LUND UNIVERSITY

Les Houches Workshop:
Physics at TeV Colliders
21 May – 1 June 2001

PYTHIA
Status Report

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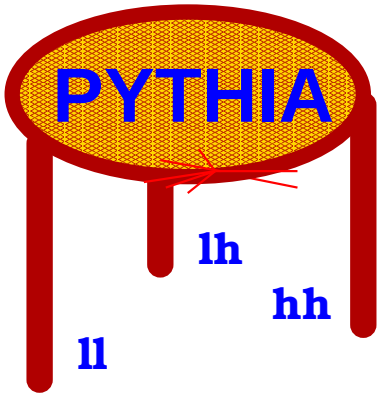


JETSET 7.4
PYTHIA 5.7
SPYTHIA

} 4 March 1997 : → PYTHIA 6.1

Currently PYTHIA 6.158 of 5 April 2001
$\sim 53,100$ lines Fortran 77

Code, manuals, sample main programs:

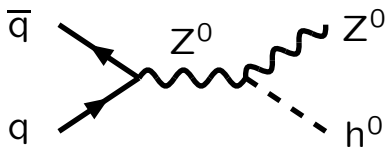
`www.thep.lu.se/~torbjorn/Pythia.html`

short writeup in T. Sjöstrand, P. Edén, C. Friberg,
L. Lönnblad, G. Miu, S. Mrenna and E. Norrbin
Computer Phys. Commun. **135** (2001) 238
[hep-ph/0010017]

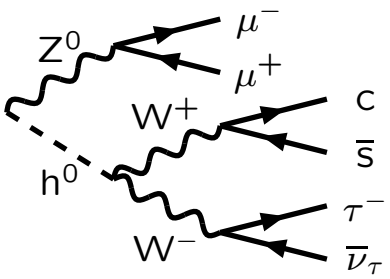
Event physics overview

Structure of the basic generation process:

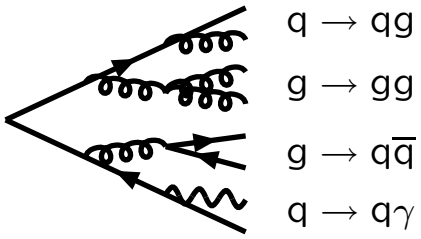
1) Hard subprocess:
$d\hat{\sigma}/d\hat{t}$, Breit-Wigners



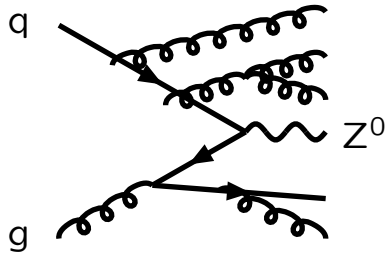
2) Resonance decays:
includes correlations
(where implemented)



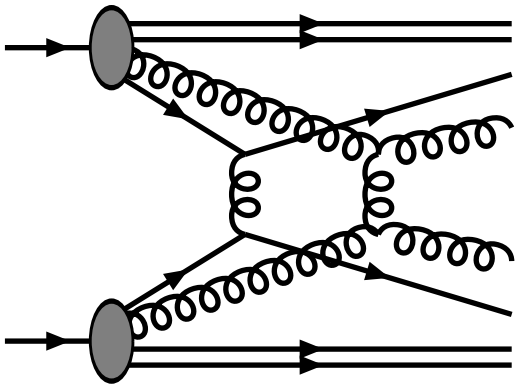
3) Final-state
parton showers:
(or matrix elements)



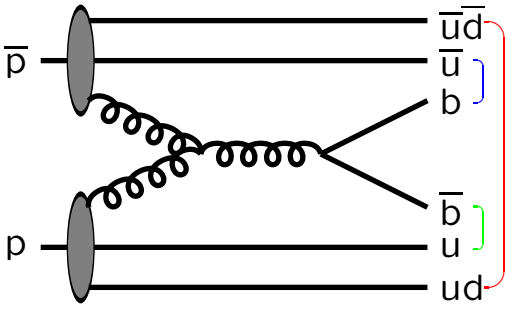
4) Initial-state
parton showers:
(or matrix elements)



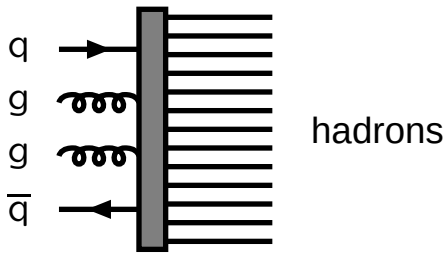
5) Multiple
parton–parton
interactions



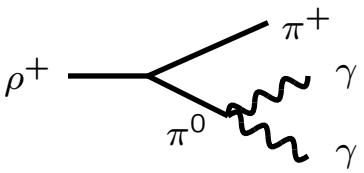
6) Beam remnants:
colour-connected
to rest of event



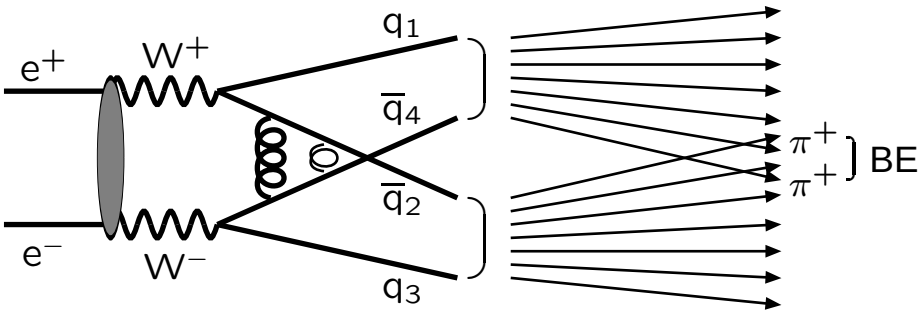
7) Hadronization
(or fragmentation)



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



9) QCD interconnection effects:



a) colour rearrangement ($\Rightarrow$ rapidity gaps?);
b) Bose-Einstein (within & between strings).

10) The forgotten/unexpected: a chain is
never stronger than its weakest link!

Subprocess summary

Processes	Examples
QCD & related	
Soft QCD	low-$p_\perp$; diffraction
Hard QCD	$qg \to qg$
Open heavy flavour	$q\bar{q} \to t\bar{t}$
Closed heavy flavour	$gg \to gJ/\psi$
$\gamma\gamma$ physics	$\gamma q \to qg$
DIS	$\gamma^* q \to q$
$\gamma^*\gamma^*$ physics	$\gamma^*_T\gamma^*_L \to q\bar{q}$
Electroweak SM	
Single $\gamma^*/Z^0/W^\pm$	$q\bar{q} \to \gamma^*/Z^0$
$(\gamma/\gamma^*/Z^0/W^\pm/f/g)^2$	$q\bar{q} \to W^+W^-$
Light SM Higgs	$gg \to h^0$
Heavy SM Higgs	$Z^0_L Z^0_L \to W^+_L W^-_L$
SUSY BSM	
$h^0/H^0/A^0/H^\pm$	$q\bar{q} \to h^0 A^0$
SUSY	$q\bar{q}' \to \tilde{\chi}^0_i \tilde{\chi}^\pm_j$
RSUSY	(in progress)
Other BSM	
Technicolor	$q\bar{q}' \to \pi^0_{tc}\pi^\pm_{tc}$
New gauge bosons	$q\bar{q} \to \gamma^*/Z^0/Z'^0$
Compositeness	$q\bar{q} \to e^\pm e^{*\mp}$
Leptoquarks	$qg \to \ell L_Q$
$H^{\pm\pm}$ (from LR-sym.)	$q\bar{q} \to H^{++}H^{--}$
Extra dimensions	$gg \to G^* \to e^+e^-$

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	$f_i \bar{f}_i \to Q_k \overline{Q}_k$
82	$gg \to Q_k \overline{Q}_k$
83	$q_i f_j \to Q_k f_l$
84	$g\gamma \to Q_k \overline{Q}_k$
85	$\gamma\gamma \to F_k \overline{F}_k$
	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	$f_i \gamma \to f_i Z^0$
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	$gg \to g\gamma$
	Deep inelastic scatt.:
10	$f_i f_j \to f_i f_j$
99	$\gamma^* f_i \to f_i$
	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	$\gamma_T^* \gamma_L^* \to f_i \bar{f}_i$

No.	Subprocess
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	$f_i \bar{f}_j \to W^\pm h^0$
102	$gg \to h^0$
103	$\gamma\gamma \to h^0$
110	$f_i \bar{f}_i \to \gamma h^0$
121	$gg \to Q_k \overline{Q}_k h^0$
122	$q_i \bar{q}_i \to Q_k \overline{Q}_k h^0$
123	$f_i f_j \to f_i f_j h^0$
124	$f_i f_j \to f_k f_l h^0$
	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 Higgses:
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	$gg \to Q_k \overline{Q}_k H^0$
182	$q_i \bar{q}_i \to Q_k \overline{Q}_k H^0$
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	$gg \to Q_k \overline{Q}_k A^0$
187	$q_i \bar{q}_i \to Q_k \overline{Q}_k A^0$
	Charged Higgs:
143	$f_i \bar{f}_j \to H^+$
161	$f_i g \to f_k H^+$
	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	$f_i \bar{f}_i \to H^+ H^-$
	Doubly-charged Higgs:
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	$f_i f_j \to f_k f_l H_R^{\pm\pm}$
	New gauge bosons:
141	$f_i \bar{f}_i \to \gamma/Z^0/Z'^0$
142	$f_i \bar{f}_j \to W'^+$
144	$f_i \bar{f}_j \to R$

No.	Subprocess
	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	$f_i \bar{f}_j \to W^\pm \pi'^0_{tc}$
	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	$f_i \bar{f}_j (\to W^\pm) \to f_k \bar{f}_l$
	Leptoquarks:
145	$q_i \ell_j \to L_Q$
162	$qg \to \ell L_Q$
163	$gg \to L_Q \overline{L}_Q$
164	$q_i \bar{q}_i \to L_Q \overline{L}_Q$
	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	$f_i \bar{f}_i \to \tilde{\tau}_1 \tilde{\tau}_2^* +$
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	$f_i \bar{f}_i \to \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp$

No.	Subprocess
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	$f_i g \to \tilde{q}_{iR} \tilde{\chi}_2$
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	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}_{jL}^*$
275	$f_i \bar{f}_j \to \tilde{q}_{iR} \tilde{q}_{jR}^*$
276	$f_i \bar{f}_j \to \tilde{q}_{iL} \tilde{q}_{jR}^* +$
277	$f_i \bar{f}_i \to \tilde{q}_{jL} \tilde{q}_{jL}^*$
278	$f_i \bar{f}_i \to \tilde{q}_{jR} \tilde{q}_{jR}^*$
279	$gg \to \tilde{q}_{iL} \tilde{q}_{iL}^*$
280	$gg \to \tilde{q}_{iR} \tilde{q}_{iR}^*$
281	$bq_i \to \tilde{b}_1 \tilde{q}_{iL}$
282	$bq_i \to \tilde{b}_2 \tilde{q}_{iR}$
283	$bq_i \to \tilde{b}_1 \tilde{q}_{iR} + \tilde{b}_2 \tilde{q}_{iL}$
284	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}_{iL}^*$
285	$b\bar{q}_i \to \tilde{b}_2 \tilde{q}_{iR}^*$
286	$b\bar{q}_i \to \tilde{b}_1 \tilde{q}_{iR}^* + \tilde{b}_2 \tilde{q}_{iL}^*$
287	$q_i \bar{q}_i \to \tilde{b}_1 \tilde{b}_1^*$
288	$q_i \bar{q}_i \to \tilde{b}_2 \tilde{b}_2^*$
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	$b\bar{b} \to \tilde{b}_1 \tilde{b}_2^* +$
	Extra dimensions:
391	$f_i \bar{f}_i \to G^*$
392	$gg \to G^*$
393	$q_i \bar{q}_i \to gG^*$
394	$q_i g \to q_i G^*$
395	$gg \to gG^*$

Final-state showers

Default PYTHIA:
evolution in $Q^2 = m^2$
+ veto against non-ordered emissions
z is energy sharing in branching (approx.)

Not as sophisticated algorithm as HERWIG or ARIADNE (dipole emission ordered in $p_\perp^2$, can be used with PYTHIA), but

- robust and flexible
- describes e^+e^- data up to LEP 2 well
- g emissions cover all of phase space

$\Rightarrow$ merging with first-order matrix elements

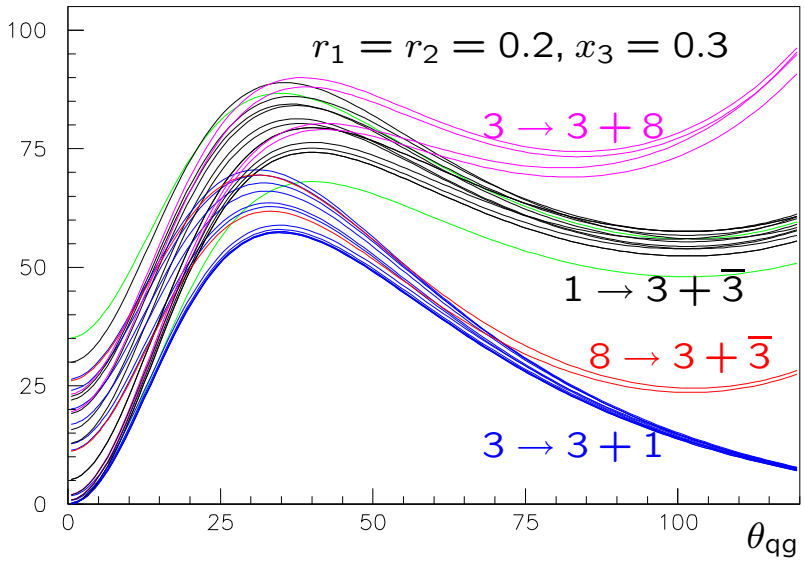
Merging with $\gamma^*/Z^0 \to q\bar{q}g$ since long
(M. Bengtsson & TS, PLB185 (1987) 435, NPB289 (1987) 810)

Problems with $\gamma^*/Z^0 \to b\bar{b}g$ noted recently
$\Rightarrow$ corrected description of mass effects,
extended to $1 \to 2$ processes in SM + MSSM
(E. Norrbin & TS, LUTP 00-42 [hep-ph/0010012] $\Rightarrow$ NPB)
Process-dependent input from calculations of

$$W^{ME}(x_1, x_2) = \frac{1}{\sigma(a \to bc)} \frac{d\sigma(a \to bcg)}{dx_1\, dx_2}$$

so that shower now depends on
mass ratios $r_1 = m_b/m_a$ and $r_2 = m_c/m_a$,
colour and spin structure, and 'parity' (γ_5)

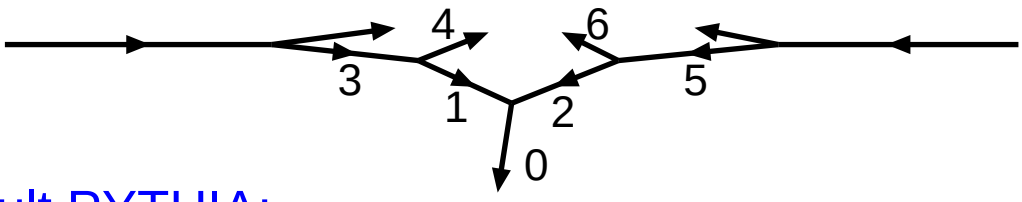
colour	spin	γ_5	example
$1 \to 3 + \bar{3}$	—	—	(eikonal)
$1 \to 3 + \bar{3}$	$1 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$Z^0 \to q\bar{q}$
$3 \to 3 + 1$	$\frac{1}{2} \to \frac{1}{2} + 1$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to bW^+$
$1 \to 3 + \bar{3}$	$0 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$H^0 \to q\bar{q}$
$3 \to 3 + 1$	$\frac{1}{2} \to \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to bH^+$
$1 \to 3 + \bar{3}$	$1 \to 0 + 0$	1	$Z^0 \to \tilde{q}\bar{\tilde{q}}$
$3 \to 3 + 1$	$0 \to 0 + 1$	1	$\tilde{q} \to \tilde{q}'W^+$
$1 \to 3 + \bar{3}$	$0 \to 0 + 0$	1	$H^0 \to \tilde{q}\bar{\tilde{q}}$
$3 \to 3 + 1$	$0 \to 0 + 0$	1	$\tilde{q} \to \tilde{q}'H^+$
$1 \to 3 + \bar{3}$	$\frac{1}{2} \to \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$\chi \to q\bar{\tilde{q}}$
$3 \to 3 + 1$	$0 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{q} \to q\chi$
$3 \to 3 + 1$	$\frac{1}{2} \to 0 + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to \tilde{t}\chi$
$8 \to 3 + \bar{3}$	$\frac{1}{2} \to \frac{1}{2} + 0$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{g} \to q\bar{\tilde{q}}$
$3 \to 3 + 8$	$0 \to \frac{1}{2} + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{q} \to q\tilde{g}$
$3 \to 3 + 8$	$\frac{1}{2} \to 0 + \frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to \tilde{t}\tilde{g}$



$W^{ME}(x_1, x_2)$

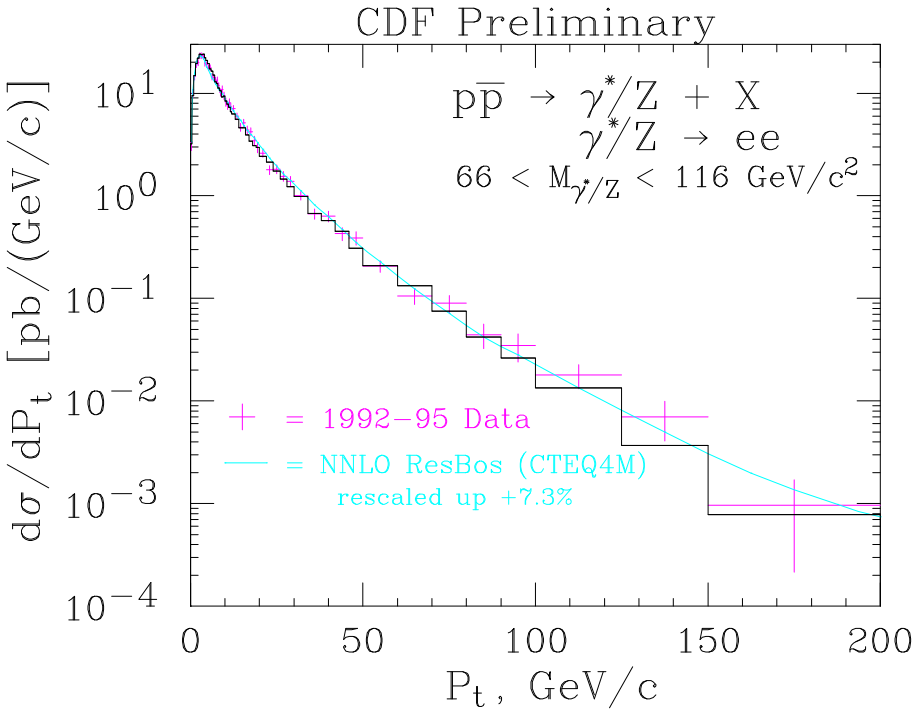
g emission rate for different colour, spin and parity structures

Initial-state showers



Default PYTHIA:
backwards evolution in $Q^2 = -m^2$
+ approximate angular ordering veto
z is $\hat{s}$ reduction by branching
(interleaved between two sides)

Merged with matrix elements for
$q\bar{q} \to (\gamma^*/Z^0/W^\pm)g$ and $qg \to (\gamma^*/Z^0/W^\pm)q'$:
(G. Miu & TS, PLB449 (1999) 313)



curve=ResBos

black=PYTHIA

$K_{\text{PYTHIA}} = 1.4$

$Q^2_{\text{max}} = s$

C. Balázs, J. Huston and I. Puljak, PRD63 (2001) 014021

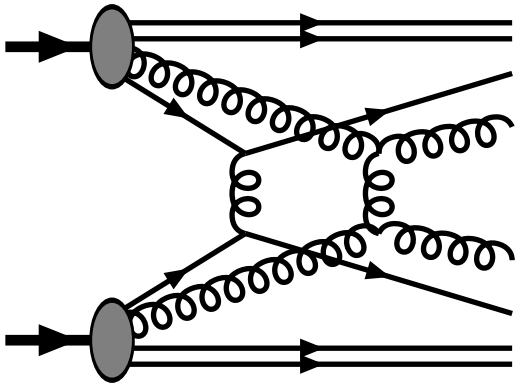
Modified algorithm also affects other processes

Multiple interactions

(TS & M. van Zijl, PRD36 (1987) 2019,

J. Dischler & TS, EPJdir C2 (2001) 1)

Consequence of composite nature of hadrons:



Evidence:

- direct observation: AFS, UA1, CDF
- implied by width of multiplicity distribution + jet universality: UA5
- forward–backward correlations: UA5
- pedestal effect: UA1, H1

(At least) one new free parameter: $p_{\perp\min}$

$$\frac{1}{2}\sigma_{\text{jet}} = \int_{p^2_{\perp\min}}^{s/4} \frac{\mathrm{d}\sigma}{\mathrm{d}p^2_\perp}\,\mathrm{d}p^2_\perp$$

$$\Leftarrow \int_0^{s/4} \frac{\mathrm{d}\sigma}{\mathrm{d}p^2_\perp}\,\frac{p^4_\perp}{(p^2_{\perp 0}+p^2_\perp)^2}\,\mathrm{d}p^2_\perp$$

Measure of colour screening length d in hadron

$p_{\perp\min}\,\langle d\rangle \approx 1 (= \hbar)$

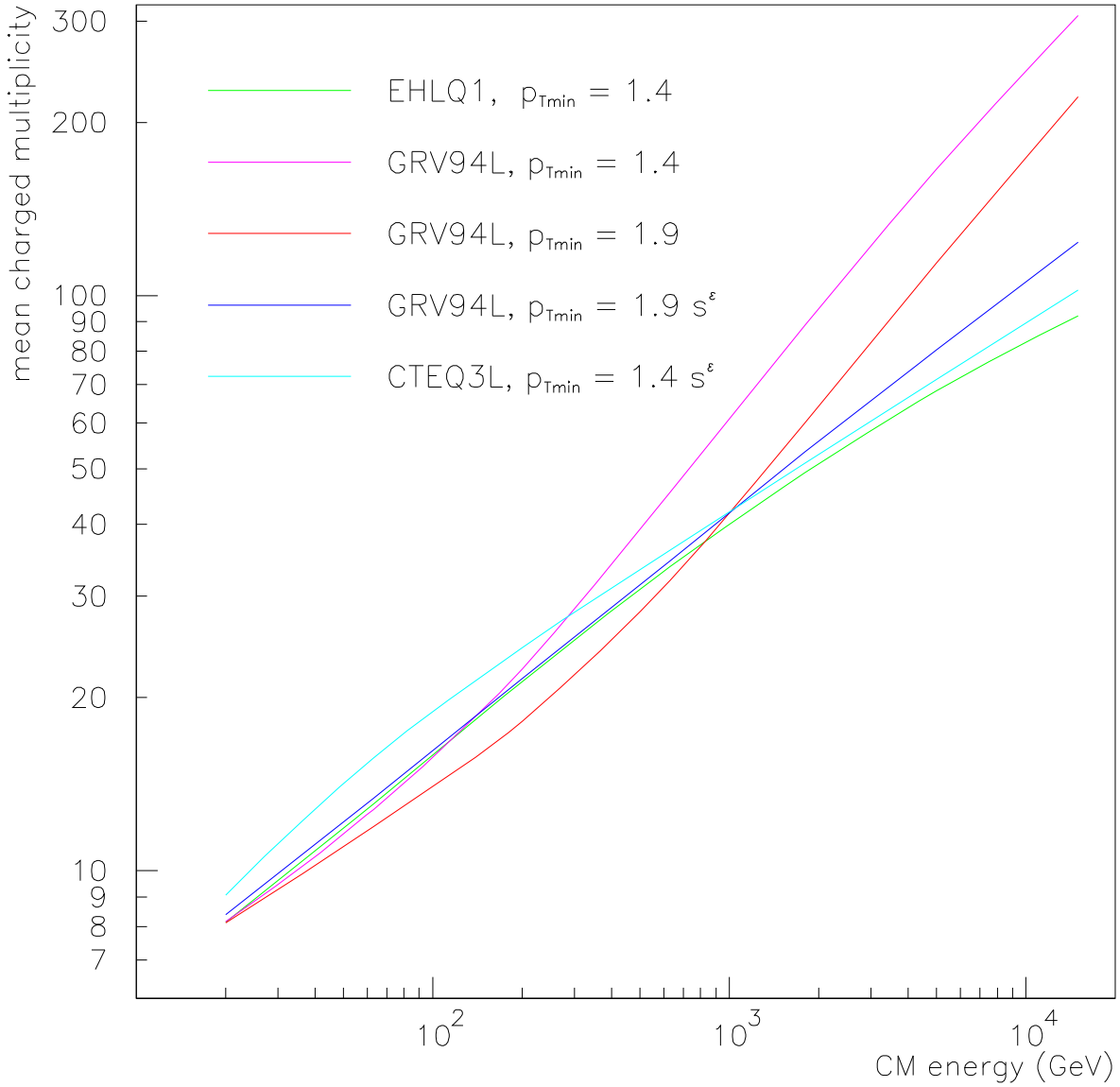
HERA $\Rightarrow$ more partons at small x and Q^2

$\Rightarrow$ energy-dependent $p_{\perp\mathrm{min}}$?

$\Rightarrow$ 'new' PYTHIA default:

$$p_{\perp\mathrm{min}} = (1.9\ \mathrm{GeV}) \left(\frac{s}{1\ \mathrm{TeV}^2} \right)^{0.08}$$

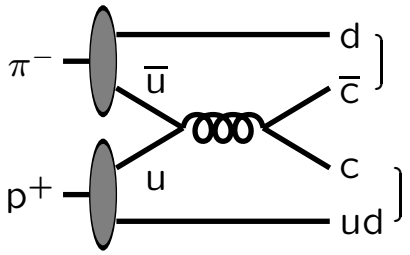
Mean charged multiplicity in inelastic non-diffractive 'minimum bias':



Beam remnant physics

(E. Norrbin & TS, PL B442 (1998) 407, EPJ C17 (2000) 137)

Colour flow connects hard scattering to beam remnants. Can have consequences, e.g.

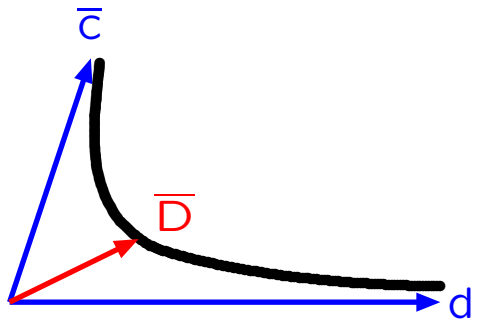


If low-mass string:

$\bar{c}d$: D^-, D^{*-}, ...

cud: Λ_c^+, Σ_c^+, Σ_c^{*+}, ...

$\Rightarrow$ flavour asymmetries

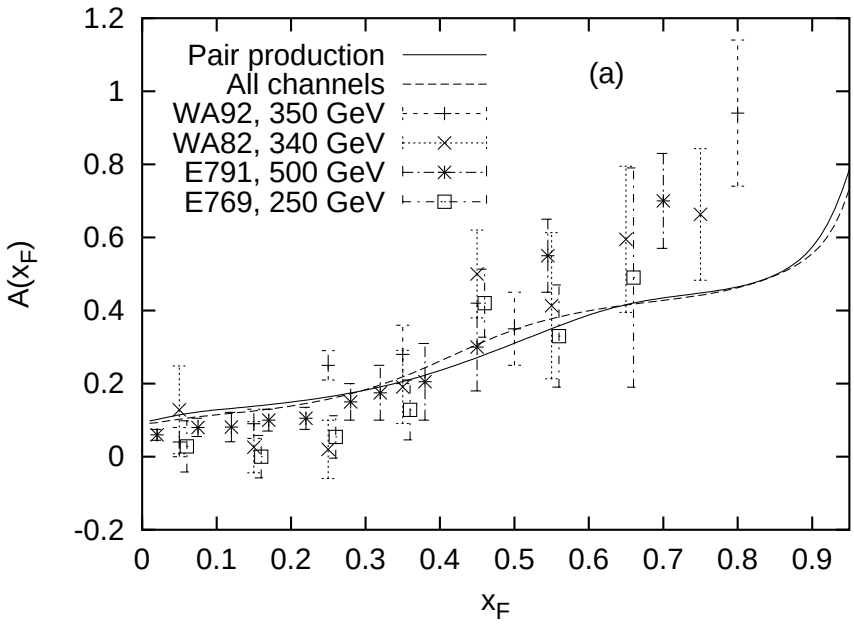


Can give D 'drag' to larger x_F than c quark for any string mass

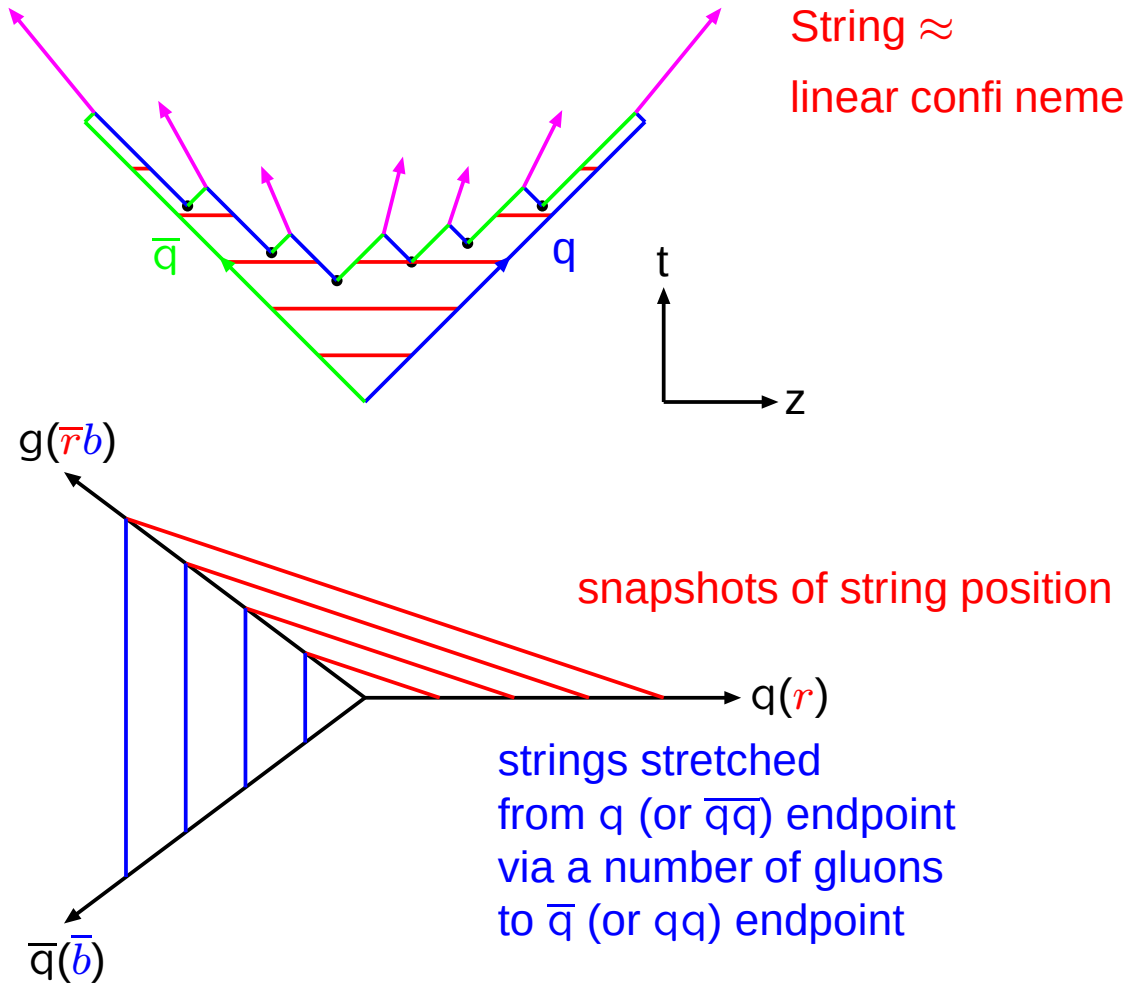
But many parameters: $\Rightarrow$ 'tune' to data

$$A(x_F) = \frac{\#D^- - \#D^+}{\#D^- + \#D^+}$$

in π^-p



Hadronization



Lund string most sophisticated and successful description of hadronization!

. . . but also many parameters and problems.

Code expanded/upgraded for

- small-mass strings and beam remnants
- baryon production (optional)
- Bose–Einstein correlations (optional)
- colour rearrangement (optional)

Future plans

Not all PYTHIA 6.1 upgrades covered here
(coding, PDF's, μ beams, histogramming,
interfaces to external generators, . . .)
$\Rightarrow$ look at Update Notes for full story

PYTHIA 6.2: before end of summer?

- Completely updated long manual
  (> 370 pp!)
- Lepton-number-violating SUSY decays
  (P. Skands)
- Complex phases in H/$\tilde{\chi}^0/\tilde{\chi}^\pm$ sectors
- ME weighting of SUSY decays
- Initial parton polarization (some proc.)
- Reversed order resonance decays and
  showers, e.g. $\mathrm{t} \to \mathrm{bW} \to \mathrm{bq\overline{q}'}$
  now: interleave decays and showers
  in 'time order'
  future: all electroweak decays before
  all showers
- Improved interfacing of external processes,
  e.g. with **COMPHEP**
  now: can only predefine electroweak
  decays before first shower
  future: can predefine full decay sequence

PYTHIA 6.?

- Steady trickle of new processes?
- Triple gauge boson production?
- Baryon-number-violating SUSY decays?
- Spin correlations in decays?
- ME/PS matching for gauge boson pairs (e.g. $q\overline{q} \to W^+W^-$) (S. Burby)?
- ME/PS matching for QCD processes?
- Improved FSR shower algorithm?
- Improved ISR shower algorithm?
- Modified ISR shower to bring in some BFKL/CCFM features?
- Understand primordial $k_\perp$ better?
- Multiple parton–parton interactions with more complicated colour topologies?

PYTHIA 7 —the C++ future (L. L önnblad)

- Mainly driven by external factors
- Generic model of event generation process
- Completely new code $\Rightarrow$ slow process
- 2000: basic generation machinery, string fragmentation
- 2001: first processes and HERWIG stuff
- 2002: parton showers $\Rightarrow$ usable (?)
- 2005: competitive with PYTHIA 6 (??)
- Death of Fortran code over $\sim 5 - 10$ years

Sociology

Requirements from chairman:
4) ideas for improving user feedback

author $\rightarrow$ user $\rightarrow$ author:

- poor at LEP ($\Leftrightarrow$ MC's successful?),
  with some exceptions: γ, b, ...
- good at HERA: HzTool, workshops, ...
- imperative at hadron colliders!
- more open information policy of experiments
- contact persons in experiments, running
- webpage/scoreboard of problems/successes

user $\rightarrow$ author $\rightarrow$ user:

- have thick manual, PYTHIA webpage, ...
- answer all questions (from trivial to bugs)

$\Rightarrow$ no problem currently? (students shy?)

- but $\gtrsim 25\%$ of my time $\Rightarrow$ untenable
- schools in particle physics phenomenology
- local experts in each experiments, to handle
  simple questions and pass on tough ones
- hire dedicated generator experts
  (cf. Fermilab: theorist in computing div.)