Zufallszahlen und MonteCarlo Methoden in der Teilchenphysik

LMU Bachelor Kurs
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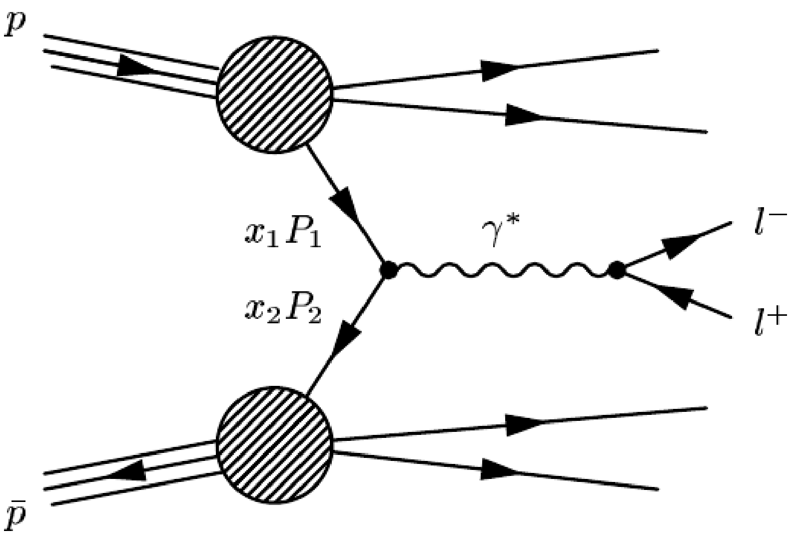
- Zufallszahlen erzeugen
  - Python notebook im github Verzeichnis
- Teilchenphysik
  - MC Ereignis Generatoren
  - Detektorsimulation
- Zusammenfassung

Material aus Slides von A. Mann (LMU Kurs) und T.Sjöstrand (Desy Training)

Monte Carlo Generatoren

Einfache Reaktion bei LHC:

pp → Z/y → e+e- + Jets



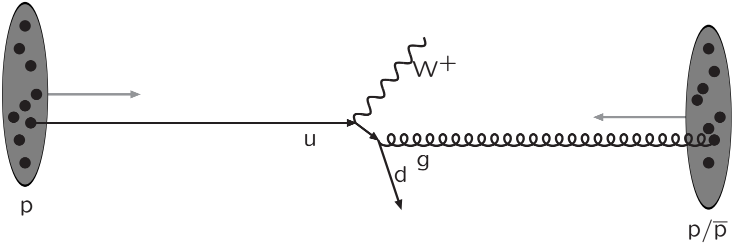
- Ereignis-Generatoren werden benutzt, um Teilchenreaktionen zu simulieren
  - z. B. Pythia, Herwig++, Sherpa, Alpgen, PowHeg, . . .
  - Ausgabe: “Kollisionsereignisse”, d. h. für jedes Ereignis wird eine Liste von Teilchen generiert zusammen mit den Vierervektoren, etc.

The structure of an event – 1

Warning: schematic only, everything simplified, nothing to scale, . . .

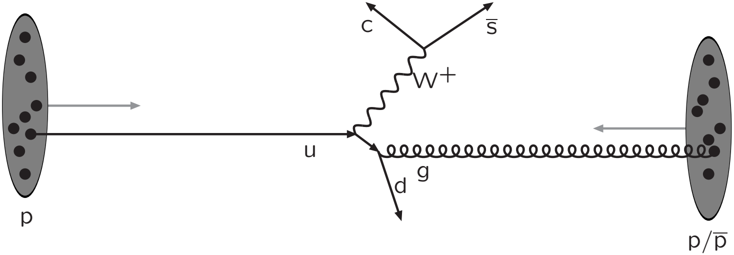
Incoming beams: parton densities

The structure of an event – 2



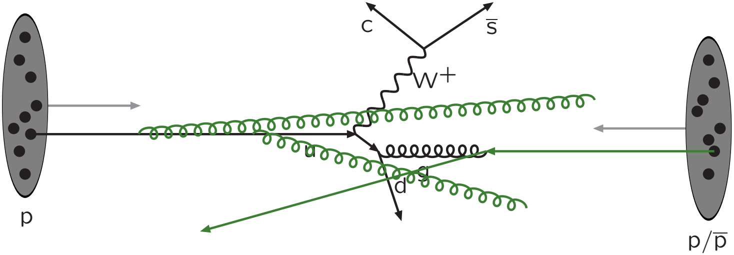
Hard subprocess: described by matrix elements

The structure of an event – 3



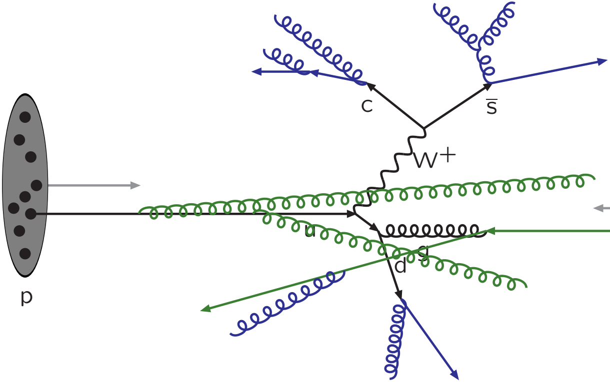
Resonance decays: correlated with hard subprocess

The structure of an event – 4



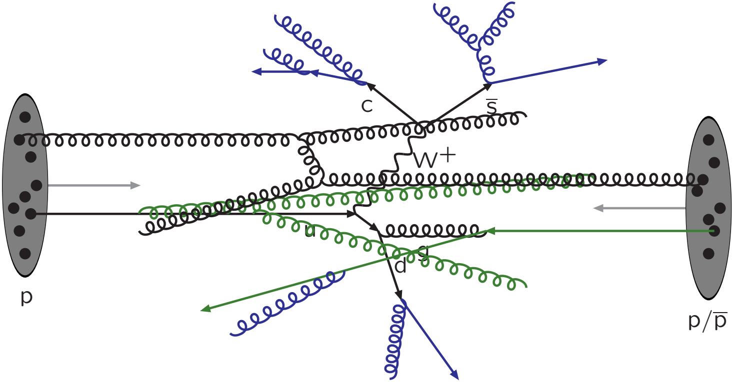
Initial-state radiation: spacelike parton showers

The structure of an event – 5



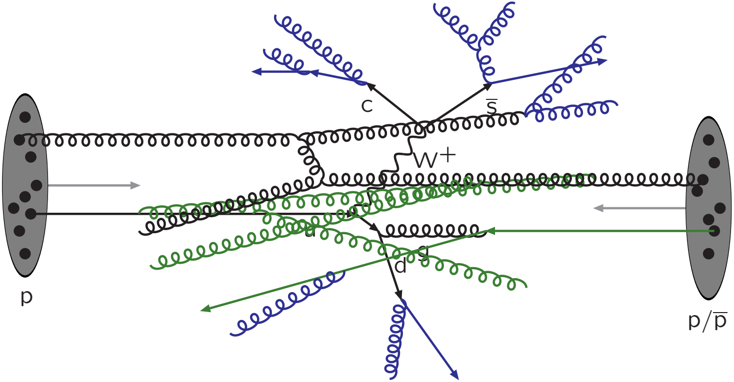
Final-state radiation: timelike parton showers

The structure of an event – 6



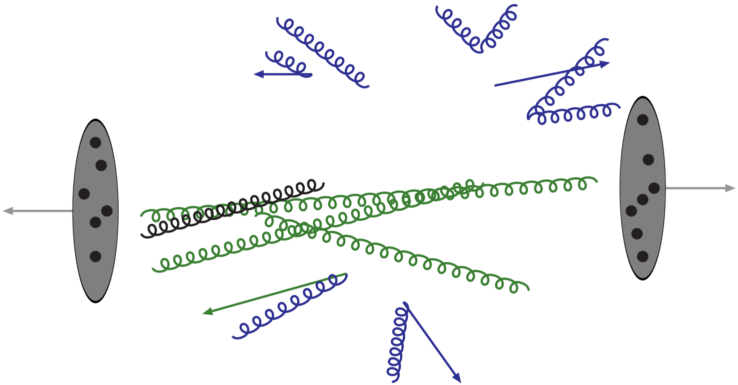
Multiple parton–parton interactions . . .

The structure of an event – 7

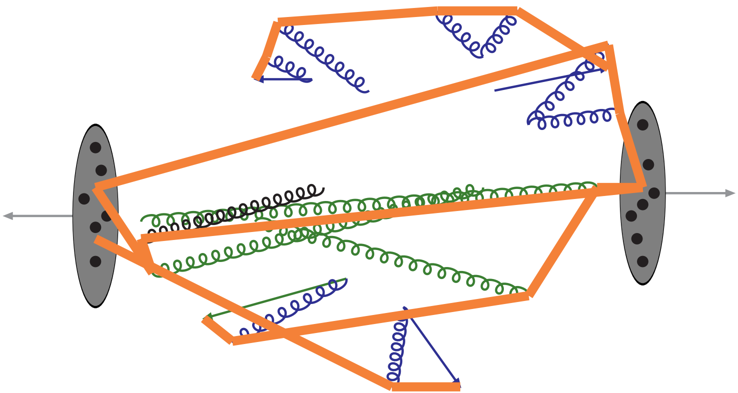


. . . with its initial- and final-state radiation

The structure of an event – 8



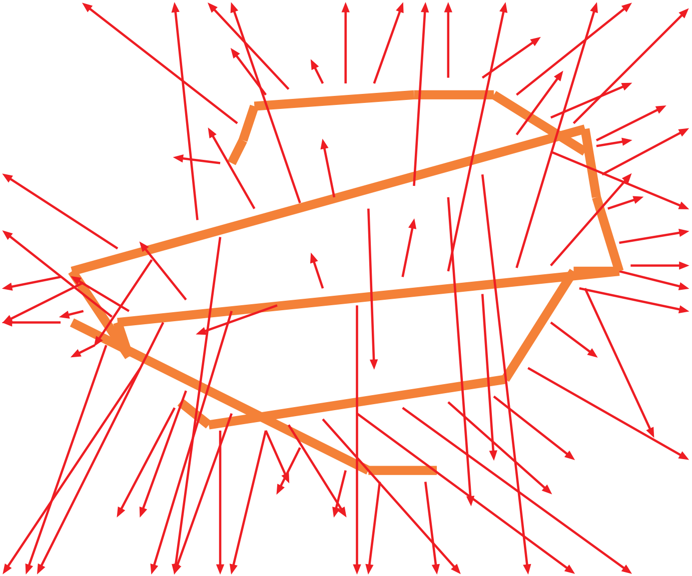
Beam remnants and other outgoing partons



Everything is connected by colour confinement strings

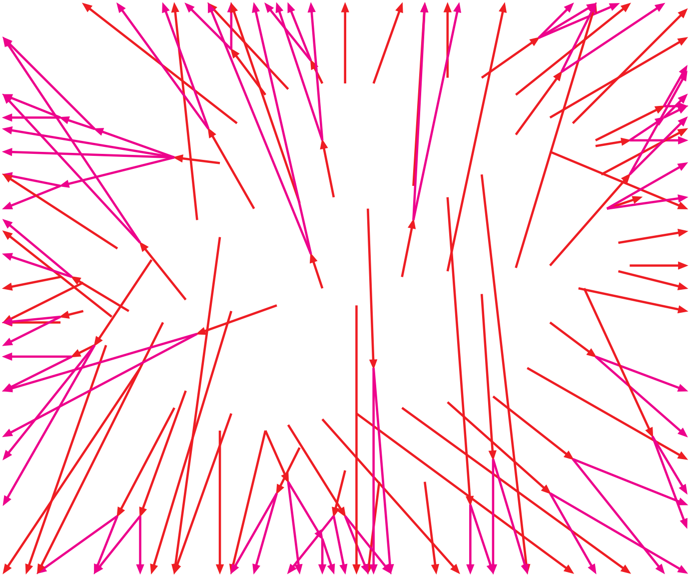
Recall! Not to scale: strings are of hadronic widths

The structure of an event – 10



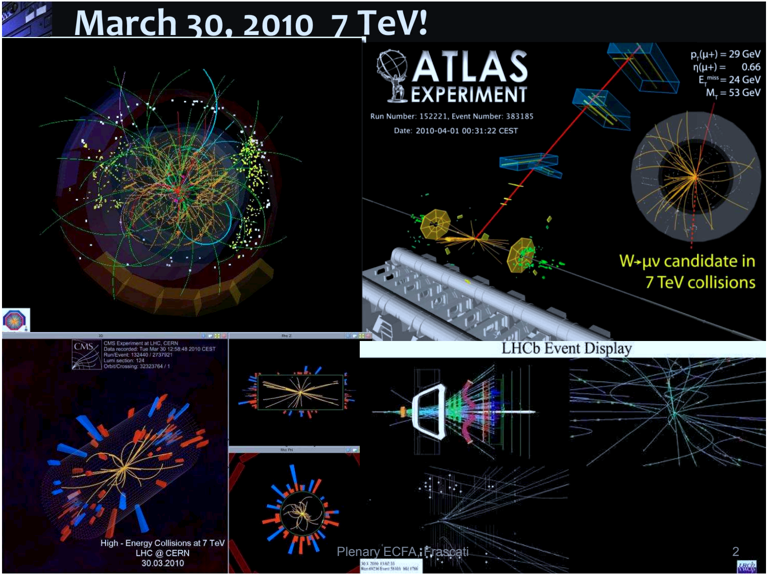
The strings fragment to produce primary hadrons

The structure of an event – 11



Many hadrons are unstable and decay further

The structure of an event – 12



These are the particles that hit the detector

MC Gen - Beispiel

```
--------  LHA event information and listing  -----------------------------------------------------------

   process =         1     weight =    1.8982e-05     scale =    3.3269e+02 (GeV)
                          alpha_em =    7.8165e-03    alpha_strong =    1.0700e-01

   Participating Particles
   no          id stat      mothers       colours       p_x         p_y         p_z          e           m        tau
    1           2   -1      0      0    501      0     0.000       0.000    2832.442    2832.442       0.000    0.000
    2          -1   -1      0      0      0    501     0.000       0.000     -60.411      60.411       0.000    0.000
    3     1000024    1      1      2      0      0    21.435     218.452     526.439     622.751     250.000    0.000
    4     1000023    1      1      2      0      0   -21.435    -218.452    2245.592    2270.102     250.000    0.000

--------  End LHA event information and listing  -------------------------------------------------------
```

$$u + \bar{d} \rightarrow \widetilde{\chi}_1^+ + \widetilde{\chi}_2^0$$

QUARKS	
d	1
u	2
s	3

$\widetilde{\chi}_1^0$	1000022^b
$\widetilde{\chi}_2^0$	1000023^b
$\widetilde{\chi}_1^+$	1000024^b
$\widetilde{\chi}_3^0$	1000025^b

(Liste der “PDG ID”s = Durchnummerierung aller Elementarteilchen)

vollständige Beschreibung des Kollisionsereignisses entsprechend umfangreich:

-------- PYTHIA Event Listing (complete event) ---

no	id	name	status	mothers		daughters		colours		p_x	p_y	p_z	e	m
0	90	(system)	-11	0	0	0	0	0	0	0.000	0.000	0.000	8000.000	8000.000
1	2212	(p+)	-12	0	0	62	0	0	0	0.000	0.000	4000.000	4000.000	0.938
2	2212	(p+)	-12	0	0	63	0	0	0	0.000	0.000	-4000.000	4000.000	0.938
3	2	(u)	-21	7	7	5	6	501	0	0.000	0.000	2832.442	2832.442	0.000
4	-1	(dbar)	-21	8	0	5	6	0	501	0.000	0.000	-60.411	60.411	0.000
5	1000024	(~chi_1+)	-22	3	4	9	9	0	0	21.435	218.452	526.439	622.751	250.000
6	1000023	(~chi_20)	-22	3	4	10	10	0	0	-21.435	-218.452	2245.592	2270.102	250.000
7	2	(u)	-42	41	41	3	3	501	0	-0.000	0.000	2832.442	2832.442	0.000
8	-1	(dbar)	-41	40	40	11	4	0	503	0.000	-0.000	-188.076	188.076	0.000
9	1000024	(~chi_1+)	-44	5	5	43	43	0	0	25.711	213.290	515.821	612.148	250.000
10	1000023	(~chi_20)	-44	6	6	44	44	0	0	-20.347	-219.766	2256.062	2280.576	250.000
11	21	(g)	-43	8	0	38	39	501	503	-5.364	6.476	-127.517	127.794	0.000
12	21	(g)	-31	19	19	14	15	505	504	0.000	0.000	20.177	20.177	0.000
13	21	(g)	-31	20	0	14	15	504	506	0.000	0.000	-9.805	9.805	0.000
14	21	(g)	-33	12	13	16	17	507	506	-3.818	1.424	-9.162	10.028	0.000
15	21	(g)	-33	12	13	18	18	505	507	3.818	-1.424	19.534	19.955	0.000
16	21	(g)	-51	14	0	21	21	508	506	-1.731	3.062	1.424	3.795	0.000
17	21	(g)	-51	14	0	23	23	507	508	-1.632	-1.807	-8.259	8.610	0.000
18	21	(g)	-52	15	15	22	22	505	507	3.363	-1.255	17.207	17.577	0.000
19	21	(g)	-42	25	25	12	12	505	504	-0.000	0.000	20.177	20.177	0.000
20	21	(g)	-41	26	0	24	13	509	506	0.000	-0.000	-41.014	41.014	0.000
21	21	(g)	-44	16	16	27	27	508	506	-1.437	3.004	1.118	3.513	0.000
22	21	(g)	-44	18	18	28	28	505	507	3.409	-1.264	17.475	17.849	0.000
23	21	(g)	-44	17	17	29	29	507	508	0.461	-2.217	-8.370	8.671	0.000
24	21	(g)	-43	20	0	30	30	509	504	-2.434	0.476	-31.059	31.158	0.000
25	21	(g)	-42	51	0	19	19	505	504	0.000	-0.000	20.177	20.177	0.000
26	2	(u)	-41	52	52	31	20	509	0	-0.000	0.000	-646.205	646.205	0.000
27	21	(g)	-44	21	21	37	37	508	506	-1.451	3.037	1.165	3.562	0.000
28	21	(g)	-44	22	22	34	34	505	507	3.407	-1.259	17.429	17.804	0.000
29	21	(g)	-44	23	23	32	33	507	508	0.362	-1.985	-8.405	8.644	0.000
30	21	(g)	-44	24	24	56	56	509	504	-2.795	1.322	-31.046	31.200	0.000
31	2	(u)	-43	26	0	57	57	506	0	0.476	-1.115	-605.171	605.172	0.330
32	21	(g)	-51	29	0	35	36	510	508	1.386	-1.799	-7.906	8.226	0.000
33	21	(g)	-51	29	0	50	50	507	510	-0.922	-0.223	0.020	0.949	0.000
34	21	(g)	-52	28	28	48	49	505	507	3.306	-1.221	16.910	17.273	0.000
35	21	(g)	-51	32	0	55	55	510	511	0.422	-1.705	-7.406	7.611	0.000
36	21	(g)	-51	32	0	59	59	511	508	0.832	0.181	-0.394	0.938	0.000
37	21	(g)	-52	27	27	53	53	508	506	-1.319	2.761	1.059	3.238	0.000
38	21	(g)	-51	11	0	45	45	501	512	-1.091	0.455	-15.992	16.035	0.000
39	21	(g)	-51	11	0	46	46	512	503	-4.273	6.022	-116.692	116.926	0.000
40	-1	(dbar)	-53	42	0	8	8	0	503	-0.000	0.000	-193.243	193.243	0.000
41	2	(u)	-42	62	62	7	7	501	0	-0.000	0.000	2832.442	2832.442	0.000
42	-1	(dbar)	-41	63	63	47	40	0	513	0.000	-0.000	-217.113	217.113	0.000
43	1000024	(~chi_1+)	-44	9	9	64	64	0	0	25.812	213.204	515.658	611.985	250.000
44	1000023	(~chi_20)	-44	10	10	65	65	0	0	-20.321	-219.788	2256.233	2280.747	250.000
45	21	(g)	-44	38	38	66	66	501	512	-1.057	0.426	-15.993	16.034	0.000
46	21	(g)	-44	39	39	67	67	512	503	-4.027	5.814	-116.702	116.916	0.000
47	21	(g)	-43	42	0	68	68	503	513	-0.408	0.343	-23.868	23.874	0.000
48	21	(g)	-51	34	0	54	54	505	514	3.119	-1.352	16.843	17.183	0.000
49	21	(g)	-51	34	0	60	60	514	507	0.109	0.112	0.069	0.171	0.000
50	21	(g)	-52	33	33	58	58	507	510	-0.844	-0.204	0.018	0.869	0.000
51	21	(g)	-41	69	69	61	25	505	515	0.000	0.000	22.541	22.541	0.000
52	2	(u)	-42	70	70	26	26	509	0	0.000	0.000	-646.205	646.205	0.000
53	21	(g)	-44	37	37	71	71	508	506	-1.310	2.800	1.037	3.261	0.000
54	21	(g)	-44	48	48	72	72	505	514	3.189	-1.040	16.848	17.179	0.000
55	21	(g)	-44	35	35	73	73	510	511	0.423	-1.703	-7.391	7.596	0.000
56	21	(g)	-44	30	30	74	74	509	504	-2.795	1.324	-31.052	31.206	0.000
57	2	(u)	-44	31	31	75	75	506	0	0.476	-1.115	-605.145	605.147	0.330
58	21	(g)	-44	50	50	76	76	507	510	-0.842	-0.196	0.022	0.865	0.000
59	21	(g)	-44	36	36	77	77	511	508	0.833	0.186	-0.398	0.942	0.000
60	21	(g)	-44	49	49	78	78	514	507	0.110	0.114	0.067	0.172	0.000
61	21	(g)	-43	51	0	79	79	504	515	-0.084	-0.369	2.348	2.378	0.000
62	2	(u)	-61	1	0	41	41	504	0	-0.592	0.805	2832.440	2832.440	0.000
63	-1	(dbar)	-61	2	0	42	42	0	504	0.466	-1.387	-217.111	217.116	0.000
64	1000024	(~chi_1+)	-62	43	43	83	84	0	0	25.798	213.056	514.977	611.359	250.000
65	1000023	(~chi_20)	-62	44	44	102	103	0	0	-20.769	-219.221	2256.941	2281.397	250.000
66	21	(g)	-62	45	45	129	129	501	512	-1.022	0.324	-15.996	16.031	0.000
67	21	(g)	-62	46	46	138	138	512	503	-3.776	5.068	-116.725	116.896	0.000
68	21	(g)	-62	47	47	137	137	503	504	-0.357	0.191	-23.869	23.872	0.000

vollständige Beschreibung des Kollisionsereignisses entsprechend umfangreich:

150	111	(pi0)	-83	129	138	241	242	0	0	0.016	-0.348	-1.427	1.475	0.135
151	-211	pi-	83	129	138	0	0	0	0	-0.713	0.092	-8.936	8.966	0.140
152	111	(pi0)	-83	129	138	243	244	0	0	-0.730	0.018	-6.471	6.514	0.135
153	2212	p+	83	129	138	0	0	0	0	0.146	-0.262	-3.643	3.774	0.938
154	-2212	pbar-	83	129	138	0	0	0	0	0.002	-0.378	-3.757	3.890	0.938
155	211	pi+	84	129	138	0	0	0	0	0.096	0.236	0.254	0.386	0.140
156	-211	pi-	84	129	138	0	0	0	0	0.022	0.034	-0.651	0.667	0.140
157	111	(pi0)	-84	129	138	245	246	0	0	0.473	0.554	-0.572	0.936	0.135
158	111	(pi0)	-84	129	138	247	248	0	0	0.076	0.007	0.592	0.612	0.135
159	211	pi+	84	129	138	0	0	0	0	-0.945	0.649	-0.623	1.312	0.140
160	-211	pi-	84	129	138	0	0	0	0	0.400	-0.003	0.444	0.613	0.140
161	111	(pi0)	-84	129	138	249	250	0	0	-0.544	0.692	0.279	0.934	0.135
162	221	(eta)	-84	129	138	251	253	0	0	0.132	0.622	0.674	1.077	0.548
163	213	(rho+)	-84	129	138	205	206	0	0	-0.021	-0.167	1.093	1.321	0.723
164	221	(eta)	-84	129	138	254	256	0	0	0.821	-0.503	3.688	3.851	0.548
165	111	(pi0)	-84	129	138	257	258	0	0	0.302	0.326	0.641	0.792	0.135
166	-211	pi-	84	129	138	0	0	0	0	0.093	-0.494	4.701	4.730	0.140
167	111	(pi0)	-84	129	138	259	260	0	0	1.988	-0.556	4.496	4.949	0.135
168	211	pi+	84	129	138	0	0	0	0	-0.301	0.076	0.851	0.916	0.140
169	-211	pi-	84	129	138	0	0	0	0	-0.097	-0.038	0.198	0.264	0.140
170	213	(rho+)	-84	129	138	207	208	0	0	0.494	0.095	2.126	2.313	0.762
171	223	(omega)	-84	129	138	261	263	0	0	-0.074	-0.733	-0.931	1.411	0.762
172	2	(u)	-71	75	75	174	187	506	0	1.129	0.455	-605.178	605.179	0.330
173	2103	(ud_1)	-71	80	80	174	187	0	506	-0.672	-0.594	1145.015	1145.016	0.771
174	213	(rho+)	-83	172	173	209	210	0	0	0.819	0.624	-324.280	324.283	0.827
175	111	(pi0)	-83	172	173	264	265	0	0	0.143	-0.327	-166.885	166.885	0.135
176	111	(pi0)	-83	172	173	266	267	0	0	0.638	-0.266	-95.690	95.693	0.135
177	111	(pi0)	-83	172	173	268	269	0	0	-0.227	0.597	-10.469	10.489	0.135
178	-211	pi-	84	172	173	0	0	0	0	-0.175	-0.348	-0.982	1.066	0.140
179	213	(rho+)	-84	172	173	211	212	0	0	0.031	-0.002	-3.682	3.750	0.710
180	-213	(rho-)	-84	172	173	213	214	0	0	-0.506	0.187	-2.946	3.097	0.786
181	213	(rho+)	-84	172	173	215	216	0	0	0.474	-0.011	3.125	3.235	0.691
182	111	(pi0)	-84	172	173	270	271	0	0	-0.054	-0.655	9.355	9.379	0.135
183	-211	pi-	84	172	173	0	0	0	0	0.044	0.546	11.291	11.305	0.140
184	211	pi+	84	172	173	0	0	0	0	-0.146	-0.116	3.783	3.790	0.140
185	-211	pi-	84	172	173	0	0	0	0	0.136	0.647	60.209	60.212	0.140
186	2224	(Delta++)	-84	172	173	217	218	0	0	-0.253	-1.201	595.259	595.261	1.141
187	-211	pi-	84	172	173	0	0	0	0	-0.467	0.186	461.750	461.750	0.140
188	211	pi+	91	118	0	0	0	0	0	15.695	41.859	132.836	140.157	0.140
189	111	(pi0)	-91	118	0	272	273	0	0	38.554	99.810	317.062	334.629	0.135
190	-211	pi-	91	119	0	0	0	0	0	0.098	0.326	1.809	1.846	0.140
191	111	(pi0)	-91	119	0	274	275	0	0	1.792	4.868	15.271	16.129	0.135
192	2212	p+	91	122	0	0	0	0	0	0.013	0.394	2.019	2.261	0.938
193	211	pi+	91	122	0	0	0	0	0	0.231	0.216	0.862	0.929	0.140
194	211	pi+	91	123	0	0	0	0	0	0.328	1.484	4.553	4.802	0.140
195	-211	pi-	91	123	0	0	0	0	0	0.252	0.085	0.991	1.036	0.140
196	310	K_S0	91	125	125	0	0	0	0	0.282	-0.250	0.413	0.749	0.498

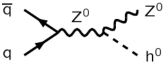
vollständige Beschreibung des Kollisionsereignisses entsprechend umfangreich:

264	22	gamma	91	175	0	0	0	0	0	0.004	-0.108	-30.867	30.868	0.000
265	22	gamma	91	175	0	0	0	0	0	0.139	-0.219	-136.017	136.018	0.000
266	22	gamma	91	176	0	0	0	0	0	0.247	-0.106	-46.600	46.601	0.000
267	22	gamma	91	176	0	0	0	0	0	0.391	-0.160	-49.090	49.092	0.000
268	22	gamma	91	177	0	0	0	0	0	-0.080	0.072	-1.807	1.810	0.000
269	22	gamma	91	177	0	0	0	0	0	-0.147	0.525	-8.662	8.679	0.000
270	22	gamma	91	182	0	0	0	0	0	-0.067	-0.169	2.172	2.179	0.000
271	22	gamma	91	182	0	0	0	0	0	0.013	-0.486	7.184	7.200	0.000
272	22	gamma	91	189	0	0	0	0	0	31.604	81.710	259.501	273.891	0.000
273	22	gamma	91	189	0	0	0	0	0	6.950	18.099	57.561	60.738	0.000
274	22	gamma	91	191	0	0	0	0	0	1.298	3.466	11.072	11.674	0.000
275	22	gamma	91	191	0	0	0	0	0	0.493	1.402	4.199	4.454	0.000
276	22	gamma	91	200	0	0	0	0	0	0.200	0.244	-1.796	1.824	0.000
277	22	gamma	91	200	0	0	0	0	0	0.104	0.016	-0.727	0.734	0.000
278	22	gamma	91	204	0	0	0	0	0	-0.185	0.244	-5.078	5.088	0.000
279	22	gamma	91	204	0	0	0	0	0	-0.216	0.552	-11.493	11.508	0.000
280	22	gamma	91	206	0	0	0	0	0	-0.075	0.141	0.469	0.496	0.000
281	22	gamma	91	206	0	0	0	0	0	-0.036	0.096	0.090	0.136	0.000
282	22	gamma	91	208	0	0	0	0	0	0.146	0.024	0.439	0.463	0.000
283	22	gamma	91	208	0	0	0	0	0	0.499	0.106	0.888	1.025	0.000
284	22	gamma	91	210	0	0	0	0	0	0.293	0.232	-166.316	166.317	0.000
285	22	gamma	91	210	0	0	0	0	0	0.220	0.286	-122.073	122.074	0.000
286	22	gamma	91	212	0	0	0	0	0	0.119	-0.015	-2.768	2.770	0.000
287	22	gamma	91	212	0	0	0	0	0	0.041	0.060	-0.632	0.636	0.000
288	22	gamma	91	214	0	0	0	0	0	-0.106	0.244	-1.883	1.902	0.000
289	22	gamma	91	214	0	0	0	0	0	-0.023	0.098	-0.321	0.336	0.000
290	22	gamma	91	216	0	0	0	0	0	0.104	-0.041	0.759	0.767	0.000
291	22	gamma	91	216	0	0	0	0	0	0.068	-0.211	1.419	1.436	0.000
292	22	gamma	91	220	0	0	0	0	0	-0.174	-0.564	3.400	3.450	0.000
293	22	gamma	91	220	0	0	0	0	0	-3.225	-10.397	59.384	60.374	0.000
294	22	gamma	91	221	0	0	0	0	0	-2.664	-7.819	47.018	47.739	0.000
295	22	gamma	91	221	0	0	0	0	0	-0.791	-2.198	13.646	13.844	0.000
296	22	gamma	91	230	0	0	0	0	0	-0.072	0.196	-2.758	2.766	0.000
297	22	gamma	91	230	0	0	0	0	0	0.003	0.139	-0.921	0.931	0.000
298	22	gamma	91	231	0	0	0	0	0	0.041	0.070	-2.433	2.435	0.000
299	22	gamma	91	231	0	0	0	0	0	0.015	0.045	-0.214	0.219	0.000
300	22	gamma	91	232	0	0	0	0	0	0.008	0.033	-0.075	0.082	0.000
301	22	gamma	91	232	0	0	0	0	0	0.089	0.005	-1.321	1.324	0.000
302	22	gamma	91	237	0	0	0	0	0	-1.449	0.969	-38.188	38.227	0.000
303	22	gamma	91	237	0	0	0	0	0	-0.015	0.009	-0.814	0.814	0.000
304	22	gamma	91	251	0	0	0	0	0	0.017	0.190	0.065	0.201	0.000
305	22	gamma	91	251	0	0	0	0	0	0.030	0.209	0.247	0.325	0.000
306	22	gamma	91	252	0	0	0	0	0	0.026	0.171	0.049	0.180	0.000
307	22	gamma	91	252	0	0	0	0	0	0.006	0.049	0.122	0.132	0.000
308	22	gamma	91	253	0	0	0	0	0	-0.035	-0.032	0.043	0.064	0.000
309	22	gamma	91	253	0	0	0	0	0	0.087	0.036	0.147	0.175	0.000
310	22	gamma	91	256	0	0	0	0	0	0.043	0.037	0.274	0.280	0.000
311	22	gamma	91	256	0	0	0	0	0	0.120	-0.088	0.322	0.355	0.000
312	22	gamma	91	263	0	0	0	0	0	0.015	-0.171	-0.139	0.221	0.000

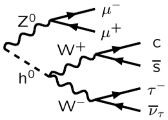
Monte Carlo generation

Matrix elements (ME):

1) Hard subprocess:
$|\mathcal{M}|^2$, Breit-Wigners,
parton densities.

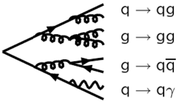


2) Resonance decays:
includes correlations.

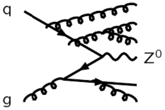


Parton Showers (PS):

3) Final-state parton showers.



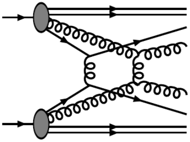
4) Initial-state parton showers.



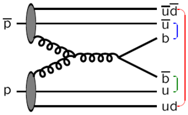
Slide: Else Lytken et al.

Monte Carlo generation

5) Multiple parton–parton interactions.

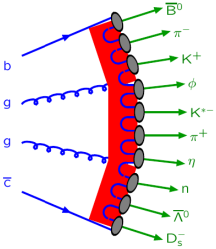


6) Beam remnants, with colour connections.

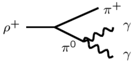


5) + 6) = Underlying Event

7) Hadronization



8) Ordinary decays: hadronic, τ, charm, . . .



Slide: Else Lytken et al.

Monte-Carlo Event Generation

Generatoren bei Belle 2

- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
  Anfangszustand genau bekannt
  → Generation startet mit Y(4S)-Teilchen
  → Zerfallskette simuliert mit EvtGen-Software
  (Verzweigungsverhältnisse und Zerfallsmodelle)

- $e^+e^- \rightarrow q\bar{q}$
  Simulation von Fragmentation
  ähnlich wie bei ATLAS

- $e^+e^- \rightarrow \ell^+\ell^-$
  Spezielle Generatoren
  basierend auf QED-Rechnungen

```
300553 (Upsilon(4S))
    521 (B+)
      443 (J/psi)
        211 (pi+)
       -211 (pi-)
        211 (pi+)
       -213 (rho-)
         -211 (pi-)
          111 (pi0)
             22 (gamma)
             22 (gamma)
      323 (K*+)
        311 (K0)
          310 (K_S0)
            211 (pi+)
           -211 (pi-)
        211 (pi+)
   -521 (B-)
      423 (D*0)
        421 (D0)
         -321 (K-)
          211 (pi+)
         22 (gamma)
       15 (tau-)
         13 (mu-)
        -14 (anti-nu_mu)
         16 (nu_tau)
      -16 (anti-nu_tau)
```

Slide: Thomas Kuhr

Monte-Carlo-Detektorsimulation

- Detektorsimulation:
  - erhält Teilchenliste aus Ereignis-Generator als Eingabe
  - simuliert Durchgang aller Teilchen durch Detektorkomponenten
    - Coulombstreuung (simuliert Streuwinkel)
    - Teilchenzerfälle (simuliert Lebensdauer)
    - Ionisierungsenergie (simuliert ΔE)
    - elektromagnetische / hadronische Schauer
  - schlussendlich: Signale in Detektorausleseelektronik
- Simulierte Ausgabe hat gleiches Format wie echte Daten
  - einfacher Vergleich zwischen Daten und MC
    (vorausgesetzt die Effizienzen sind gleich)
- Programmpaket: GEANT4 (*toolkit for the simulation of the passage of particles through matter* using MC methods, initiated 1994, CERN)
  - verwendet von ATLAS, CMS, ALICE, LHCb, ILC, Belle-II, . . . , Astrophysikern, für klinische Studien, für Simulation von Strahlungsgefahr für Astronauten, in der Mikroelektronik, . . .

Komplexes Beispiel zur Monte Carlo Methode

Moderne Experimente der Hochenergiephysik bestehen aus sehr vielen einzelnen Detektoren

- L3 am LEP Beschleuniger (CERN) hatte u.a. etwa $11\,000$ Kristalle zur Energiemessung
- CMS am LHC Beschleuniger wird ca. $15\,000$ Silizium-Streifendetektoren enthalten mit etwa 10^7 einzelnen Kanälen

Zur Analyse der Daten werden sehr detailierte MC Simulationen benötigt

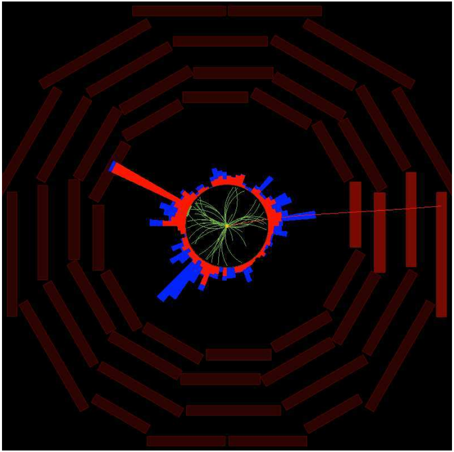
- Simulation der physikalischen Reaktion:
  alle enstehenden Teilchen und deren erwartete Energie-, Impuls- und Winkelverteilungen
- Nachweiswahrscheinlichkeit für jedes Detektorelement
- Orts- und Energieauflösung jeder einzelnen Detektorkomponente

Am Ende der Simulation stehen digitalisierte Signale der einzelnen Detektorkomponenten, die sich nicht von echten Daten unterscheiden

Der simulierte Datensatz dient dann zur Optimierung der Selektion und Bestimmung der Akzeptanz

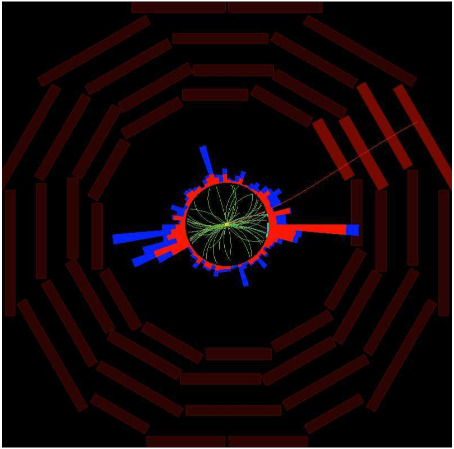
Komplexes Beispiel zur Monte Carlo Methode

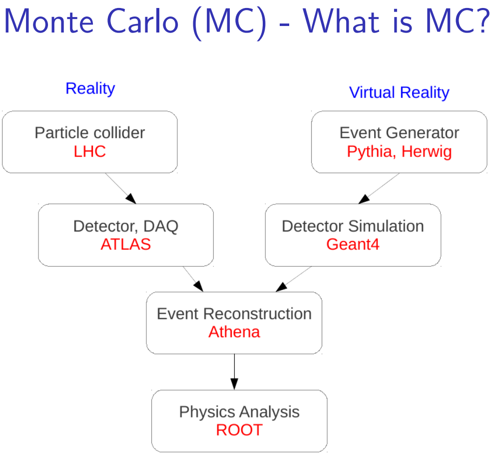
CMS Experiment am LHC Beschleuniger am CERN:
Simulation eines Top-Paar-Ereignisses $\mathrm{pp} \rightarrow \mathrm{t\bar{t}} + X$



Komplexes Beispiel zur Monte Carlo Methode

CMS Experiment am LHC Beschleuniger am CERN:
Im Vergleich zu einem realen Ereignisse in den Daten $\mathrm{pp} \to \mathrm{t}\bar{\mathrm{t}} + X$





- MC simulates what happens at the *LHC* and *ATLAS*
- Many different programmes can be used at each stage

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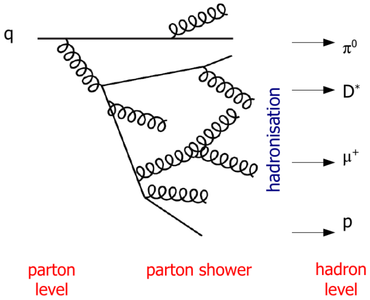
MC Generation



- MC Generator stops with set of “stable” final state particles
- Complete 4-vector info is known about every particle
- All parent-daughter relations are known and stored
- High energy parton state known as parton level
- Stable particle state known as hadron level

- This level of information is often called the truth record
- This is the pure event before it interacts with any apparatus

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Monte-Carlo Event Generation: "Reconstruction"

Reconstruction

Going from electronic pulses to analysis objects

- Data and MC pass through the same reconstruction algorithms
- Raw electronic pulses reconstructed into:
  - Tracks
  - Calorimeter deposits
- Which are then reconstructed into:
  - Jets, electron, muons, taus,
  - Photons, tracks, missing E_{T}

Real life issues need to be reflected in the MC

- Some parts of the detector become faulty over time
- e.g. - A section of the calorimeter readout dies and cannot be repaired until the detector is opened up in a shutdown
- Lets say that this affects x% of the data luminosity
- Need to generate MC with this problem in x% of the MC
  - Cannot know x until end of year
  - $\Rightarrow$ Need to reprocess the MC at the end of the year
- Some MC bugs do not become apparent for some time

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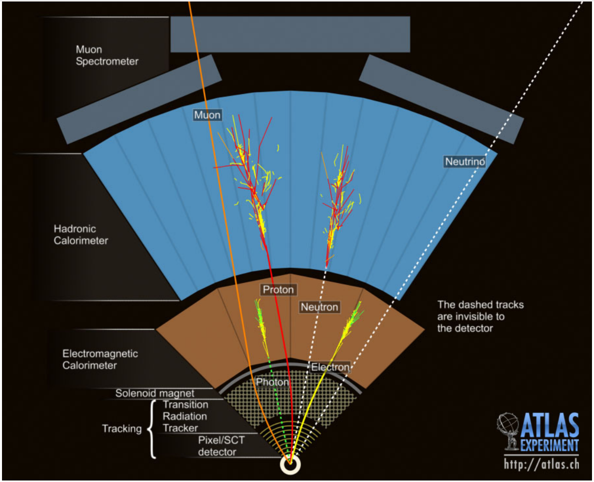
Teilchenidentifikation in ATLAS

- Schematische Darstellung von Teilchenidentifikation in ATLAS (und ähnlich aufgebauten Detektoren)
- Tatsächliche Implementation = komplexe Algorithmen, oftmals mit ML



Zusammenfassung

Kurzer Überblick zu

- Monte Carlo Methoden
- Zufallszahlen erzeugen
- Beliebig verteilte Zufallszahlen
- Ereignis-Generatoren in der Teilchenphysik
- Detektorsimulation

Zufallszahlen und MC Simulation auch für viele andere Bereiche wichtig:

- Statistik, “Toy”-Experimente, Risikoabschätzung, …
- “digital twin” in modernem ML slang ...