Event Generator Physics

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Event Generator Physics

1. Basic principles
2. Parton showers
3. Hadronization
4. Survey of Event Generators
5. Matching

Event Generators

- PYTHIA
  - Virtuality/k_T-ordered shower, string hadronization
  - v6 Fortran; v8 C++
- HERWIG
  - Angular-ordered shower, cluster hadronization
  - v6 Fortran; Herwig++
- SHERPA
  - Virtuality-ordered shower, string/cluster hadronization
  - C++

Monte Carlo Programs in Practice

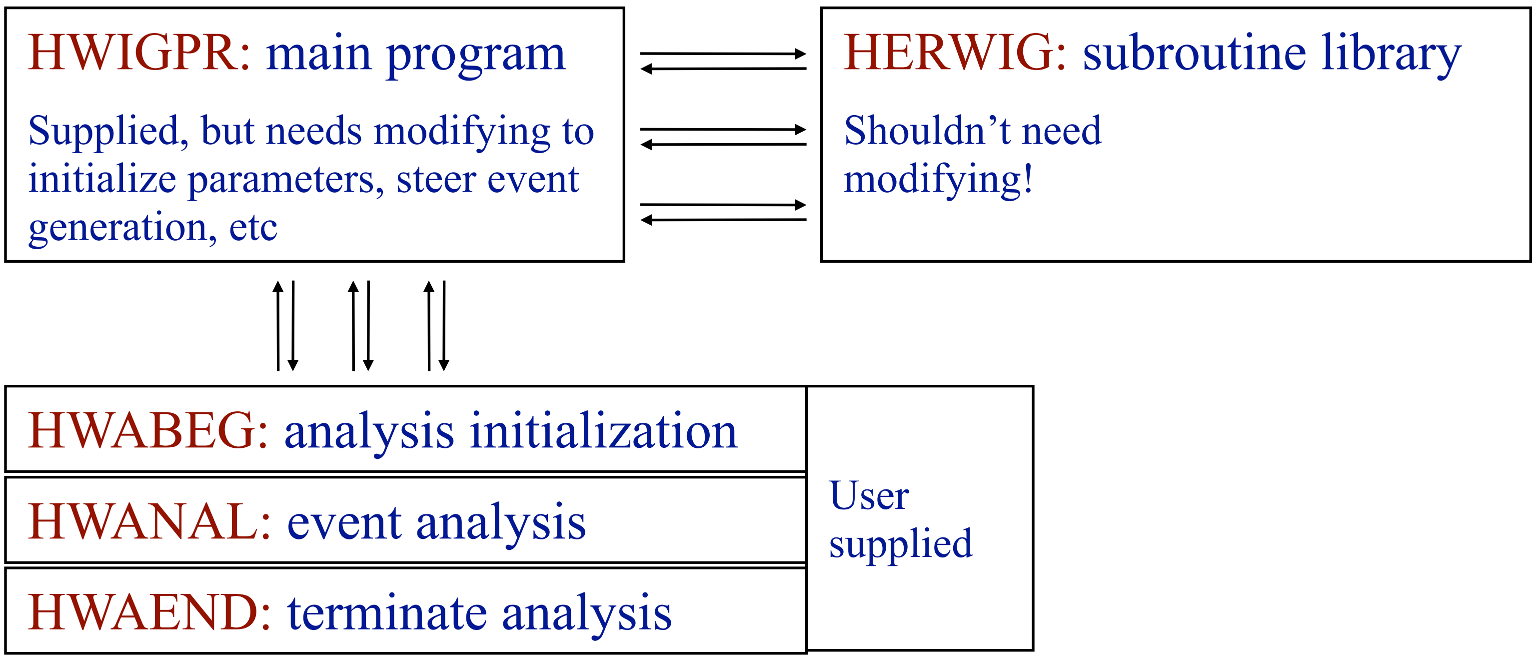
1. HERWIG 6
   - Status and Structure
   - Example input, control parameters
   - Example output
   - Physics examples
2. PYTHIA 6
   - Status and Structure
   - Example input, control parameters
   - Example output
   - Physics examples
3. Object Oriented Event Generators
   - PYTHIA 8
   - HERWIG++
   - SHERPA

Thanks to Mike Seymour, Torbjörn Sjöstrand, Stefan Gieseke, Frank Krauss and Peter Richardson

HERWIG 6

- Current status:
- Version 6.510 released on October 31st 2005
  - http://hepwww.rl.ac.uk/theory/seymour/herwig/
  - ~ 64,000 lines of FORTRAN, 11 authors (5 currently active)
- 6.51* will be the last FORTRAN version
- Some features:
  - Many built-in SM and MSSM processes
  - Les Houches Accord interface for arbitrary hard processes
  - Spin correlation algorithm → see later
  - Interface to MC@NLO program (Frixione & Webber) → see later
  - Interface to JIMMY multiple interaction underlying event model

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 CONSTAN
      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	$\ell^+\ell^- \to Z^0H^0_{\rm SM} \to Z^0q\bar{q}$ (all flavours)
300+IQ	$\ell^+\ell^- \to Z^0H^0_{\rm SM} \to Z^0q\bar{q}$ (IQ as above)
306+IL	$\ell^+\ell^- \to Z^0H^0_{\rm SM} \to Z^0\ell\bar{\ell}$ (IL as above)
310, 311	$\ell^+\ell^- \to Z^0H^0_{\rm SM} \to Z^0W^+W^-,\ Z^0Z^0Z^0$
IPROC	Process
312	$\ell^+\ell^- \to Z^0H^0_{\rm SM} \to Z^0\gamma\gamma$
399	$\ell^+\ell^- \to Z^0H^0_{\rm SM} \to Z^0$ anything
400+ID	$\ell^+\ell^- \to \nu\bar{\nu}H^0_{\rm SM} + \ell^+\ell^-H^0_{\rm SM}$ (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	$\ell^+\ell^- \to q\bar{q}gg,\ q\bar{q}q'\bar{q}'$ (all q flavours)
600+IQ	$\ell^+\ell^- \to q\bar{q}gg,\ q\bar{q}q'\bar{q}'$ (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	$\ell^+\ell^- \to \tilde{\chi}^0_{\rm IN1}\tilde{\chi}^0_{\rm IN2}$ (IN1,2=neutralino mass eigenstate)
730	$\ell^+\ell^- \to$ chargino pairs (all charginos)
728+2IC1+IC2	$\ell^+\ell^- \to \tilde{\chi}^+_{\rm IC1}\tilde{\chi}^-_{\rm IC2}$ (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	$\ell^+\ell^- \to \tilde{\chi}^0_{\rm IN}\nu_i$ (IN=neutralino mass state)
820	$\ell^+\ell^- \to \tilde{\chi}^-e^+_i$ (all charginos)
820+IC	$\ell^+\ell^- \to \tilde{\chi}^-_{\rm IC}e^+_i$ (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	$\ell^+\ell^- \to \ell_{\rm IL1}\bar{\ell}_{\rm IL2}$ (IL1,2=1,2,3 for e,μ,τ)

IPROC	Process
880	$\ell^+\ell^- \to d\bar{d}$, via LLE and LQD
877+3IQ1+IQ2	$\ell^+\ell^- \to d_{\rm IL1}\bar{d}_{\rm IL2}$ (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	$\ell^+\ell^- \to t\bar{t}H^0_{\rm SM}$ (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	$gg/q\bar{q} \to H^0_{\rm SM}$ (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	$q\bar{q} \to q'\bar{q}'W^+W^-/Z^0Z^0 \to q'\bar{q}'H^0_{\rm SM}$ (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	$c\bar{b} \to s\bar{t}$, $s\bar{b} \to c\bar{t}$, $\bar{s}b \to \bar{c}t$, $cb \to st$
2100	$W^\pm$ + jet production
2110	$W^\pm$ + jet production (Compton only: $gq \to Wq$)
2120	$W^\pm$ + jet production (annihilation only: $q\bar{q} \to Wg$)
2150	Z^0 + jet production
2160	Z^0 + jet production (Compton only: $gq \to Zq$)
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	$gg/q\bar{q} \to t\bar{t}H^0_{\rm SM}$ (ID as in IPROC=300+ID)
2600+ID	$q\bar{q}' \to W^\pm H^0_{\rm SM}$ (ID as in IPROC=300+ID)
2700+ID	$q\bar{q} \to Z^0H^0_{\rm SM}$ (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 $Q = d \ldots t$)
2910+IQ	$gg + q\bar{q} \to Q\bar{Q}Z^0$, for massive Q and $\bar{Q}$ (IQ=1…6 for $Q = d \ldots t$)
3000-3999	Minimal Supersymmetric Standard Model (MSSM) processes
3000	2-parton $\to$ 2-sparticle processes (sum of those below)
3010	2-parton $\to$ 2-sparton processes
3020	2-parton $\to$ 2-gaugino processes
3030	2-parton $\to$ 2-slepton processes
3100+ISQ	$gg/q\bar{q} \to \tilde{q}\bar{\tilde{q}}'H^\pm$ (ISQ=IPROC–3100 as from table 15)
3200+ISQ	$gg/q\bar{q} \to \tilde{q}\bar{\tilde{q}}h,H,A$ (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	$bg \to b\,h^0 +$ ch. conj.
3420	$bg \to b\,H^0 +$ ch. conj.
3430	$bg \to b\,A^0 +$ ch. conj.
3450	$bg \to t\,H^- +$ 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	$\bar{u}_jd_k \to \tilde{\chi}^0l^-_i$, $\bar{d}_jd_k \to \tilde{\chi}^0\nu_i$ (all neutralinos)
4010+IN	$\bar{u}_jd_k \to \tilde{\chi}^0_{\rm IN}l^-_i$, $\bar{d}_jd_k \to \tilde{\chi}^0_{\rm IN}\nu_i$ (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	$\bar{u}_jd_k \to \tilde{\chi}^-_{\rm IC}\nu_i$, $\bar{d}_jd_k \to \tilde{\chi}^-_{\rm IC}e^+_i$ (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	$u_j\bar{d}_k \to \tilde{e}^+_ih^0/H^0/A^0$, $u_j\bar{d}_k \to \tilde{\nu}_iH^+$ 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	$u_id_j \to \tilde{\chi}^0_{\rm IN}\bar{d}_k$, $d_jd_k \to \tilde{\chi}^0_{\rm IN}\bar{u}_i$ (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	$u_id_j \to \tilde{\chi}^+_{\rm IC}\bar{u}_k$, $d_jd_k \to \tilde{\chi}^-_{\rm IC}\bar{d}_i$ (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	$u_id_j \to \tilde{d}_{k1}h^0/H^0/A^0$, $d_jd_k \to \tilde{u}_{i1}h^0/H^0/A^0$, $u_id_j \to \tilde{u}^*_{k\alpha}H^+$, $d_jd_k \to \tilde{d}^*_{i\alpha}H^-$
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	$gg/q\bar{q} \to G \to W^+W^-/Z^0Z^0/H^0_{\rm SM}H^0_{\rm SM}$
4271	$gg/q\bar{q} \to G \to W^+W^-$
4272	$gg/q\bar{q} \to G \to Z^0Z^0$
4273	$gg/q\bar{q} \to G \to H^0_{\rm SM}H^0_{\rm SM}$
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

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 $d - t, \bar{d} - \bar{t}$)
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	$W^+W^-/Z^0Z^0 \to H^0_{\rm SM}$ 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

```
HERWIG 6.510  31st Oct. 2005

Please reference:  G. Marchesini, B.R. Webber,
G.Abbiendi, I.G.Knowles, M.H.Seymour & L.Stanco
Computer Physics Communications 67 (1992) 465
                   and
G.Corcella, I.G.Knowles, G.Marchesini, S.Moretti,
K.Odagiri, P.Richardson, M.H.Seymour & B.R.Webber,
JHEP 0101 (2001) 010

INPUT CONDITIONS FOR THIS RUN

BEAM 1 (E+      ) MOM. =    174.30
BEAM 2 (E-      ) MOM. =    174.30
PROCESS CODE (IPROC)   =     106
NUMBER OF FLAVOURS     =    6
STRUCTURE FUNCTION SET =    8
AZIM SPIN CORRELATIONS =    T
AZIM SOFT CORRELATIONS =    T
QCD LAMBDA (GEV)       =    0.1800
DOWN     QUARK  MASS   =    0.3200
UP       QUARK  MASS   =    0.3200
STRANGE  QUARK  MASS   =    0.5000
CHARMED  QUARK  MASS   =    1.5500
BOTTOM   QUARK  MASS   =    4.9500
TOP      QUARK  MASS   =  174.3000
GLUON EFFECTIVE MASS   =    0.7500
EXTRA SHOWER CUTOFF (Q)=    0.4800
EXTRA SHOWER CUTOFF (G)=    0.1000
PHOTON SHOWER CUTOFF   =    0.4000
CLUSTER MASS PARAMETER =    3.3500
SPACELIKE EVOLN CUTOFF =    2.5000
INTRINSIC P-TRAN (RMS) =    0.0000
DECAY SPIN CORRELATIONS=    T
SUSY THREE BODY ME     =    T
SUSY FOUR  BODY ME     =    F
HARD M.E. MATCHING     =    T
SOFT M.E. MATCHING     =    T
MIN MTM FRAC FOR ISR   =1.0000E-04
1-MAX MTM FRAC FOR ISR =1.0000E-06

NO EVENTS WILL BE WRITTEN TO DISK

E+      Beam polarisation=   -1.0000    0.0000    0.0000
E-      Beam polarisation=    1.0000    0.0000    0.0000

PARTICLE TYPE  21=PI0      SET STABLE

INITIAL SEARCH FOR MAX WEIGHT

PROCESS CODE IPROC =          106
RANDOM NO. SEED 1  =      1246579
           SEED 2  =      8447766
NUMBER OF SHOTS    =        10000
NEW MAXIMUM WEIGHT =  3.8353798136424571E-08

INITIAL SEARCH FINISHED

OUTPUT ON ELEMENTARY PROCESS

N.B. NEGATIVE WEIGHTS NOT ALLOWED

NUMBER OF EVENTS   =            0
NUMBER OF WEIGHTS  =        10000
```

```
MEAN VALUE OF WGT   =  1.0844E-09
RMS SPREAD IN WGT   =  6.0525E-09
ACTUAL MAX WEIGHT   =  3.4867E-08
ASSUMED MAX WEIGHT =  3.8354E-08

PROCESS CODE IPROC =          106
CROSS SECTION (PB) =  1.0844E-06
ERROR IN C-S  (PB) =  6.0525E-08
EFFICIENCY PERCENT =   2.827


EVENT        1:  174.30 GEV/C E+       ON   174.30 GEV/C E-       PROCESS:   106
SEEDS:      2049773 &     11719155   STATUS:  100 ERROR:    0  WEIGHT:  1.0844E-09


                               ---INITIAL STATE---

IHEP    ID       IDPDG IST MO1 MO2 DA1 DA2    P-X      P-Y      P-Z  ENERGY    MASS
   1 E+            -11 101   0   0   0   0    0.00     0.00  174.3  174.3    0.00
   2 E-             11 102   0   0   0   0    0.00     0.00 -174.3  174.3    0.00
   3 CMF             0 103   1   2   0   0    0.00     0.00    0.0  348.6  348.60

                              ---HARD SUBPROCESS---

IHEP    ID       IDPDG IST MO1 MO2 DA1 DA2    P-X      P-Y      P-Z  ENERGY    MASS
   4 Z0/GAMA*       23 120   1   2   5   6    0.00     0.00    0.0  348.6  348.60

                            ---H/W/Z BOSON DECAYS---

IHEP    ID       IDPDG IST MO1 MO2 DA1 DA2    P-X      P-Y      P-Z  ENERGY    MASS
   5 TQRK            6 123   4   6   7   6    0.00     0.00    0.0  174.3  174.30
   6 TBAR           -6 124   4   5   9   5    0.00     0.00    0.0  174.3  174.30

                               ---PARTON SHOWERS---

IHEP    ID       IDPDG IST MO1 MO2 DA1 DA2    P-X      P-Y      P-Z  ENERGY    MASS
   7 TQRK           94 143   5   4   8   8    0.00     0.00    0.0  174.3  174.30
   8 TQRK            6   3   7   7  11  11    0.00     0.00    0.0  174.3  174.30
   9 TBAR           94 144   6   4  10  10    0.00     0.00    0.0  174.3  174.30
  10 TBAR           -6   3   9   9  23  23    0.00     0.00    0.0  174.3  174.30

                          ---HEAVY PARTICLE DECAYS---

IHEP    ID       IDPDG IST MO1 MO2 DA1 DA2    P-X      P-Y      P-Z  ENERGY    MASS
  11 TQRK            6 155   7  23  12  13    0.00     0.00    0.0  174.3  174.30
  12 W+             24 123  11  12  14  12   50.76   -31.35  -35.3  104.8   78.64
  13 BQRK            5 124  11  11  15  11  -50.76    31.35   35.3   69.5    4.95
  14 W+             24 195  12  11  19  20   50.36   -31.10  -35.0  104.5   78.64

                               ---PARTON SHOWERS---

IHEP    ID       IDPDG IST MO1 MO2 DA1 DA2    P-X      P-Y      P-Z  ENERGY    MASS
  15 BQRK           94 144  13  11  17  18  -50.36    31.10   35.0   69.8   12.28
  16 CONE            0 100  13  11   0   0   -0.52    -0.85    0.0    1.0    0.00
  17 BQRK            5   2  15  18  36  31  -44.10    22.46   28.2   57.2    4.95
  18 GLUON          21   2  15  29  37  38   -6.26     8.64    6.8   12.7    0.75

                            ---H/W/Z BOSON DECAYS---

IHEP    ID       IDPDG IST MO1 MO2 DA1 DA2    P-X      P-Y      P-Z  ENERGY    MASS
  19 NU_E           12 123  14  20  21  20   47.44    16.68  -14.0   52.2    0.00
  20 E+            -11 124  14  19  22  19    2.92   -47.78  -21.0   52.3    0.00
  21 NU_E           12   1  19  14   0   0   47.44    16.68  -14.0   52.2    0.00
```

22	E+	-11	1	20	14	0	0	2.92	-47.78	-21.0	52.3	0.00

---HEAVY PARTICLE DECAYS---

IHEP	ID	IDPDG	IST	MO1	MO2	DA1	DA2	P-X	P-Y	P-Z	ENERGY	MASS
23	TBAR	-6	155	9	17	24	25	0.00	0.00	0.0	174.3	174.30
24	W-	-24	123	23	24	26	24	-9.40	-65.65	-13.2	106.5	82.28
25	BBAR	-5	124	23	23	27	23	9.40	65.65	13.2	67.8	4.95
26	W-	-24	195	24	23	32	33	-9.37	-65.43	-13.1	106.4	82.28

---PARTON SHOWERS---

IHEP	ID	IDPDG	IST	MO1	MO2	DA1	DA2	P-X	P-Y	P-Z	ENERGY	MASS
27	BBAR	94	144	25	23	29	31	9.37	65.43	13.1	67.9	8.66
28	CONE	0	100	25	23	0	0	-0.95	0.08	0.3	1.0	0.00
29	GLUON	21	2	27	30	39	40	-0.06	7.48	1.6	7.7	0.75
30	GLUON	21	2	27	31	41	42	0.01	8.49	1.0	8.6	0.75
31	BBAR	-5	2	27	36	43	42	9.41	49.46	10.5	51.7	4.95

---H/W/Z BOSON DECAYS---

IHEP	ID	IDPDG	IST	MO1	MO2	DA1	DA2	P-X	P-Y	P-Z	ENERGY	MASS
32	NU_EBAR	-12	123	26	33	34	33	9.82	-31.69	-45.2	56.0	0.00
33	E-	11	124	26	32	35	32	-19.19	-33.74	32.0	50.3	0.00
34	NU_EBAR	-12	1	32	26	0	0	9.82	-31.69	-45.2	56.0	0.00
35	E-	11	1	33	26	0	0	-19.19	-33.74	32.0	50.3	0.00

---GLUON SPLITTING---

IHEP	ID	IDPDG	IST	MO1	MO2	DA1	DA2	P-X	P-Y	P-Z	ENERGY	MASS
36	BQRK	5	158	15	44	50	43	-40.51	20.80	26.0	52.7	4.95
37	UBAR	-2	158	15	38	54	45	-1.24	1.75	1.3	2.5	0.32
38	UQRK	2	158	15	46	51	37	-3.38	4.53	3.6	6.7	0.32
39	UBAR	-2	158	27	40	55	47	-0.16	1.94	0.5	2.0	0.32
40	UQRK	2	158	27	41	52	39	0.16	4.05	0.8	4.2	0.32
41	DBAR	-1	158	27	42	52	40	0.14	3.82	0.6	3.9	0.32
42	DQRK	1	158	27	48	53	41	0.17	2.12	0.3	2.2	0.32
43	BBAR	-5	158	27	36	56	49	8.19	45.00	9.3	46.9	4.95
44	SBAR	-3	159	15	45	50	36	-1.49	1.12	1.1	2.2	0.50
45	SQRK	3	159	15	37	54	44	-2.68	1.48	1.8	3.6	0.50
46	DBAR	-1	159	27	47	51	38	-0.16	1.51	0.4	1.6	0.32
47	DQRK	1	159	15	39	55	46	-0.96	1.39	1.0	2.0	0.32
48	SBAR	-3	159	27	49	53	42	0.53	3.63	0.7	3.8	0.50
49	SQRK	3	159	27	43	56	48	0.40	3.38	0.6	3.5	0.50

---CLUSTER FORMATION---

IHEP	ID	IDPDG	IST	MO1	MO2	DA1	DA2	P-X	P-Y	P-Z	ENERGY	MASS
50	CLUS	91	183	36	44	57	58	-41.99	21.93	27.1	54.9	5.86
51	CLUS	91	183	38	46	59	60	-3.54	6.04	4.0	8.3	2.01
52	CLUS	91	183	40	41	61	62	0.30	7.87	1.4	8.0	0.67
53	CLUS	91	183	42	48	63	64	0.70	5.75	1.0	5.9	0.85
54	CLUS	91	183	45	37	65	66	-3.92	3.23	3.1	6.1	1.41
55	CLUS	91	183	47	39	67	68	-1.16	3.36	1.6	4.1	1.28
56	CLUS	91	183	49	43	69	69	8.62	48.35	9.9	50.4	5.37

---CLUSTER DECAYS---

IHEP	ID	IDPDG	IST	MO1	MO2	DA1	DA2	P-X	P-Y	P-Z	ENERGY	MASS
57	B*BAR0	-513	197	50	15	70	71	-39.41	20.49	25.4	51.4	5.32
58	K0	311	197	50	15	72	72	-2.59	1.44	1.7	3.5	0.50
59	RHO+	213	197	51	15	73	74	-1.59	2.21	1.7	3.3	0.77
60	HL_10	10223	197	51	15	75	76	-1.95	3.83	2.4	5.0	1.17
61	PI0	111	1	52	27	0	0	0.48	5.68	1.0	5.8	0.13
62	PI+	211	1	52	27	0	0	-0.18	2.19	0.4	2.2	0.14
63	PI-	-211	1	53	27	0	0	0.46	3.45	0.7	3.6	0.14
64	K+	321	1	53	27	0	0	0.23	2.30	0.3	2.4	0.49
65	KBAR0	-311	197	54	15	77	77	-1.98	1.28	1.3	2.7	0.50
66	RHO-	-213	197	54	15	78	79	-1.94	1.96	1.8	3.4	0.77
67	PI-	-211	1	55	15	0	0	-1.06	2.53	1.7	3.2	0.14
68	PI0	111	1	55	15	0	0	-0.10	0.83	-0.1	0.9	0.13
69	B_S0	531	1	56	27	0	0	8.62	48.35	9.9	50.4	5.37

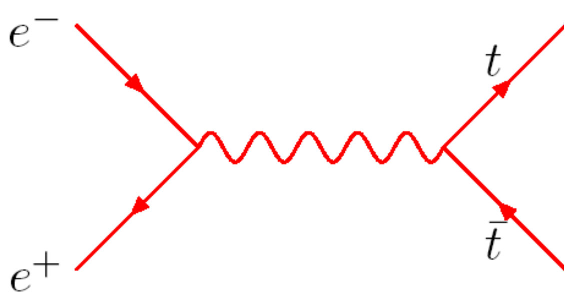
---STRONG HADRON DECAYS---

IHEP	ID	IDPDG	IST	MO1	MO2	DA1	DA2	P-X	P-Y	P-Z	ENERGY	MASS
70	B_DBAR0	-511	1	57	15	0	0	-38.82	20.19	25.1	50.7	5.28
71	GAMMA	22	1	57	15	0	0	-0.59	0.30	0.3	0.7	0.00
72	K_S0	310	198	58	15	80	81	-2.59	1.44	1.7	3.5	0.50
73	PI+	211	1	59	15	0	0	-1.06	1.92	1.4	2.6	0.14
74	PI0	111	1	59	15	0	0	-0.53	0.29	0.2	0.7	0.13
75	RHO+	213	198	60	15	82	83	-1.53	2.87	2.1	4.0	0.77
76	PI-	-211	1	60	15	0	0	-0.42	0.95	0.2	1.1	0.14
77	K_L0	130	1	65	15	0	0	-1.98	1.28	1.3	2.7	0.50
78	PI-	-211	1	66	15	0	0	-0.15	0.09	0.0	0.2	0.14
79	PI0	111	1	66	15	0	0	-1.80	1.87	1.8	3.2	0.13
80	PI+	211	1	72	15	0	0	-2.24	1.16	1.5	3.0	0.14
81	PI-	-211	1	72	15	0	0	-0.35	0.28	0.2	0.5	0.14
82	PI+	211	1	75	15	0	0	-0.80	0.79	0.8	1.4	0.14
83	PI0	111	1	75	15	0	0	-0.73	2.08	1.4	2.6	0.13

```
OUTPUT ON ELEMENTARY PROCESS

N.B. NEGATIVE WEIGHTS NOT ALLOWED

NUMBER OF EVENTS    =        1000
NUMBER OF WEIGHTS   =       34502
MEAN VALUE OF WGT   =  1.1127E-09
RMS SPREAD IN WGT   =  6.1284E-09
ACTUAL MAX WEIGHT   =  3.4867E-08
ASSUMED MAX WEIGHT  =  3.8354E-08

PROCESS CODE IPROC  =         106
CROSS SECTION (PB)  =  1.1127E-06
ERROR IN C-S   (PB) =  3.2993E-08
EFFICIENCY PERCENT  =   2.901
```

Production/Decay Spin Correlations

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



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

$$|\mathcal{M}_{\text{total}}|^2 = \mathcal{M}^{t\to b\ell\nu}_{\lambda_t}\mathcal{M}^{*t\to b\ell\nu}_{\lambda_t'} \quad {}_c^{\lambda_c\lambda_c'}D_d^{\lambda_d\lambda_d'}$$

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

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

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

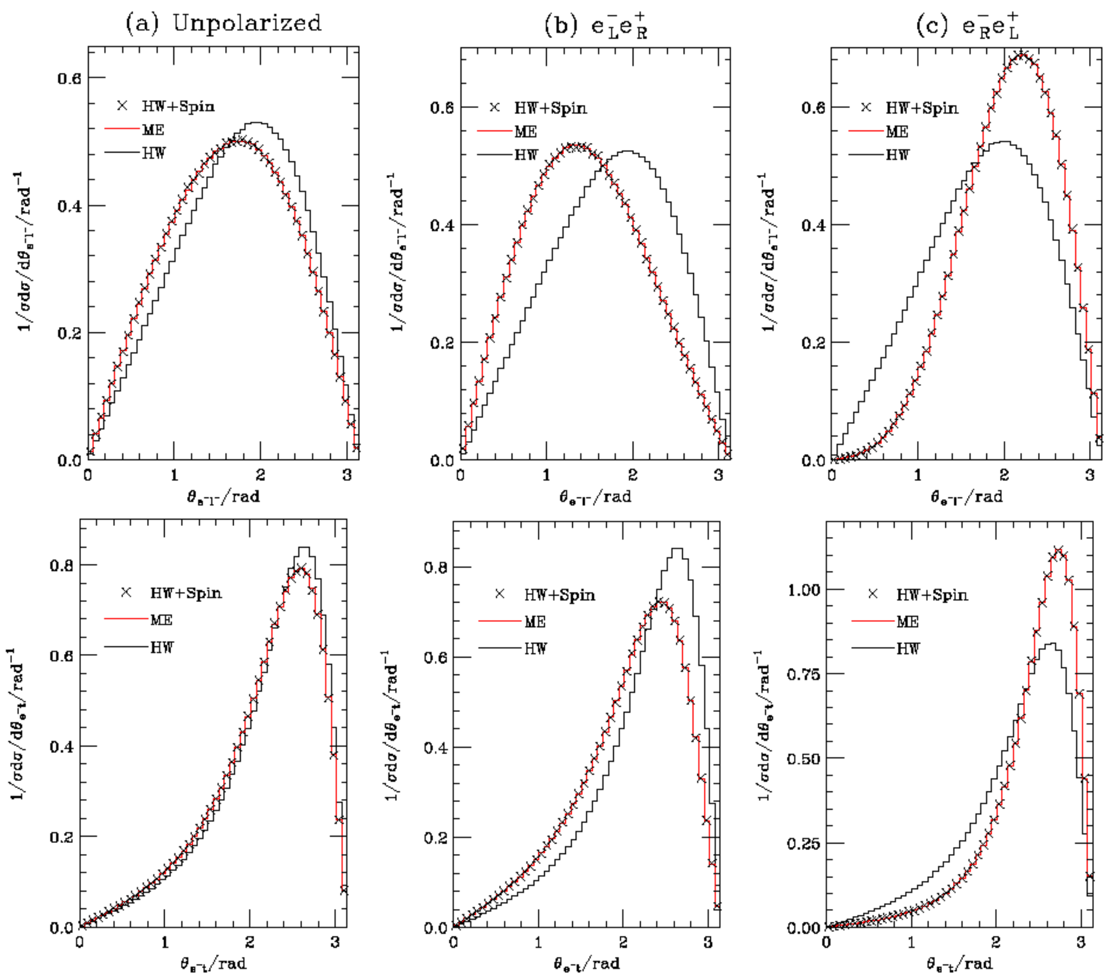
Full spin correlations included, by factorized, step-by-step algorithm

Production/Decay Spin Correlations

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

Correlation between lepton and beam

Correlation between lepton and top



PYTHIA 6

- Current status:
- Version 6.410 released on January 30th 2007
  - http://www.thep.lu.se/~torbjorn/Pythia.html
  - ~ 73,000 lines of FORTRAN
- Some features:
  - Many built-in SM and BSM processes
  - Les Houches accord interface for arbitrary hard processes
  - Mass effects in gluon emission (!= dead cone) → see later
  - Option of virtuality- or k_T-ordered shower
  - Multiple interaction models for min bias and underlying events

Subprocess summary

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

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	$f_i f_j \to f_i f_j$
99	$\gamma^* f_i \to f_i$
Photon-induced:	
33	$f_i \gamma \to f_i g$
34	$f_i \gamma \to f_i \gamma$
54	$g\gamma \to f_k \bar{f}_k$
58	$\gamma\gamma \to f_k \bar{f}_k$
131	$f_i \gamma^*_T \to f_i g$
132	$f_i \gamma^*_L \to f_i g$
133	$f_i \gamma^*_T \to f_i \gamma$
134	$f_i \gamma^*_L \to f_i \gamma$
135	$g \gamma^*_T \to f_i \bar{f}_i$
136	$g \gamma^*_L \to f_i \bar{f}_i$
137	$\gamma^*_T \gamma^*_T \to f_i \bar{f}_i$
138	$\gamma^*_T \gamma^*_L \to f_i \bar{f}_i$
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.

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.                          **
**                                                                          **
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**                                                                          **
**                                                                          **
******************************************************************************
******************************************************************************

****************** 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 ********

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

********************* 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   000000000000000000000000000000000000001111000000000000000000000000000000000000000
         *10** 1   000000000000000000000000000000000011235088162211000000000000000000000000000000000
         *10** 0   000010000101000110020201223926375046385449381867786732404001114021200012101150 1
         *10**-1   000000000000000000000000000000000000000000000000000000000000000000000000000000000

       Low edge
         *10** 2   222222222222222222222222222222222222222233333333333333333333333333333333333333333
         *10** 1   000011112222333344445555666677778888999900001111222233334444555566667777888899999
         *10** 0   035803580358035803580358035803580358035803580358035803580358035803580358035803580

    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 =
```

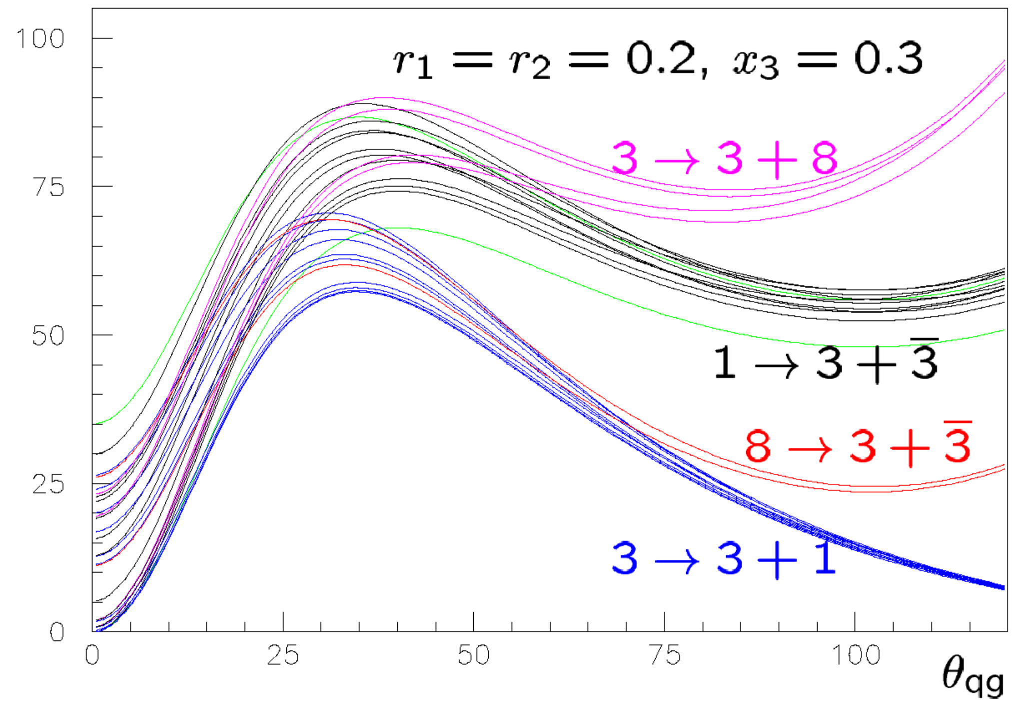
Mass Effects in PYTHIA

- 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

→ 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	$\tilde{q} \to \tilde{q}'H^+$
$1 \to 3+\bar{3}$	$\frac{1}{2} \to \frac{1}{2}+0$	$1, \gamma_5, 1 \pm \gamma_5$	$\chi \to q\bar{\tilde{q}}$
$3 \to 3+1$	$0 \to \frac{1}{2}+\frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{q} \to q\chi$
$3 \to 3+1$	$\frac{1}{2} \to 0+\frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to \tilde{t}\chi$
$8 \to 3+\bar{3}$	$\frac{1}{2} \to \frac{1}{2}+0$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{g} \to q\bar{\tilde{q}}$
$3 \to 3+8$	$0 \to \frac{1}{2}+\frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$\tilde{q} \to q\tilde{g}$
$3 \to 3+8$	$\frac{1}{2} \to 0+\frac{1}{2}$	$1, \gamma_5, 1 \pm \gamma_5$	$t \to \tilde{t}\tilde{g}$

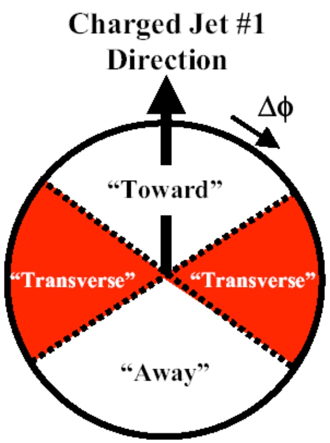


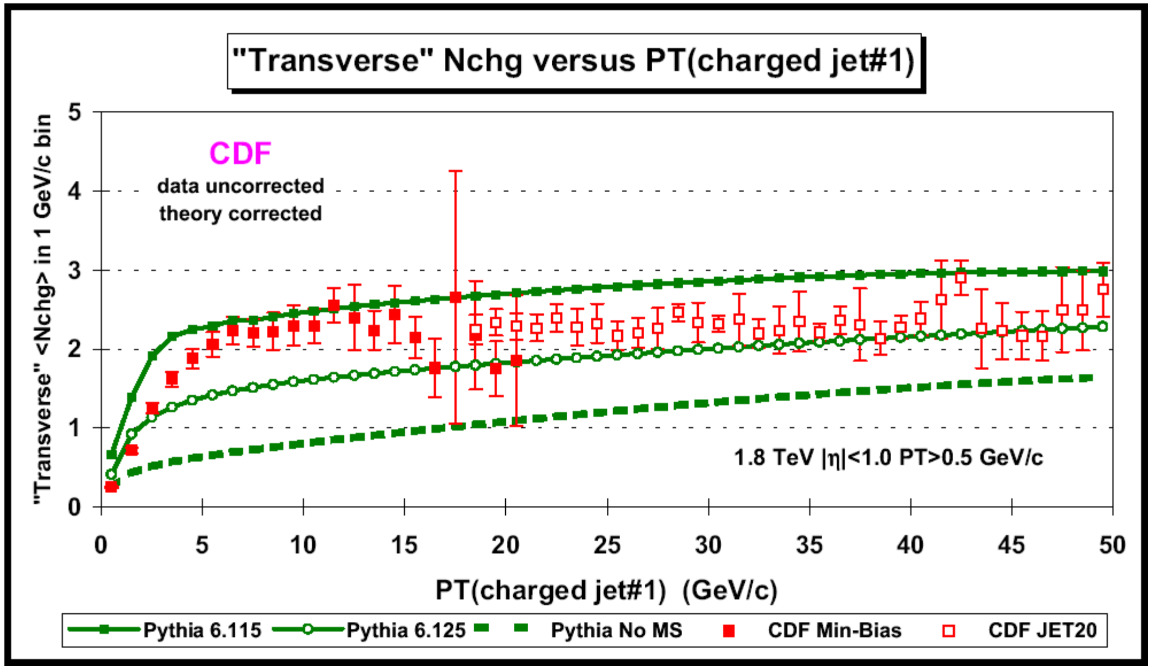
PYTHIA Underlying Event Models

Parameter	**Value**	**Description**
MSTP(81)	0,10,20	Multiple-Parton Scattering off, for old, intermediate & new models
	1,11,21	Multiple-Parton Scattering on, for old, intermediate & new models
MSTP(82)	1 2	Multiple interactions with fixed probability & abrupt cut-off PTmin=PARP(81) or smooth turn-off at PARP(82)
MSTP(82)	3	Multiple interactions with varying impact parameter & hadronic matter overlap with single Gaussian matter distribution, with smooth turn-off at PARP(82)
MSTP(82)	4 5	Multiple interactions with varying impact parameter and a hadronic matter overlap with double Gaussian matter distribution (governed by PARP(83) and PARP(84)), or distribution $\propto \exp(-b^d), \; d =$ PARP(83), both with smooth turn-off at PARP(82)

Tuning PYTHIA to the Underlying Event

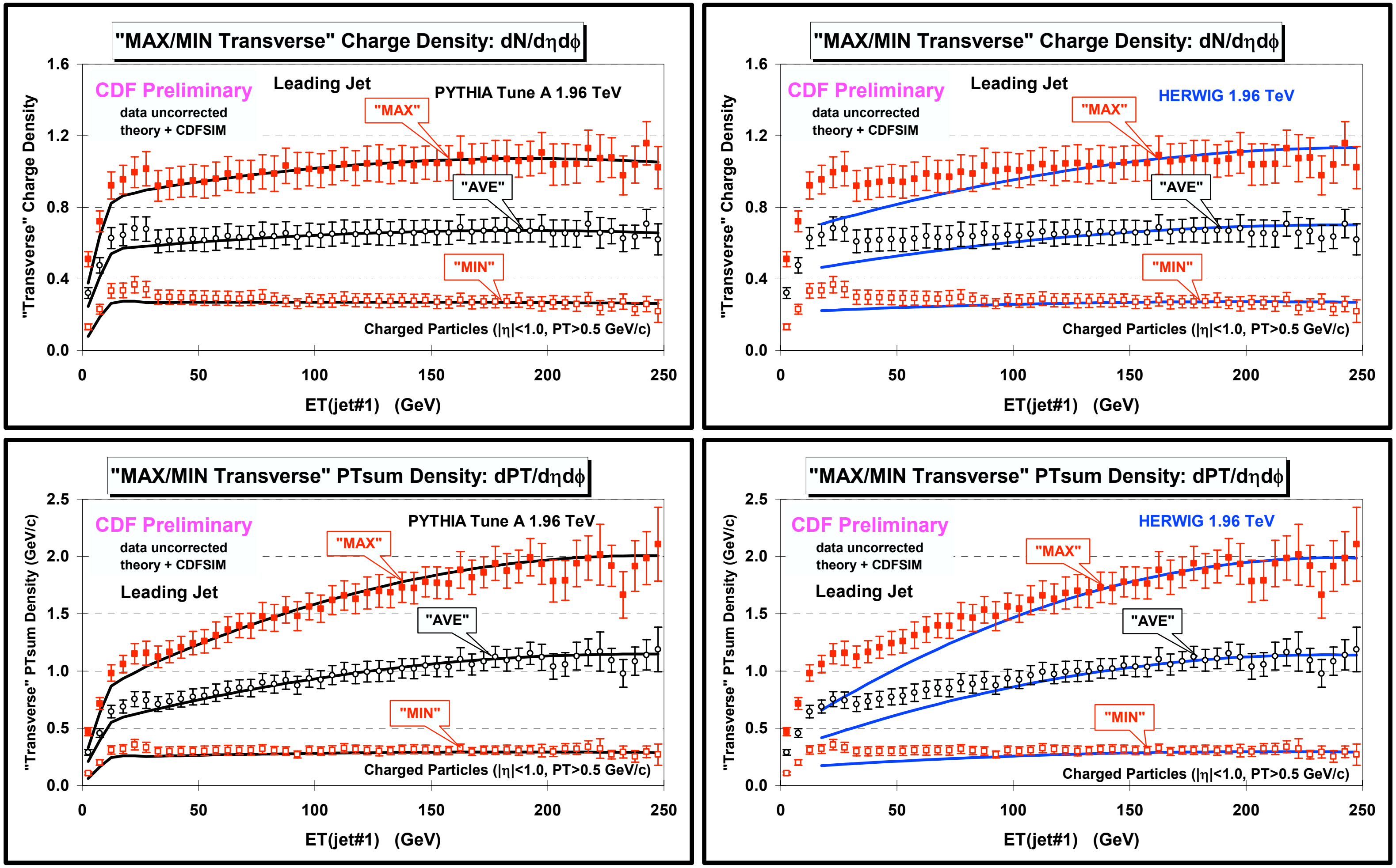
- Rick Field (CDF): keep all parameters that can be fixed by LEP or HERA at their default values. What's left?
- Underlying event. Big uncertainties at LHC...





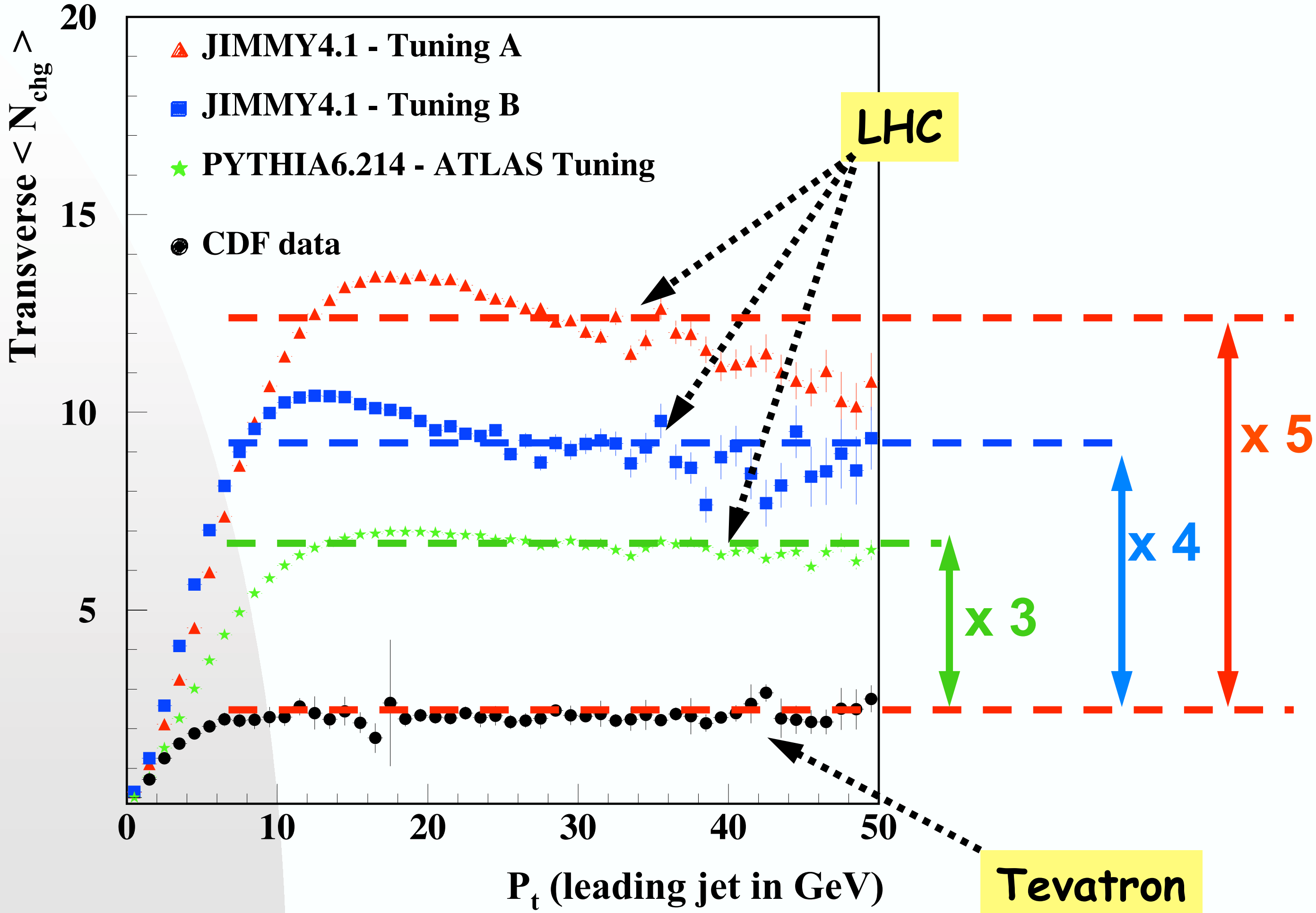
Leading Jet: "MAX & MIN Transverse" Densities

PYTHIA Tune A HERWIG



Charged particle density and PTsum density for "leading jet" events versus E_T(jet#1) for PYTHIA Tune A and HERWIG.

LHC predictions: JIMMY4.1 Tunings A and B vs. PYTHIA6.214 – ATLAS Tuning (DC2)



A. M. Moraes

Minimum-bias and the Underlying Event at the LHC

5th November 2004

Object Oriented Event Generators

- ThePEG: Toolkit for High Energy Physics Event Generation, used by Herwig++ (and ARIADNE++?)

- Herwig++: Physics improvements from HERWIG 6

- PYTHIA 8: Implementation of physics of PYTHIA 6 plus some improvements

- SHERPA: Completely new event generator

Herwig++ Status

- The current release 2.0, S. Gieseke et. al. hep-ph/0609306 includes:
  - Initial-State showers;
  - Top Decay Shower;
  - UA5 Soft Underlying event model;
  - QED Radiation;
  - Many important hadron-hadron matrix elements.
- This version can be used for hadron collider physics.

- After this version there are a number of features which we still need to include:
  - JIMMY multiple scattering model for the underlying event;
  - different kinematic reconstruction procedures for the shower;
  - BSM Physics;
  - new hadron decay model;
  - spin correlations throughout the simulation.

  In order for the simulation to be as good as, or better than, the FORTRAN for everything.

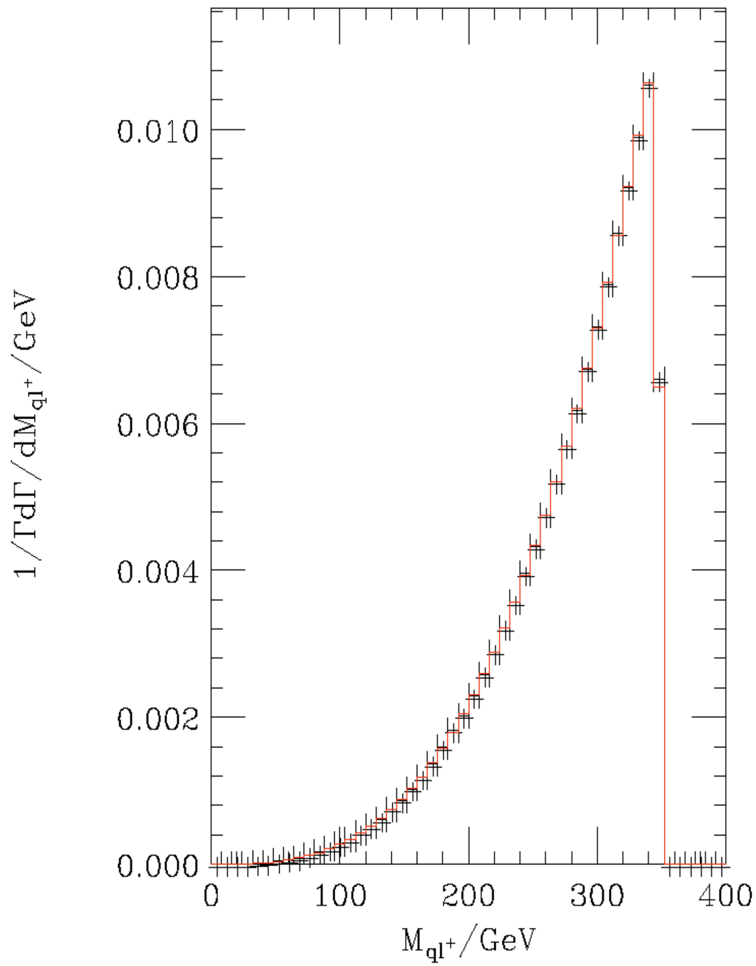
Hard Processes and New Physics

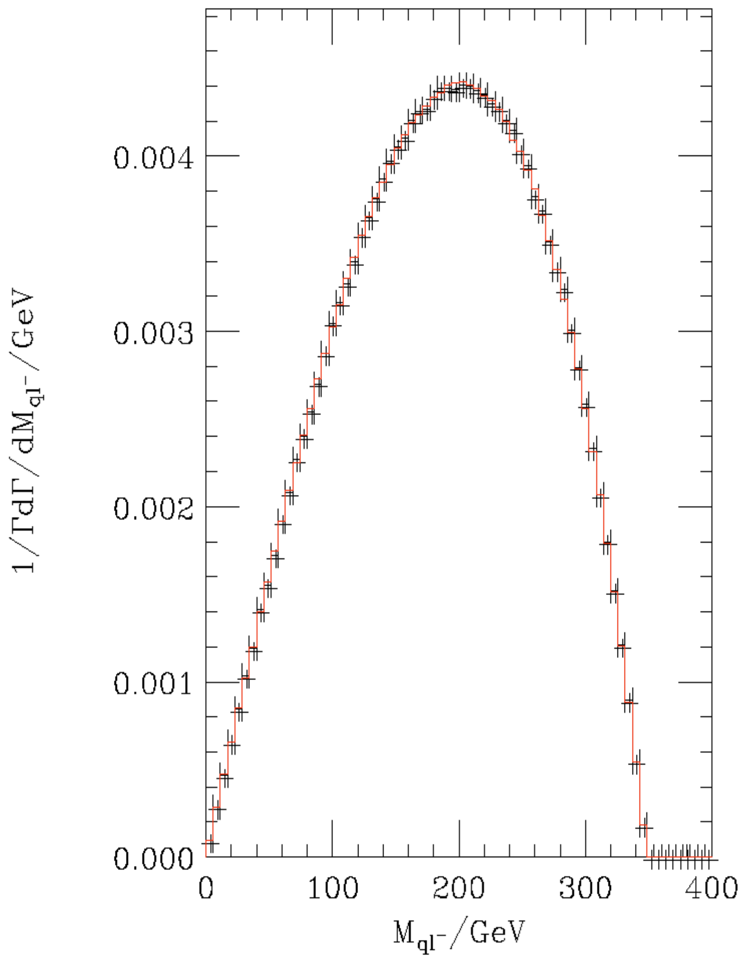
- In the FORTRAN each hard process and decay matrix element was typed in by hand.
  - Isn't a good use of time.
  - Meant that models of new physics were very hard to include.
- In the C++ we have used an entirely different philosophy.
  - A C++ helicity library based on the HELAS formalism is used for all matrix element and decay calculations.
  - Code the hard $2\to2$ matrix elements based on the spin structures.
  - Code the $1\to2$ decays in the same way and use phase space for the $1\to3$ decays to start with.
  - Easy to include spin correlations as we have access to the spin unaveraged matrix elements.

M Gigg and P Richardson hep-ph/0703199

New Physics: MSSM

$$\tilde{q}_L \to q\tilde{\chi}_2^0 \to q l^{\pm}\tilde{l}^{\mp}$$

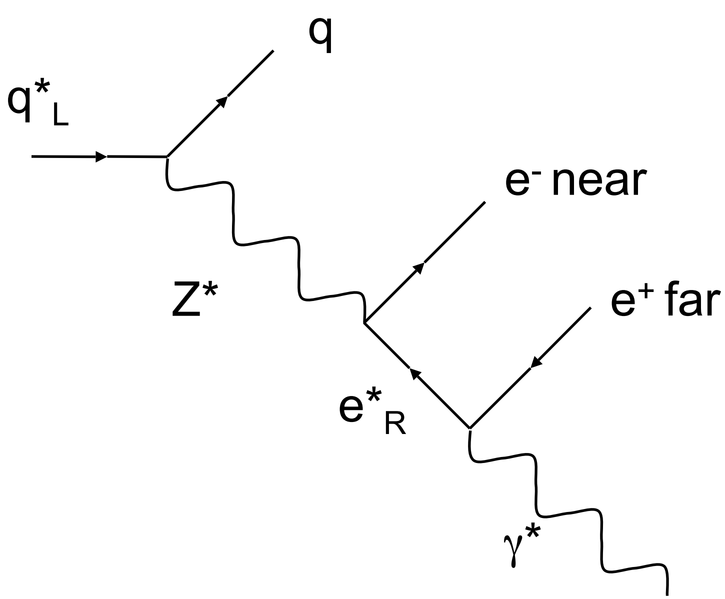


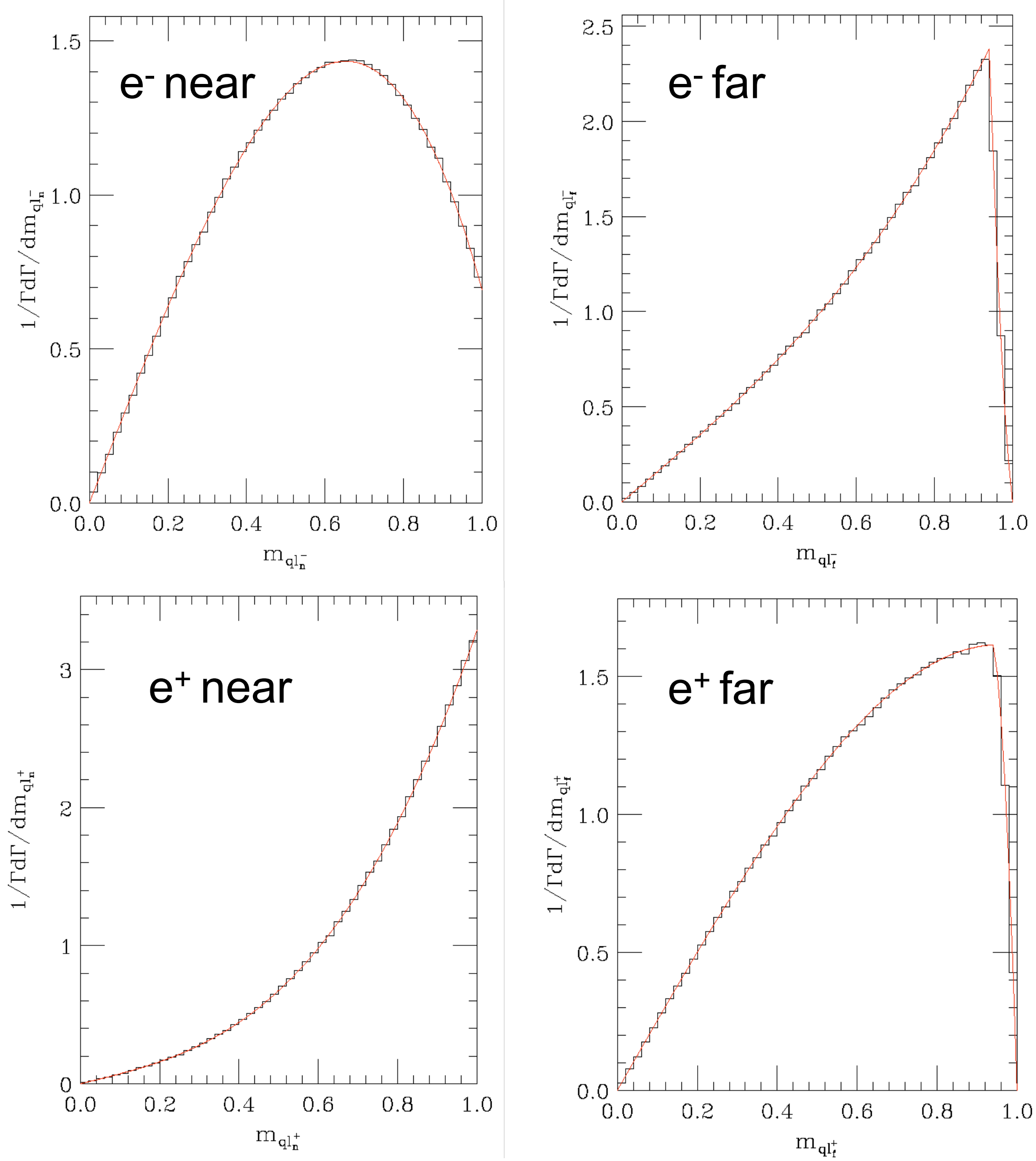


M Gigg and P Richardson hep-ph/0703199

New Physics: UED

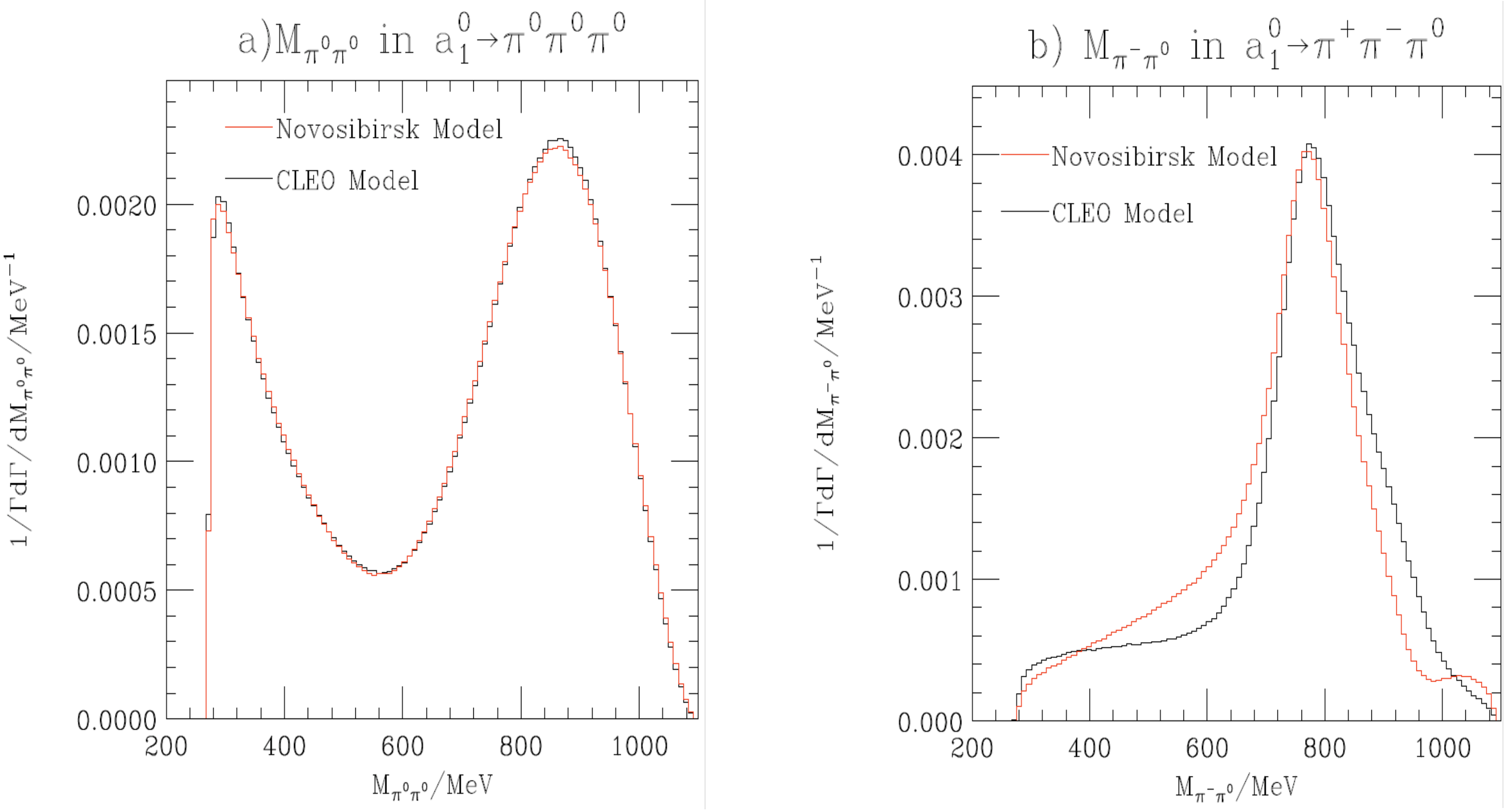
Look at the decay





J Smillie, BW JHEP10 (2005), hep-ph/0507170

Hadron Decays

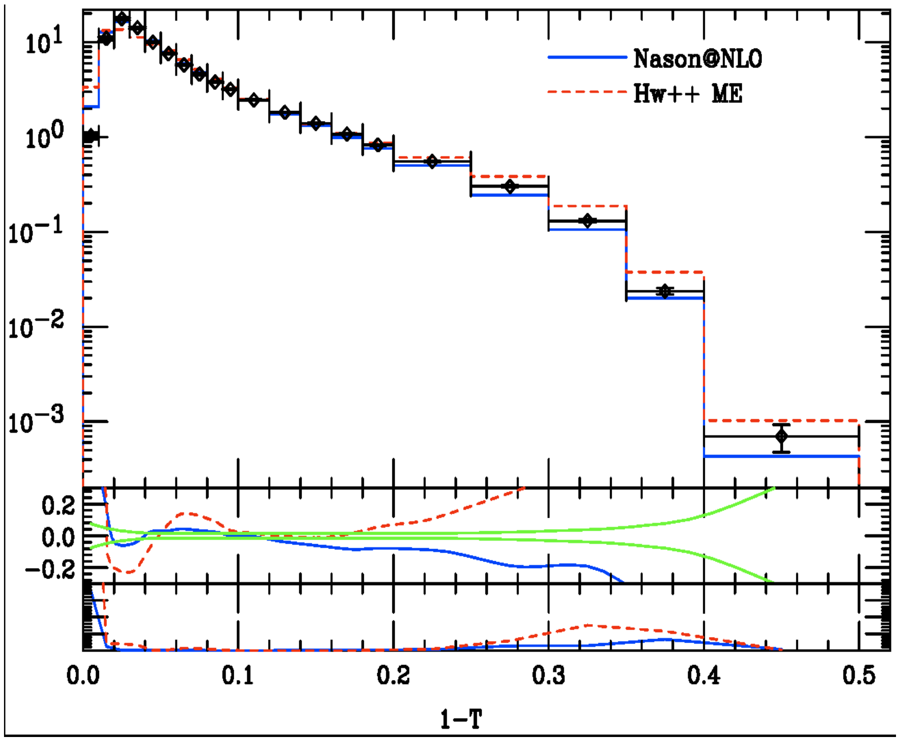


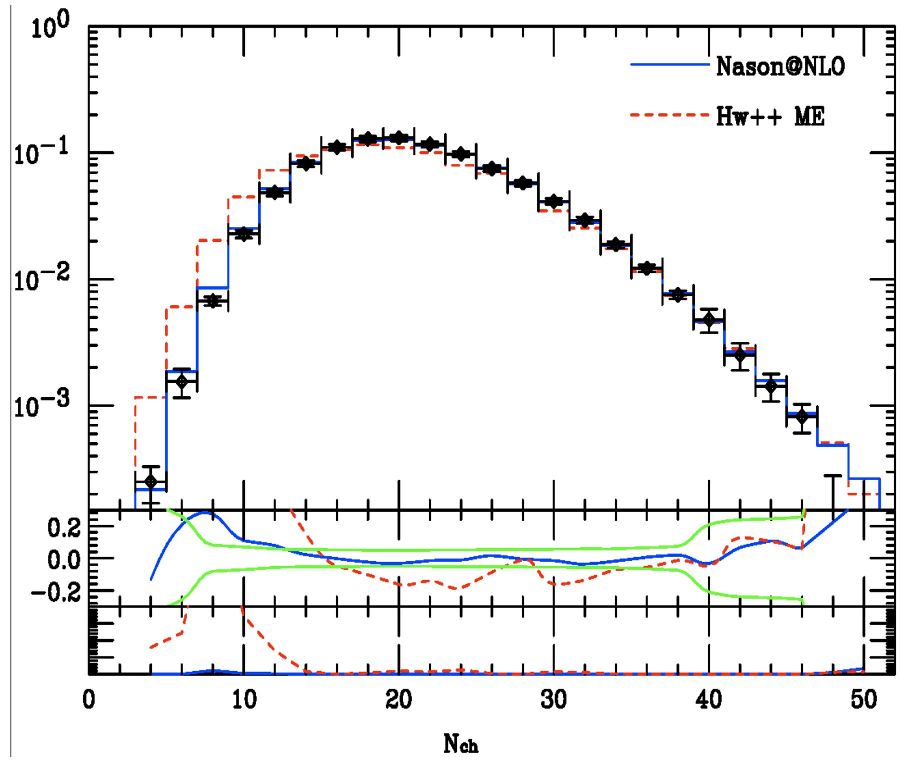
- The program includes detailed modelling of many decays

Future Shower Improvements

- In addition to the other features one of the main reasons for going to C++ was to allow improvements to the shower algorithm.
  - CKKW matrix element matching
  - The multi-scale shower
  - MC@NLO
  - The Nason approach to MC@NLO

Nason Approach to MC@NLO





O Latunde-Dada, S Gieseke, B Webber, JHEP02 (2007) 051, hep-ph/0612281

Herwig++ Summary

- Herwig++ is now ready for hadron collisions.
- Many further improvements are planned.
- There will be a new release in the summer which will include the new simulation of BSM physics, hadron decays and some shower improvements.
- In the near future the C++ simulation will replace the FORTRAN.

PYTHIA history

- 1978: work begun on JETSET: string fragmentation in e^+e^-
- 1982: work begun on PYTHIA: hadron collisions on top of JETSET
- 1997: the two program combined under PYTHIA label
- today: PYTHIA 6.410, 75 000 lines of code, 580 pp manual (JHEP), author team: Torbjörn Sjöstrand, Stephen Mrenna, Peter Skands
- intensely used for LEP, Tevatron, LHC (since 1990!), ...

... but

- only add, never subtract

$\Rightarrow$ has become bloated and unmanageable

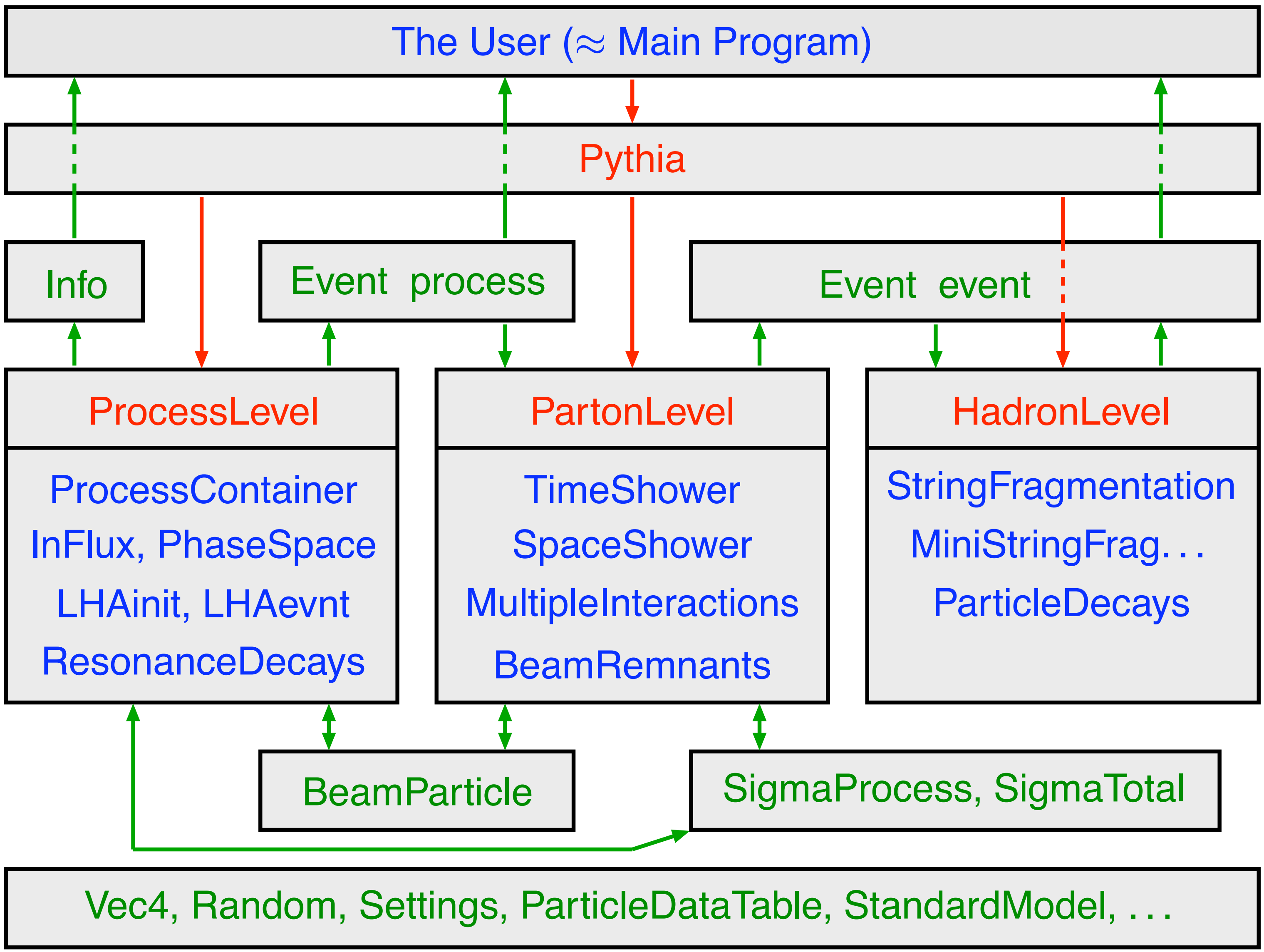
- is in Fortran 77, so not understood by young people

- 1998: C++ PYTHIA 7 begun $\Longrightarrow$ THEPEG, physics stalled
- Sep 2004: C++ PYTHIA 8 begun
- $\sim$1 sub-subversion per working week (T. Sjöstrand on "sabbatical")
- March 2007: PYTHIA 8.080
- $<$ end 2007: PYTHIA 8.100; overtakes PYTHIA 6 as "current" (?)

PYTHIA 8 status

task	status
administative structure	operational; extensions planned
hard processes, internal	only small selection; more needed
resonance decays	primitive; work needed
hard processes, external	interfaces to LHA F77, LHEF, PYTHIA 6
SUSY(+more) parameters	primitive SLHA2
initial-state showers	operational
final-state showers	operational
matching ME's to showers	some exists, much more needed
multiple interactions	operational; extensions planned
beam remnants & colour flow	operational; alternatives to come
parton densities	only 2 internal, but interface to LHAPDF
string fragmentation	operational; improvements planned
decays & particle data	operational; may need updates
Bose-Einstein	still to be done
analysis	some simple tools; may be enough
graphical user interface	operational; could be extended
tuning	major task for MCnet postdocs!

Current PYTHIA 8 structure



Introducing SHERPA

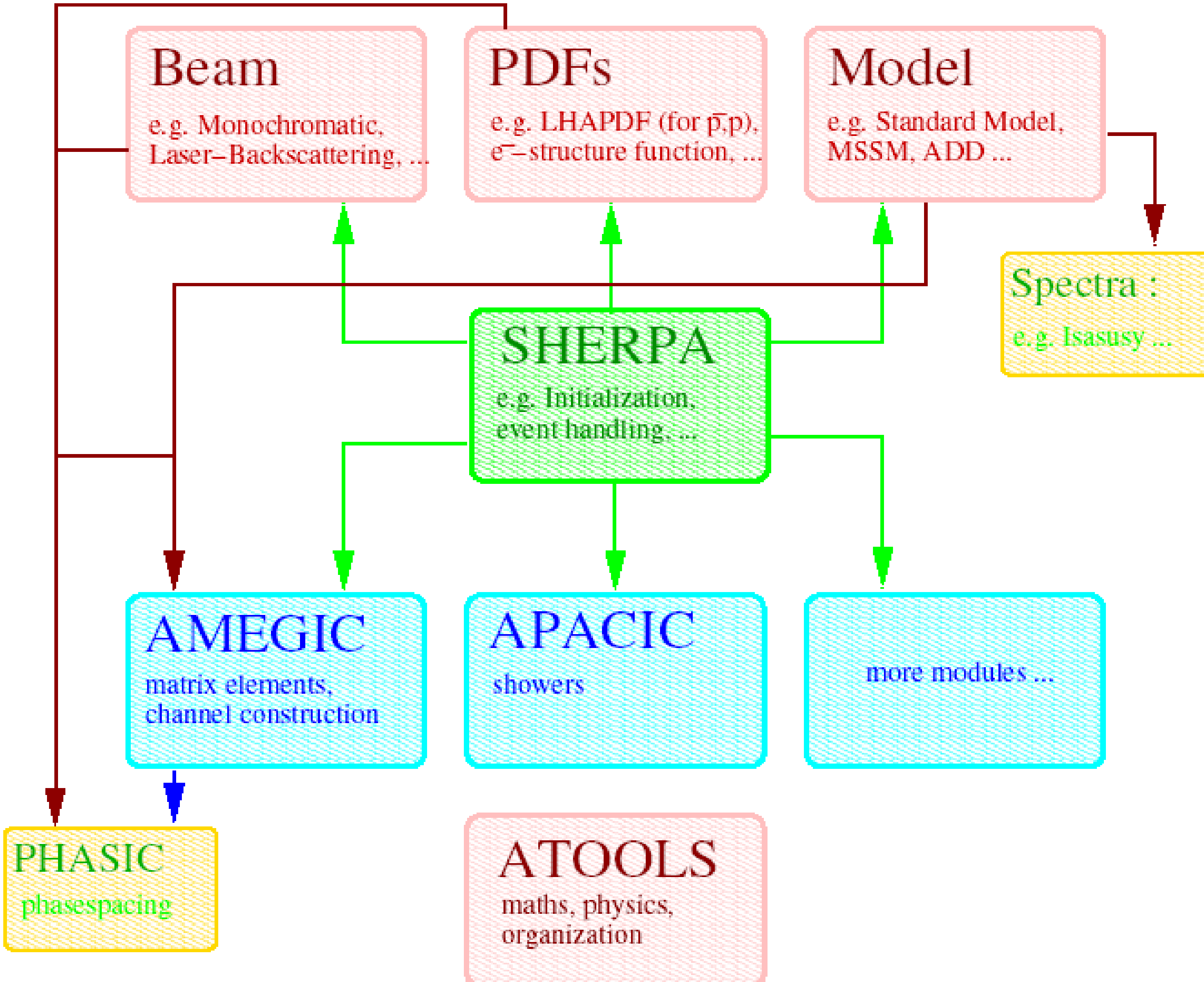
Physics of SHERPA

T.Gleisberg, S.Höche, F.K., A.Schälicke, S.Schumann and J.C.Winter, JHEP **0402** (2004) 056

- New event generator, written from scratch in C++.
- Matrix elements from AMEGIC,
  combined with own parton shower implementation

  (F.K., A.Schälicke and G.Soff, arXiv:hep-ph/0503087; similar to shower in PYTHIA)
- Hadronization of Pythia interfaced,
  will be replaced by own cluster model

  (J.Winter, F.K. and G.Soff, Eur. Phys. J. C**36** (2004) 381)
- Tested in a number of processes (highlights see below).
- A few other implementations exist for specific channels.


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

Automatic cross section calculators

Example: AMEGIC++

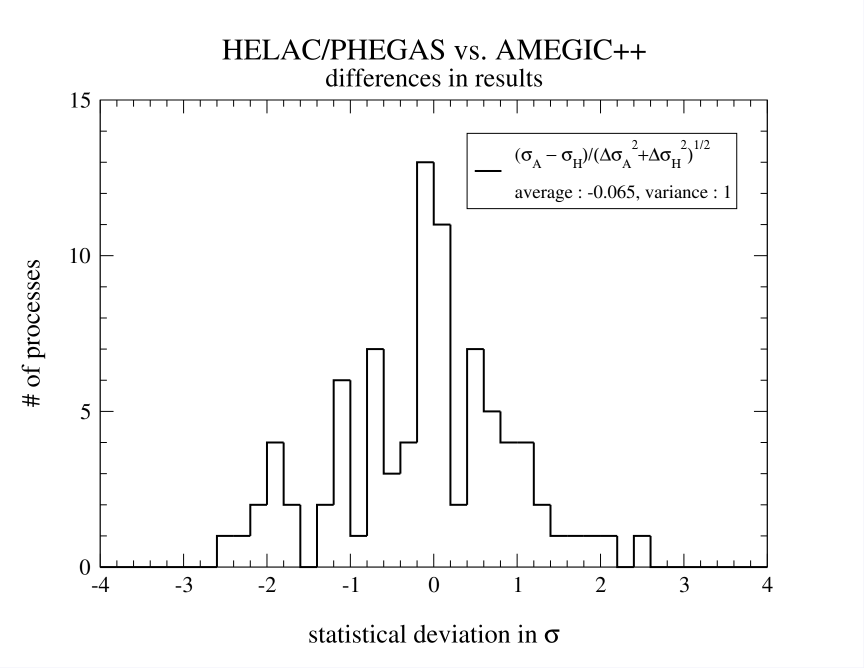
F.K., R.Kuhn, G.Soff, JHEP **0202** (2002) 044.

- Uses helicity method + multi-channeling.
  Operational mode: 2 runs.
  - Generation run:
    - Generate Feynman diagrams,
    - construct and simplify helicity amplitudes,
    - produce integration channels,
    - write out library files.
  - Compile & link libraries.
  - Production run:
    - cross section calculations,
    - parton level events.
- Implemented & tested models: SM, MSSM, ADD.

Standard Model @ Linear Collider

Consistency of HELAC/PHEGAS & AMEGIC++

T.Gleisberg, F.K., C.Papadopoulos, A.Schälicke and S.Schumann, Eur. Phys. J. C **34** (2004) 173



MSSM

Automated tools

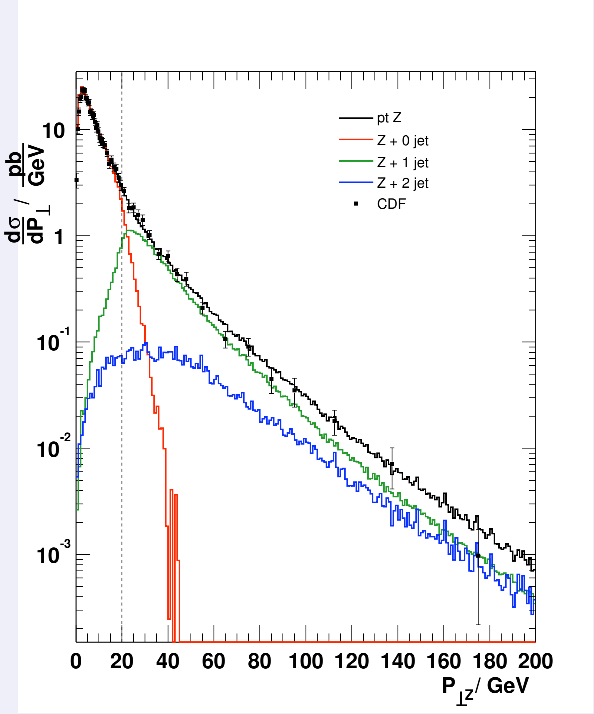
K.Hagiwara *et al.*, arXiv:hep-ph/0512260;

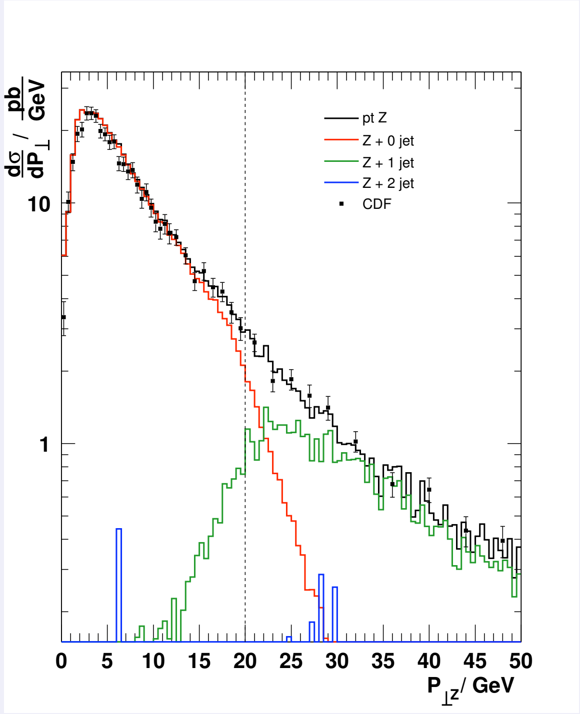
- 3 validated tools for MSSM studies: (S)MadGraph, O'Mega/Whizard & Amegic;
- completely different approaches & notations;
- SUSY spectra through SLHA interface;
- checked roughly 500 pair-production processes;
- some simple studies for LHC and LC.

Comparison with data from Tevatron

$p_\perp$ of Z-bosons in $p\bar{p} \longrightarrow Z + X$

Data from CDF, Phys. Rev. Lett. 84 (2000) 845

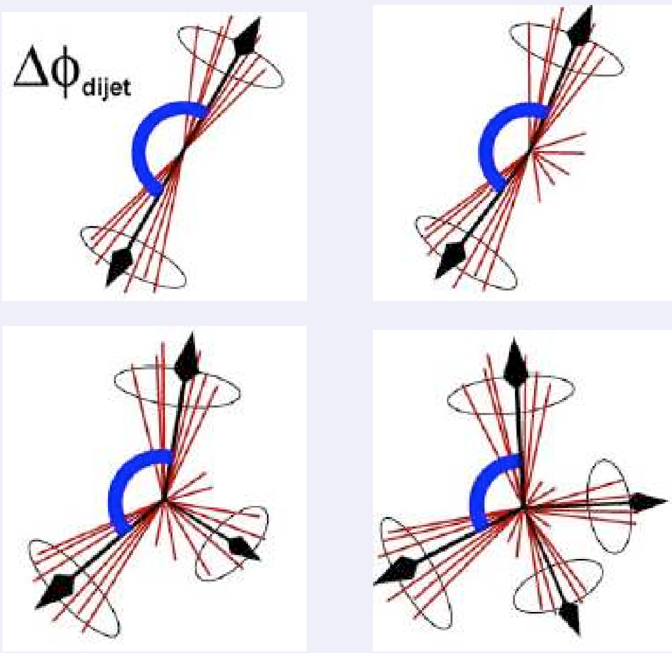




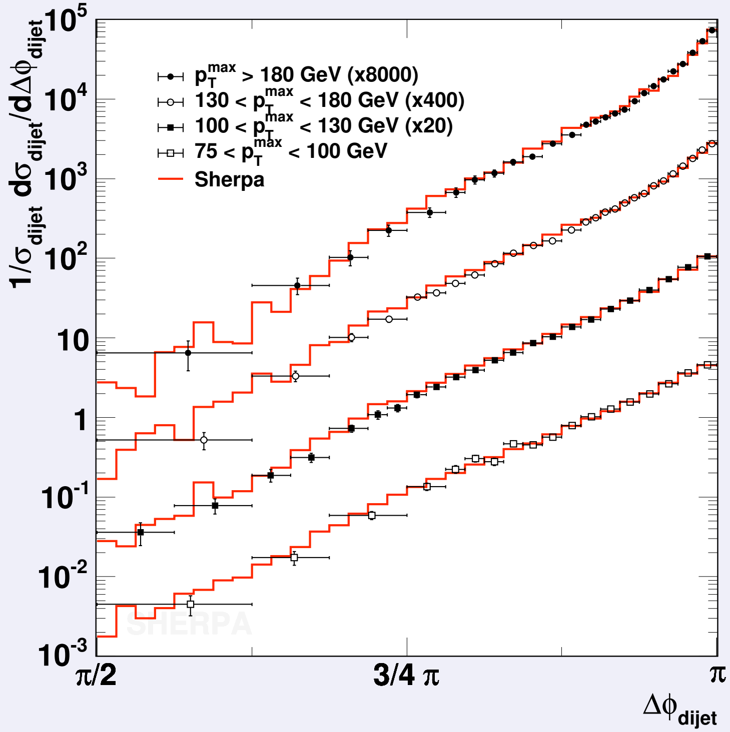
Azimuthal decorrelations of jets at the Tevatron

Idea

- Check QCD radiation pattern



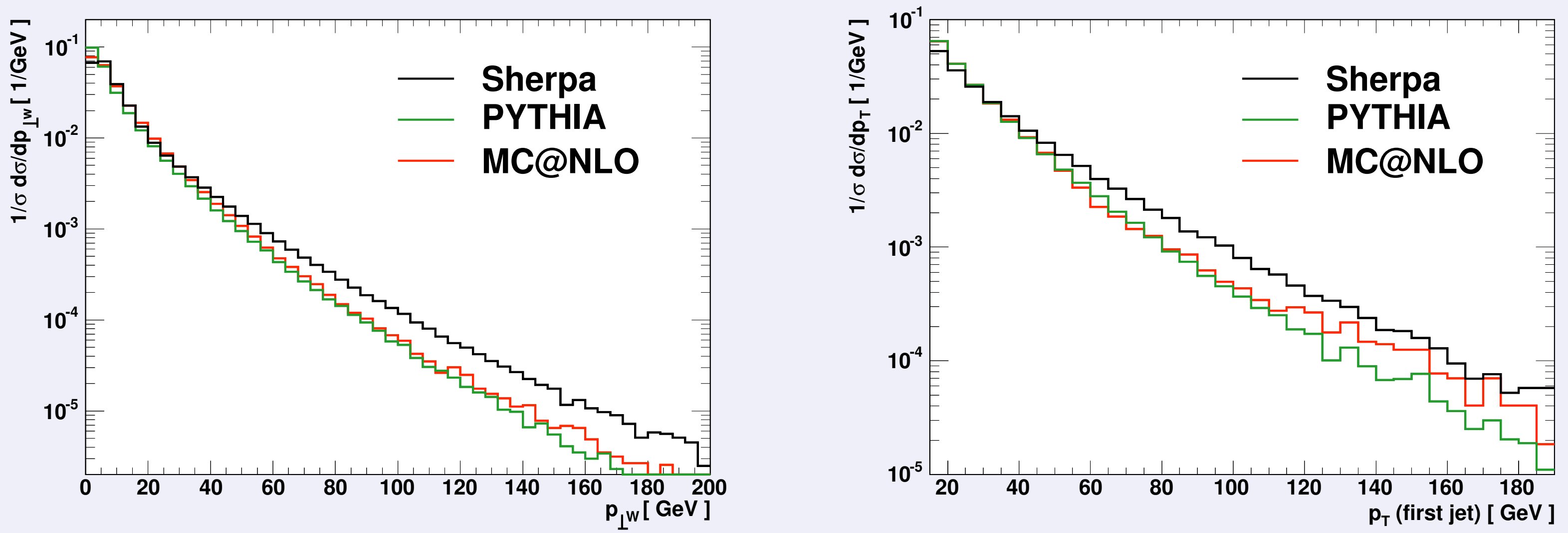
Distributions @ Run II



Comparison with other codes

$p_\perp$ of W-bosons & jets in $p\bar{p} \to W + X$ @ Tevatron

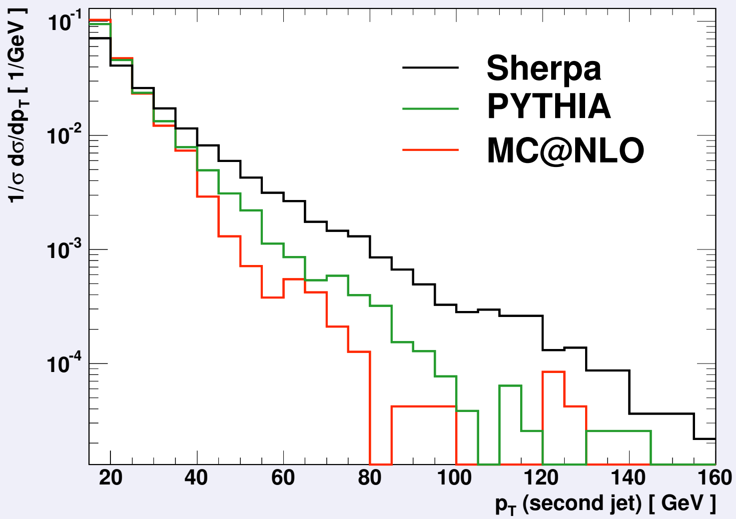
$p_\perp^W$ $\qquad$ $p_\perp^{\text{1st jet}}$

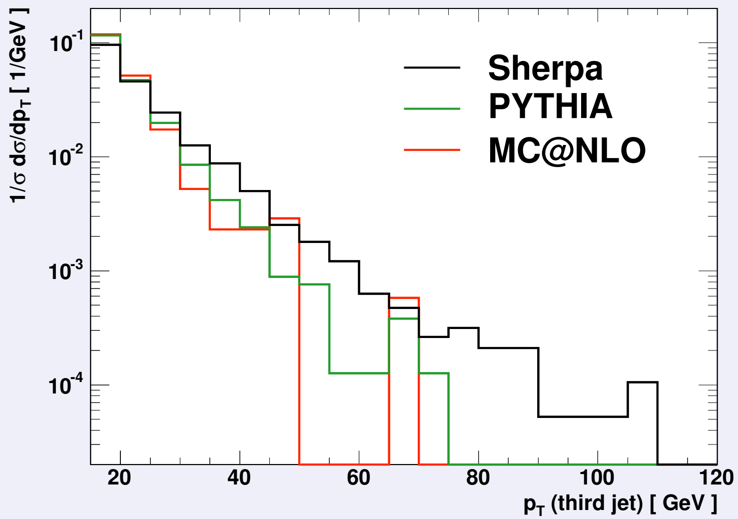


Comparison with other codes

$p_\perp$ of W-bosons & jets in $p\bar{p} \longrightarrow W + X$ @ Tevatron

$p_\perp^{\rm 2nd\,jet}$ $p_\perp^{\rm 3rd\,jet}$





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 here…
  - Software improvements
  - Physics improvements