X_{max} Distributions for HiRes Stereo Data

R.U. Abbasi[1], T. Abu-Zayyad[1], M. Al-Seady[1], M. Allen[1], J.F. Amman[2], R.J. Anderson[1], G. Archbold[1], K. Belov[1], J.W. Belz[1,†], D.R. Bergman[1,3], S.A. Blake[1], O.A. Brusova[1], G.W. Burt[1], C. Cannon[1], Z. Cao[1], W. Deng[1], Y. Fedorova[1], C.B. Finley[4], R.C. Gray[1], W.F. Hanlon[1], C.M. Hoffman[2], M.H. Holzscheiter[2], G. Hughes[3], P. Hüntemeyer[1], D. Ivanov[3], B.F Jones[1], C.C.H. Jui[1], K. Kim[1], M.A. Kirn[5], E.C. Loh[1], J. Liu[1], J.P. Lundquist[1], M.M. Maestas[1], N. Manago[6], L.J. Marek[2], K. Martens[1], J.A.J. Matthews[7], J.N. Matthews[1], S.A. Moore[1], A. O'Neill[4], C.A. Painter[2], L. Perera[3], K. Reil[1], R. Riehle[1], M. Roberts[7], D. Rodriguez[1], N. Sasaki[6], S.R. Schnetzer[3], L.M. Scott[3], G. Sinnis[2], J.D. Smith[1], P. Sokolsky[1], C. Song[4], R.W. Springer[1], B.T. Stokes[1], S. Stratton[3], S.B. Thomas[1], J.R. Thomas[1], G.B. Thomson[1,3], D. Tupa[2], A. Zech[3], and X. Zhang[4]

The High Resolution Fly's Eye Collaboration

[1]University of Utah, Department of Physics, Salt Lake City, UT, USA
[2]Los Alamos National Laboratory, Los Alamos, NM, USA
[3]Rutgers University — The State University of New Jersey, Department of Physics and Astronomy, Piscataway, NJ, USA
[4]Columbia University, Department of Physics and Nevis Laboratory, New York, NY, USA
[5]Montana State University, Department of Physics, Bozeman, MT , USA
[6]University of Tokyo, Institute for Cosmic Ray Research, Kashiwa, Japan
[7]University of New Mexico, Department of Physics, Albuquerque, NM, USA

[†]Corresponding Author: *belz@physics.utah.edu*

This note is a supplement to the recent HiRes PRL, *Indications of Proton-Dominated Cosmic-Ray Composition above 1.6 EeV* [1]. It includes a list of X_{max} and energy of HiRes stereo events included in the PRL X_{max} composition study, and a set of data/Monte Carlo overlays comparing the X_{max} distribution of events to simulated proton- and iron-induced air showers.

$\log E$	X_{max}	$\log E$	X_{max}	$\log E$	X_{max}	$\log E$	X_{max}
19.292	737.017	19.160	794.276	18.398	717.050	18.810	808.483
18.471	788.025	18.980	815.164	18.653	792.220	18.761	718.483
18.286	678.559	18.864	680.652	18.517	808.241	18.511	656.939
18.455	651.640	19.096	811.897	18.526	660.350	18.370	688.239
18.961	690.471	18.573	674.777	18.704	770.166	18.725	777.223
19.072	708.606	18.676	769.114	18.738	642.646	18.701	754.018
18.756	718.353	18.601	844.033	18.995	694.173	19.678	706.770
18.539	700.619	18.993	801.302	19.516	697.220	19.022	666.993
18.456	743.282	18.999	764.199	18.233	814.122	18.211	721.477
19.032	711.267	18.861	678.777	18.895	701.155	19.175	755.700
18.501	812.381	18.689	805.111	18.957	797.174	18.414	729.422
18.618	643.532	18.745	908.719	18.934	834.071	19.222	703.472
18.861	680.536	18.536	663.647	18.285	797.823	18.577	781.310
19.308	762.798	18.481	743.161	18.754	841.029	18.473	768.712
18.896	664.057	18.233	672.305	18.879	755.166	18.451	690.281
18.920	705.239	18.631	680.739	18.668	658.327	19.038	741.763
18.794	672.809	18.330	636.544	18.496	645.298	19.196	698.845
18.951	734.034	18.290	1038.796	18.538	669.057	19.613	761.006
18.612	837.442	18.472	704.993	18.389	737.252	19.376	704.080
18.744	720.348	18.942	674.654	18.484	775.090	18.566	726.576
19.156	783.664	18.331	846.994	18.891	747.157	18.971	757.773
18.450	762.071	18.920	639.533	18.985	871.138	18.484	768.293
18.245	638.014	18.439	669.424	18.662	728.325	18.470	734.146
18.547	746.679	18.470	680.853	18.776	746.707	18.234	619.732
18.888	885.437	18.395	731.048	18.554	804.098	19.030	711.347
18.383	778.864	18.472	791.455	18.362	733.028	18.646	697.249
18.574	676.994	18.710	630.241	18.705	721.142	19.482	753.392
18.463	734.852	19.108	658.748	19.276	789.610	19.198	744.616
18.217	711.900	18.236	655.901	18.715	736.695	19.129	734.193
18.956	739.515	19.194	786.082	18.220	648.250	18.927	920.208
18.304	755.876	18.486	738.765	18.704	703.013	18.311	719.682
18.383	791.099	18.470	756.089	18.377	753.254	18.284	751.071
18.571	646.122	18.450	959.264	18.508	694.277	18.974	721.100
18.938	722.946	18.682	745.391	18.469	641.458	18.444	710.391
18.643	778.664	18.491	680.835	18.404	730.304	18.819	731.310
18.273	643.413	18.531	739.265	18.631	778.499	19.418	780.010
18.326	741.183	19.042	735.269	18.866	802.644	18.614	694.396
18.399	685.589	18.459	724.324	18.731	665.563	19.120	820.885
18.339	863.479	19.024	708.406	18.281	687.937	18.769	723.672
18.414	708.789	18.415	708.517	18.891	705.313	19.419	684.549
18.752	698.143	18.928	693.809	18.845	635.041	18.976	685.826

$\log E$	X_{max}	$\log E$	X_{max}	$\log E$	X_{max}	$\log E$	X_{max}
18.567	694.779	18.475	712.913	18.499	635.591	19.122	760.906
18.930	655.110	18.417	777.323	18.548	734.634	18.239	621.811
18.577	684.318	18.476	766.495	19.227	738.191	18.290	697.296
19.171	751.634	18.209	665.864	18.583	844.479	18.256	694.827
18.454	665.580	18.485	713.935	18.284	757.044	18.400	717.448
18.548	624.270	18.653	668.427	18.752	696.576	18.934	709.819
18.548	711.269	18.684	761.221	18.727	716.502	18.861	819.438
18.485	726.876	18.902	683.156	18.944	705.089	18.785	750.159
18.233	779.446	19.274	684.687	18.379	676.091	18.259	583.609
18.574	671.855	18.999	734.805	18.402	768.413	18.351	661.504
19.397	666.445	18.703	669.512	18.424	742.829	18.561	852.853
18.846	723.035	18.616	665.019	18.733	686.459	19.255	859.914
18.412	707.164	18.240	676.339	18.837	999.983	18.245	618.370
18.482	855.865	18.275	615.998	18.800	721.075	18.332	728.879
18.554	769.057	18.690	717.709	18.850	749.778	18.362	693.703
18.861	739.343	18.287	663.864	18.292	647.609	18.334	737.133
18.370	725.158	18.202	683.704	18.515	787.039	19.443	826.200
18.371	762.476	18.570	787.449	18.212	762.720	18.226	712.515
18.786	862.151	18.367	944.748	19.640	753.558	18.211	638.938
18.999	759.901	19.385	785.786	18.275	781.467	18.604	844.494
18.570	763.857	19.309	789.304	19.009	741.759	18.576	718.032
19.066	756.762	18.466	640.344	18.839	812.873	18.496	701.862
18.379	683.382	19.145	764.158	18.891	712.065	18.687	682.465
18.414	698.994	18.238	688.968	18.473	686.792	18.358	851.692
18.352	753.219	18.396	680.096	18.227	730.450	19.193	714.059
18.300	759.626	18.840	680.636	18.413	770.417	19.164	750.645
18.527	720.301	18.309	668.553	18.552	752.974	18.308	715.106
18.582	701.295	18.807	731.454	18.387	712.852	18.517	713.379
19.018	759.567	18.341	678.124	18.251	659.245	18.551	736.052
18.346	698.853	18.862	690.570	18.613	630.469	18.847	766.691
18.202	709.207	19.283	711.562	18.965	716.174	18.639	665.352
18.652	811.690	18.366	697.726	19.017	696.547	18.725	674.563
18.653	713.142	18.438	689.708	18.984	746.455	18.604	733.408
18.380	740.441	18.741	759.561	18.321	642.502	18.201	659.327
18.366	599.415	18.263	615.859	18.554	862.759	18.466	855.840
18.367	709.603	18.457	746.817	19.275	761.252	18.524	730.094
18.627	782.868	18.262	631.134	19.060	730.138	18.448	706.508
18.244	661.513	18.236	721.786	18.610	760.008	19.117	734.843
18.608	711.394	18.807	627.479	18.978	752.509	18.730	776.849
18.572	756.380	18.205	653.290	18.532	704.023	19.365	747.387
18.269	702.559	18.310	681.463	18.298	723.463	18.531	674.008

$\log E$	X_{max}	$\log E$	X_{max}	$\log E$	X_{max}	$\log E$	X_{max}
18.848	667.658	18.584	717.156	18.436	710.640	18.954	818.567
18.522	797.301	18.383	676.919	18.546	741.587	18.593	692.656
19.485	771.319	18.713	772.686	18.542	717.420	18.251	676.687
18.586	733.210	19.210	737.166	18.784	719.336	18.470	676.990
18.391	683.964	19.021	791.038	18.400	749.302	18.688	790.314
18.458	723.717	18.986	783.487	18.462	733.878	19.249	807.243
18.757	695.990	18.758	787.229	18.406	832.984	18.475	938.482
18.812	686.528	18.776	709.887	18.336	662.473	18.373	694.831
18.808	720.410	18.625	838.097	18.670	759.994	18.471	726.235
19.196	750.090	18.505	676.466	18.445	741.526	19.375	748.676
18.513	707.551	18.572	717.055	18.366	781.867	18.397	705.171
18.376	639.810	18.753	823.975	18.747	759.099	19.215	748.566
18.900	754.522	18.415	704.049	18.400	731.618	18.266	740.539
18.891	676.984	18.942	731.294	18.555	744.825	18.616	993.854
18.452	704.047	19.349	751.364	18.203	626.502	18.488	666.845
18.367	728.639	18.490	793.352	18.472	794.472	18.234	722.778
18.861	722.304	18.520	680.840	18.237	624.262	18.520	777.168
18.455	694.833	18.955	751.090	18.524	729.651	18.481	686.285
18.740	833.258	18.205	738.612	18.797	811.099	18.209	735.231
18.773	751.802	18.306	701.624	19.132	717.537	18.499	734.815
18.400	805.410	18.584	653.631	18.407	706.683	18.713	752.476
18.837	796.127	18.857	714.759	18.318	684.214	19.123	767.932
18.964	726.615	18.608	912.640	18.536	774.237	18.414	689.802
18.441	792.078	18.577	713.371	19.188	681.407	18.301	727.150
18.937	762.213	18.742	641.837	18.640	784.503	19.021	721.512
19.104	933.873	18.238	776.209	18.418	684.648	18.347	691.543
19.392	749.646	18.392	728.315	18.382	800.127	18.749	810.349
18.208	811.309	19.332	799.981	18.719	700.313	19.286	831.854
18.266	1008.028	18.374	758.441	18.994	680.377	18.848	715.255
18.278	689.213	18.465	713.781	19.124	789.142	18.603	731.641
18.338	703.926	18.410	735.961	18.696	657.313	18.482	627.201
18.945	719.346	18.596	739.869	18.607	744.542	19.139	739.590
18.300	693.184	18.753	708.982	18.574	709.640	18.733	694.180
18.513	718.262	18.499	716.538	19.186	724.236	18.654	754.329
18.423	809.097	19.027	727.806	18.708	756.662	18.929	781.132
18.444	818.993	19.616	798.955	19.573	771.019	18.289	687.762
18.300	736.038	18.638	758.337	18.262	584.380	18.427	689.393
19.173	706.980	18.401	692.118	18.665	746.204	18.630	777.556
18.414	714.556	18.337	781.909	18.419	624.310	18.931	745.513
18.567	714.335	18.717	742.387	18.371	764.756	18.283	707.894
18.274	639.565	18.594	654.030	18.824	721.674	18.646	734.546

$\log E$	X_{max}	$\log E$	X_{max}	$\log E$	X_{max}	$\log E$	X_{max}
18.828	755.033	19.283	795.443	18.541	663.778	18.602	808.043
18.473	851.142	18.629	852.381	18.280	681.340	19.109	833.287
18.246	699.226	18.514	724.842	18.294	760.833	18.291	722.092
18.406	729.208	19.220	820.363	18.787	718.970	18.799	788.112
18.760	669.649	19.221	680.460	19.340	732.317	18.270	831.607
18.337	610.817	18.917	771.777	18.324	677.298	18.520	641.615
18.514	711.236	18.478	744.141	18.526	795.421	18.472	702.511
18.357	729.045	18.472	704.706	18.442	721.899	18.369	664.364
18.474	767.329	19.203	836.854	18.805	763.029	18.655	740.697
18.300	747.675	18.540	726.959	19.481	735.846	18.697	730.512
18.561	844.667	18.351	691.785	18.408	730.569	18.504	722.747
18.533	729.293	18.919	725.649	18.779	778.285	18.673	745.651
18.320	697.933	18.430	698.477	18.731	753.795	18.767	813.469
19.068	769.670	18.261	690.530	18.755	720.523	18.731	743.398
18.234	801.027	18.541	822.568	18.442	784.994	18.630	709.728
19.269	897.228	18.401	805.910	19.482	776.406	19.085	806.699
18.297	670.773	18.272	687.334	18.250	763.227	18.658	812.586
19.783	848.890	18.382	787.044	18.209	671.652	18.370	683.348
18.540	689.284	18.645	670.040	18.409	684.371	18.881	878.454
19.111	710.119	18.342	657.040	18.447	676.703	18.242	724.336
18.370	825.682	18.286	715.066	18.277	778.697	18.399	794.838
18.202	807.174	18.506	692.847	18.335	680.743	18.510	717.132
18.224	668.266	18.238	769.510	18.787	808.115	18.228	672.785
18.435	696.788	19.091	689.630	18.312	702.664	18.358	727.436
18.716	743.458	18.702	720.330	19.106	767.206	18.581	697.741
18.477	711.800	18.728	698.695	19.086	962.026	18.877	716.960
18.796	725.071	18.250	782.663	19.278	774.847	19.749	846.301
18.289	725.540	18.418	727.295	18.562	713.527	18.500	708.816
18.406	721.632	18.471	681.051	19.015	761.150	18.614	719.630
18.371	692.184	18.256	737.653	18.398	733.467	18.623	669.570
18.618	759.518	18.251	649.934	18.208	615.111	18.445	782.848
18.818	797.716	18.899	765.588	19.316	778.411	18.455	721.495
19.277	797.356	18.326	645.048	18.294	701.294	18.837	735.713
19.385	751.011	18.859	817.389	18.274	643.055	18.727	732.231
18.604	683.464	18.758	709.004	18.854	881.776	18.574	694.734
18.492	695.729	18.219	666.131	18.594	749.719	18.394	743.546
18.532	751.351	18.376	762.943	18.504	739.357	18.598	671.795
18.509	764.872	19.082	756.723	18.526	775.315	18.922	813.532
18.598	761.523	19.216	788.012	19.231	758.288	18.269	810.471
18.299	707.482	19.203	646.075	18.790	728.642	18.581	921.871
18.427	694.711	18.237	655.206	19.509	852.078	18.295	701.522

$\log E$	X_{max}	$\log E$	X_{max}	$\log E$	X_{max}	$\log E$	X_{max}
19.039	810.159	18.544	723.558	18.386	669.261	18.555	682.107
18.242	684.357	18.300	753.965	19.134	820.252	18.402	717.853
19.292	769.391	18.683	725.244	18.937	837.440	18.844	730.953
18.663	750.483	18.619	825.412	18.939	726.963	18.364	700.630
18.595	705.560	18.921	699.911	18.266	767.022	18.365	721.570
18.571	724.446	18.300	751.766	18.803	752.595	18.301	795.547
18.313	746.352	18.415	702.440	18.446	757.668	18.563	719.706
18.698	798.992	18.381	782.600	18.347	728.449	18.264	685.471
18.349	670.686	19.140	871.831	18.357	704.835	18.216	733.472
18.439	757.008	19.394	779.394	18.375	785.447	18.649	751.444
18.378	792.487	18.732	943.822	19.040	709.010	18.686	645.451
18.529	689.188	18.528	825.950	18.910	796.880	19.018	752.206
18.840	752.026	18.893	746.710	18.455	792.143	18.205	920.476
19.035	708.950	18.718	644.918	18.427	697.607	18.331	662.624
19.123	776.413	18.388	664.332	18.938	876.153	18.926	728.635
18.652	871.865	18.486	694.817	18.488	747.961	18.496	721.224
18.216	747.618	19.032	787.849	18.464	666.447	18.637	880.035
18.634	708.025	18.333	679.524	18.818	688.361	18.688	685.177
18.232	660.110	19.630	786.279	18.478	657.137	18.329	662.722
18.426	719.643	18.458	708.290	19.086	782.884	19.064	772.483
18.385	654.708	18.317	796.281	18.447	710.033	18.496	757.028
18.690	713.088	18.783	783.839	18.279	679.439	18.254	745.055
18.583	730.871	18.760	711.167	18.268	784.285	18.820	769.060
19.020	946.226	18.691	745.021	18.484	850.617	18.365	647.356
18.857	835.194	18.251	672.955	18.489	712.631	18.471	711.788
18.509	722.492	18.660	899.526	18.619	862.556	18.429	623.551
19.071	763.669	18.845	755.031	19.043	799.220	18.321	714.731
18.235	726.392	18.229	710.731	18.676	691.293	18.868	721.872
18.207	757.211	18.413	732.252	18.340	730.397	19.264	748.378
19.182	725.632	18.739	611.805	18.206	738.379	18.746	737.715
18.294	735.927	19.009	766.889	19.390	815.477	19.023	810.627
19.017	786.269	19.617	772.862	18.764	764.193	18.846	840.714
18.449	678.614	18.667	898.531	18.354	712.445	18.925	857.585
18.982	755.372	18.818	777.122	18.664	714.550	18.568	795.672
18.693	890.812	18.456	668.738	19.217	780.201	18.321	726.341
18.786	855.224	18.574	721.169	18.485	730.597	18.692	716.890
18.744	818.558	18.526	911.004	18.515	852.508	18.422	697.069
18.525	752.921	18.443	680.165	18.911	784.021	18.330	855.460
18.985	742.990	18.500	778.745	18.684	867.809	19.177	690.252
18.290	691.745	18.642	685.892	18.666	763.646		

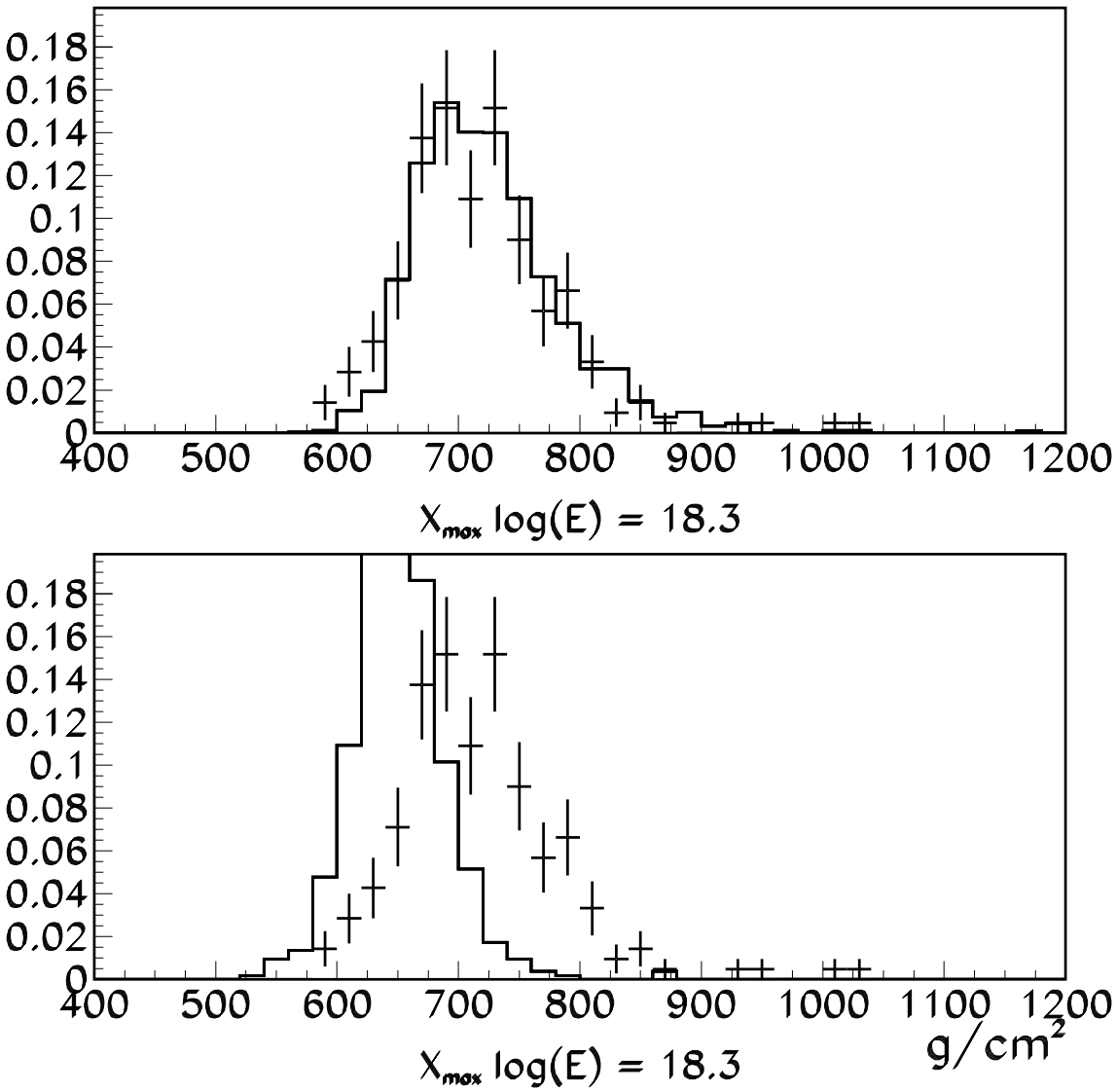

Figure 1: *Top:* X_{max} distribution, in the energy bin centered at $\log E(eV) = 18.3$, for HiRes stereo data (points), overlaid on the X_{max} distribution for Monte Carlo proton-induced showers (histogram) generated by the CORSIKA [2] package with the QGSJET-II [3] high-energy hadronic interaction model. All atmospheric, detector, and triggering effects have been applied to the Monte Carlo simulation. *Bottom:* X_{max} distribution for HiRes stereo data (points) overlaid on Monte Carlo iron-induced showers. All distributions have been normalized to unit area.

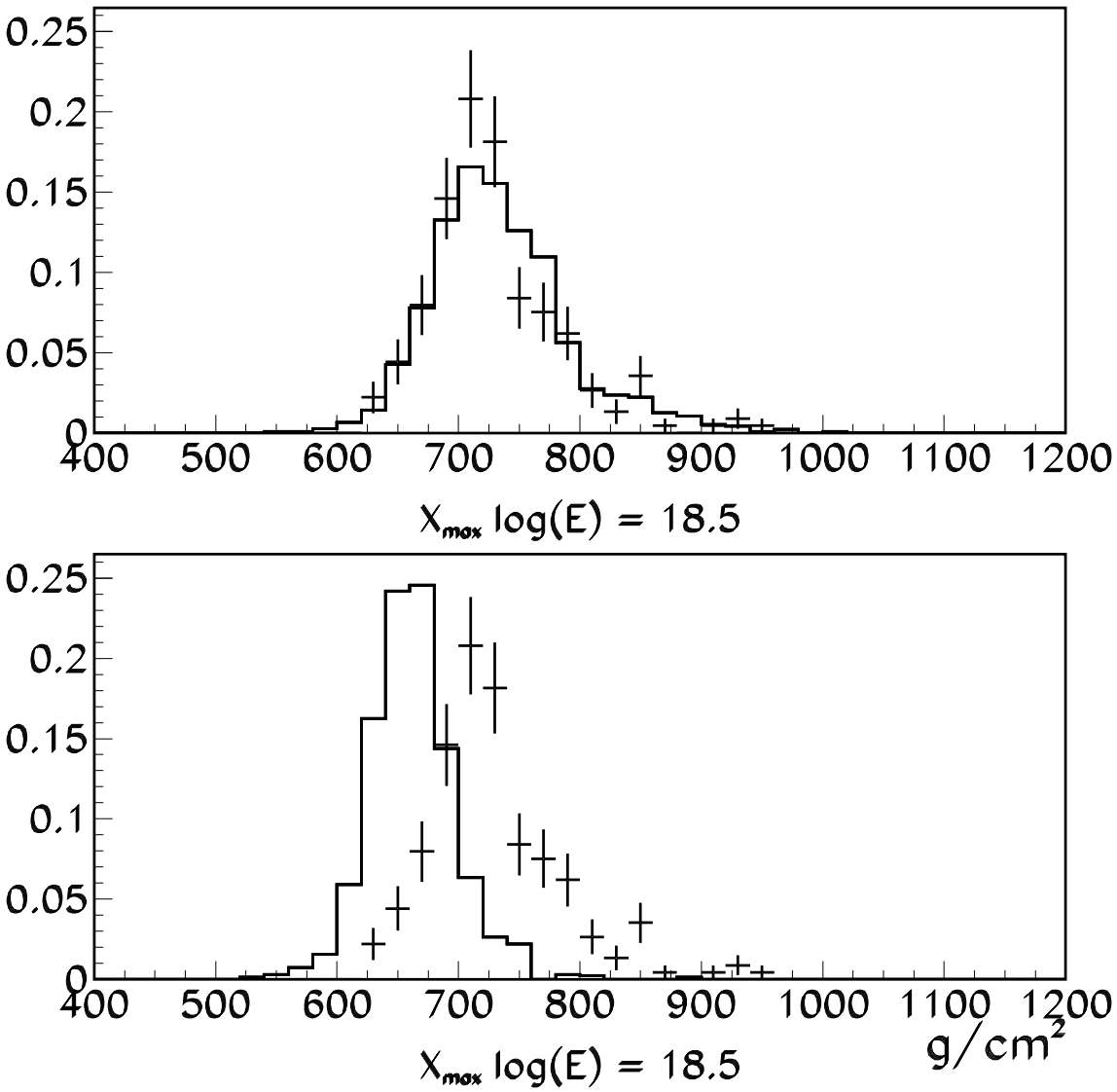

Figure 2: *Top:* X_{max} distribution, in the energy bin centered at $\log E(eV) = 18.5$, for HiRes stereo data (points), overlaid on the X_{max} distribution for Monte Carlo proton-induced showers (histogram) generated by the CORSIKA [2] package with the QGSJET-II [3] high-energy hadronic interaction model. All atmospheric, detector, and triggering effects have been applied to the Monte Carlo simulation. *Bottom:* X_{max} distribution for HiRes stereo data (points) overlaid on Monte Carlo iron-induced showers. All distributions have been normalized to unit area.

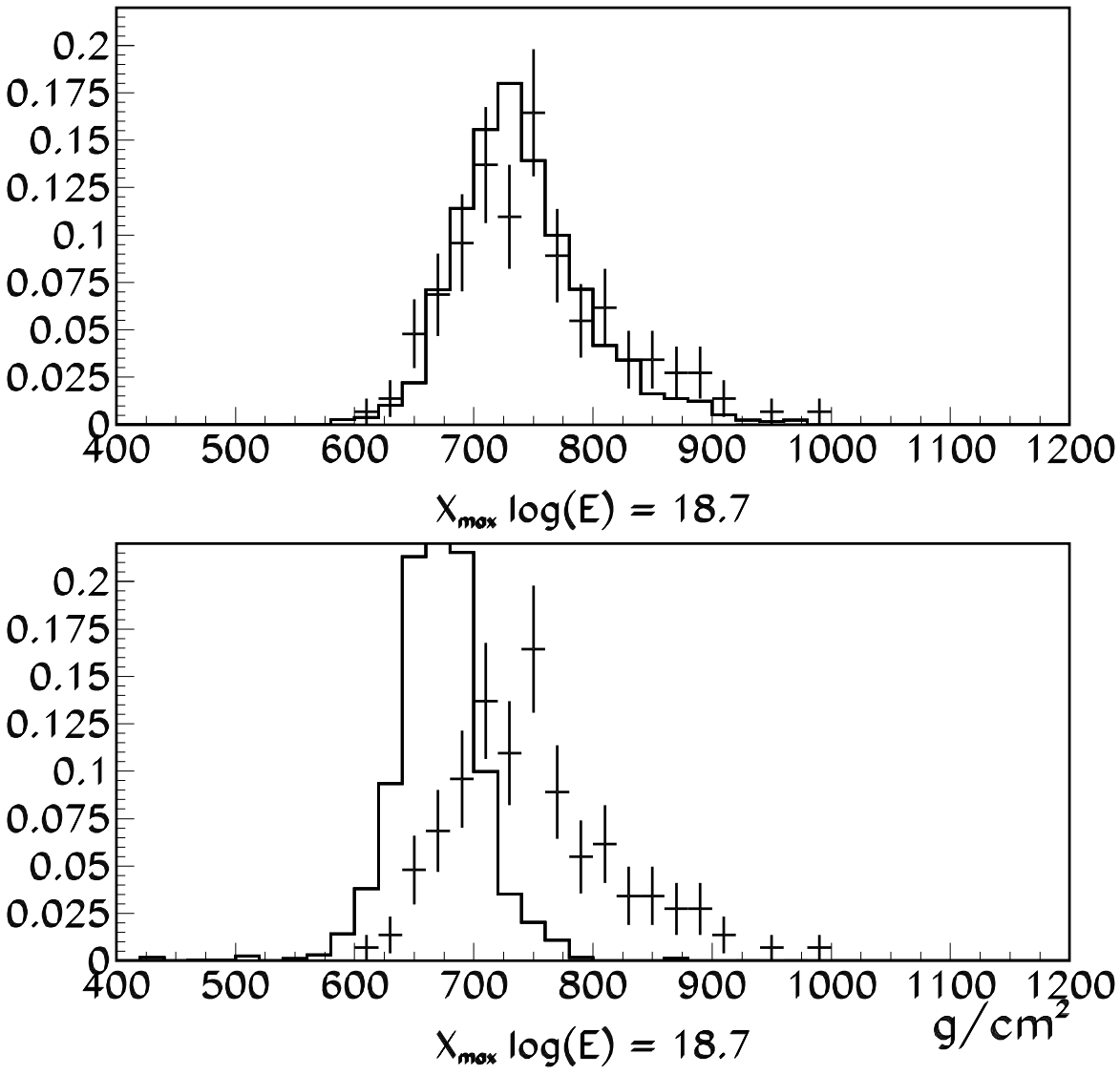

Figure 3: *Top:* X_{max} distribution, in the energy bin centered at $\log E(eV) = 18.7$, for HiRes stereo data (points), overlaid on the X_{max} distribution for Monte Carlo proton-induced showers (histogram) generated by the CORSIKA [2] package with the QGSJET-II [3] high-energy hadronic interaction model. All atmospheric, detector, and triggering effects have been applied to the Monte Carlo simulation. *Bottom:* X_{max} distribution for HiRes stereo data (points) overlaid on Monte Carlo iron-induced showers. All distributions have been normalized to unit area.

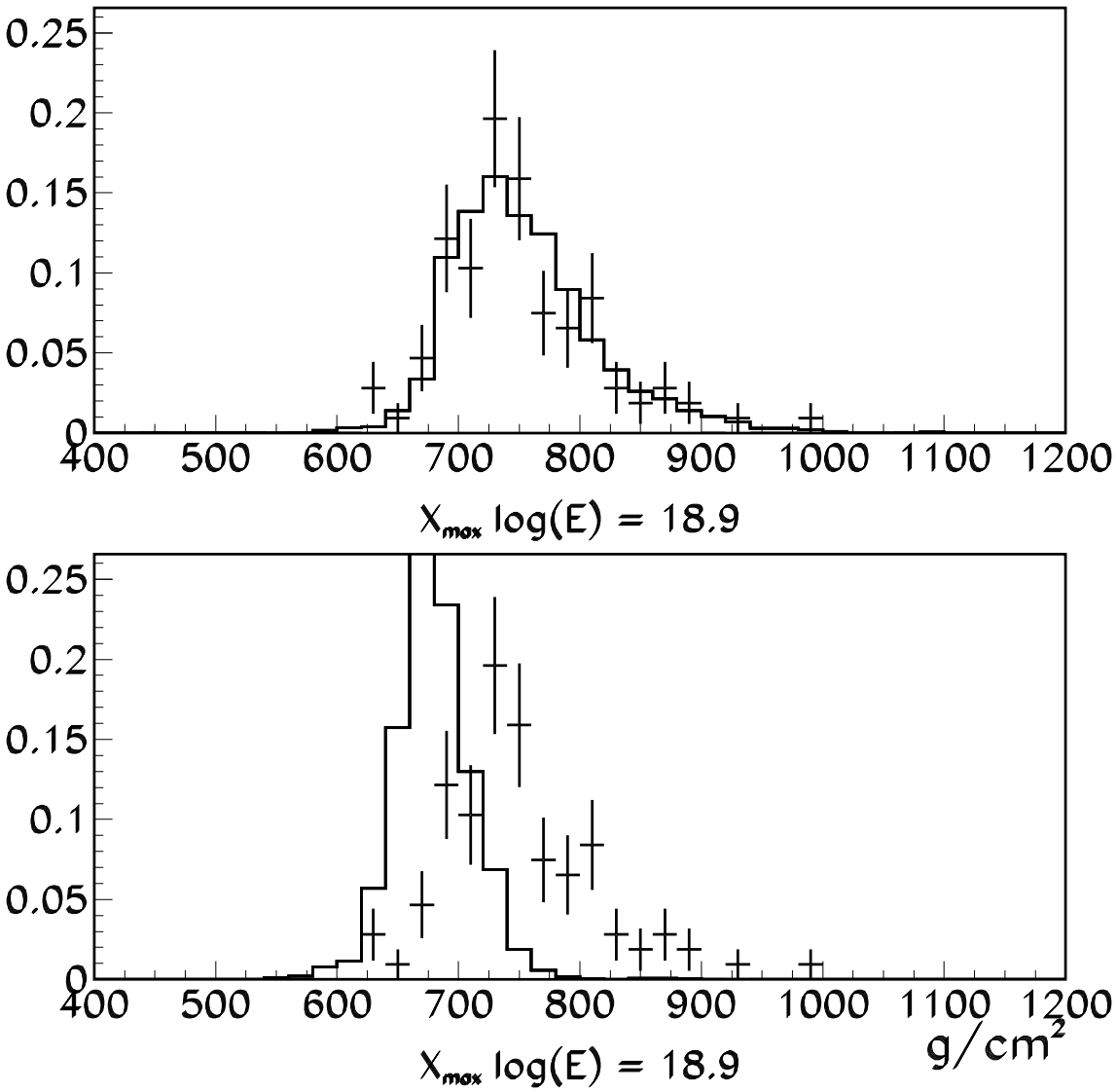

Figure 4: *Top:* X_{max} distribution, in the energy bin centered at $\log E(eV) = 18.9$, for HiRes stereo data (points), overlaid on the X_{max} distribution for Monte Carlo proton-induced showers (histogram) generated by the CORSIKA [2] package with the QGSJET-II [3] high-energy hadronic interaction model. All atmospheric, detector, and triggering effects have been applied to the Monte Carlo simulation. *Bottom:* X_{max} distribution for HiRes stereo data (points) overlaid on Monte Carlo iron-induced showers. All distributions have been normalized to unit area.

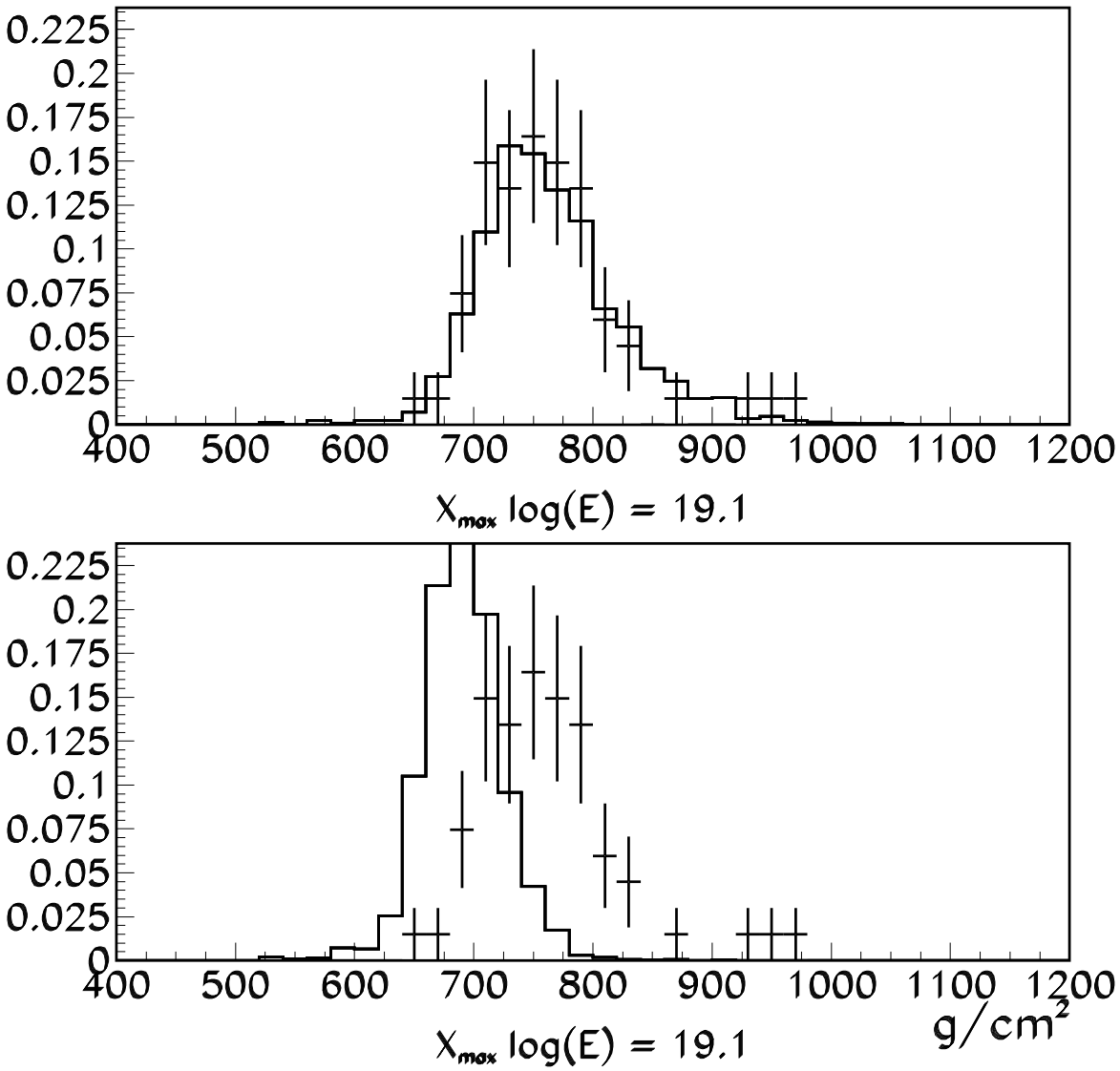

Figure 5: *Top:* X_{max} distribution, in the energy bin centered at $\log E(eV) = 19.1$, for HiRes stereo data (points), overlaid on the X_{max} distribution for Monte Carlo proton-induced showers (histogram) generated by the CORSIKA [2] package with the QGSJET-II [3] high-energy hadronic interaction model. All atmospheric, detector, and triggering effects have been applied to the Monte Carlo simulation. *Bottom:* X_{max} distribution for HiRes stereo data (points) overlaid on Monte Carlo iron-induced showers. All distributions have been normalized to unit area.

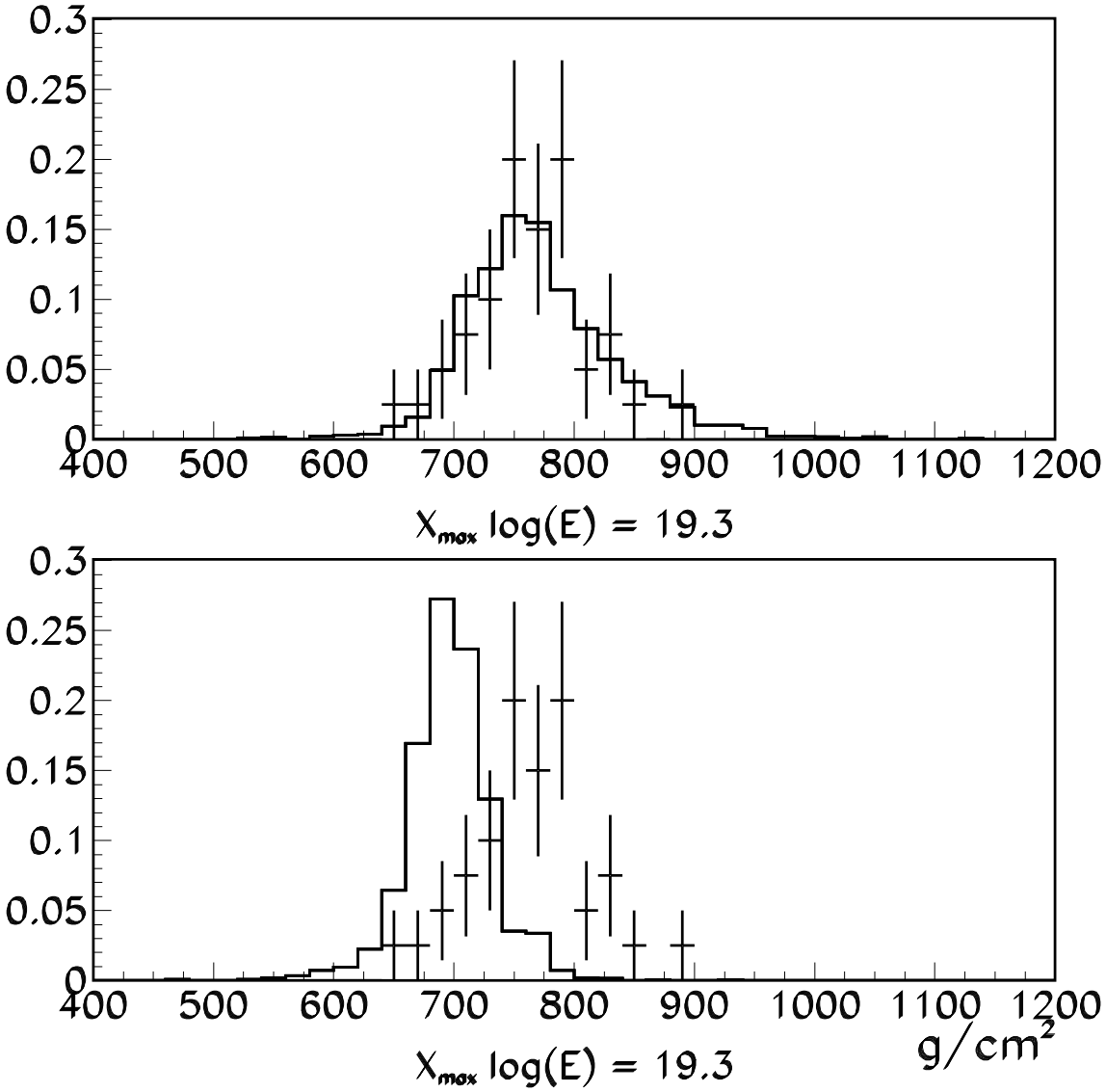

Figure 6: *Top:* X_{max} distribution, in the energy bin centered at $\log E(eV) = 19.3$, for HiRes stereo data (points), overlaid on the X_{max} distribution for Monte Carlo proton-induced showers (histogram) generated by the CORSIKA [2] package with the QGSJET-II [3] high-energy hadronic interaction model. All atmospheric, detector, and triggering effects have been applied to the Monte Carlo simulation. *Bottom:* X_{max} distribution for HiRes stereo data (points) overlaid on Monte Carlo iron-induced showers. All distributions have been normalized to unit area.

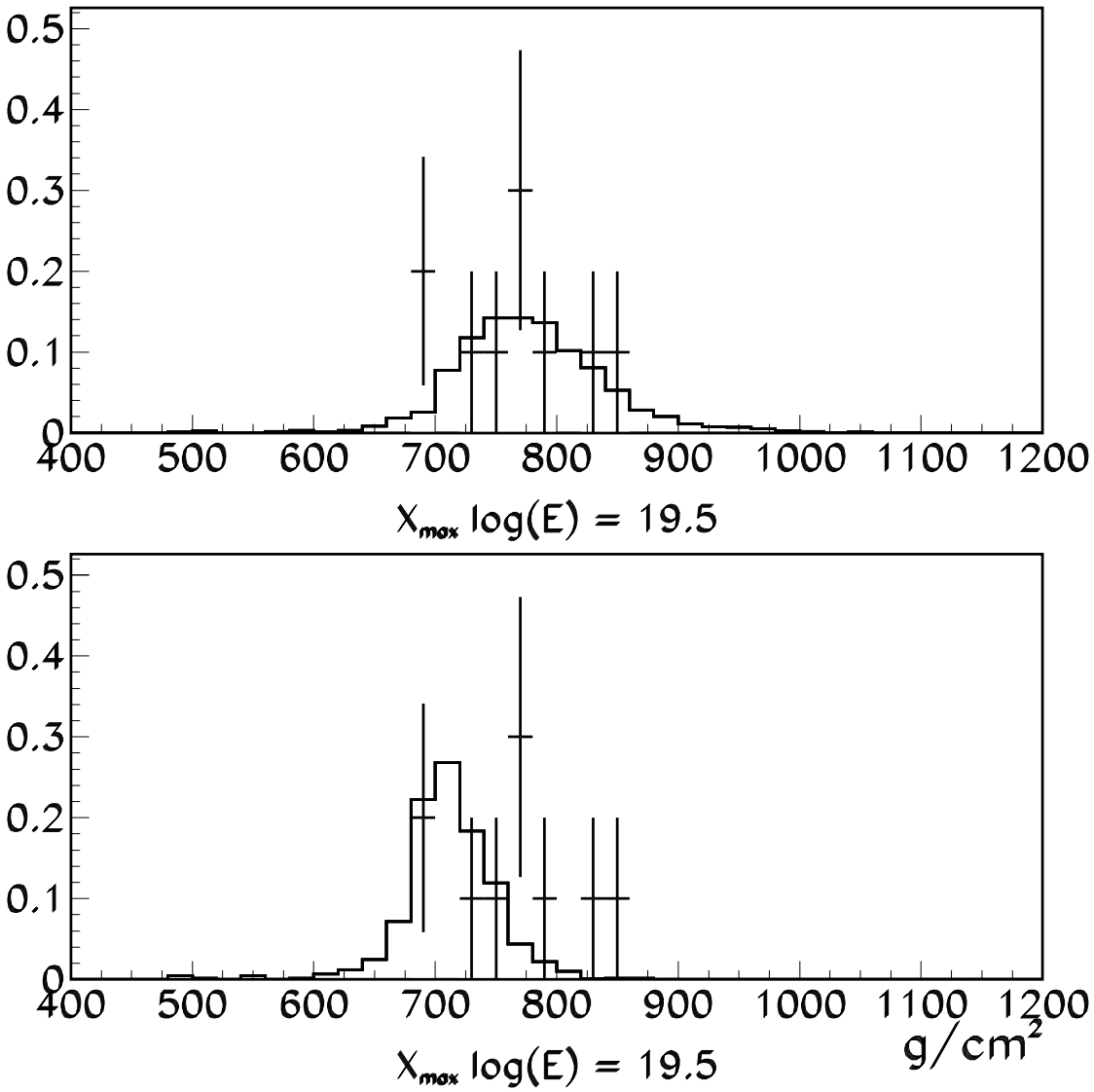

Figure 7: *Top:* X_{max} distribution, in the energy bin centered at $\log E(eV) = 19.5$, for HiRes stereo data (points), overlaid on the X_{max} distribution for Monte Carlo proton-induced showers (histogram) generated by the CORSIKA [2] package with the QGSJET-II [3] high-energy hadronic interaction model. All atmospheric, detector, and triggering effects have been applied to the Monte Carlo simulation. *Bottom:* X_{max} distribution for HiRes stereo data (points) overlaid on Monte Carlo iron-induced showers. All distributions have been normalized to unit area.

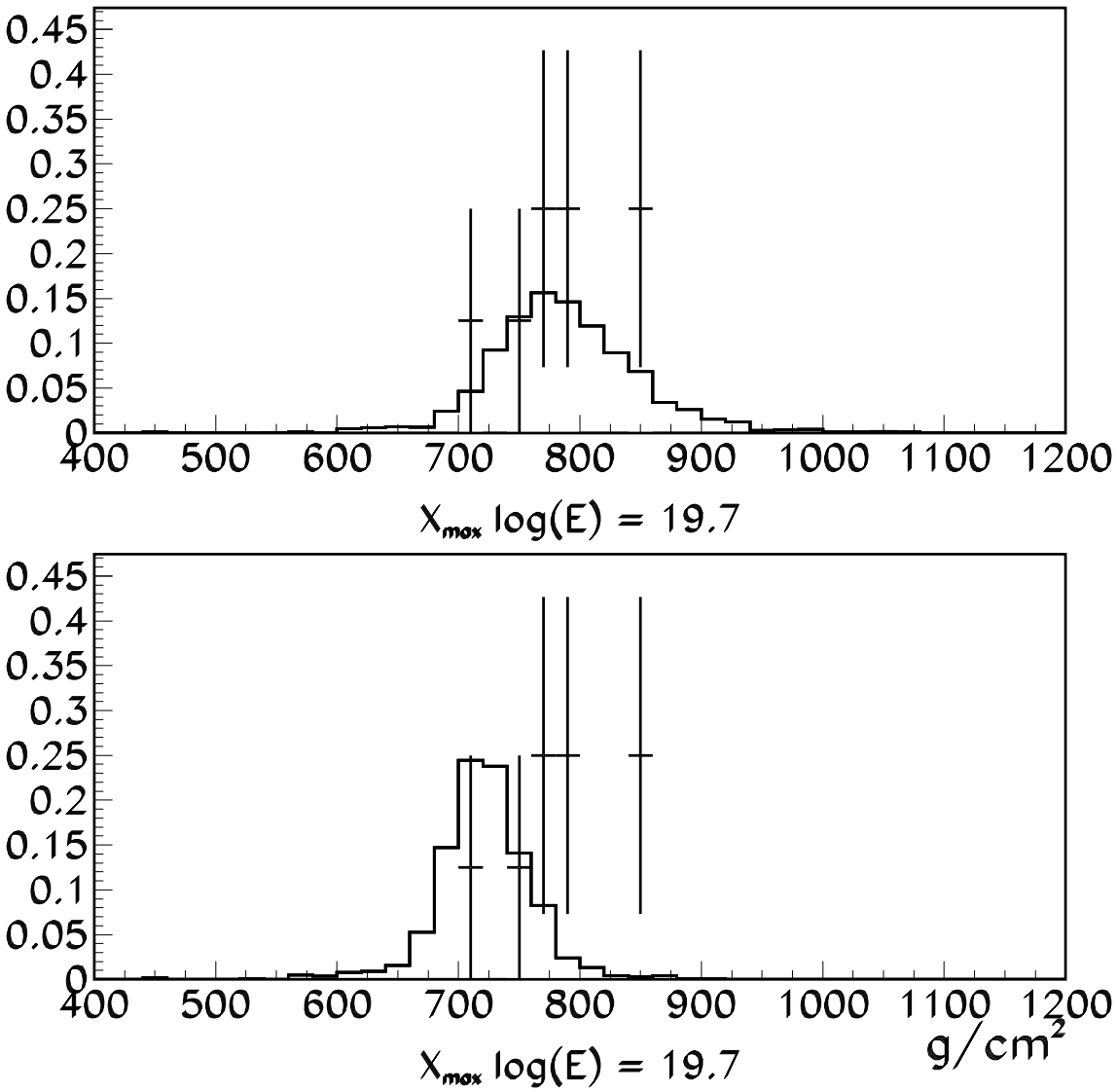

Figure 8: *Top:* X_{max} distribution, in the energy bin centered at $\log E(eV) = 19.7$, for HiRes stereo data (points), overlaid on the X_{max} distribution for Monte Carlo proton-induced showers (histogram) generated by the CORSIKA [2] package with the QGSJET-II [3] high-energy hadronic interaction model. All atmospheric, detector, and triggering effects have been applied to the Monte Carlo simulation. *Bottom:* X_{max} distribution for HiRes stereo data (points) overlaid on Monte Carlo iron-induced showers. All distributions have been normalized to unit area.

Bibliography

[1] R.U. Abbasi *et al.*, Phys. Rev. Lett. **104** 161101 (2010).

[2] D. Heck *et al.*, Forschungzentrum Karlsruhe Tech. Rep. FZKA 6019 (1998).

[3] S. Ostapchenko, Nucl. Phys. B, Proc. Suppl. **151** 143 (2006).