SFT group meeting
CERN
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LUND UNIVERSITY

PYTHIA: Past, Present and Future

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The Physics of Event Generators

The Event Generator Landscape

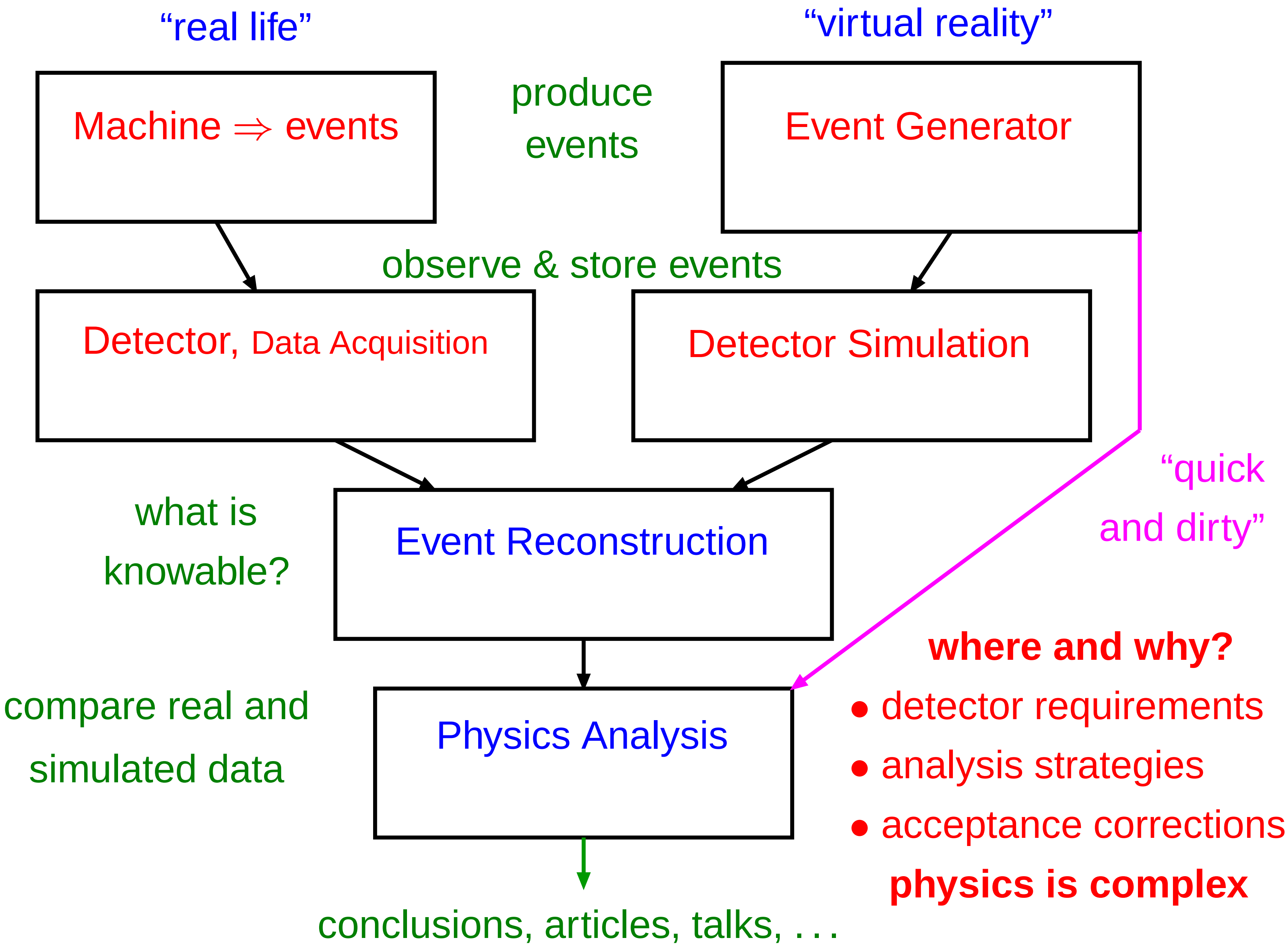
The move to C++

PYTHIA8 sneak preview

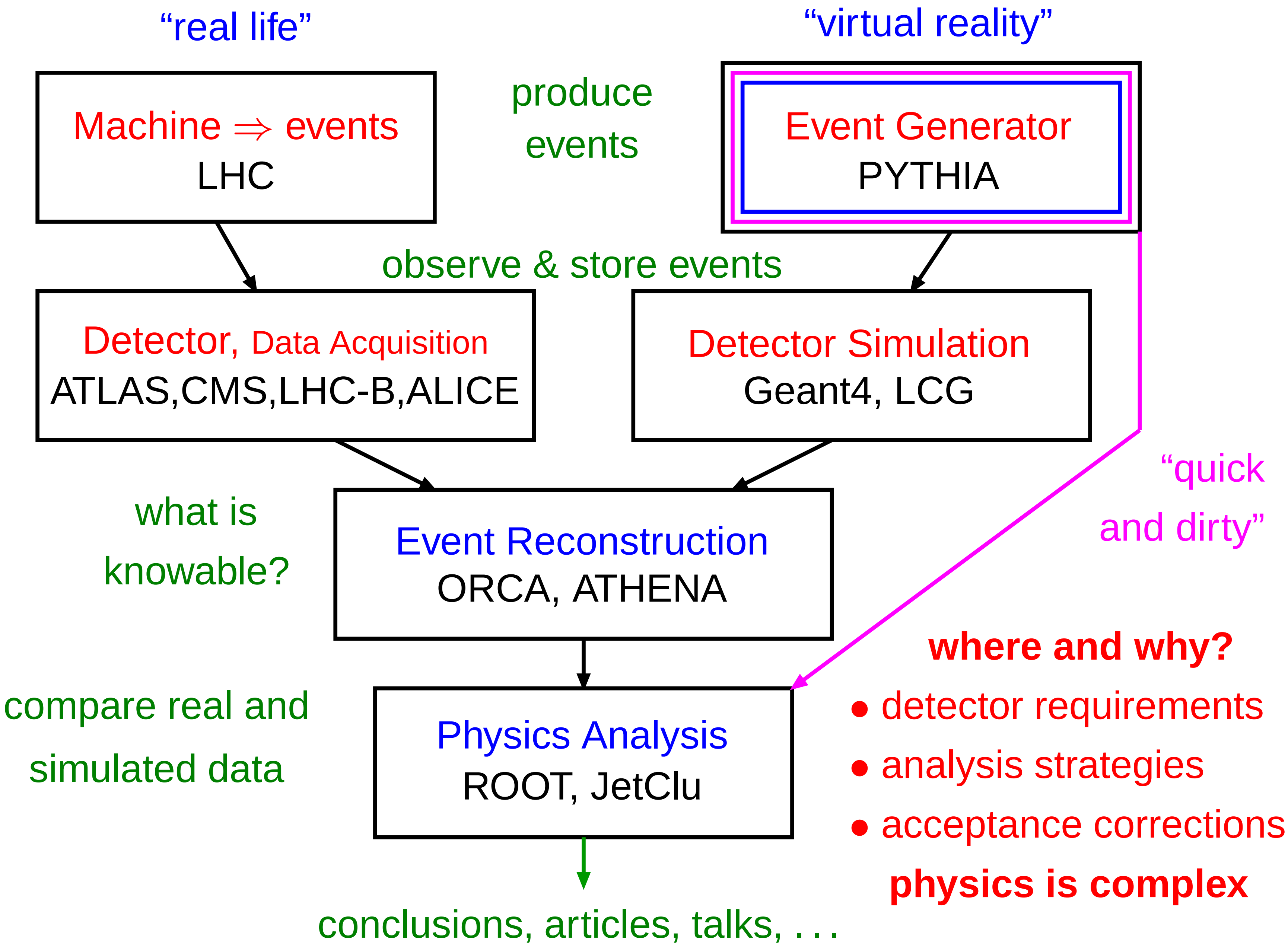
Who was Pythia?

The Oracle of Delphi: ca. 1000 B.C. — 390 A.D.

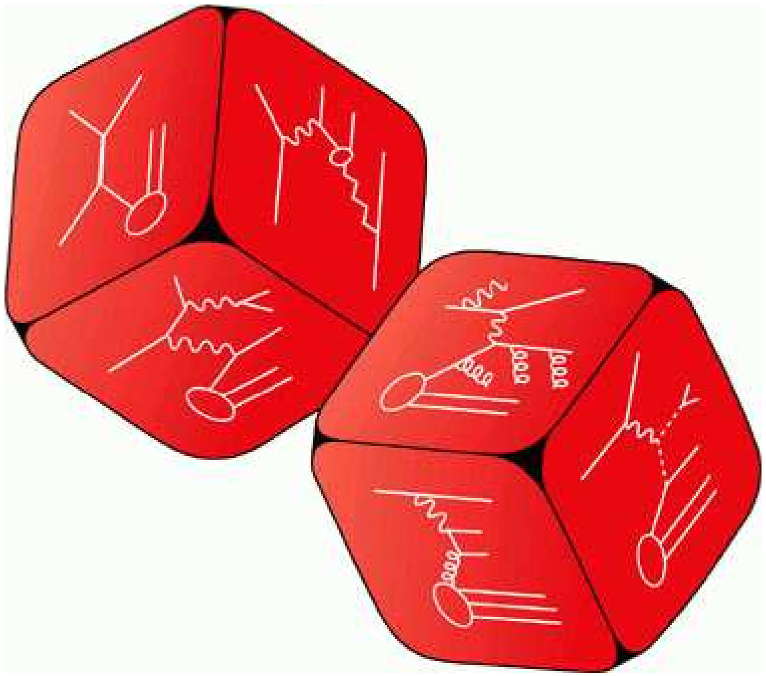
What is PYTHIA?



What is PYTHIA?



A tour to Monte Carlo



. . . because Einstein was wrong: God does throw dice!

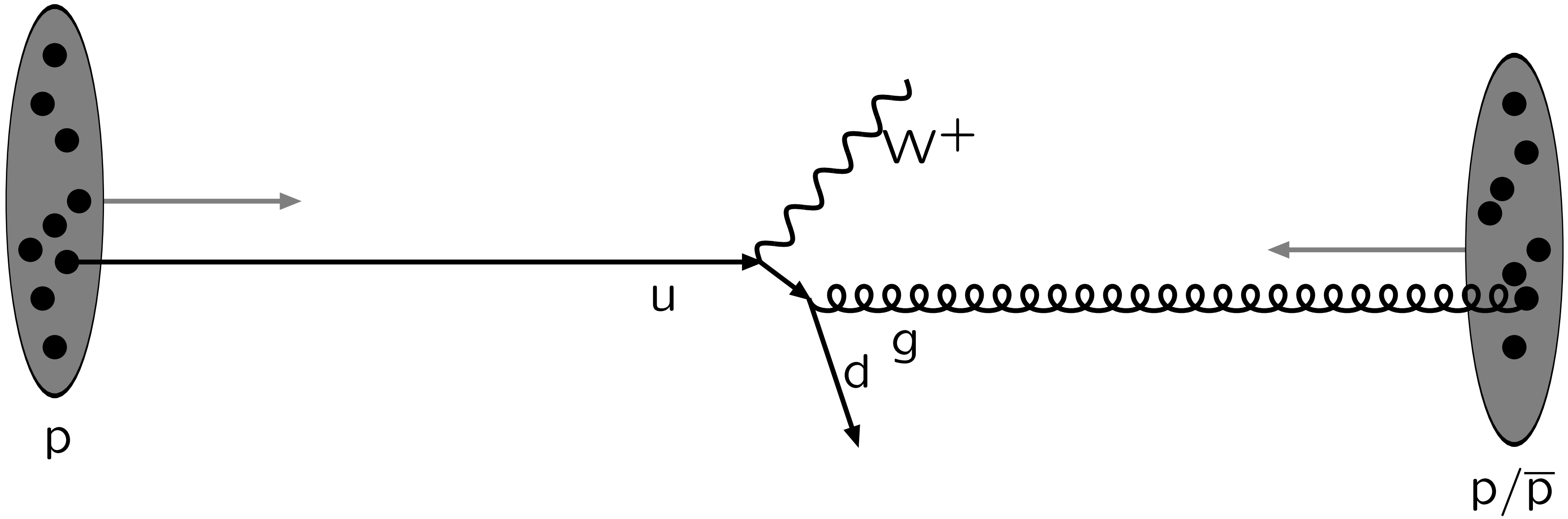
Quantum mechanics: amplitudes $\Longrightarrow$ probabilities

Anything that possibly can happen, will! (but more or less often)

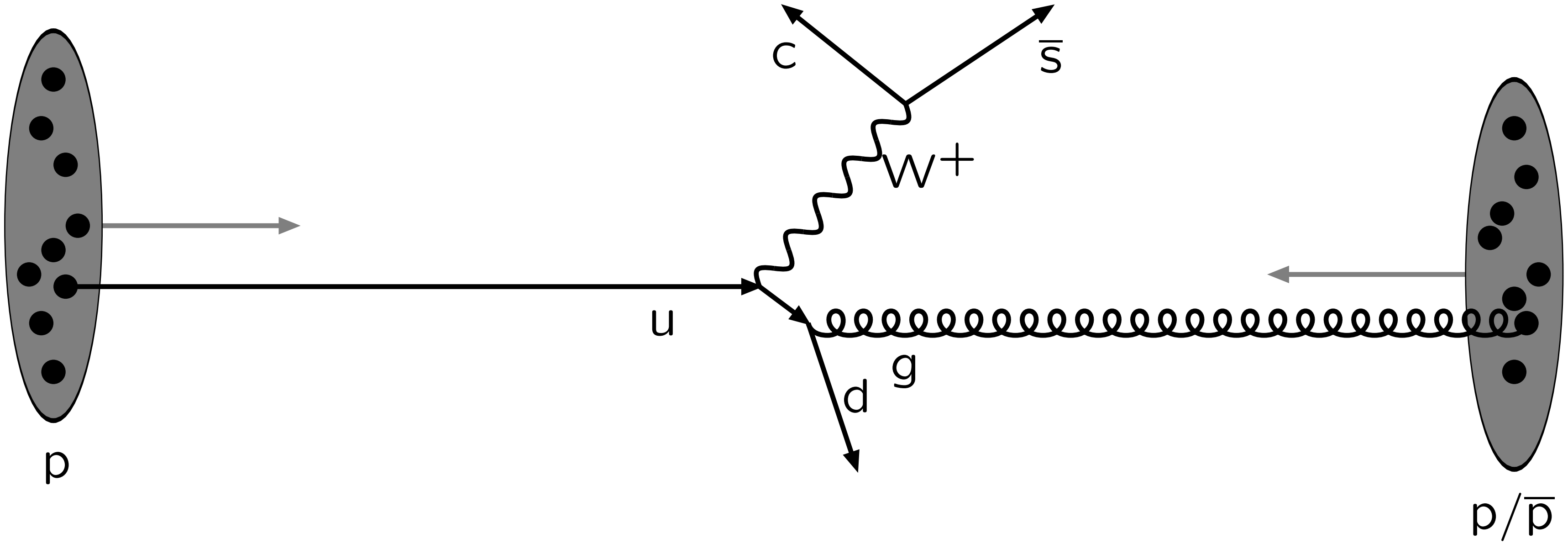
The structure of an event

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

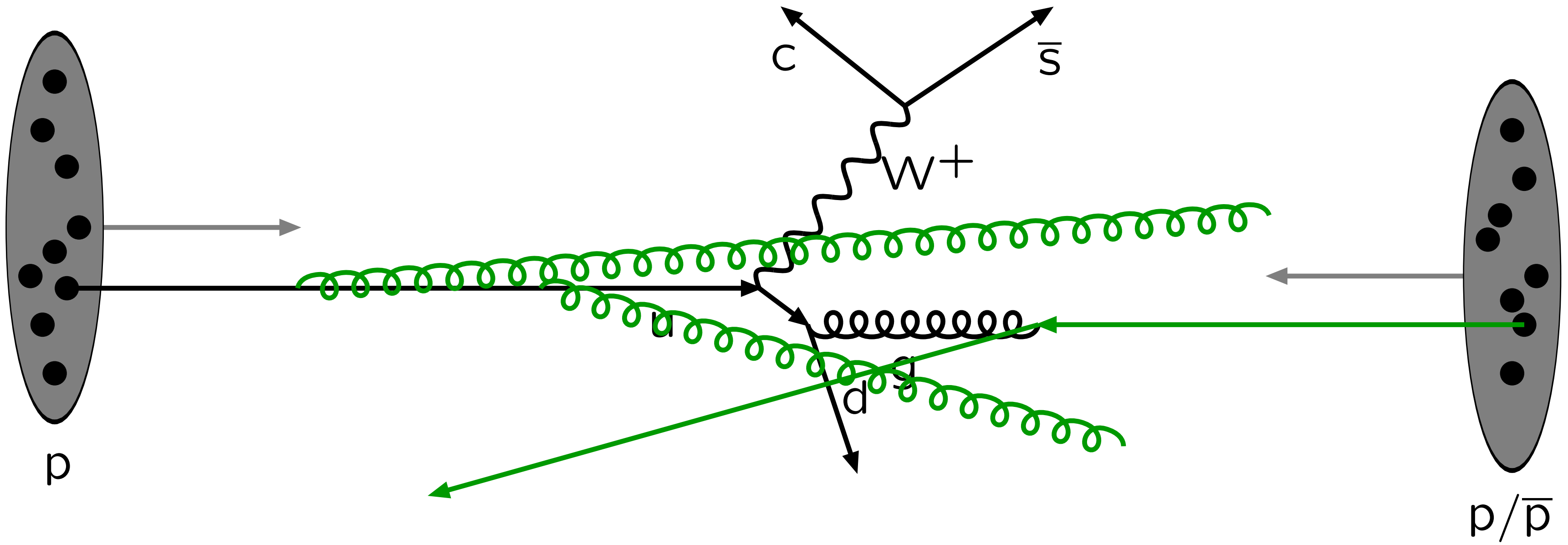
Incoming beams: parton densities



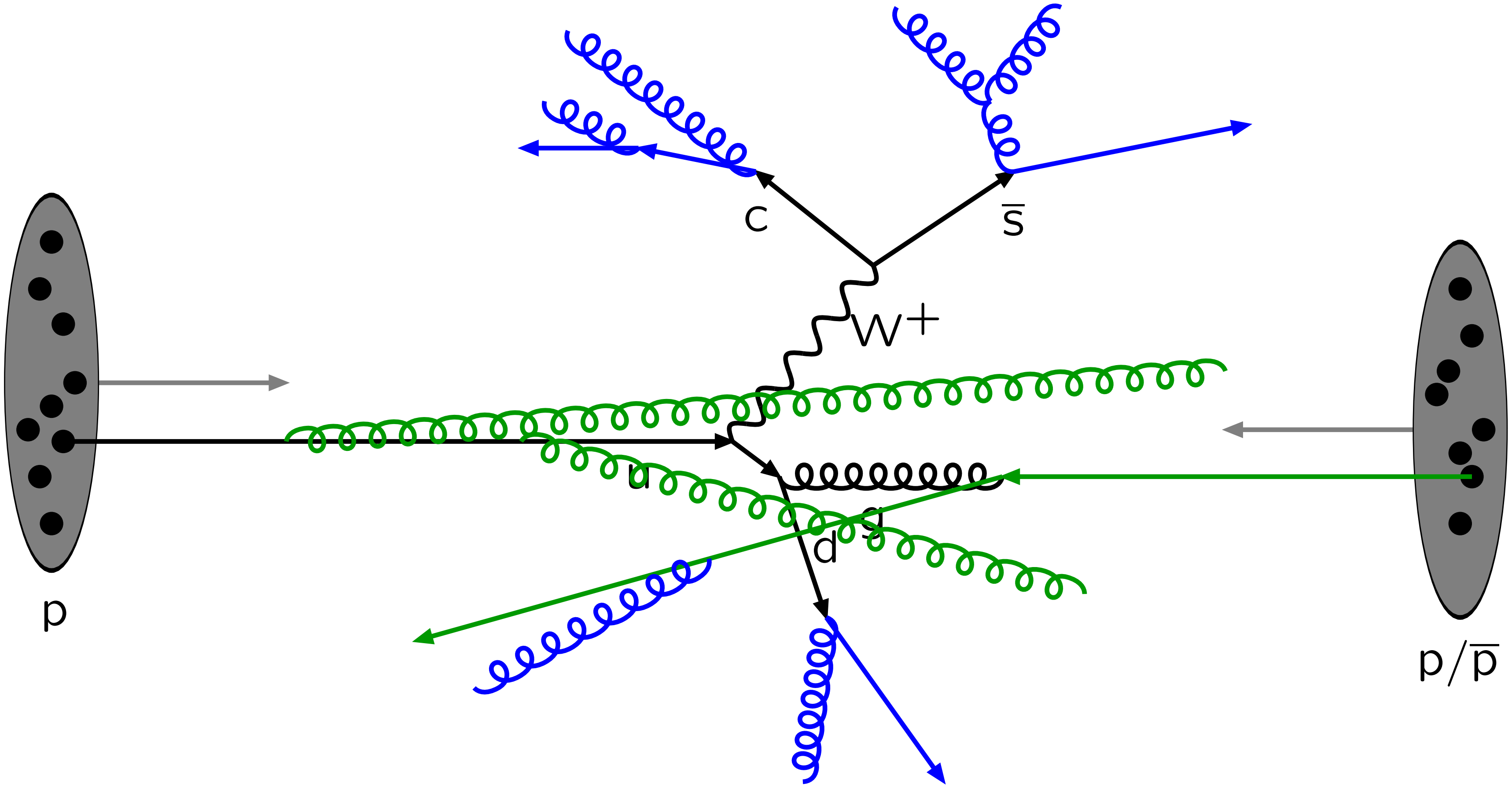
Hard subprocess: described by matrix elements



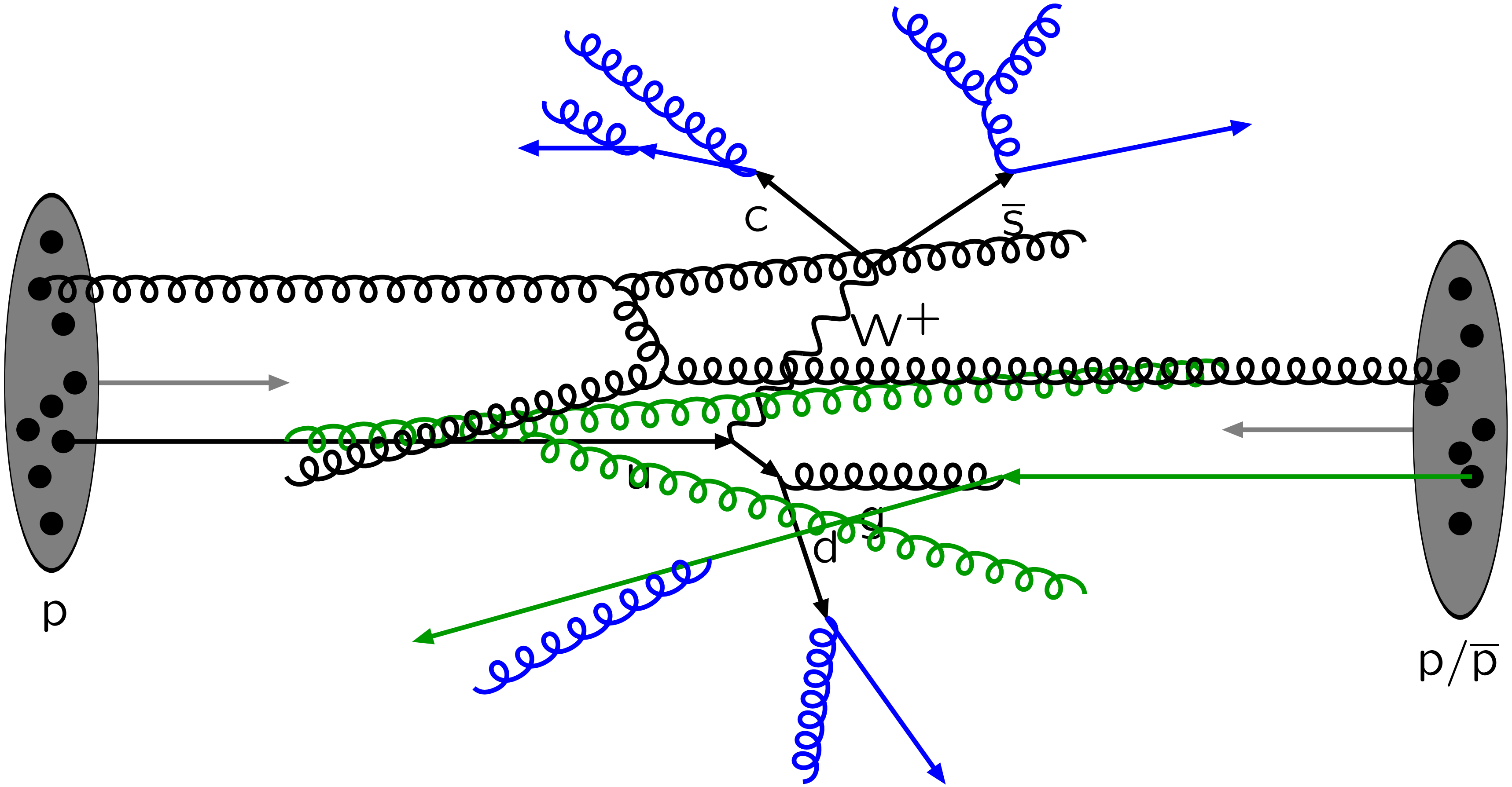
Resonance decays: correlated with hard subprocess



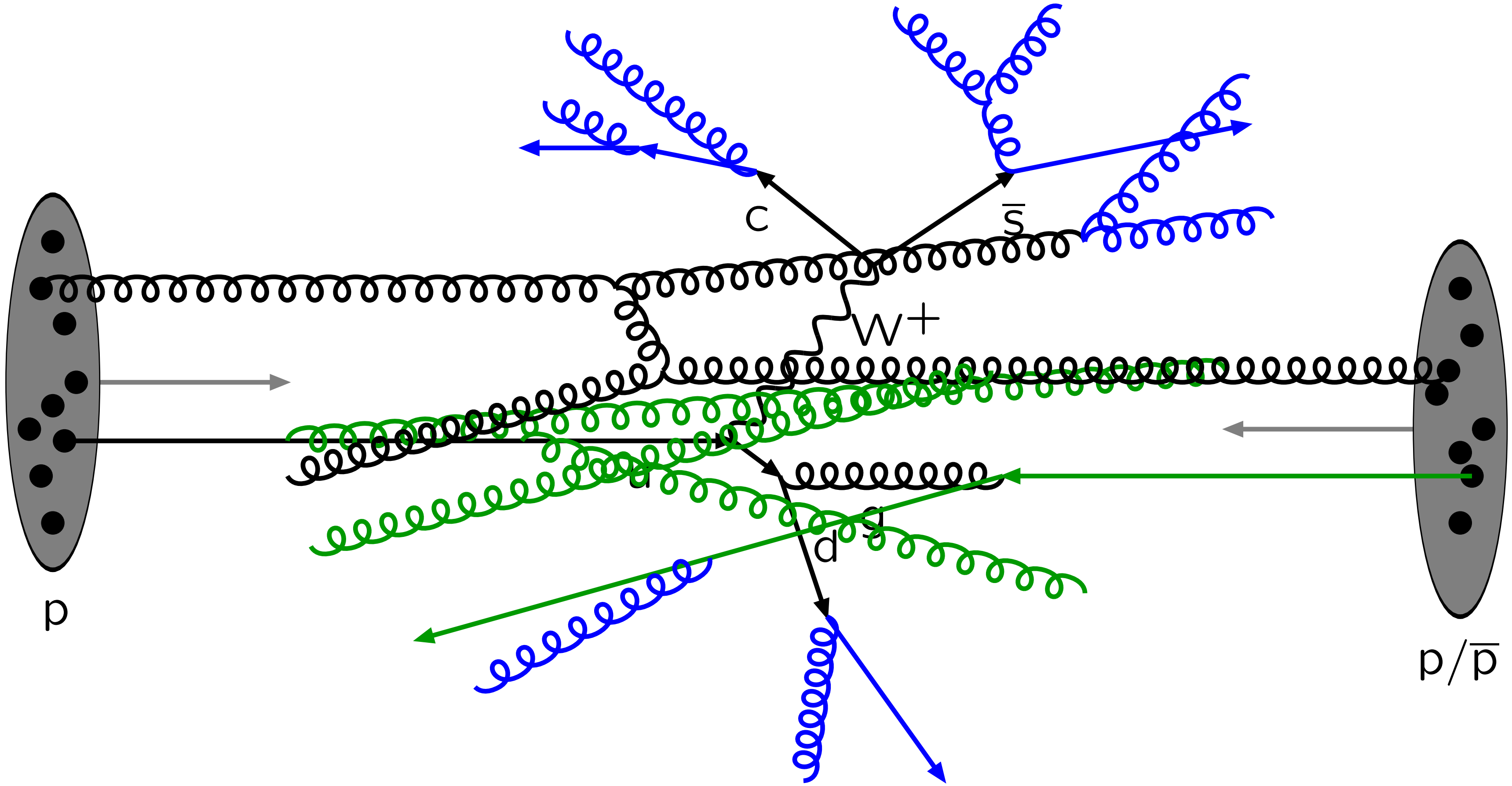
Initial-state radiation: spacelike parton showers



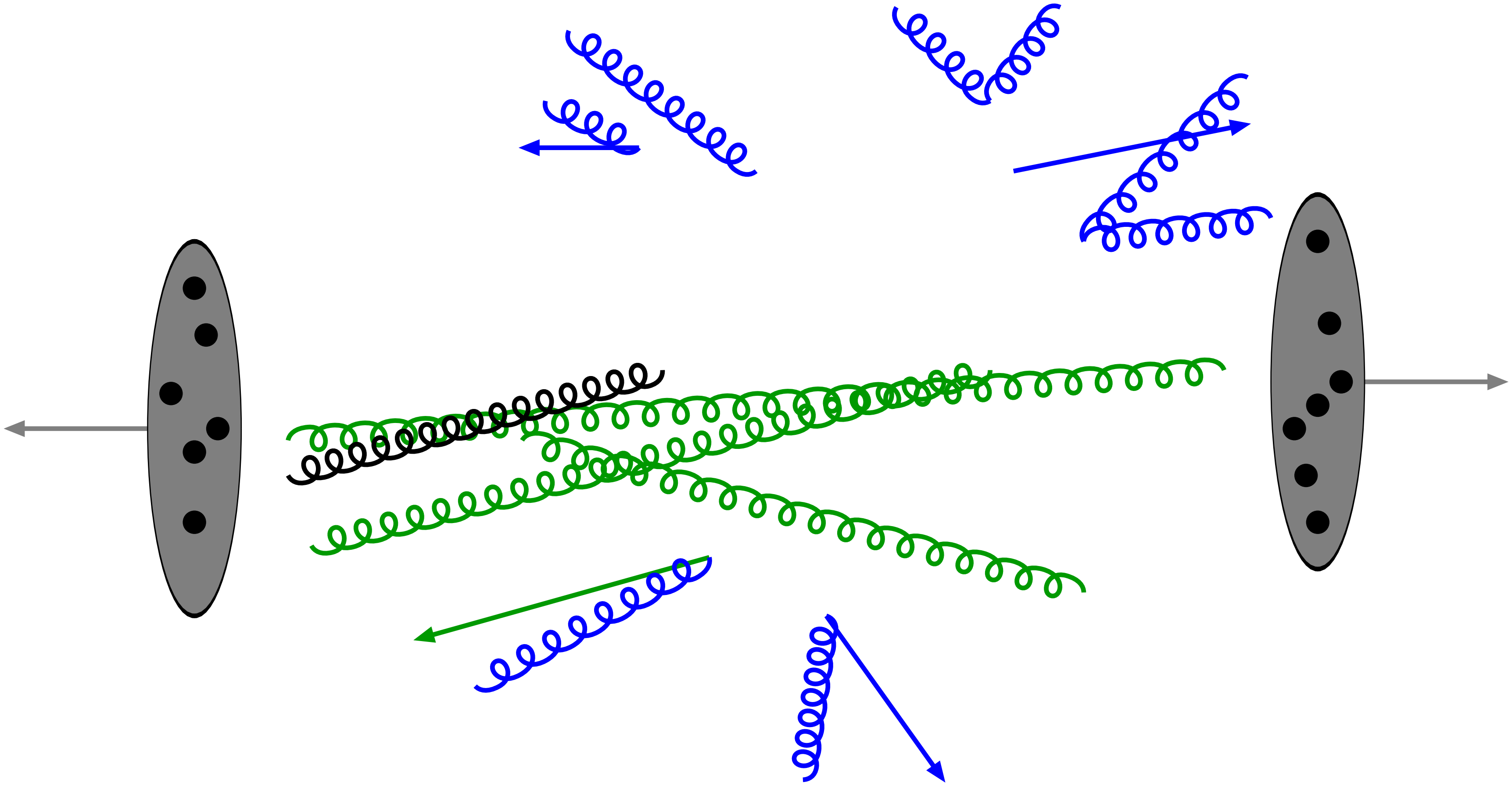
Final-state radiation: timelike parton showers



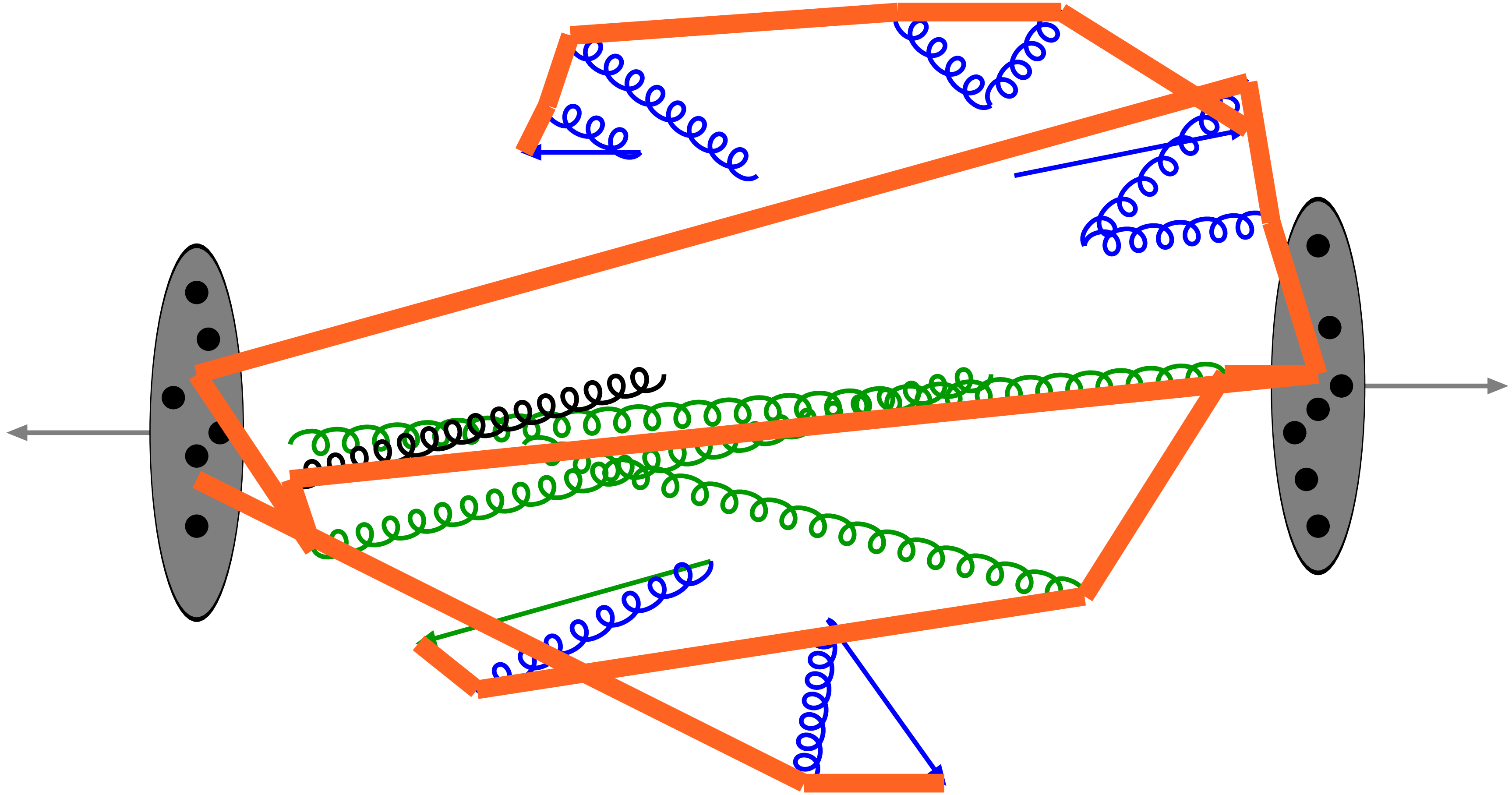
Multiple parton–parton interactions . . .



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

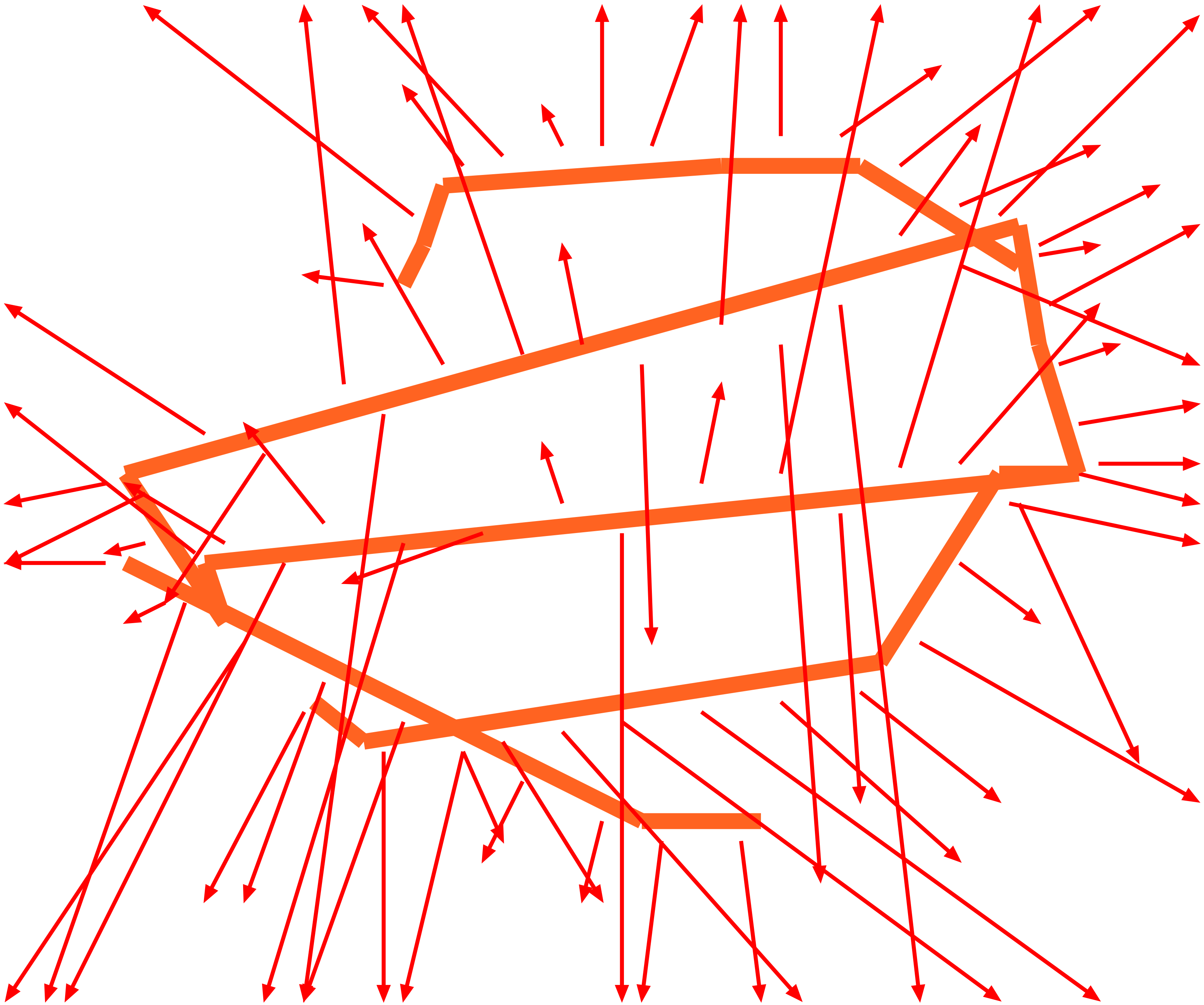


Beam remnants and other outgoing partons

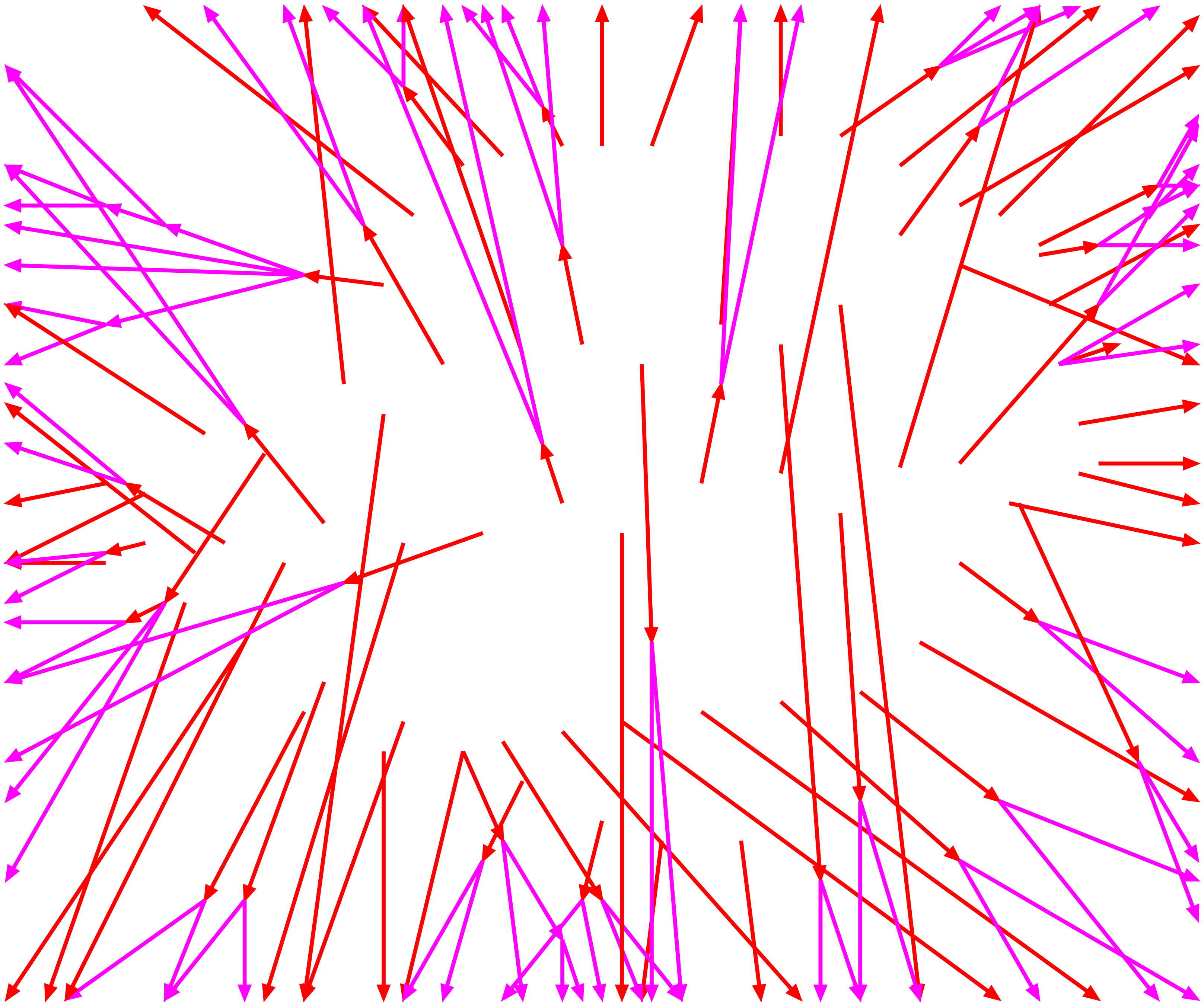


Everything is connected by colour confinement strings

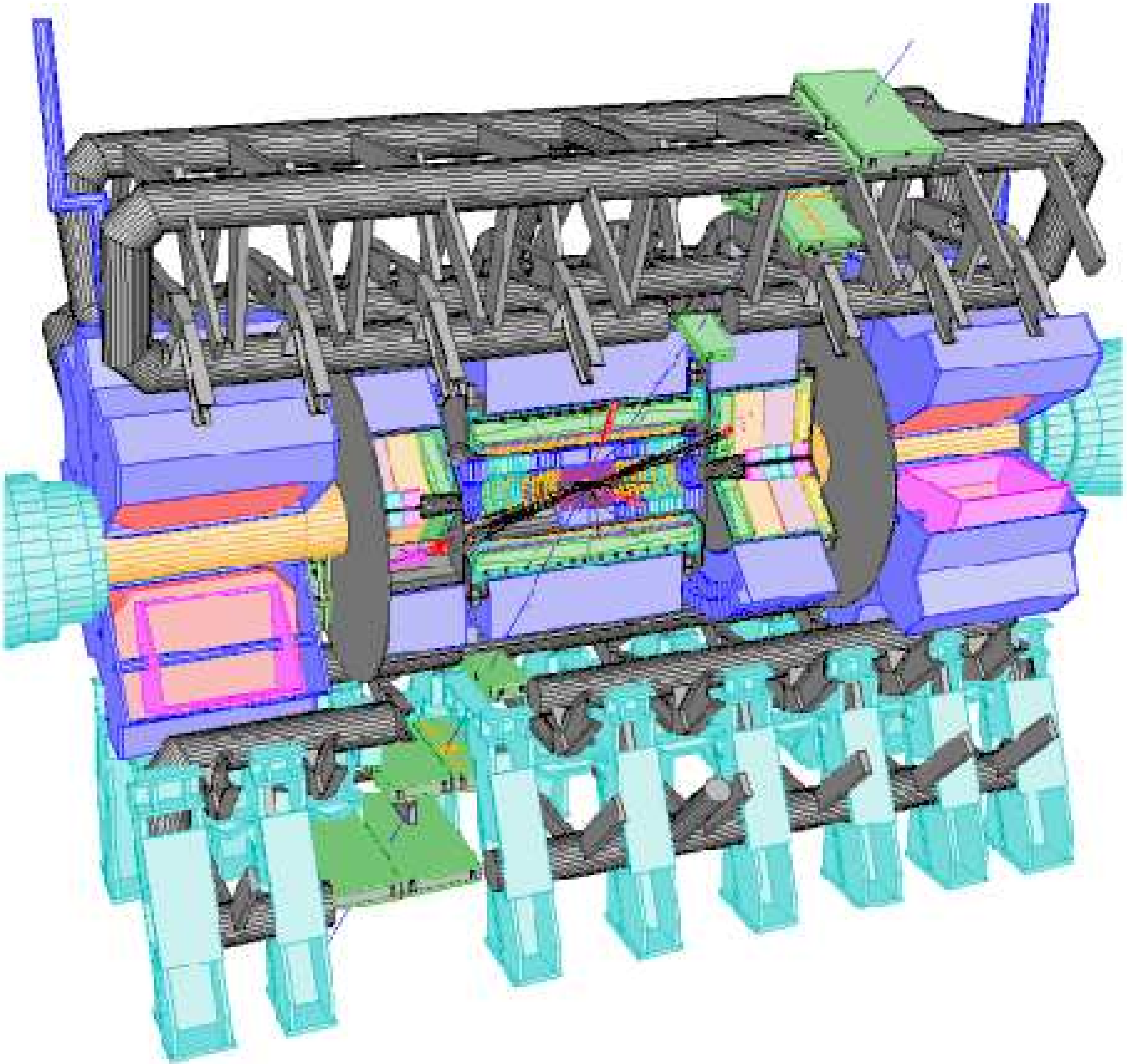
Recall! Not to scale: strings are of hadronic widths



The strings fragment to produce primary hadrons



Many hadrons are unstable and decay further



These are the particles that hit the detector

The Monte Carlo method

Want to generate events in as much detail as Mother Nature
$\Longrightarrow$ get average *and* fluctutations right
$\Longrightarrow$ make random choices, $\sim$ as in nature

$$\sigma_{\text{final state}} = \sigma_{\text{hard process}} \mathcal{P}_{\text{tot,hard process}\to\text{final state}}$$

(appropriately summed & integrated over non-distinguished final states)

where $\mathcal{P}_{\text{tot}} = \mathcal{P}_{\text{res}} \mathcal{P}_{\text{ISR}} \mathcal{P}_{\text{FSR}} \mathcal{P}_{\text{MI}} \mathcal{P}_{\text{remnants}} \mathcal{P}_{\text{hadronization}} \mathcal{P}_{\text{decays}}$

with $\mathcal{P}_i = \prod_j \mathcal{P}_{ij} = \prod_j \prod_k \mathcal{P}_{ijk} = \ldots$ in its turn

$\Longrightarrow$ **divide and conquer**

an event with n particles involves $\mathcal{O}(10n)$ random choices,
(flavour, mass, momentum, spin, production vertex, lifetime, ...)
LHC: ~ 100 charged and ~ 200 neutral ($+$ intermediate stages)
$\Longrightarrow$ several thousand choices
(of $\mathcal{O}(100)$ different kinds)

Generator Landscape

	General-Purpose	Specialized
Hard Processes		a lot
Resonance Decays	**HERWIG**	HDECAY, . . .
Parton Showers	**PYTHIA**	Ariadne/LDC, NLLjet
Underlying Event	ISAJET	DPMJET
Hadronization	SHERPA	none (?)
Ordinary Decays		TAUOLA, EvtGen

specialized often best at given task, but need General-Purpose core

PYTHIA Process Library

No.	Subprocess
Hard QCD processes:	
11	$f_i f_j \to f_i f_j$
12	$f_i \bar{f}_i \to f_k \bar{f}_k$
13	$f_i \bar{f}_i \to gg$
28	$f_i g \to f_i g$
53	$gg \to f_k \bar{f}_k$
68	$gg \to gg$
Soft QCD processes:	
91	elastic scattering
92	single diffraction (XB)
93	single diffraction (AX)
94	double diffraction
95	low-$p_\perp$ production
Open heavy flavour: (also fourth generation)	
81	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
82	$gg \to Q_k \bar{Q}_k$
83	$q_i f_j \to Q_k f_l$
84	$g\gamma \to Q_k \bar{Q}_k$
85	$\gamma\gamma \to F_k \bar{F}_k$
Closed heavy flavour:	
86	$gg \to J/\psi g$
87	$gg \to \chi_{0c} g$
88	$gg \to \chi_{1c} g$
89	$gg \to \chi_{2c} g$
104	$gg \to \chi_{0c}$
105	$gg \to \chi_{2c}$
106	$gg \to J/\psi\gamma$
107	$g\gamma \to J/\psi g$
108	$\gamma\gamma \to J/\psi\gamma$
W/Z production:	
1	$f_i \bar{f}_i \to \gamma^*/Z^0$
2	$f_i \bar{f}_j \to W^\pm$
22	$f_i \bar{f}_i \to Z^0 Z^0$
23	$f_i \bar{f}_j \to Z^0 W^\pm$
25	$f_i \bar{f}_i \to W^+ W^-$
15	$f_i \bar{f}_i \to g Z^0$
16	$f_i \bar{f}_j \to g W^\pm$
30	$f_i g \to f_i Z^0$
31	$f_i g \to f_k W^\pm$
19	$f_i \bar{f}_i \to \gamma Z^0$
20	$f_i \bar{f}_j \to \gamma W^\pm$
35	$f_i \gamma \to f_i Z^0$

No.	Subprocess
36	$f_i \gamma \to f_k W^\pm$
69	$\gamma\gamma \to W^+ W^-$
70	$\gamma W^\pm \to Z^0 W^\pm$
Prompt photons:	
14	$f_i \bar{f}_i \to g\gamma$
18	$f_i \bar{f}_i \to \gamma\gamma$
29	$f_i g \to f_i \gamma$
114	$gg \to \gamma\gamma$
115	$gg \to g\gamma$
Deeply Inel. Scatt.:	
10	$f_i f_j \to f_k f_l$
99	$\gamma^* q \to q$
Photon-induced:	
33	$f_i \gamma \to f_i g$
34	$f_i \gamma \to f_i \gamma$
54	$g\gamma \to f_k \bar{f}_k$
58	$\gamma\gamma \to f_k \bar{f}_k$
131	$f_i \gamma_T^* \to f_i g$
132	$f_i \gamma_L^* \to f_i g$
133	$f_i \gamma_T^* \to f_i \gamma$
134	$f_i \gamma_L^* \to f_i \gamma$
135	$g\gamma_T^* \to f_i \bar{f}_i$
136	$g\gamma_L^* \to f_i \bar{f}_i$
137	$\gamma_T^* \gamma_T^* \to f_i \bar{f}_i$
138	$\gamma_T^* \gamma_L^* \to f_i \bar{f}_i$
139	$\gamma_L^* \gamma_T^* \to f_i \bar{f}_i$
140	$\gamma_L^* \gamma_L^* \to f_i \bar{f}_i$
80	$q_i \gamma \to q_k \pi^\pm$
Light SM Higgs:	
3	$f_i \bar{f}_i \to h^0$
24	$f_i \bar{f}_i \to Z^0 h^0$
26	$f_i \bar{f}_j \to W^\pm h^0$
32	$f_i g \to f_i h^0$
102	$gg \to h^0$
103	$\gamma\gamma \to h^0$
110	$f_i \bar{f}_i \to \gamma h^0$
111	$f_i \bar{f}_i \to g h^0$
112	$f_i g \to f_i h^0$
113	$gg \to g h^0$
121	$gg \to Q_k \bar{Q}_k h^0$
122	$q_i \bar{q}_i \to Q_k \bar{Q}_k h^0$
123	$f_i f_j \to f_i f_j h^0$
124	$f_i f_j \to f_k f_l h^0$

No.	Subprocess
New gauge bosons:	
141	$f_i \bar{f}_i \to \gamma/Z^0/Z'^0$
142	$f_i \bar{f}_j \to W'^+$
144	$f_i \bar{f}_j \to R$
Heavy SM Higgs:	
5	$Z^0 Z^0 \to h^0$
8	$W^+ W^- \to h^0$
71	$Z_L^0 Z_L^0 \to Z_L^0 Z_L^0$
72	$Z_L^0 Z_L^0 \to W_L^+ W_L^-$
73	$Z_L^0 W_L^\pm \to Z_L^0 W_L^\pm$
76	$W_L^+ W_L^- \to Z_L^0 Z_L^0$
77	$W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm$
BSM Neutral Higgs:	
151	$f_i \bar{f}_i \to H^0$
152	$gg \to H^0$
153	$\gamma\gamma \to H^0$
171	$f_i \bar{f}_i \to Z^0 H^0$
172	$f_i \bar{f}_j \to W^\pm H^0$
173	$f_i f_j \to f_i f_j H^0$
174	$f_i f_j \to f_k f_l H^0$
181	$gg \to Q_k \bar{Q}_k H^0$
182	$q_i \bar{q}_i \to Q_k \bar{Q}_k H^0$
183	$f_i \bar{f}_i \to g H^0$
184	$f_i g \to f_i H^0$
185	$gg \to g H^0$
156	$f_i \bar{f}_i \to A^0$
157	$gg \to A^0$
158	$\gamma\gamma \to A^0$
176	$f_i \bar{f}_i \to Z^0 A^0$
177	$f_i \bar{f}_j \to W^\pm A^0$
178	$f_i f_j \to f_i f_j A^0$
179	$f_i f_j \to f_k f_l A^0$
186	$gg \to Q_k \bar{Q}_k A^0$
187	$q_i \bar{q}_i \to Q_k \bar{Q}_k A^0$
188	$f_i \bar{f}_i \to g A^0$
189	$f_i g \to f_i A^0$
190	$gg \to g A^0$
Charged Higgs:	
143	$f_i \bar{f}_j \to H^+$
161	$f_i g \to f_k H^+$
401	$gg \to \bar{t} b H^+$
402	$q\bar{q} \to \bar{t} b H^+$

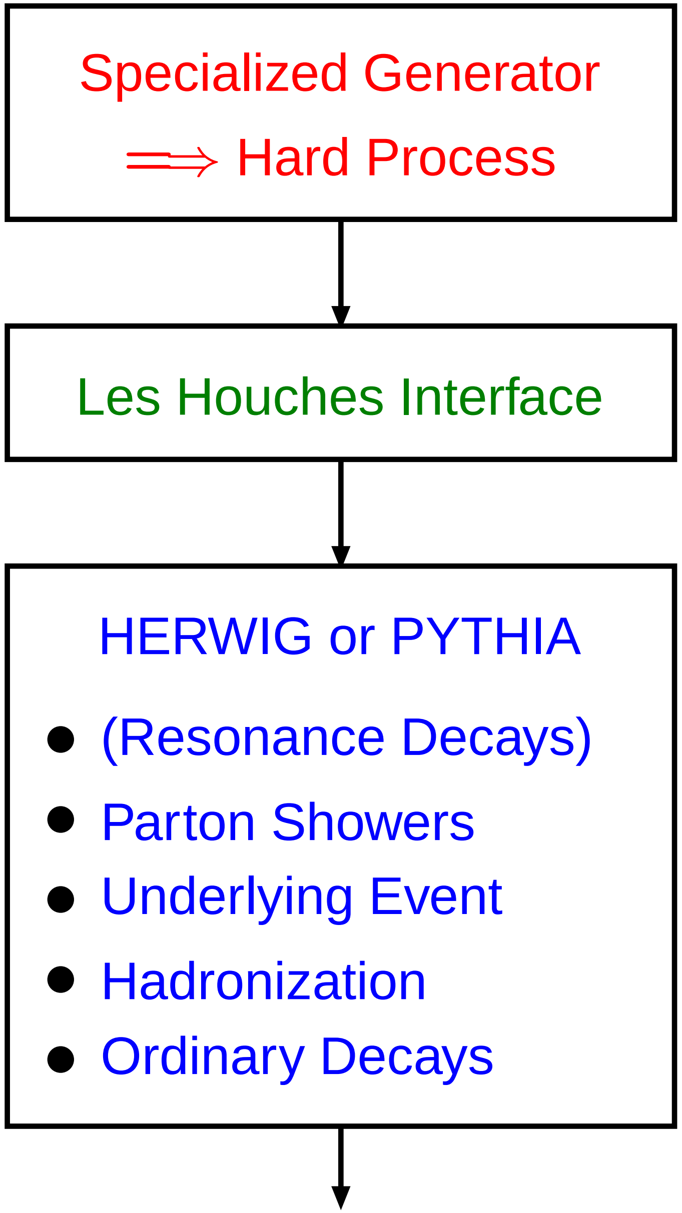
No.	Subprocess
Higgs pairs:	
297	$f_i \bar{f}_j \to H^\pm h^0$
298	$f_i \bar{f}_j \to H^\pm H^0$
299	$f_i \bar{f}_i \to A^0 h^0$
300	$f_i \bar{f}_i \to A^0 H^0$
301	$f_i \bar{f}_i \to H^+ H^-$
Leptoquarks:	
145	$q_i \ell_j \to L_Q$
162	$qg \to \ell L_Q$
163	$gg \to L_Q \bar{L}_Q$
164	$q_i \bar{q}_i \to L_Q \bar{L}_Q$
Technicolor:	
149	$gg \to \eta_{tc}$
191	$f_i \bar{f}_i \to \rho_{tc}^0$
192	$f_i \bar{f}_j \to \rho_{tc}^+$
193	$f_i \bar{f}_i \to \omega_{tc}^0$
194	$f_i \bar{f}_i \to f_k \bar{f}_k$
195	$f_i \bar{f}_j \to f_k \bar{f}_l$
361	$f_i \bar{f}_i \to W_L^+ W_L^-$
362	$f_i \bar{f}_i \to W_L^\pm \pi_{tc}^\mp$
363	$f_i \bar{f}_i \to \pi_{tc}^+ \pi_{tc}^-$
364	$f_i \bar{f}_i \to \gamma \pi_{tc}^0$
365	$f_i \bar{f}_i \to \gamma \pi'^0_{tc}$
366	$f_i \bar{f}_i \to Z^0 \pi_{tc}^0$
367	$f_i \bar{f}_i \to Z^0 \pi'^0_{tc}$
368	$f_i \bar{f}_i \to W^\pm \pi_{tc}^\mp$
370	$f_i \bar{f}_j \to W_L^\pm Z_L^0$
371	$f_i \bar{f}_j \to W_L^\pm \pi_{tc}^0$
372	$f_i \bar{f}_j \to \pi_{tc}^\pm Z_L^0$
373	$f_i \bar{f}_j \to \pi_{tc}^\pm \pi_{tc}^0$
374	$f_i \bar{f}_j \to \gamma \pi_{tc}^\pm$
375	$f_i \bar{f}_j \to Z^0 \pi_{tc}^\pm$
376	$f_i \bar{f}_j \to W^\pm \pi_{tc}^0$
377	$f_i \bar{f}_j \to W^\pm \pi'^0_{tc}$
381	$q_i q_j \to q_i q_j$
382	$q_i \bar{q}_i \to q_k \bar{q}_k$
383	$q_i \bar{q}_i \to gg$
384	$f_i g \to f_i g$
385	$gg \to q_k \bar{q}_k$
386	$gg \to gg$
387	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
388	$gg \to Q_k \bar{Q}_k$

No.	Subprocess
Compositeness:	
146	$e\gamma \to e^*$
147	$dg \to d^*$
148	$ug \to u^*$
167	$q_i q_j \to d^* q_k$
168	$q_i q_j \to u^* q_k$
169	$q_i \bar{q}_i \to e^\pm e^{*\mp}$
165	$f_i \bar{f}_i (\to \gamma^*/Z^0) \to f_k \bar{f}_k$
166	$f_i \bar{f}_j (\to W^\pm) \to f_k \bar{f}_l$
Extra Dimensions:	
391	$f\bar{f} \to G^*$
392	$gg \to G^*$
393	$q\bar{q} \to gG^*$
394	$qg \to qG^*$
395	$gg \to gG^*$
Left–right symmetry:	
341	$\ell_i \ell_j \to H_L^{\pm\pm}$
342	$\ell_i \ell_j \to H_R^{\pm\pm}$
343	$\ell_i^\pm \gamma \to H_L^{\pm\pm} e^\mp$
344	$\ell_i^\pm \gamma \to H_R^{\pm\pm} e^\mp$
345	$\ell_i^\pm \gamma \to H_L^{\pm\pm} \mu^\mp$
346	$\ell_i^\pm \gamma \to H_R^{\pm\pm} \mu^\mp$
347	$\ell_i^\pm \gamma \to H_L^{\pm\pm} \tau^\mp$
348	$\ell_i^\pm \gamma \to H_R^{\pm\pm} \tau^\mp$
349	$f_i \bar{f}_i \to H_L^{++} H_L^{--}$
350	$f_i \bar{f}_i \to H_R^{++} H_R^{--}$
351	$f_i f_j \to f_k f_l H_L^{\pm\pm}$
352	$f_i f_j \to f_k f_l H_R^{\pm\pm}$
353	$f_i \bar{f}_i \to Z_R^0$
354	$f_i \bar{f}_j \to W_R^\pm$
SUSY:	
201	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}_L^*$
202	$f_i \bar{f}_i \to \tilde{e}_R \tilde{e}_R^*$
203	$f_i \bar{f}_i \to \tilde{e}_L \tilde{e}_R^* +$
204	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}_L^*$
205	$f_i \bar{f}_i \to \tilde{\mu}_R \tilde{\mu}_R^*$
206	$f_i \bar{f}_i \to \tilde{\mu}_L \tilde{\mu}_R^* +$
207	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}_1^*$
208	$f_i \bar{f}_i \to \tilde{\tau}_2 \tilde{\tau}_2^*$
209	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}_2^* +$

No.	Subprocess
210	$f_i \bar{f}_j \to \tilde{\ell}_L \tilde{\nu}_\ell^* +$
211	$f_i \bar{f}_j \to \tilde{\tau}_1 \tilde{\nu}_\tau^* +$
212	$f_i \bar{f}_j \to \tilde{\tau}_2 \tilde{\nu}_\tau^* +$
213	$f_i \bar{f}_i \to \tilde{\nu}_\ell \tilde{\nu}_\ell^*$
214	$f_i \bar{f}_i \to \tilde{\nu}_\tau \tilde{\nu}_\tau^*$
216	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_1$
217	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_2$
218	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_3$
219	$f_i \bar{f}_i \to \tilde{\chi}_4 \tilde{\chi}_4$
220	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_2$
221	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_3$
222	$f_i \bar{f}_i \to \tilde{\chi}_1 \tilde{\chi}_4$
223	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_3$
224	$f_i \bar{f}_i \to \tilde{\chi}_2 \tilde{\chi}_4$
225	$f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_4$
226	$f_i \bar{f}_i \to \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$
227	$f_i \bar{f}_i \to \tilde{\chi}_2^\pm \tilde{\chi}_2^\mp$
228	$f_i \bar{f}_i \to \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$
229	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}_1^\pm$
230	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}_1^\pm$
231	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}_1^\pm$
232	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}_1^\pm$
233	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}_2^\pm$
234	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}_2^\pm$
235	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}_2^\pm$
236	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}_2^\pm$
237	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_1$
238	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_2$
239	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_3$
240	$f_i \bar{f}_i \to \tilde{g} \tilde{\chi}_4$
241	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}_1^\pm$
242	$f_i \bar{f}_j \to \tilde{g} \tilde{\chi}_2^\pm$
243	$f_i \bar{f}_i \to \tilde{g} \tilde{g}$
244	$gg \to \tilde{g} \tilde{g}$
246	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_1$
247	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_1$
248	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_2$
249	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_2$

No.	Subprocess
250	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_3$
251	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_3$
252	$f_i g \to \tilde{q}_{iL} \tilde{\chi}_4$
253	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_4$
254	$f_i g \to \tilde{q}_{jL} \tilde{\chi}_1^\pm$
256	$f_i g \to \tilde{q}_{jL} \tilde{\chi}_2^\pm$
258	$f_i g \to \tilde{q}_{iL} \tilde{g}$
259	$f_i g \to \tilde{q}_{iR} \tilde{g}$
261	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}_1^*$
262	$f_i \bar{f}_i \to \tilde{t}_2 \tilde{t}_2^*$
263	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}_2^* +$
264	$gg \to \tilde{t}_1 \tilde{t}_1^*$
265	$gg \to \tilde{t}_2 \tilde{t}_2^*$
271	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jL}$
272	$f_i f_j \to \tilde{q}_{iR} \tilde{q}_{jR}$
273	$f_i f_j \to \tilde{q}_{iL} \tilde{q}_{jR} +$
274	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}_{j}^*{}_L$
275	$f_i \bar{f}_j \to \tilde{q}_{iR} \tilde{q}_{j}^*{}_R$
276	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}_{j}^*{}_R +$
277	$f_i \bar{f}_i \to \tilde{q}_{jL} \tilde{q}_{j}^*{}_L$
278	$f_i \bar{f}_i \to \tilde{q}_{jR} \tilde{q}_{j}^*{}_R$
279	$gg \to \tilde{q}_{iL} \tilde{q}_{i}^*{}_L$
280	$gg \to \tilde{q}_{iR} \tilde{q}_{i}^*{}_R$
281	$bq_i \to \tilde{b}_1 \tilde{q}_{iL}$
282	$bq_i \to \tilde{b}_2 \tilde{q}_{iR}$
283	$bq_i \to \tilde{b}_1 \tilde{q}_{iR} +$
284	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}_{i}^*{}_L$
285	$b\bar{q}_i \to \tilde{b}_2 \tilde{q}_{i}^*{}_R$
286	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}_{i}^*{}_R +$
287	$f_i \bar{f}_i \to \tilde{b}_1 \tilde{b}_1^*$
288	$f_i \bar{f}_i \to \tilde{b}_2 \tilde{b}_2^*$
289	$gg \to \tilde{b}_1 \tilde{b}_1^*$
290	$gg \to \tilde{b}_2 \tilde{b}_2^*$
291	$bb \to \tilde{b}_1 \tilde{b}_1$
292	$bb \to \tilde{b}_2 \tilde{b}_2$
293	$bb \to \tilde{b}_1 \tilde{b}_2$
294	$bg \to \tilde{b}_1 \tilde{g}$
295	$bg \to \tilde{b}_2 \tilde{g}$
296	$b\bar{b} \to \tilde{b}_1 \tilde{b}_2^* +$

The Les Houches Accord

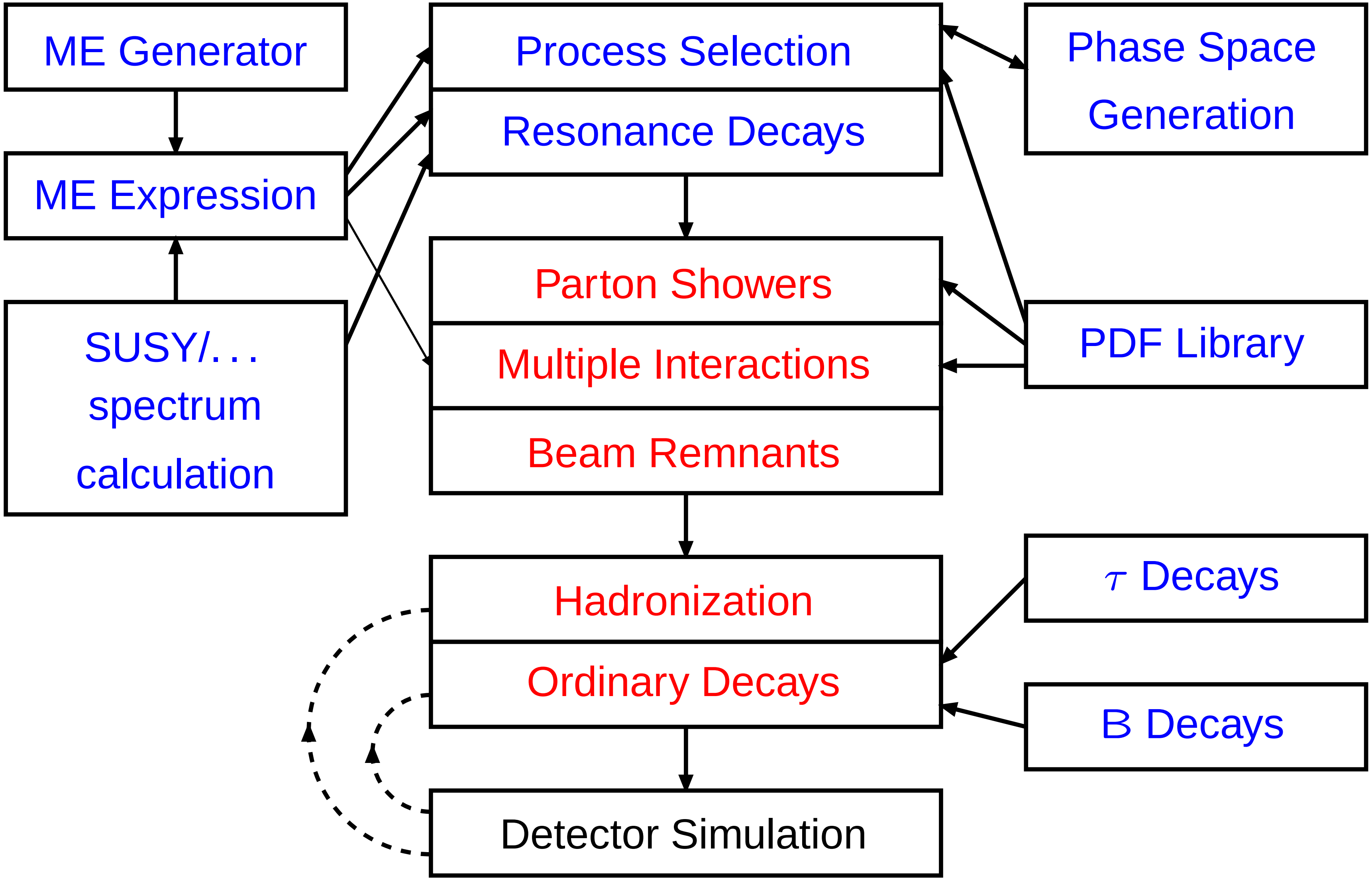


Some Specialized Generators:

- AcerMC: $\mathrm{t\bar{t}b\bar{b}}, \ldots$
- ALPGEN: $\mathrm{W/Z} + \leq 6\mathrm{j}$, $n\mathrm{W} + m\mathrm{Z} + k\mathrm{H} + \leq 3\mathrm{j}, \ldots$
- AMEGIC++: generic LO
- CompHEP: generic LO
- GRACE+Bases/Spring: generic LO+ some NLO loops
- GR@PPA: $\mathrm{b\bar{b}b\bar{b}}$
- MadCUP: $\mathrm{W/Z} + \leq 3\mathrm{j}, \mathrm{t\bar{t}b\bar{b}}$
- MadGraph+HELAS: generic LO
- MCFM: NLO $\mathrm{W/Z} + \leq 2\mathrm{j}$, $\mathrm{WZ}, \mathrm{WH}, \mathrm{H} + \leq 1\mathrm{j}$
- O'Mega+WHIZARD: generic LO
- VECBOS: $\mathrm{W/Z} + \leq 4\mathrm{j}$

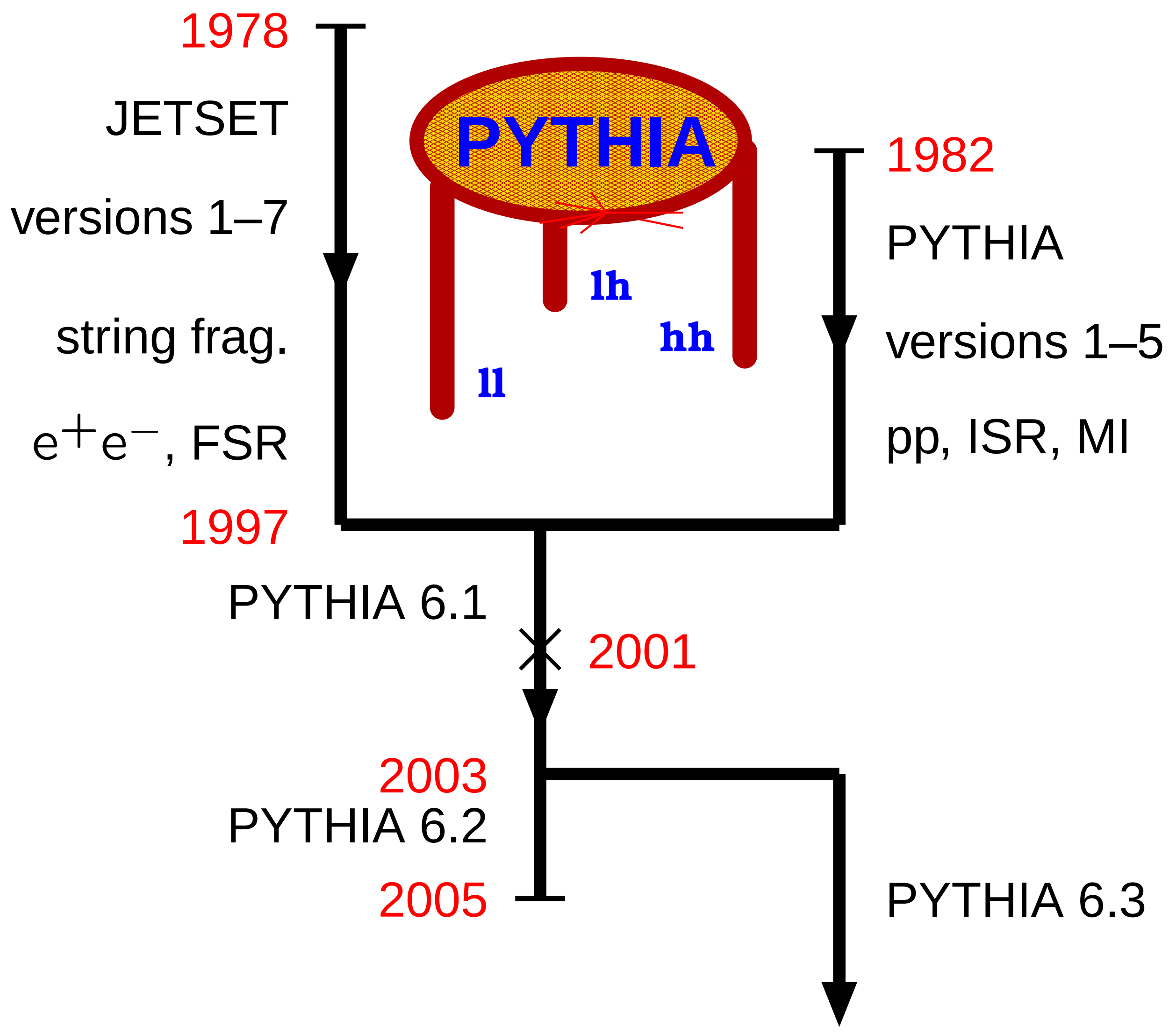
Apologies for all unlisted programs

The Bigger Picture



$\Longrightarrow$ need standardized interfaces (LHAPDF, SUSY LHA, . . .)

PYTHIA history



All in Fortran 77

Time axis
not to scale

PYTHIA standalone,
but other programs
rely on PYTHIA:
LEPTO
ARIADNE/LDC
RAPGAP/CASCADE
POMPYT
HIJING
SHERPA
EVTGEN
. . .

On To C++

Currently HERWIG and PYTHIA are successfully being used,
also in new LHC environments, using C++ wrappers

Q: Why rewrite?
A1: Need to clean up!
A2: Fortran 77 is limiting

Q: Why C++?
A1: All the reasons for ROOT, Geant4, . . .
("a better language", industrial standard, . . .)
A2: Young experimentalists will expect C++
(educational and professional continuity)
A3: Only game in town! Fortran 90

So far mixed experience:

- Conversion effort: everything takes longer and costs more
(as for LHC machine, detectors and software)
- The physics hurdle is as steep as the C++ learning curve

C++ Players

PYTHIA7 project $\Longrightarrow$ **ThePEG**

Toolkit for High Energy Physics Event Generation

(L. Lönnblad; S. Gieseke, A. Ribon, P. Richardson)

HERWIG++: complete reimplementation

(B.R. Webber; S. Gieseke, A. Ribon, P. Richardson,

M. Seymour, P. Stephens, 3 new)

ARIADNE/LDC: to do ISR/FSR showers, multiple interactions

(L. Lönnblad; N. Lavesson)

SHERPA: in C++ from start, partly wrappers to PYTHIA Fortran

(F. Krauss; T. Gleisberg, S. Hoeche, A. Schaelicke,

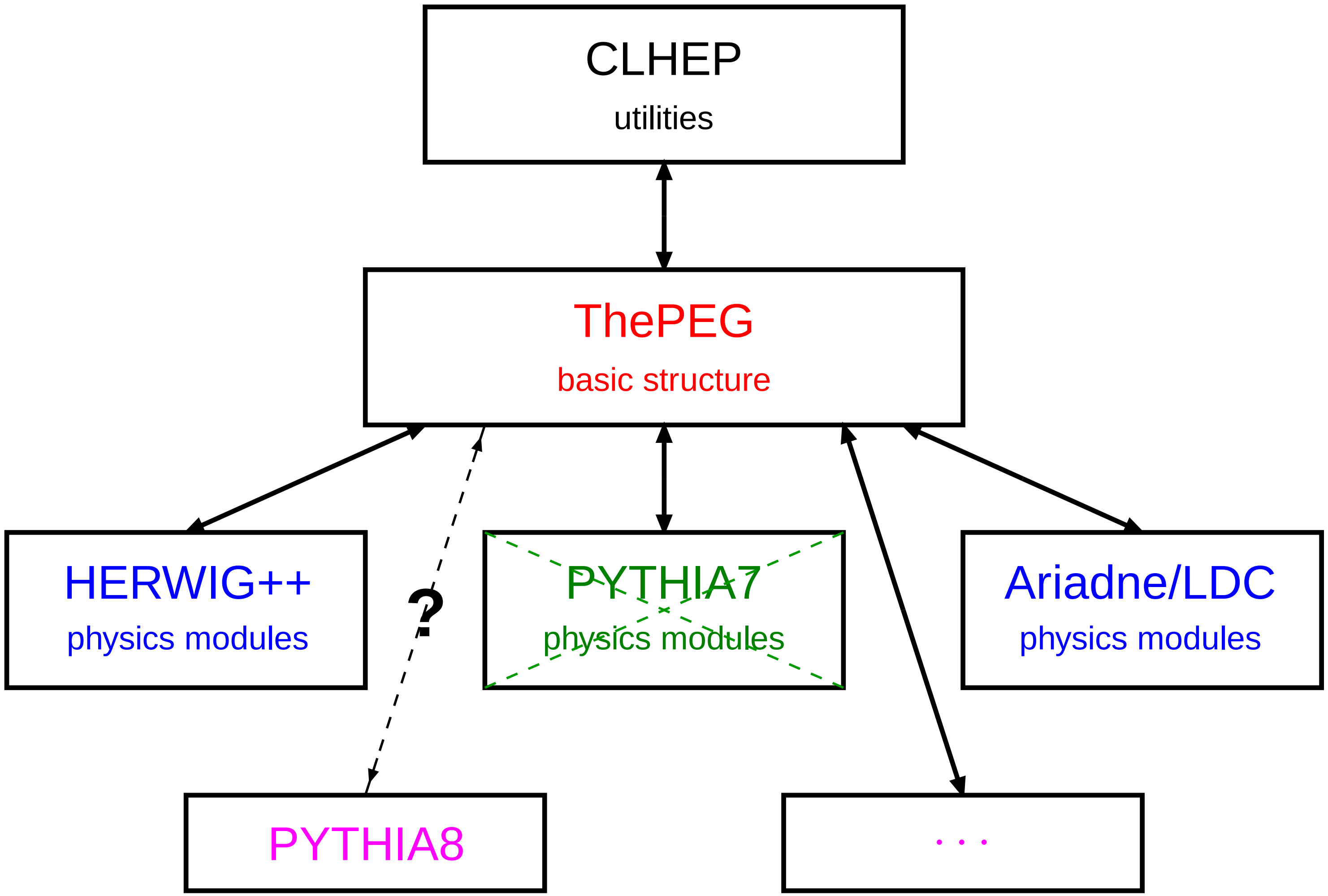
S. Schumann, J. Winter)

PYTHIA8: restart to write complete event generator

(T. Sjöstrand, (S. Mrenna?, P. Skands?))

What is ThePEG?

Toolkit for High Energy Physics Event Generation

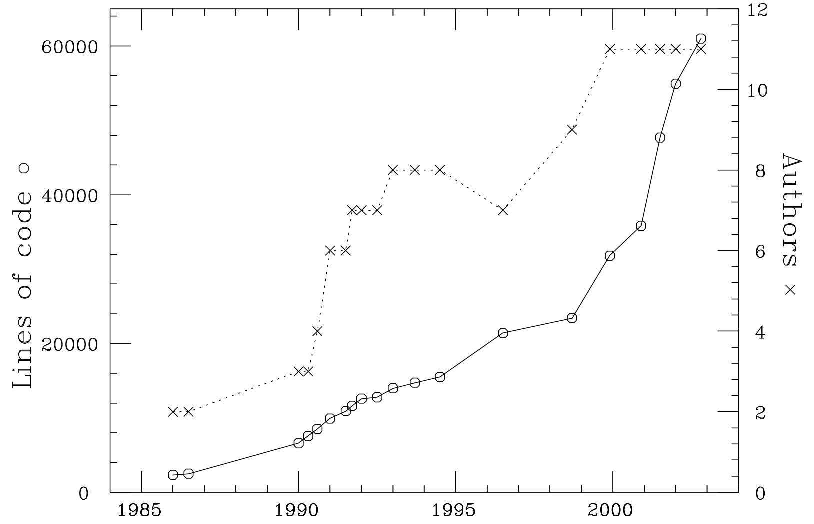


not SHERPA

The new generator Herwig++

A completely new event generator in C++

- Aiming at full multi–purpose generator for LHC and future colliders.
- Preserving main features of HERWIG such as
  - angular ordered parton shower
  - cluster hadronization
- New features and improvements
  - covariant shower formulation
  - improved parton shower evolution for heavy quarks
  - consistent radiation from unstable particles (multiscale evolution)



Growth of Fortran HERWIG

What's next?

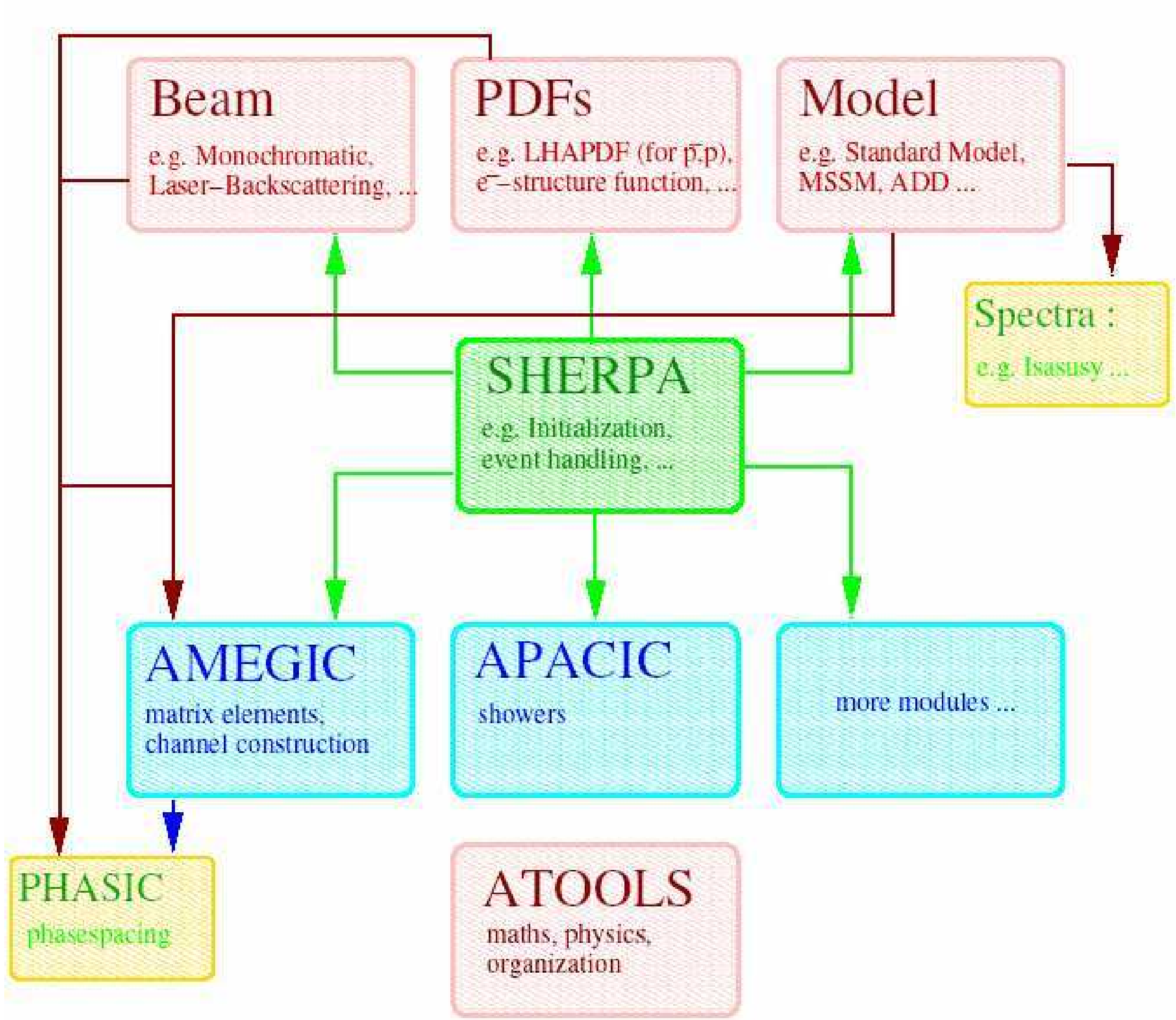
Near Future...

- ★ Initial state shower:
  - Complete implementation and tests.
- ★ Refine e^+e^-:
  - Full CKKW ME+PS matching.
  - Precision tune to LEP data should be possible.
- ★ with IS and FS showers running:
  - we can start to test Drell–Yan and jets in pp collisions.
  - cross check with Tevatron data and finally make predictions for the LHC.
- ★ Underlying Event.
- ★ Hadronic Decays: *NEW!* many new decayers, τ–decays, Spin correlations (P Richardson).
- ★ New Ideas: soft gluons, improved shower algorithm, NLO, . . .

Schedule?

- Ready for LHC!

SHERPA



Beam
e.g. Monochromatic,
Laser–Backscattering, ...
PDFs
e.g. LHAPDF (for p̄,p),
e⁻–structure function, ...
Model
e.g. Standard Model,
MSSM, ADD ...
Spectra :
e.g. Isasusy ...
SHERPA
e.g. Initialization,
event handling, ...
AMEGIC
matrix elements,
channel construction
APACIC
showers
more modules ...
PHASIC
phasespacing
ATOOLS
maths, physics,
organization

PYTHIA8: A fresh start

Problem: Leif not committed to PYTHIA, no other manpower

Solution?: take a sabbatical and work "full-time"!

Tentative schedule:

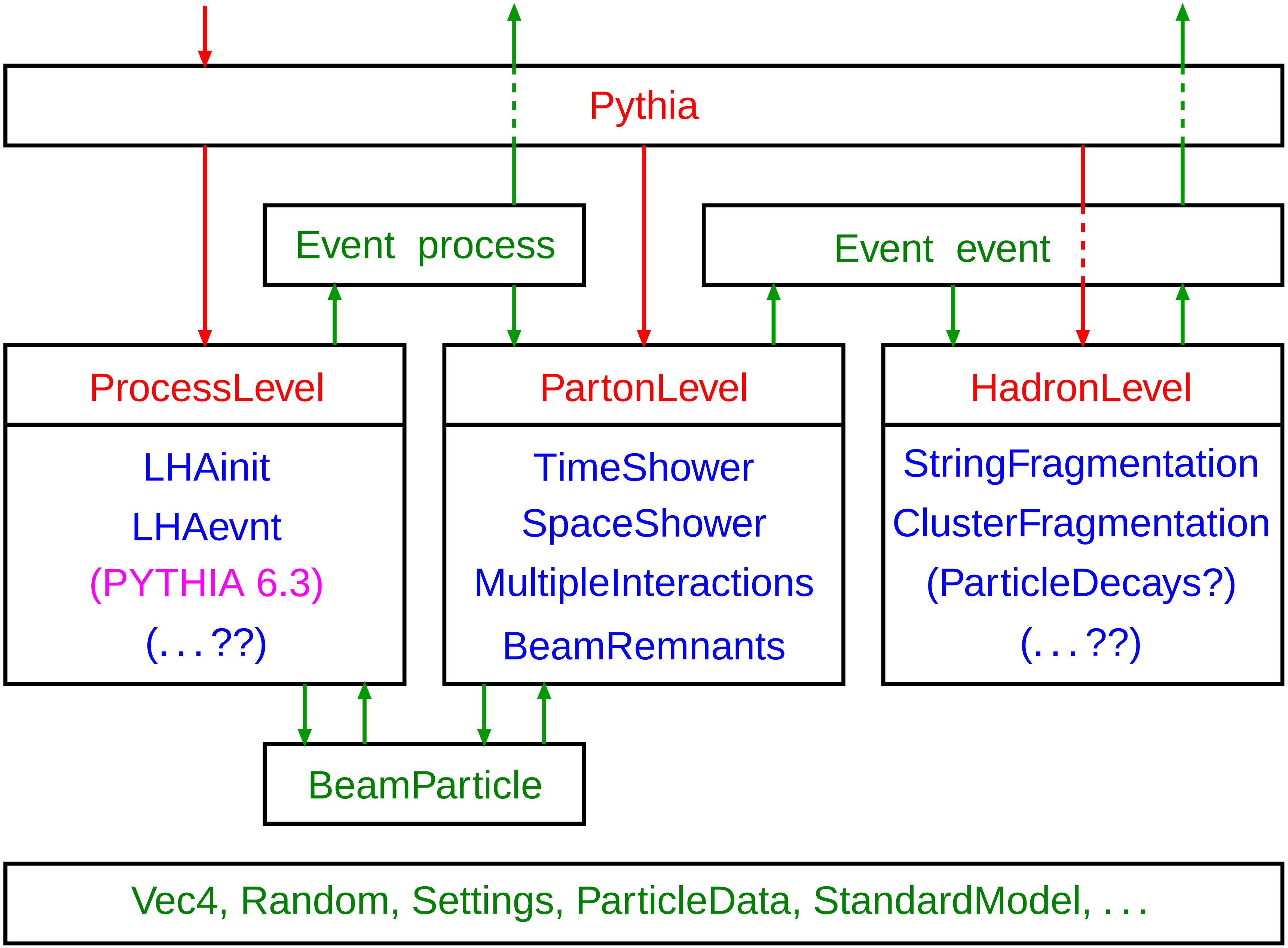
time	date	processes	final states
0 =	1 Sept. 2004	—	—
1 =	1 Sept. 2005	LHA-style input	incomplete draft
2 =	1 Sept. 2006	a few processes	complete, buggy(?)
3 =	1 Sept. 2007	more processes	stable, debugged

. . . but don't forget Murphy's law

Objectives:

- concentrate on physics, not administration
- clean up, keep the most recent models
- pure standard C++, no fancy programming tricks
- independent of ThePEG (or anything else), but
- Les Houches Accord style input central
- interface to ThePEG later written by Leif (?)

Current PYTHIA8 structure



Current PYTHIA8 status

Existing classes

Process Level	LHAinit	⋆
	LHAevnt	⋆⋆
	(PYTHIA 6.3)	⋆ ⋆ ⋆
Parton Level	TimeShower	⋆⋆
	SpaceShower	⋆⋆
	MultipleInteractions	⋆
	BeamRemnants	⋆
Hadron Level	StringFragmentation	⋆
	ClusterFragmentation	⋆
—	Event	⋆⋆
	BeamParticle	⋆⋆
	Vec4, Random	⋆ ⋆ ⋆
	Settings	⋆⋆
	ParticleData	⋆

Missing classes

ThePEG input, alternatively
Cross section administration
Phase space selection
Process matrix elements
Parton density libraries
Resonance decays
. . .

ME/PS matching

Junction fragmentation
ParticleDecays
Bose-Einstein
. . .

$\Longrightarrow$ Roughly according to three-year plan so far!
(1 year = no processes; 80% of other physics with 50% of the total effort)

Event generation structure

1) Initialization step

- select process(es) to study
- modify physics parameters: m_{t}, m_{h}, ...
- set kinematics constraints
- modify generator performance
- initialize generator
- book histograms

2) Generation loop

- generate one event at a time
- analyze it (or store for later use)
- add results to histograms
- print a few events

3) Finishing step

- print deduced cross-sections
- print/save histograms etc.

Sample run

Main program `test37.cc`, with run data in `test37.cmnd`:

```
#include "Pythia.h"

using namespace Pythia8;

int main() {

  // Generator. Shorthand for the event and the (static) Settings.
  Pythia pythia;
  Event& event = pythia.event;
  Settings& settings = pythia.settings;

  // Read in commands from external file.
  pythia.readFile("test37.cmnd");

  // Extract settings to be used in the main program.
  int idBeamA = settings.mode("Main:idBeamA");
  int idBeamB = settings.mode("Main:idBeamB");
  double eCM = settings.parameter("Main:eCM");
  int nEvent = settings.mode("Main:numberOfEvents");
  int nPrint = settings.mode("Main:numberToPrint");
  int nShow = settings.mode("Main:numberToShow");
  bool showChangedSettings = settings.flag("Main:showChangedSettings");
  bool showAllSettings = settings.flag("Main:showAllSettings");
```

```
// Initialization for Pythia6 event input.
pythia.init( idBeamA, idBeamB, eCM);

// List changed data.
if (showChangedSettings) settings.listChanged();
if (showAllSettings) settings.listAll();

// Histograms.
double epTol = 1e-8 * eCM;
Hist epCons("deviation from energy-momentum conservation",100,0.,epTol);
Hist nFinal("final particle multiplicity",100,-0.5,499.5);
Hist dnparticledy("dn/dy for particles",100,-10.,10.);

// Begin event loop.
int nPace = max(1,nEvent/nShow);
for (int iEvent = 0; iEvent < nEvent; ++iEvent) {
  if (iEvent%nPace == 0) cout << " Now begin event " << iEvent << "\n";

  // Generate events. Quit if failure.
  if (!pythia.next()) {
    cout << " Event generation aborted prematurely, owing to error!\n";
    break;
  }

  // List first few events, both hard process and complete events.
  if (iEvent < nPrint) {
    pythia.process.list();
    event.list();
  }
```

```
    // Loop over final particles in the event.
    int nFin = 0;
    Vec4 pSum;
    for (int i = 0; i < event.size(); ++i) if (event[i].remains()) {
      nFin++;
      pSum += event[i].p();
      dnparticledy.fill(event[i].y());
    }

    // Check and print event with too big energy-momentum deviation.
    nFinal.fill(nFin);
    double epDev = abs(pSum.e() - eCM) + abs(pSum.px()) + abs(pSum.py())
      + abs(pSum.pz());
    epCons.fill(epDev);
    if (epDev > epTol) {
      cout << " Warning! Event with epDev = " << scientific
           << setprecision(4) << epDev << " now listed:";
      event.list();
    }

  // End of event loop.
  }

  // Final statistics and histogram output.
  pythia.statistics();
  cout << epCons << nFinal << dnparticledy;

  return 0;
}
```

Sample input cards

```
! This file contains commands to be read in for a Pythia8 run.
! Lines not beginning with a letter are comments.

! 1) Settings that could be used in a main program, if desired.
Main:idBeamA = 2212                    ! first beam, p = 2212, pbar = -2212
Main:idBeamB = 2212                    ! second beam, p = 2212, pbar = -2212
Main:eCM = 14000.                      ! CM energy of collision
Main:numberOfEvents = 1000             ! number of events to generate
Main:numberToPrint = 2                 ! number of events to print
Main:numberToShow = 50                 ! show how far along run is
Main:showChangedSettings = on          ! print changed flags/modes/parameters
Main:showAllSettings = off             ! print all flags/modes/parameters

! 2) Settings for the hard-process generation.
! Based on an interface to the Fortran Pythia6 program.
#Pythia6:msel = 1                       ! QCD production
#Pythia6:ckin(3) = 100.                  ! pTmin cut
Pythia6:msel = 6                       ! t tbar production

! 3) Settings for the event generation process in the Pythia8 library.
#PartonLevel:MI = off                   ! no multiple interactions
#PartonLevel:ISR = off                  ! no initial-state radiation
PartonLevel:FSR = off                  ! no final-state radiation
#HadronLevel:Hadronize = off            ! no hadronization
SpaceShower:pT0 = 2.0                  ! dampening of pT -> 0 divergence
MultipleInteractions:pTmin = 3.0       ! lower pT cutoff for interactions
```

Sample output from run

```
--------  Pythia Flag + Mode + Parameter Settings (changes only)  ----------------

  Kind  Name                                          Now   Default       Min       Max
double  Main:eCM                                 1.40e+04 2000.0000    0.0000  1.00e+05
double  MultipleInteractions:pTmin                 3.0000    2.0000    0.5000   10.0000
  bool  PartonLevel:FSR                               off        on
double  SpaceShower:pT0                            2.0000    0.5000    0.0000   10.0000

--------  End Pythia Flag + Mode + Parameter Settings  ---------------------------

--------  Pythia Event Listing  (hard process)  -----------------------------------

   no        id   name          status     mothers   daughters     colours      p_x
    0        90   (system)         -11     0     0     0     0     0     0      0.000
    1      2212   (p+)             -12     0     0     3     0     0     0      0.000
    2      2212   (p+)             -12     0     0     4     0     0     0      0.000
    3        21   (g)              -21     1     0     5     6   101   102      0.000
    4        21   (g)              -21     2     0     5     6   103   101      0.000
    5        -6   (tbar)           -22     3     4     7     8     0   102   -107.572
    6         6   (t)              -22     3     4     9    10   103     0    107.572
    7       -24   (W-)             -22     5     0    11    12     0     0    -71.772
    8        -5   bbar              23     5     0     0     0     0   102    -35.799
    9        24   (W+)             -22     6     0    13    14     0     0    113.539
   10         5   b                 23     6     0     0     0   103     0     -5.968
   11        11   e-                23     7     0     0     0     0     0    -38.516
   12       -12   nu_ebar           23     7     0     0     0     0     0    -33.256
   13        -1   dbar              23     9     0     0     0     0   104     24.321
   14         2   u                 23     9     0     0     0   104     0     89.218
                                                                     Sum:     -0.000
--------  End Pythia Event Listing  ----------------------------------------------
```

```
--------  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  14000.000  14000.000
     1      2212   (p+)               -12     0     0   187     0     0     0      0.000      0.000   7000.000   7000.000      0.938
     2      2212   (p+)               -12     0     0   188     0     0     0      0.000      0.000  -7000.000   7000.000      0.938
     3        21   (g)                -21     7     0     5     6   101   102      0.000      0.000     53.792     53.792      0.000
     4        21   (g)                -21     8     8     5     6   103   101      0.000      0.000   -829.022    829.022      0.000
     5        -6   (tbar)             -22     3     4     9     9     0   102   -107.572    -45.614   -345.827    404.638    174.595
     6         6   (t)                -22     3     4    10    10   103     0    107.572     45.614   -429.402    478.176    174.969
     7        21   (g)                -41    12    12    11     3   105   102     -0.000     -0.000     76.351     76.351      0.000
     8        21   (g)                -42    13     0     4     4   103   101     -0.000      0.000   -829.022    829.022      0.000
     9        -6   (tbar)             -44     5     5    14    14     0   102   -127.853    -17.612   -332.165    396.829    174.595
    10         6   (t)                -44     6     6    15    15   103     0     90.752     68.837   -379.579    433.208    174.969
    11        21   (g)                -43     7     0    16    16   105   101     37.101    -51.226    -40.927     75.336      0.000
   (skipped)
    63        21   (g)                -31   111     0    65    66   112   111      0.000      0.000      0.070      0.070      0.000
    64        -4   (cbar)             -31   112   112    65    66     0   110      0.000      0.000   -926.957    926.957      0.000
    65        21   (g)                -33    63    64   113   113   112   110      5.011     -0.788   -104.687    104.810      0.000
    66        -4   (cbar)             -33    63    64   114   114     0   111     -5.011      0.788   -822.200    822.217      1.500
   (skipped)
   237      2101   (ud_0)             -63     1     0     0     0     0   137      0.240     -0.007   3177.306   3177.306      0.579
   238        -1   (dbar)             -63     1     0     0     0     0   124      1.153     -0.432    839.002    839.003      0.330
   239      2101   (ud_0)             -63     2     0     0     0     0   142     -1.091      0.128  -2613.733   2613.733      0.579
   240         4   (c)                -63     2     0     0     0   142     0     -0.557      1.321   -174.031    174.043      1.500
   (skipped)
   241       -24   (W-)               -22   195     0   245   245     0     0   -102.292    -46.372   -349.729    376.307     81.747
   242        -5   (bbar)             -23   195     0   243   244     0   102    -39.504     23.812     -8.300     47.111      4.800
   243        -5   (bbar)             -51   242     0   248   248     0   144    -26.921     15.510     -8.835     32.656      4.800
   244        21   (g)                -51   242     0   246   247   144   102    -12.740      8.184     -0.143     15.143      0.000
   245       -24   (W-)               -52   241   241   263   264     0     0   -102.135    -46.255   -349.051    375.619     81.747
   (skipped)
   263        11   (e-)               -23   245     0   265   266     0     0    -49.476     20.517   -126.258    137.149      0.001
   264       -12   (nu_ebar)          -23   245     0   267   267     0     0    -52.659    -66.772   -222.793    238.470      0.000
   265        11   e-                  51   263     0     0     0     0     0    -48.966     20.308   -124.957    135.736      0.001
   266        22   gamma               51   263     0     0     0     0     0     -0.510      0.210     -1.301      1.413      0.000
   267       -12   nu_ebar             52   264   264     0     0     0     0    -52.659    -66.772   -222.793    238.470      0.000
   (skipped)
   285       323   K*+                 73   247     0     0     0     0     0     -8.774      4.484     -1.202      9.966      0.892
   286       533   B*_s0               73   248     0     0     0     0     0    -24.787     14.045     -6.657     29.754      5.416
   287       423   D*0                 73   240     0     0     0     0     0     -0.604      1.434   -307.590    307.600      2.007
   288       223   omega               73   240     0     0     0     0     0     -0.097     -0.243   -316.742    316.743      0.782
   289       113   rho0                73   239     0     0     0     0     0     -0.424     -0.021   -525.177    525.178      0.768
   290      2212   p+                  73   239     0     0     0     0     0     -0.522      0.279  -1638.254   1638.254      0.938
   (skipped)
   490       223   omega               73   237     0     0     0     0     0      0.481     -0.049    154.560    154.563      0.782
   491      2212   p+                  73   237     0     0     0     0     0     -0.269     -0.100   2588.971   2588.972      0.938
                                                                   Sum:     -0.000     -0.000     -0.000  14000.000  14000.000
--------  End Pythia Event Listing  -----------------------------------------------------------------------------------------------
```

Sample run with Les Houches input

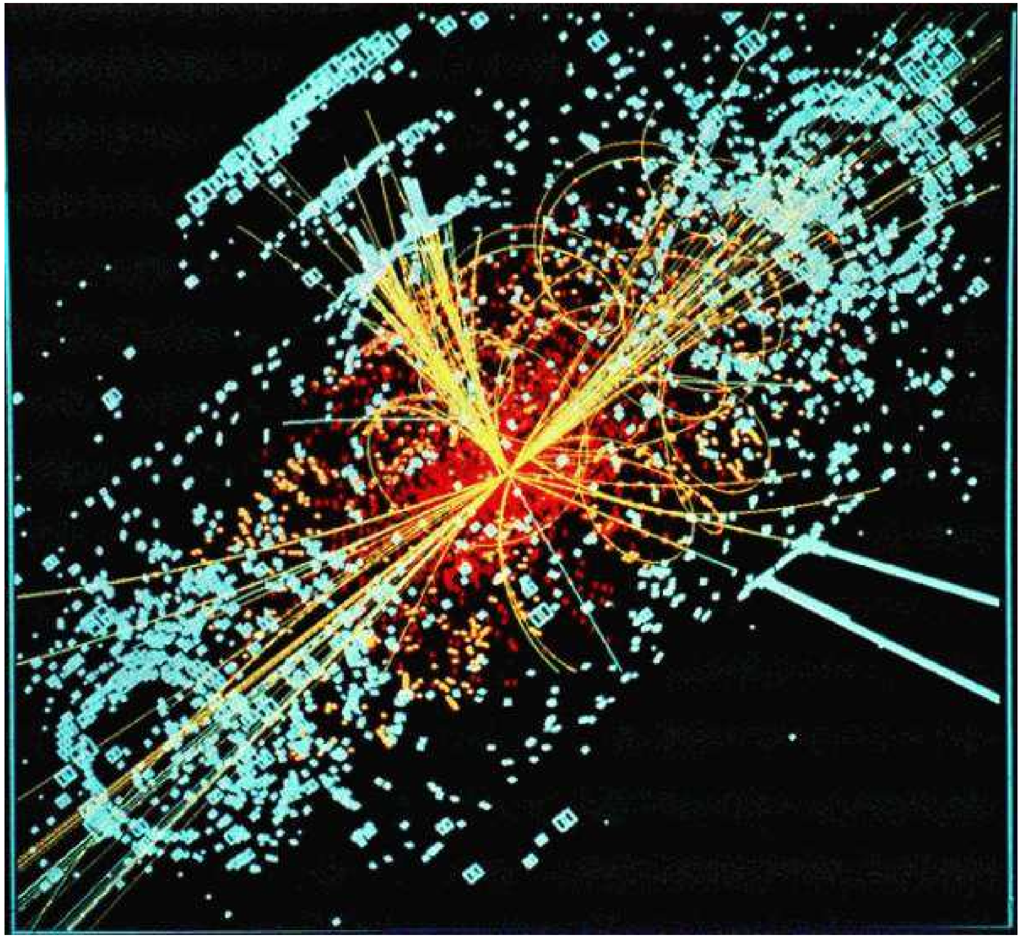
```
#include "Pythia.h"
using namespace Pythia8;
int main() {

  int nPrint = 2;                                // Number of events to print.
  Pythia pythia;                                 // Generator.
  pythia.readLine("PartonLevel:MI = off");      // No multiple interactions.
  pythia.readLine("SpaceShower:pTmin = 1.0");   // Change pTmin cutoff of ISR.
  LHAinitPythia6 lhaInit("sample.init");        // Les Houches initialization object.
  LHAevntPythia6 lhaEvnt("sample.evnt");        // Les Houches event object.
  pythia.init(&lhaInit, &lhaEvnt);              // Initialize with pointers.
  cout << lhaInit;                               // List initialization information.
  Hist nFinal("final particle multiplicity",100,-0.5,499.5);        // Histogram.

  int iEvent = 0;                                // Begin event loop
  while (pythia.next()) {                        // Generate event until none left.
    if (iEvent++ < nPrint) {                     // List first few events.
      cout << lhaEvnt;                           // List Les Houches input event.
      pythia.process.list();                     // List Pythia hard-process event.
      pythia.event.list();                       // List Pythia complete event.
    }                                            // End listing.
    int nFin = 0;                                // Sum up final multiplicity
    for (int i = 0; i < pythia.event.size(); ++i)
      if (pythia.event[i].remains()) nFin++;
    nFinal.fill(nFin);                           // Fill histogram.
  }                                              // End of event loop.

  cout << nFinal;                                // Print histogram.
  return 0;                                      // Done.
}
```

C++ Issues (bones of contention)

- not extreme object orientation: physics is "procedural" $\approx$ "time ordered"
- standalone $\Rightarrow$ reduced dependency problems, simpler debugging
- try to limit "code fragmentation" and "code indirection"
- header files is having humans do compiler work
- ˆ for bitwise XOR is bad, pow() is bad, pow(x,2) a disgrace
- string is good, char[] is bad
- references are good, pointers are dangerous
- vector$<>$ is good, new/delete are dangerous
- indexed loops are good, iterators are cumbersome
- first element always at index zero is bad
- operator overloading is good, if used sparingly, e.g. Vec4
- recipes for chaos: typedef's, 6 different integer types, $\ldots$
- How much use static classes & shared data?
  So far Random, Settings, ParticleData
- Generalize cout (cerr) to file alternative?
- What kind of licence to use?
  Want: free access to study, but not free licence to steal

Summary and Outlook

PYTHIA8 roughly on track with three-year plan.
First public “proof-of-concept” version by GENSER July meeting (!?)



But always remember:
physics is complex,
events are complex,
so generators
have to be complex!
Plenty of room for

and other delays.