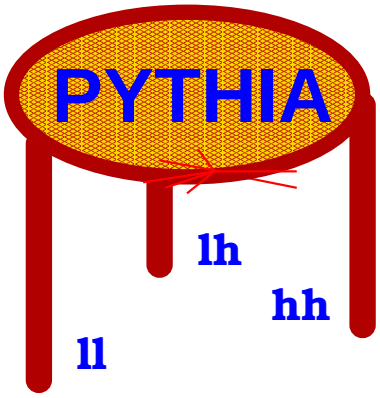
LUND UNIVERSITY

Linear Collider Workshop 2000
FNAL, October 24-28, 2000

# PYTHIA
# Status Report

Torbjörn Sjöstrand




based on TS, P. Edén, C. Friberg,
L. Lönnblad, G. Miu, S. Mrenna and E. Norrbin
LU TP 00-30 (hep-ph/0010017) ⇒ CPC

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JETSET 7.4
PYTHIA 5.7
SPYTHIA

} 4 March 1997 : → PYTHIA 6.1

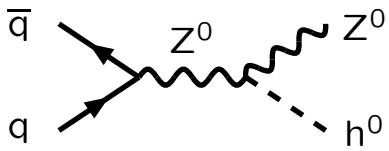
Currently PYTHIA 6.154 of 29 Sept. 2000
$\sim 52,800$ lines Fortran 77

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

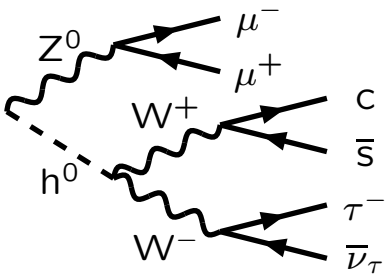
# Event physics overview

Structure of the basic generation process:

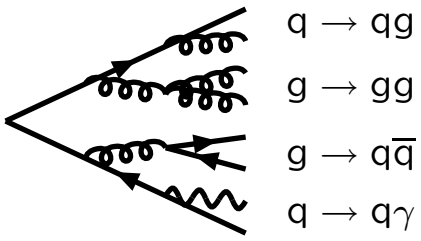
1) Hard subprocess:
$\mathrm{d}\hat{\sigma}/\mathrm{d}\hat{t}$, Breit-Wigners.



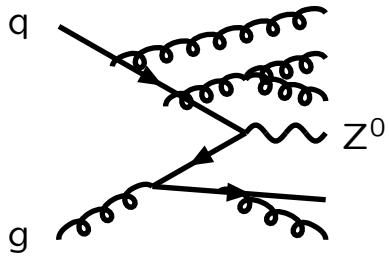

2) Resonance decays:
includes correlations.



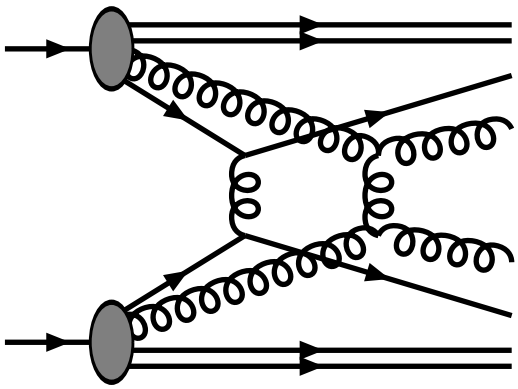

3) Final-state
parton showers:
(or matrix elements).



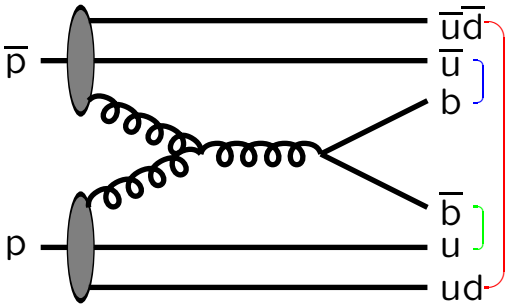

4) Initial-state
parton showers:
(or matrix elements).



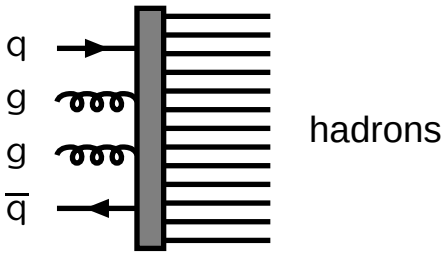

5) Multiple
parton–parton
interactions.



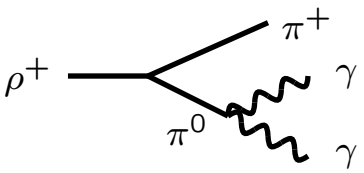
6) Beam remnants:
colour-connected
to rest of event



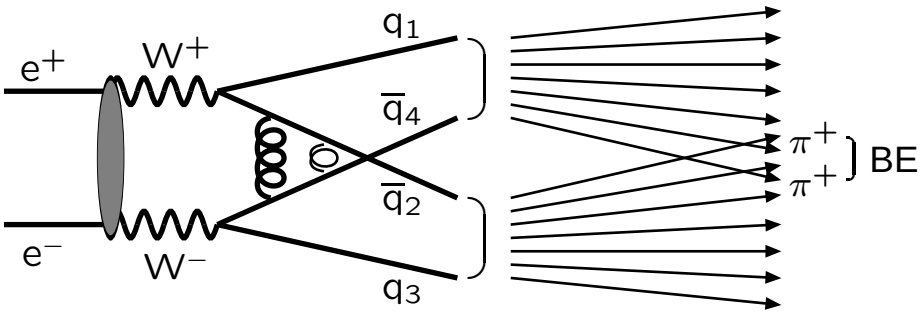

7) Hadronization
(PYTHIA: string;
HERWIG: cluster;
ISAJET: independent).




8) Normal decays:
hadronic, $\tau$, charm, ...




9) QCD interconnection effects:




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

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

# Subprocess survey

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

⋆ = yes, (⋆) = partial/in progress, — = no

| 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 | $g\gamma_L^* \to f_i \bar{f}_i$ |

| No. | Subprocess |
|---|---|
| 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 | $f_i \bar{f}_j \to W^\pm h^0$ |
| 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 | $q_i \overline{q}_i \to Q_k \overline{Q}_k h^0$ |
| 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 | $q_i \overline{q}_i \to Q_k \overline{Q}_k H^0$ |
| 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 | $q_i \overline{q}_i \to Q_k \overline{Q}_k A^0$ |
| 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 | $f_i f_j \to f_k f_l H_R^{\pm\pm}$ |

| 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 | $f_i \bar{f}_j \to R$ |
| 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 | $q_i \overline{q}_i \to e^\pm e^{*\mp}$ |
| 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 | $q_i \overline{q}_i \to L_Q \overline{L}_Q$ |
| 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 | $f_i \bar{f}_i \to \tilde{\chi}_3 \tilde{\chi}_4$ |

| No. | Subprocess |
|---|---|
| 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 | $f_i g \to \tilde{q}_{iR} \tilde{\chi}_2$ |
| 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 | $b q_i \to \tilde{b}_1 \tilde{q}_{iL}$ |
| 282 | $b q_i \to \tilde{b}_2 \tilde{q}_{iR}$ |
| 283 | $b q_i \to \tilde{b}_1 \tilde{q}_{iR} + \tilde{b}_2 \tilde{q}_{iL}$ |
| 284 | $b \overline{q}_i \to \tilde{b}_1 \tilde{q}_{iL}^*$ |
| 285 | $b \overline{q}_i \to \tilde{b}_2 \tilde{q}_{iR}^*$ |
| 286 | $b \overline{q}_i \to \tilde{b}_1 \tilde{q}_{iR}^* + \tilde{b}_2 \tilde{q}_{iL}^*$ |
| 287 | $q_i \overline{q}_i \to \tilde{b}_1 \tilde{b}_1^*$ |
| 288 | $q_i \overline{q}_i \to \tilde{b}_2 \tilde{b}_2^*$ |
| 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 | $b\overline{b} \to \tilde{b}_1 \tilde{b}_2^* +$ |
| Extra dimensions: | |
| 391 | $f_i \bar{f}_i \to G^*$ |
| 392 | $gg \to G^*$ |

# $\gamma^{(*)}\gamma^{(*)}$ physics

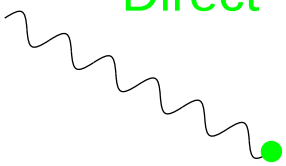
(see talk in QCD/$\gamma\gamma$ session)

Objective: "complete" framework for
$\gamma\gamma/\gamma^*\gamma/\gamma^*\gamma^*$ interactions at all $Q_i^2$,
especially transition region $Q_i^2 \sim m_\rho^2$

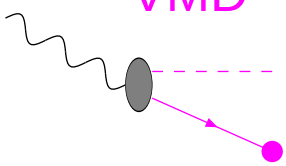
New machinery for flux of bremsstrahlung $\gamma$'s
(transverse and longitudinal)

Real photons can be of three kinds
(with further subdivisions):

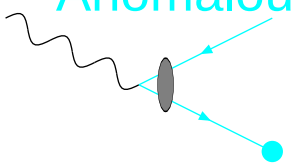
Direct



VMD



Anomalous



Direct: point-like
All: 'high'-$p_\perp$ jets;

Resolved: hadronic state
resolved: also soft physics

Virtual photon: add the DIS process $\gamma^*$q $\rightarrow$ q,
e.g. q in (VMD) $\rho^0$

| | | |
|---|---|---|
| $\gamma\gamma$: | 9 | combinations = (dir+VMD+GVMD)$^2$ |
| $\gamma^*\gamma^*$: | + 4 | combinations = 2 sides$\times$(VMD+GVMD) |
| | 13 | !! |

Have to include dampening factors to remove double-counting (reasonably) consistently

# Beyond the Standard Model

SUSY: reasonably complete set of $2 \to 2$
MSSM $R$-conserving processes;

new:
- $\tilde{b}_1/\tilde{b}_2$ production, also b in PDF;
- $\tilde{G}$ as LSP (optionally)
- 3-body SUSY decays
- displaced vertices

Technicolor: new set of pair production of
$\pi_{tc}^{\pm}/\pi_{tc}^{0}/\pi_{tc}^{\prime 0}/W_L^{\pm}/Z_L^0/W^{\pm}/Z^0/\gamma$,
with interference $\rho_{tc}^{\pm}/W^{\pm}$ and $\rho_{tc}^{0}/\omega_{tc}^{0}/Z^0/\gamma^*$

$Z'^0$: flavour-dependent couplings

Higgs: pair production, e.g. $h^0A^0$ or $h^0H^{\pm}$
(earlier partly as $\gamma^*/Z^0/Z'^0$ decays)

Left-right symmetry: $H_{L,R}^{\pm\pm}$ production
$H_{L,R}^{\pm\pm} \to \ell^{\pm}\ell^{\pm}/W_{L,R}^{\pm}W_{L,R}^{\pm}$ $\qquad$ $W_R^{+} \to q_i\overline{q}_j/\ell^{+}\nu_R$

Compositeness:
a few further processes for $e^*/q^*$

Extra dimensions: only begun
recently: narrow graviton excitation $G^*$

# QCD Final-State Showers

(see talk in top/QCD session)

Shower: effective&efficient resummation of multiple-gluon-emission effects.

Objective:
- improved parton shower description,
- including mass effects ("dead cone"), and
- matched to process-specific $\mathcal{O}(\alpha_s)$ ME's

$Q^2$: evolution variable, $= m^2$ in PYTHIA
$z$: energy/momentum sharing in branching

3-jet events in $e^+e^- \to \gamma^*/Z^* \to q\bar{q} \to q\bar{q}g$:
map PS variables on to ME ones:

$$\Rightarrow \quad \frac{1}{\sigma_0}\frac{d\sigma_{ME}}{dx_1\,dx_2} \leq \frac{1}{\sigma_0}\frac{d\sigma_{PS}}{dQ^2\,dz} \qquad \text{for } m_q = 0$$

so can generate events with PS
and correct first branching by ME/PS

Fails for $m_q > 0$ in part of phase space
$\Rightarrow$ have had exaggerated dead cone effect

Restore by $Q_j^2 = m^2_{j,\text{offshell}} - m^2_{j,\text{onshell}}$

Also works for decaying coloured state,
e.g. ME for $t \to bWg$ matches PS for $b \to bg$

$\Rightarrow$ can match PS to generic $a \to bcg$ ME

. . . but often ME $\ll$ PS

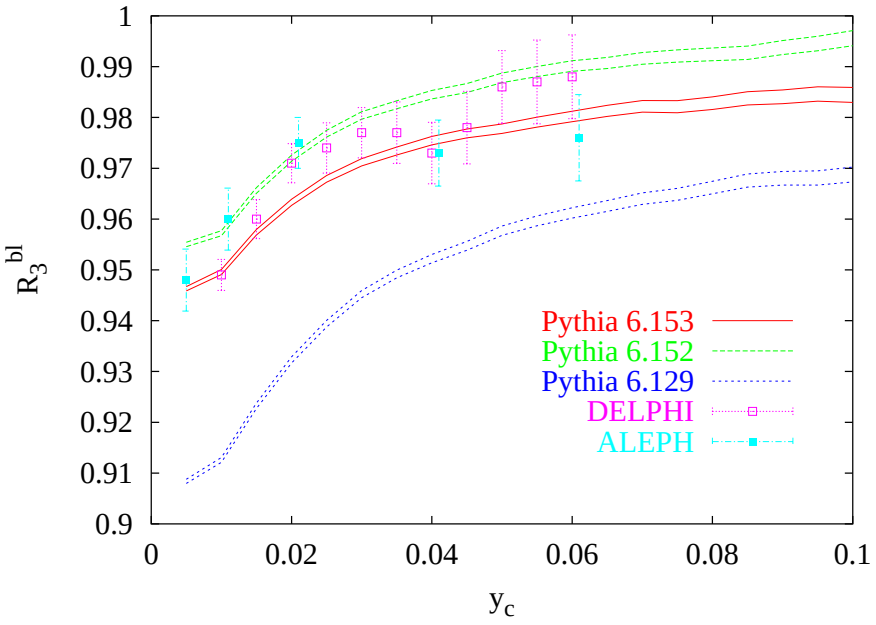
$\Rightarrow$ need ME input for good description

Calculate for $1 \to 2$ processes in SM + MSSM:

$$\frac{1}{\sigma(a \to bc)} \frac{\mathrm{d}\sigma(a \to bcg)}{\mathrm{d}x_1\,\mathrm{d}x_2}$$

Depends on mass ratios, colour and spin structure, and parity ($\gamma_5$)

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

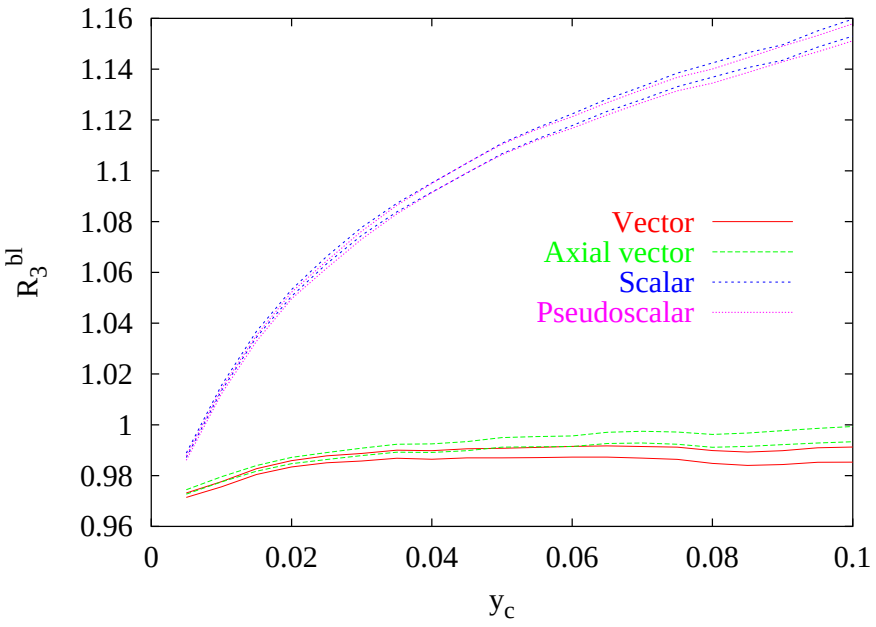



## LEP1 3jet $b\bar{b}$/light: $R_3^{bl}(y_c)$

$E_{CM} = 91$ GeV

$m_b = 4.8$ GeV

corrected to parton level

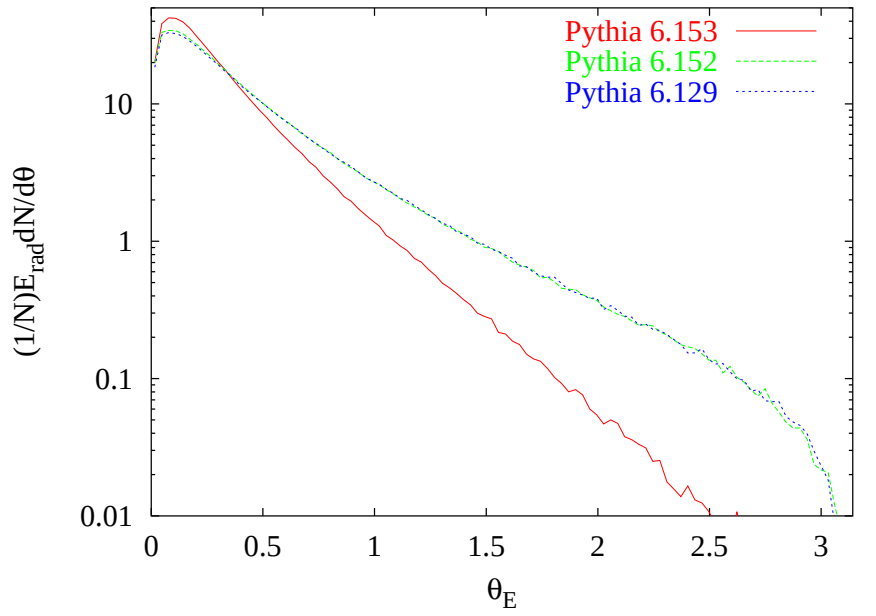



## Higgs: $R_3^{bl}(y_c)$

$E_{CM} = m_{h/H/A}$ $= 120$ GeV

$m_b = 4.8$ GeV

reference light q from $\gamma^*/Z^*$




## top decay:

less emission at large angles

$\theta_E$ w.r.t. original b axis

$\Rightarrow$ W at 180°

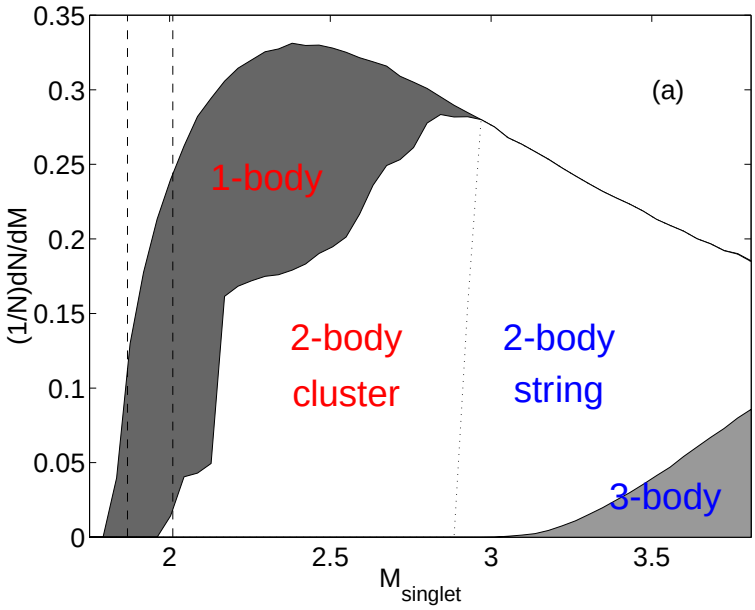
# Hadronization of low-mass strings

## $\Rightarrow$ 'cluster', e.g. by $g \rightarrow q\bar{q}$ in shower

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

Improved description of when collapse occurs
(mass spectrum $\Leftarrow$ constituent quark masses)

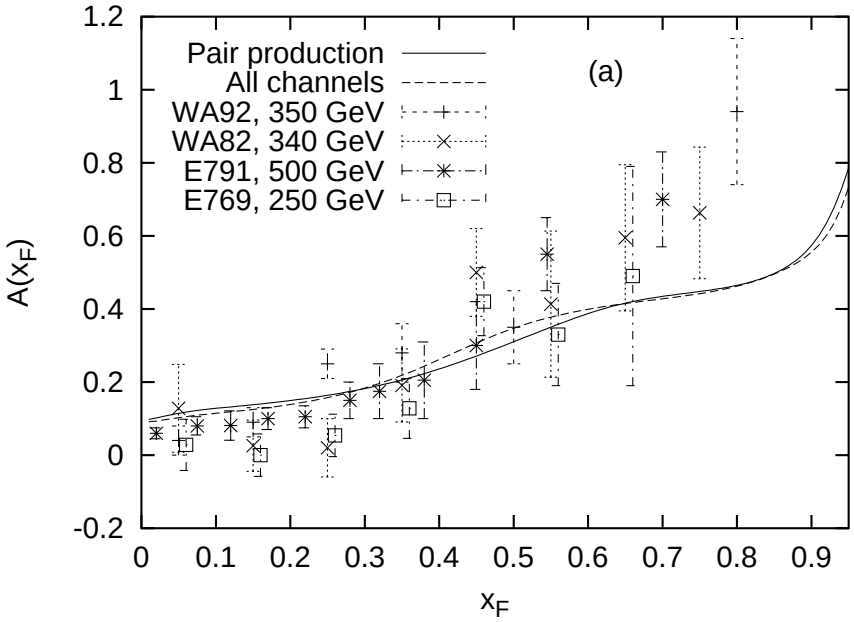
example:
charm
string
in $\pi p$
collision




and
1-body collapse: energy-momentum shuffling
2-body decay: smoother joining to string
picture (matched anisotropic decay)

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

in $\pi^- p$



# Other PYTHIA 6.1 news

- JETSET routines renamed:
  `LUxxxx` $\longrightarrow$ `PYxxxx` + some more
- All real variables in `DOUBLE PRECISION`
- Many improved resonance decays
- Newer parton distributions (but . . . )
- QED radiation off an incoming muon
- Energy-dependent $p_{\perp\mathrm{min}}$ in multiple interactions
- Colour rearrangement options for $\mathrm{W}^+\mathrm{W}^-$
- Expanded Bose-Einstein algorithm
- New baryon production scheme (optional)
- One-dimensional histograms (GBOOK)

2–, 4– and 6–fermion standard interfaces for showers and hadronization:

```
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)
```

$\mathrm{q\bar{q}gg}$ and $\mathrm{q\bar{q}q'\bar{q}'}$ QCD 4–jet standard interface for showers and hadronization:

```
CALL PY4JET(PMAX,IRAD,ICOM)
```

# On to C++

(L. Lönnblad, CPC 118 (1999) 213;
M. Bertini, L. Lönnblad & TS, LUTP 00-23 (hep-ph/0006152);
input to `leif@thep.lu.se`)

Why Fortran $\longrightarrow$ C++?

- SLAC $\longrightarrow$, FNAL $\longrightarrow$, CERN $\longrightarrow$ LHC era.
- Industrial standard.
- Educational and professional continuity for students.
- Better to program – for experts.
- User-friendy interfaces – for the rest of us.

PYTHIA 7 milestones:

- January 1998: project formally started.
- June 2000: "proof of concept" version, with generic event generation machinery, some processes and string fragmentation.
- 2001–2002: useful version (?), but limited in scope.
- ??: more and better than current PYTHIA.

HERWIG++ progress:
PPARC funds 2 dedicated "postdocs",
3-year work recently started.