Monte Carlos for LHC

Torbjörn Sjöstrand
CERN and Lund University

Generator and Physics Overview
Matrix Elements vs. Parton Showers
Underlying Event and Hadronization
Outlook
Event Generator Position

“real life”

Machine $\Rightarrow$ events

produce events

observe & store events

Detector, Data Acquisition

Detector Simulation

“virtual reality”

Event Generator

Event Reconstruction

what is knowable?

compare real and simulated data

where and why?

- detector requirements
- analysis strategies
- acceptance corrections

physics is complex

conclusions, articles, talks, ...
Event Physics Overview

Structure of the basic generation process:

1) Hard subprocess: $|\mathcal{M}|^2$, Breit-Wigners, parton densities.

2) Resonance decays: includes correlations.

3) Final-state parton showers.

4) Initial-state parton showers.
5) Multiple parton–parton interactions.

6) Beam remnants, with colour connections.

5) + 6) = Underlying Event

7) Hadronization

8) Ordinary decays: hadronic, τ, charm, ...
9) QCD interconnection effects:

\[
\begin{align*}
e^+ & \rightarrow W^+ & q_1 \\
e^- & \rightarrow W^- & q_3 \\
\end{align*}
\]

\( \bar{q}_4 \)

\( \bar{q}_2 \)

\( \pi^+ \) \( \Rightarrow \) BE

a) colour rearrangement

\( \Rightarrow \) rapidity gaps?

b) Bose-Einstein.

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

Many aspects still poorly understood, but most good enough to work with.
Generator Landscape

<table>
<thead>
<tr>
<th>Hard Processes</th>
<th>General-Purpose</th>
<th>Specialized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonance Decays</td>
<td>HERWIG</td>
<td>a lot</td>
</tr>
<tr>
<td>Parton Showers</td>
<td>PYTHIA</td>
<td>HDECAY, ...</td>
</tr>
<tr>
<td>Underlying Event</td>
<td>ISAJET</td>
<td>Ariadne/LDC, NLLjet</td>
</tr>
<tr>
<td>Hadronization</td>
<td>SHERPA</td>
<td>DPMJET</td>
</tr>
<tr>
<td>Ordinary Decays</td>
<td></td>
<td>none (?)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TAUOLA, EvtGen</td>
</tr>
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</table>

specialized often best at given task, but need General-Purpose core
The Smaller Picture: Subprocess Survey

<table>
<thead>
<tr>
<th>Kind</th>
<th>Process</th>
<th>PYT</th>
<th>HER</th>
<th>ISA</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD &amp; related</td>
<td>Soft QCD</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td></td>
<td>Hard QCD</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td></td>
<td>Heavy flavour</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>Electroweak SM</td>
<td>Single $\gamma^*/Z^0/W^\pm$</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td></td>
<td>$(\gamma/\gamma^*/Z^0/W^\pm/f/g)^2$</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td></td>
<td>Light SM Higgs</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td></td>
<td>Heavy SM Higgs</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td>SUSY BSM</td>
<td>$h^0/H^0/A^0/H^\pm$</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td></td>
<td>SUSY</td>
<td>★</td>
<td>★</td>
<td>★</td>
</tr>
<tr>
<td></td>
<td>R SUSY</td>
<td>★</td>
<td>★</td>
<td>—</td>
</tr>
<tr>
<td>Other BSM</td>
<td>Technicolor</td>
<td>★</td>
<td>—</td>
<td>(★)</td>
</tr>
<tr>
<td></td>
<td>New gauge bosons</td>
<td>★</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Compositeness</td>
<td>★</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Leptoquarks</td>
<td>★</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>$H^{\pm\pm}$ (from LR-sym.)</td>
<td>★</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Extra dimensions</td>
<td>(★)</td>
<td>(★)</td>
<td>(★)</td>
</tr>
</tbody>
</table>

...but processes usually only in lowest nontrivial order
need standardized interfaces
The Les Houches Accord

Specialized Generator \( \Rightarrow \) Hard Process

Les Houches Interface

HERWIG or PYTHIA
- (Resonance Decays)
- Parton Showers
- Underlying Event
- Hadronization
- Ordinary Decays

Some Specialized Generators:
- AcerMC: \( t\bar{t}b\bar{b}, \ldots \)
- ALPGEN: \( W/Z^+ \leq 6j, \quad nW + mZ + kH^+ \leq 3j, \ldots \)
- AMEGIC++: generic LO
- CompHEP: generic LO
- GRACE+Bases/Spring: generic LO+ some NLO loops
- GR@PPA: \( b\bar{b}b\bar{b} \)
- MadCUP: \( W/Z^+ \leq 3j, t\bar{t}b\bar{b} \)
- MadGraph+HELAS: generic LO
- MCFM: NLO \( W/Z^+ \leq 2j, \quad WZ, WH, H^+ \leq 1j \)
- O’Mega+WHIZARD: generic LO
- VECBOS: \( W/Z^+ \leq 4j \)

Apologies for all unlisted programs
Matrix Elements vs. Parton Showers

ME: Matrix Elements
+ systematic expansion in $\alpha_s$ (‘exact’)
+ powerful for multiparton Born level
+ flexible phase space cuts
  - loop calculations very tough
  - negative cross section in collinear regions
    $\Rightarrow$ unpredictable jet/event structure
  - no easy match to hadronization

PS: Parton Showers
- approximate, to LL (or NLL)
- main topology not predetermined
  $\Rightarrow$ inefficient for exclusive states
+ process-generic $\Rightarrow$ simple multiparton
+ Sudakov form factors/resummation
  $\Rightarrow$ sensible jet/event structure
+ easy to match to hadronization
Parton Shower Approach

3 common algorithms:
HERWIG: $\theta$-ordered emissions (ISR & FSR)
PYTHIA: $M^2, Q^2$-ordered emissions (ISR & FSR)
ARIADNE: $p_\perp$-ordered emissions (FSR primarily)

Steady evolution:
HERWIG: new angular evolution variable
⇒ improved phase space coverage,
  better massive quark treatment
PYTHIA: $p_\perp$-ordered emissions (ISR & FSR)
⇒ improved coherence,
  interleaved multiple interactions,
  (to prove:) simplified vetoed parton showers
LDCMD, CASCADE: CCFM generators for ISR at small $x$
Matrix Elements and Parton Showers

Marriage desirable! But how?

Problems:

- gaps in coverage?
- doublecounting of radiation?
- Sudakov?
- NLO consistency?

Much work ongoing $\implies$ no established orthodoxy

Three main areas, in ascending order of complication:

1) Match to lowest-order nontrivial process — merging

2) Combine leading-order multiparton process — vetoed parton showers (cf. talk by M. Mangano)

3) Match to next-to-leading order process — MC@NLO (covered in talk by S. Frixione)
Merging

= cover full phase space with smooth transition ME/PS

Want to reproduce

\[ W^{\text{ME}} = \frac{1}{\sigma(\text{LO})} \int \frac{d\sigma(\text{LO} + g)}{d(\text{phasespace})} \]

by shower generation + correction procedure

\[ \frac{\hat{W}^{\text{ME}}}{\hat{W}^{\text{PS}}} = \frac{\hat{W}^{\text{PS}}}{\hat{W}^{\text{PS}}} \]

- Exponentiate ME correction by shower Sudakov form factor:

\[ W^{\text{PS}}_{\text{actual}}(Q^2) = W^{\text{ME}}(Q^2) \exp \left( - \int_{Q_2}^{Q_{\text{max}}} W^{\text{ME}}(Q') dQ'^2 \right) \]

- Normally several shower histories ⇒ ~equivalent approaches

- Use \( d\sigma = K \sigma_0 \ dW^{\text{PS}} \)

where \( K = 1 + \mathcal{O}(\alpha_s) \) is set separately (ambiguity of \( \mathcal{O}(\alpha_s^2) \))
PYTHIA performs merging with generic FSR \( a \rightarrow b c g \) ME, in SM: \( \gamma^*/Z^0/W^\pm \rightarrow q\bar{q}, \ t \rightarrow bW^+, \ H^0 \rightarrow q\bar{q}, \) and MSSM: \( t \rightarrow bH^+, \ Z^0 \rightarrow q\bar{q}, \ q \rightarrow q'W^+, \ H^0 \rightarrow q\bar{q}, \ q \rightarrow q'H^+, \chi \rightarrow q\bar{q}, \chi \rightarrow q\bar{q}, \ q \rightarrow q\chi, \ t \rightarrow \tilde{t}\chi, \tilde{g} \rightarrow q\bar{q}, \ q \rightarrow q\tilde{g}, \ t \rightarrow \tilde{t}\tilde{g} \)

\( g \) emission for different colour, spin and parity:

\[
R_{3bl}(y_c): \text{mass effects in Higgs decay:}
\]

PYTHIA ISR: only \( q\bar{q} \rightarrow \gamma^*/Z^0/W^\pm \) and \( gg \rightarrow H^0 \) (for \( m_t \rightarrow \infty \)) (but \( K \) factor not implemented here)

HERWIG: fewer for FSR, comparable for ISR
Vetoed Parton Showers


Generic method to combine ME’s of several different orders to NLL accuracy; will be a ‘standard tool’ in the future

Basic idea:
• consider (differential) cross sections \( \sigma_0, \sigma_1, \sigma_2, \sigma_3, \ldots \), corresponding to a lowest-order process (e.g. W or H production), with more jets added to describe more complicated topologies, in each case to the respective leading order
• \( \sigma_i, i \geq 1 \), are divergent in soft/collinear limits
• absent virtual corrections would have ensured “detailed balance”, i.e. an emission that adds to \( \sigma_{i+1} \) subtracts from \( \sigma_i \)
• such virtual corrections correspond (approximately) to the Sudakov form factors of parton showers
• so use shower routines to provide missing virtual corrections \( \Rightarrow \) rejection of events (especially) in soft/collinear regions
Veto scheme:
1) Pick hard process, mixing according to $\sigma_0 : \sigma_1 : \sigma_2 : \ldots$, above some ME cutoff, with large fixed $\alpha_s_0$
2) Reconstruct imagined shower history (in different ways)
3) Weight $W_{\alpha} = \prod_{\text{branchings}} \left( \frac{\alpha_s(k^2_{\perp, i})}{\alpha_s_0} \right) \Rightarrow \text{accept/reject}$

CKKW-L:
4) Sudakov factor for non-emission on all lines above ME cutoff
   $W_{\text{Sud}} = \prod \text{“propagators”} \ \text{Sudakov}(k^2_{\perp, \text{beg}}, k^2_{\perp, \text{end}})$
4a) CKKW : use NLL Sudakovs
4b) L: use trial showers
5) $W_{\text{Sud}} \Rightarrow \text{accept/reject}$
6) do shower,
   vetoing emissions above cutoff

MLM:
4) do parton showers
5) (cone-)cluster showered event
6) match partons and jets
7) if all partons are matched, and $n_{\text{jet}} = n_{\text{parton}}$,
   keep the event,
   else discard it
Multiple Interactions

Consequence of composite nature of hadrons!

Evidence:
- direct observation: AFS, UA1, CDF
- implied by width of multiplicity distribution + jet universality: UA5
- forward–backward correlations: UA5
- pedestal effect: UA1, H1, CDF

One new free parameter: $p_{\perp \text{min}}$

$$\frac{1}{2} \sigma_{\text{jet}} = \int_{s/4}^{\infty} \frac{d\sigma}{dp_{\perp}^2} dp_{\perp}^2 \quad \leftarrow \quad \int_{0}^{s/4} \frac{d\sigma}{dp_{\perp}^2} \frac{p_{\perp}^4}{(p_{\perp 0}^2 + p_{\perp}^2)^2} dp_{\perp}^2$$

Measure of colour screening length $d$ in hadron:

$$p_{\perp \text{min}} \langle d \rangle \approx 1(\equiv \bar{n})$$
Event Structure and Beam Remnants

(TS & P.Z. Skands, JHEP 03 (2004) 053)

Need to assign:
- correlated flavours
- correlated $x_i = p_{zi}/p_{ztot}$
- correlated primordial $k_{\perp i}$
- correlated colours for initiators and remnants + showers

Example: parton densities after first interaction:
- valence: scale by #remaining/#original
- sea: bookkeep ‘companion’ by

$$\bar{s}(x'; x) \propto \frac{g(x + x')}{x + x'} P_{g\to s\bar{s}} \left( \frac{x}{x + x'} \right)$$
Interleaved Multiple Interactions

(TS & P.Z. Skands, hep-ph/0408302)

Data comparisons:
usually $\sim$ Tune A
but need good tuning

$\langle p_\perp \rangle (n_{\text{ch}})$ problem:
colour correlations?
Hadronization: Lund String Model

In QCD, for large charge separation, field lines seem to be compressed to tubelike region(s) \( \Rightarrow \text{string(s)} \)

String tension: \( F(r) \approx \text{const} = \kappa \iff V(r) \approx \kappa r \)

Confirmed e.g. by quenched lattice QCD
Unquenched \( \Rightarrow \) nonperturbative string breakings

Gluon = kink on string, carrying energy and momentum.

Force ratio
Glue/ quark = 2,
cf. QCD \( N_C/C_F = 9/4 \)

- Few parameters to describe energy–momentum structure!
- Many parameters to describe flavour composition!
Lund hadronization news: fragmentation of junction topology, in $R$-parity violating SUSY decays $\tilde{\chi}_1^0 \rightarrow uds$, or when 2 valence quarks kicked out of proton beam


More complicated (but $\approx$ solved) with gluon emission and massive quarks

Also new: fragmentation of stable gluino
Hadronization: HERWIG Cluster Model

Introduce forced $g \rightarrow q\bar{q}$ branchings:

Large-mass clusters require special attention
- Many parameters to describe energy–momentum structure!
- Few parameters to describe flavour composition!
Standards and Interfaces

★★★★ PDG particle codes
★★★★ HEPEVT hadron-level Event Record
★★★★ Les Houches Accord User Process Interface
★★★★ LHAPDF: Les Houches Accord Parton Density Functions (supersedes PDFLIB)
★★★★ SLHA: SUSY mass/coupling spectrum calculator interface
★★ HepMC hadron-level Event Record in C++
★★ JetWeb/HZtools: automated data comparisons
★ StdHep, StdHepC++: converts non-standard particle codes
★ HepPDT particle data tables in C++
★ ? For C++ era: (improved) Les Houches Interface for HO or NLO ME’s, standardized cuts, standard cone clustering algorithm, ...
On To C++

PYTHIA7 project $\iff$ ThePEG
Toolkit for High Energy Physics Event Generation:
general-purpose framework, kinematics, ME machinery, decays, ...
(L. Lönnblad; S. Gieseke, A. Ribon, P. Richardson)

ARIADNE/LDC: to do ISR/FSR showers, multiple interactions
(L. Lönnblad; N. Lavesson)

PYTHIA7 leftover: old showers + incomplete string fragmentation
$\Rightarrow$ restart from scratch 2 months ago (TS)

HERWIG++: new final-state shower + improved cluster model
and decays $\Rightarrow$ $e^+e^-$ complete, pp underway
(B.R. Webber; S. Gieseke, A. Ribon, P. Richardson, M. Seymour, P. Stephens)

SHERPA: does pp, but partly wrappers to PYTHIA Fortran; has CKKW
(F. Krauss; T. Gleisberg, S. Hoeche, A. Schaelicke, S. Schumann, J. Winter)

• Conversion effort: everything takes longer and costs more
  (as for LHC machine, detectors and software)
• The physics hurdle is as steep as the C++ learning curve
Outlook

Generators in state of continuous development:

- better & more user-friendly general-purpose
  matrix element calculators+integrators
- new libraries of physics processes, also to NLO
  - more precise parton showers
- better matching matrix elements ↔ showers
- improved models for underlying events / minimum bias
  - upgrades of hadronization and decays
  - moving to C++
    ⇒ always better, but never enough

But what are the alternatives, when event structures are complicated
and analytical methods inadequate?