Monte Carlo Methods in Particle Physics

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IMPRS, Munich
19-23 November 2007
Monte Carlo Event Generation

- Basic Principles
- Event Generation
- Parton Showers
- Hadronization
- Underlying Event
- Event Generator Survey
- Matching to Fixed Order
- Beyond Standard Model
Event Generators

- **HERWIG**
  - Angular-ordered shower, cluster hadronization
  - v6 Fortran; Herwig++

- **PYTHIA**
  - Virtuality/$k_T$-ordered shower, string hadronization
  - v6 Fortran; v8 C++

- **SHERPA**
  - Virtuality-ordered shower, string/cluster hadronization
  - C++
HERWIG 6

• Current status:
  – version 6.510 released on October 31st 2005
    – http://projects.hepforge.org/fherwig/
    – ~ 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 \( \Rightarrow \text{see later} \)
  – Interface to MC@NLO program (Frixione & Webber) \( \Rightarrow \text{see later} \)
  – Interface to JIMMY multiple interaction underlying event model
  – Angular cutoff \( \theta > m/E \Rightarrow \text{“dead cone” for heavy quarks} \)
Production/Decay Spin Correlations

• Example: top quark pairs in e+e- annihilation:

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

\[
|M|^2 = \rho_{\text{prod}} \left( \frac{\lambda_c \lambda'_c \lambda_d \lambda'_d}{\rho_{\text{prod}} \lambda_c \lambda'_c \lambda_d \lambda'_d} \right) \left( \frac{\lambda_c \lambda'_c \lambda_d \lambda'_d}{\rho_{\text{prod}} \lambda_c \lambda'_c \lambda_d \lambda'_d} \right)
\]

\[
\rho_{\text{prod}}^{\lambda_c \lambda'_c \lambda_d \lambda'_d} = M_{ab\rightarrow cd}^{\lambda_c \lambda_d} M_{ab\rightarrow cd}^{* \lambda'_c \lambda'_d},
\]

\[
D_c^{\lambda_c \lambda'_c} = M_{c \rightarrow \text{decay}}^{\lambda_c} M_{c \rightarrow \text{decay}}^{* \lambda'_c},
\]
Production/Decay Spin Correlations

- Top quark pairs in $e^+e^-$ annihilation:

  Correlation between lepton and beam

  Correlation between lepton and top

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PYTHIA 6

- **Current status:**
  - Version 6.413 released September 2007
    - [http://projects.hepforge.org/pythia6/](http://projects.hepforge.org/pythia6/)
    - ~75,000 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 ("no dead cone") → see later
  - Option of virtuality- or k\(_T\)-ordered shower
  - Multiple interaction models for min bias and underlying events
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

<table>
<thead>
<tr>
<th>colour</th>
<th>spin</th>
<th>$\gamma_s$</th>
<th>example</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \rightarrow 3 + \bar{3}$</td>
<td>---</td>
<td>---</td>
<td>(eikonal)</td>
</tr>
<tr>
<td>$1 \rightarrow 3 + \bar{3}$</td>
<td>$1 \rightarrow \frac{1}{2} + \frac{1}{2}$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$Z^0 \rightarrow q\bar{q}$</td>
</tr>
<tr>
<td>$3 \rightarrow 3 + 1$</td>
<td>$\frac{1}{2} \rightarrow \frac{1}{2} + 1$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$t \rightarrow bW^+$</td>
</tr>
<tr>
<td>$1 \rightarrow 3 + \bar{3}$</td>
<td>$0 \rightarrow \frac{1}{2} + \frac{1}{2}$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$H^0 \rightarrow q\bar{q}$</td>
</tr>
<tr>
<td>$3 \rightarrow 3 + 1$</td>
<td>$\frac{1}{2} \rightarrow \frac{1}{2} + 0$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$t \rightarrow bH^+$</td>
</tr>
<tr>
<td>$1 \rightarrow 3 + \bar{3}$</td>
<td>$1 \rightarrow 0 + 0$</td>
<td>1</td>
<td>$Z^0 \rightarrow q\bar{q}$</td>
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<tr>
<td>$3 \rightarrow 3 + 1$</td>
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<td>1</td>
<td>$q \rightarrow qW^+$</td>
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<td>$0 \rightarrow 0 + 0$</td>
<td>1</td>
<td>$H^0 \rightarrow q\bar{q}$</td>
</tr>
<tr>
<td>$3 \rightarrow 3 + 1$</td>
<td>$0 \rightarrow 0 + 0$</td>
<td>1</td>
<td>$q \rightarrow q'q$</td>
</tr>
<tr>
<td>$1 \rightarrow 3 + \bar{3}$</td>
<td>$\frac{1}{2} \rightarrow \frac{1}{2} + 0$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$\chi \rightarrow q\bar{q}$</td>
</tr>
<tr>
<td>$3 \rightarrow 3 + 1$</td>
<td>$0 \rightarrow \frac{1}{2} + \frac{1}{2}$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$q \rightarrow q\chi$</td>
</tr>
<tr>
<td>$3 \rightarrow 3 + 1$</td>
<td>$\frac{1}{2} \rightarrow 0 + \frac{1}{2}$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$t \rightarrow t\chi$</td>
</tr>
<tr>
<td>$8 \rightarrow 3 + \bar{3}$</td>
<td>$\frac{1}{2} \rightarrow \frac{1}{2} + 0$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$g \rightarrow q\bar{q}$</td>
</tr>
<tr>
<td>$3 \rightarrow 3 + 8$</td>
<td>$0 \rightarrow \frac{1}{2} + \frac{1}{2}$</td>
<td>$1, \gamma_5, 1 \pm \gamma_5$</td>
<td>$q \rightarrow qg$</td>
</tr>
<tr>
<td>$3 \rightarrow 3 + 8$</td>
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</tr>
</tbody>
</table>
## PYTHIA Underlying Event Models

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSTP(81)</td>
<td>0,10,20</td>
<td>Multiple-Parton Scattering off, for old, intermediate &amp; new models</td>
</tr>
<tr>
<td></td>
<td>1,11,21</td>
<td>Multiple-Parton Scattering on, for old, intermediate &amp; new models</td>
</tr>
<tr>
<td>MSTP(82)</td>
<td>1</td>
<td>Multiple interactions with fixed probability &amp; abrupt cut-off PTmin=PARP(81) or smooth turn-off at PARP(82)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Multiple interactions with varying impact parameter &amp; hadronic matter overlap with single Gaussian matter distribution, with smooth turn-off at PARP(82)</td>
</tr>
<tr>
<td>MSTP(82)</td>
<td>3</td>
<td>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 $\Delta \phi^{(WW)} \simeq 0$ PARP(83), both with smooth turn-off at PARP(82)</td>
</tr>
</tbody>
</table>

$\Delta \phi^{(WW)} \simeq 0$
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: see http://www.thep.lu.se/~torbjorn
- SHERPA: Completely new event generator
  http://projects.hepforge.org/
Hard Processes in Herwig++

- In FORTRAN HERWIG 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.
- Herwig++ uses 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 $2 \rightarrow 2$ matrix elements based on the spin structures.
  - Code the $1 \rightarrow 2$ decays in the same way and use phase space for the $1 \rightarrow 3$ 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
M Bähr et al. arXiv:0711.3137 (today!)
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Herwig++ New Physics: MSSM

\[
\tilde{q}_L \rightarrow q\tilde{\chi}_2^0 \rightarrow ql^\pm\tilde{\ell}^\mp \rightarrow ql^\pm l^\mp \tilde{\chi}_1^0
\]
Analogous decay:

\[ q^*_L \rightarrow q \rightarrow Z^* \rightarrow e^*_R \rightarrow e^+ \text{ far} \]

\[ e^- \text{ near} \rightarrow e^- \text{ far} \]

\[ e^- \text{ near} \rightarrow e^- \text{ far} \]

\[ e^+ \text{ near} \rightarrow e^+ \text{ far} \]

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

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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
  ⇒ has become bloated and unmanageable
- is in Fortran 77, so not understood by young people

- 1998: C++ PYTHIA 7 begun ⇒ THEPEG, physics stalled
- Sep 2004: C++ PYTHIA 8 begun
- ~1 sub-subversion per working week (T. Sjöstrand on “sabbatical”)
- March 2007: PYTHIA 8.080
- October 2007: PYTHIA 8.100; overtakes PYTHIA 6 as “current”
## PYTHIA 8 status

### task
- administratitive structure
- hard processes, internal resonance decays
- hard processes, external SUSY (+more) parameters
- initial-state showers
- final-state showers
- matching ME’s to showers
- multiple interactions
- beam remnants & colour flow parton densities
- string fragmentation
- decays & particle data
- Bose-Einstein analysis
- graphical user interface tuning

### status
- operational; extensions planned
- Standard Model 2 $\rightarrow$ 1/2; more needed
- Standard Model; more needed interfaces to LHA F77, LHEF, PYTHIA 6
- primitive SLHA2; more needed operational
- operational
- some exists; much more needed operational; extensions planned
- operational; alternatives to come
- only 2 internal, but interface to LHAPDF operational; improvements planned
- operational; may need updates operational; off by default (tuning)
- some simple tools; may be enough operational; could be extended major task for MCnet postdocs!
Current PYTHIA 8 structure

The User (≈ Main Program)

Pythia

Event process

Event event

ProcessLevel
ProcessContainer
InFlux, PhaseSpace
LHAinit, LHAevnt
ResonanceDecays

PartonLevel
TimeShower
SpaceShower
MultipleInteractions
BeamRemnants

HadronLevel
StringFragmentation
MiniStringFrag...
ParticleDecays

BeamParticle
SigmaProcess, SigmaTotal

Vec4, Random, Settings, ParticleDataTable, StandardModel, …
Introducing SHERPA

Physics of SHERPA

- 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
  

- Tested in a number of processes (highlights see below).
- A few other implementations exist for specific channels.
Automatic cross section calculators

Example: AMEGIC++

- 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.

Consistency of HELAC/PHEGAS & AMEGIC++


The graph shows the differences in results between HELAC/PHEGAS and AMEGIC++. It is represented by the formula:

\[
\frac{(\sigma_A - \sigma_H)}{(\Delta \sigma_A^2 + \Delta \sigma_H^2)^{1/2}}
\]

where \(\sigma_A\) and \(\sigma_H\) are the statistical deviations in the results from HELAC/PHEGAS and AMEGIC++, respectively. The average is approximately -0.065 and the variance is 1.
Azimuthal decorrelations of jets at the Tevatron

Idea

- Check QCD radiation pattern

Distributions @ Run II

- $p_T^{\text{max}} > 180 \text{ GeV (x8000)}$
- $130 < p_T^{\text{max}} < 180 \text{ GeV (x400)}$
- $100 < p_T^{\text{max}} < 130 \text{ GeV (x20)}$
- $75 < p_T^{\text{max}} < 100 \text{ GeV}$

F. Krauss
Basics of event generation for high-energy experiments

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Comparison with data from Tevatron

\[ p_\perp \text{ of } Z\text{-bosons in } p\bar{p} \rightarrow Z + X \]

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

- 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.

K. Hagiwara et al., arXiv:hep-ph/0512260;
Summary on Event Generators

• Get to know your event generator!
• 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