Monte Carlo event generators for LHC physics

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http://seymour.home.cern.ch/seymour/slides/CERNlectures.html

Monte Carlo for the LHC

1. Basic principles
2. Parton showers
3. Hadronization
4. Monte Carlo programs in practice
5. Questions and answers

Monte Carlo Programs in Practice

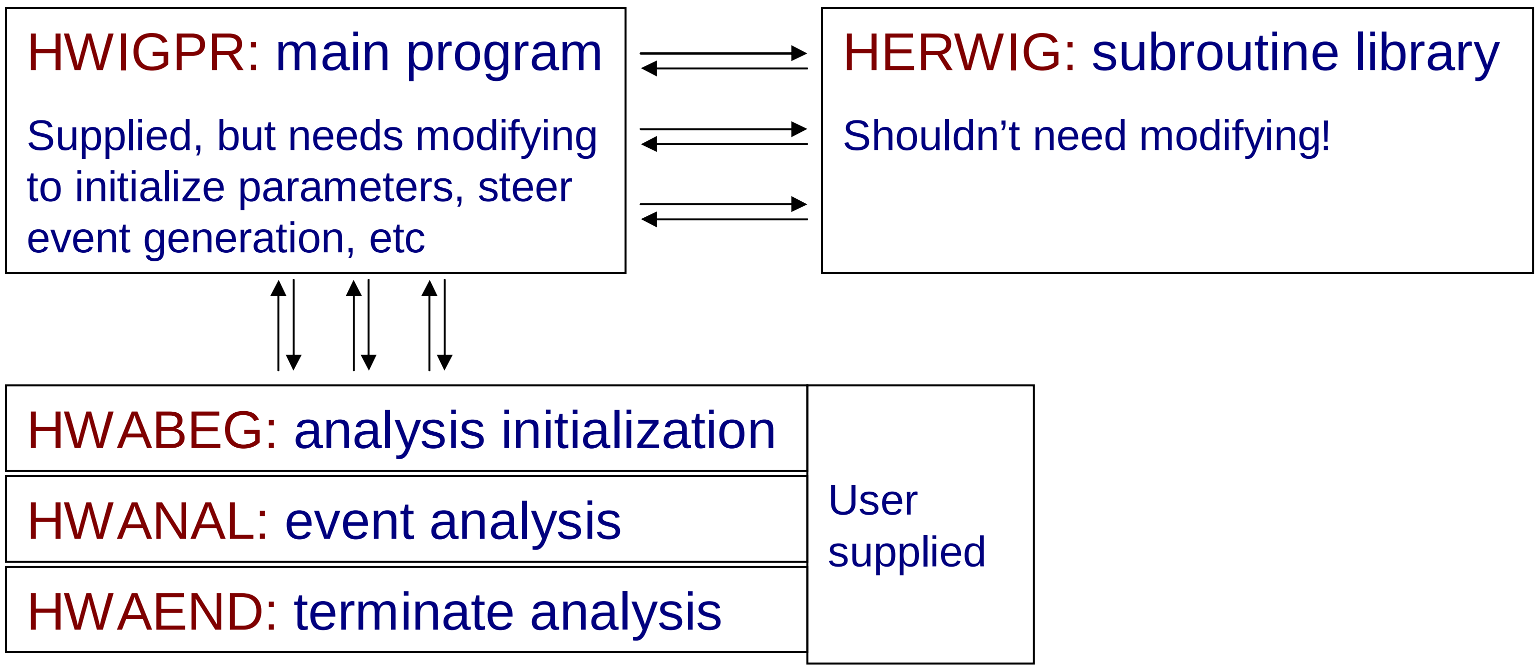
1. HERWIG
   - Status and Structure
   - Example input, control parameters
   - Example output
   - Physics examples
2. PYTHIA
   - Status and Structure
   - Example input, control parameters
   - Example output
   - Physics examples
3. The Future – Object Oriented Event Generators
   - ThePEG and PYTHIA7
   - HERWIG++
   - SHERPA

With thanks to Torbjörn Sjöstrand, Stefan Gieseke, Frank Krauss and Peter Richardson

HERWIG

- Current status:
- Version 6.500 released on October 16th 2002
  - http://hepwww.rl.ac.uk/theory/seymour/herwig/
  - ~ 60,000 lines of FORTRAN, 11 authors (6 currently active)
- "The last FORTRAN version"?
- Recent new features:
  - Les Houches accord interface for arbitrary hard processes
  - Spin correlation algorithm à see later
  - Additional SM, MSSM and other BSM processes
  - Interface to MC@NLO program (Frixione & Webber)
- Forthcoming features: (!)
  - CKKW-like multijet matrix element matching
  - Multiple hard and soft interaction underlying event model (Jimmy+Ivan)

Structure


HWIGPR: main program
Supplied, but needs modifying to initialize parameters, steer event generation, etc
HERWIG: subroutine library
Shouldn’t need modifying!
HWABEG: analysis initialization
HWANAL: event analysis
HWAEND: terminate analysis
User supplied

Example Main Program

```
      PROGRAM HWIGPR
C---COMMON BLOCKS ARE INCLUDED AS FILE HERWIG65.INC
      INCLUDE 'HERWIG65.INC'
      INTEGER N
      EXTERNAL HWUDAT
C---MAX NUMBER OF EVENTS THIS RUN
      MAXEV=100
C---BEAM PARTICLES
      PART1='P'
      PART2='P'
C---BEAM MOMENTA
      PBEAM1=7000.
      PBEAM2=PBEAM1
C---PROCESS
      IPROC=3000
C---INITIALISE OTHER COMMON BLOCKS
      CALL HWIGIN
C---USER CAN RESET PARAMETERS AT
C    THIS POINT, OTHERWISE
C    VALUES IN HWIGIN WILL
      PRVTX=.FALSE.
      MAXER=MAXEV/100
      MAXPR=0
      PTMIN=100.
C    N.B. TO READ SUDAKOV FORM FACTOR FILE ON UNIT 77
C    INSERT THE FOLLOWING TWO LINES IN SUBSEQUENT RUNS
C       LRSUD=77
C       LWSUD=0
C---READ IN SUSY INPUT FILE, IN THIS CASE LHC SUGRA POINT 2
      OPEN(UNIT=LRSUSY,FORM='FORMATTED',STATUS='OLD',ERR=999,
     &     FILE='sugra_pt2.1200.in')
      CALL HWISSP
      CLOSE(UNIT=LRSUSY)
C---COMPUTE PARAMETER-DEPENDENT CONSTANT
      CALL HWUINC
C---CALL HWUSTA TO MAKE ANY PAR
      CALL HWUSTA('PI0     ')
C---USER'S INITIAL CALCULATIONS
      CALL HWABEG
```

Process code: see list

Phase space cuts: process dependent

Read in SUSY parameters (from ISAWIG)

```
C---INITIALISE ELEMENTARY PROCESS
      CALL HWEINI
C---LOOP OVER EVENTS
      DO 100 N=1,MAXEV
C---INITIALISE EVENT
      CALL HWUINE
C---GENERATE HARD SUBPROCESS
      CALL HWEPRO
C---GENERATE PARTON CASCADES
      CALL HWBGEN
C---DO HEAVY OBJECT DECAYS
      CALL HWDHOB
C---DO CLUSTER FORMATION
      CALL HWCFOR
C---DO CLUSTER DECAYS
      CALL HWCDEC
C---DO UNSTABLE PARTICLE DECAYS
      CALL HWDHAD
C---DO HEAVY FLAVOUR HADRON DECAYS
      CALL HWDHVY
C---ADD SOFT UNDERLYING EVENT IF NEEDED
      CALL HWMEVT
C---FINISH EVENT
      CALL HWUFNE
C---USER'S EVENT ANALYSIS
      CALL HWANAL
  100 CONTINUE
C---TERMINATE ELEMENTARY PROCESS
      CALL HWEFIN
C---USER'S TERMINAL CALCULATIONS
      CALL HWAEND
      STOP
     'SUSY input file did not open correctly.'
     'Please check that it is in the right place.'
     'Examples can be obtained from the ISAWIG web page.'
      WRITE (6,*)
      END
```

Processes Available

IPROC	Process
100	$\ell^+\ell^- \to q\bar{q}(g)$ (all q flavours)
100+IQ	$\ell^+\ell^- \to q\bar{q}(g)$ (IQ $= 1,2,3,4,5,6$ for $q = d,u,s,c,b,t$)
107	$\ell^+\ell^- \to gg(g)$ (fictitious process)
110	$\ell^+\ell^- \to q\bar{q}g$ (all flavours)
110+IQ	$\ell^+\ell^- \to q\bar{q}g$ (IQ as above)
120	$\ell^+\ell^- \to q\bar{q}$ (all flavours, no hard gluon correction)
120+IQ	$\ell^+\ell^- \to q\bar{q}$ (IQ as above, no hard gluon correction)
127	$\ell^+\ell^- \to gg$ (fictitious process, no hard gluon correction)
150+IL	$\ell^+\ell^- \to \ell'\bar{\ell}'$ (IL $= 1,2,3$ for $\ell' = e,\mu,\tau$, N.B. $\ell \neq \ell'$)
200	$\ell^+\ell^- \to W^+W^-$ (see sect. 4.3.2 on control of W/Z decays)
250	$\ell^+\ell^- \to Z^0Z^0$ (see sect. 4.3.2 on control of W/Z decays)
300	$\ell^+\ell^- \to Z^0H^0_{SM} \to Z^0q\bar{q}$ (all flavours)
300+IQ	$\ell^+\ell^- \to Z^0H^0_{SM} \to Z^0q\bar{q}$ (IQ as above)
306+IL	$\ell^+\ell^- \to Z^0H^0_{SM} \to Z^0\ell\bar{\ell}$ (IL as above)
310, 311	$\ell^+\ell^- \to Z^0H^0_{SM} \to Z^0W^+W^-,\ Z^0Z^0Z^0$

IPROC	Process
312	$\ell^+\ell^- \to Z^0H^0_{SM} \to Z^0\gamma\gamma$
399	$\ell^+\ell^- \to Z^0H^0_{SM} \to Z^0$ anything
400+ID	$\ell^+\ell^- \to \nu\bar{\nu}H^0_{SM} + \ell^+\ell^-H^0_{SM}$ (ID as in IPROC $= 300 +$ ID)
500+ID	$\ell^+\ell^- \to \ell^+\ell^-\gamma\gamma \to \ell^+\ell^-q\bar{q}/\ell\bar{\ell}/W^+W^-$ (ID=0–10 as in IPROC $= 300 +$ ID)
550+ID	$\ell^+\ell^- \to \ell\nu_\ell\gamma W \to \ell\nu_\ell q\bar{q}'/\ell\bar{\ell}'$ (ID=0–9 as in IPROC $= 300 +$ ID)
600	$\ell^+\ell^- \to q\bar{q}g g,\ q\bar{q}q'\bar{q}'$ (all q flavours)
600+IQ	$\ell^+\ell^- \to q\bar{q}g g,\ q\bar{q}q'\bar{q}'$ (IQ as above)
	After generation, IHPRO is subprocess (see sect. 4.3.5)
700-99	Minimal Supersymmetric Standard Model (MSSM) processes
700	$\ell^+\ell^- \to$ 2-sparticle processes (sum of 710, 730, 740 and 760)
710	$\ell^+\ell^- \to$ neutralino pairs (all neutralinos)
706+4IN1+IN2	$\ell^+\ell^- \to \tilde{\chi}^0_{IN1}\tilde{\chi}^0_{IN2}$ (IN1,2=neutralino mass eigenstate)
730	$\ell^+\ell^- \to$ chargino pairs (all charginos)
728+2IC1+IC2	$\ell^+\ell^- \to \tilde{\chi}^+_{IC1}\tilde{\chi}^-_{IC2}$ (IC1,2=chargino mass eigenstate)
740	$\ell^+\ell^- \to$ slepton pairs (all flavours)
736+5IL	$\ell^+\ell^- \to \tilde{\ell}_{L,R}\tilde{\ell}^*_{L,R}$ (IL $= 1,2,3$ for $\tilde{\ell} = \tilde{e},\tilde{\mu},\tilde{\tau}$)
737+5IL	$\ell^+\ell^- \to \tilde{\ell}_L\tilde{\ell}^*_L$ (IL as above)
738+5IL	$\ell^+\ell^- \to \tilde{\ell}_L\tilde{\ell}^*_R$ (IL as above)
739+5IL	$\ell^+\ell^- \to \tilde{\ell}_R\tilde{\ell}^*_R$ (IL as above)
740+5IL	$\ell^+\ell^- \to \tilde{\nu}_L\tilde{\nu}^*_L$ (IL $= 1,2,3$ for $\tilde{\nu}_e,\tilde{\nu}_\mu,\tilde{\nu}_\tau$)
760	$\ell^+\ell^- \to$ squark pairs (all flavours)
757+4IQ	$\ell^+\ell^- \to \tilde{q}_{L,R}\tilde{q}^*_{L,R}$ (IQ $= 1,2,3,4,5,6$ for $\tilde{q} = \tilde{d},\tilde{u},\tilde{s},\tilde{c},\tilde{b},\tilde{t}$)
758+4IQ	$\ell^+\ell^- \to \tilde{q}_L\tilde{q}^*_L$ (IQ as above)
759+4IQ	$\ell^+\ell^- \to \tilde{q}_L\tilde{q}^*_R$ (IQ as above)
760+4IQ	$\ell^+\ell^- \to \tilde{q}_R\tilde{q}^*_R$ (IQ as above)
800-99	R-parity violating supersymmetric processes
800	Single sparticle production, sum of 810–840
810	$\ell^+\ell^- \to \tilde{\chi}^0\nu_i$, (all neutralinos)
810+IN	$\ell^+\ell^- \to \tilde{\chi}^0_{IN}\nu_i$, (IN=neutralino mass state)
820	$\ell^+\ell^- \to \tilde{\chi}^-e^+_i$ (all charginos)
820+IC	$\ell^+\ell^- \to \tilde{\chi}^-_{IC}e^+_i$, (IC=chargino mass state)
830	$\ell^+\ell^- \to \tilde{\nu}_iZ^0$ and $\ell^+\ell^- \to \tilde{e}^+_iW^-$
840	$\ell^+\ell^- \to \tilde{\nu}_ih^0/H^0/A^0$ and $\ell^+\ell^- \to \tilde{e}^+_iH^-$
850	$\ell^+\ell^- \to \tilde{\nu}_i\gamma$
860	Sum of 870 and 880
870	$\ell^+\ell^- \to \ell^+\ell^-$, via LLE only
867+3IL1+IL2	$\ell^+\ell^- \to \ell^+_{IL1}\ell^-_{IL2}$ (IL1,2=1,2,3 for e,μ,τ)

IPROC	Process
7999	generated by HERBVI package
8000	Minimum bias soft hadron-hadron event
9000	Deep inelastic lepton scattering (all neutral current)
9000+IQ	Deep inelastic lepton scattering (NC on flavour IQ)
9010	Deep inelastic lepton scattering (all charged current)
9010+IQ	Deep inelastic lepton scattering (CC on flavour IQ)
9100	Boson-gluon fusion in neutral current DIS (all flavours)
9100+IQ	Boson-gluon fusion in neutral current DIS (IQ as above)
9107	J/ψ + gluon production by boson-gluon fusion
9110	QCD Compton process in neutral current DIS (all flavours)
9110+IP	QCD Compton process in NC DIS (IP=1–12 for $d - \bar{t}, \bar{d} - \bar{t}$)
9130	All $\mathcal{O}(\alpha_S)$ NC processes (i.e. 9100+9110)
9140+IP	Heavy quark production by charged-current boson-gluon fusion
	IP: $1 = s\bar{c}, 2 = b\bar{c}, 3 = s\bar{t}, 4 = b\bar{t}$ (+ ch. conj.)
9500+ID	$W^+W^-/Z^0Z^0 \to H^0_{SM}$ in DIS (ID as in IPROC $= 300 +$ ID)
10000+IP	as IPROC = IP but with soft underlying event
	(soft remnant fragmentation in lepton-hadron) suppressed

IPROC	Process
880	$\ell^+\ell^- \to d\bar{d}$, via LLE and LQD
877+3IQ1+IQ2	$\ell^+\ell^- \to d_{IL1}\bar{d}_{IL2}$ (IQ1,2=1,2,3 for d,s,b)
910	$\ell^+\ell^- \to \nu_e\bar{\nu}_eh^0 + e^+e^-h^0$
920	$\ell^+\ell^- \to \nu_e\bar{\nu}_eH^0 + e^+e^-H^0$
960	$\ell^+\ell^- \to Z^0h^0$
970	$\ell^+\ell^- \to Z^0H^0$
955	$\ell^+\ell^- \to H^+H^-$
965	$\ell^+\ell^- \to A^0h^0$
965	$\ell^+\ell^- \to A^0H^0$
1000+ID	$\ell^+\ell^- \to t\bar{t}H^0_{SM}$ (ID as in IPROC=300+ID)
1110+IQ	$\ell^+\ell^- \to q\bar{q}h^0$ (IQ as in IPROC=100+IQ)
1116+IL	$\ell^+\ell^- \to \ell^+\ell^-h^0$ (IL=1,2,3 for e,μ,τ)
1120+IQ	$\ell^+\ell^- \to q\bar{q}H^0$ (IQ as in IPROC=100+IQ)
1126+IL	$\ell^+\ell^- \to \ell^+\ell^-H^0$ (IL=1,2,3 for e,μ,τ)
1130+IQ	$\ell^+\ell^- \to q\bar{q}A^0$ (IQ as in IPROC=100+IQ)
1136+IL	$\ell^+\ell^- \to \ell^+\ell^-A^0$ (IL=1,2,3 for e,μ,τ)
1140	$\ell^+\ell^- \to d\bar{u}H^+$+ ch. conj.
1141	$\ell^+\ell^- \to s\bar{c}H^+$+ ch. conj.
1142	$\ell^+\ell^- \to b\bar{t}H^+$+ ch. conj.
1143	$\ell^+\ell^- \to e\bar{\nu}_eH^+$+ ch. conj.
1144	$\ell^+\ell^- \to \mu\bar{\nu}_\mu H^+$+ ch. conj.
1145	$\ell^+\ell^- \to \tau\bar{\nu}_\tau H^+$+ ch. conj.
1200–99	Reserved for other $\ell^+\ell^-$ processes
1300	$q\bar{q} \to Z^0/\gamma \to q'\bar{q}'$ (all flavours)
1300+IQ	$q\bar{q} \to Z^0/\gamma \to q'\bar{q}'$ (IQ $= 1,2,3,4,5,6$ for $q = d,u,s,c,b,t$)
1350	$q\bar{q} \to Z^0/\gamma \to \ell\bar{\ell}$ (all lepton species)
1350+IL	$q\bar{q} \to Z^0/\gamma \to \ell\bar{\ell}$ (IL $= 1-6$ for $\ell = e,\nu_e,\mu,\nu_\mu$, etc.)
1399	$q\bar{q} \to Z^0/\gamma \to$ anything
1400	$q\bar{q} \to W^\pm \to q'\bar{q}''$ (all flavours)
1400+IQ	$q\bar{q} \to W^\pm \to q'\bar{q}''$ (q' or q'' as above)
1450	$q\bar{q} \to W^\pm \to \ell\nu_\ell$ (all lepton species)
1450+IL	$q\bar{q} \to W^\pm \to \ell\nu_\ell$ (IL $= 1,2,3$ for $\ell = e,\mu,\tau$)
1499	$q\bar{q} \to W^\pm \to$ anything
1500	QCD $2 \to 2$ hard parton scattering
	After generation, IHPRO is subprocess (see sect. 4.6.2)
1600+ID	$gg/q\bar{q} \to H^0_{SM}$ (ID as in IPROC $= 300 +$ ID)
1700+IQ	QCD heavy quark production (IQ as above)
	After generation, IHPRO is subprocess (see sect. 4.6.2)
1800	QCD direct photon + jet production

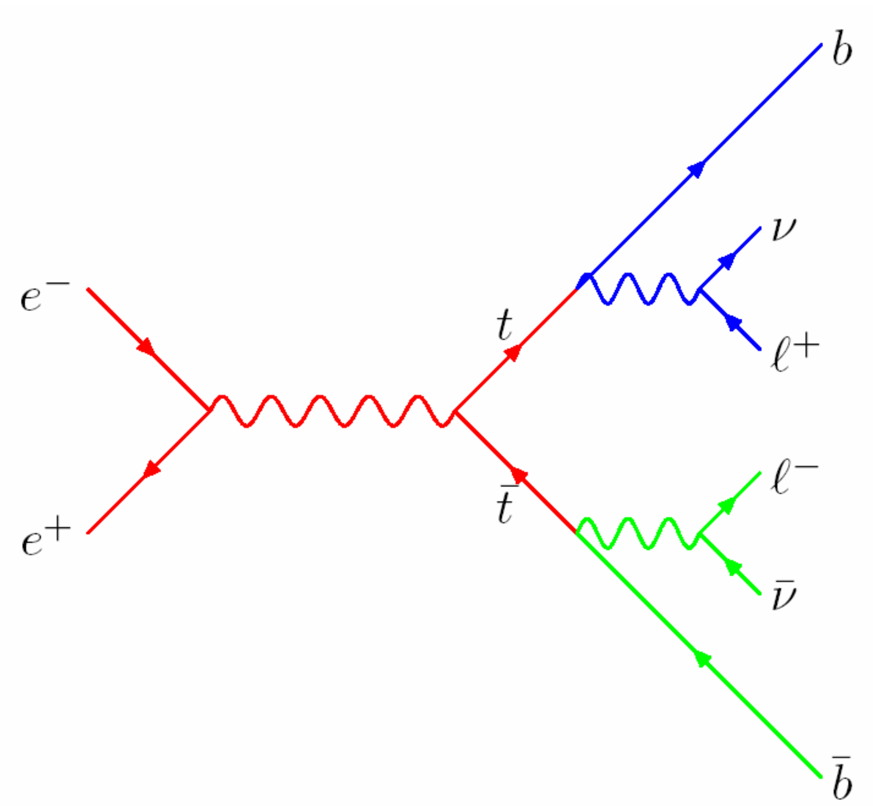
IPROC	Process
	After generation, IHPRO is subprocess (see sect. 4.6.5)
1900+ID	$q\bar{q} \to q'\bar{q}'W^+W^-/Z^0Z^0 \to q'\bar{q}'H^0_{SM}$ (ID as in IPROC $= 300 +$ ID)
2000	t production via $W^\pm$ exchange (sum of 2001–2008)
2001–4	$u\bar{b} \to d\bar{t}$, $d\bar{b} \to u\bar{t}$, $\bar{d}\bar{b} \to \bar{u}\bar{t}$, $ub \to dt$
2005–8	$\bar{c}b \to \bar{s}t$, $s\bar{b} \to c\bar{t}$, $\bar{s}b \to \bar{c}t$, $cb \to st$
2100	$W^\pm$ + jet production
2110	$W^\pm$ + jet production (Compton only: $qg \to Wq$)
2120	$W^\pm$ + jet production (annihilation only: $q\bar{q} \to Wg$)
2150	Z^0 + jet production
2160	Z^0 + jet production (Compton only: $qg \to Zq$)
2170	Z^0 + jet production (annihilation only: $q\bar{q} \to Zg$)
2200	QCD direct photon pair production
	After generation, IHPRO is subprocess (see sect. 4.6.5)
2300+ID	QCD SM Higgs + jet production (ID as in IPROC=300+ID)
	After generation, IHPRO is subprocess (see sect. 4.6.10)
2400	Mueller-Tang colour singlet exchange
2450	Quark scattering via photon exchange
2500+ID	$gg/q\bar{q} \to t\bar{t}H^0_{SM}$ (ID as in IPROC=300+ID)
2600+ID	$q\bar{q}' \to W^\pm H^0_{SM}$ (ID as in IPROC=300+ID)
2700+ID	$q\bar{q} \to Z^0H^0_{SM}$ (ID as in IPROC=300+ID)
2800	W^+W^- production in hadron-hadron collisions
2810	Z^0Z^0 production in hadron-hadron collisions (including photon terms)
2815	Z^0Z^0 production in hadron-hadron collisions (Z^0 only)
2820	$W^\pm Z^0$ production in hadron-hadron collisions (including photon terms)
2825	$W^\pm Z^0$ production in hadron-hadron collisions (Z^0 only)
2850	hadron-hadron $\to W^+W^-X$ using MC@NLO
2860	hadron-hadron $\to Z^0Z^0X$ using MC@NLO
2870	hadron-hadron $\to W^+Z^0X$ using MC@NLO
2880	hadron-hadron $\to W^-Z^0X$ using MC@NLO
2900+IQ	$gg + q\bar{q} \to Q\bar{Q}Z^0$ for massless Q and $\bar{Q}$ (IQ=1…6 for $Q = d \dots t$)
2910+IQ	$gg + q\bar{q} \to Q\bar{Q}Z^0$, for massive Q and $\bar{Q}$ (IQ=1…6 for $Q = d \dots t$)
3000-3999	Minimal Supersymmetric Standard Model (MSSM) processes
3000	2-parton $\to$ 2-sparticle processes (sum of those below)
3010	2-parton $\to$ 2-spartons processes
3020	2-parton $\to$ 2-gaugino processes
3030	2-parton $\to$ 2-slepton processes
3100+ISQ	$gg/q\bar{q} \to \tilde{q}\tilde{q}'^*\tilde{H}^\pm$ (ISQ=IPROC–3100 as from table 15)
3200+ISQ	$gg/q\bar{q} \to \tilde{q}\tilde{q}'^*h, H, A$ (ISQ=IPROC–3200 as from table 16)

IPROC	Process
3310,3315	$q\bar{q}' \to W^\pm h^0, H^\pm h^0$(all q, q' flavours – gauge bosons mediated only)
3320,3325	$q\bar{q}' \to W^\pm H^0, H^\pm H^0$ (")
3335	$q\bar{q}' \to H^\pm A^0$ (")
3350	$q\bar{q} \to W^\pm H^\mp$ (Higgstrahlung and Higgs mediated)
3355	$q\bar{q} \to H^\pm H^\mp$ (all q flavours — gauge boson mediated only)
3360,3365	$q\bar{q} \to Z^0h^0, A^0h^0$ (")
3370,3375	$q\bar{q} \to Z^0H^0, A^0H^0$ (")
3410	$bq \to b\,h^0$ + ch. conj.
3420	$bq \to b\,H^0$ + ch. conj.
3430	$bq \to b\,A^0$ + ch. conj.
3450	$bq \to t\,H^-$ + ch. conj.
3500	$bq \to bq'H^\pm$ + ch. conj.
3610	$q\bar{q}/gg \to h^0$ (light scalar Higgs)
3620	$q\bar{q}/gg \to H^0$ (heavy scalar Higgs)
3630	$q\bar{q}/gg \to A^0$ (pseudoscalar Higgs)
3710	$q\bar{q} \to q'\bar{q}'W^+W^-/Z^0Z^0 \to q'\bar{q}'h^0$
3720	$q\bar{q} \to q'\bar{q}'W^+W^-/Z^0Z^0 \to q'\bar{q}'H^0$
3810+IQ	$gg + q\bar{q} \to Q\bar{Q}h^0$ (all q flavours in s-channel, IQ as usual for Q flavour)
3820+IQ	$gg + q\bar{q} \to Q\bar{Q}H^0$ (")
3830+IQ	$gg + q\bar{q} \to Q\bar{Q}A^0$ (")
3839	$gg + q\bar{q} \to b\bar{t}H^+$ + ch. conjg. (all q flavours in s-channel)
3840+IQ	$gg \to Q\bar{Q}h^0$ (IQ as above)
3850+IQ	$gg \to Q\bar{Q}H^0$ (")
3860+IQ	$gg \to Q\bar{Q}A^0$ (")
3869	$gg \to b\bar{t}H^+$ + ch. conjg.
3870+IQ	$q\bar{q} \to Q\bar{Q}h^0$ (all q flavours in s-channel, IQ as above)
3880+IQ	$q\bar{q} \to Q\bar{Q}H^0$ (")
3890+IQ	$q\bar{q} \to Q\bar{Q}A^0$ (")
3899	$q\bar{q} \to b\bar{t}H^+$ + ch. conjg. (all q flavours in s-channel)
3900–99	Reserved for other hadron-hadron MSSM processes
4000–99	R-parity violating supersymmetric processes via LQD
4000	single sparticle production, sum of 4010–4050
4010	$\bar{u}_jd_k \to \tilde{\chi}^0\ell^-_i$, $\bar{d}_jd_k \to \tilde{\chi}^0\nu_i$ (all neutralinos)
4010+IN	$\bar{u}_jd_k \to \tilde{\chi}^0_{IN}\ell^-_i$, $\bar{d}_jd_k \to \tilde{\chi}^0_{IN}\nu_i$ (IN=neutralino mass state)
4020	$\bar{u}_jd_k \to \tilde{\chi}^-\nu_i$, $\bar{d}_jd_k \to \tilde{\chi}^-e^+_i$ (all charginos)
4020+IC	$\bar{u}_jd_k \to \tilde{\chi}^-_{IC}\nu_i$, $\bar{d}_jd_k \to \tilde{\chi}^-_{IC}e^+_i$ (IC=chargino mass state)
4040	$u_j\bar{d}_k \to \tilde{\tau}^+_iZ^0$, $u_j\bar{d}_k \to \tilde{\nu}_iW^+$ and $d_j\bar{d}_k \to \tilde{e}^+_iW^-$
4050	$u_j\bar{d}_k \to \tilde{\ell}^+_ih^0/H^0/A^0$, $u_j\bar{d}_k \to \tilde{\nu}_iH^+$ and $d_j\bar{d}_k \to \tilde{e}^+_iH^-$

IPROC	Process
4060	Sum of 4070 and 4080
4070	$\bar{u}_jd_k \to \bar{u}_ld_m$ and $\bar{d}_jd_k \to \bar{d}_ld_m$, via LQD only
4080	$\bar{u}_jd_k \to \nu_il^-_k$ and $\bar{d}_jd_k \to l^+_il^-_k$, via LQD and LLE
4100-99	R-parity violating supersymmetric processes via UDD
4100	single sparticle production, sum of 4110–4150
4110	$u_id_j \to \tilde{\chi}^0\bar{d}_k$, $d_jd_k \to \tilde{\chi}^0\bar{u}_i$ (all neutralinos)
4110 +IN	$u_id_j \to \tilde{\chi}^0_{IN}\bar{d}_k$, $d_jd_k \to \tilde{\chi}^0_{IN}\bar{u}_i$(IN as above)
4120	$u_id_j \to \tilde{\chi}^+\bar{u}_k$, $d_jd_k \to \tilde{\chi}^-\bar{d}_i$ (all charginos)
4120 +IC	$u_id_j \to \tilde{\chi}^+_{IC}\bar{u}_k$, $d_jd_k \to \tilde{\chi}^-_{IC}\bar{d}_i$ (IC as above)
4130	$u_id_j \to \tilde{g}\bar{d}_k$, $d_jd_k \to \tilde{g}\bar{u}_i$
4140	$u_id_j \to \tilde{b}^*_1Z^0$, $d_jd_k \to \tilde{t}^*_1Z^0$, $u_id_j \to \tilde{t}^*_1W^+$ and $d_jd_k \to \tilde{b}^*_1W^-$
4150	$u_id_j \to \tilde{d}^*_{k1}h^0/H^0/A^0$, $d_jd_k \to \tilde{u}^*_{i1}h^0/H^0/A^0$, $u_id_j \to \tilde{u}^*_{kα}H^+$, $d_jd_k \to \tilde{d}^*_{iα}H^-$
4160	$u_id_j \to u_ld_m$, $d_jd_k \to d_ld_m$ via UDD.
4200-99	Graviton resonance production
4200	Sum of 4210, 4250 and 4270
4210	$gg/q\bar{q} \to G \to gg/q\bar{q}$ (all partons)
4210+IQ	$gg/q\bar{q} \to G \to q\bar{q}$ (IQ as above)
4220	$gg/q\bar{q} \to G \to gg$
4250	$gg/q\bar{q} \to G \to \ell\bar{\ell}$ (all leptons)
4250+IL	$gg/q\bar{q} \to G \to \ell\bar{\ell}$ (IL $= 1-6$ for $\ell = e,\nu_e,\mu,\nu_\mu$, etc.)
4260	$gg/q\bar{q} \to G \to \gamma\gamma$
4270	$gg/q\bar{q} \to G \to W^+W^-/Z^0Z^0/H^0_{SM}H^0_{SM}$
4271	$gg/q\bar{q} \to G \to W^+W^-$
4272	$gg/q\bar{q} \to G \to Z^0Z^0$
4273	$gg/q\bar{q} \to G \to H^0_{SM}H^0_{SM}$
5000	Pointlike photon-hadron jet production (all flavours)
5100+IQ	Pointlike photon heavy flavour pair production (IQ as above)
5200+IQ	Pointlike photon heavy flavour single excitation (IQ as above)
	After generation, IHPRO is subprocess (see sect. 4.6.5)
5300	Quark-photon Compton scattering
5500	Pointlike photon production of light (u,d,s) L=0 mesons
5510,20	S=0 mesons only, S=1 mesons only
	After generation, IHPRO is subprocess (see sect. 4.6.5)
6000	$\gamma\gamma \to q\bar{q}$ (all flavours)
6000+IQ	$\gamma\gamma \to q\bar{q}$ (IQ as above)
6006+IL	$\gamma\gamma \to \ell\bar{\ell}$ (IL $= 1,2,3$ for $\ell = e,\mu,\tau$)
6010	$\gamma\gamma \to W^+W^-$
7000 –	Baryon-number violating and other multi-$W^\pm$ processes

Production/Decay Spin Correlations

- eg top quark pairs in e+e- annihilation:



$$\mathcal{M}_{\text{total}} = \frac{1}{m_a\Gamma_a}\frac{1}{m_b\Gamma_b}\sum_{\lambda_c\lambda_d}\mathcal{M}^{\lambda_c\lambda_d}_{ab\to cd}\mathcal{M}^{\lambda_c}_{c\ \text{decay}}\mathcal{M}^{\lambda_d}_{d\ \text{decay}}$$

$$|\mathcal{M}_{\text{total}}|^2 = \frac{1}{m_a^2\Gamma_a^2}\frac{1}{m_b^2\Gamma_b^2}\rho^{\lambda_c\lambda'_c\lambda_d\lambda'_d}D_c^{\lambda_c\lambda'_c}D_d^{\lambda_d\lambda'_d}$$

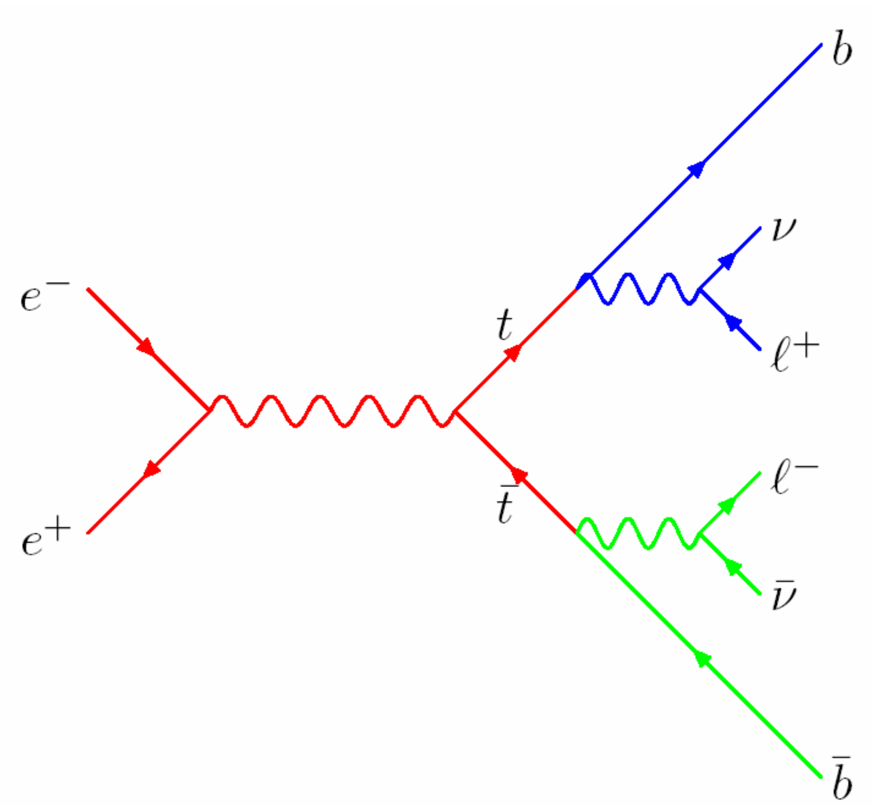
$$\rho_{\text{prod}}^{\lambda_c\lambda'_c\lambda_d\lambda'_d} = \mathcal{M}^{\lambda_c\lambda_d}_{ab\to cd}\mathcal{M}^{*\lambda'_c\lambda'_d}_{ab\to cd},$$

$$D_c^{\lambda_c\lambda'_c} = \mathcal{M}^{\lambda_c}_{c\ \text{decay}}\mathcal{M}^{*\lambda'_c}_{c\ \text{decay}},$$

Mike Seymour

Production/Decay Spin Correlations

- eg top quark pairs in e+e- annihilation:



$$|\mathcal{M}|^2 = \rho^1_{\kappa_1\kappa_1'}\rho^2_{\kappa_2\kappa_2'}\mathcal{M}^{e^+e^-\to t\bar{t}}_{\kappa_1\kappa_2;\lambda_t\lambda_{\bar{t}}}\mathcal{M}^{*e^+e^-\to t\bar{t}}_{\kappa_1'\kappa_2';\lambda_t'\lambda_{\bar{t}}'}$$

$$\mathcal{M}^{t\to b\ell\nu}_{\lambda_t}\mathcal{M}^{*t\to b\ell\nu}_{\lambda_t'}$$

$$\mathcal{M}^{\bar{t}\to \bar{b}\ell\nu}_{\lambda_{\bar{t}}}\mathcal{M}^{*\bar{t}\to \bar{b}\ell\nu}_{\lambda_{\bar{t}}'}$$

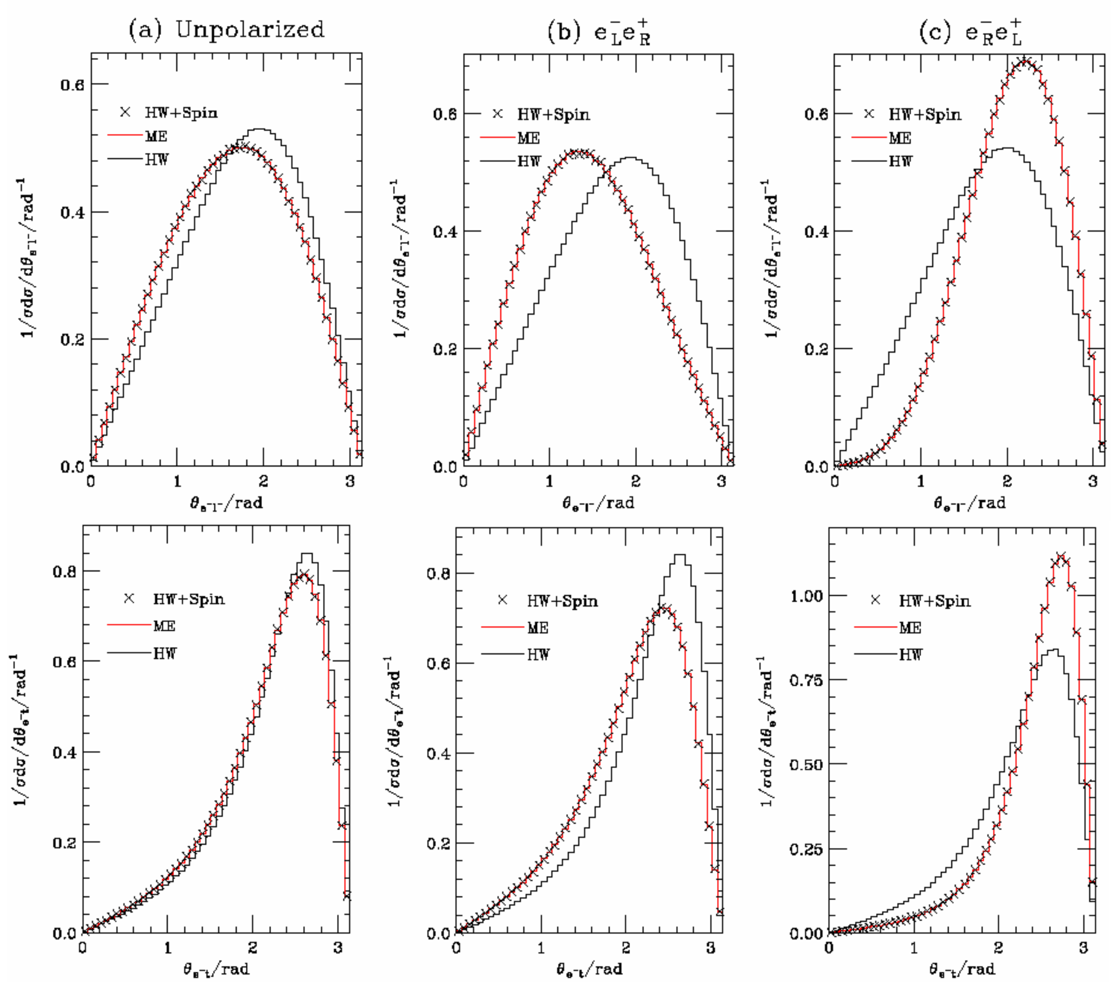
Full spin correlations included, by factorized, step-by-step algorithm

Production/Decay Spin Correlations

- eg top quark pairs in e+e- annihilation:

Correlation between lepton and beam

Correlation between lepton and top



PYTHIA

- Current status:
- Version 6.218 released on June 30th 2003
  - http://www.thep.lu.se/~torbjorn/Pythia.html
  - ~ 60,000 lines of FORTRAN
- Recent new features:
  - Les Houches accord interface for arbitrary hard processes
  - Baryon-number violating decays in R-parity violation
  - Mass effects in gluon emission (!= dead cone) à see later
  - Additional SM, MSSM and other BSM processes
- Forthcoming features:
  - New multiple interaction model

PYTHIA Status

Currently **PYTHIA 6.218**
of 30 June 2003
~ 60,000 lines Fortran 77

Code, manual, sample main programs, more:

`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]

long writeup in T. Sjöstrand,
L. Lönnblad, S. Mrenna and P. Skands,
LU TP 01-21 [hep-ph/0108264],
third edition April 2003: ~ 440 pages

Coming soon: **PYTHIA 6.300**
⋆ New multiple interactions framework ⋆
(under development,still unstable)

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	$q\bar{q}' \to \tilde{\chi}^0_i \tilde{\chi}^\pm_j$
$\not{R}$ SUSY	$\tilde{\chi}^0_i \to bcs$
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	$f_i \bar{f}_i \to Q_k \bar{Q}_k$
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	$f_i \gamma \to f_i Z^0$
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	$f_i f_j \to f_k f_l$
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	$\gamma^*_T \gamma^*_L \to f_i \bar{f}_i$
139	$\gamma^*_L \gamma^*_T \to f_i \bar{f}_i$
140	$\gamma^*_L \gamma^*_L \to f_i \bar{f}_i$
80	$q_i \gamma \to q_k \pi^\pm$

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	$f_i \bar{f}_i \to \gamma h^0$
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	$f_i f_j \to f_k f_l h^0$
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	$gg \to Q_k \bar{Q}_k H^0$
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	$f_i g \to f_k H^+$
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	$f_i \bar{f}_i \to H^+ H^-$
Left-right symmetry:	
341	$\ell_i \ell_j \to H^{\pm\pm}_L$
342	$\ell_i \ell_j \to H^{\pm\pm}_R$
343	$\ell^\pm_i \gamma \to H^{\pm\pm}_L e^\mp$
344	$\ell^\pm_i \gamma \to H^{\pm\pm}_R e^\mp$
345	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \mu^\mp$
346	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \mu^\mp$
347	$\ell^\pm_i \gamma \to H^{\pm\pm}_L \tau^\mp$
348	$\ell^\pm_i \gamma \to H^{\pm\pm}_R \tau^\mp$
349	$f_i \bar{f}_i \to H^{++}_L H^{--}_L$
350	$f_i \bar{f}_i \to H^{++}_R H^{--}_R$
351	$f_i f_j \to f_k f_l H^{\pm\pm}_L$
352	$f_i f_j \to f_k f_l H^{\pm\pm}_R$
353	$f_i \bar{f}_i \to Z^0_R$
354	$f_i \bar{f}_j \to W^\pm_R$

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	$f_i \bar{f}_i \to \rho^0_{tc}$
192	$f_i \bar{f}_j \to \rho^+_{tc}$
193	$f_i \bar{f}_i \to \omega^0_{tc}$
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	$f_i \bar{f}_i \to W^\pm_L \pi^\mp_{tc}$
363	$f_i \bar{f}_i \to \pi^+_{tc} \pi^-_{tc}$
364	$f_i \bar{f}_i \to \gamma \pi^0_{tc}$
365	$f_i \bar{f}_i \to \gamma \pi'^0_{tc}$
366	$f_i \bar{f}_i \to Z^0 \pi^0_{tc}$
367	$f_i \bar{f}_i \to Z^0 \pi'^0_{tc}$
368	$f_i \bar{f}_i \to W^\pm \pi^\mp_{tc}$
370	$f_i \bar{f}_j \to W^\pm_L Z^0_L$
371	$f_i \bar{f}_j \to W^\pm_L \pi^0_{tc}$
372	$f_i \bar{f}_j \to \pi^\pm_{tc} Z^0_L$
373	$f_i \bar{f}_j \to \pi^\pm_{tc} \pi^0_{tc}$
374	$f_i \bar{f}_j \to \gamma \pi^\pm_{tc}$
375	$f_i \bar{f}_j \to Z^0 \pi^\pm_{tc}$
376	$f_i \bar{f}_j \to W^\pm \pi^0_{tc}$
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	$gg \to L_Q \bar{L}_Q$
164	$q_i \bar{q}_i \to L_Q \bar{L}_Q$
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	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$

No.	Subprocess
227	$f_i \bar{f}_i \to \tilde{\chi}^\pm_2 \tilde{\chi}^\mp_2$
228	$f_i \bar{f}_i \to \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_2$
229	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_1$
230	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_1$
231	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_1$
232	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_1$
233	$f_i \bar{f}_j \to \tilde{\chi}_1 \tilde{\chi}^\pm_2$
234	$f_i \bar{f}_j \to \tilde{\chi}_2 \tilde{\chi}^\pm_2$
235	$f_i \bar{f}_j \to \tilde{\chi}_3 \tilde{\chi}^\pm_2$
236	$f_i \bar{f}_j \to \tilde{\chi}_4 \tilde{\chi}^\pm_2$
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	$f_i \bar{f}_i \to \tilde{t}_1 \tilde{t}^*_2 +$
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	$q_i \bar{q}_i \to g G^*$
394	$q_i g \to q_i G^*$
395	$gg \to g G^*$

$\sum \approx 250$ processes

User program 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.

HERWIG, ISAJET: generator contains main program, user writes subroutines

PYTHIA: generator is subroutine package, user writes main program

Higgs production with PYTHIA

```
C...Arithmetic in double precision; integer functions; PYDATA.
      IMPLICIT DOUBLE PRECISION(A-H, O-Z)
      INTEGER PYK,PYCHGE,PYCOMP
      EXTERNAL PYDATA
C...The event record and other common blocks.
      COMMON/PYJETS/N,NPAD,K(4000,5),P(4000,5),V(4000,5)
      COMMON/PYDAT2/KCHG(500,4),PMAS(500,4),PARF(2000),VCKM(4,4)
      COMMON/PYSUBS/MSEL,MSELPD,MSUB(500),KFIN(2,-40:40),CKIN(200)
      COMMON/PYPARS/MSTP(200),PARP(200),MSTI(200),PARI(200)
C...Physics scenario.
      MSEL=0           ! Mix subprocesses freely
      MSUB(102)=1      ! g + g -> h0
      MSUB(123)=1      ! f + f' -> f + f' + h0
      MSUB(124)=1      ! f + f' -> f" + f"' + h0
      PMAS(25,1)=300D0 ! Nominal Higgs mass.
C...Run parameters.
      NEV=1000         ! Number of events
      ECM=14000D0      ! CM energy of run
      CKIN(1)=200D0    ! Minimum Higgs mass.
      CKIN(2)=400D0    ! Maximum Higgs mass.
C...Switch off unnecessary aspects (for faster simulation).
      MSTP(61)=0       ! No initial-state showers
      MSTP(71)=0       ! No final-state showers
      MSTP(81)=0       ! No multiple interactions
      MSTP(111)=0      ! No hadronization
C...Initialize and book histogram(s).
      CALL PYINIT('CMS','p','p',ECM)
      CALL PYBOOK(1,'Higgs mass distribution',80,200D0,400D0)
C...Generate events and look at first few.
      DO 200 IEV=1,NEV
        CALL PYEVNT
        IF(IEV.LE.1) CALL PYLIST(1)
C...Find Higgs and fill its mass. End event loop.
        DO 150 I=7,9
          IF(K(I,2).EQ.25) CALL PYFILL(1,P(I,5),1D0)
  150   CONTINUE
  200 CONTINUE
C...Final output.
      CALL PYSTAT(1)   ! Print cross section table
      CALL PYHIST      ! Print histogram(s)
      END
```

```
******************************************************************************
******************************************************************************
**                                                                          **
**                                                                          **
**              *......*                  Welcome to the Lund Monte Carlo!  **
**         *:::!!:::::::::::*                                               **
**      *::::::!!::::::::::::::*          PPP  Y   Y TTTTT H   H III   A    **
**    *::::::::!!::::::::::::::::*        P  P  Y Y    T   H   H  I   A A   **
**   *:::::::::!!:::::::::::::::::*       PPP    Y     T   HHHHH  I  AAAAA  **
**   *:::::::::!!:::::::::::::::::*       P      Y     T   H   H  I  A   A  **
**    *::::::::!!::::::::::::::::*!       P      Y     T   H   H III A   A  **
**      *::::::!!::::::::::::::* !!                                         **
**      !! *:::!!:::::::::::*    !!       This is PYTHIA version 6.210      **
**      !!     !* -><- *         !!       Last date of change: 25 Sep 2002  **
**      !!     !!                !!                                         **
**      !!     !!                !!       Now is  3 Nov 2002 at 13:23:46    **
**      !!                       !!                                         **
**      !!        lh             !!       Disclaimer: this program comes    **
**      !!                       !!       without any guarantees. Beware    **
**      !!                 hh    !!       of errors and use common sense    **
**      !!    ll                 !!       when interpreting results.        **
**      !!                       !!                                         **
**      !!                                Copyright T. Sjostrand (2001)     **
**                                                                          **
** An archive of program versions and documentation is found on the web:   **
** http://www.thep.lu.se/~torbjorn/Pythia.html                              **
**                                                                          **
** When you cite this program, currently the official reference is         **
** T. Sjostrand, P. Eden, C. Friberg, L. Lonnblad, G. Miu, S. Mrenna and   **
** E. Norrbin, Computer Physics Commun. 135 (2001) 238.                     **
** The large manual is                                                      **
** T. Sjostrand, L. Lonnblad and S. Mrenna, LU TP 01-21 [hep-ph/0108264].  **
** Also remember that the program, to a large extent, represents original  **
** physics research. Other publications of special relevance to your       **
** studies may therefore deserve separate mention.                          **
**                                                                          **
** Main author: Torbjorn Sjostrand; Department of Theoretical Physics 2,    **
**   Lund University, Solvegatan 14A, S-223 62 Lund, Sweden;                **
**   phone: + 46 - 46 - 222 48 16; e-mail: torbjorn@thep.lu.se              **
** Author: Leif Lonnblad; Department of Theoretical Physics 2,              **
**   Lund University, Solvegatan 14A, S-223 62 Lund, Sweden;                **
**   phone: + 46 - 46 - 222 77 80; e-mail: leif@thep.lu.se                  **
** Author: Stephen Mrenna; Computing Division, Simulations Group,           **
**   Fermi National Accelerator Laboratory, MS 234, Batavia, IL 60510, USA; **
**   phone: + 1 - 630 - 840 - 2556; e-mail: mrenna@fnal.gov                 **
** Author: Peter Skands; Department of Theoretical Physics 2,               **
**   Lund University, Solvegatan 14A, S-223 62 Lund, Sweden;                **
**   phone: + 46 - 46 - 222 31 92; e-mail: zeiler@thep.lu.se                **
**                                                                          **
**                                                                          **
******************************************************************************
******************************************************************************

****************** PYINIT: initialization of PYTHIA routines *****************
```

```
==========================================================================
I                                                                        I
I           PYTHIA will be initialized for a p on p collider             I
I                at  14000.000 GeV center-of-mass energy                 I
I                                                                        I
==========================================================================
```

******** PYMAXI: summary of differential cross-section maximum search ********

ISUB	Subprocess name	Maximum value
102	g + g -> h0	1.3350E-08
123	f + f' -> f + f' + h0	1.1535E-08
124	f + f' -> f" + f"' + h0	2.4378E-08

********************* PYINIT: initialization completed *********************

Event listing (summary)

I	particle/jet		KS	KF	orig	p_x	p_y	p_z	E	m
1	!p+!		21	2212	0	0.000	0.000	7000.000	7000.000	0.938
2	!p+!		21	2212	0	0.000	0.000	-7000.000	7000.000	0.938
3	!g!		21	21	1	-0.563	-1.015	184.296	184.300	0.000
4	!g!		21	21	2	-0.683	-0.161	-121.731	121.733	0.000
5	!g!		21	21	3	-0.563	-1.015	184.296	184.300	0.000
6	!g!		21	21	4	-0.683	-0.161	-121.731	121.733	0.000
7	!h0!		21	25	0	-1.246	-1.176	62.566	306.033	299.564
8	!W+!		21	24	7	12.840	-99.922	-11.519	157.993	121.160
9	!W-!		21	-24	7	-14.086	98.746	74.085	148.040	80.486
10	!tau+!		21	-15	8	-29.129	-60.885	-54.158	86.555	1.777
11	!nu_tau!		21	16	8	41.969	-39.037	42.639	71.438	0.000
12	!d!		21	1	9	30.402	25.174	9.757	40.660	0.330
13	!ubar!		21	-2	9	-44.488	73.572	64.328	107.379	0.330
14	(h0)		11	25	7	-1.246	-1.176	62.566	306.033	299.564
15	(W+)		11	24	8	12.840	-99.922	-11.519	157.993	121.160
16	(W-)		11	-24	9	-14.086	98.746	74.085	148.040	80.486
17	tau+		1	-15	10	-29.129	-60.885	-54.158	86.555	1.777
18	nu_tau		1	16	11	41.969	-39.037	42.639	71.438	0.000
19	d	A	2	1	12	30.402	25.174	9.757	40.660	0.330
20	ubar	V	1	-2	13	-44.488	73.572	64.328	107.379	0.330
21	uu_1	A	2	2203	1	-0.025	0.695	5678.842	5678.842	0.771
22	d	V	1	1	2	0.262	0.010	-1888.460	1888.460	0.330
23	d	A	2	1	1	0.588	0.320	1136.861	1136.861	0.330
24	uu_1	V	1	2203	2	0.421	0.151	-4989.808	4989.808	0.771
			sum:	2.00		0.00	0.00	0.00	14000.01	14000.01

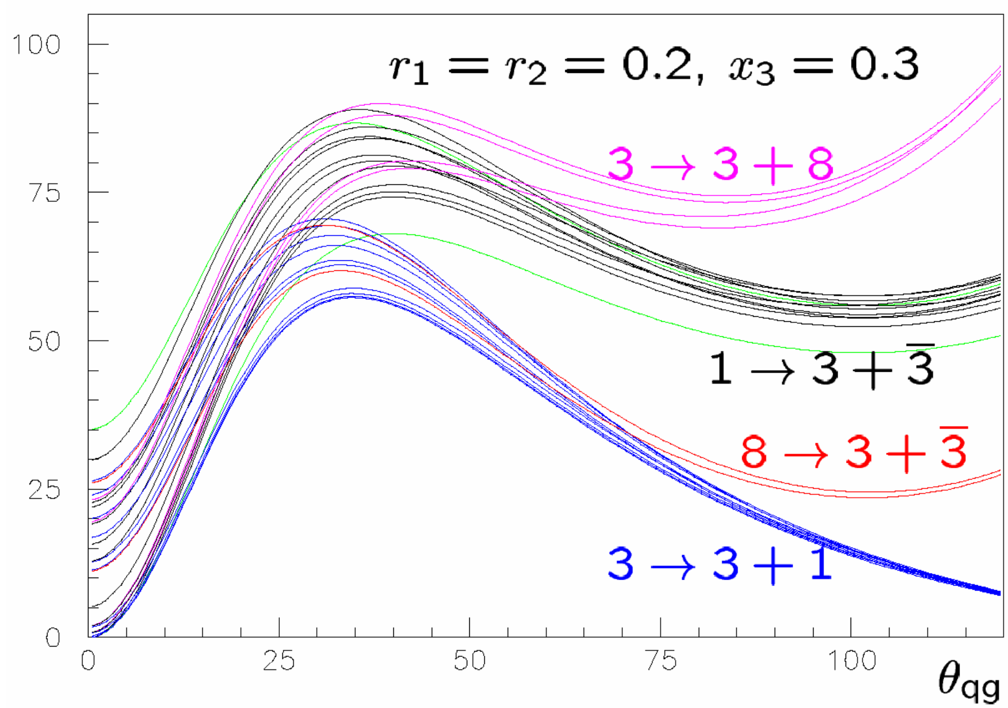
```
********* PYSTAT:  Statistics on Number of Events and Cross-sections *********

==============================================================================
I                                  I                            I            I
I            Subprocess            I      Number of points      I    Sigma   I
I                                  I                            I            I
I----------------------------------I----------------------------I    (mb)    I
I                                  I                            I            I
I N:o Type                         I    Generated         Tried I            I
I                                  I                            I            I
==============================================================================
I                                  I                            I            I
I   0 All included subprocesses    I         1000          9642 I  5.126E-09 I
I 102 g + g -> h0                  I          756          2672 I  3.799E-09 I
I 123 f + f' -> f + f' + h0        I           68          2243 I  3.500E-10 I
I 124 f + f' -> f" + f"' + h0      I          176          4727 I  9.763E-10 I
I                                  I                            I            I
==============================================================================

********* Fraction of events that fail fragmentation cuts =  0.00000 *********

    Histogram no    1      Higgs mass distribution                                2002-

    1.90*10** 2                                         44
    1.80*10** 2                                         XX
    1.70*10** 2                                         XX
    1.60*10** 2                                         XX
    1.50*10** 2                                         XX
    1.40*10** 2                                         XX
    1.30*10** 2                                         XX
    1.20*10** 2                                         XX9
    1.10*10** 2                                        5XXX
    1.00*10** 2                                        XXXX
    0.90*10** 2                                        XXXX
    0.80*10** 2                                        XXXX
    0.70*10** 2                                        XXXX3
    0.60*10** 2                                      8XXXXX
    0.50*10** 2                                      XXXXXX
    0.40*10** 2                                     3XXXXXX
    0.30*10** 2                                    6XXXXXXX81
    0.20*10** 2                                   4XXXXXXXXXX86
    0.10*10** 2       1    1 1   11  2 2 1223926375XXXXXXXXXXXXXX77867324 4  1114 212   121 115 1

       Contents
        *10** 2   00000000000000000000000000000000000000111000000000000000000000000000000000000000
        *10** 1   00000000000000000000000000000000011235088162211000000000000000000000000000000000
        *10** 0   0000100001010001100202012239263750463854493818677867324040011140212000121011501
        *10**-1   00000000000000000000000000000000000000000000000000000000000000000000000000000000

       Low edge
        *10** 2   22222222222222222222222222222222222222223333333333333333333333333333333333333333
        *10** 1   00001111222233334444555566667777888899990000111122223333444455556666777788889999
        *10** 0   03580358035803580358035803580358035803580358035803580358035803580358035803580358

    Entries  =         1000     Mean =  3.0152E+02     Underflow =  0.0000E+00     Low edge  =
    All chan =   1.0000E+03     Rms  =  1.6320E+01     Overflow  =  0.0000E+00     High edge =
```

Mass Effects in PYTHIA

- Dead cone only exact for
  - emission from spin-0 particle, or
  - infinitely soft emitted gluon
- In general, depends on
  - energy of gluon
  - colours and spins of emitting particle and colour partner

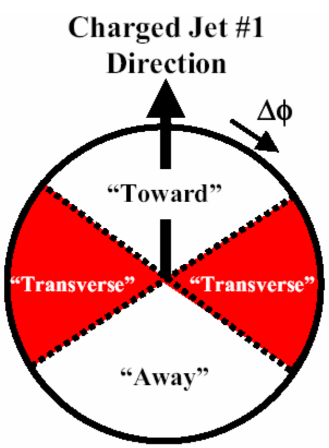
à process-dependent mass corrections

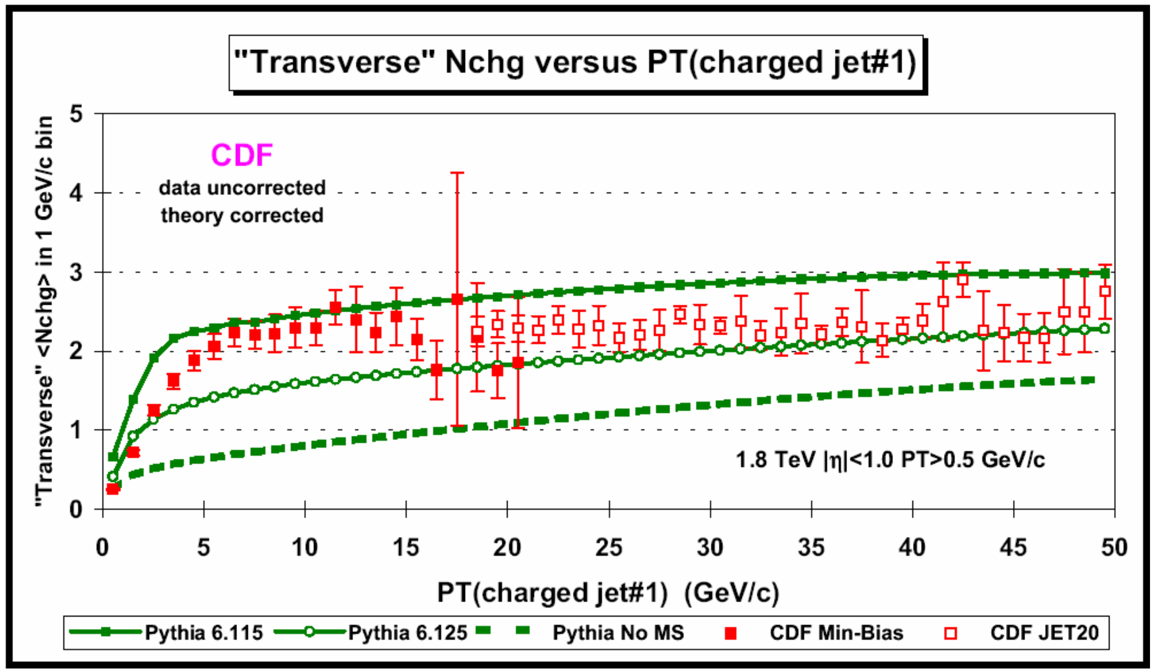
colour	spin	γ_5	example
$1 \to 3+\bar{3}$	—	—	(eikonal)
$1 \to 3+\bar{3}$	$1 \to \frac{1}{2}+\frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$Z^0 \to q\bar{q}$
$3 \to 3+1$	$\frac{1}{2} \to \frac{1}{2}+1$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to bW^+$
$1 \to 3+\bar{3}$	$0 \to \frac{1}{2}+\frac{1}{2}$	$1, \gamma_5,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



Tuning PYTHIA to the Underlying Event

- Rick Field (CDF): keep all parameters that can be fixed by LEP or HERA at their default values. What's left?
- Underlying event. Big uncertainties…





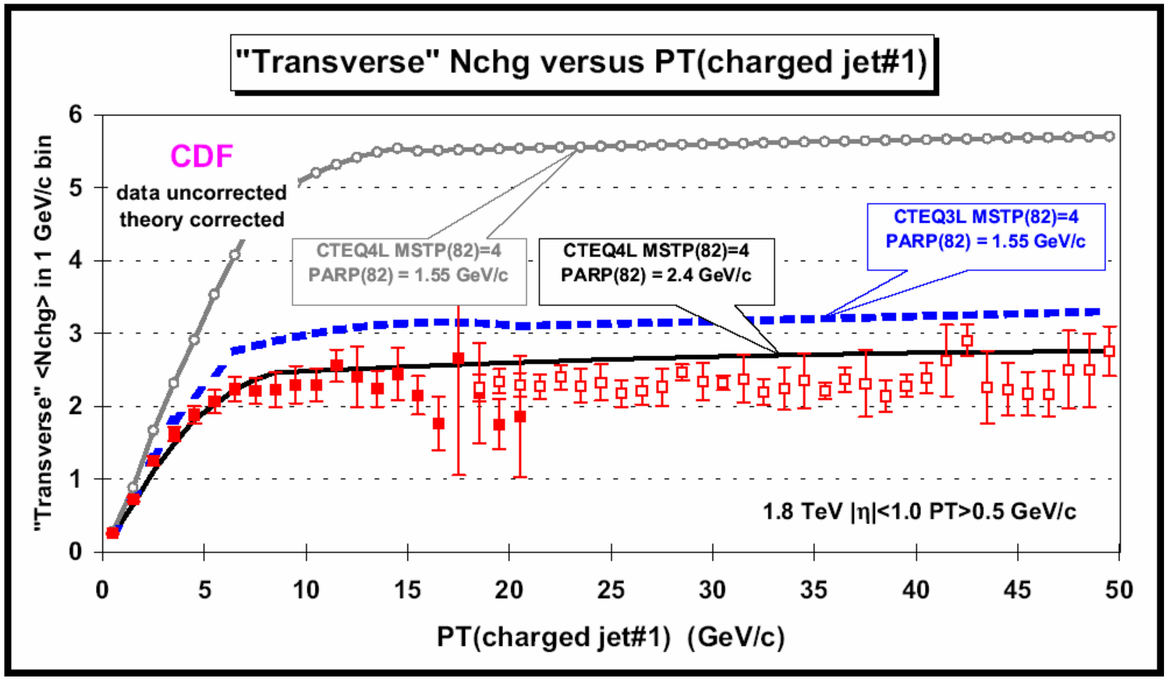
http://www.phys.ufl.edu/~rfield/cdf/chgjet/chgjet_intro.html

Parameter	Value	Description
MSTP(81)	0	Multiple-Parton Scattering off
	1	Multiple-Parton Scattering on
MSTP(82)	1	Multiple interactions assuming the same probability, with an abrupt cut-off PTmin=PARP(81)
MSTP(82)	3	Multiple interactions assuming a varying impact parameter and a hadronic matter overlap consistent with a single Gaussian matter distribution, with a smooth turn-off PT0=PARP(82)
MSTP(82)	4	Multiple interactions assuming a varying impact parameter and a hadronic matter overlap consistent with a double Gaussian matter distribution (governed by PARP(83) and PARP(84)), with a smooth turn-off PT0=PARP(82)

Parameter	PYTHIA 6.115	PYTHIA 6.125
MSTP(81)	1	1
MSTP(82)	1	1
PARP(81)	1.4 GeV/c	1.9 GeV/c
PARP(82)	1.55 GeV/c	2.1 GeV/c
PARP(83)	0.5	0.5
PARP(84)	0.2	0.2

Mike Seymour

Beware, multiple interaction parameters strongly correlated with parton distribution functions…

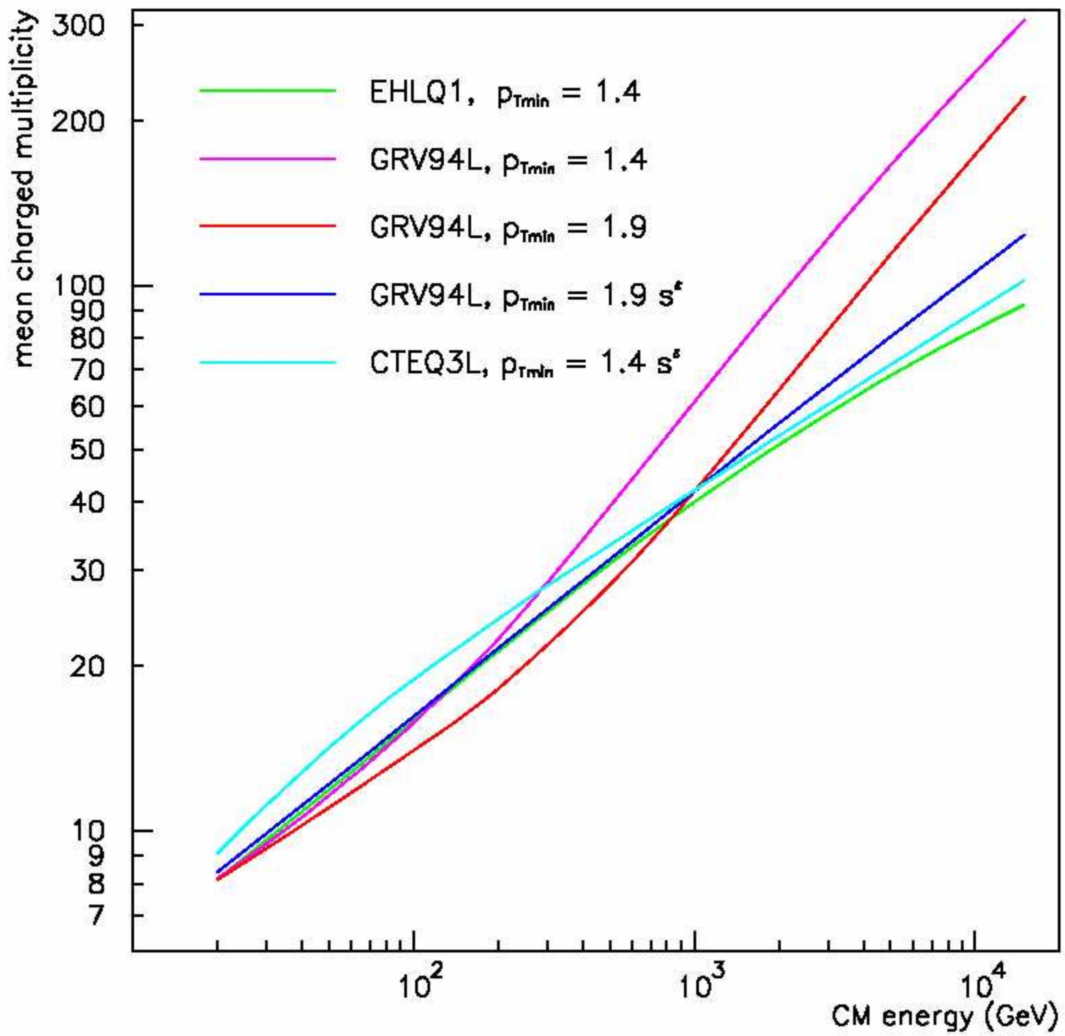


Small-x behaviour:
In olden days
$xg(x, Q_0^2) \to$ const.
but post-HERA
$xg(x, Q_0^2) \sim x^{-\epsilon}$,
with some $\epsilon \gtrsim 0.08$
$\Rightarrow p_{\perp\text{min}} \sim \frac{1}{\langle d \rangle}$
$\sim N_{\text{partons}} \sim s^{\epsilon}$
so 'new' PYTHIA
default $p_{\perp\text{min}} =$
$(1.9 \text{ GeV}) \left(\frac{s}{1 \text{ TeV}^2}\right)^{0.08}$

Importance:

- comparison of data at 630 GeV & 1.8 TeV
- LHC extrapolations

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

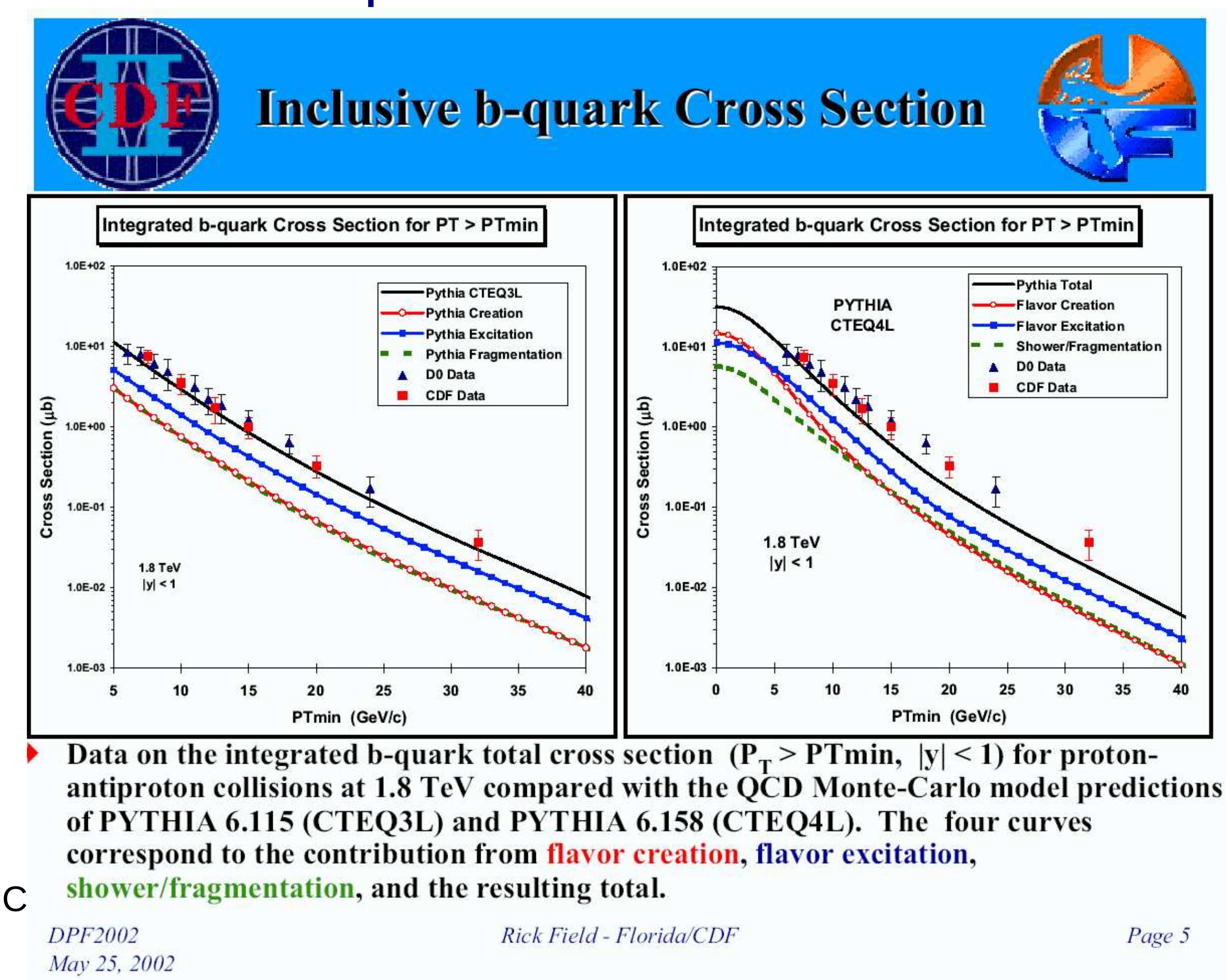


(TS & M. van Zijl, PRD36 (1987) 2019; J. Dischler & TS, EPJdir C2 (2001) 1)

- Conclusion: can fit these data but in many different ways

à Large uncertainty in high energy extrapolation

- Also able to fit b production cross section…



Object Oriented Event Generators

- ThePEG: Toolkit for High Energy Physics Event Generation
- PYTHIA7: Implementation of physics of PYTHIA6 plus some improvements
- HERWIG++: Physics improvements from HERWIG plus backward compatibility

- SHERPA: completely new event generator

New C++ Generators

Besides new projects (like SHERPA), the two traditional programs `Pythia` and `Herwig` are in the process of being rewritten as Pythia7 and Herwig++.

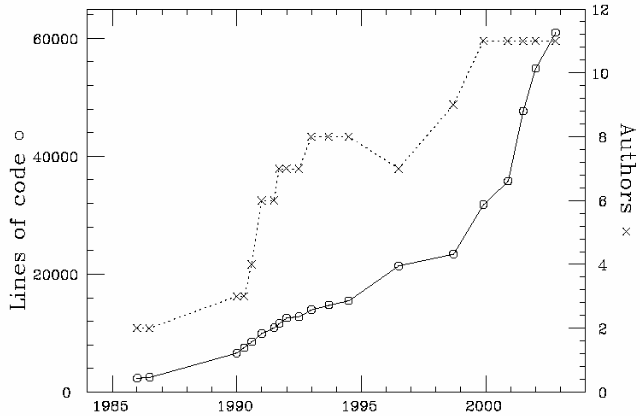
Pythia7 and Herwig++

- will use a common administrative part ThePEG (formerly also known as Pythia7). Providing particle record, interfaces, overall structure.
- Pythia7, detached from the library and aims at reproducing/improving what is now known as `Pythia6.xxx`.
- Herwig++ is supposed to do the same job for what is know the latest version, `HERWIG 6.5`.

SHERPA

- completely independent.
- unifies the codes APACIC++ and AMEGIC++ in a common framework.
- adds new modules.

Why moving towards C++?



Why C++? Well. . .

- C++ is standard in the Unix/Linux world
- New experiments use it
- Maintenance
- Encapsulation of code
- Easy to implement new physics

The obvious advantages. . .

Use of ThePEG in Herwig++

*T*oolkit for *h*igh energy *P*hysics *E*vent *G*eneration

Won't re-invent the wheel

Share administrative overhead, common to event generators with Pythia7

Independent *physics* implementation

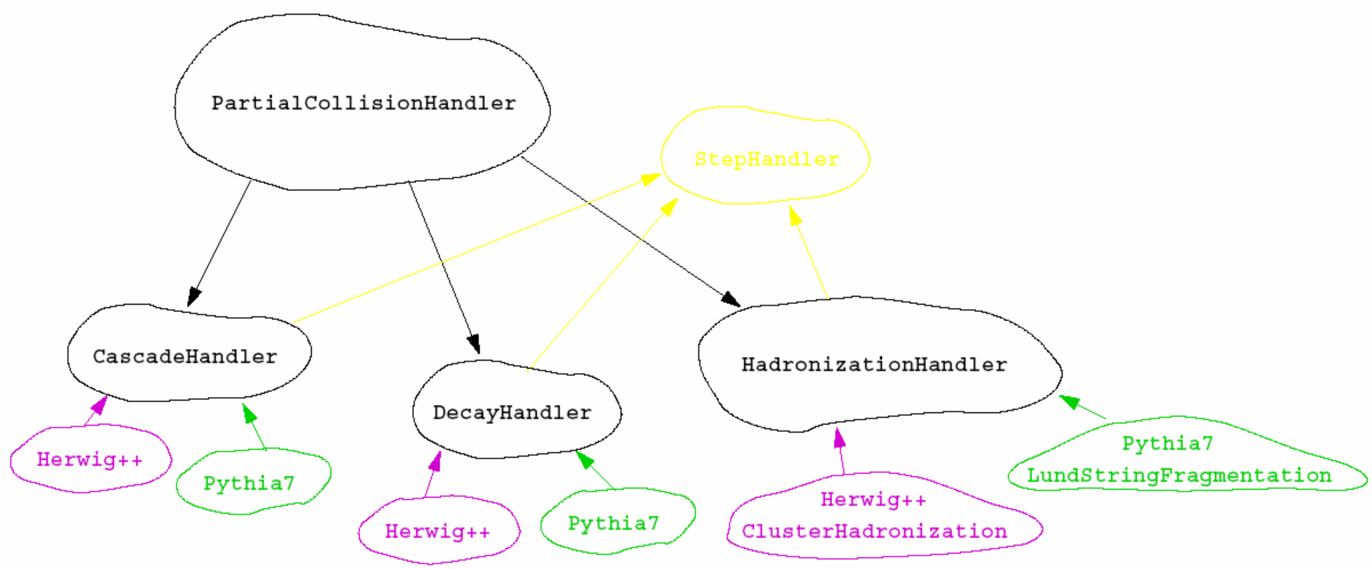
Large but very flexible implementation

Common basis for Pythia7/Herwig++:

- Lack of independence.
- Miss the possiblity to test codes against each other.
- Physics, however, is still independent.
- Beneficial for the user to have the same framework.
- Running Herwig++ with the Lund String Fragmentation from Pythia7 is very simple!

PartialCollisionHandlers

How Herwig++/Pythia7 link into ThePEG



Status of Herwig++

S. Gieseke, A. Ribon, M.H. Seymour, P. Stephens, B.R. Webber
(Cambridge, Manchester, CERN)
http://www.hep.phy.cam.ac.uk/~gieseke/Herwig++

Hard Matrix Elements

- Simple $2 \to 2$ ME so far.
- We have a working interface to AMEGIC++. For e^+e^- this will do the job for up to 6 jets.
- The ME+PS matching algorithm of Catani, Krauss, Kühn and Webber will be implemented.
- More processes straightforward.
- Users can easily and safely include their own matrix elements.

Parton Shower

- New parton shower developed.
- *Multiscale shower* designed for general treatment of instable particles (no physics implementation yet).
- New evolution variables for better treatment of heavy quarks and smooth coverage of phase space.
- Extension to spacelike shower for pp and ep ongoing.

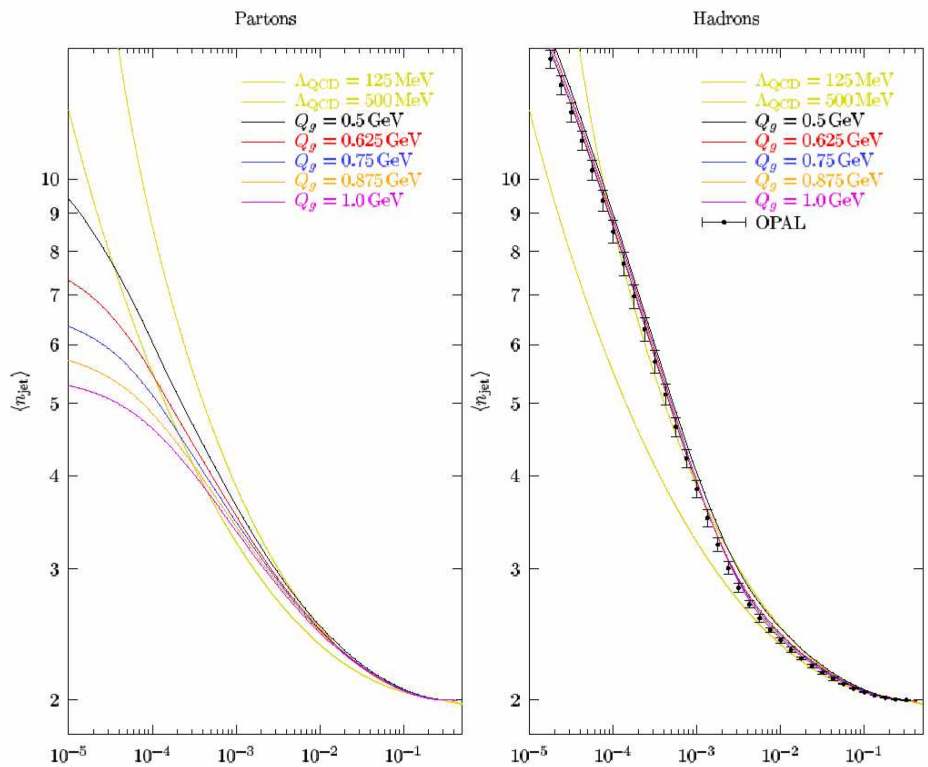
Status of Herwig++ (ctnd')

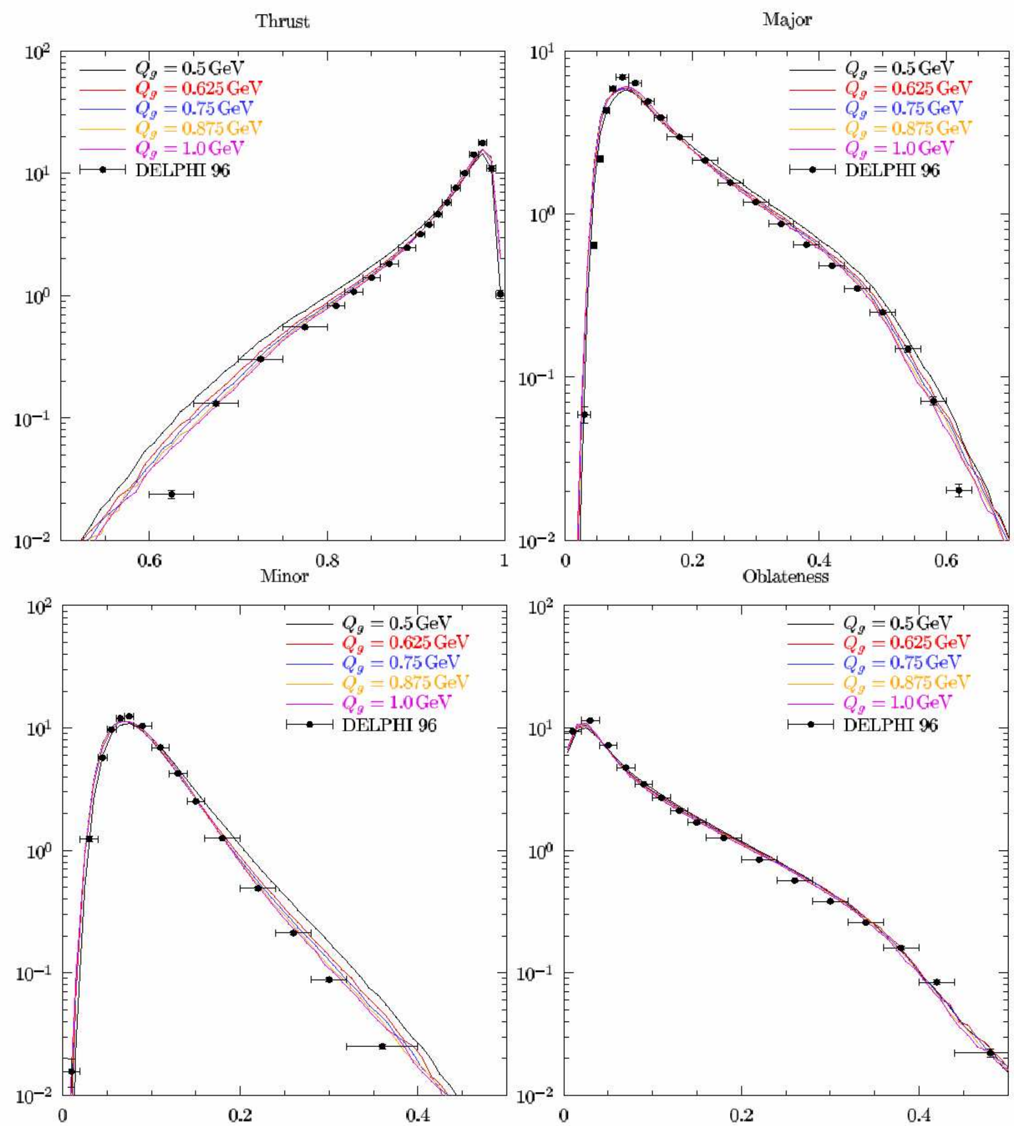
Decays

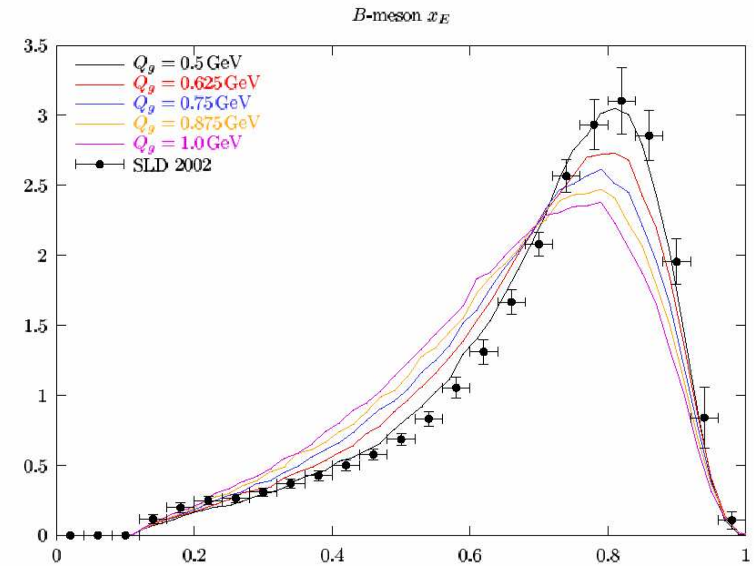
- HERWIG–decays are reproduced with a class Hw64Decayer using the same Matrix element codes as before.
- DecayerAMEGIC gets final states for a decay mode (eg. for t decay, SUSY in the future) directly from AMEGIC++
- works very well, further thorough tests required.
- More to come (EvtGen,. . .)?

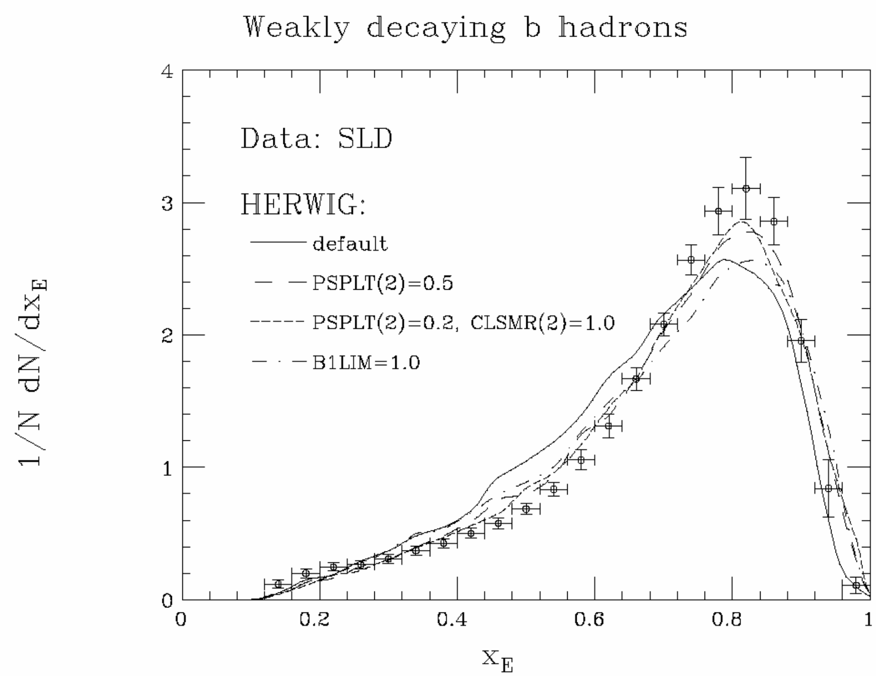
Hadronization

- Cluster Hadronization is designed and implemented completely.
- Works very well, further thorough tests ongoing.
- Aside, the Lund String Fragmentation model is implemented in Pythia7 and will work together with Herwig++.
- Hadronic decays $\rightarrow$ above.

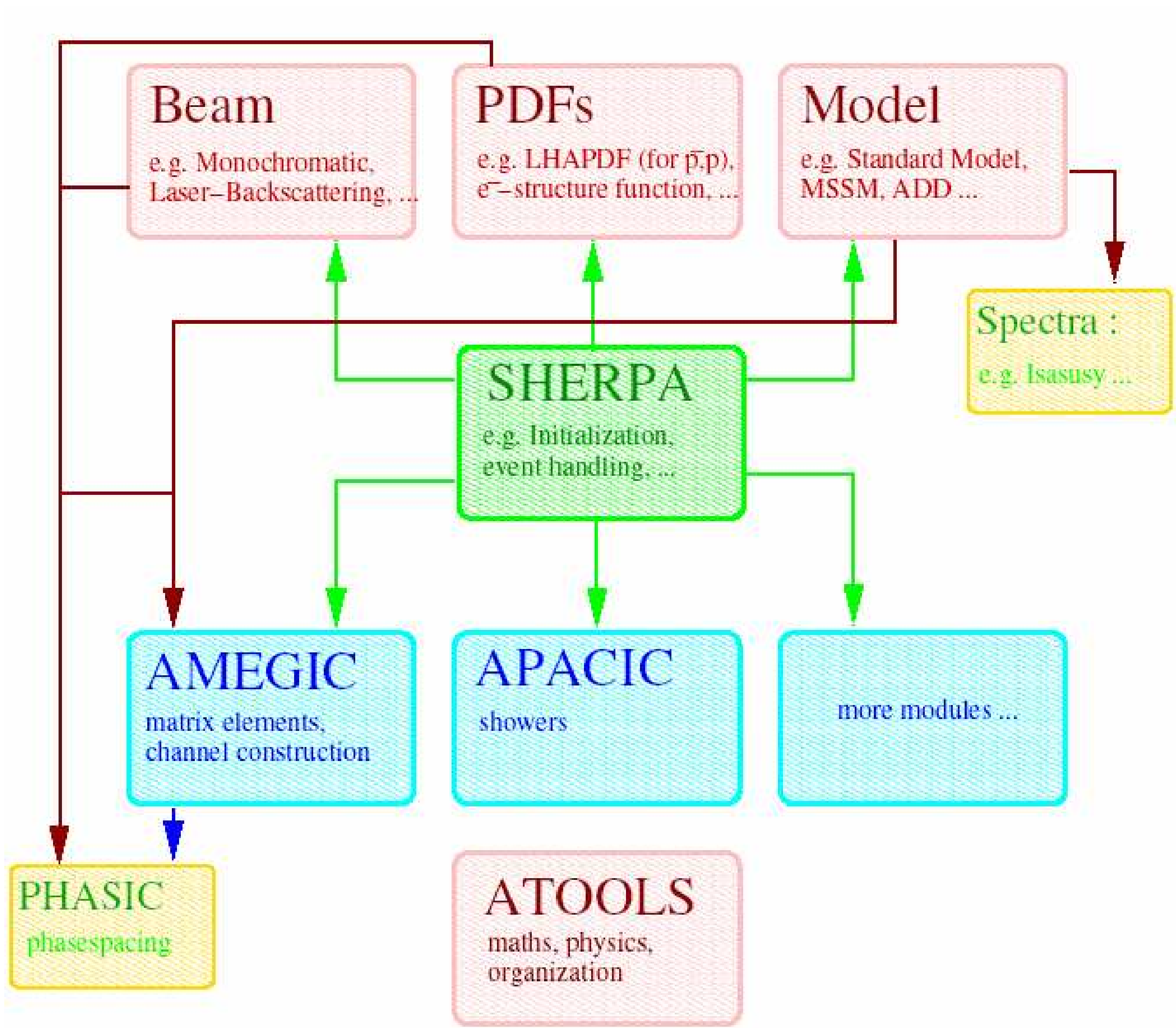

Partons
Hadrons
$\Lambda_{QCD} = 125$ MeV
$\Lambda_{QCD} = 500$ MeV
$Q_g = 0.5$ GeV
$Q_g = 0.625$ GeV
$Q_g = 0.75$ GeV
$Q_g = 0.875$ GeV
$Q_g = 1.0$ GeV
OPAL
$\langle n_{jet} \rangle$


Thrust
Major
Minor
Oblateness
$Q_g = 0.5\,\mathrm{GeV}$
$Q_g = 0.625\,\mathrm{GeV}$
$Q_g = 0.75\,\mathrm{GeV}$
$Q_g = 0.875\,\mathrm{GeV}$
$Q_g = 1.0\,\mathrm{GeV}$
DELPHI 96





Mike Seymour


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

Conclusions

- Get to know your Monte Carlo!
- Remember what is fixed by LEP and HERA data
- Question what isn't
- Tevatron data crucial testing ground

- The next generation is coming…
  - Software improvements
  - Physics improvements

Announcement

- Several members of BSM Monte Carlo working group expressed interest in a tutorial on

How to write a 2à 2 event generator

and interface it through the

Les Houches Accord

- Peter Richardson has agreed to give one
  ~ middle of next week
- Anyone interested email me and I will pass on to Peter…

Reminder – FAQs

Lecture 5, Friday 11th July:

Question and Answer session

Email questions to: M.H.Seymour@rl.ac.uk

Cutoff: Thursday 10th July, 2pm

http://seymour.home.cern.ch/seymour/slides/CERNlectures.html