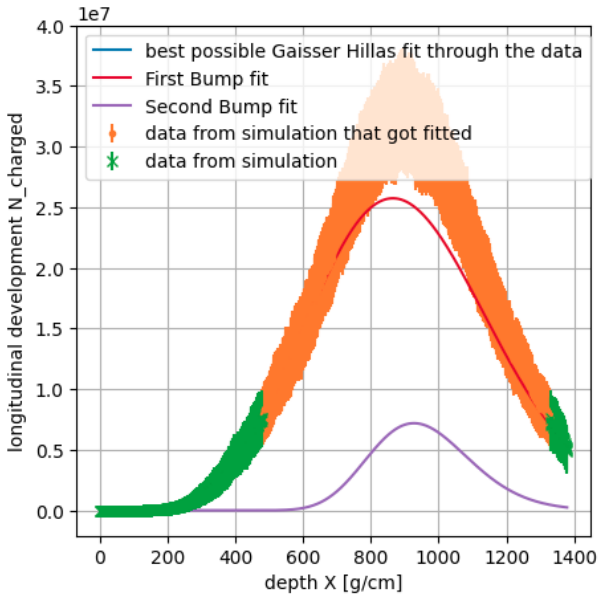
- $abs(X_{max_1} - X_{max_2}) > 300$
- $N_{max_2} > 0.2 * N_{max_1}$
- $200 < X_{max_1} < 2000$ and $200 < X_{max_2} < 2000$
- $(\Delta\chi^2)/\chi^2_{1\,bumb} > 0.75$

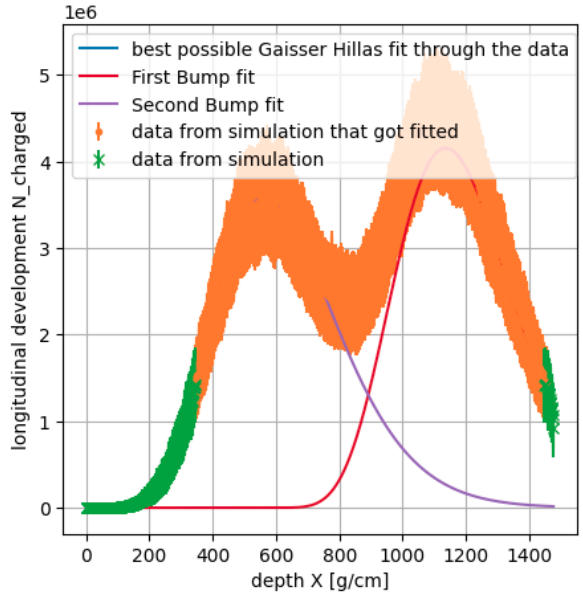
Method 2:

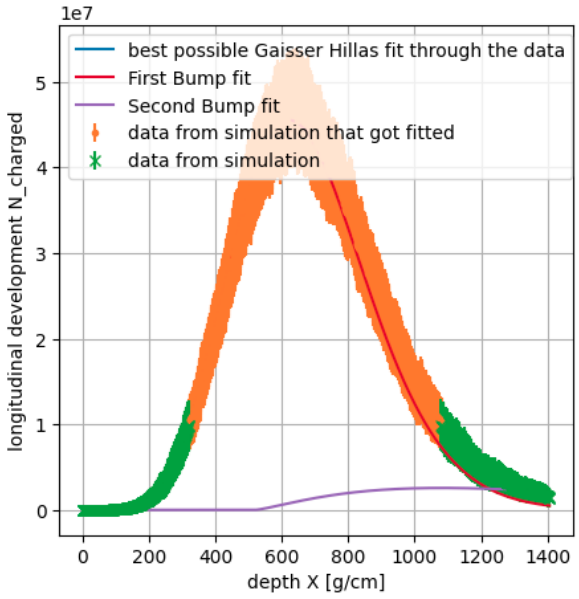
- $\mathrm{AIC} = 2k - 2\ln(\hat{L}) = 2k + \chi^2$
- likelihood = $\exp((AIC_{min} - AIC_i)/2)$

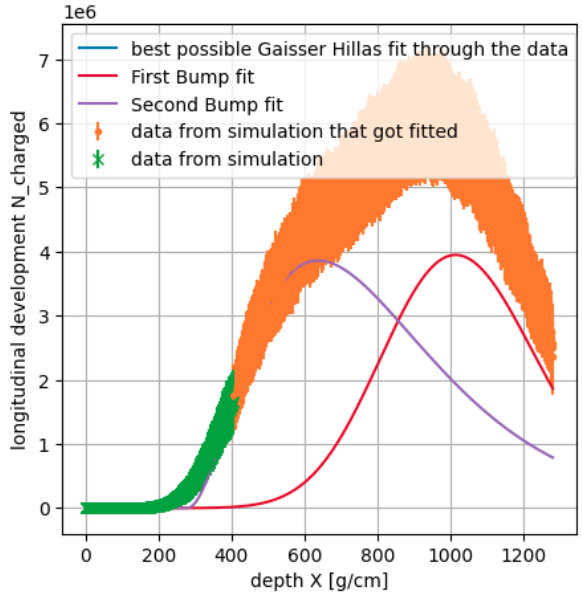
[1] Anomalous Longitudinal Shower Profiles and Hadronic Interactions: arXiv:1111.0504

EXAMPLES WITH FIT

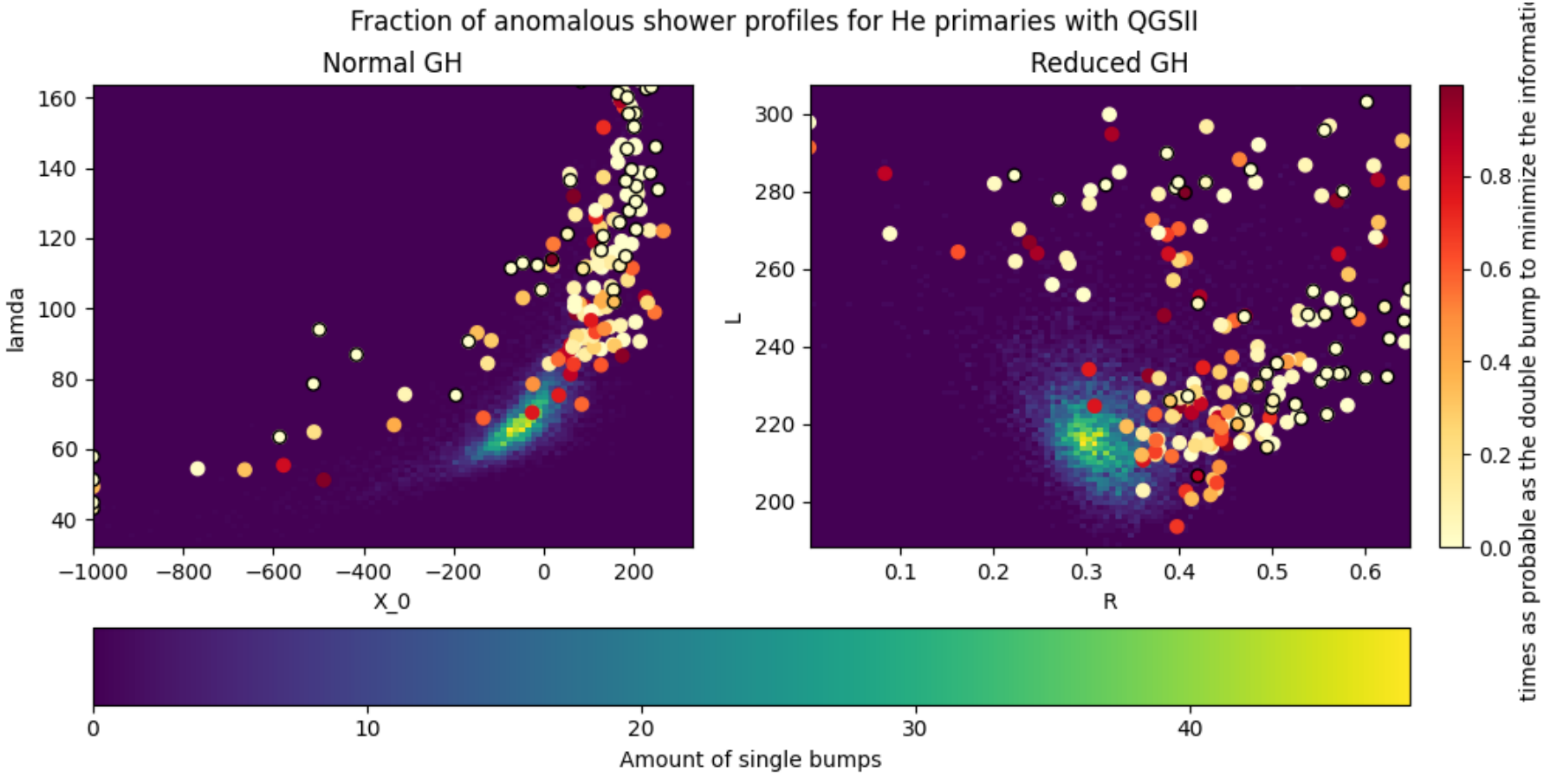








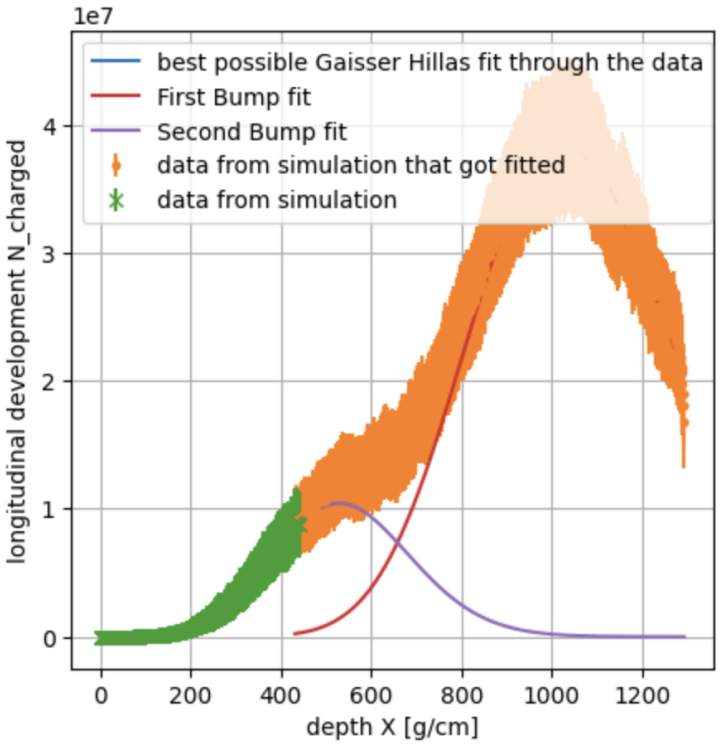
EFFECT OF THE DOUBLE BUMP CHECK

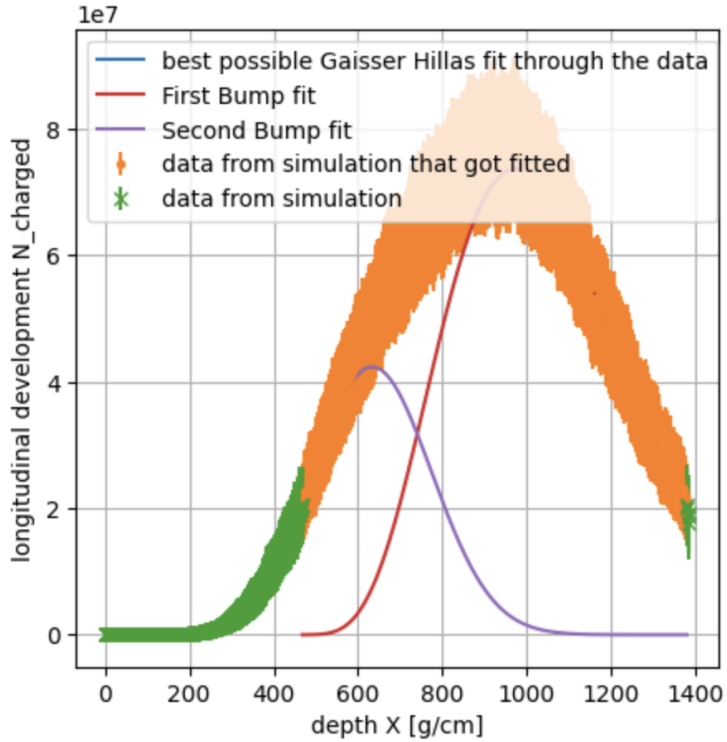


EFFECT OF THE DOUBLE BUMP CHECK

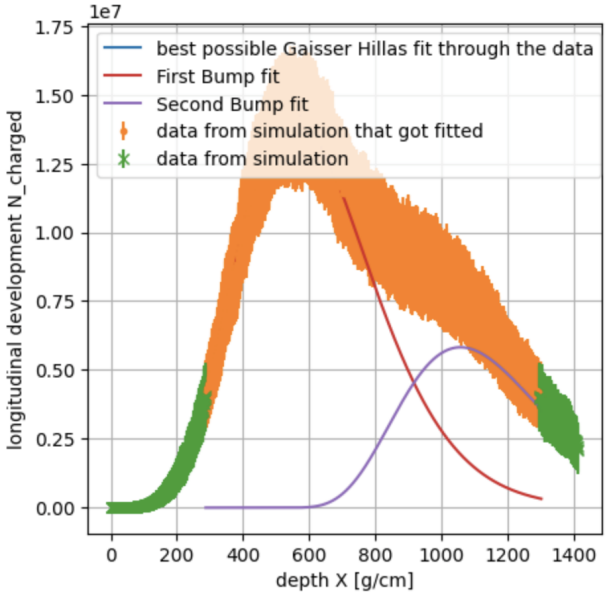
- Amount of DB found with new method: 381
- Amount of extra DB found with new method: 277
- Amount of old DB not found with new method: 0
- Amount of DB found by both n and r: 354
- Amount of DB found by normal not reduced: 15
- Amount of DB found by reduced not normal: 12

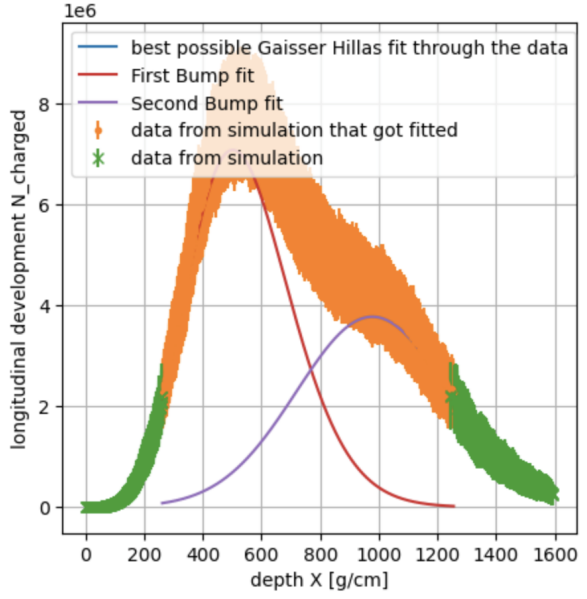
REALLY LOW R SHOWERS

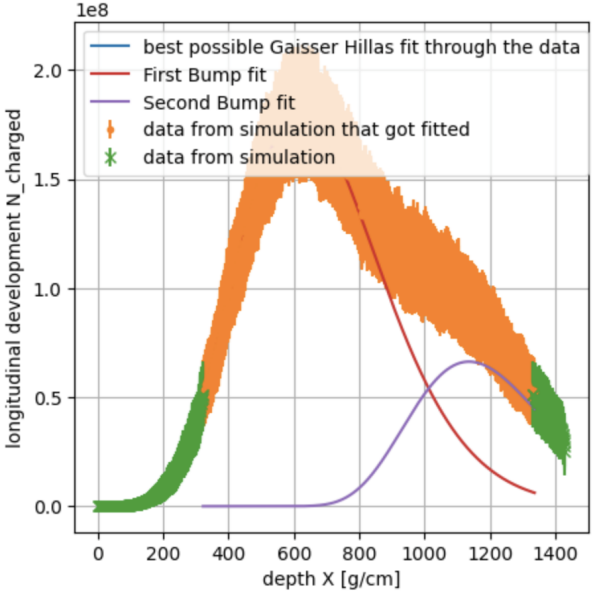


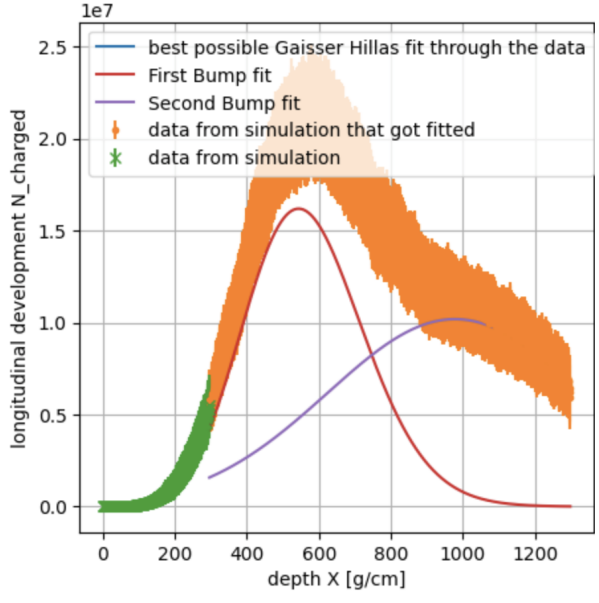


SHOWERS WITH $L > 270$ AND $R > 0.9$ (TOTAL 17)

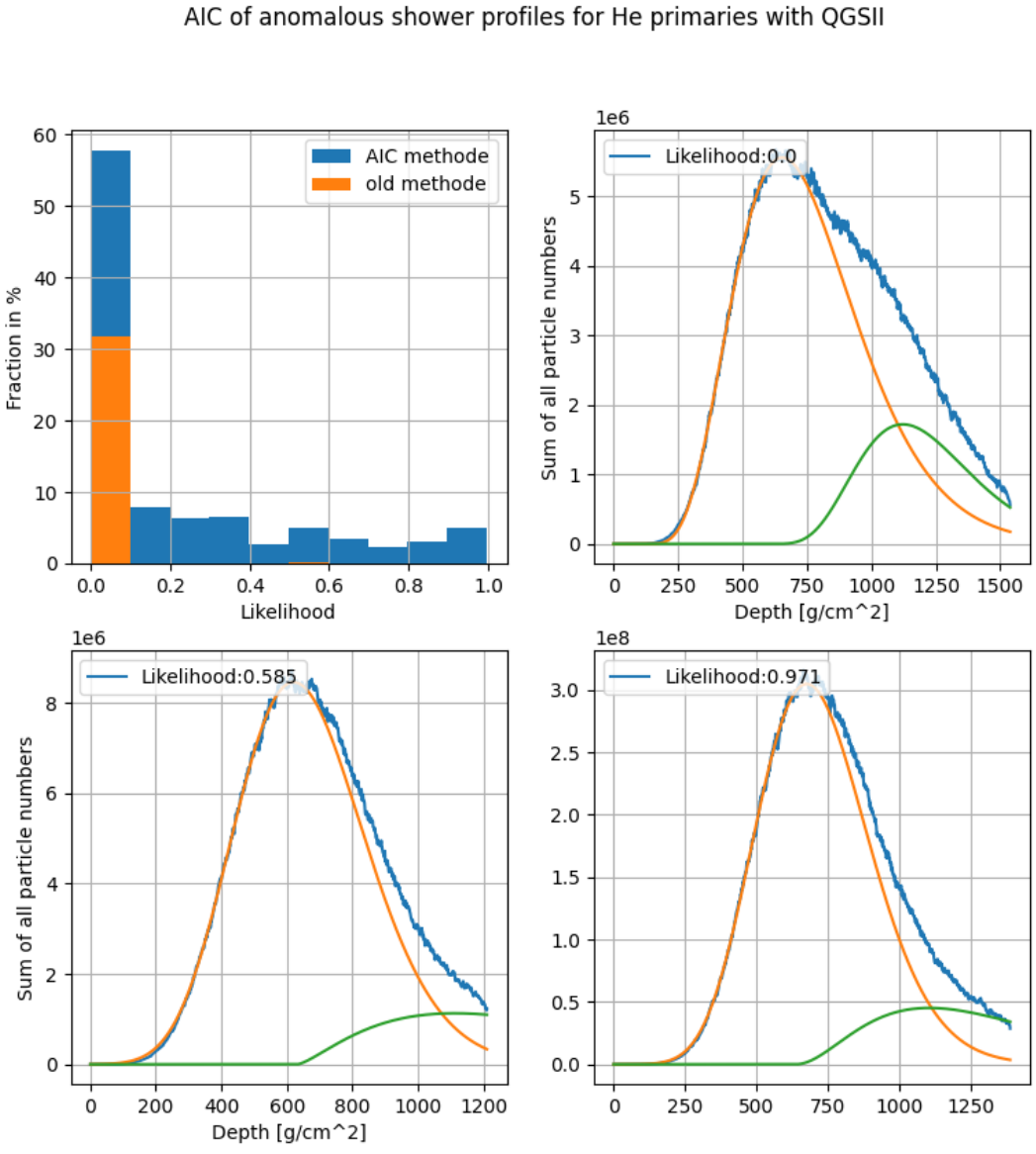




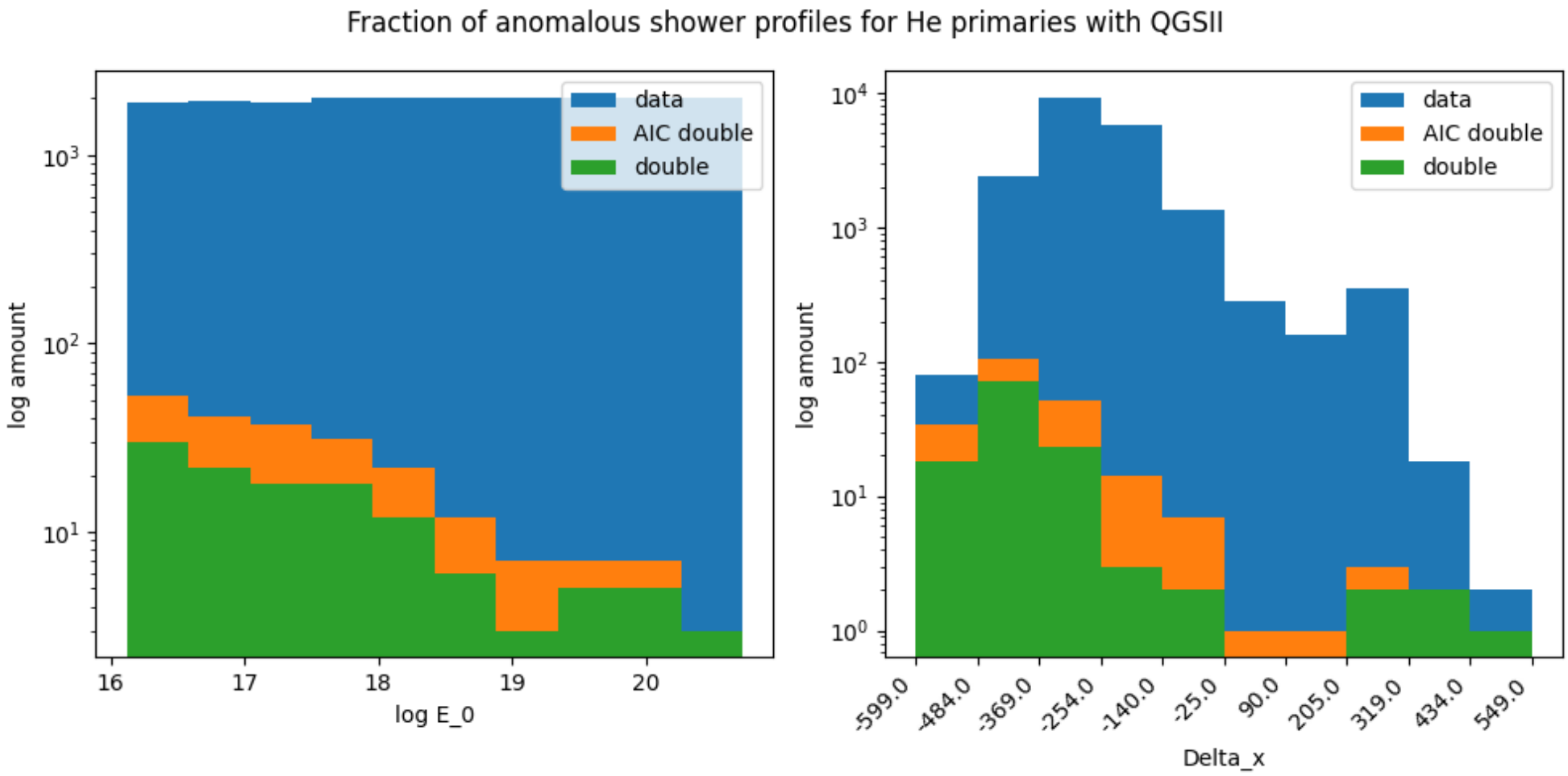




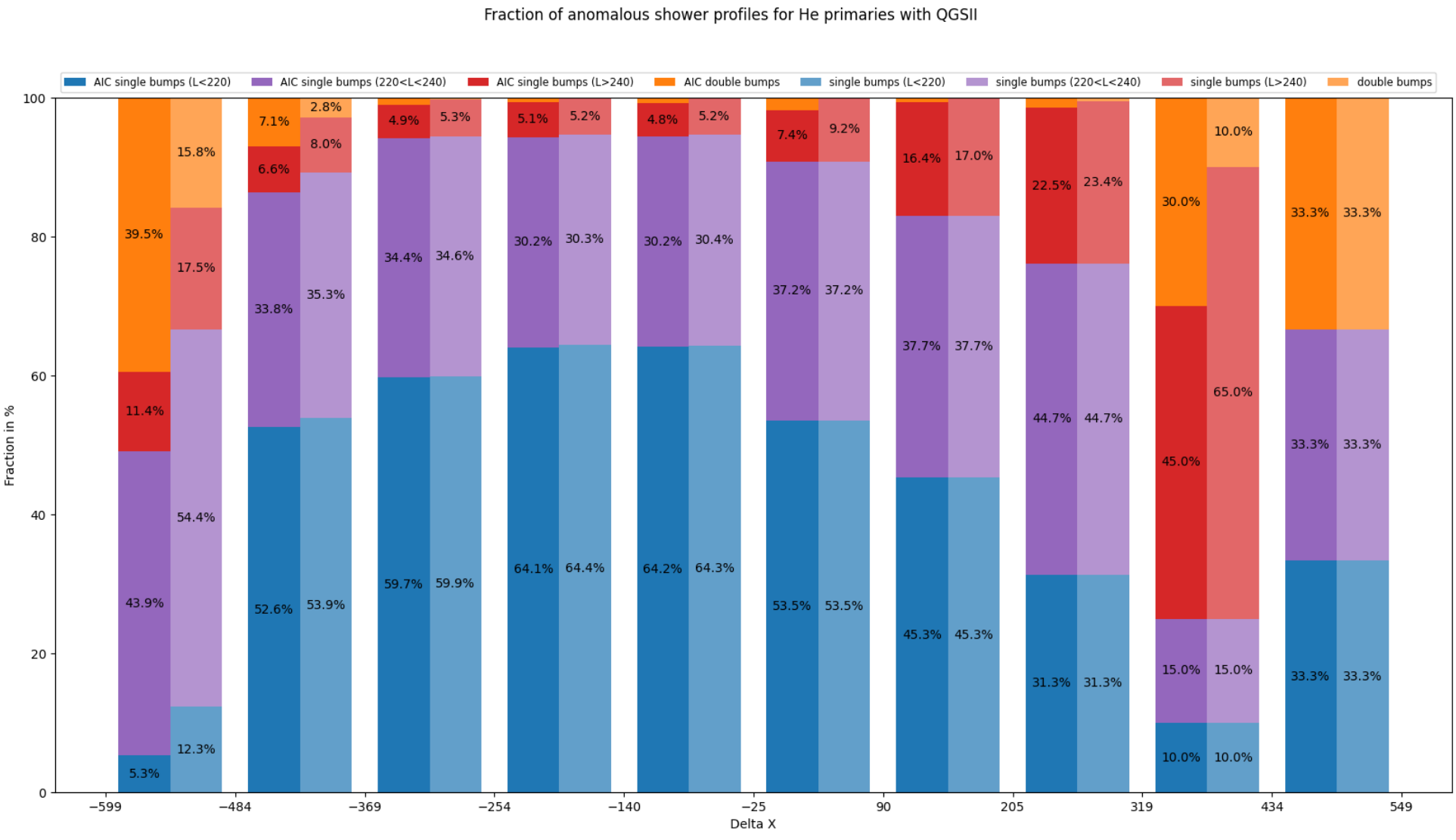
EFFECT OF THE DOUBLE BUMP CHECK CUT-OFF



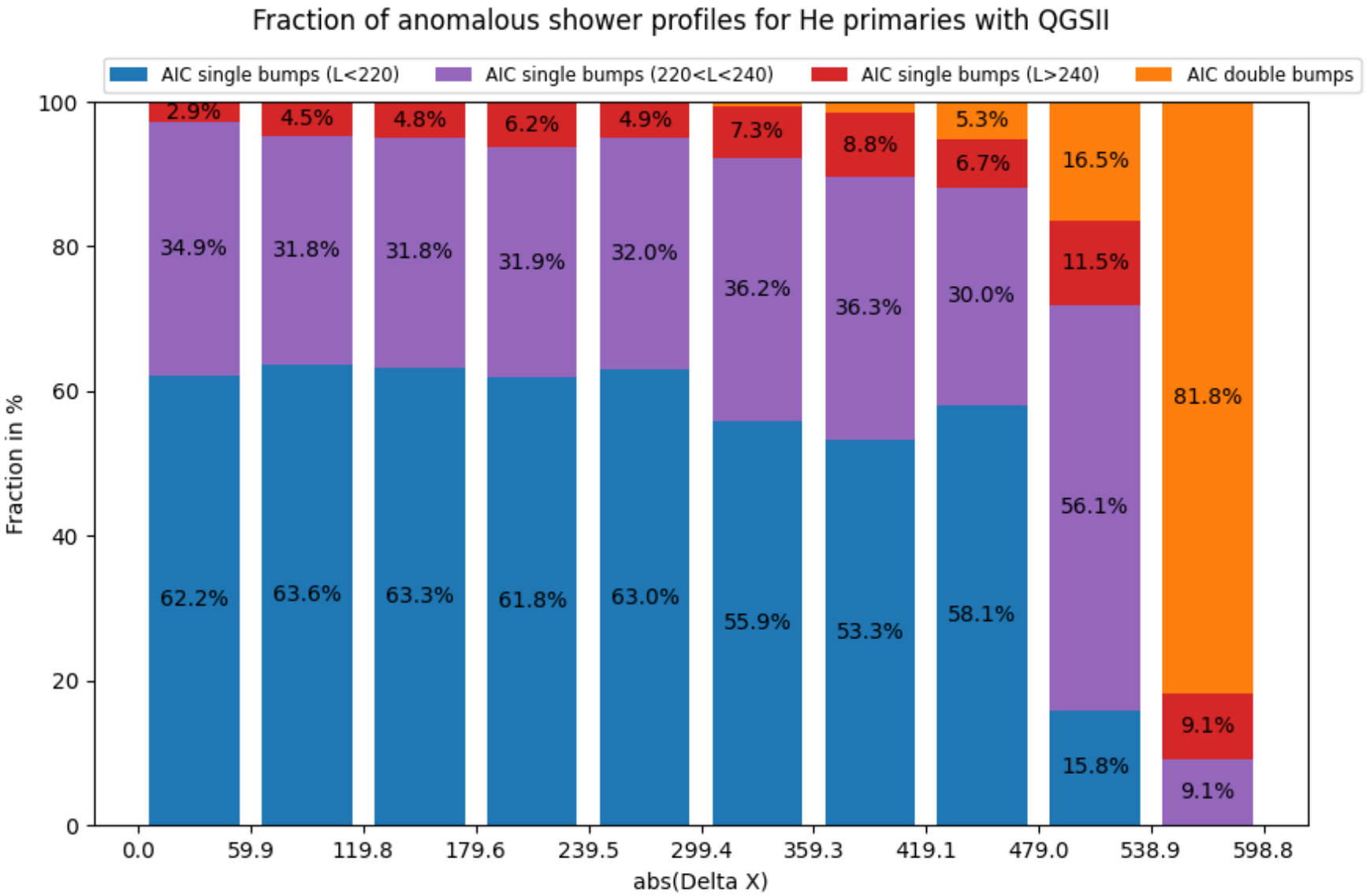
DOUBLE BUMP DISTRIBUTION IN *E* AND Δ*X*



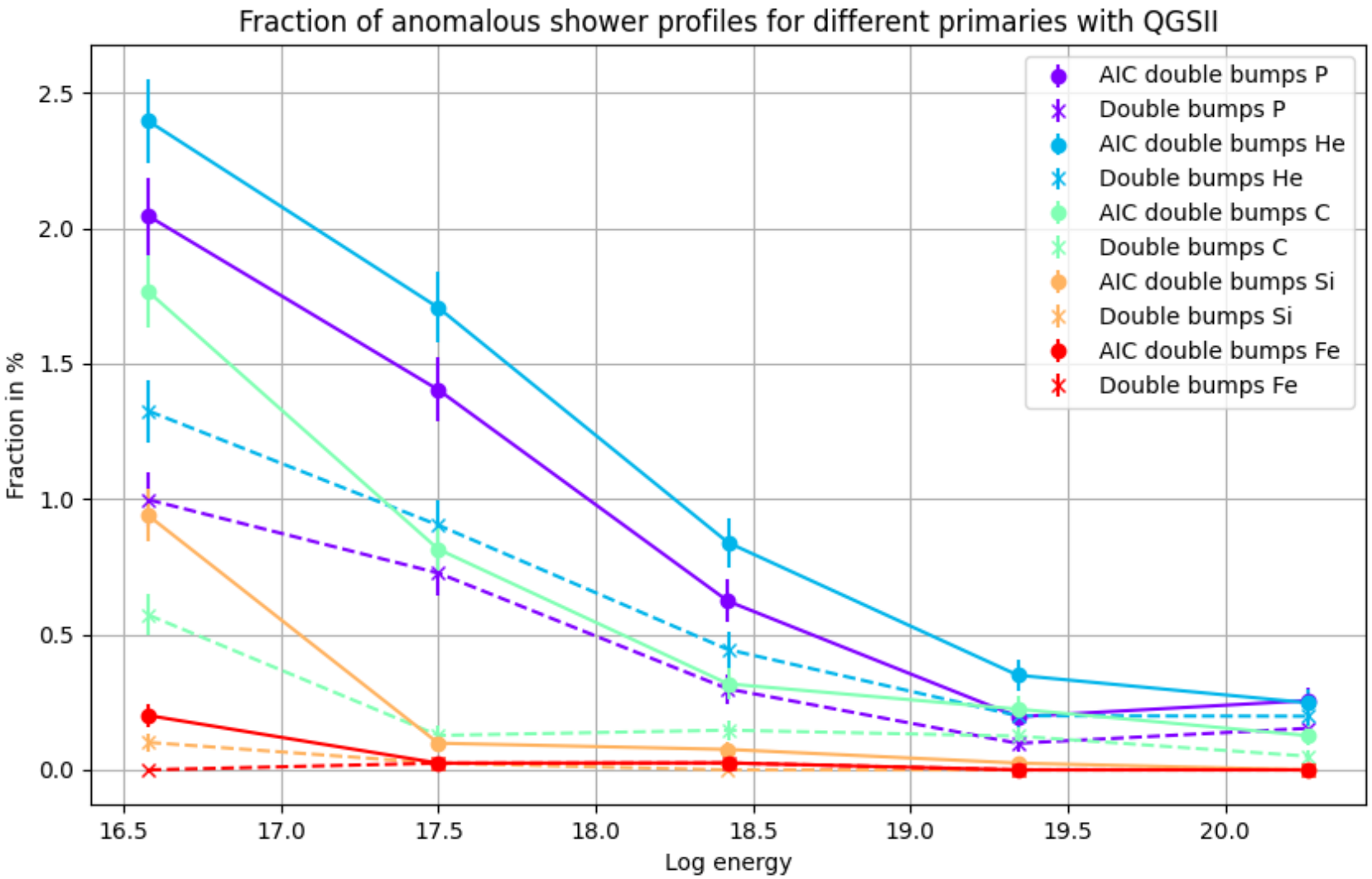
SHOWER TYPE DISTRIBUTION ΔX



SHOWER TYPE DISTRIBUTION | ΔX |



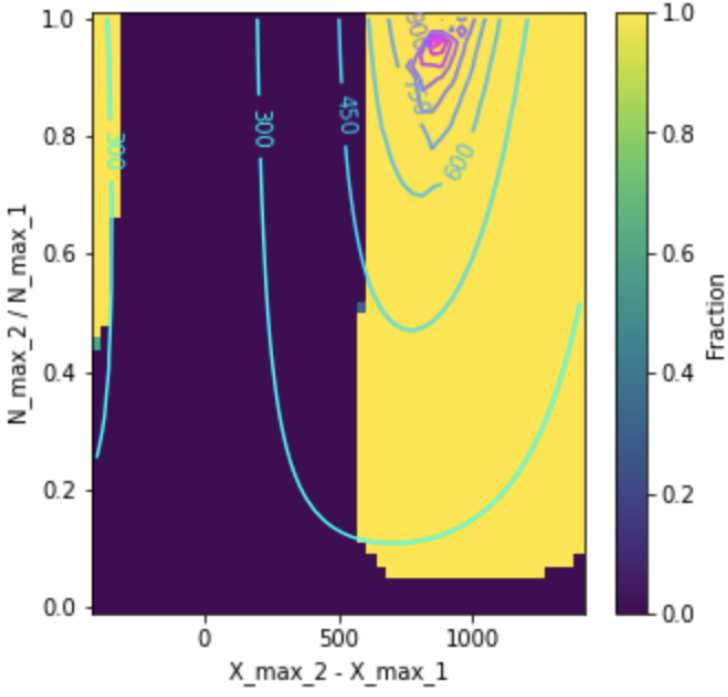
DOUBLE BUMP DISTRIBUTION IN *E*

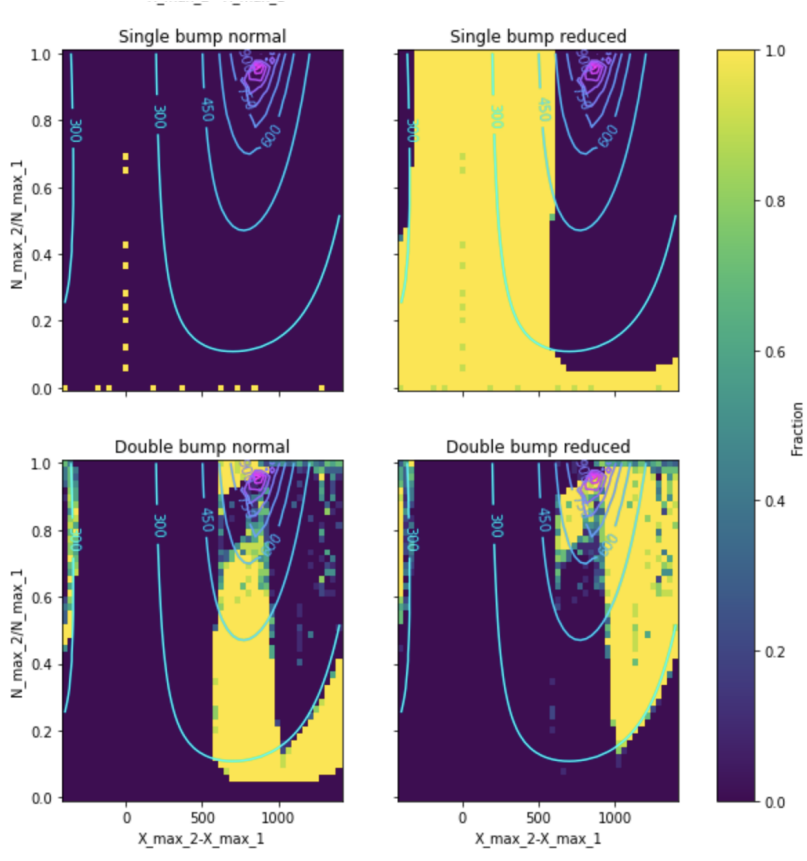


FUTURE PLANS

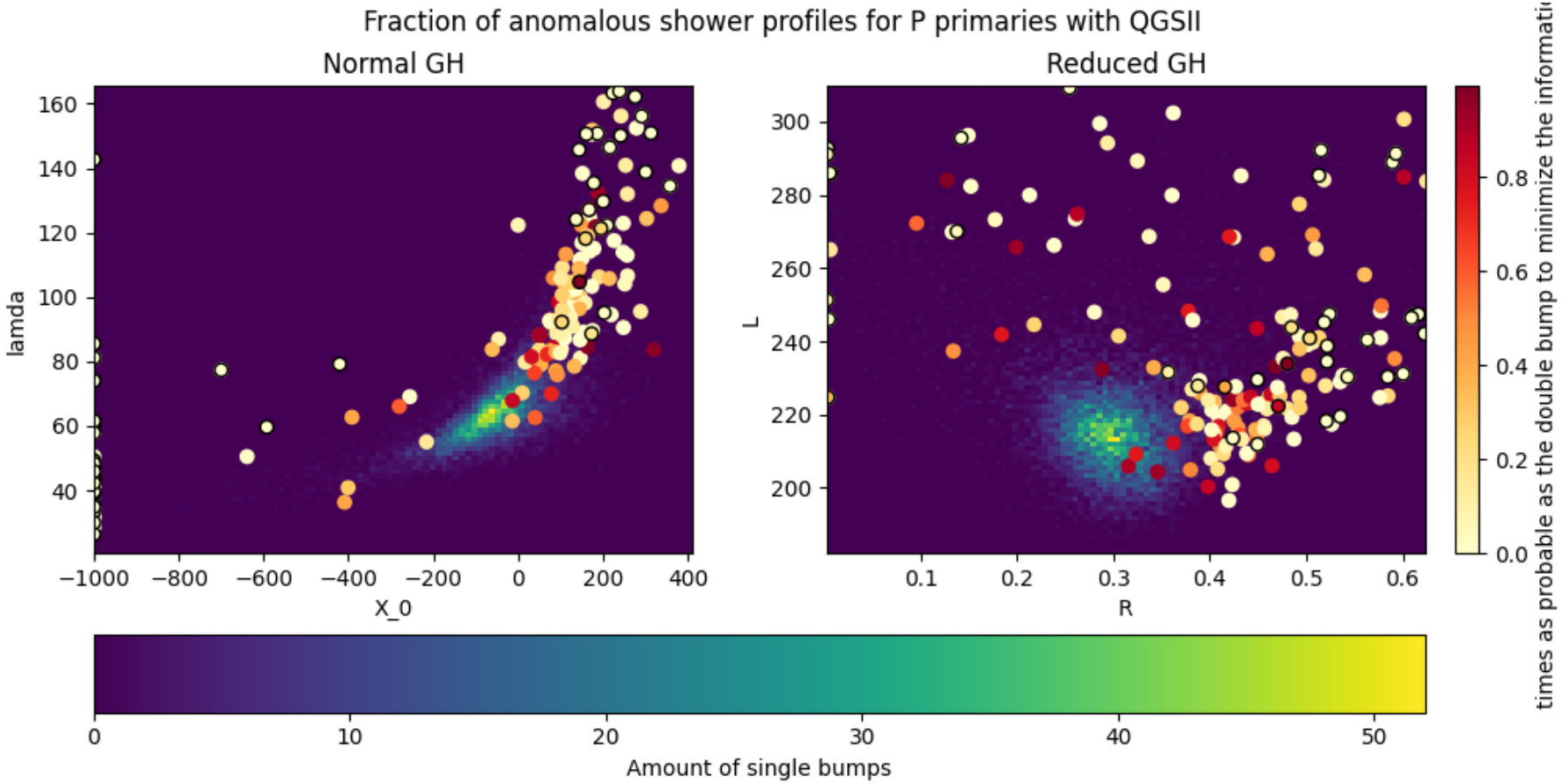
- Try to find the dominant particle.
- What kind of science can SKA do with double bumps?

APPENDIX

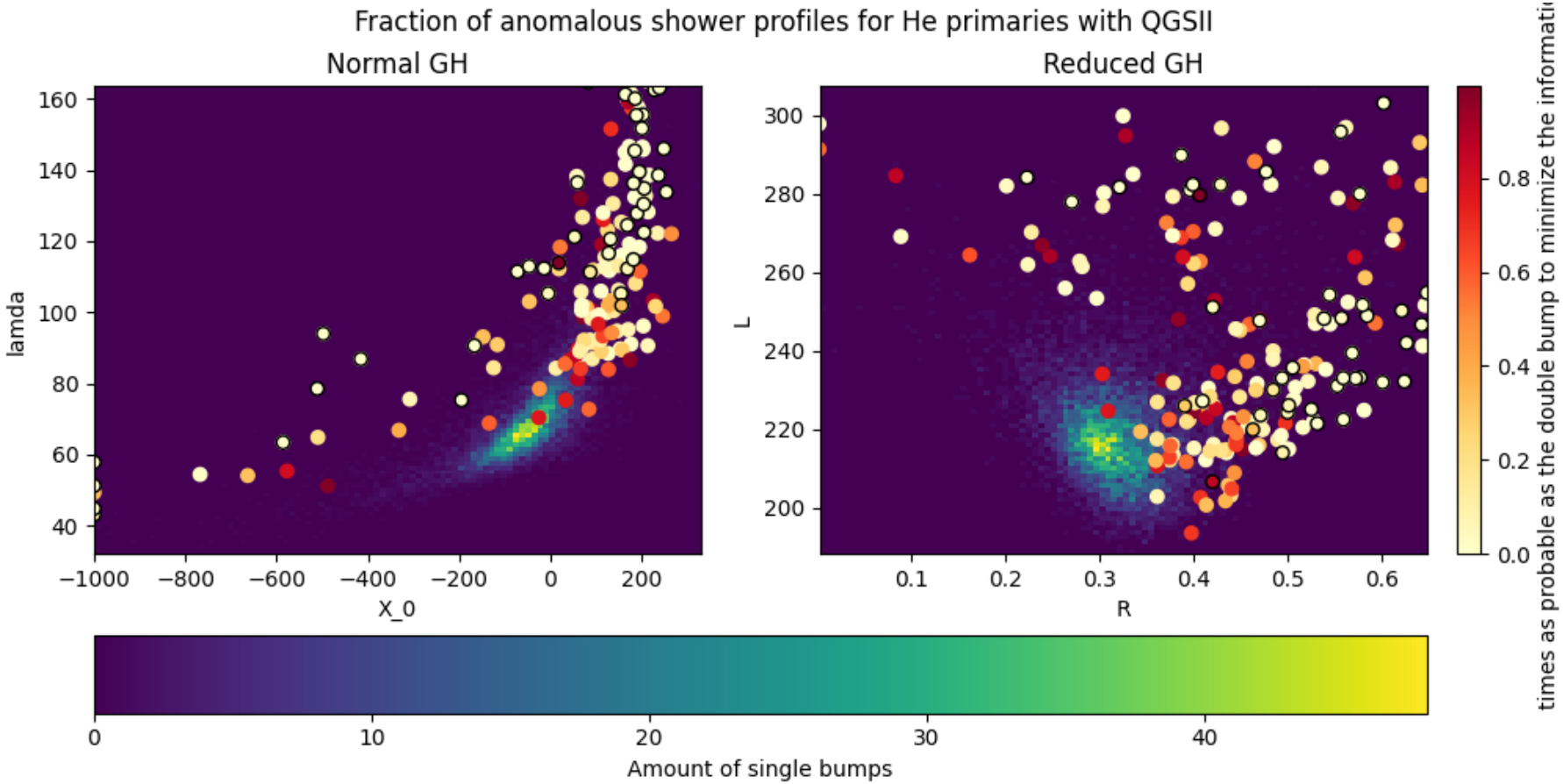

N_max_2 / N_max_1
X_max_2 - X_max_1
Fraction
300
450
600


Single bump normal
Single bump reduced
Double bump normal
Double bump reduced
N_max_2/N_max_1
X_max_2-X_max_1
Fraction

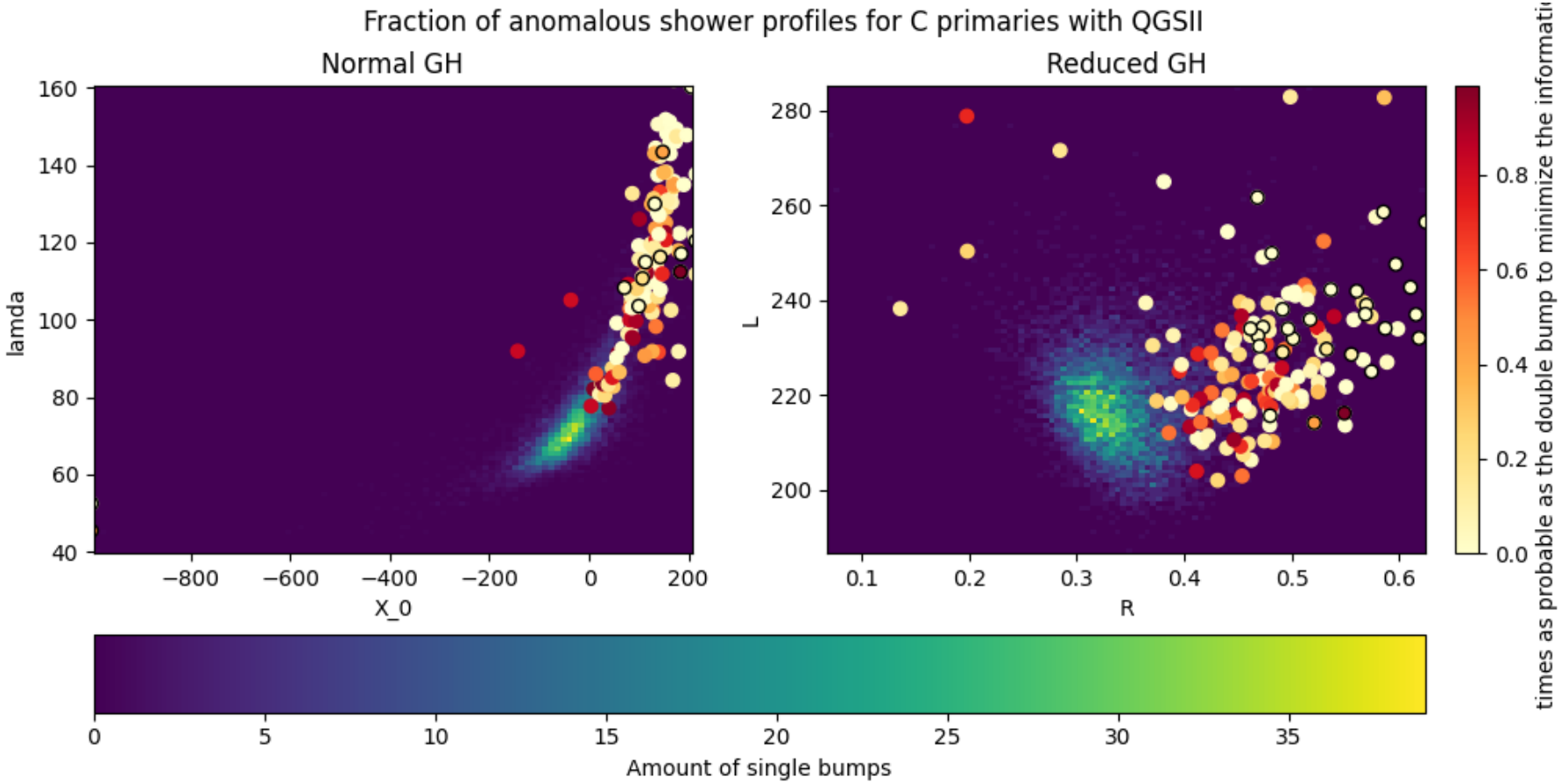
APPENDIX


Fraction of anomalous shower profiles for P primaries with QGSII
Normal GH
Reduced GH
lamda
X_0
L
R
Amount of single bumps
times as probable as the double bump to minimize the informati

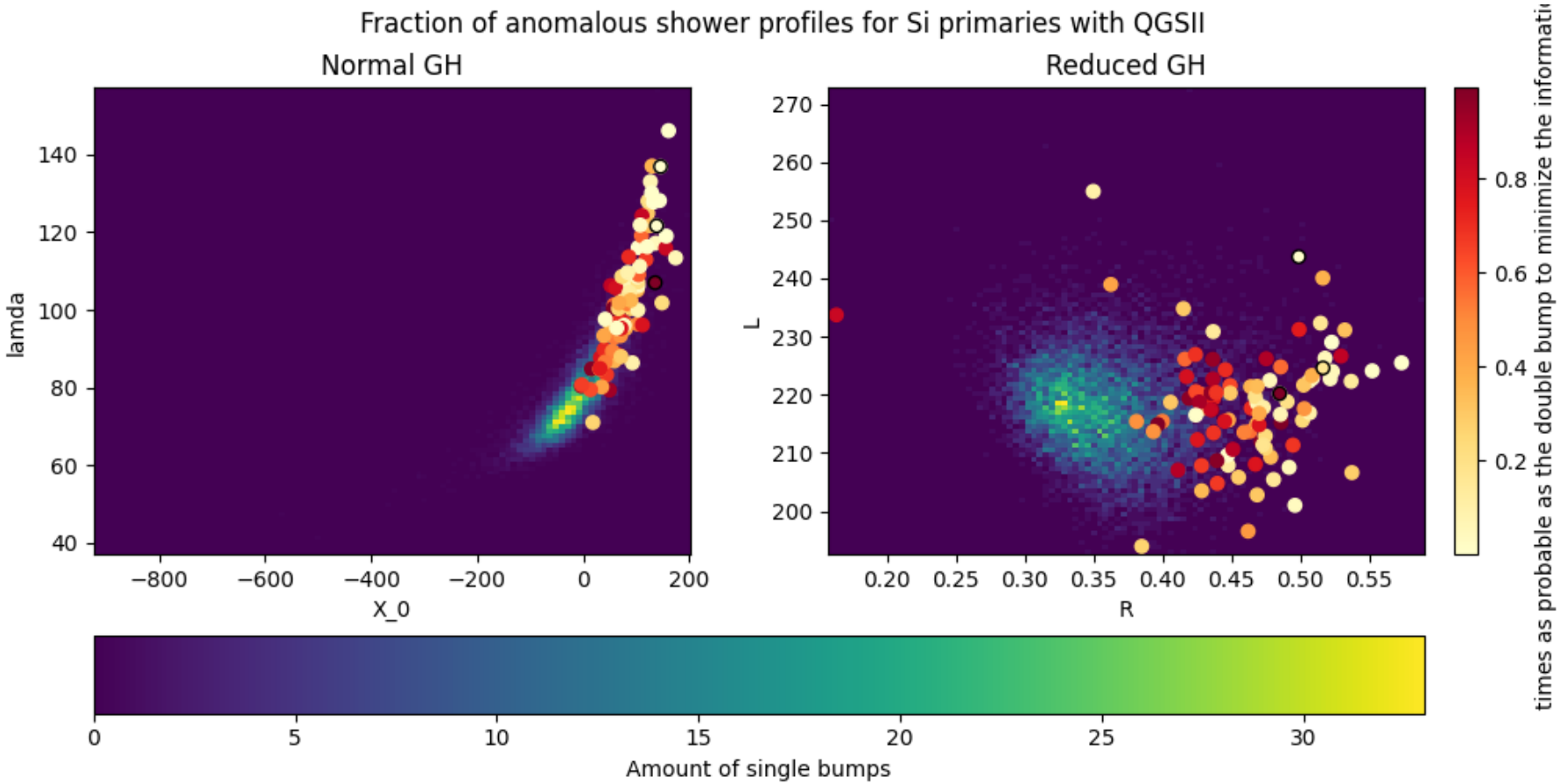
APPENDIX


Fraction of anomalous shower profiles for He primaries with QGSII
Normal GH
Reduced GH
lamda
X_0
L
R
Amount of single bumps
times as probable as the double bump to minimize the informati

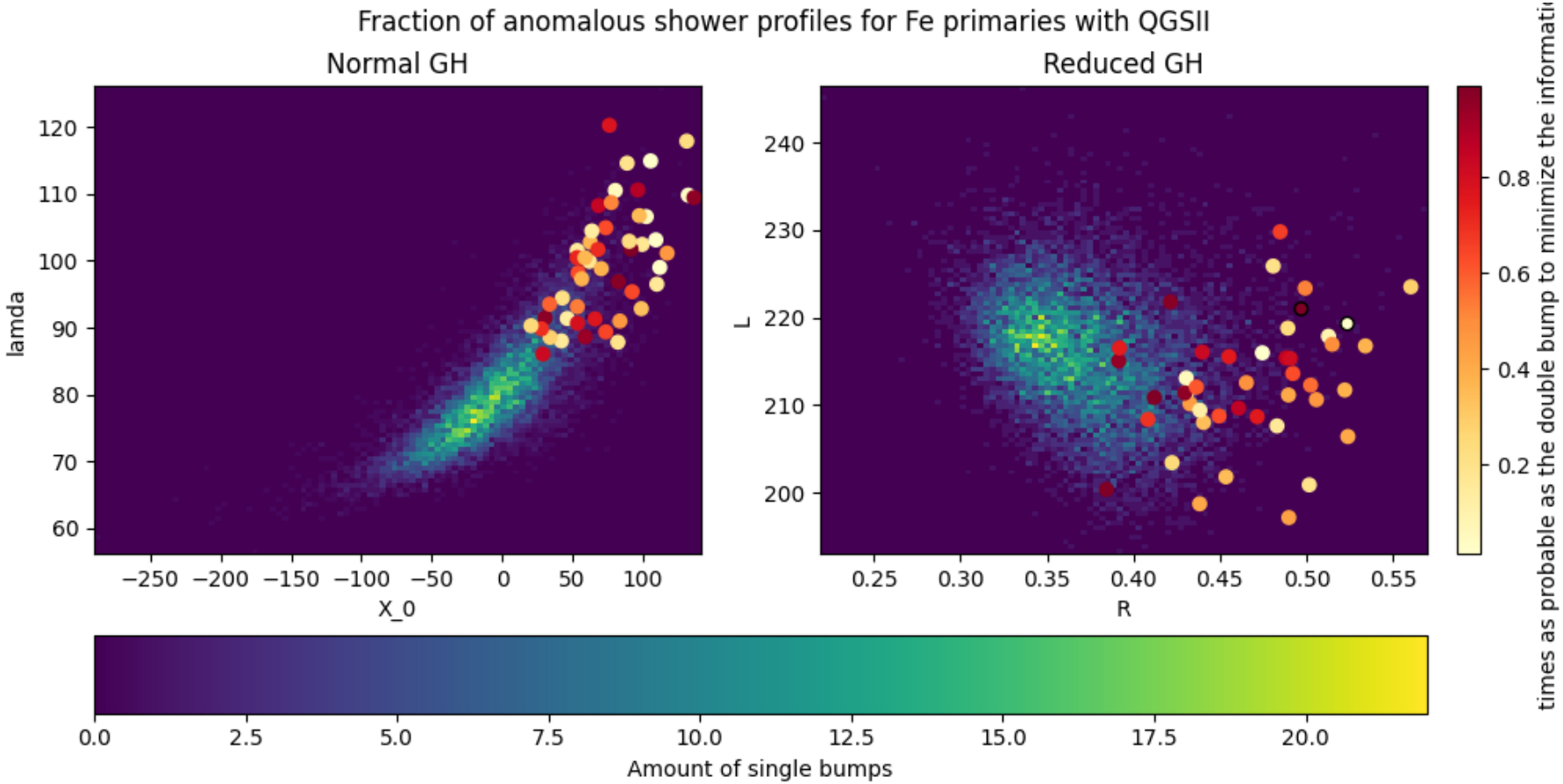
APPENDIX


Fraction of anomalous shower profiles for C primaries with QGSII
Normal GH
Reduced GH
lamda
X_0
L
R
times as probable as the double bump to minimize the informati
Amount of single bumps

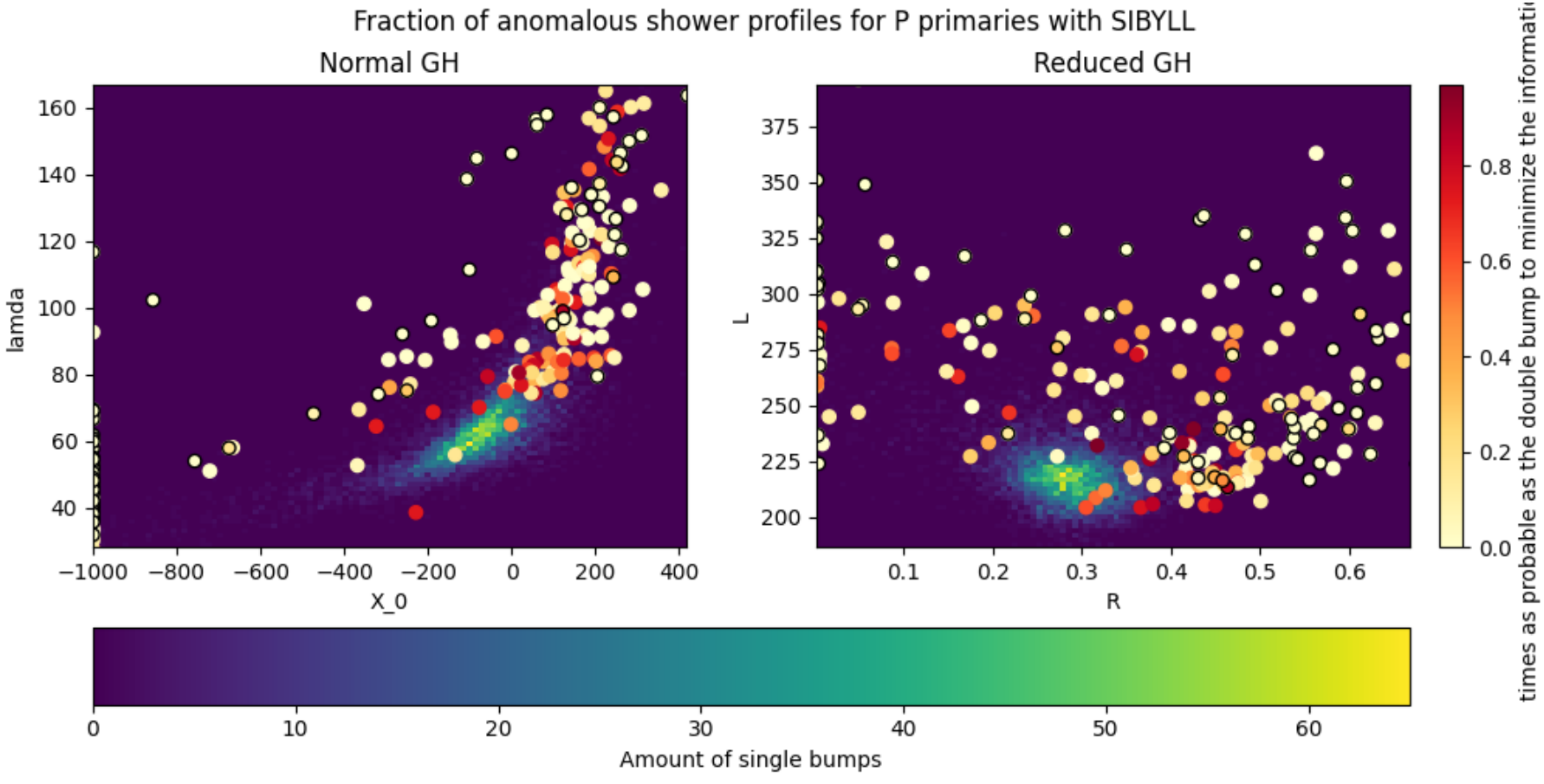
APPENDIX


Fraction of anomalous shower profiles for Si primaries with QGSII
Normal GH
Reduced GH
lamda
X_0
L
R
Amount of single bumps
times as probable as the double bump to minimize the informati

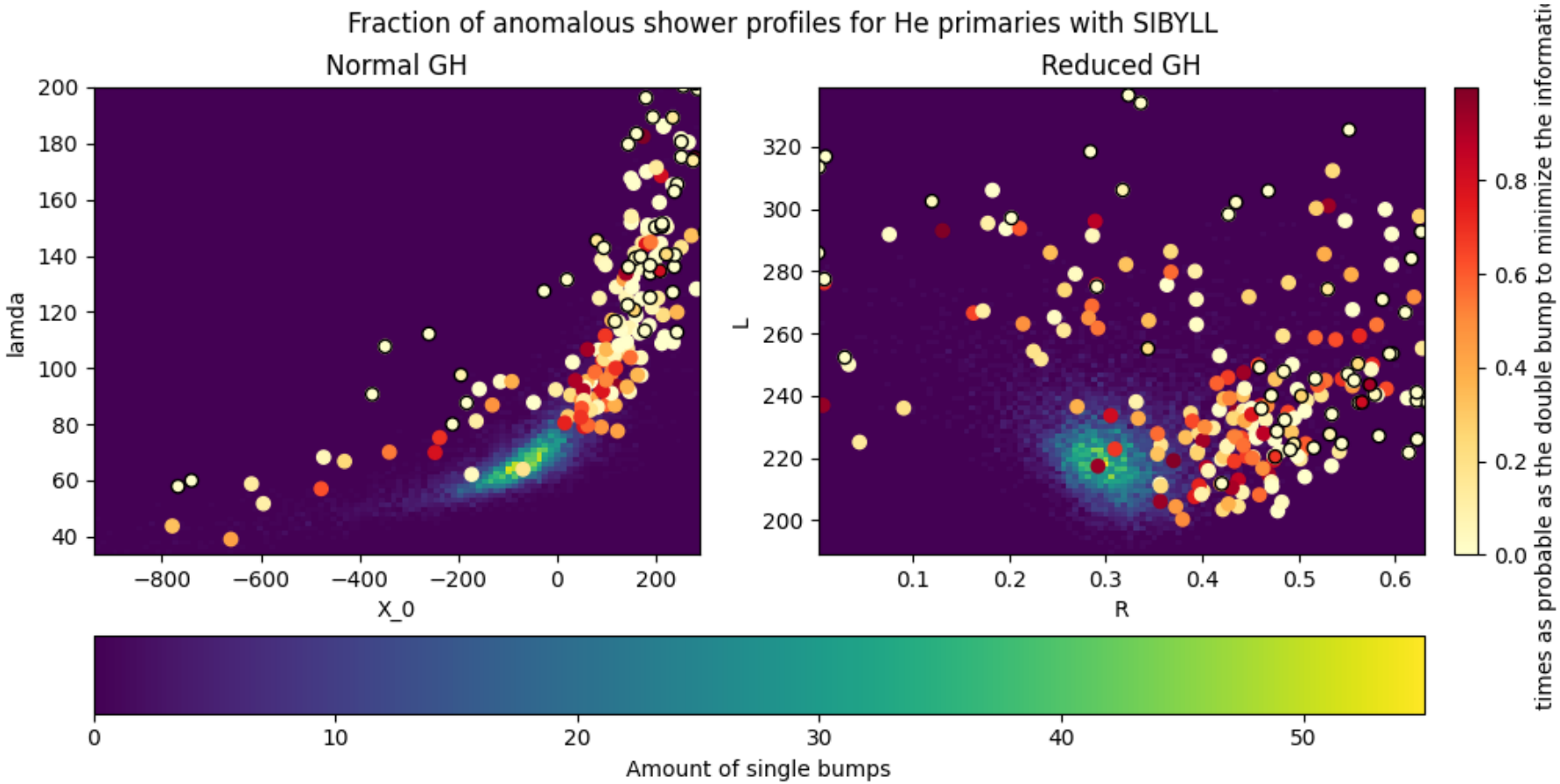
APPENDIX


Fraction of anomalous shower profiles for Fe primaries with QGSII
Normal GH
Reduced GH
lamda
X_0
L
R
Amount of single bumps
times as probable as the double bump to minimize the informati

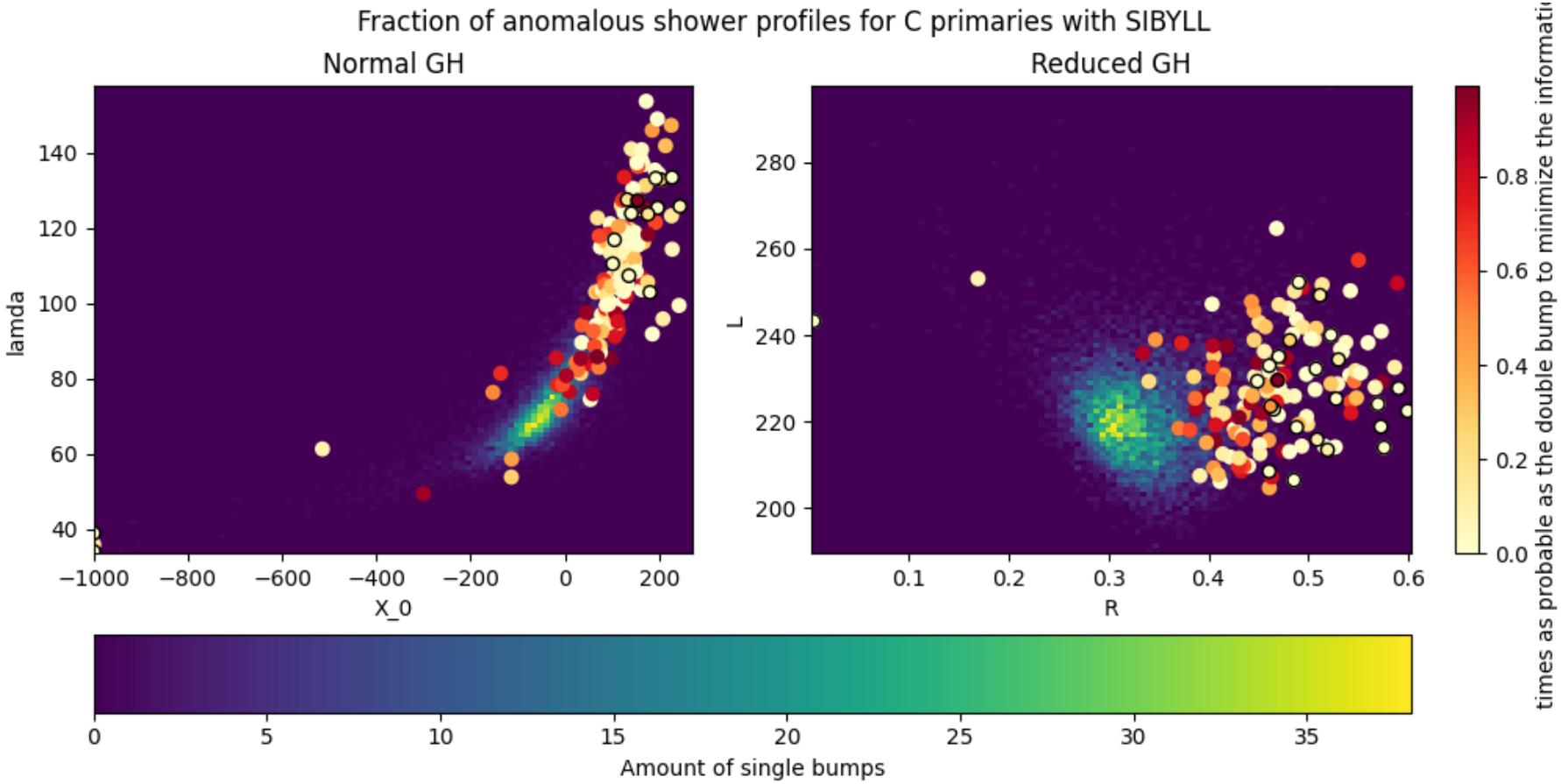
APPENDIX


Fraction of anomalous shower profiles for P primaries with SIBYLL
Normal GH
Reduced GH
lamda
X_0
L
R
Amount of single bumps
times as probable as the double bump to minimize the informati

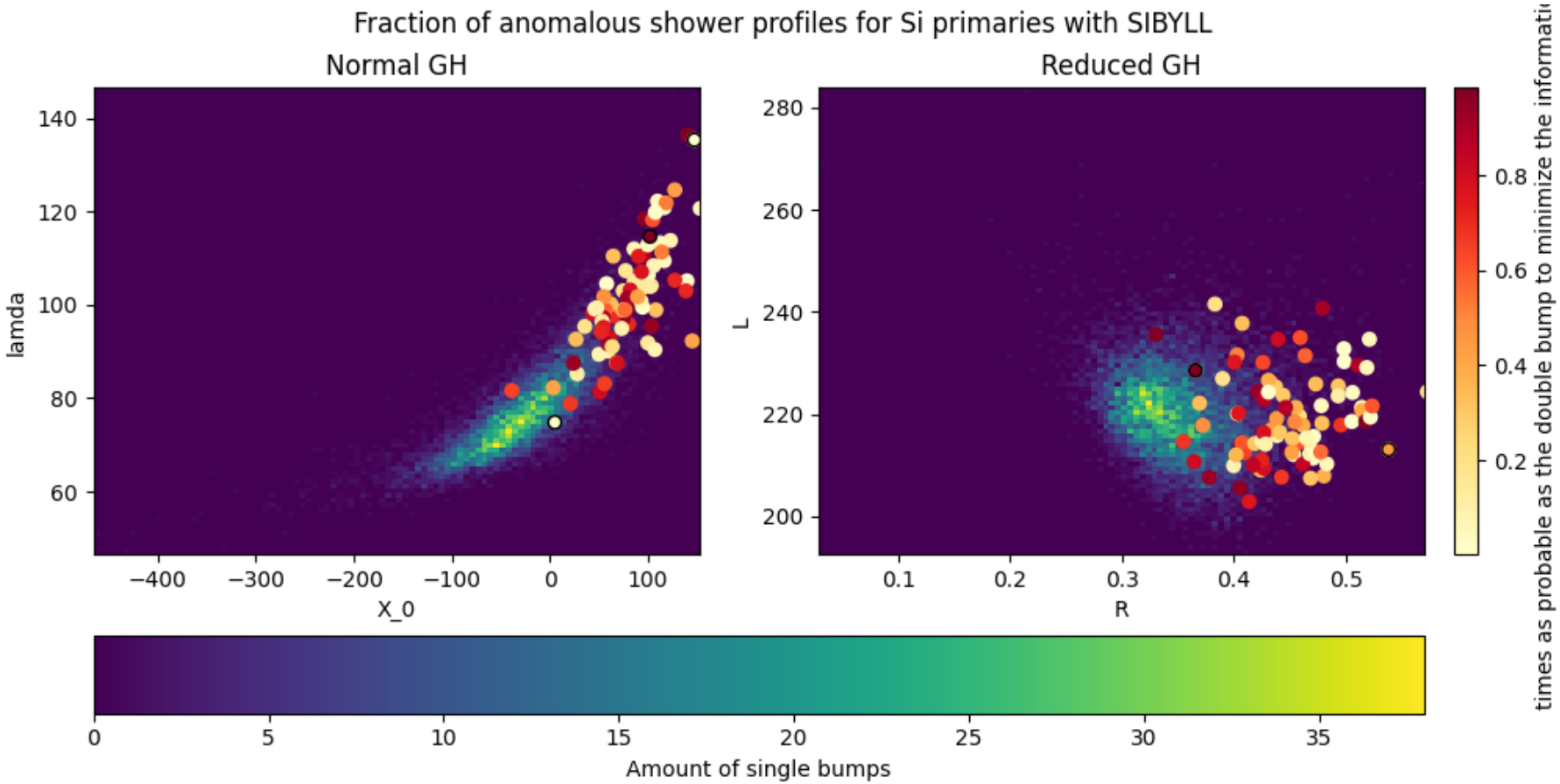
APPENDIX


Fraction of anomalous shower profiles for He primaries with SIBYLL
Normal GH
Reduced GH
lamda
X_0
L
R
Amount of single bumps
times as probable as the double bump to minimize the informati

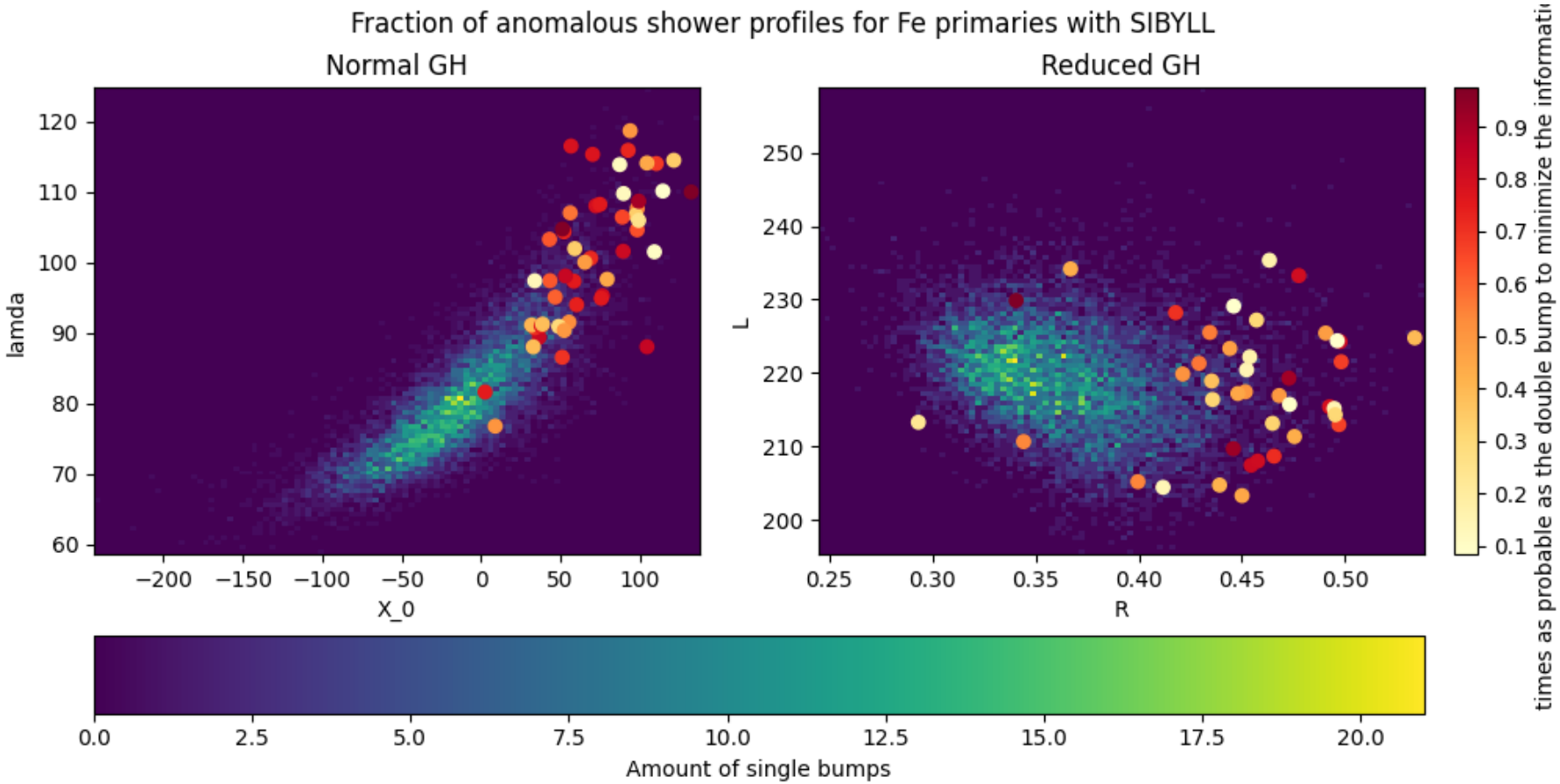
APPENDIX


Fraction of anomalous shower profiles for C primaries with SIBYLL
Normal GH
Reduced GH
lamda
X_0
L
R
times as probable as the double bump to minimize the informati
Amount of single bumps

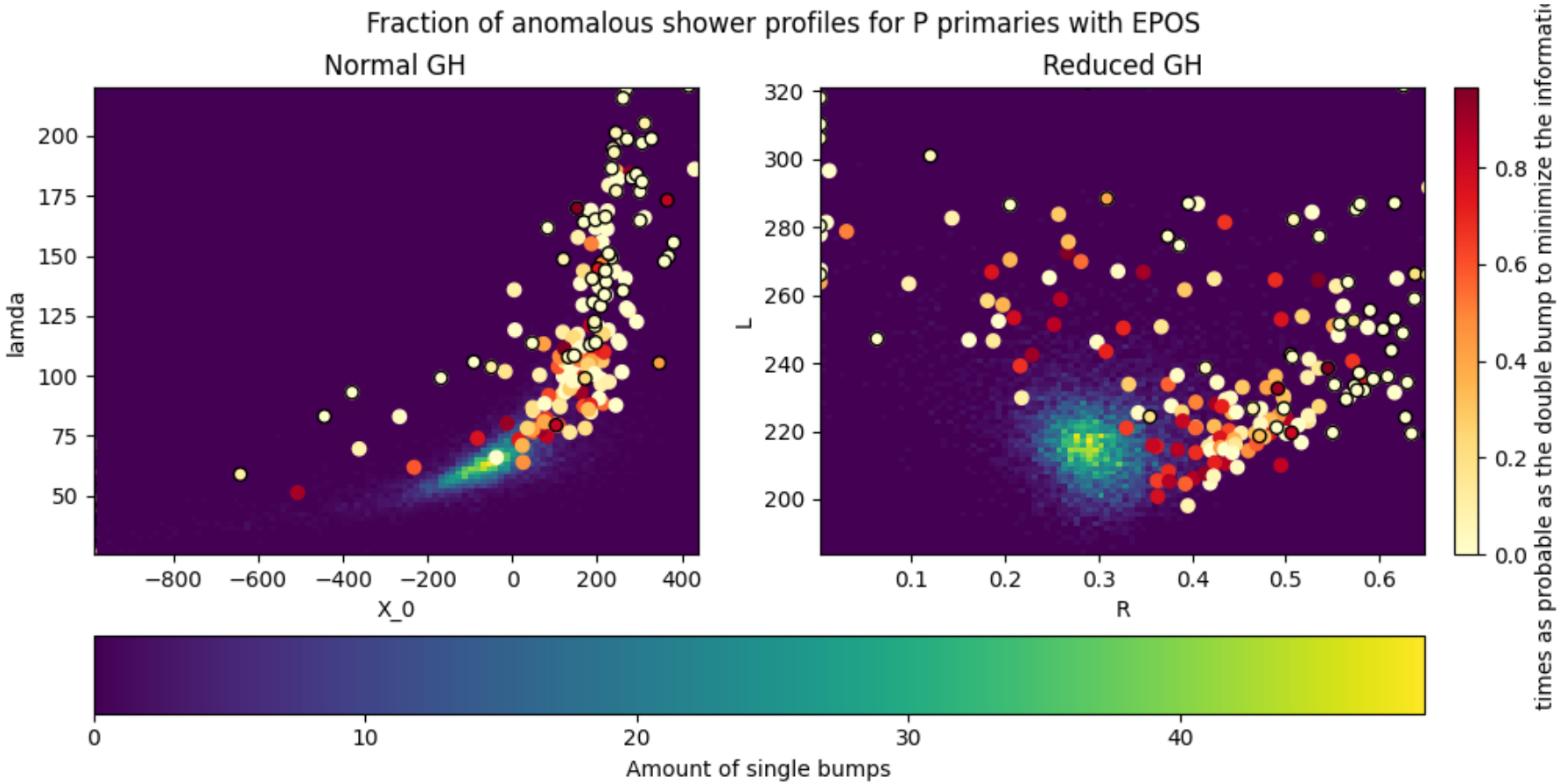
APPENDIX


Fraction of anomalous shower profiles for Si primaries with SIBYLL
Normal GH
Reduced GH
lamda
X_0
L
R
Amount of single bumps
times as probable as the double bump to minimize the informati

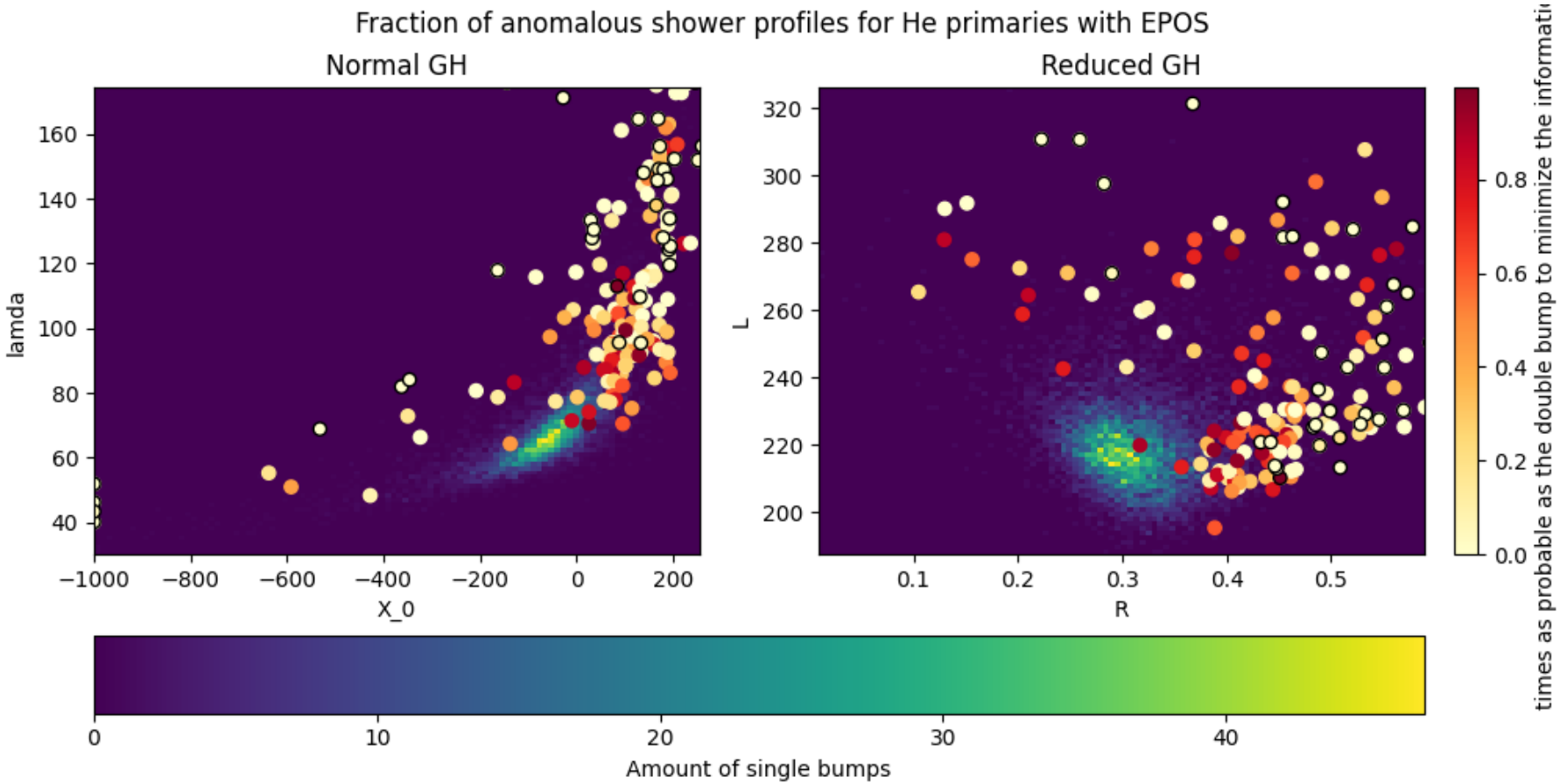
APPENDIX


Fraction of anomalous shower profiles for Fe primaries with SIBYLL
Normal GH
Reduced GH
lamda
X_0
L
R
Amount of single bumps
times as probable as the double bump to minimize the informati

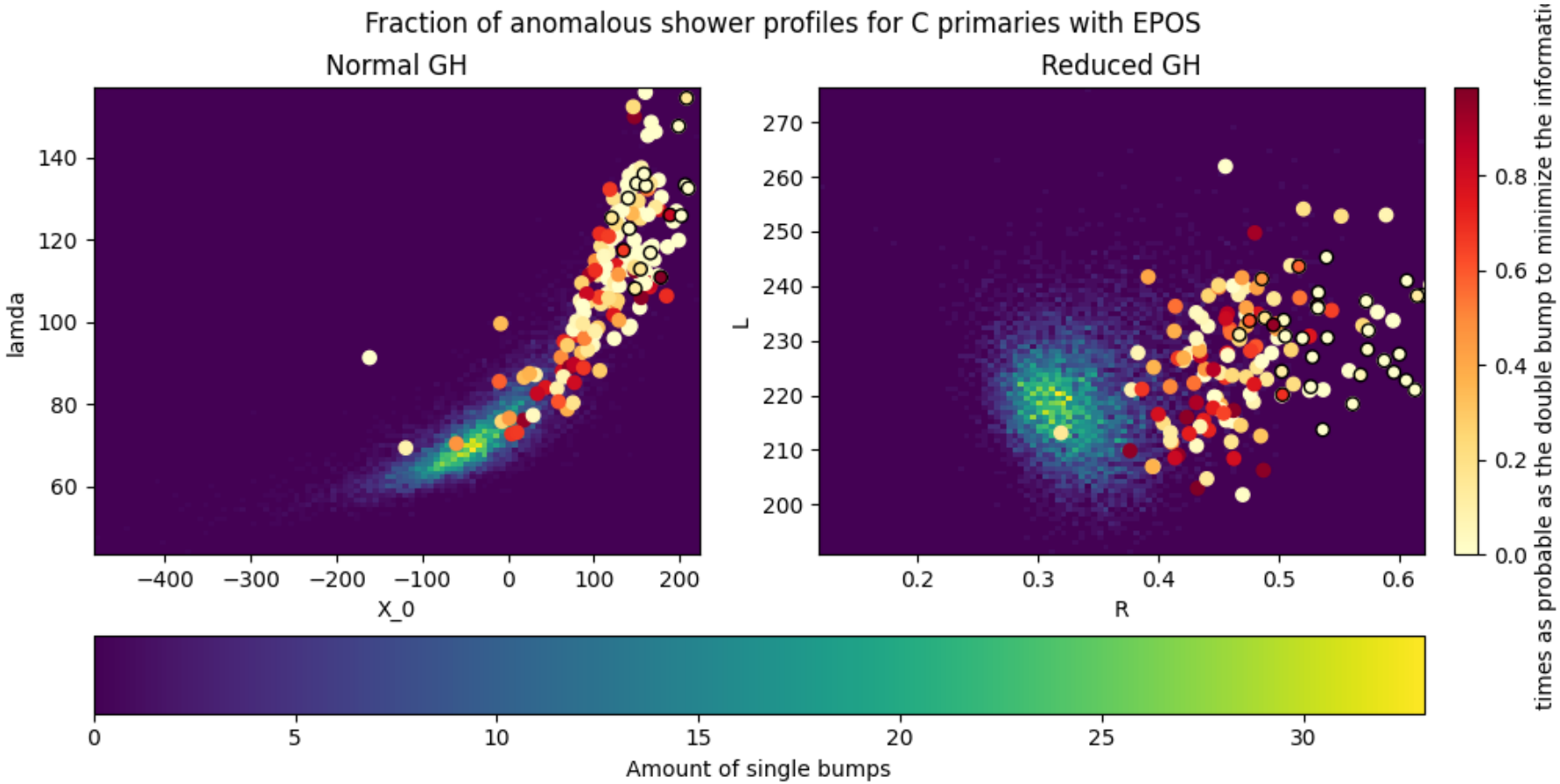
APPENDIX


Fraction of anomalous shower profiles for P primaries with EPOS
Normal GH
Reduced GH
lamda
X_0
L
R
Amount of single bumps
times as probable as the double bump to minimize the informati

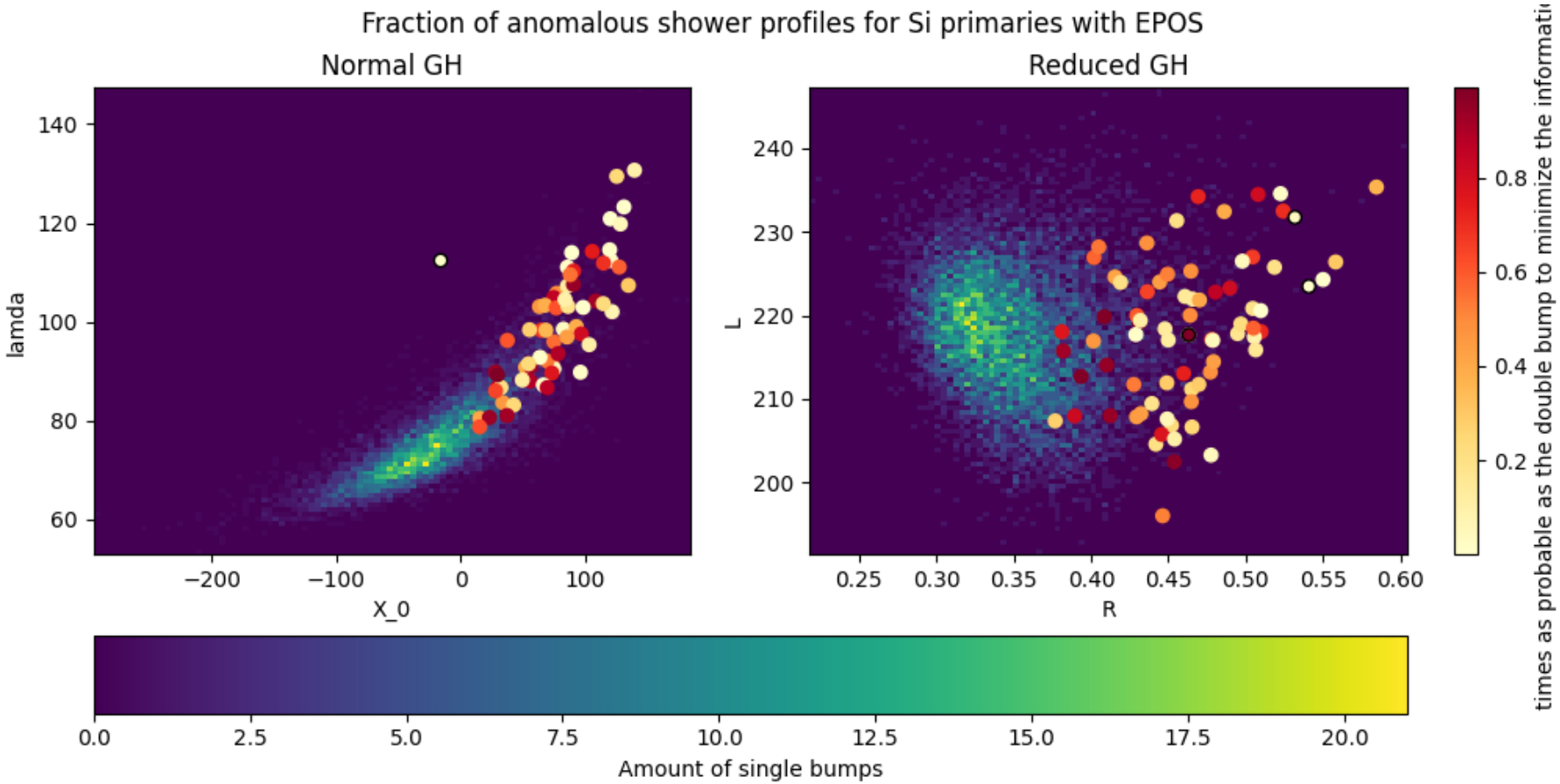
APPENDIX


Fraction of anomalous shower profiles for He primaries with EPOS
Normal GH
Reduced GH
lamda
X_0
L
R
Amount of single bumps
times as probable as the double bump to minimize the informati

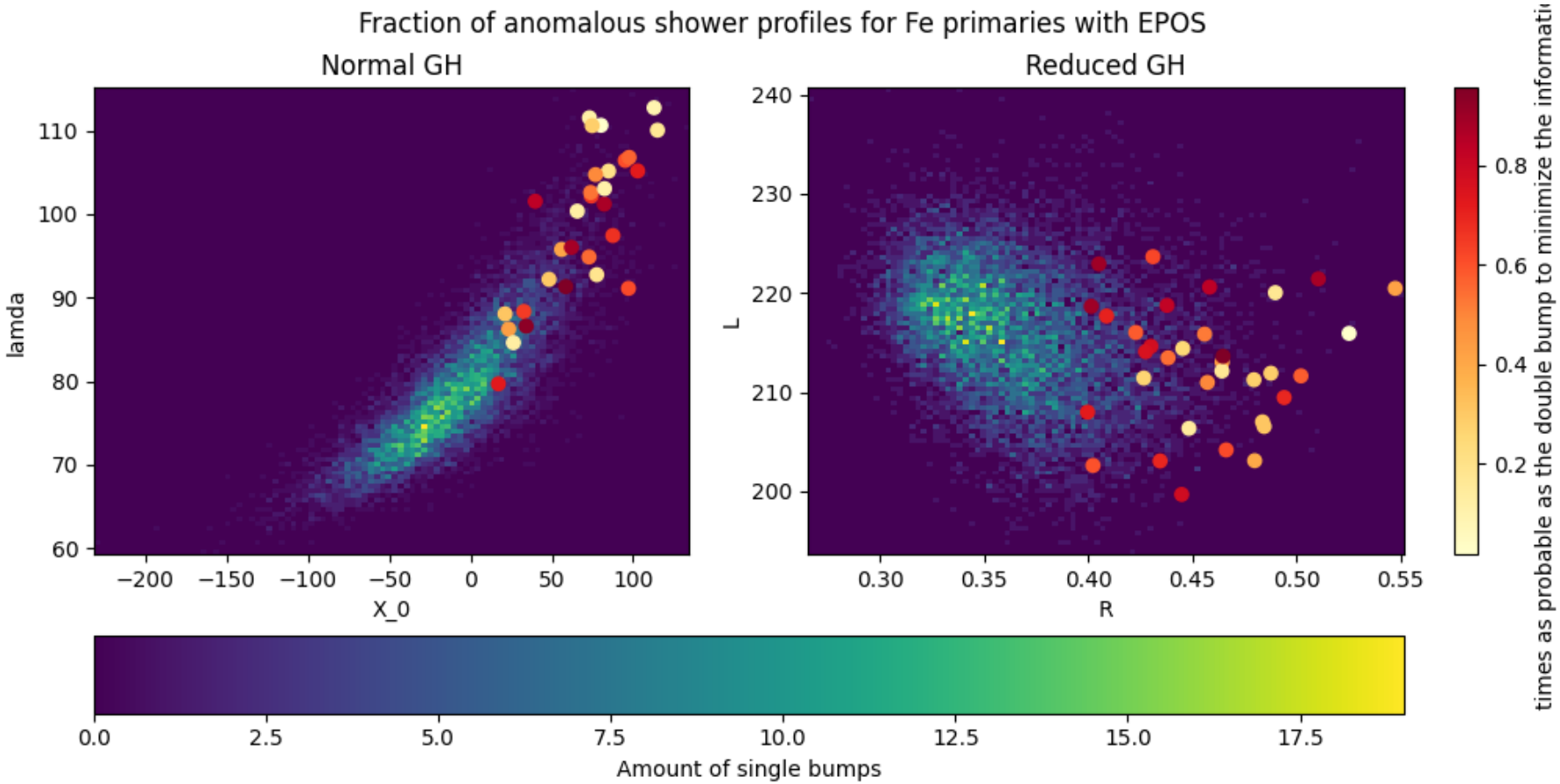
APPENDIX


Fraction of anomalous shower profiles for C primaries with EPOS
Normal GH
Reduced GH
lamda
X_0
L
R
Amount of single bumps
times as probable as the double bump to minimize the informati

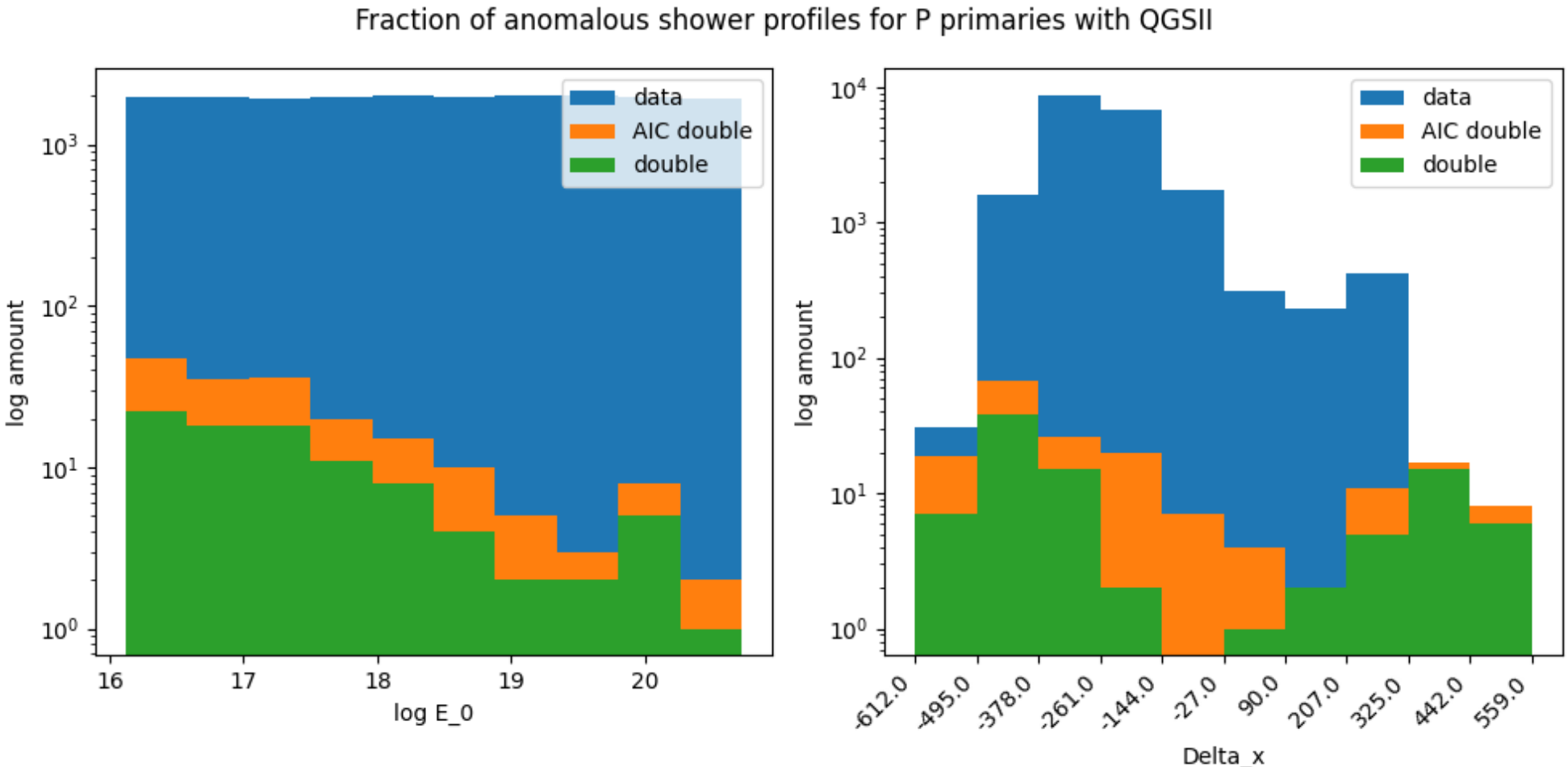
APPENDIX


Fraction of anomalous shower profiles for Si primaries with EPOS
Normal GH
Reduced GH
lamda
X_0
L
R
Amount of single bumps
times as probable as the double bump to minimize the informati

APPENDIX

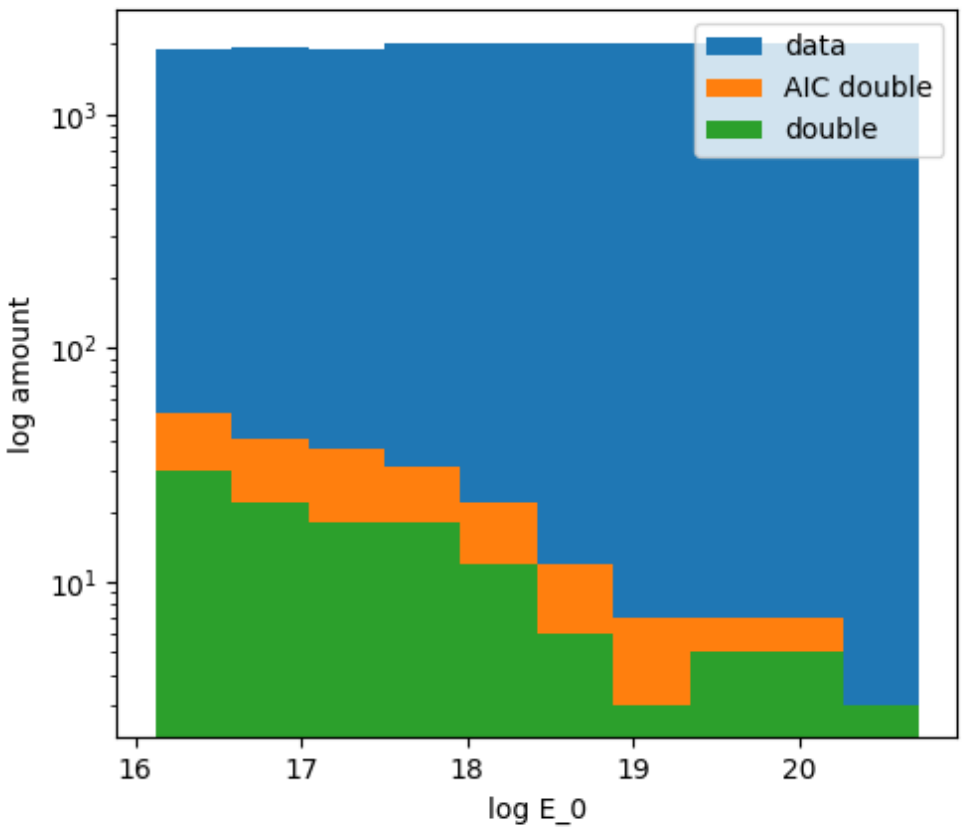

Fraction of anomalous shower profiles for Fe primaries with EPOS
Normal GH
Reduced GH
lamda
X_0
L
R
Amount of single bumps
times as probable as the double bump to minimize the informati

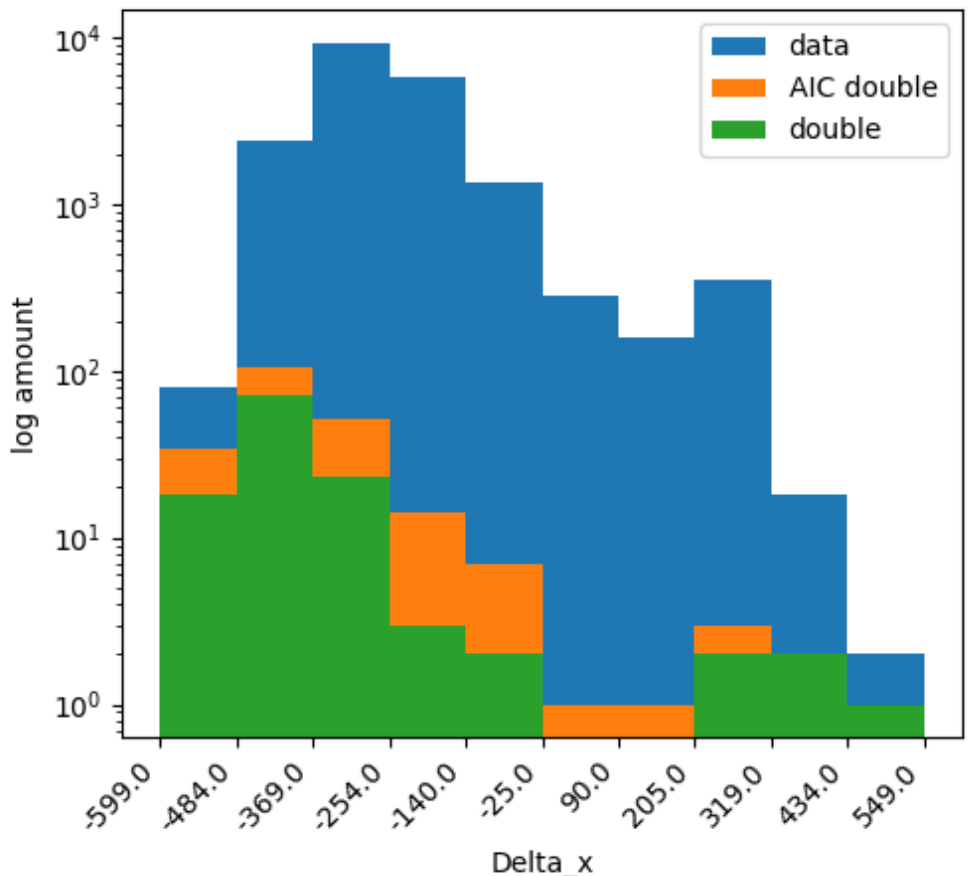
APPENDIX


Fraction of anomalous shower profiles for P primaries with QGSII
data
AIC double
double
log amount
log E_0
16
17
18
19
20
Delta_x

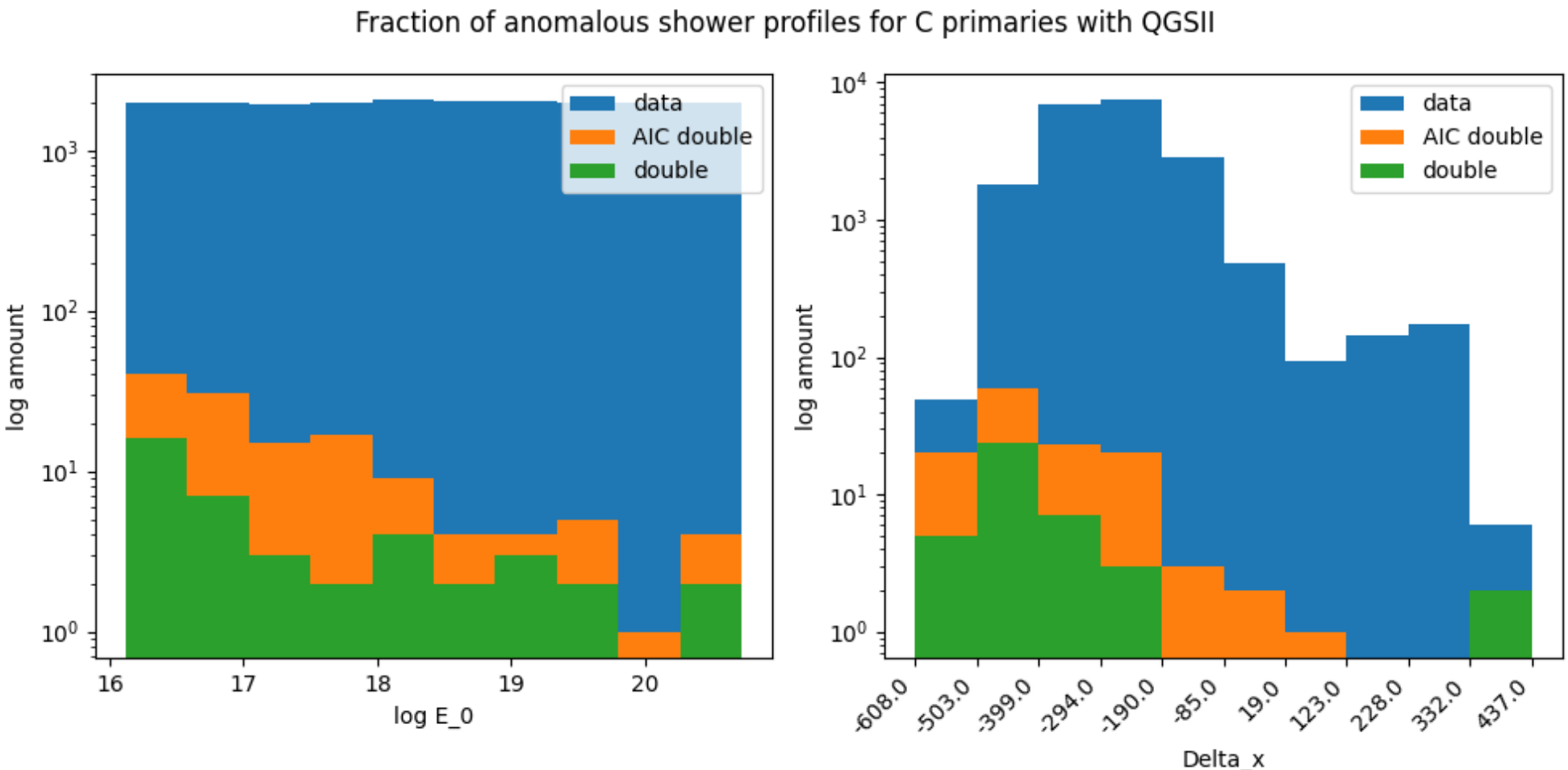
APPENDIX

Fraction of anomalous shower profiles for He primaries with QGSII

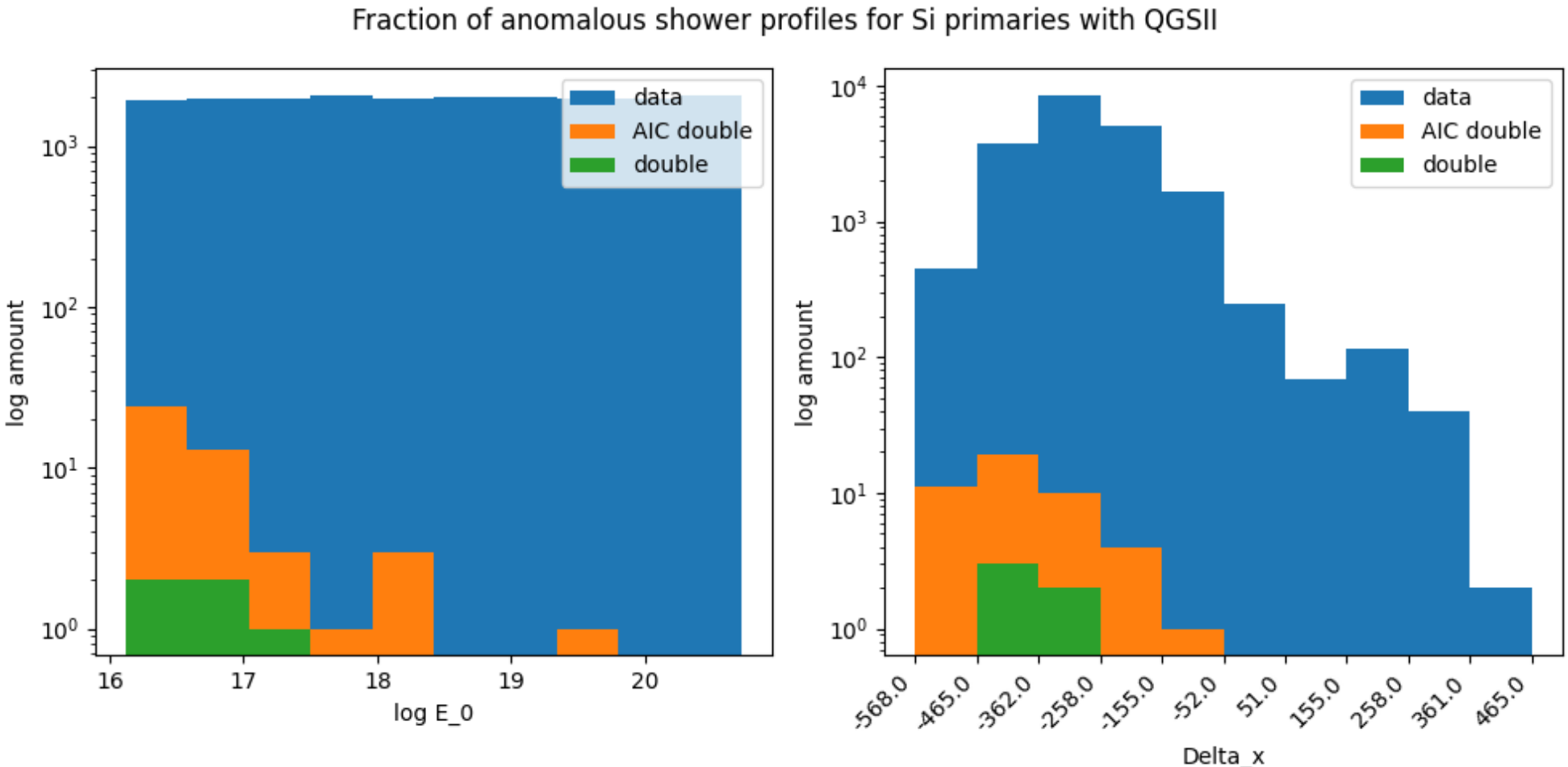




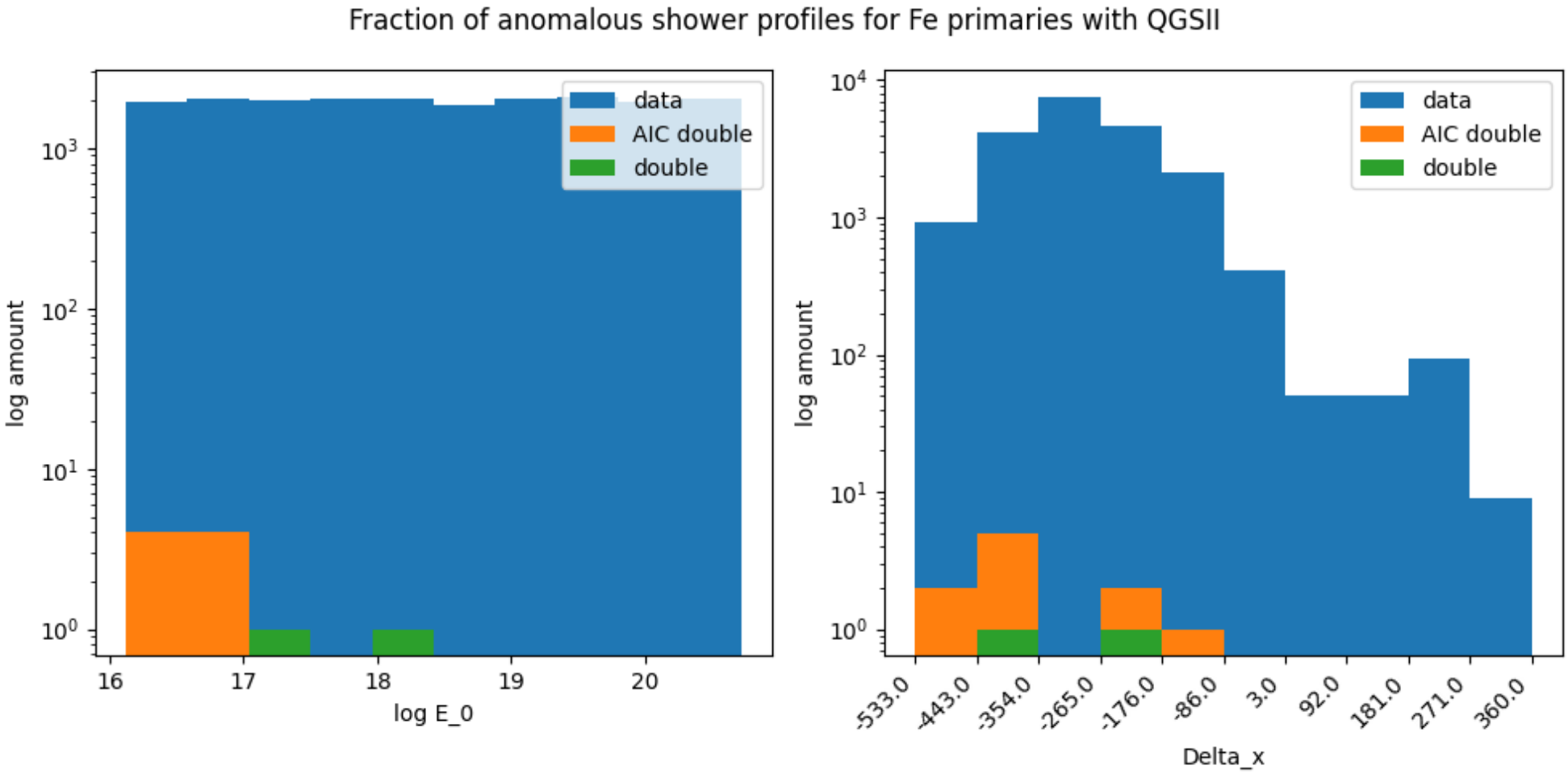
APPENDIX


Fraction of anomalous shower profiles for C primaries with QGSII
data
AIC double
double
log amount
log E_0
Delta_x

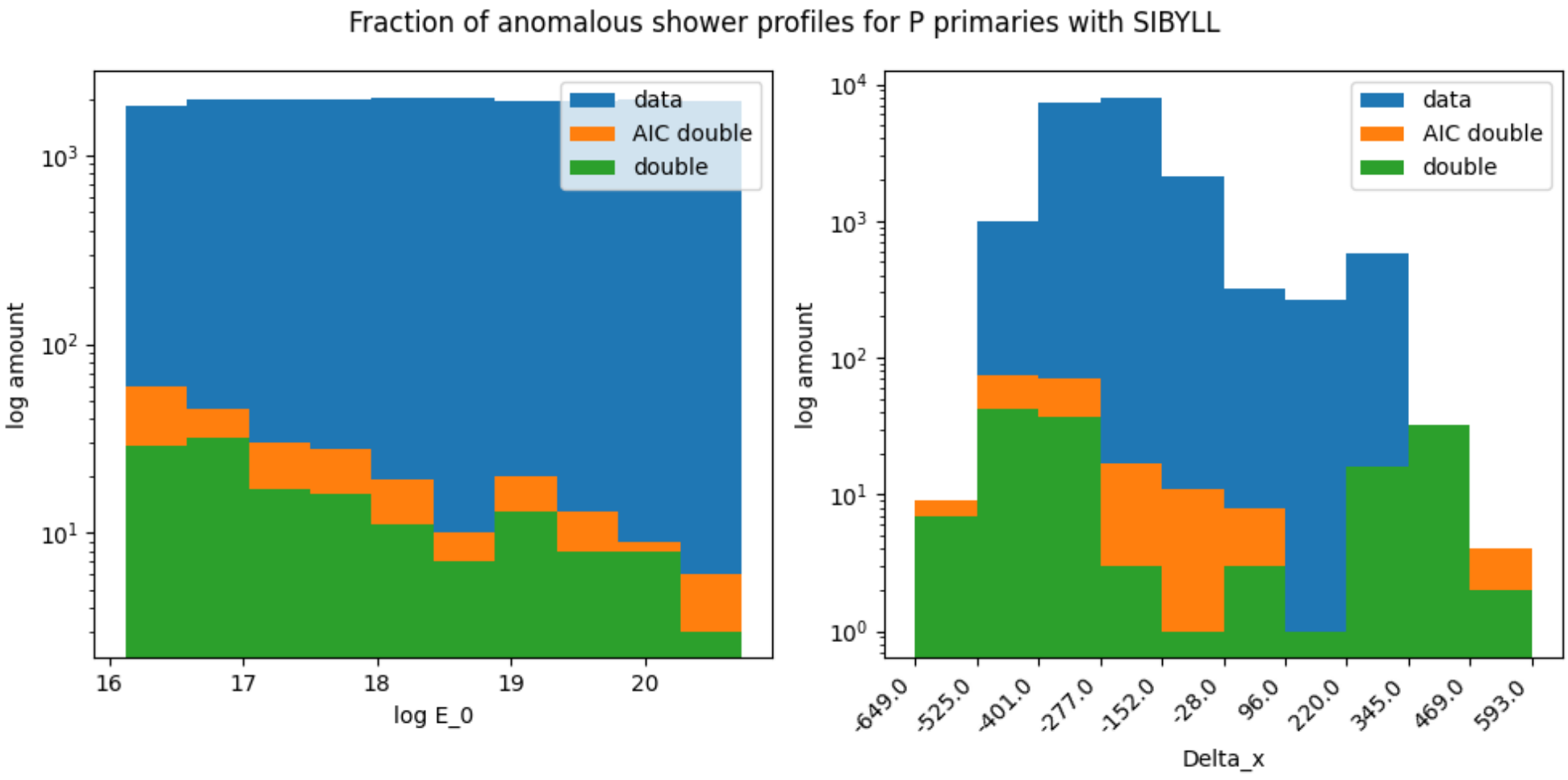
APPENDIX


Fraction of anomalous shower profiles for Si primaries with QGSII
data
AIC double
double
log amount
log E_0
Delta_x

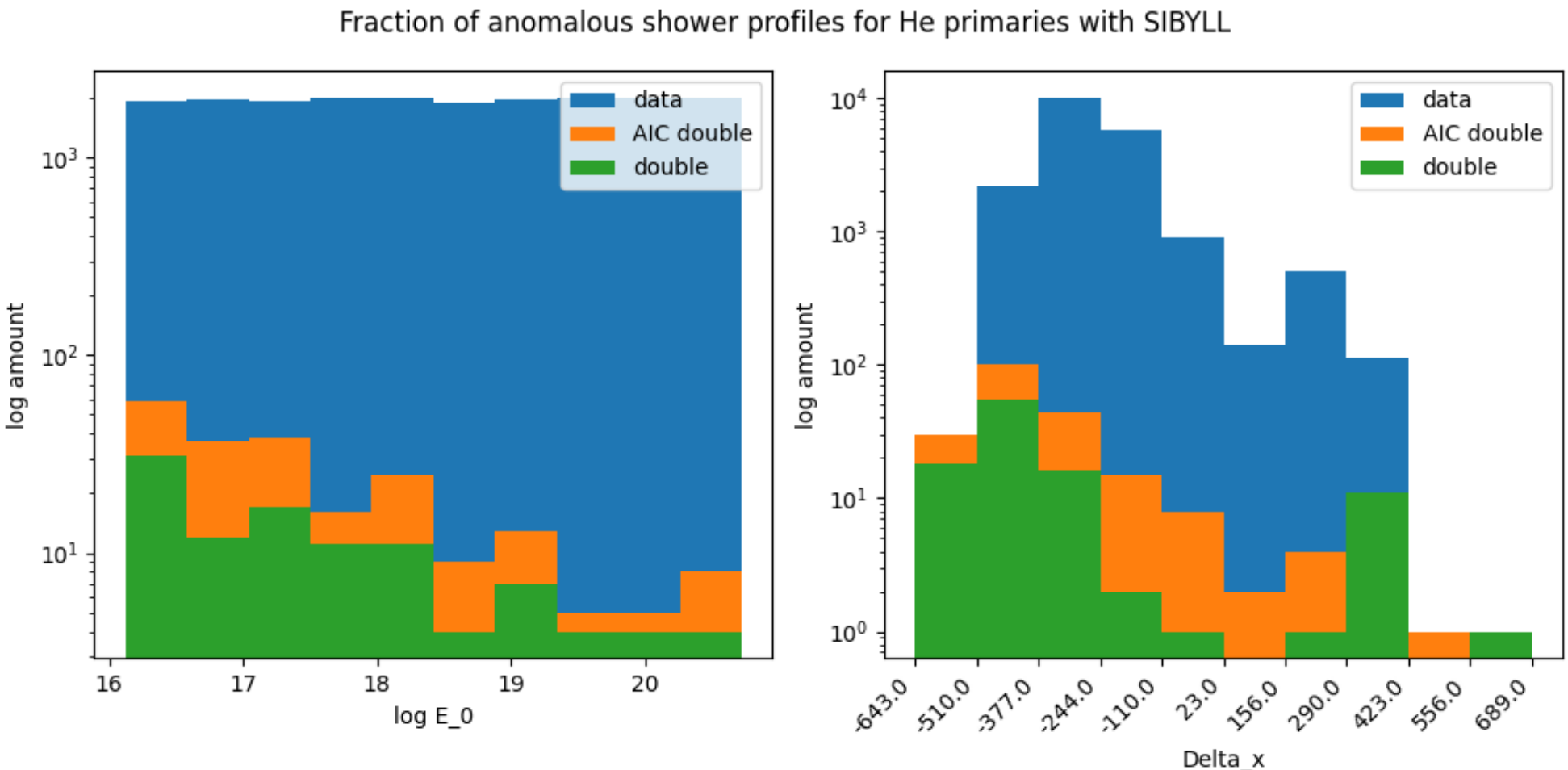
APPENDIX


Fraction of anomalous shower profiles for Fe primaries with QGSII
data
AIC double
double
log amount
log E_0
16
17
18
19
20
Delta_x
-533.0
-443.0
-354.0
-265.0
-176.0
-86.0
3.0
92.0
181.0
271.0
360.0

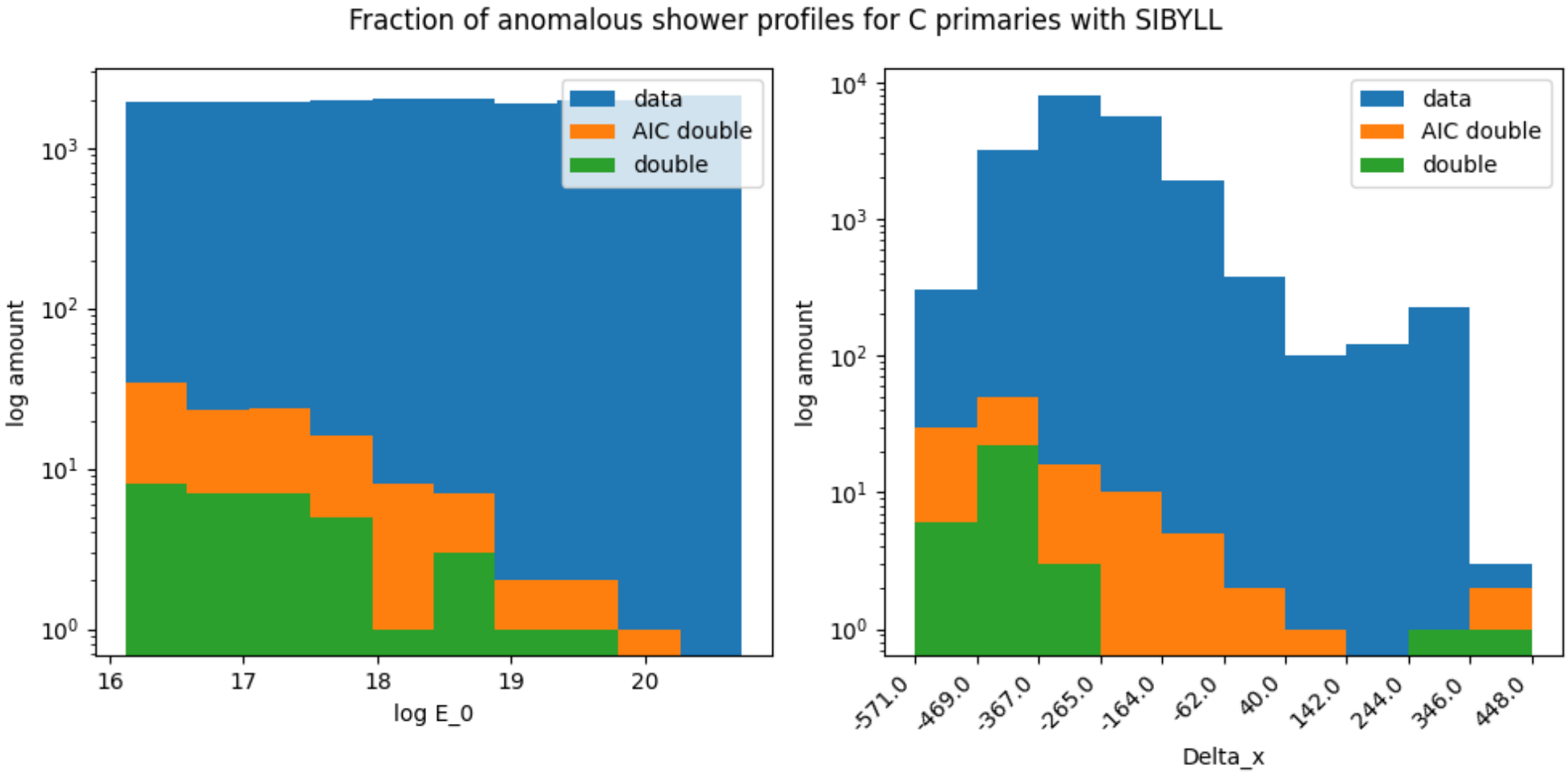
APPENDIX


Fraction of anomalous shower profiles for P primaries with SIBYLL
data
AIC double
double
log amount
log E_0
16
17
18
19
20
10^1
10^2
10^3
data
AIC double
double
log amount
Delta_x
10^0
10^1
10^2
10^3
10^4
-649.0
-525.0
-401.0
-277.0
-152.0
-28.0
96.0
220.0
345.0
469.0
593.0

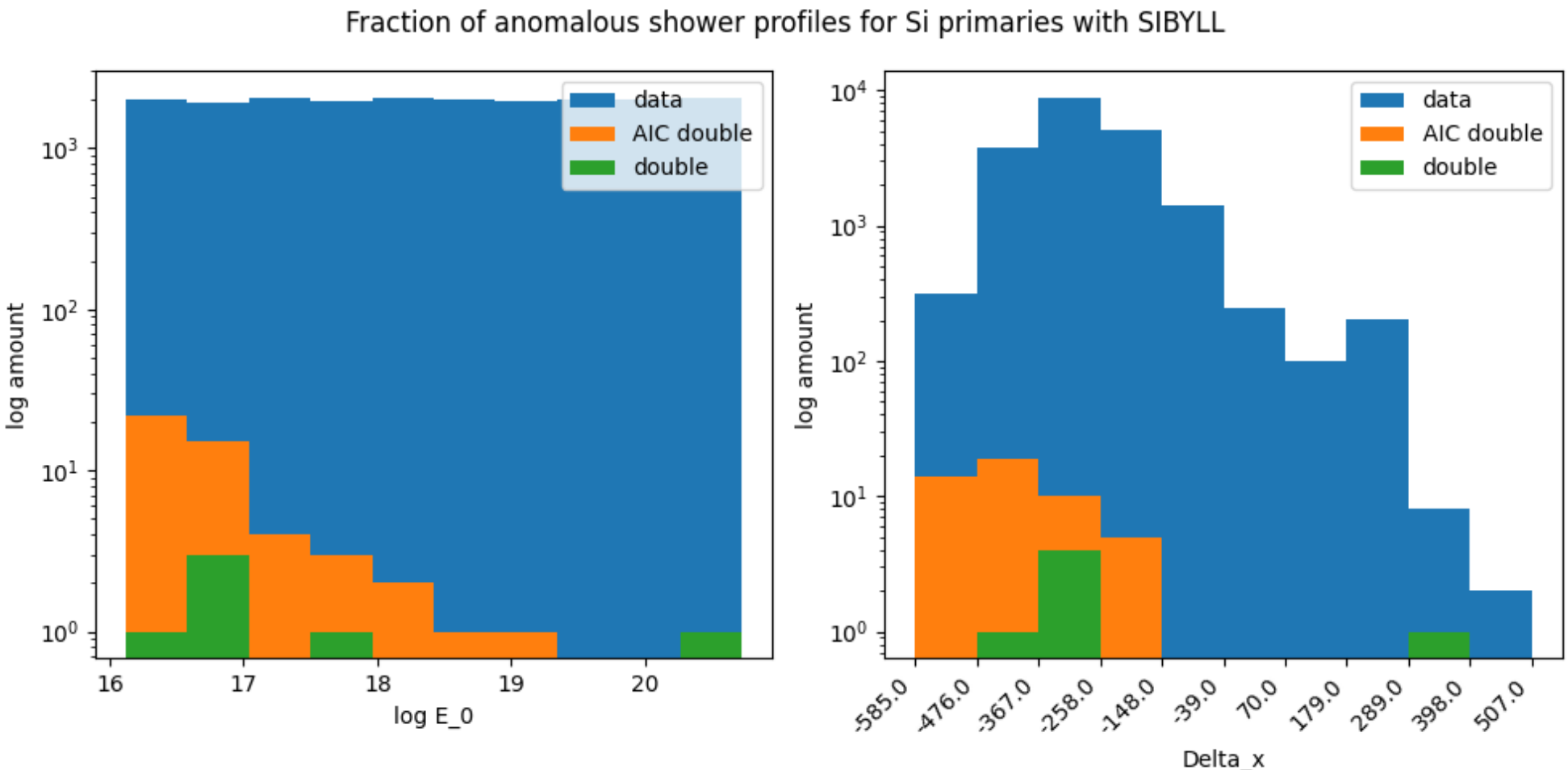
APPENDIX


Fraction of anomalous shower profiles for He primaries with SIBYLL
data
AIC double
double
log amount
log E_0
16
17
18
19
20
10^1
10^2
10^3
data
AIC double
double
log amount
Delta_x
10^0
10^1
10^2
10^3
10^4
-643.0
-510.0
-377.0
-244.0
-110.0
23.0
156.0
290.0
423.0
556.0
689.0

APPENDIX

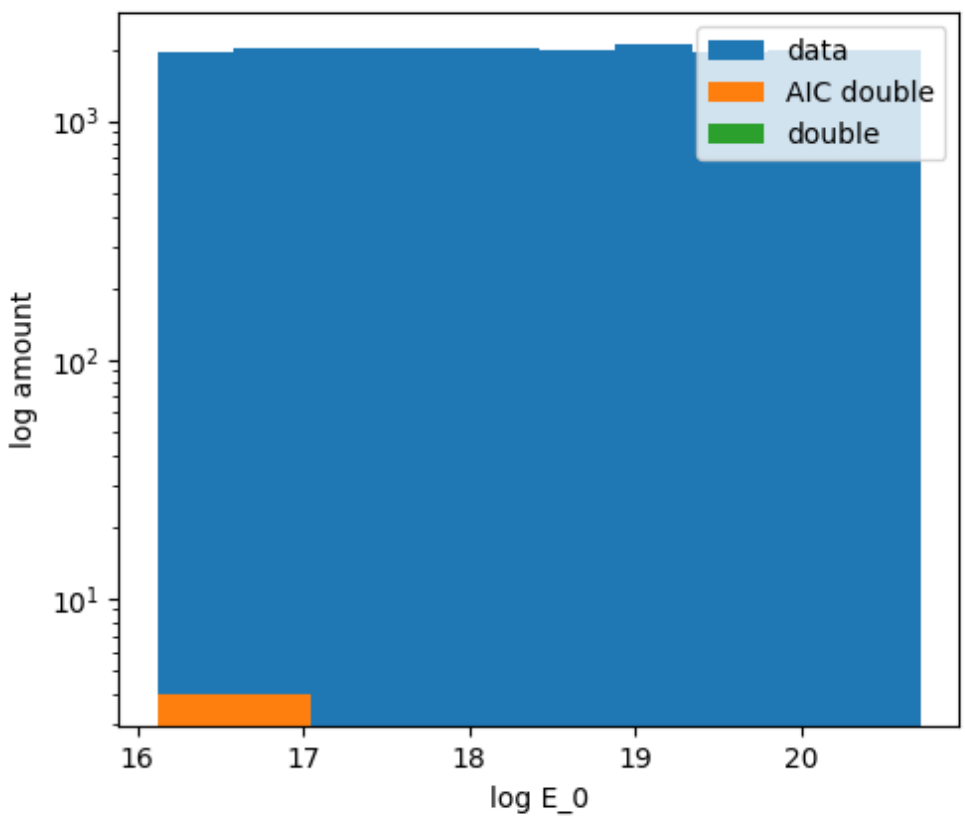

Fraction of anomalous shower profiles for C primaries with SIBYLL
data
AIC double
double
log amount
log E_0
16
17
18
19
20
Delta_x

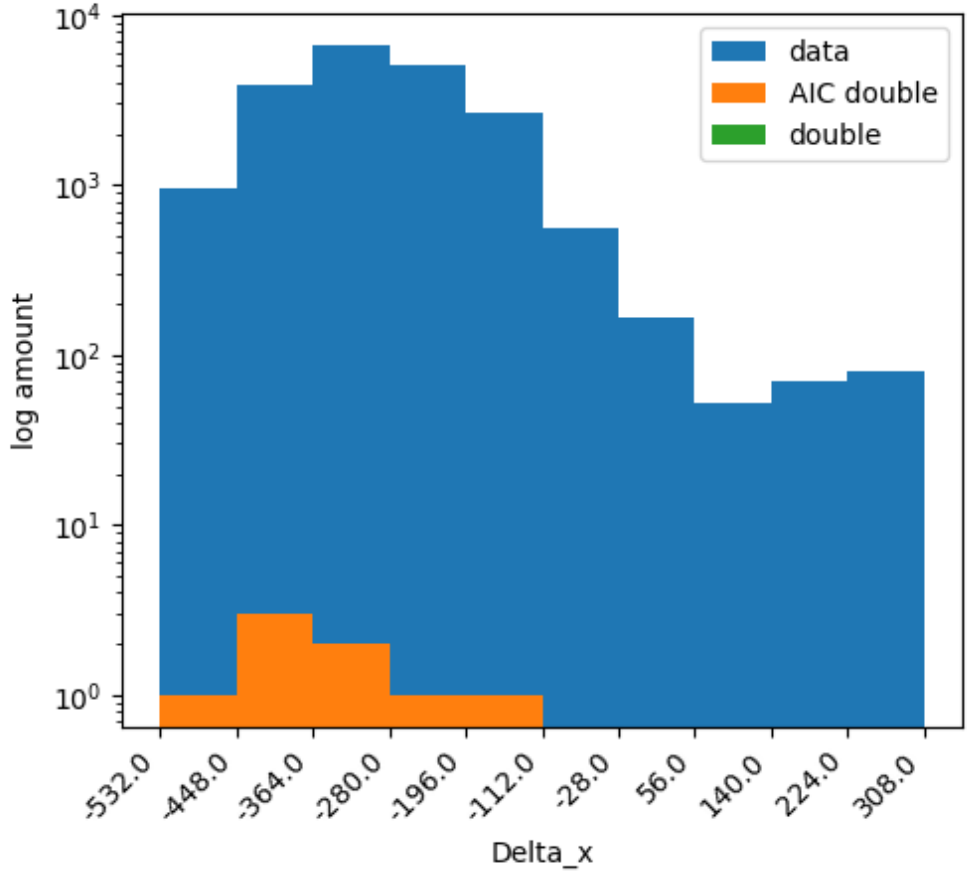
APPENDIX


Fraction of anomalous shower profiles for Si primaries with SIBYLL
data
AIC double
double
log amount
log E_0
16
17
18
19
20
10^0
10^1
10^2
10^3
data
AIC double
double
log amount
Delta_x
10^0
10^1
10^2
10^3
10^4
-585.0
-476.0
-367.0
-258.0
-148.0
-39.0
70.0
179.0
289.0
398.0
507.0

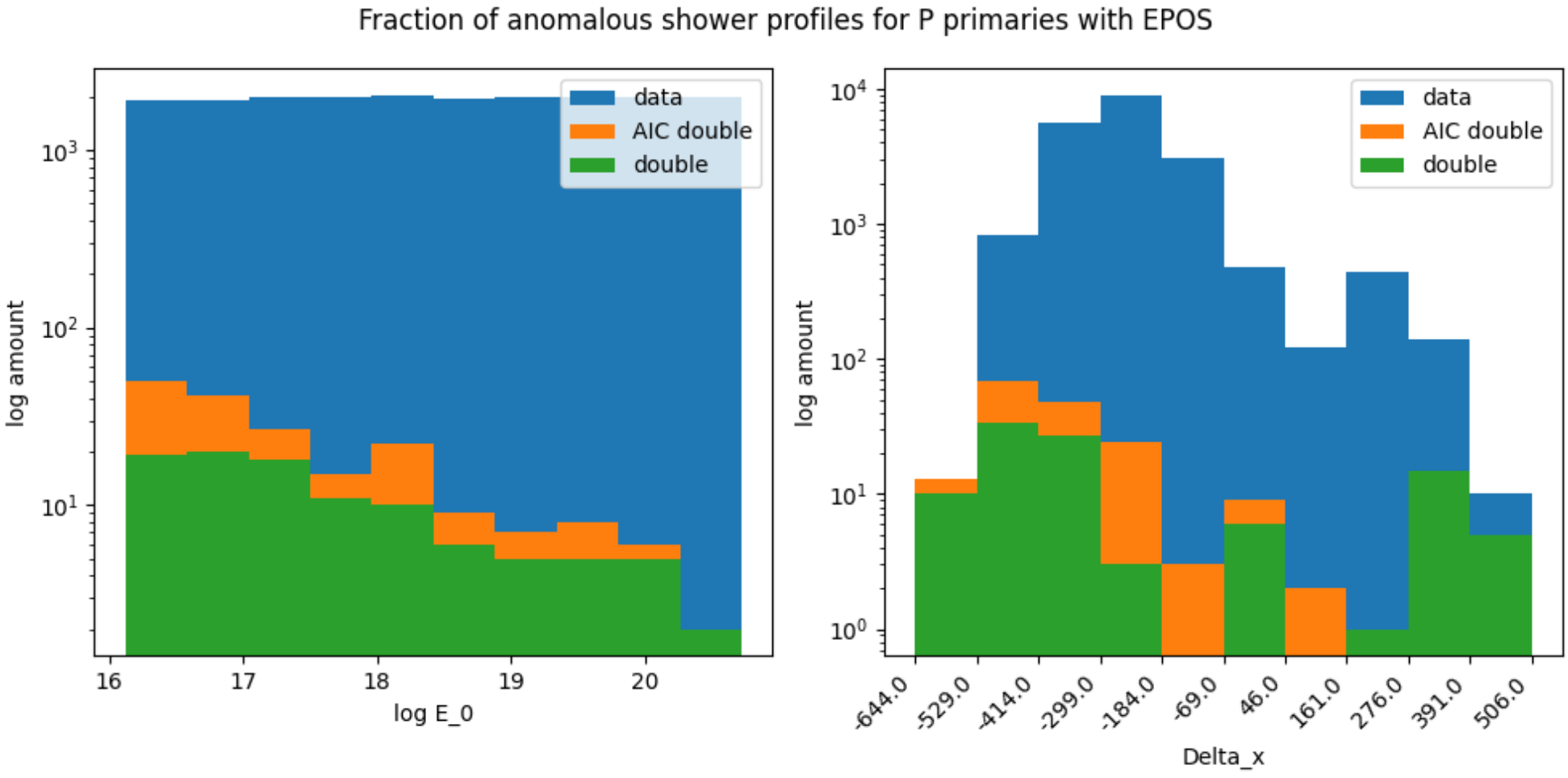
APPENDIX

Fraction of anomalous shower profiles for Fe primaries with SIBYLL

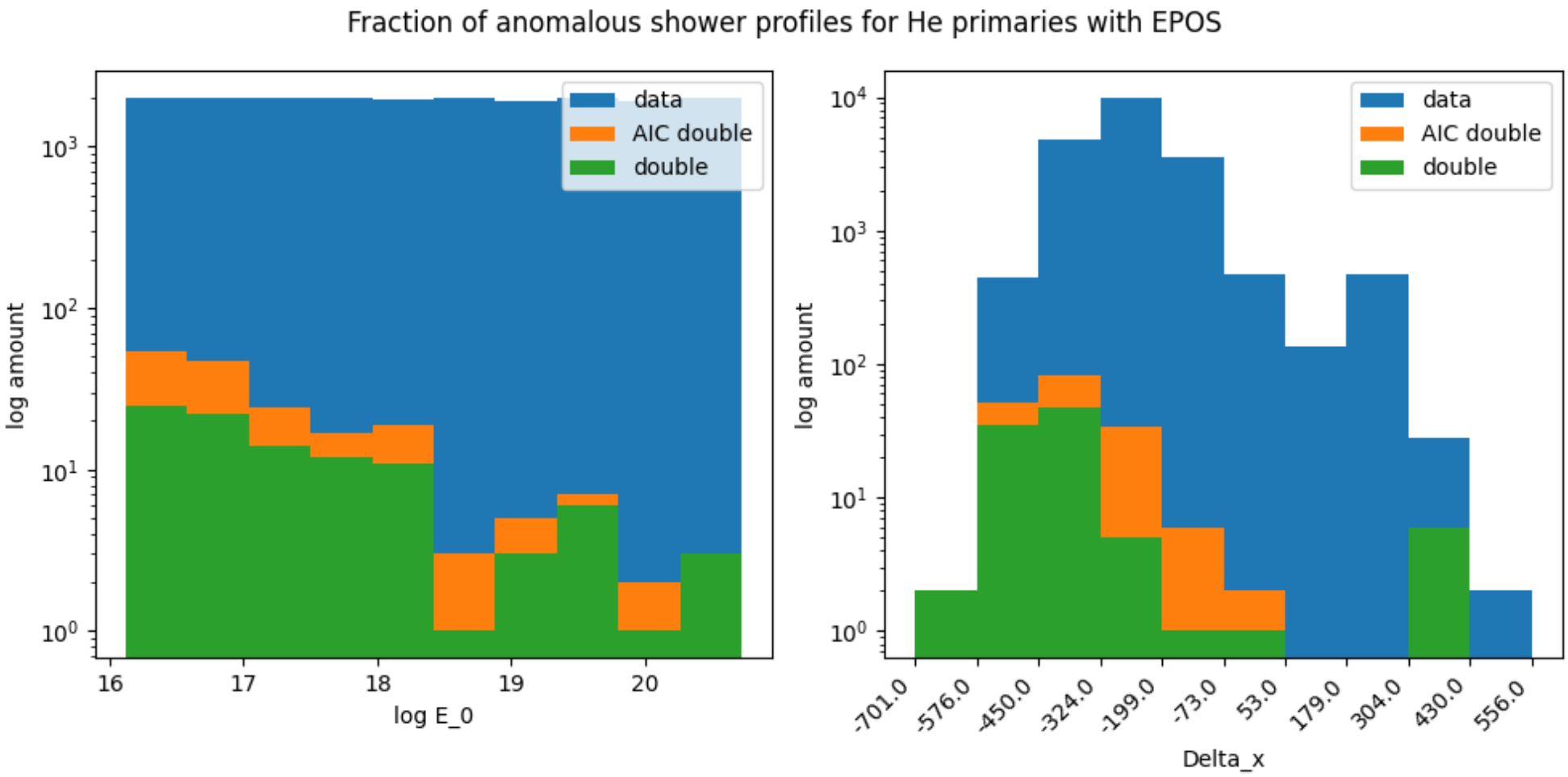




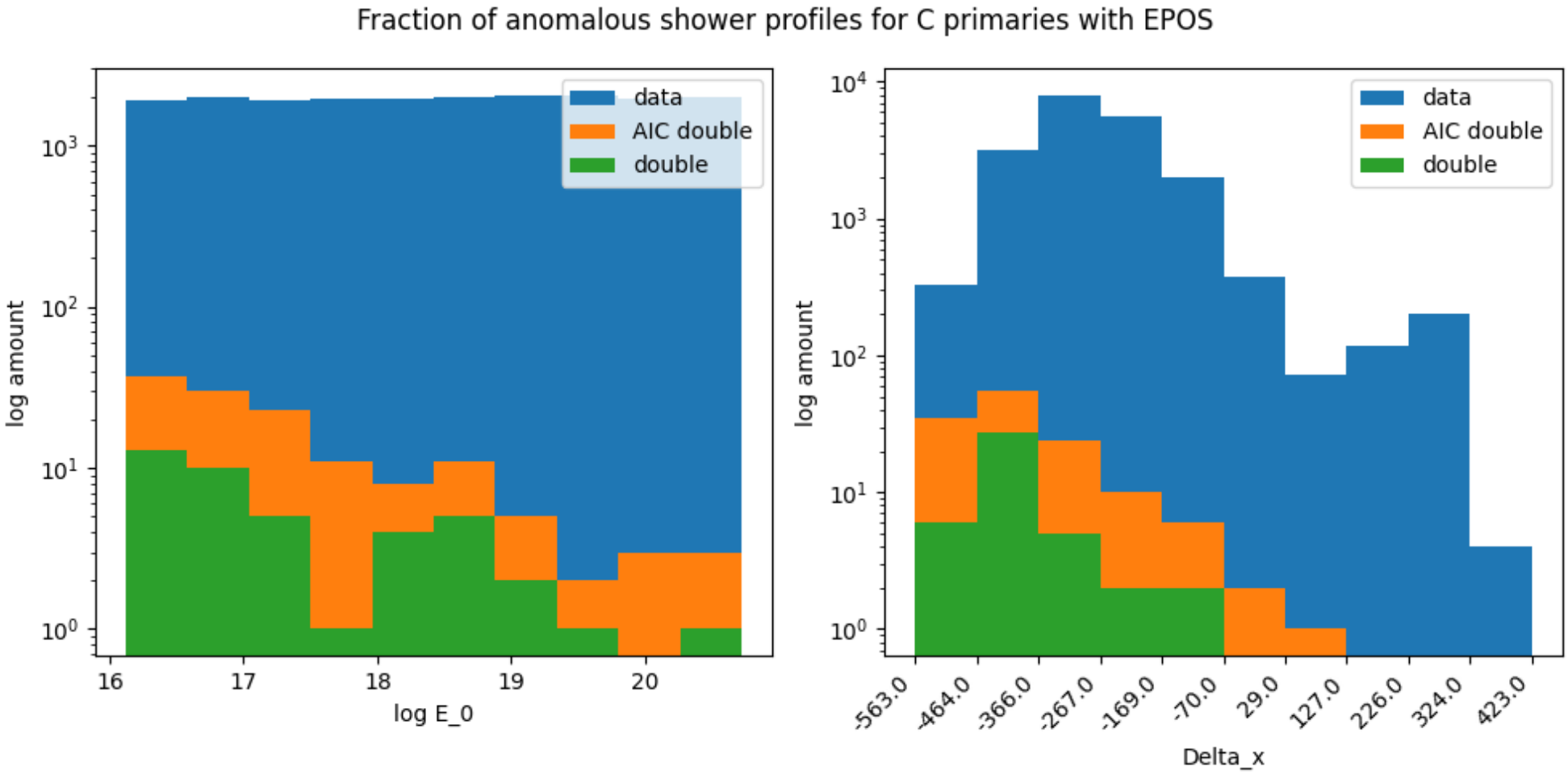
APPENDIX


Fraction of anomalous shower profiles for P primaries with EPOS
data
AIC double
double
log amount
log E_0
16
17
18
19
20
Delta_x
-644.0
-529.0
-414.0
-299.0
-184.0
-69.0
46.0
161.0
276.0
391.0
506.0

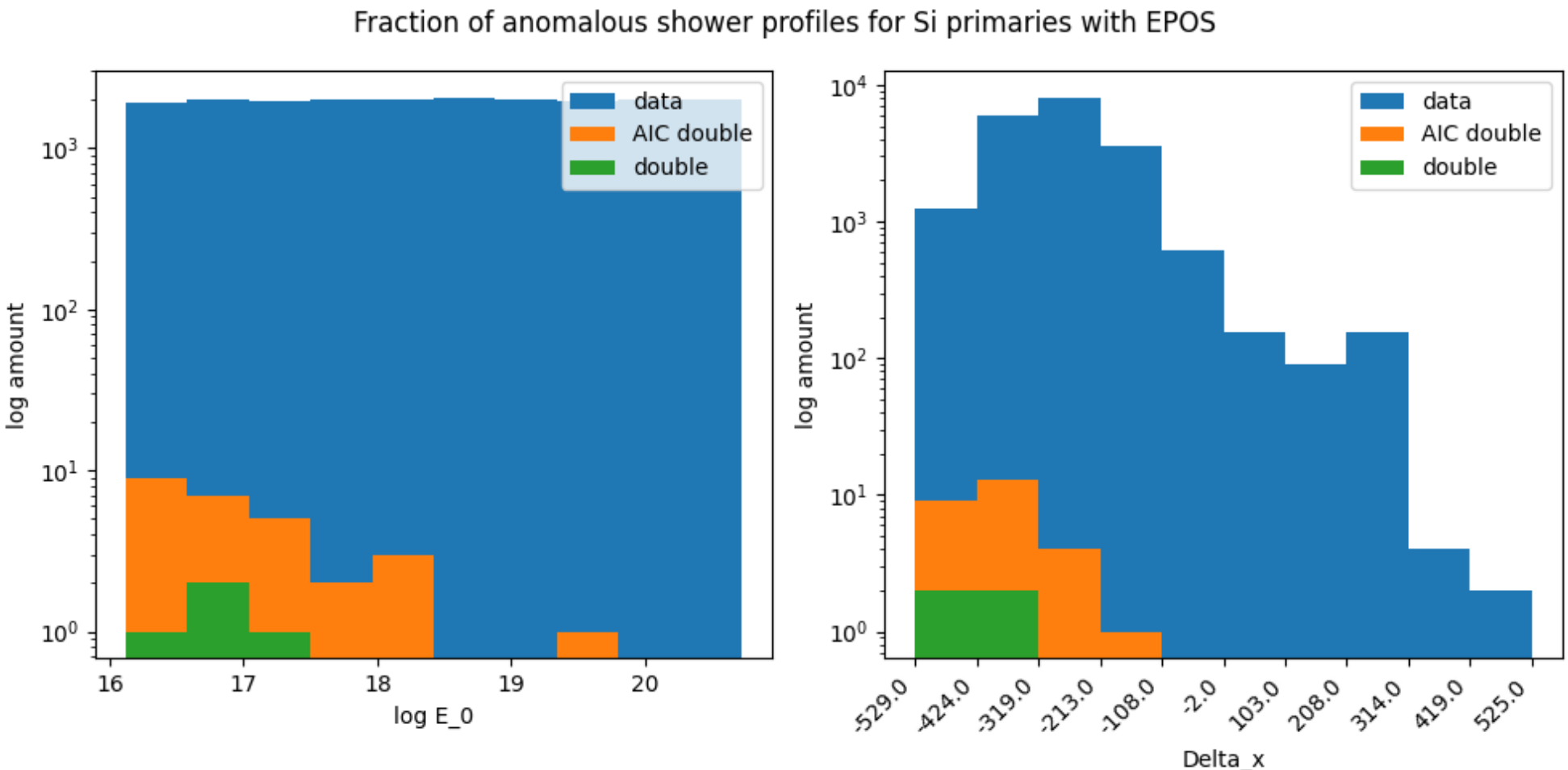
APPENDIX


Fraction of anomalous shower profiles for He primaries with EPOS
data
AIC double
double
log amount
log E_0
16
17
18
19
20
Delta_x
-701.0
-576.0
-450.0
-324.0
-199.0
-73.0
53.0
179.0
304.0
430.0
556.0

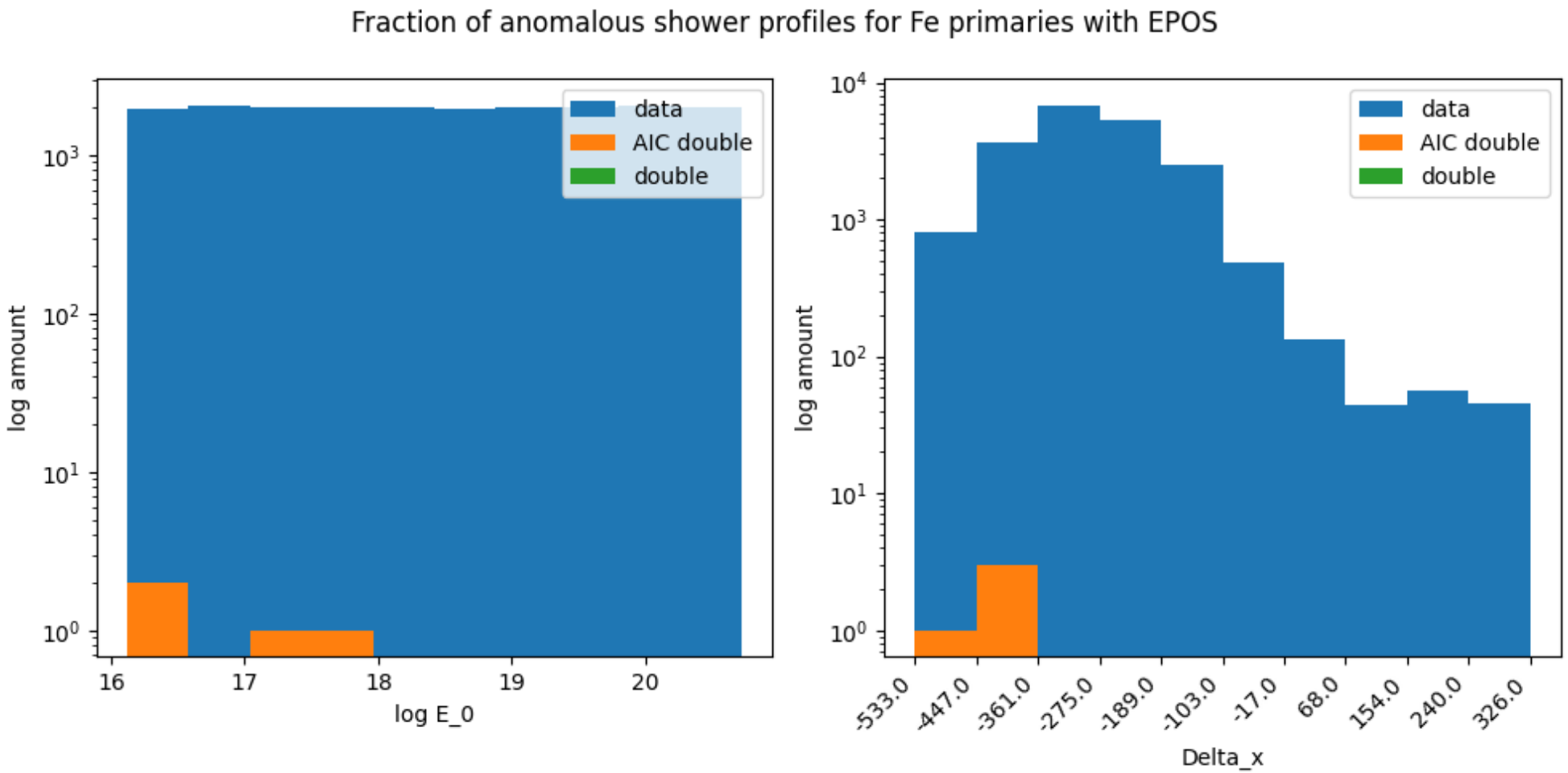
APPENDIX


Fraction of anomalous shower profiles for C primaries with EPOS
data
AIC double
double
log amount
log E_0
16
17
18
19
20
Delta_x
-563.0
-464.0
-366.0
-267.0
-169.0
-70.0
29.0
127.0
226.0
324.0
423.0

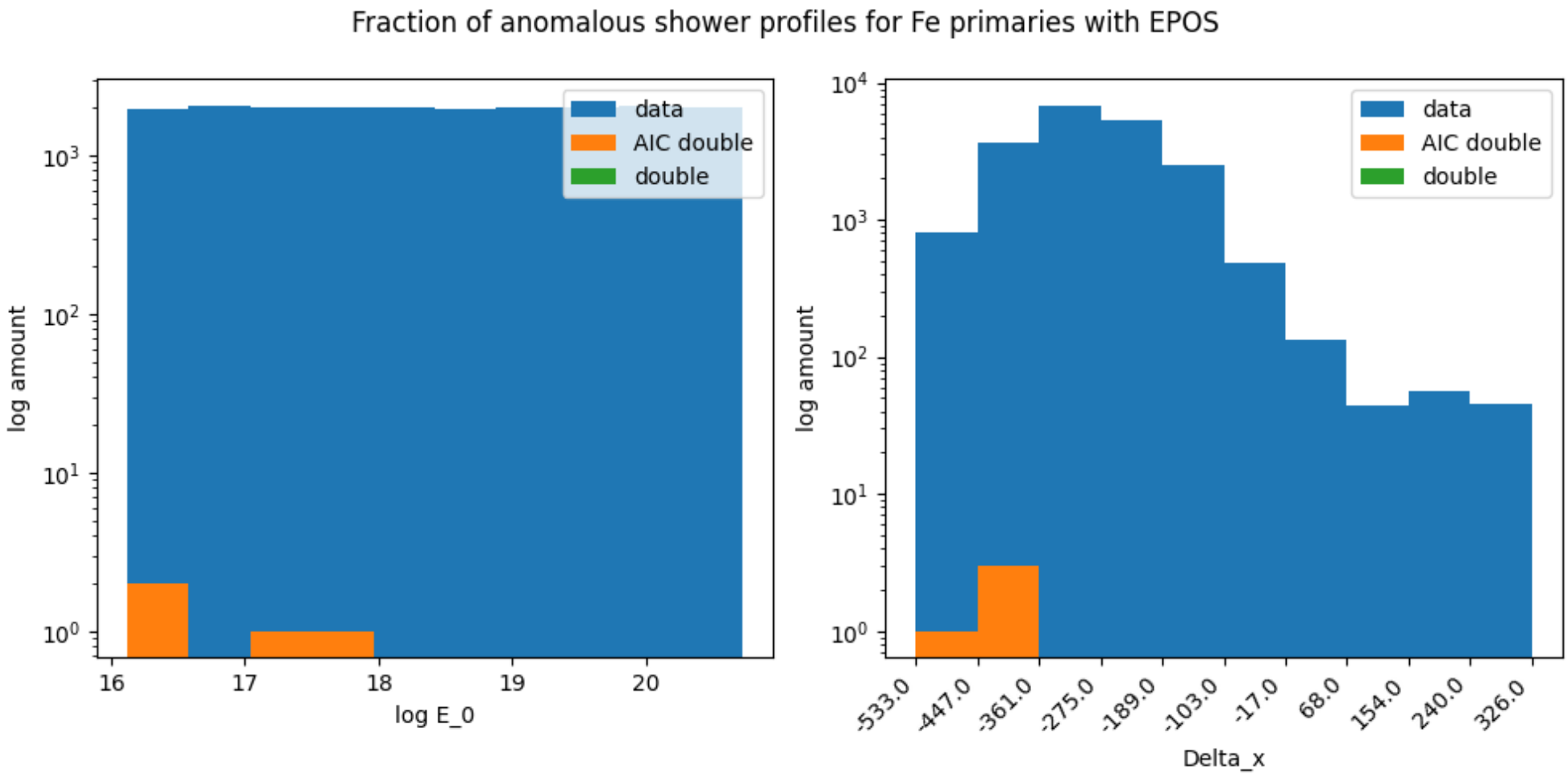
APPENDIX


Fraction of anomalous shower profiles for Si primaries with EPOS
data
AIC double
double
log amount
log E_0
16
17
18
19
20
Delta_x

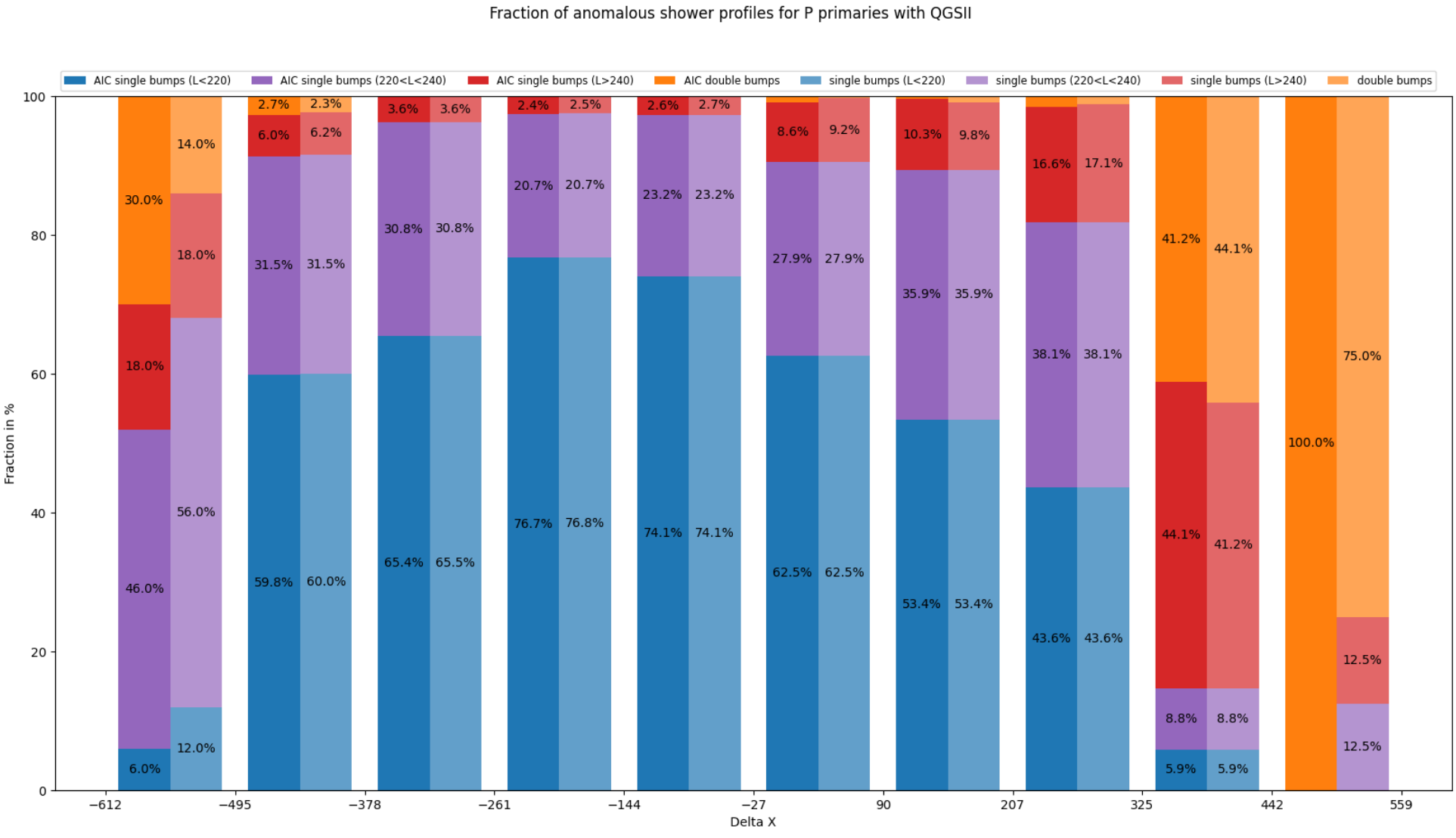
APPENDIX


Fraction of anomalous shower profiles for Fe primaries with EPOS
data
AIC double
double
log amount
log E_0
16
17
18
19
20
Delta_x

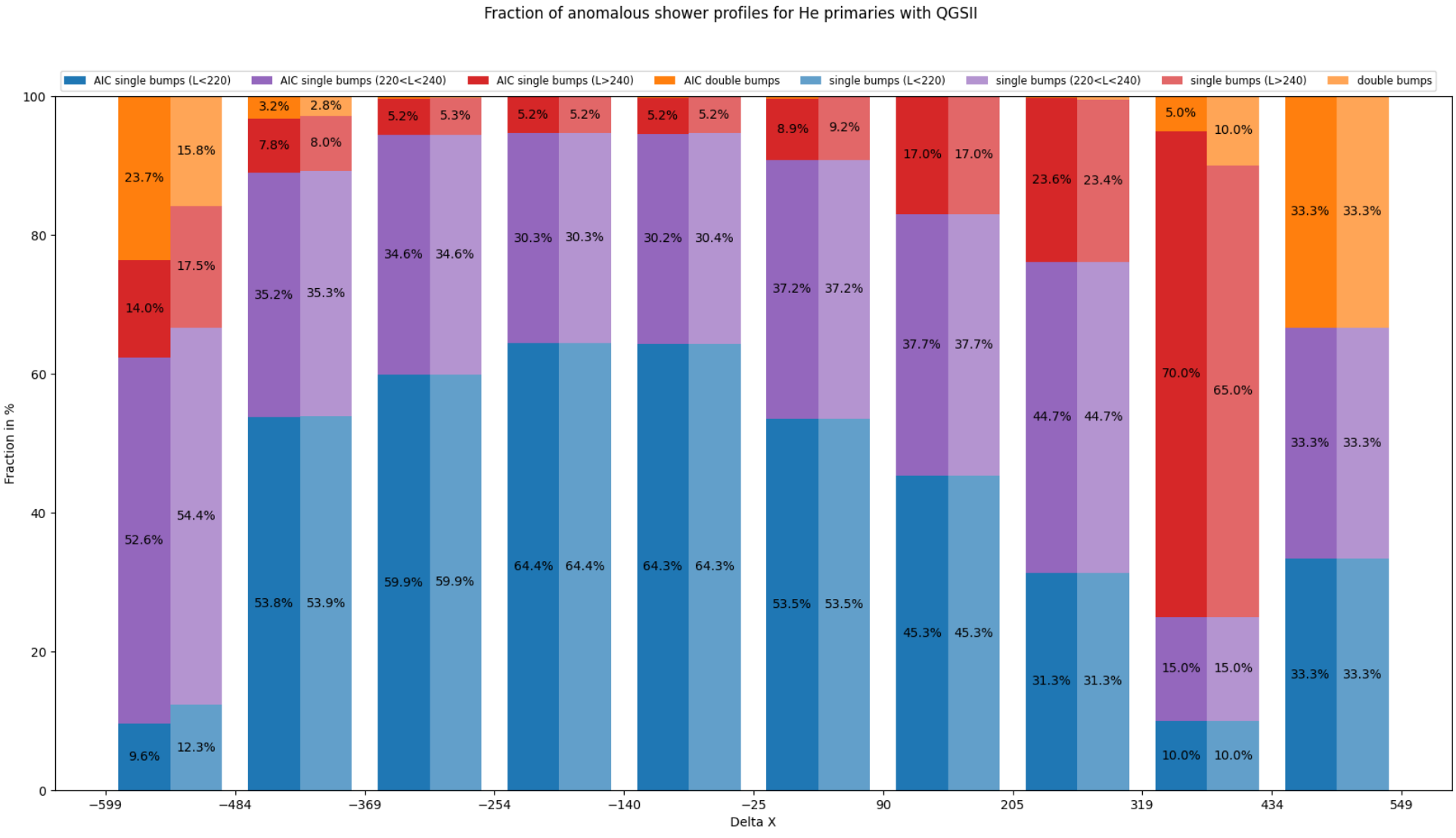
APPENDIX


Fraction of anomalous shower profiles for Fe primaries with EPOS
data
AIC double
double
log amount
log E_0
16
17
18
19
20
Delta_x

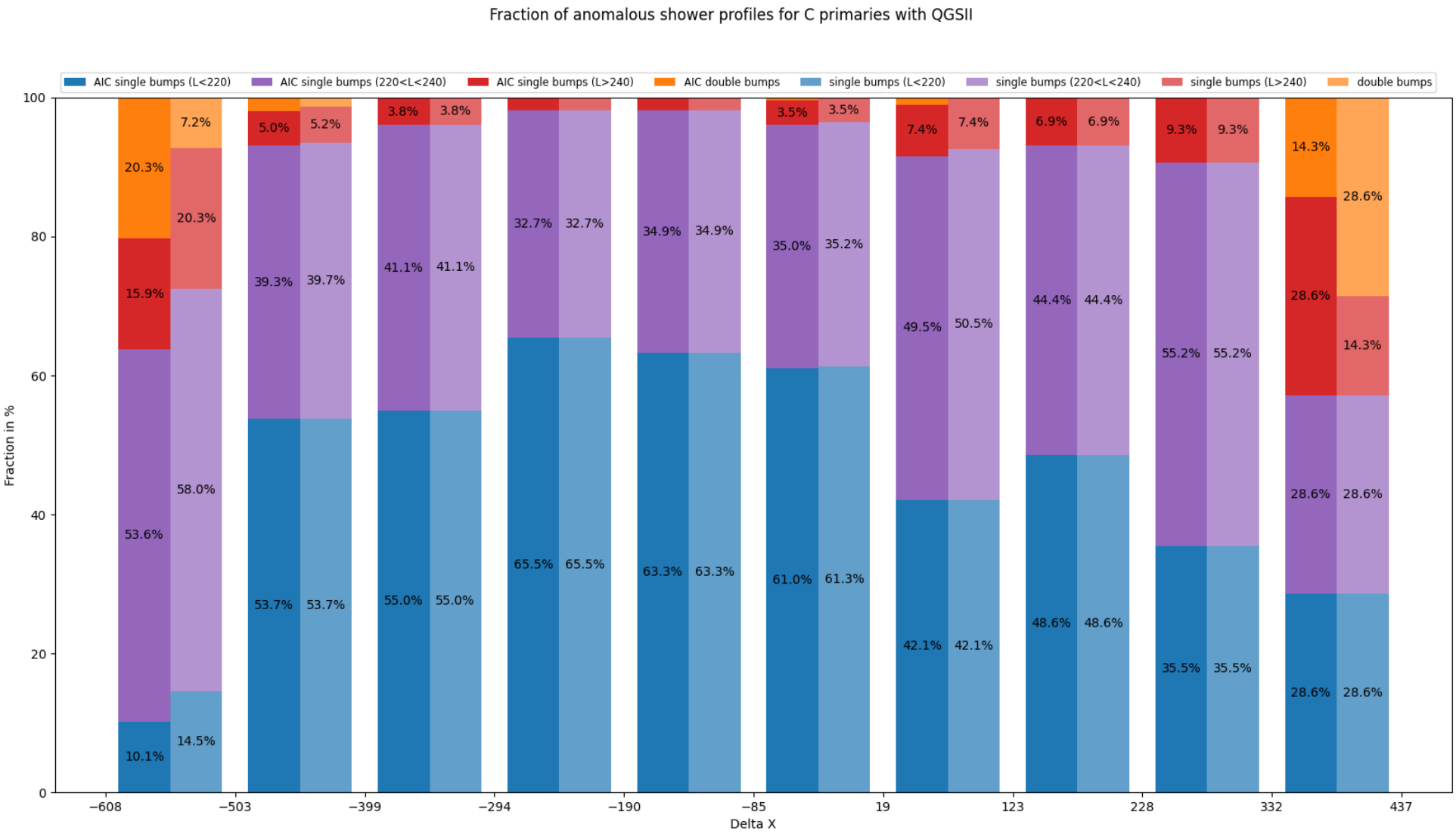
APPENDIX


Fraction of anomalous shower profiles for P primaries with QGSII
AIC single bumps (L<220)
AIC single bumps (220<L<240)
AIC single bumps (L>240)
AIC double bumps
single bumps (L<220)
single bumps (220<L<240)
single bumps (L>240)
double bumps
Fraction in %
Delta X
−612
−495
−378
−261
−144
−27
90
207
325
442
559
0
20
40
60
80
100
6.0%
46.0%
18.0%
30.0%
12.0%
56.0%
18.0%
14.0%
59.8%
31.5%
6.0%
2.7%
60.0%
31.5%
6.2%
2.3%
65.4%
30.8%
3.6%
65.5%
30.8%
3.6%
76.7%
20.7%
2.4%
76.8%
20.7%
2.5%
74.1%
23.2%
2.6%
74.1%
23.2%
2.7%
62.5%
27.9%
8.6%
62.5%
27.9%
9.2%
53.4%
35.9%
10.3%
53.4%
35.9%
9.8%
43.6%
38.1%
16.6%
43.6%
38.1%
17.1%
5.9%
8.8%
44.1%
41.2%
5.9%
8.8%
41.2%
44.1%
100.0%
12.5%
75.0%
12.5%

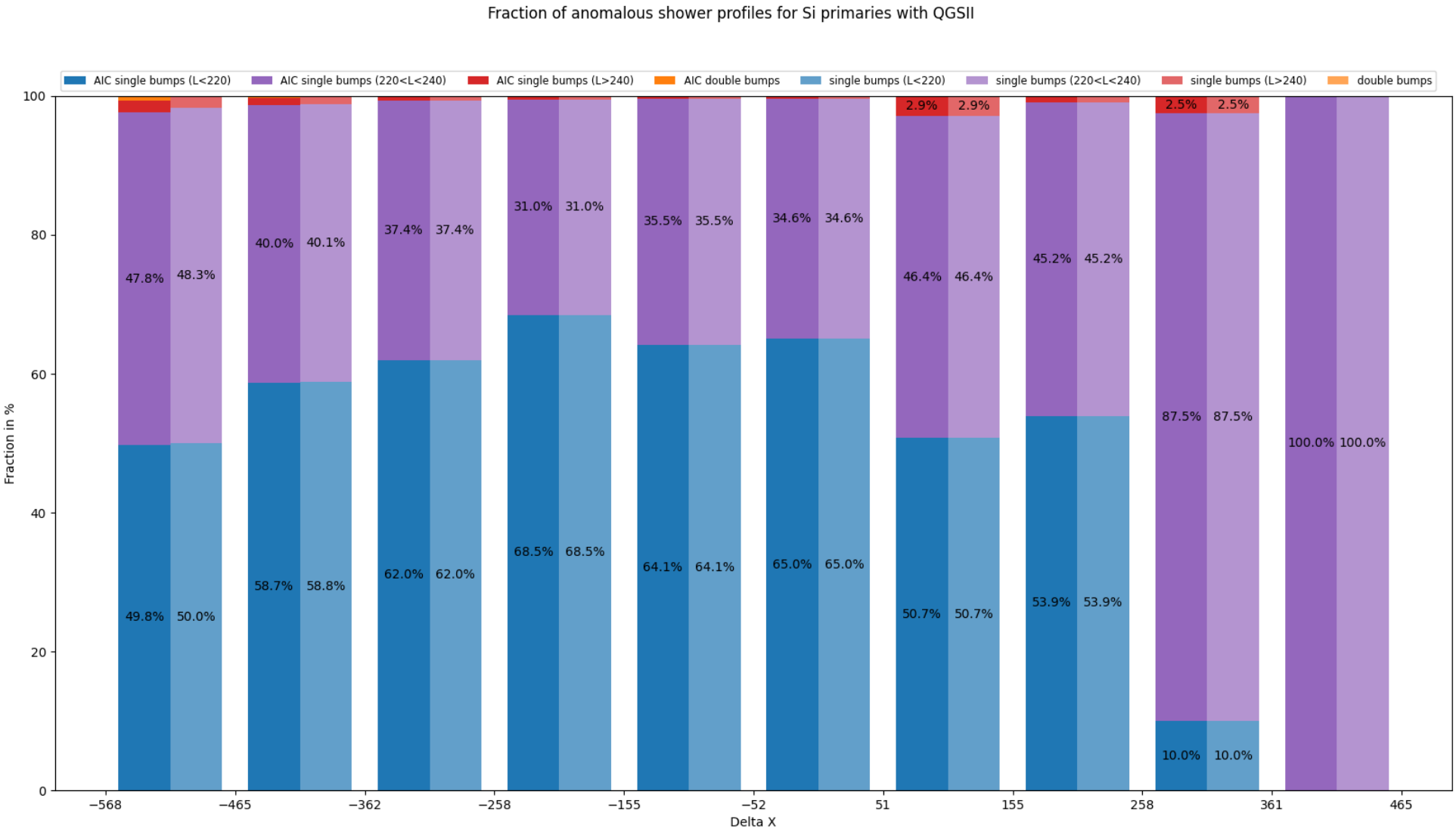
APPENDIX


Fraction of anomalous shower profiles for He primaries with QGSII
AIC single bumps (L<220)
AIC single bumps (220<L<240)
AIC single bumps (L>240)
AIC double bumps
single bumps (L<220)
single bumps (220<L<240)
single bumps (L>240)
double bumps
Fraction in %
Delta X
−599
−484
−369
−254
−140
−25
90
205
319
434
549
0
20
40
60
80
100
9.6%
52.6%
14.0%
23.7%
12.3%
54.4%
17.5%
15.8%
53.8%
35.2%
7.8%
3.2%
53.9%
35.3%
8.0%
2.8%
59.9%
34.6%
5.2%
59.9%
34.6%
5.3%
64.4%
30.3%
5.2%
64.4%
30.3%
5.2%
64.3%
30.2%
5.2%
64.3%
30.4%
5.2%
53.5%
37.2%
8.9%
53.5%
37.2%
9.2%
45.3%
37.7%
17.0%
45.3%
37.7%
17.0%
31.3%
44.7%
23.6%
31.3%
44.7%
23.4%
10.0%
70.0%
15.0%
5.0%
10.0%
65.0%
15.0%
33.3%
33.3%
33.3%
33.3%
33.3%
33.3%

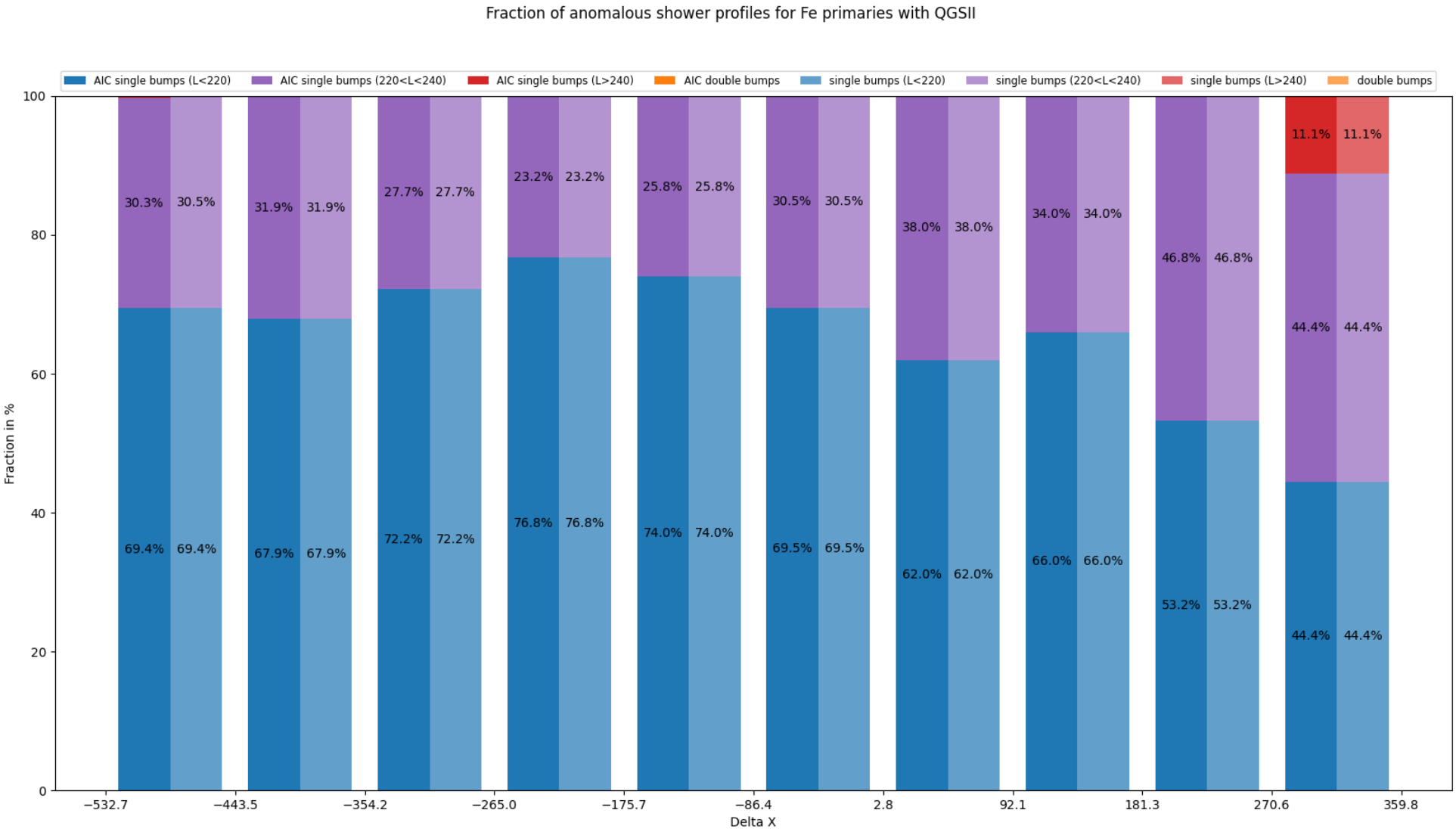
APPENDIX


Fraction of anomalous shower profiles for C primaries with QGSII
AIC single bumps (L<220)
AIC single bumps (220<L<240)
AIC single bumps (L>240)
AIC double bumps
single bumps (L<220)
single bumps (220<L<240)
single bumps (L>240)
double bumps
Fraction in %
Delta X
−608
−503
−399
−294
−190
−85
19
123
228
332
437
10.1%
53.6%
15.9%
20.3%
14.5%
58.0%
20.3%
7.2%
53.7%
39.3%
5.0%
53.7%
39.7%
5.2%
55.0%
41.1%
3.8%
55.0%
41.1%
3.8%
65.5%
32.7%
65.5%
32.7%
63.3%
34.9%
63.3%
34.9%
61.0%
35.0%
3.5%
61.3%
35.2%
3.5%
42.1%
49.5%
7.4%
42.1%
50.5%
7.4%
48.6%
44.4%
6.9%
48.6%
44.4%
6.9%
35.5%
55.2%
9.3%
35.5%
55.2%
9.3%
28.6%
28.6%
28.6%
14.3%
28.6%
28.6%
28.6%
14.3%

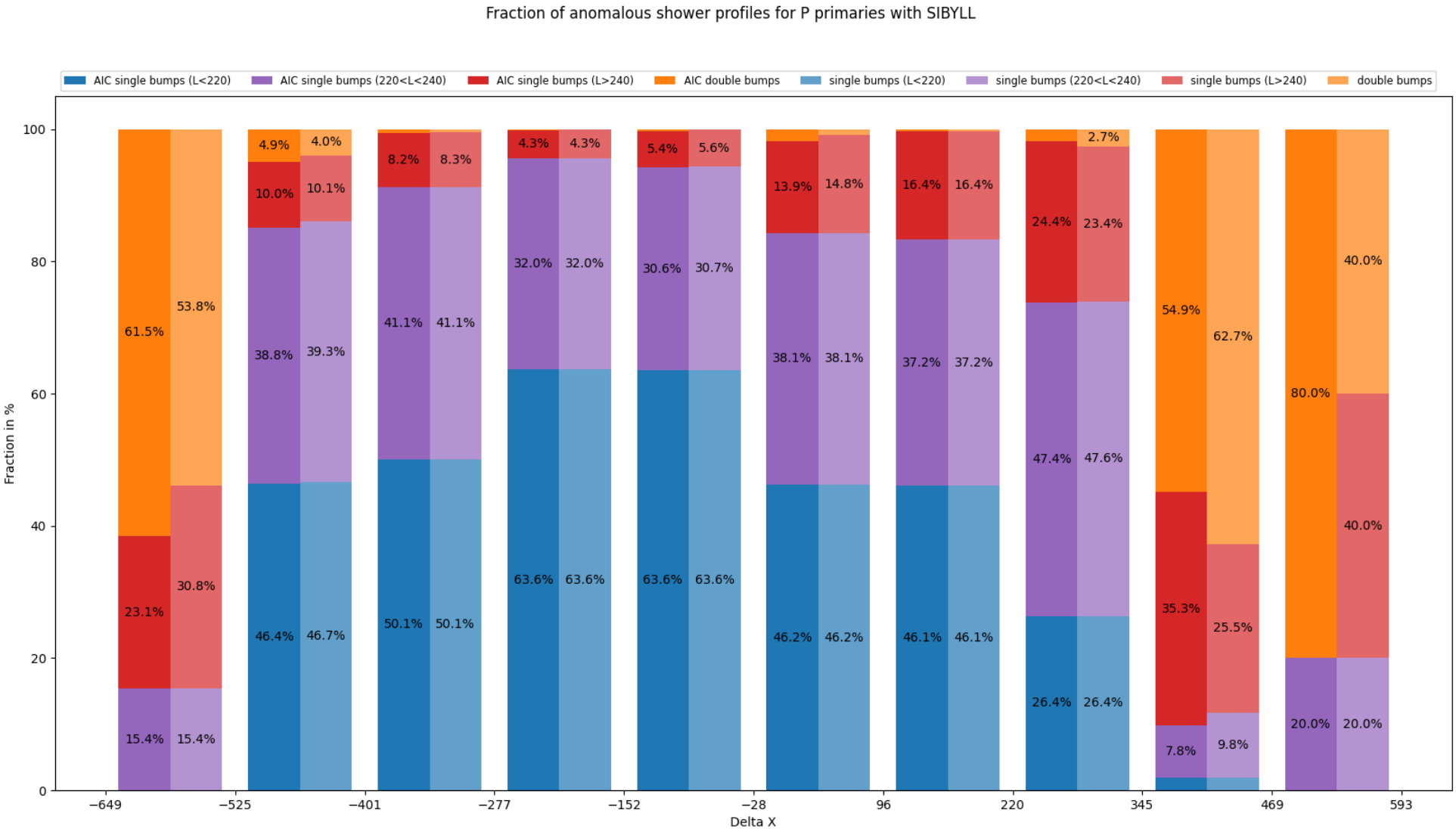
APPENDIX


Fraction of anomalous shower profiles for Si primaries with QGSII
AIC single bumps (L<220)
AIC single bumps (220<L<240)
AIC single bumps (L>240)
AIC double bumps
single bumps (L<220)
single bumps (220<L<240)
single bumps (L>240)
double bumps
Fraction in %
Delta X
47.8%
48.3%
49.8%
50.0%
40.0%
40.1%
58.7%
58.8%
37.4%
37.4%
62.0%
62.0%
31.0%
31.0%
68.5%
68.5%
35.5%
35.5%
64.1%
64.1%
34.6%
34.6%
65.0%
65.0%
2.9%
2.9%
46.4%
46.4%
50.7%
50.7%
45.2%
45.2%
53.9%
53.9%
2.5%
2.5%
87.5%
87.5%
10.0%
10.0%
100.0%
100.0%

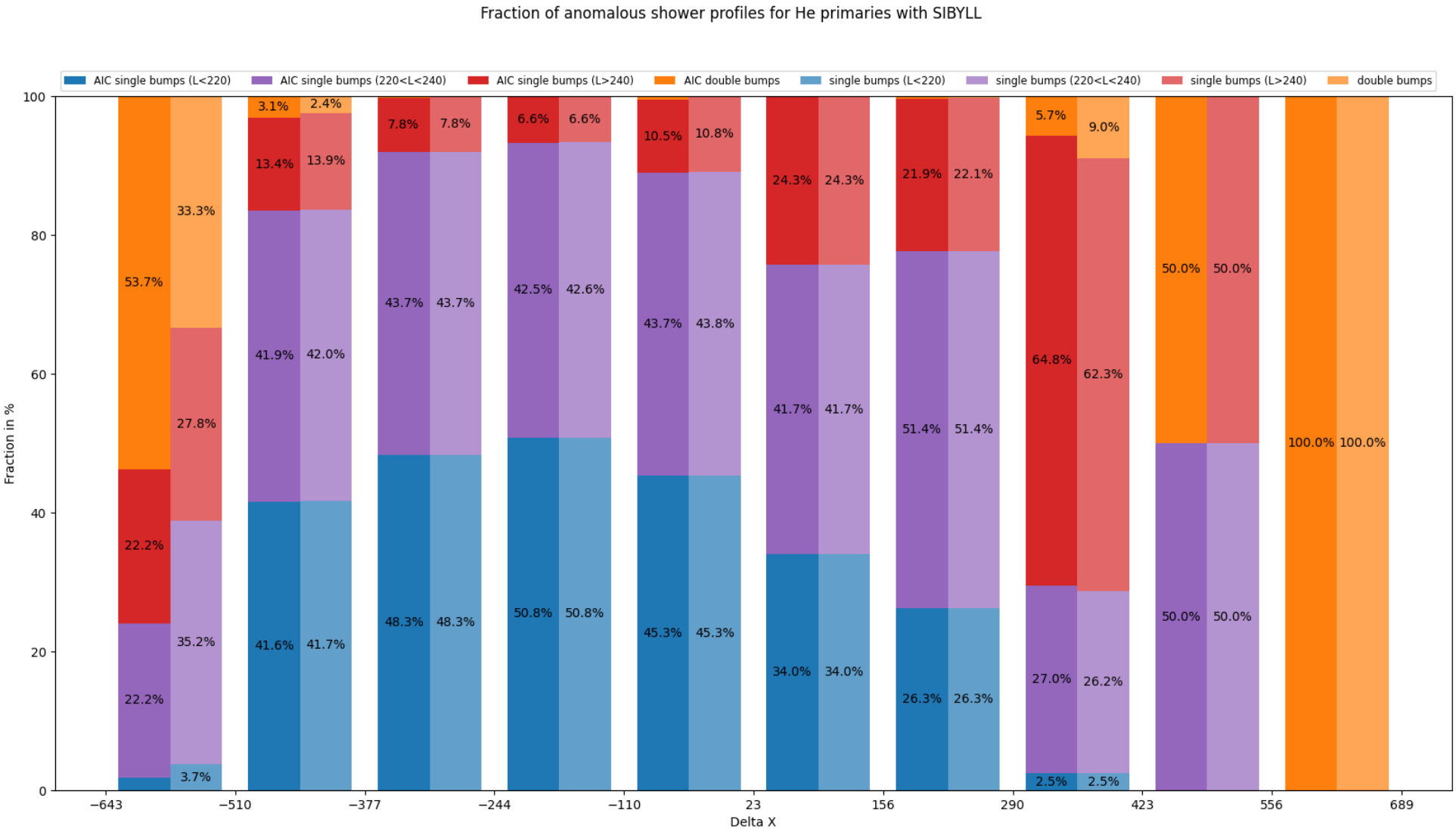
APPENDIX


Fraction of anomalous shower profiles for Fe primaries with QGSII
AIC single bumps (L<220)
AIC single bumps (220<L<240)
AIC single bumps (L>240)
AIC double bumps
single bumps (L<220)
single bumps (220<L<240)
single bumps (L>240)
double bumps
Fraction in %
Delta X
−532.7
−443.5
−354.2
−265.0
−175.7
−86.4
2.8
92.1
181.3
270.6
359.8
30.3%
30.5%
31.9%
31.9%
27.7%
27.7%
23.2%
23.2%
25.8%
25.8%
30.5%
30.5%
38.0%
38.0%
34.0%
34.0%
46.8%
46.8%
11.1%
11.1%
44.4%
44.4%
69.4%
69.4%
67.9%
67.9%
72.2%
72.2%
76.8%
76.8%
74.0%
74.0%
69.5%
69.5%
62.0%
62.0%
66.0%
66.0%
53.2%
53.2%
44.4%
44.4%

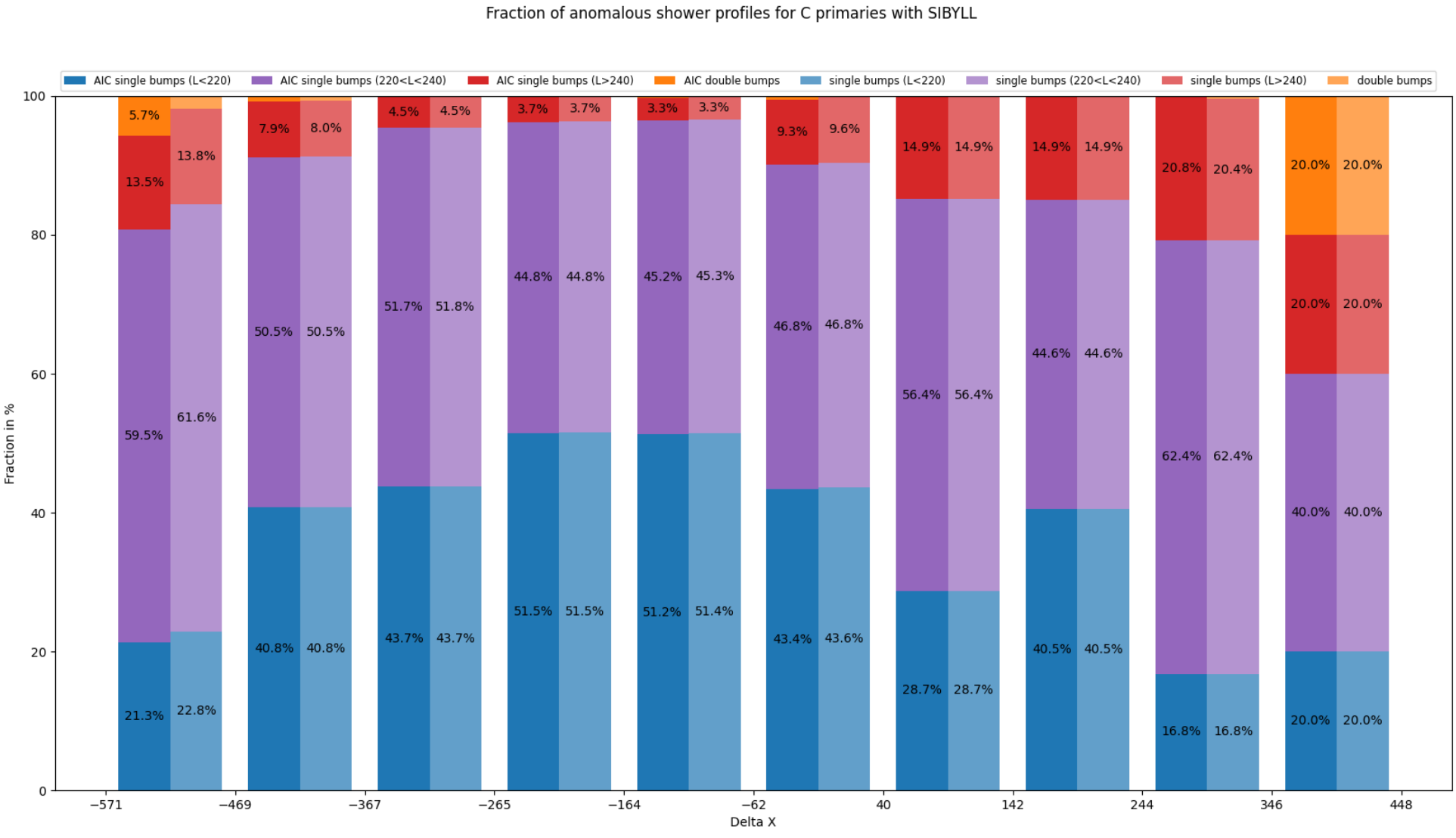
APPENDIX


Fraction of anomalous shower profiles for P primaries with SIBYLL
AIC single bumps (L<220)
AIC single bumps (220<L<240)
AIC single bumps (L>240)
AIC double bumps
single bumps (L<220)
single bumps (220<L<240)
single bumps (L>240)
double bumps
Fraction in %
Delta X
0
20
40
60
80
100
−649
−525
−401
−277
−152
−28
96
220
345
469
593
61.5%
23.1%
15.4%
53.8%
30.8%
15.4%
4.9%
10.0%
38.8%
46.4%
4.0%
10.1%
39.3%
46.7%
8.2%
41.1%
50.1%
8.3%
41.1%
50.1%
4.3%
32.0%
63.6%
4.3%
32.0%
63.6%
5.4%
30.6%
63.6%
5.6%
30.7%
63.6%
13.9%
38.1%
46.2%
14.8%
38.1%
46.2%
16.4%
37.2%
46.1%
16.4%
37.2%
46.1%
24.4%
47.4%
26.4%
2.7%
23.4%
47.6%
26.4%
54.9%
35.3%
7.8%
62.7%
25.5%
9.8%
80.0%
20.0%
40.0%
20.0%

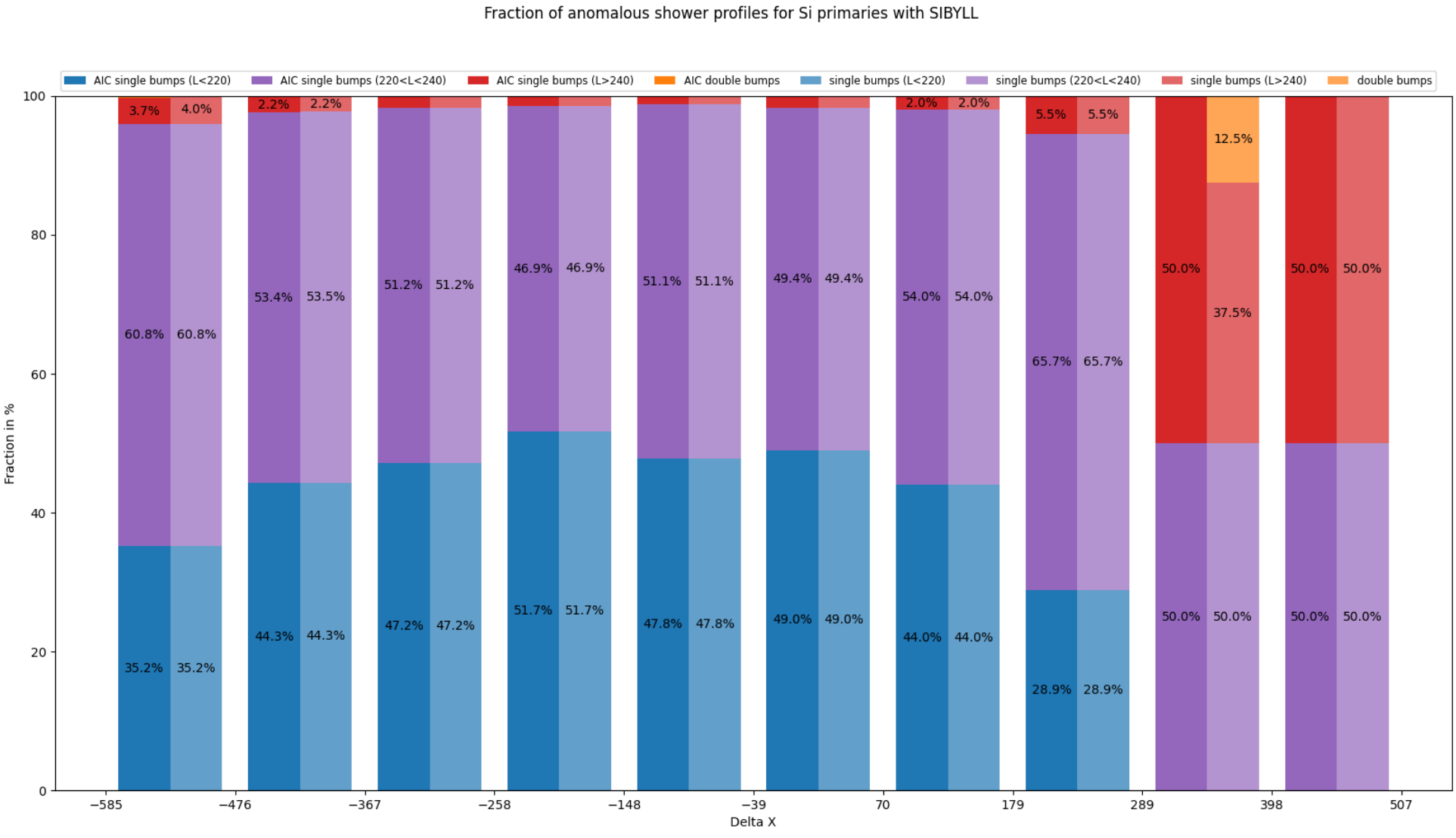
APPENDIX


Fraction of anomalous shower profiles for He primaries with SIBYLL
AIC single bumps (L<220)
AIC single bumps (220<L<240)
AIC single bumps (L>240)
AIC double bumps
single bumps (L<220)
single bumps (220<L<240)
single bumps (L>240)
double bumps
Fraction in %
Delta X
−643
−510
−377
−244
−110
23
156
290
423
556
689
53.7%
22.2%
22.2%
3.7%
33.3%
27.8%
35.2%
3.1%
13.4%
41.9%
41.6%
2.4%
13.9%
42.0%
41.7%
7.8%
43.7%
48.3%
7.8%
43.7%
48.3%
6.6%
42.5%
50.8%
6.6%
42.6%
50.8%
10.5%
43.7%
45.3%
10.8%
43.8%
45.3%
24.3%
41.7%
34.0%
24.3%
41.7%
34.0%
21.9%
51.4%
26.3%
22.1%
51.4%
26.3%
5.7%
64.8%
27.0%
2.5%
9.0%
62.3%
26.2%
2.5%
50.0%
50.0%
50.0%
50.0%
100.0%
100.0%

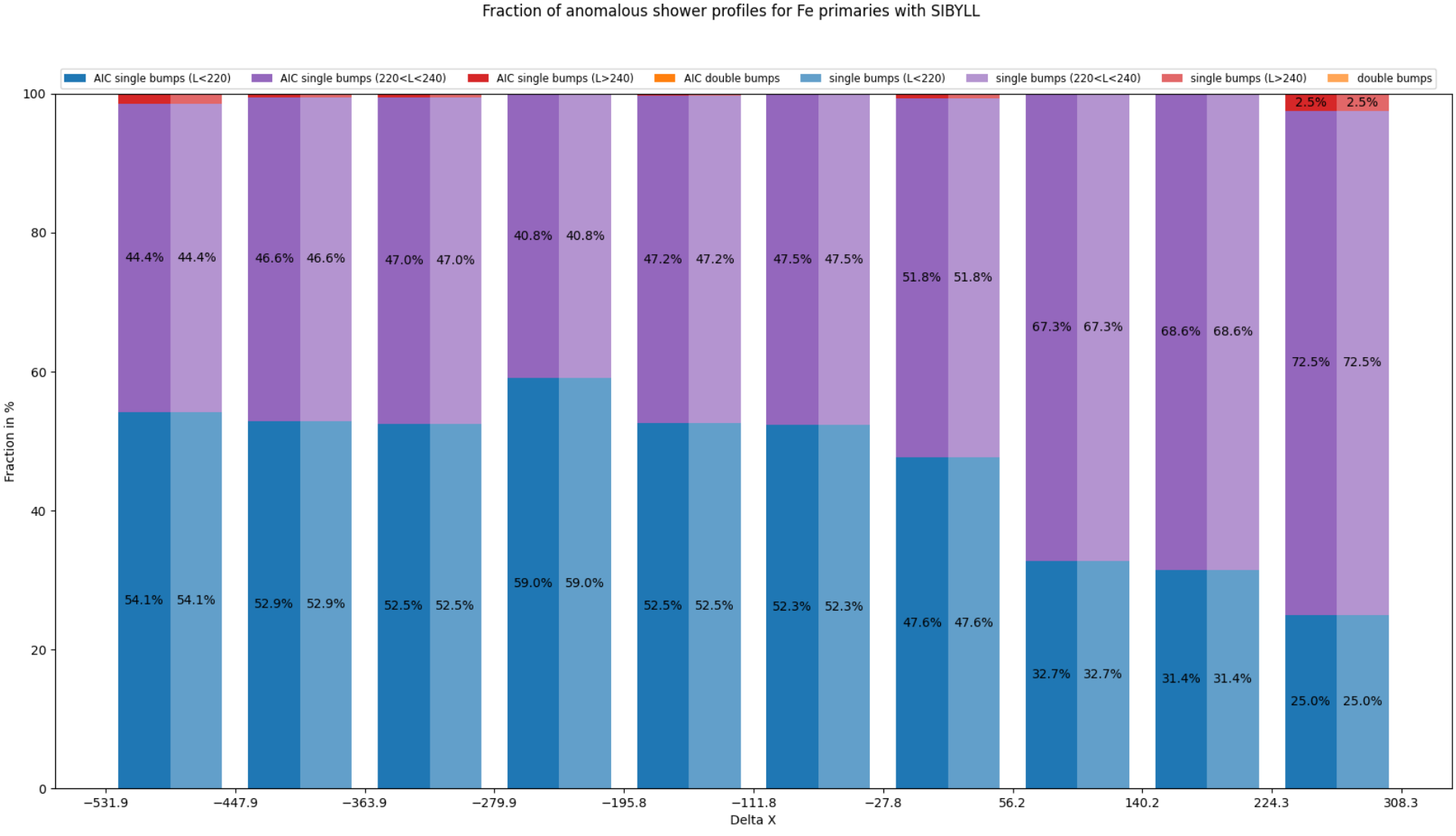
APPENDIX


Fraction of anomalous shower profiles for C primaries with SIBYLL
AIC single bumps (L<220)
AIC single bumps (220<L<240)
AIC single bumps (L>240)
AIC double bumps
single bumps (L<220)
single bumps (220<L<240)
single bumps (L>240)
double bumps
Fraction in %
Delta X
−571
−469
−367
−265
−164
−62
40
142
244
346
448
0
20
40
60
80
100
5.7%
13.5%
59.5%
21.3%
13.8%
61.6%
22.8%
7.9%
50.5%
40.8%
8.0%
50.5%
40.8%
4.5%
51.7%
43.7%
4.5%
51.8%
43.7%
3.7%
44.8%
51.5%
3.7%
44.8%
51.5%
3.3%
45.2%
51.2%
3.3%
45.3%
51.4%
9.3%
46.8%
43.4%
9.6%
46.8%
43.6%
14.9%
56.4%
28.7%
14.9%
56.4%
28.7%
14.9%
44.6%
40.5%
14.9%
44.6%
40.5%
20.8%
62.4%
16.8%
20.4%
62.4%
16.8%
20.0%
20.0%
40.0%
20.0%
20.0%
20.0%
40.0%
20.0%

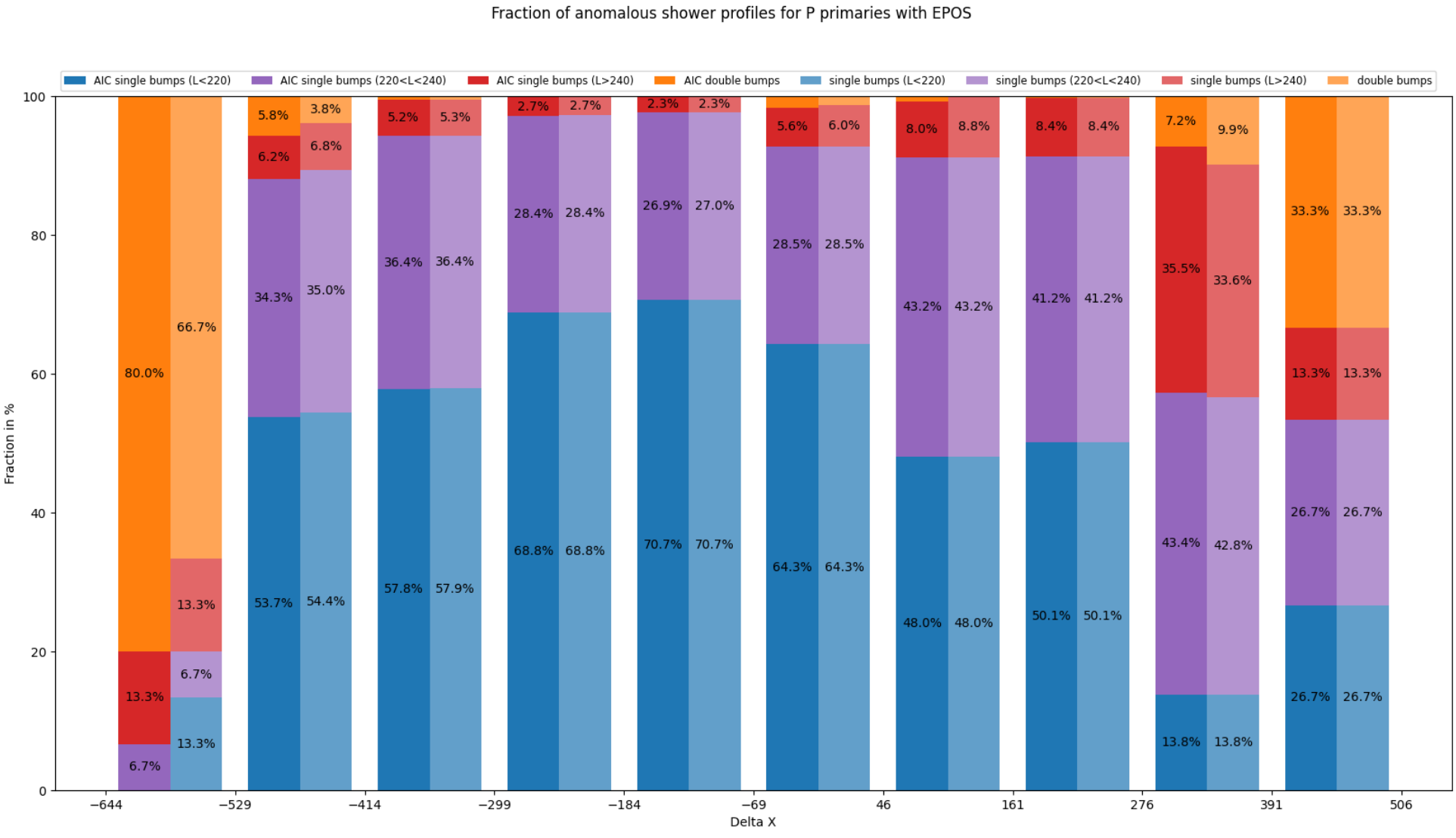
APPENDIX


Fraction of anomalous shower profiles for Si primaries with SIBYLL
AIC single bumps (L<220)
AIC single bumps (220<L<240)
AIC single bumps (L>240)
AIC double bumps
single bumps (L<220)
single bumps (220<L<240)
single bumps (L>240)
double bumps
Fraction in %
Delta X
−585
−476
−367
−258
−148
−39
70
179
289
398
507
3.7%
4.0%
60.8%
60.8%
35.2%
35.2%
2.2%
2.2%
53.4%
53.5%
44.3%
44.3%
51.2%
51.2%
47.2%
47.2%
46.9%
46.9%
51.7%
51.7%
51.1%
51.1%
47.8%
47.8%
49.4%
49.4%
49.0%
49.0%
2.0%
2.0%
54.0%
54.0%
44.0%
44.0%
5.5%
5.5%
65.7%
65.7%
28.9%
28.9%
50.0%
12.5%
37.5%
50.0%
50.0%
50.0%
50.0%

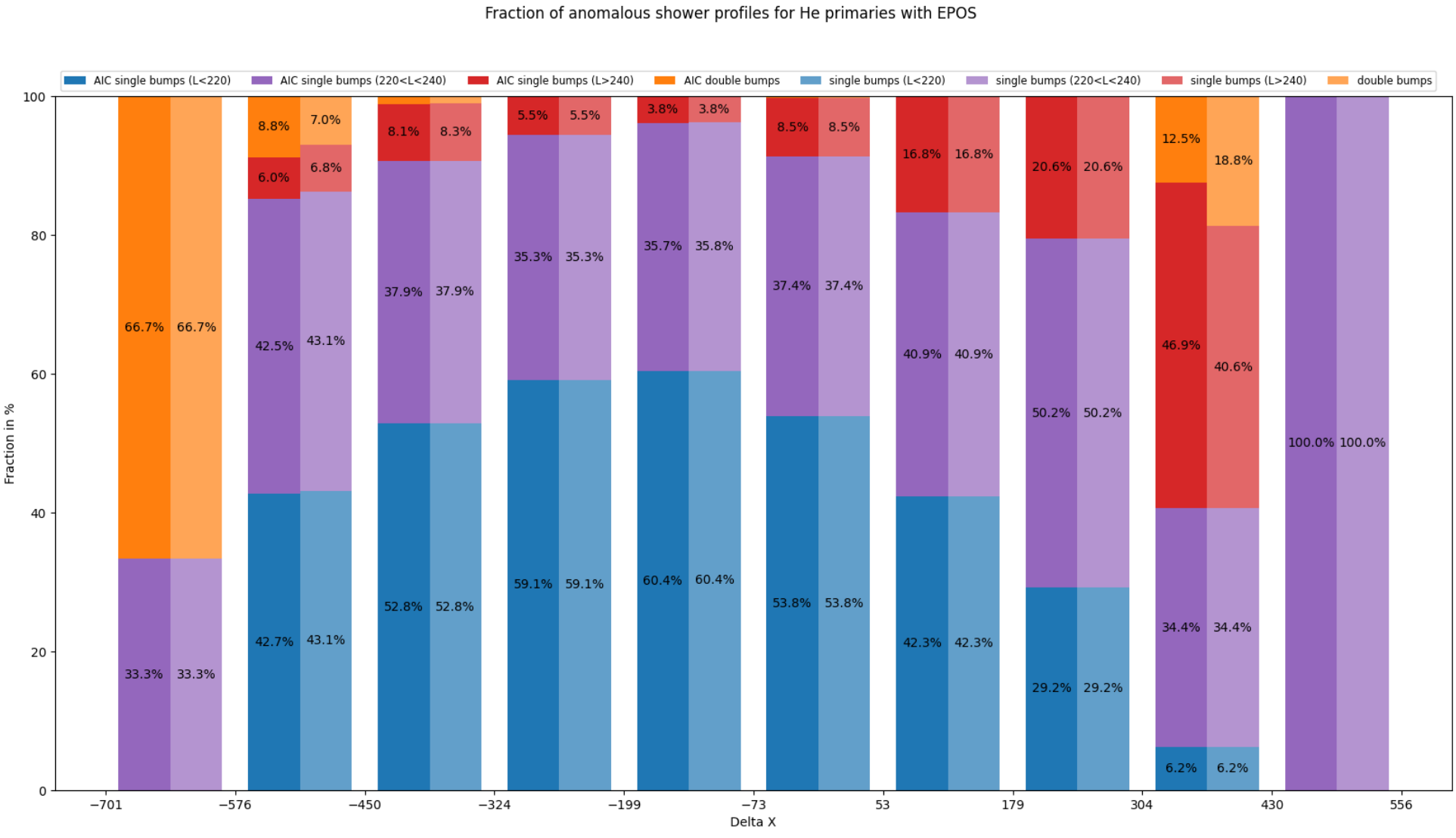
APPENDIX


Fraction of anomalous shower profiles for Fe primaries with SIBYLL
AIC single bumps (L<220)
AIC single bumps (220<L<240)
AIC single bumps (L>240)
AIC double bumps
single bumps (L<220)
single bumps (220<L<240)
single bumps (L>240)
double bumps
Fraction in %
Delta X
−531.9
−447.9
−363.9
−279.9
−195.8
−111.8
−27.8
56.2
140.2
224.3
308.3
44.4% 44.4%
46.6% 46.6%
47.0% 47.0%
40.8% 40.8%
47.2% 47.2%
47.5% 47.5%
51.8% 51.8%
67.3% 67.3%
68.6% 68.6%
2.5% 2.5%
72.5% 72.5%
54.1% 54.1%
52.9% 52.9%
52.5% 52.5%
59.0% 59.0%
52.5% 52.5%
52.3% 52.3%
47.6% 47.6%
32.7% 32.7%
31.4% 31.4%
25.0% 25.0%

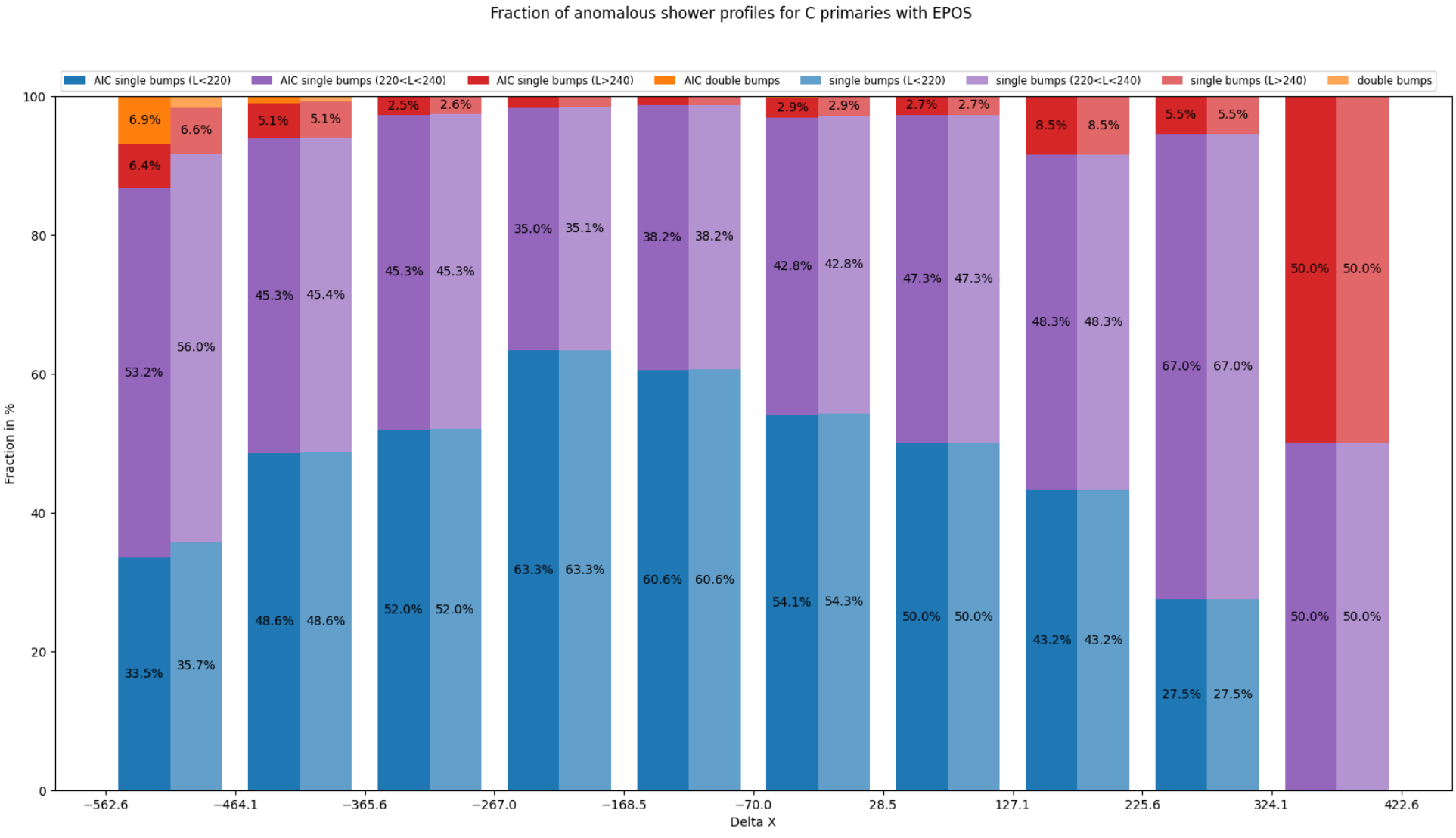
APPENDIX


Fraction of anomalous shower profiles for P primaries with EPOS
AIC single bumps (L<220)
AIC single bumps (220<L<240)
AIC single bumps (L>240)
AIC double bumps
single bumps (L<220)
single bumps (220<L<240)
single bumps (L>240)
double bumps
Fraction in %
Delta X
−644
−529
−414
−299
−184
−69
46
161
276
391
506
80.0%
66.7%
13.3%
6.7%
13.3%
6.7%
5.8%
3.8%
6.2%
6.8%
34.3%
35.0%
53.7%
54.4%
5.2%
5.3%
36.4%
36.4%
57.8%
57.9%
2.7%
2.7%
28.4%
28.4%
68.8%
68.8%
2.3%
2.3%
26.9%
27.0%
70.7%
70.7%
5.6%
6.0%
28.5%
28.5%
64.3%
64.3%
8.0%
8.8%
43.2%
43.2%
48.0%
48.0%
8.4%
8.4%
41.2%
41.2%
50.1%
50.1%
7.2%
9.9%
35.5%
33.6%
43.4%
42.8%
13.8%
13.8%
33.3%
33.3%
13.3%
13.3%
26.7%
26.7%
26.7%
26.7%

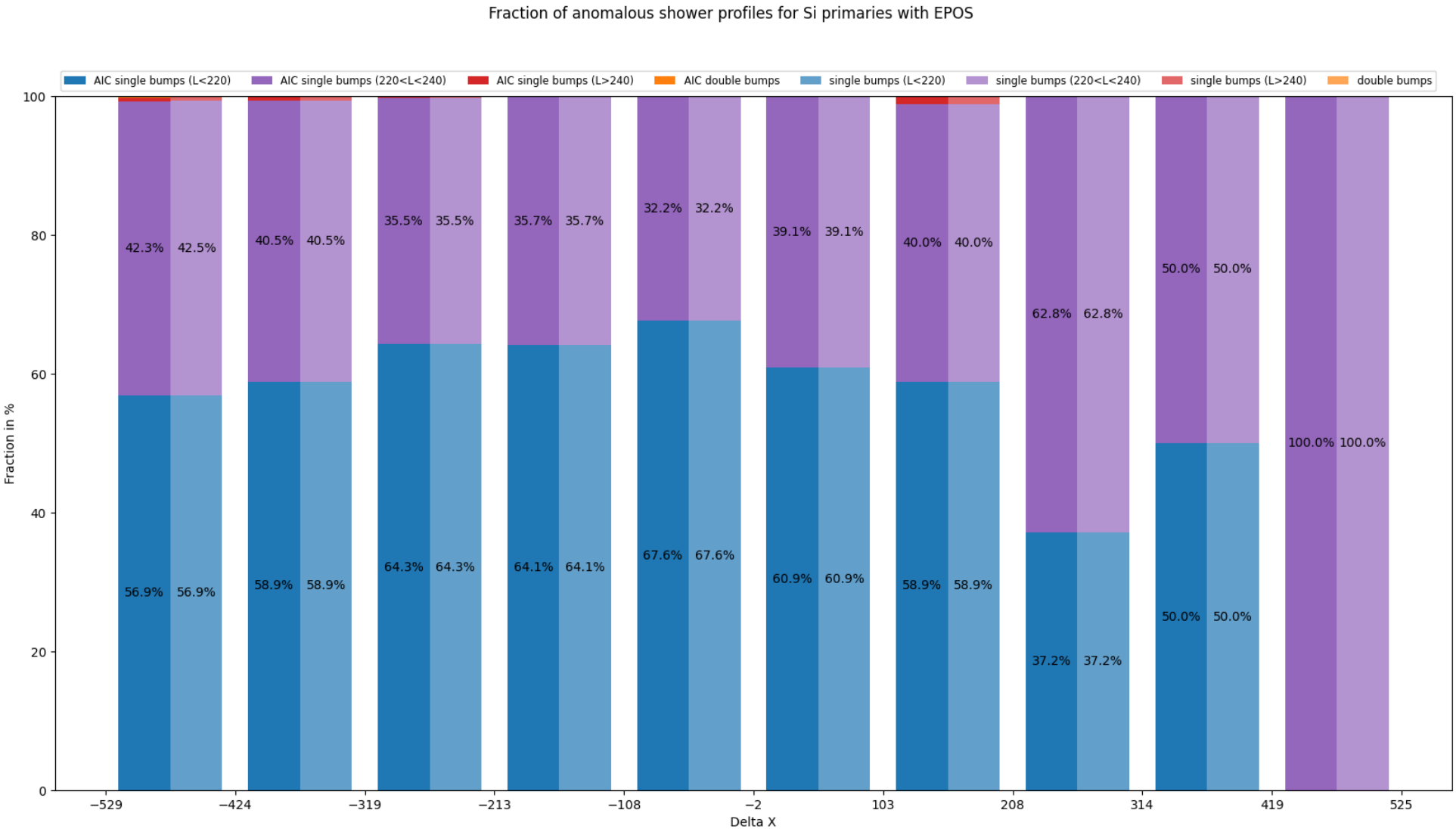
APPENDIX


Fraction of anomalous shower profiles for He primaries with EPOS
AIC single bumps (L<220)
AIC single bumps (220<L<240)
AIC single bumps (L>240)
AIC double bumps
single bumps (L<220)
single bumps (220<L<240)
single bumps (L>240)
double bumps
Fraction in %
Delta X
−701
−576
−450
−324
−199
−73
53
179
304
430
556
66.7%
66.7%
33.3%
33.3%
8.8%
7.0%
6.0%
6.8%
42.5%
43.1%
42.7%
43.1%
8.1%
8.3%
37.9%
37.9%
52.8%
52.8%
5.5%
5.5%
35.3%
35.3%
59.1%
59.1%
3.8%
3.8%
35.7%
35.8%
60.4%
60.4%
8.5%
8.5%
37.4%
37.4%
53.8%
53.8%
16.8%
16.8%
40.9%
40.9%
42.3%
42.3%
20.6%
20.6%
50.2%
50.2%
29.2%
29.2%
12.5%
18.8%
46.9%
40.6%
34.4%
34.4%
6.2%
6.2%
100.0%
100.0%

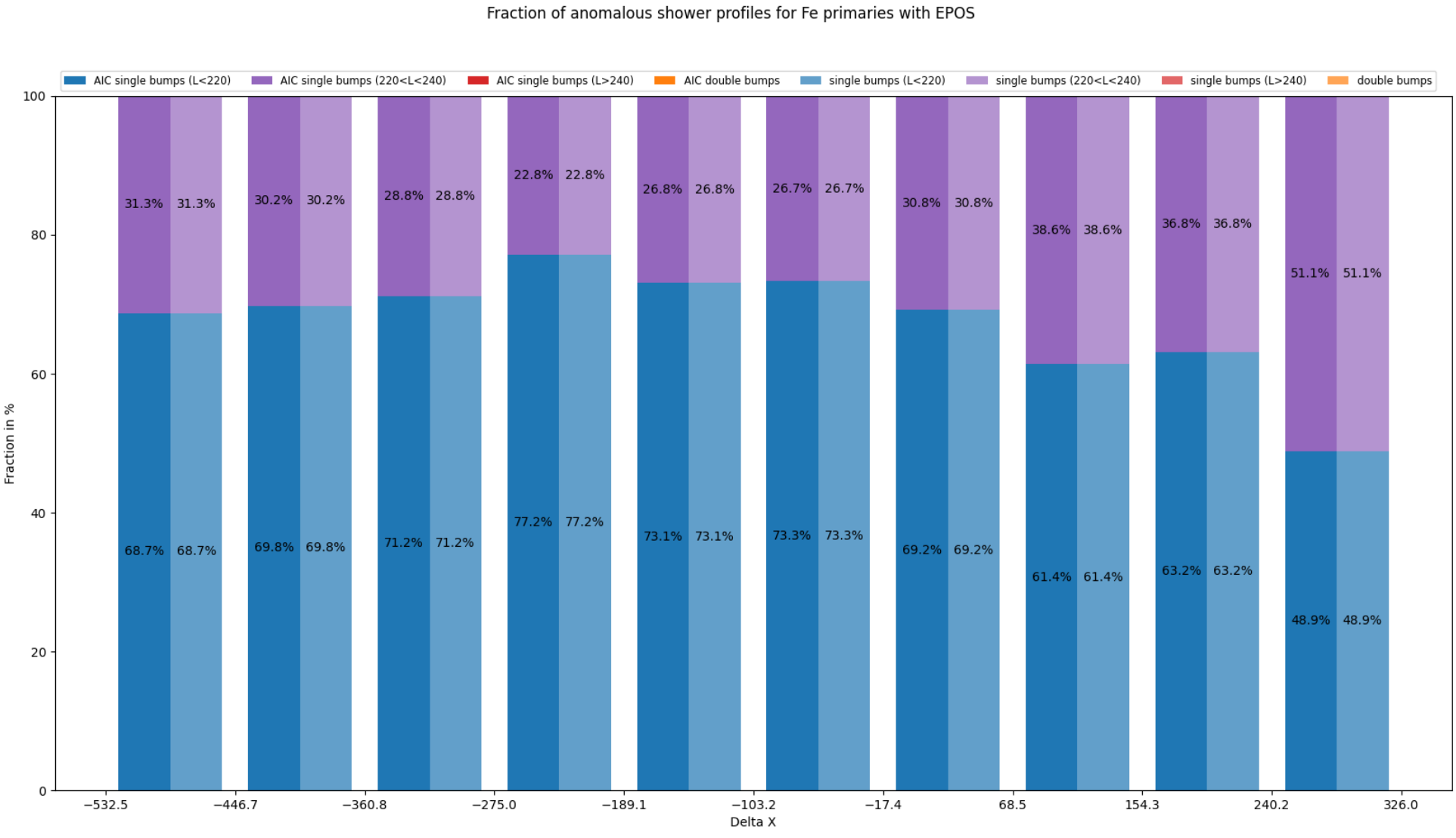
APPENDIX


Fraction of anomalous shower profiles for C primaries with EPOS
AIC single bumps (L<220)
AIC single bumps (220<L<240)
AIC single bumps (L>240)
AIC double bumps
single bumps (L<220)
single bumps (220<L<240)
single bumps (L>240)
double bumps
Fraction in %
Delta X
−562.6
−464.1
−365.6
−267.0
−168.5
−70.0
28.5
127.1
225.6
324.1
422.6
6.9%
6.6%
6.4%
53.2%
56.0%
33.5%
35.7%
5.1%
5.1%
45.3%
45.4%
48.6%
48.6%
2.5%
2.6%
45.3%
45.3%
52.0%
52.0%
35.0%
35.1%
63.3%
63.3%
38.2%
38.2%
60.6%
60.6%
2.9%
2.9%
42.8%
42.8%
54.1%
54.3%
2.7%
2.7%
47.3%
47.3%
50.0%
50.0%
8.5%
8.5%
48.3%
48.3%
43.2%
43.2%
5.5%
5.5%
67.0%
67.0%
27.5%
27.5%
50.0%
50.0%
50.0%
50.0%

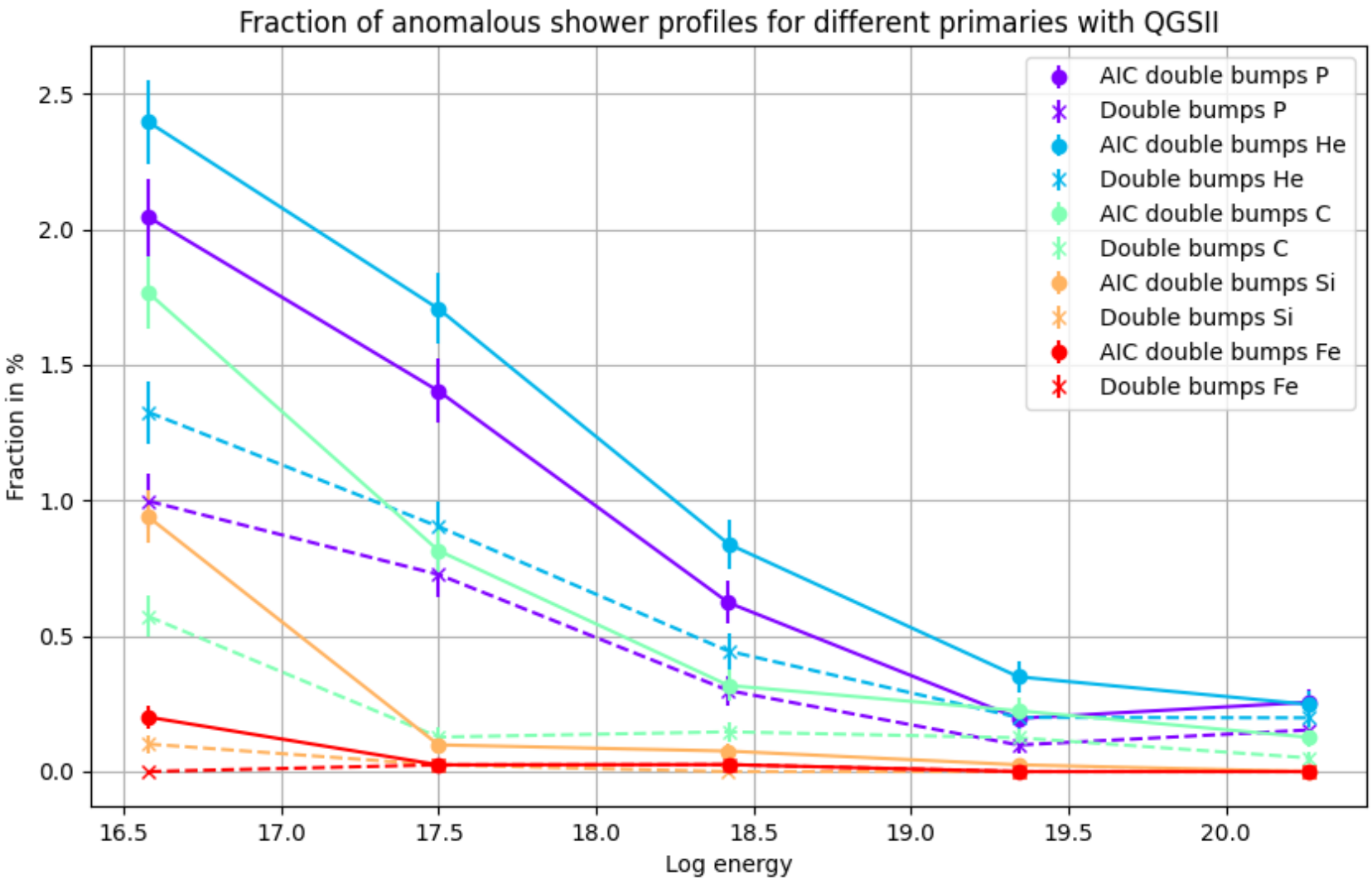
APPENDIX


Fraction of anomalous shower profiles for Si primaries with EPOS
AIC single bumps (L<220)
AIC single bumps (220<L<240)
AIC single bumps (L>240)
AIC double bumps
single bumps (L<220)
single bumps (220<L<240)
single bumps (L>240)
double bumps
Fraction in %
Delta X
0
20
40
60
80
100
−529
−424
−319
−213
−108
−2
103
208
314
419
525
56.9%
56.9%
42.3%
42.5%
58.9%
58.9%
40.5%
40.5%
64.3%
64.3%
35.5%
35.5%
64.1%
64.1%
35.7%
35.7%
67.6%
67.6%
32.2%
32.2%
60.9%
60.9%
39.1%
39.1%
58.9%
58.9%
40.0%
40.0%
37.2%
37.2%
62.8%
62.8%
50.0%
50.0%
50.0%
50.0%
100.0%
100.0%

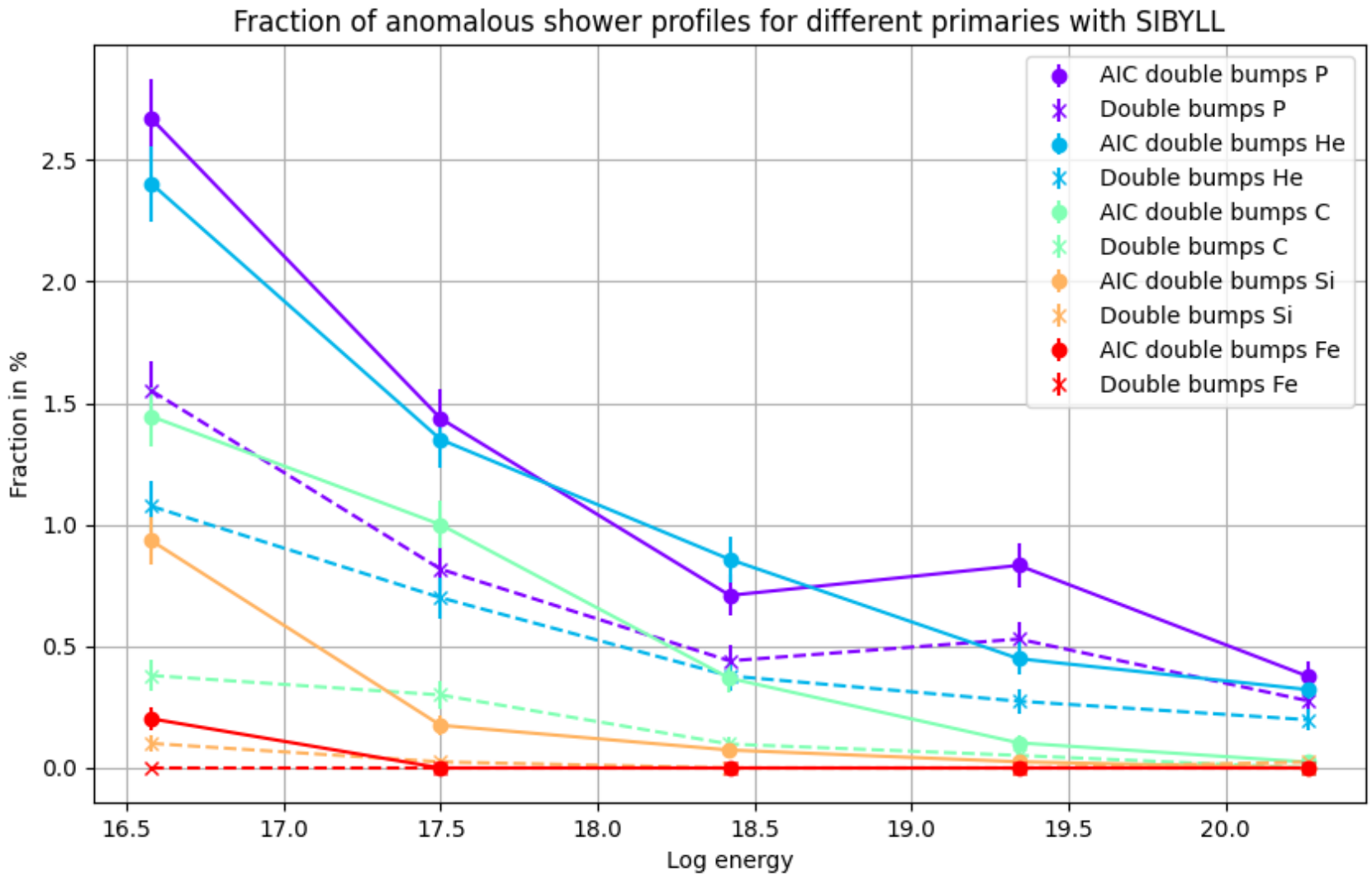
APPENDIX


Fraction of anomalous shower profiles for Fe primaries with EPOS
AIC single bumps (L<220)
AIC single bumps (220<L<240)
AIC single bumps (L>240)
AIC double bumps
single bumps (L<220)
single bumps (220<L<240)
single bumps (L>240)
double bumps
Fraction in %
Delta X
−532.5
−446.7
−360.8
−275.0
−189.1
−103.2
−17.4
68.5
154.3
240.2
326.0
31.3% 31.3%
30.2% 30.2%
28.8% 28.8%
22.8% 22.8%
26.8% 26.8%
26.7% 26.7%
30.8% 30.8%
38.6% 38.6%
36.8% 36.8%
51.1% 51.1%
68.7% 68.7%
69.8% 69.8%
71.2% 71.2%
77.2% 77.2%
73.1% 73.1%
73.3% 73.3%
69.2% 69.2%
61.4% 61.4%
63.2% 63.2%
48.9% 48.9%

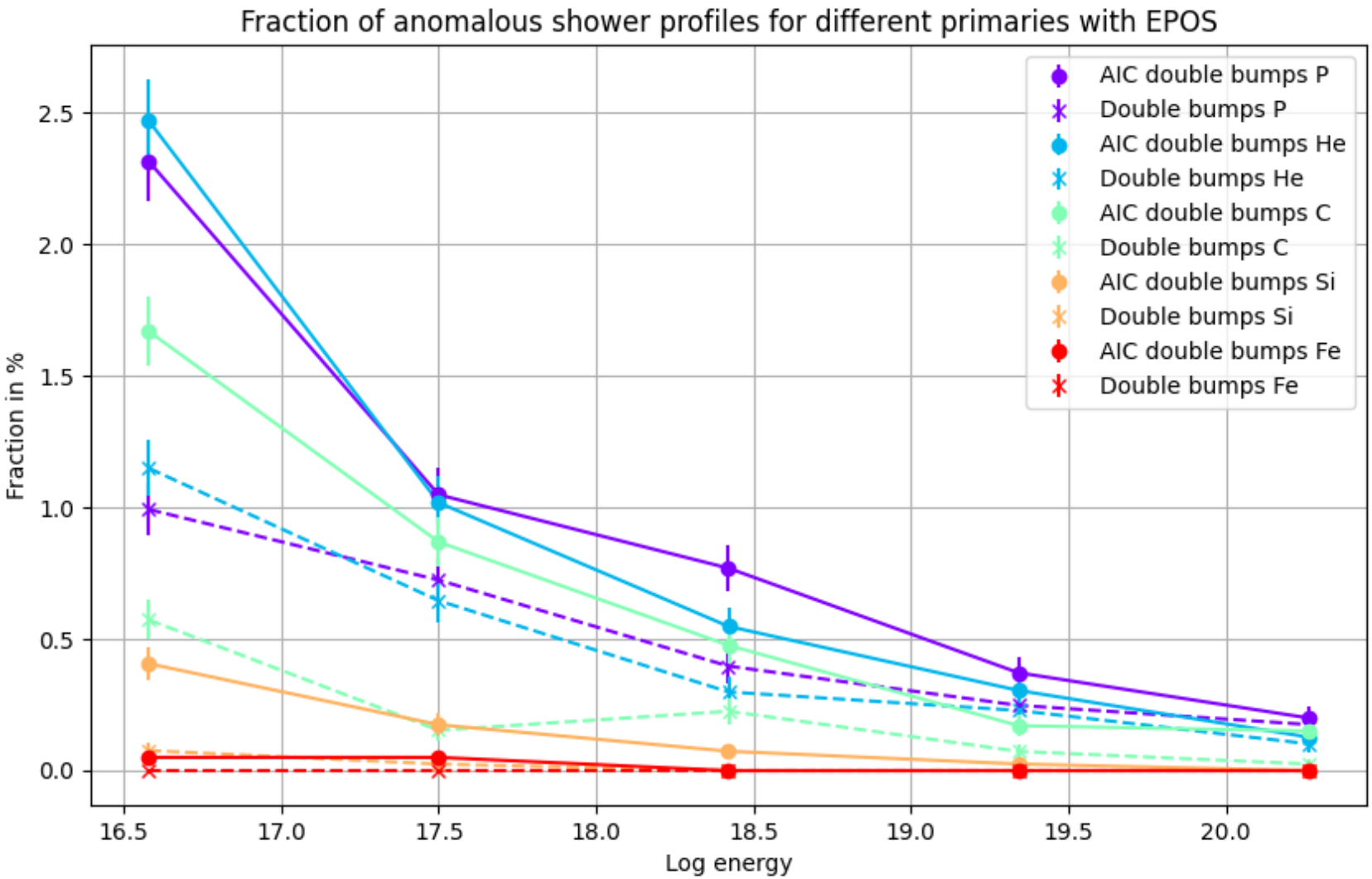
APPENDIX


Fraction of anomalous shower profiles for different primaries with QGSII
AIC double bumps P
Double bumps P
AIC double bumps He
Double bumps He
AIC double bumps C
Double bumps C
AIC double bumps Si
Double bumps Si
AIC double bumps Fe
Double bumps Fe
Fraction in %
Log energy
0.0
0.5
1.0
1.5
2.0
2.5
16.5
17.0
17.5
18.0
18.5
19.0
19.5
20.0

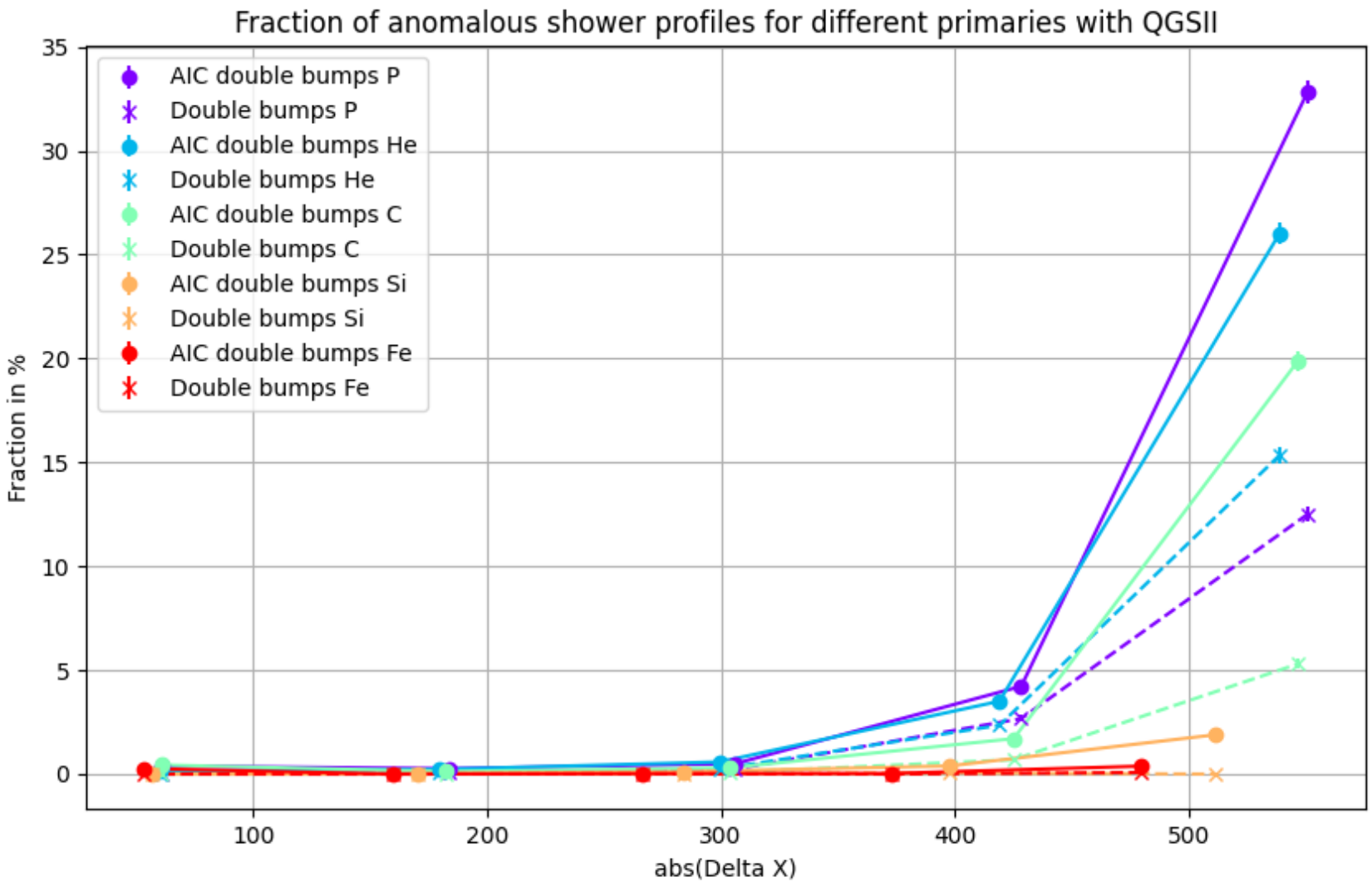
APPENDIX


Fraction of anomalous shower profiles for different primaries with SIBYLL
AIC double bumps P
Double bumps P
AIC double bumps He
Double bumps He
AIC double bumps C
Double bumps C
AIC double bumps Si
Double bumps Si
AIC double bumps Fe
Double bumps Fe
Fraction in %
0.0
0.5
1.0
1.5
2.0
2.5
16.5
17.0
17.5
18.0
18.5
19.0
19.5
20.0
Log energy

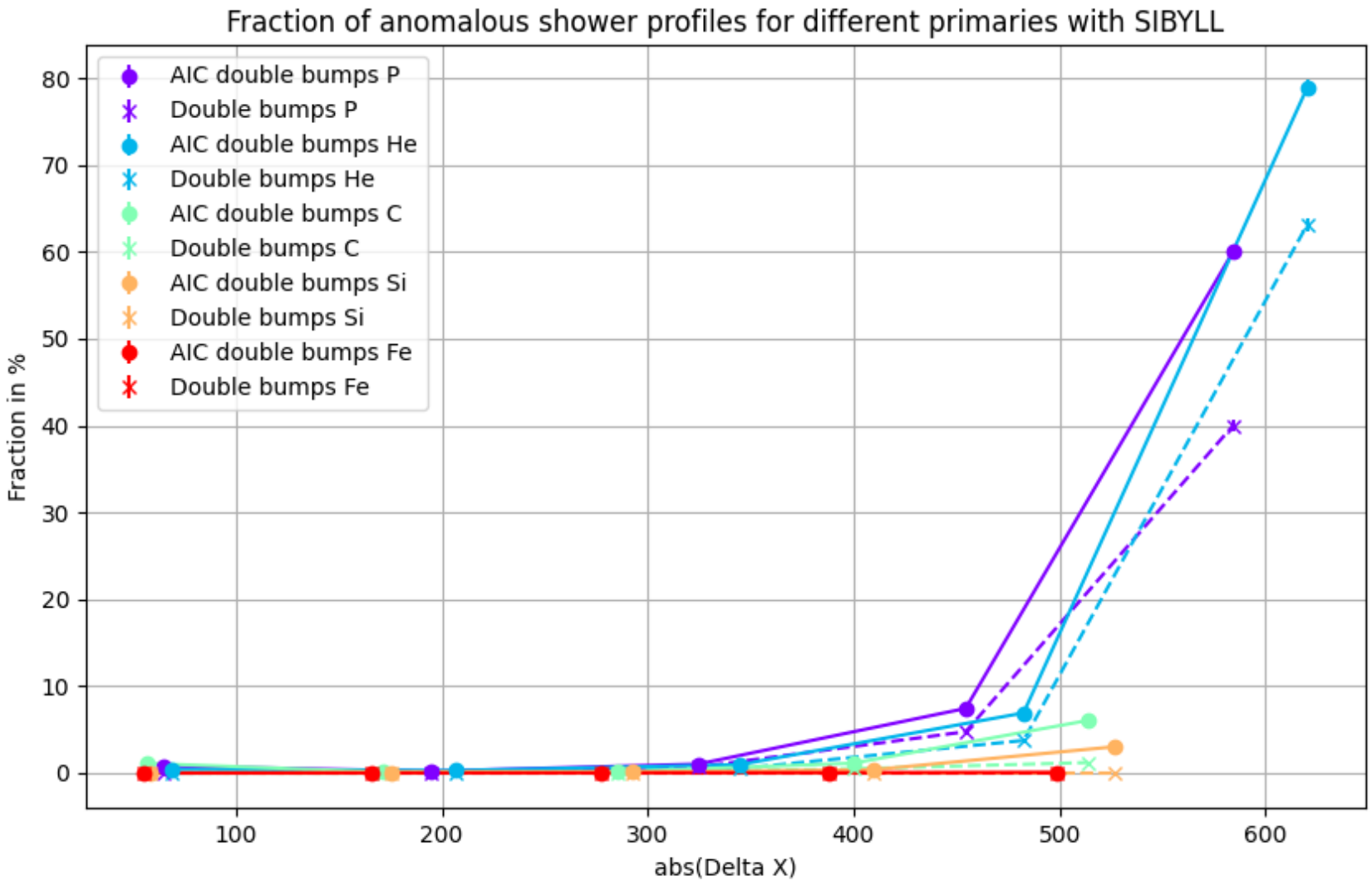
APPENDIX


Fraction of anomalous shower profiles for different primaries with EPOS
AIC double bumps P
Double bumps P
AIC double bumps He
Double bumps He
AIC double bumps C
Double bumps C
AIC double bumps Si
Double bumps Si
AIC double bumps Fe
Double bumps Fe
Fraction in %
0.0
0.5
1.0
1.5
2.0
2.5
16.5
17.0
17.5
18.0
18.5
19.0
19.5
20.0
Log energy

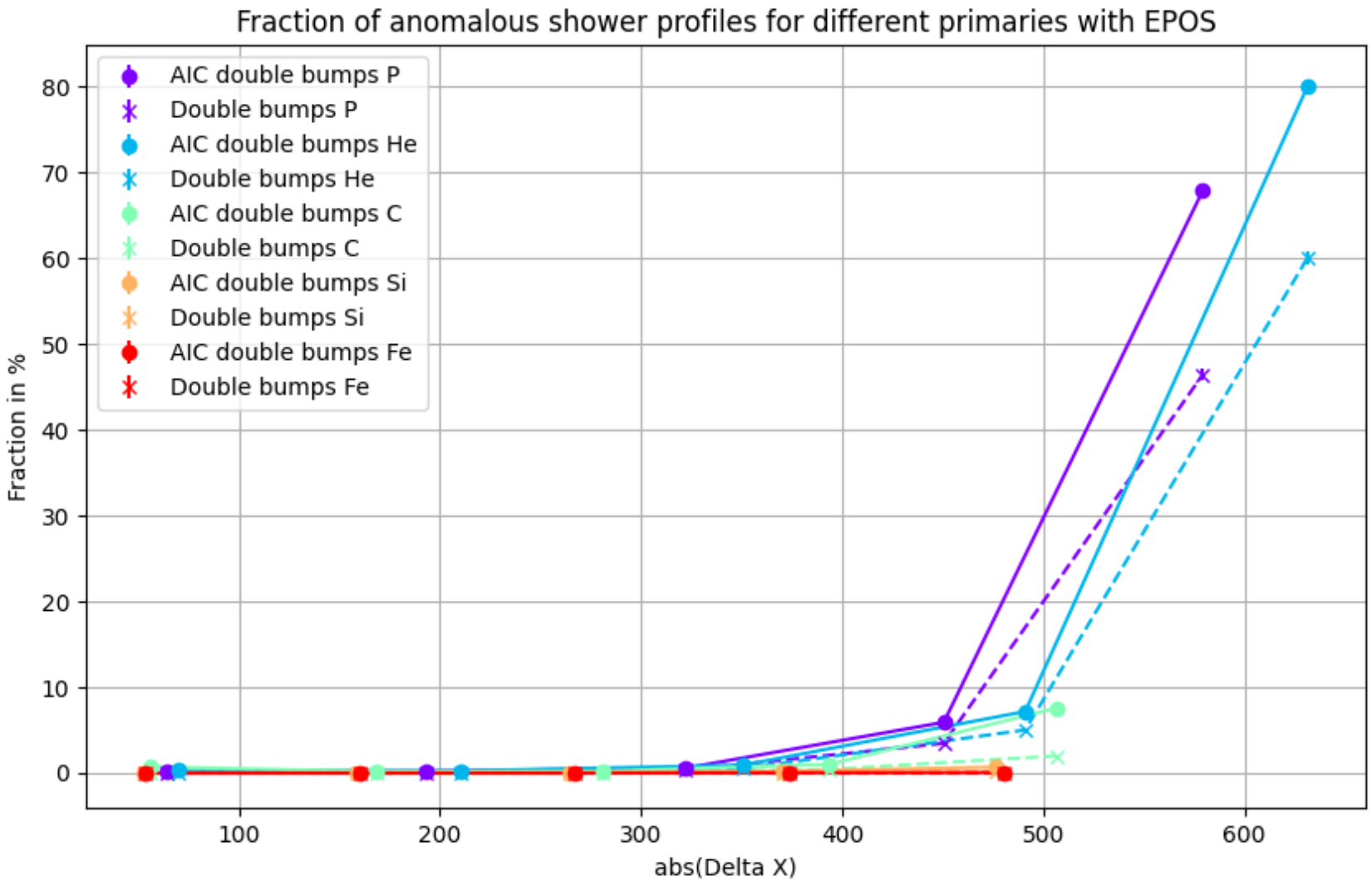
APPENDIX


Fraction of anomalous shower profiles for different primaries with QGSII
AIC double bumps P
Double bumps P
AIC double bumps He
Double bumps He
AIC double bumps C
Double bumps C
AIC double bumps Si
Double bumps Si
AIC double bumps Fe
Double bumps Fe
Fraction in %
abs(Delta X)
0
5
10
15
20
25
30
35
100
200
300
400
500

APPENDIX


Fraction of anomalous shower profiles for different primaries with SIBYLL
AIC double bumps P
Double bumps P
AIC double bumps He
Double bumps He
AIC double bumps C
Double bumps C
AIC double bumps Si
Double bumps Si
AIC double bumps Fe
Double bumps Fe
Fraction in %
0
10
20
30
40
50
60
70
80
100
200
300
400
500
600
abs(Delta X)

APPENDIX


Fraction of anomalous shower profiles for different primaries with EPOS
AIC double bumps P
Double bumps P
AIC double bumps He
Double bumps He
AIC double bumps C
Double bumps C
AIC double bumps Si
Double bumps Si
AIC double bumps Fe
Double bumps Fe
Fraction in %
0
10
20
30
40
50
60
70
80
100
200
300
400
500
600
abs(Delta X)