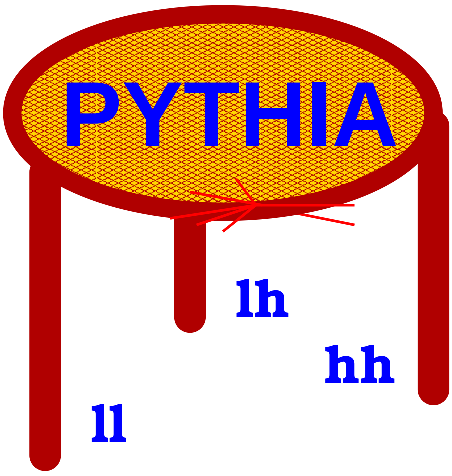
Nordic LHC Physics Workshop
Lund 16–18 March 2000

Implementation of New Physics in



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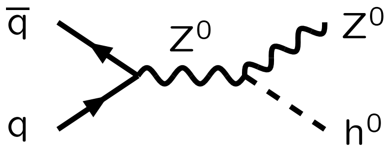
Event Physics overview
PYTHIA status
Subprocess survey
How-to: new processes
as event weight
hardcoded
as external process
How-to: new particles and decays
Problem areas

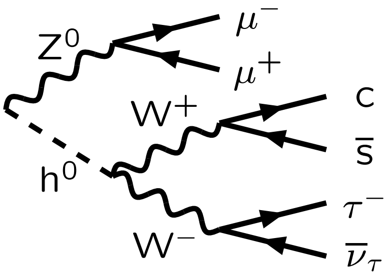
Event physics overview

Structure of the basic generation process:

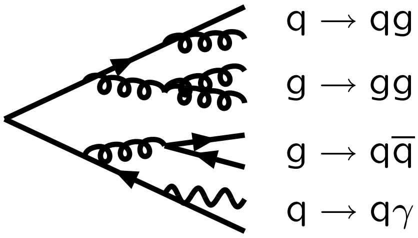
1) Hard subprocess:
$\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t}$, Breit-Wigners.



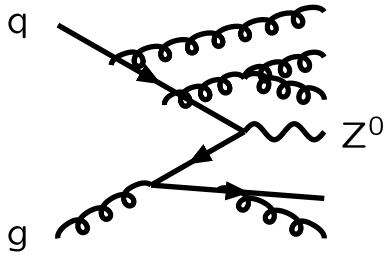
2) Resonance decays:
includes correlations.



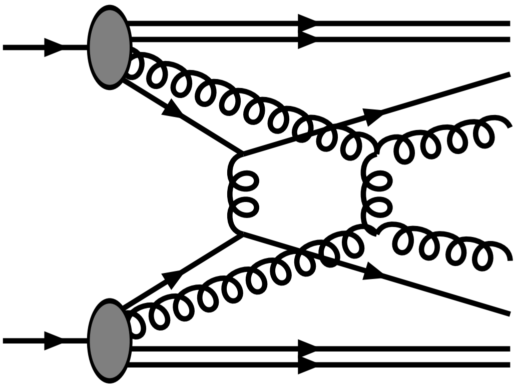
3) Final-state
parton showers:
(or matrix elements).



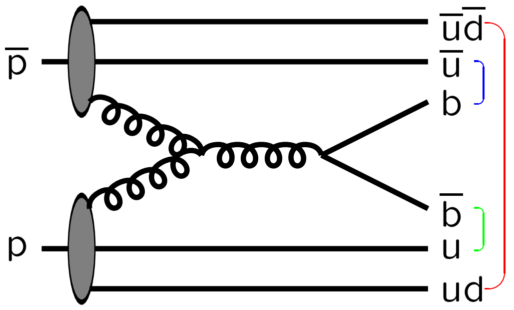
4) Initial-state
parton showers:
(or matrix elements).



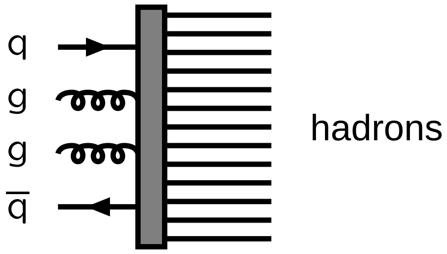
5) Multiple
parton–parton
interactions.



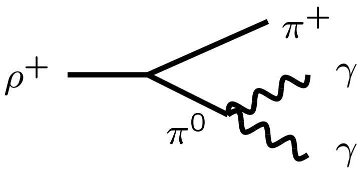
6) Beam remnants:
colour-connected
to rest of event



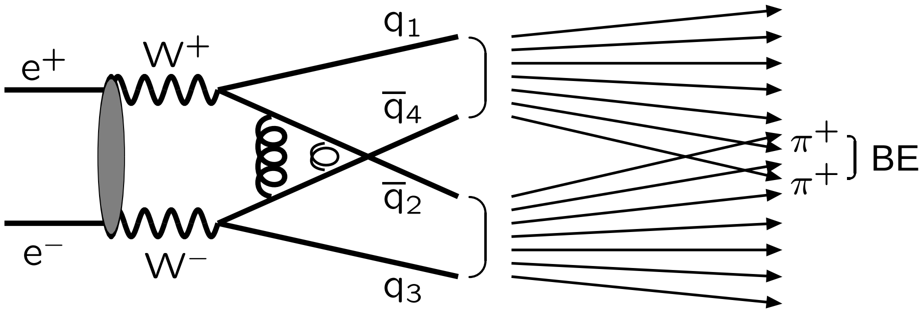
7) Hadronization
(PYTHIA: string;
HERWIG: cluster;
ISAJET: independent).



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



9) QCD interconnection effects:



a) colour rearrangement (⇒ rapidity gaps?);
b) Bose-Einstein.

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

PYTHIA status

$$\left.\begin{array}{l}\text{JETSET 7.4}\\ \text{PYTHIA 5.7}\\ \text{SPYTHIA}\end{array}\right\}\xrightarrow{\text{4 March 1997 :}}\text{PYTHIA 6.1}$$

Currently PYTHIA 6.138 of 2 March 2000
$\sim$ 51k lines Fortran 77
(PYTHIA 7 in C++: Leif Lönnblad)

Code, manuals, sample main programs:
`http://www.thep.lu.se/~torbjorn/Pythia.html`

Some PYTHIA 6.1 main news:

- JETSET routines renamed:
  `LUxxxx` → `PYxxxx` + some more
- All real variables in `DOUBLE PRECISION`
- New processes for SUSY, Higgs, technicolor, . . .
- Initial-state showers matched to (some) matrix elements
- Energy-dependent $p_{\perp\mathrm{min}}$ in multiple interactions
- Newer parton distributions (but . . .)
- Improved resonance decay machinery

- Improved charm/bottom hadronization
- Colour rearrangement options for W^+W^-
- Expanded Bose-Einstein algorithm
- New baryon production scheme (optional)

Subprocess survey

Process	PYTH	HERW	ISAJ
QCD & related			
Soft QCD	$\star$	$\star$	$\star$
Hard QCD	$\star$	$\star$	$\star$
Heavy flavour	$\star$	$\star$	$\star$
Top threshold	—	—	—
$\gamma\gamma$ physics	$\star$	$\star$	—
DIS	$\star$	$\star$	—
$\gamma^*\gamma^*$ physics	$(\star)$	$(\star)$	—
Electroweak SM			
Single $\gamma^*/\mathrm{Z}^0/\mathrm{W}^\pm$	$\star$	$\star$	$\star$
$(\gamma/\gamma^*/\mathrm{Z}^0/\mathrm{W}^\pm/\mathrm{f}/\mathrm{g})^2$	$\star$	$\star$	$\star$
Light SM Higgs	$\star$	$\star$	$\star$
Heavy SM Higgs	$(\star)$	$\star$	$\star$
SUSY BSM			
$\mathrm{h}^0/\mathrm{H}^0/\mathrm{A}^0/\mathrm{H}^\pm$	$\star$	$\star$	$\star$
SUSY	$\star$	$\star$	$\star$
$\not R$SUSY	—	$\star$	—
Other BSM			
Technicolor	$\star$	—	$\star$
New gauge bosons	$\star$	—	—
Compositeness	$\star$	—	—
Leptoquarks	$\star$	—	—
$\mathrm{H}^{\pm\pm}$ (from LR-sym.)	$\star$	—	—
Extra dimensions	—	—	$(\star)$

$\star$ = yes, $(\star)$ = partial/in progress, — = no

Subprocesses (1)

No.	Subprocess
W/Z production:	
1	$f_i\bar{f}_i \rightarrow \gamma^*/Z^0$
2	$f_i\bar{f}_j \rightarrow W^\pm$
22	$f_i\bar{f}_i \rightarrow Z^0Z^0$
23	$f_i\bar{f}_j \rightarrow Z^0W^\pm$
25	$f_i\bar{f}_i \rightarrow W^+W^-$
15	$f_i\bar{f}_i \rightarrow gZ^0$
16	$f_i\bar{f}_j \rightarrow gW^\pm$
30	$f_ig \rightarrow f_iZ^0$
31	$f_ig \rightarrow f_kW^\pm$
19	$f_i\bar{f}_i \rightarrow \gamma Z^0$
20	$f_i\bar{f}_j \rightarrow \gamma W^\pm$
35	$f_i\gamma \rightarrow f_iZ^0$
36	$f_i\gamma \rightarrow f_kW^\pm$
69	$\gamma\gamma \rightarrow W^+W^-$
70	$\gamma W^\pm \rightarrow Z^0W^\pm$
Hard QCD processes:	
11	$f_if_j \rightarrow f_if_j$
12	$f_i\bar{f}_i \rightarrow f_k\bar{f}_k$
13	$f_i\bar{f}_i \rightarrow gg$
28	$f_ig \rightarrow f_ig$
53	$gg \rightarrow f_k\bar{f}_k$
68	$gg \rightarrow gg$
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	$f_i\bar{f}_i \rightarrow Q_k\bar{Q}_k$
82	$gg \rightarrow Q_k\bar{Q}_k$
83	$q_if_j \rightarrow Q_kf_l$
84	$g\gamma \rightarrow Q_k\bar{Q}_k$
85	$\gamma\gamma \rightarrow F_k\bar{F}_k$

No.	Subprocess
Closed heavy flavour:	
86	$gg \rightarrow J/\psi g$
87	$gg \rightarrow \chi_{0c}g$
88	$gg \rightarrow \chi_{1c}g$
89	$gg \rightarrow \chi_{2c}g$
104	$gg \rightarrow \chi_{0c}$
105	$gg \rightarrow \chi_{2c}$
106	$gg \rightarrow J/\psi\gamma$
107	$g\gamma \rightarrow J/\psi g$
108	$\gamma\gamma \rightarrow J/\psi\gamma$
Prompt-photon production:	
14	$f_i\bar{f}_i \rightarrow g\gamma$
18	$f_i\bar{f}_i \rightarrow \gamma\gamma$
29	$f_ig \rightarrow f_i\gamma$
114	$gg \rightarrow \gamma\gamma$
115	$gg \rightarrow g\gamma$
Deep inelastic scattering	
10	$f_if_j \rightarrow f_if_j$
Photon-induced processes:	
33	$f_i\gamma \rightarrow f_ig$
34	$f_i\gamma \rightarrow f_i\gamma$
54	$g\gamma \rightarrow f_k\bar{f}_k$
58	$\gamma\gamma \rightarrow f_k\bar{f}_k$
80	$q_i\gamma \rightarrow q_k\pi^\pm$
131	$f_i\gamma^*_T \rightarrow f_ig$
132	$f_i\gamma^*_L \rightarrow f_ig$
133	$f_i\gamma^*_T \rightarrow f_i\gamma$
134	$f_i\gamma^*_L \rightarrow f_i\gamma$
135	$g\gamma^*_T \rightarrow f_i\bar{f}_i$
136	$g\gamma^*_L \rightarrow f_i\bar{f}_i$
137	$\gamma^*_T\gamma^*_T \rightarrow f_i\bar{f}_i$
138	$\gamma^*_T\gamma^*_L \rightarrow f_i\bar{f}_i$
139	$\gamma^*_L\gamma^*_T \rightarrow f_i\bar{f}_i$
140	$\gamma^*_L\gamma^*_L \rightarrow f_i\bar{f}_i$

Subprocesses (2)

No.	Subprocess
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	$Z^0_L Z^0_L \to Z^0_L Z^0_L$
72	$Z^0_L Z^0_L \to W^+_L W^-_L$
73	$Z^0_L W^\pm_L \to Z^0_L W^\pm_L$
76	$W^+_L W^-_L \to Z^0_L Z^0_L$
77	$W^\pm_L W^\pm_L \to W^\pm_L W^\pm_L$
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	$q_i \bar{q}_i \to Q_k \overline{Q}_k A^0$

No.	Subprocess
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	$f_i \bar{f}_j \to R$
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	$q_i \bar{q}_i \to e^{*+} e^- + e^+ e^{*-}$
165	$f_i \bar{f}_i (\to \gamma^*/Z^0) \to f_k \bar{f}_k$
166	$f_i \bar{f}_j (\to W^\pm) \to f_k \bar{f}_l$

Subprocesses (3)

No.	Subprocess
Leptoquarks:	
145	$q_i\ell_j \to L_Q$
162	$qg \to \ell L_Q$
163	$gg \to L_Q\overline{L}_Q$
164	$q_i\overline{q}_i \to L_Q\overline{L}_Q$
Technicolor:	
149	$gg \to \eta_{tc}$
191	$f_i\overline{f}_i \to \rho^0_{tc}$
192	$f_i\overline{f}_j \to \rho^+_{tc}$
193	$f_i\overline{f}_i \to \omega^0_{tc}$
194	$f_i\overline{f}_i \to f_k\overline{f}_k$
195	$f_i\overline{f}_j \to f_k\overline{f}_l$
361	$f_i\overline{f}_i \to W^+_L W^-_L$
362	$f_i\overline{f}_i \to W^\pm_L\pi^\mp_{tc}$
363	$f_i\overline{f}_i \to \pi^+_{tc}\pi^-_{tc}$
364	$f_i\overline{f}_i \to \gamma\pi^0_{tc}$
365	$f_i\overline{f}_i \to \gamma\pi'^0_{tc}$
366	$f_i\overline{f}_i \to Z^0\pi^0_{tc}$
367	$f_i\overline{f}_i \to Z^0\pi'^0_{tc}$
368	$f_i\overline{f}_i \to W^\pm\pi^\mp_{tc}$
370	$f_i\overline{f}_j \to W^\pm_L Z^0_L$
371	$f_i\overline{f}_j \to W^\pm_L\pi^0_{tc}$
372	$f_i\overline{f}_j \to \pi^\pm_{tc}Z^0_L$
373	$f_i\overline{f}_j \to \pi^\pm_{tc}\pi^0_{tc}$
374	$f_i\overline{f}_j \to \gamma\pi^\pm_{tc}$
375	$f_i\overline{f}_j \to Z^0\pi^\pm_{tc}$
376	$f_i\overline{f}_j \to W^\pm\pi^0_{tc}$
377	$f_i\overline{f}_j \to W^\pm\pi'^0_{tc}$

No.	Subprocess
SUSY:	
201	$f_i\overline{f}_i \to \tilde{e}_L\tilde{e}^*_L$
202	$f_i\overline{f}_i \to \tilde{e}_R\tilde{e}^*_R$
203	$f_i\overline{f}_i \to \tilde{e}_L\tilde{e}^*_R + \tilde{e}^*_L\tilde{e}_R$
204	$f_i\overline{f}_i \to \tilde{\mu}_L\tilde{\mu}^*_L$
205	$f_i\overline{f}_i \to \tilde{\mu}_R\tilde{\mu}^*_R$
206	$f_i\overline{f}_i \to \tilde{\mu}_L\tilde{\mu}^*_R + \tilde{\mu}^*_L\tilde{\mu}_R$
207	$f_i\overline{f}_i \to \tilde{\tau}_1\tilde{\tau}^*_1$
208	$f_i\overline{f}_i \to \tilde{\tau}_2\tilde{\tau}^*_2$
209	$f_i\overline{f}_i \to \tilde{\tau}_1\tilde{\tau}^*_2 + \tilde{\tau}^*_1\tilde{\tau}_2$
210	$f_i\overline{f}_j \to \tilde{\ell}_L\tilde{\nu}^*_\ell + \tilde{\ell}^*_L\tilde{\nu}_\ell$
211	$f_i\overline{f}_j \to \tilde{\tau}_1\tilde{\nu}^*_\tau + \tilde{\tau}^*_1\tilde{\nu}_\tau$
212	$f_i\overline{f}_j \to \tilde{\tau}_2\tilde{\nu}_\tau{}^* + \tilde{\tau}^*_2\tilde{\nu}_\tau$
213	$f_i\overline{f}_i \to \tilde{\nu}_\ell\tilde{\nu}_\ell{}^*$
214	$f_i\overline{f}_i \to \tilde{\nu}_\tau\tilde{\nu}^*_\tau$
216	$f_i\overline{f}_i \to \tilde{\chi}_1\tilde{\chi}_1$
217	$f_i\overline{f}_i \to \tilde{\chi}_2\tilde{\chi}_2$
218	$f_i\overline{f}_i \to \tilde{\chi}_3\tilde{\chi}_3$
219	$f_i\overline{f}_i \to \tilde{\chi}_4\tilde{\chi}_4$
220	$f_i\overline{f}_i \to \tilde{\chi}_1\tilde{\chi}_2$
221	$f_i\overline{f}_i \to \tilde{\chi}_1\tilde{\chi}_3$
222	$f_i\overline{f}_i \to \tilde{\chi}_1\tilde{\chi}_4$
223	$f_i\overline{f}_i \to \tilde{\chi}_2\tilde{\chi}_3$
224	$f_i\overline{f}_i \to \tilde{\chi}_2\tilde{\chi}_4$
225	$f_i\overline{f}_i \to \tilde{\chi}_3\tilde{\chi}_4$
226	$f_i\overline{f}_i \to \tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$
227	$f_i\overline{f}_i \to \tilde{\chi}^\pm_2\tilde{\chi}^\mp_2$
228	$f_i\overline{f}_i \to \tilde{\chi}^\pm_1\tilde{\chi}^\mp_2$
229	$f_i\overline{f}_j \to \tilde{\chi}_1\tilde{\chi}^\pm_1$
230	$f_i\overline{f}_j \to \tilde{\chi}_2\tilde{\chi}^\pm_1$
231	$f_i\overline{f}_j \to \tilde{\chi}_3\tilde{\chi}^\pm_1$
232	$f_i\overline{f}_j \to \tilde{\chi}_4\tilde{\chi}^\pm_1$
233	$f_i\overline{f}_j \to \tilde{\chi}_1\tilde{\chi}^\pm_2$
234	$f_i\overline{f}_j \to \tilde{\chi}_2\tilde{\chi}^\pm_2$
235	$f_i\overline{f}_j \to \tilde{\chi}_3\tilde{\chi}^\pm_2$
236	$f_i\overline{f}_j \to \tilde{\chi}_4\tilde{\chi}^\pm_2$

Subprocesses (4)

No.	Subprocess
SUSY:	
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	$f_i\bar{f}_j \to \tilde{g}\tilde{\chi}^\pm_1$
242	$f_i\bar{f}_j \to \tilde{g}\tilde{\chi}^\pm_2$
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	$f_i g \to \tilde{q}_{jL}\tilde{\chi}^\pm_1$
256	$f_i g \to \tilde{q}_{jL}\tilde{\chi}^\pm_2$
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	$f_i\bar{f}_i \to \tilde{t}_1\tilde{t}^*_2 + \tilde{t}^*_1\tilde{t}_2$
264	$gg \to \tilde{t}_1\tilde{t}^*_1$
265	$gg \to \tilde{t}_2\tilde{t}^*_2$
271	$f_if_j \to \tilde{q}_{iL}\tilde{q}_{jL}$
272	$f_if_j \to \tilde{q}_{iR}\tilde{q}_{jR}$
273	$f_if_j \to \tilde{q}_{iL}\tilde{q}_{jR} + \tilde{q}_{iR}\tilde{q}_{jL}$
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	$f_i\bar{f}_j \to \tilde{q}_{iL}\tilde{q}^*_{jR} + \tilde{q}_{iR}\tilde{q}^*_{jL}$
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	$gg \to \tilde{q}_{iR}\tilde{q}^*_{iR}$

No.	Subprocess
SUSY:	
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	$b\bar{q}_i \to \tilde{b}_1\tilde{q}^*_{iR} + \tilde{b}_2\tilde{q}^*_{jL}$
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	$b\bar{b} \to \tilde{b}_1\tilde{b}^*_2 + \tilde{b}_2\tilde{b}^*_1$

Implementing new processes

1. Convince a PYTHIA author to do it for you
   SUSY, technicolor: Steve Mrenna
   the rest: Torbjörn
   but please have necessary formulae ready
2. Reweight existing cross section
   with `PYEVWT`: simple
3. Hardcode from scratch: for brave only
4. Hardcode by modifying existing process:
   rather safe, but dead end
5. Hardcode by copying existing process:
   more useful, but less trivial
6. Include as external process:
   the official standard path,
   good if you have a working parton generator, but nontrivial if you don't
7. Use standard interfaces: mainly for e^+e^-

```
 CALL PY2FRM(IRAD,ITAU,ICOM)
 CALL PY4FRM(ATOTSQ,A1SQ,A2SQ,ISTRAT,
&IRAD,ITAU,ICOM)
 CALL PY6FRM(P12,P13,P21,P23,P31,P32,PTOP,
&IRAD,ITAU,ICOM)
 CALL PY4JET(PMAX,IRAD,ICOM)
```

Event weight

Example: contact interaction modification to process 16, $\mathrm{q}_i\overline{\mathrm{q}}_j \to \mathrm{gW}^{\pm}$

```
     FACWG=COMFAC*AS*AEM/XW*2D0/9D0*
    &(TH2+UH2+2D0*SQM4*SH)/(TH*UH)
```

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{t}} = \frac{\pi}{\hat{s}^2}\,\frac{\alpha_{\mathrm{s}}\alpha_{\mathrm{em}}}{\sin^2\theta_W}\,\frac{2}{9}\,\frac{\hat{t}^2+\hat{u}^2+2m_{\mathrm{W}}^2\hat{s}}{\hat{t}\hat{u}}\,|V_{ij}|^2$$

Assume modification of character

$$\frac{\hat{t}^2+\hat{u}^2+2m_{\mathrm{W}}^2\hat{s}}{\hat{t}\hat{u}} \longrightarrow \frac{\hat{t}^2+\hat{u}^2+2m_{\mathrm{W}}^2\hat{s}}{\hat{t}\hat{u}} + N\frac{\hat{s}^2}{\Lambda^4}$$

```
C...Double precision and integer declarations.
      IMPLICIT DOUBLE PRECISION(A-H, O-Z)
      IMPLICIT INTEGER(I-N)
      INTEGER PYK,PYCHGE,PYCOMP
C...Commonblocks.
      COMMON/PYSUBS/MSEL,MSELPD,MSUB(500),KFIN(2,-40:40),CKIN(200)
      COMMON/PYPARS/MSTP(200),PARP(200),MSTI(200),PARI(200)
      COMMON/MYCOMM/ANORM,ALAMDA

C...Select subprocess.
      MSEL=0
      MSUB(16)=1

C...Weighted events.
      MSTP(142)=2

C...Contact couplings.
      ANORM=1D0
      ALAMDA=1000D0
```

```
C...Initialize.
      CALL PYINIT('CMS','P','P',14000D0)

C...Generate events.
      DO 100 IEV=1,100
        CALL PYEVNT
 100  CONTINUE

C...Cross section.
      CALL PYSTAT(1)

      END

C*************************************************************

      SUBROUTINE PYEVWT(WTXS)

C...Double precision and integer declarations.
      IMPLICIT DOUBLE PRECISION(A-H, O-Z)
      IMPLICIT INTEGER(I-N)
      INTEGER PYK,PYCHGE,PYCOMP
C...Commonblocks.
      COMMON/PYINT1/MINT(400),VINT(400)
      COMMON/MYCOMM/ANORM,ALAMDA
      SAVE /PYINT1/,/MYCOMM/

C...Set default weight for WTXS.
      WTXS=1D0

C...Read out subprocess number and kinematics.
      ISUB=MINT(1)
      SHAT=VINT(44)
      THAT=VINT(45)
      UHAT=VINT(46)

C...Modifications by user to be put here.
      IF(ISUB.EQ.16) THEN
        WMSQ=SHAT+THAT+UHAT
        WMEOLD=(THAT**2+UHAT**2+2D0*WMSQ*SHAT)/(THAT*UHAT)
        WMENEW=ANORM*SHAT**2/ALAMDA**4
        WTXS=(WMEOLD+WMENEW)/WMEOLD
      ENDIF

      RETURN
      END
```

Hardcoding

0) Select empty `ISUB` number
in range 401 – 500.

1) In `PYDATA` or commonblocks:

`PROC(ISUB)` = ' process name '
`ISET(ISUB)` = 1 or 2 for 2 → 1 or 2 → 2 process
`KFPR(ISUB,1)` = KF code of first product
`KFPR(ISUB,2)` = KF code of second product

can have `KFPR` info in code instead;
advantage with `KFPR` is possibility to modify or duplicate process,
e.g. `KFPR(86,1) = 443`: $gg \to J/\psi g$ is default
but `KFPR(86,1) = 553`: $gg \to \Upsilon g$ (+ coupling)

2) In `PYSIGH`:
implement matrix elements, including loop over possible incoming flavours

```
C...f + fbar -> gamma + gamma
      ELSEIF(ISUB.EQ.18) THEN
C...COMFAC already contains factor pi/shat**2 for 2->2
C...and preweighting of phase space
        FACGG=COMFAC*AEM**2*2D0*(TH2+UH2)/(TH*UH)
C...Loop over all flavours and check them
        DO 380 I=MMINA,MMAXA
          IF(I.EQ.0.OR.KFAC(1,I)*KFAC(2,-I).EQ.0)
     &    GOTO 380
```

```
C...Charge; colour factor for quark annihilation.
          EI=KCHG(IABS(I),1)/3D0
          FCOI=1D0
          IF(IABS(I).LE.10) FCOI=FACA/3D0
C...One 'channel' for each flavour, with incoming
C...flavours, colour flow enumerator and cross section.
          NCHN=NCHN+1
          ISIG(NCHN,1)=I
          ISIG(NCHN,2)=-I
          ISIG(NCHN,3)=1
          SIGH(NCHN)=0.5D0*FACGG*FCOI*EI**4
  380   CONTINUE
```

Many complications, e.g.

- Breit-Wigners for resonances
- flavour-dependent interference (γ^*/Z^0)
- several colour flows

3) In PYSCAT:
fill in final state for selected process

```
C...f + fbar' -> g + W+/-;
C...th = (p(f)-p(W-))**2 or (p(fbar')-p(W+))**2
       ELSEIF(ISUB.EQ.16) THEN
C...MINT(15) and MINT(16) incoming partons;
C...charges -> W+ or W-.
         KCH1=KCHG(IABS(MINT(15)),1)*ISIGN(1,MINT(15))
         KCH2=KCHG(IABS(MINT(16)),1)*ISIGN(1,MINT(16))
C...Order of outgoing particles must reflect
C...t-hat definition; JS=1 is default.
         IF(MINT(15)*(KCH1+KCH2).LT.0) JS=2
C...Fill outgoing particles in MINT(21) and MINT(22).
         MINT(20+JS)=21
         MINT(23-JS)=ISIGN(24,KCH1+KCH2)
C...Colour flow code: always pick by analogy
C...with similar existing process.
         KCC=17+JS
```

External processes

Convenient when you already have parton-level generator available;
used e.g. by COMPHEP group

0) Select empty `ISUB` number(s)
in range 401 – 500.

1) In main program before `CALL PYINIT` :

```
      CALL PYUPIN(ISUB,TITLE,SIGMAX)
      MSUB(ISUB)=1
```

`TITLE` = ' process name '

`SIGMAX` = maximum of event weights to be encountered

2) Suppy subroutine that will be called from `PYEVNT`, and that for each call generates and returns an event of kind `ISUB`:

```
      SUBROUTINE PYUPEV(ISUB,SIGEV)
```

`ISUB` = inparameter to allow mixing of several external processes

`SIGEV` = cross section (or weight) for event,
$\frac{d\sigma}{d\Omega} \int d\Omega$, with Ω (biased) phase space, and
`SIGEV/SIGMAX` : event survival probability.

`SIGEV = SIGMAX = 1D0` : accept all events,
but no cross section info.

3) Subroutine `PYUPEV` must provide event info (mini event record) in

```
      COMMON/PYUPPR/NUP,KUP(20,7),PUP(20,5),
     &NFUP,IFUP(10,2),Q2UP(0:10)
```

`NUP` : number of entries, first two incoming partons, the rest outgoing particles

`KUP(I,1)` : 1 normally, 2 for documentation

`KUP(I,2)` : PDG particle code

`KUP(I,3)` : 0, or mother I where known

`KUP(I,4)` : origin of final-state colour

`KUP(I,5)` : origin of final-state anticolour

`KUP(I,6)` : destination of initial-state colour

`KUP(I,7)` : destination of initial-state anticolour

`PUP(I,J)` : (p_x, p_y, p_z, E, m) in GeV

`Q2UP(0)` : Q^2 scale of initial-state shower ($\simeq \hat{s}$?)

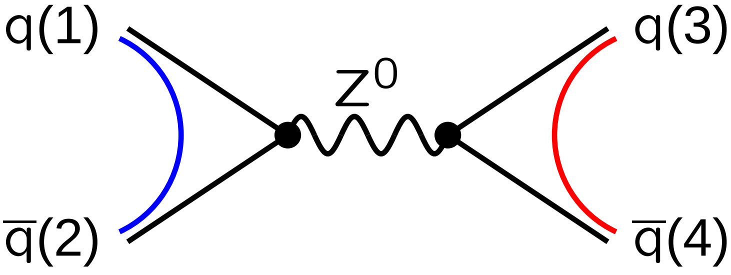
`NFUP` : number of final-state showers

`KFUP(IF,1),KFUP(IF,2)` : pair of partons or particles that shower (one non-radiating particle is OK; to take recoil)

`Q2UP(IF)` : Q^2 scale of final-state shower ($\simeq m^2$)

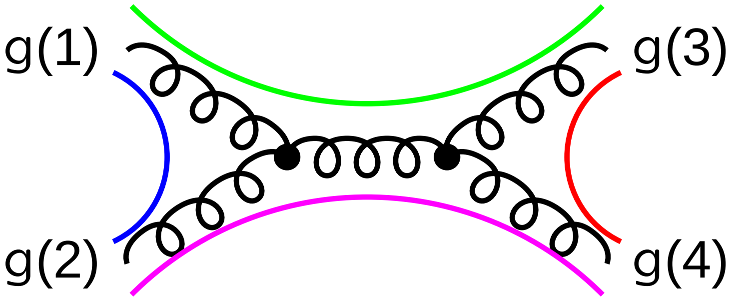
For a complete example, see
`http://www.thep.lu.se/∼torbjorn/pythia/main51.f`

example 1:
s-channel
colour singlet
exchange



	colour from	anticol from	colour to	anticol to
`I`	`KUP(I,4)`	`KUP(I,5)`	`KUP(I,6)`	`KUP(I,7)`
1	0	0	2	0
2	0	0	0	1
3	4	0	0	0
4	0	3	0	0

example 2:
gg → gg,
one of 6 possible
colour flows



	colour from	anticol from	colour to	anticol to
`I`	`KUP(I,4)`	`KUP(I,5)`	`KUP(I,6)`	`KUP(I,7)`
1	0	0	3	2
2	0	0	1	4
3	1	4	0	0
4	3	2	0	0

Most parton-level generators do not give colour info ⇒ have to make sensible choices, e.g. mix according to $\prod 1/m_{ij}^2$ where ij is any parton pair connected by string.

New particles

0) Select flavour code `KF`, according to PDG rules.

1) Modify particle data in `PYDATA`, best by editing table:

`CALL PYUPDA(1,LFN)` : writes table on unit `LFN`

`CALL PYUPDA(2,LFN)` : reads table from unit `LFN` for complete replacement

`CALL PYUPDA(3,LFN)` : reads table from unit `LFN` for new particles or a few updated old particles Use similar existing particle as template!

Example (here edited to fit page size;
in real life column alignment is important)

```
4000002 u* u*bar 2 1 1 400.00000 2.65499 26.54994 0.00000E+00 1 1
   1 0 0.853165 21 2 0 0 0
   1 0 0.021144 22 2 0 0 0
   1 0 0.029361 23 2 0 0 0
   1 0 0.096329 24 1 0 0 0
```

First line: PDG code, particle name, antiparticle name, 3*charge, colour charge classification, particle/antiparticle distinction, mass, width, cutoff of tails, lifetime, width rescaling (see below), decay on/off.

Subsequent lines: decay channels with channel on/off, matrix-element code, branching ratio, PDG codes for up to 5 decay products.

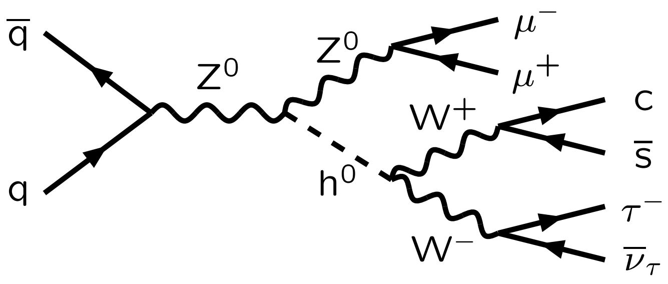
2) Width treatment in `PYWIDT` routine:
allows dynamic calculation of partial widths,
e.g. $\Gamma_{\mathrm{h}}(m_{\mathrm{h}})$ or $\gamma^*/\mathrm{Z}^0 \to \mathrm{t}\bar{\mathrm{t}}$
but normally overkill for narrow mass peak.

Set 0 or 2 in width rescaling input on particle line to avoid need for `PYWIDT` implementation.

3) Decay treatment

a) in `PYDECY` routine: simple phase-space multibody decay, up to 10 particles, isotropic or with some matrix element; obtained for width rescaling input = 0.

b) in `PYRESD` routine: more sophisticated resonance description obtained for width rescaling input ≥ 1. Optimized for two simultaneous decays to two particles each, with automatic showering where possible, but can handle three products.



Allows non-isotropic decays, in several steps if required. But nontrivial to program; may be easier to do isotropic decays (default) and reweight final events.

Problem areas

- Mass spectrum of resonance often shows extra peak near lower cut-off (2 GeV by default) because parton distributions may increase faster at small x than a Breit-Wigner decreases. But can't trust Breit-Wigner too far from main peak anyway, so cut tails e.g. with `CKIN`.
- Long-lived new coloured particles would form "hadrons", e.g. $\tilde{\mathrm{g}} \to \tilde{\mathrm{g}}\mathrm{q}\overline{\mathrm{q}}$ or $\tilde{\mathrm{g}}\mathrm{g}$. Not currently considered. Experience from top and leptoquarks show small differences, mainly in soft-hadron region.
- QCD showering off $\tilde{\mathrm{q}}, \tilde{\mathrm{g}}$ still missing: to be done.
- Multibody final states: no efficient biased phase space generator.
- SUSY $\not{R}$ processes introduce new colour flow topologies with junctions. Hadronization supported (though not told how in manual) but consistent showering machinery missing.