Status and Developments of Event Generators

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Further talks by Gavin Salam, Rikkert Frederix, Tomas Jezo, Marek Schönherr, Frank Tackmann, . . .
. . . and several of the experimental presentations (?)
1976: Lund QCD Phenomenology group

Created by Bo Andersson and Gösta Gustafson

**Lund string model**: \(\sim\) like rubber band that is pulled apart and breaks into pieces, or like a magnet broken into smaller pieces.

Complete, consistent description of 2-jet events — but not necessarily perfect.
1978: JETSET version 1

SUBROUTINE JETGEN(in)
COMMON /JET/ K(100:2), P(100:5)
COMMON /PART/ PD, PSI, SIGMA, CH2, BES, WFIN, IFLEBEF
COMMON /DATA/ T(100:2), CMIX(100:2), PMAJ(10)
IFLEBEF(10:IFLEBEF/2)
END

1978: JETSET version 1

SUBROUTINE DECAY(IPP)
COMMON /JET/ K(100:2), P(100:5)
COMMON /DATA/ T(100:2), CMIX(100:2), PMAJ(10)
DIMENSION U(2, 2)

C 1 DECAY CHANNEL choice GIVES DECY PRODUCTS

C 1 RANDOM CHOICE OF X=EXP(252MEGON)/EXP(AVAILABLE GIVES E AND P)
IRRANG(0) = X = IPEND(0) IRRANG(0), PTCV(1, 1) = X = Y ,
C 1 IF(IRRANG(0).EQ.0) IRRANG(1) = IPEND(0) X = Y ,
C 4 IF UNSTABLE DECAY CHAIN INTO STABLE PARTICLES

C 7 FLAVOUR AND PT OF QUARK FORMED IN DECAY WITH ANTIQUARK ABOVE

C 8 IF ENOUGH EPZ LEFT 60 TO 2

SUBROUTINE LISTIN
COMMON /JET/ K(100:2), P(100:5)
COMMON /DATA/ CHA(19), CHA(19), CHA(32)
K(100:2) = 100
DO 100 I = 1
IF (K(1:1).EQ.0) RETURN
C 1 FLAVOUR AND PT FOR FIRST QUARK

C 2 THREE-PARTICLE DECAY CHOICE OF INVARIANT MASS OF PRODUCTS 2+3

C 3 TWO-PARTICLE DECAY IN CM, TWICE TO SIMULATE THREE-PARTICLE DECAY

C 4 DECAY PRODUCTS LORENTZ TRANSFORMED TO LAB SYSTEM

SUBROUTINE EDITIN
COMMON /JET/ K(100:2), P(100:5)
COMMON /JETPAR/ ITHROW, PMIN, PMIN, THETA, PHI, BETA(3)
REAL ROT(3, 3), PHI(3)
C 1 THROW AWAY NEUTRAL OR UNSTABLE OR WITH TOO LOW PZ OR P

END

≈ 200 punched cards

Fortran code
1980: string (colour coherence) effect

Predicted unique event structure; inside & between jets. Confirmed first by JADE 1980.

Generator crucial to sell physics! (today: PS, M&M, MPI, . . . )

String motion in the event plane (without breakups)
1980: string (colour coherence) effect

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(today: PS, M&M, MPI, ...)

string motion in the event plane (without breakups)
Lund contributions

Physics:
- string fragmentation
  (& colour coherence)
- dipole showers
- backwards evolution (for ISR)
- multiparton interactions (MPI)
- colour reconnection (CR)
- matching (POWHEG style)
  & merging (CKKW-L, . . .)
- small-\(x\) evolution (CCFM, . . .)
- interleaved evolution
- heavy-ion collisions
- QCD effects for BSM

Generators:
- JETSET
- PYTHIA
- Fritiof
- Ariadne
- LDC
- DIPSY
- Lepto
- VINCIA
- DIRE
- RapGap
- HIJING
- GEANT
The workhorses

Herwig, PYTHIA and Sherpa offer convenient frameworks for LHC physics studies, covering all aspects above, but with slightly different history/emphasis:

**PYTHIA** (successor to JETSET, begun in 1978):
originated in hadronization studies,
still special interest in soft physics.

**Herwig** (successor to EARWIG, begun in 1984):
originated in coherent showers (angular ordering),
cluster hadronization as simple complement.

**Sherpa** (APACIC++/AMEGIC++, begun in 2000):
had own matrix-element calculator/generator
originated with matching & merging issues.
All full-fledged generators need to address many issues:
MCnet

Herwig
PYTHIA
Sherpa
MadGraph
Plugin:
Ariadne
DIPSY
HEJ
CEDAR:
Rivet
Professor
HepForge
LHAPDF
HepMC

- Generator development
- Services to community
- PhD student training
- Common activities

Nodes:
Manchester
CERN
Durham
Glasgow
Göttingen
Heidelberg
Karlsruhe
UC London
Louvain
Lund
Monash (Au)
SLAC (US)

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- EU-funded 2007–10, 2013–16, **2017–20**
- Generator development
- Services to community
- PhD student training
- Common activities
- Short-term studentships (3 - 6 months).
  Experimentalists welcome!
- Summer schools
  2016: DESY (w. CTEQ)
  2017: Lund, 3 - 7 July

**Send your students!**

Nodes:
Manchester
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Göttingen
Heidelberg
Karlsruhe
UC London
Louvain
Lund
SLAC (US)

Monash (Au)
Herwig++ 3.0 ⇒ **Herwig 7.0** (December 2015). Concludes 16 years effort to replace Fortran Herwig 6.

- **NLO** matched to parton showers **default** for hard process.
  - Fully **automated**: no external codes to run, no intermediate event files.
  - Choice of **subtractive** (MC@NLO type) or **multiplicative** (PowHeg type) matching.
Matchbox in Herwig 7

Matchbox
- MadGraph
- HJets++
- Recola
- ColorFull
- CVolver
- GoSam
- NJet
- OpenLoops
- VBFNLO

Matching subtractions
- ME corrections
  - QTildeShower
  - DipoleShower
  - Eikonal MPI
  - Cluster Hadronization
  - Decays
  - Built-in ME BSM & UFO

script downloads & sets up external libraries (above + more)

(figure by S. Plätzer)
Herwig++ 3.0 ⇒ **Herwig 7.0** (December 2015). Concludes 16 years effort to replace Fortran Herwig 6.

- **NLO** matched to parton showers default for hard process.
  - Fully *automated*: no external codes to run, no intermediate event files.
  - Choice of *subtractive* (MC@NLO type) or *multiplicative* (PowHeg type) matching.

- Two showers: angular ordered or **dipole**.
  - Spin correlations and QED radiation in the former.

- Facilities for parton-shower uncertainties.

- New tunes, including MB/UE.

- Vastly improved documentation, usage and installation.

- Several parallelization options.
LO → NLO ⇒ major improvements in $e^+e^-$ and pp alike.
Subtractive or multiplicative matching less important.
Ditto angular-ordered or dipole shower.
Herwig 7.1 later this year:

- **NLO multijet merging** (unitarized merging ideas).
- Loop-induced processes.
- Extended UFO-model support.
- Extended reweighting: weight vectors in HepMC files.
- Improved top decay in dipole shower.
- Interface to HEJ.
- Soft interactions and diffraction.

In the longer run:

- Code now 500k lines ⇒ need for significant restructuring.
- Amplitude-based parton showers.
Recent news:

- **DIRE shower** (see below).
- **UNNLOPS** - first results on NNLO merging.
Sherpa NNLO QCD with parton showers

W production @ NNLO+PS with SHERPA + BLACKHAT

[Höche et al. arXiv:1507.05325]

Inclusive Jet Multiplicity

\[ \sigma(W + \geq N_{\text{jet}} \text{ jets}) \text{ [pb]} \]

- fully differential hadron-level NNLO+PS simulation
  - inclusive (born-like) distribution NNLO accurate
  - 0-jet bin NNLO, 1-jet bin NLO, 2-jet bin LO, \( \geq 3 \)-jets shower accuracy
- small corrections away from Born kinematics
Sherpa 2.2 news and activities

Recent news:

- **DIRE shower** (see below).
- **UNNLOPS** - first results on NNLO merging.
- On-the-fly **scale variations** of NLO ME + PS. ME observables through interpolating grids (ApplGrid, FastNLO, MCgrid, ...).
- **Electroweak NLO corrections**, together with OpenLoops.
- Merging for loop-induced processes.
Sherpa QCD coherence test

Study events with two hard and one further softer third jets. Angular distribution of third around second probes colour coherence:

\[ \eta_2 \text{ central} \quad \eta_2 \text{ forward} \]

CMS, \[ \sqrt{s} = 7 \text{ TeV} \], jet 2–3 correlation, \( 0.8 < |\eta_2| < 2.5 \)

PYTHIA/Herwig does not quite describe data, whereas Sherpa fares much better.
Recent news:

- DIRE shower (see below).
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- Merging for loop-induced processes.

Ongoing work and plans:

- Full NNLO QCD + NLO EW (for $2 \rightarrow 1$, $2 \rightarrow 2$).
- Higher-order shower (one-loop splitting functions, sub-leading colour).
- Automated $N$-jettiness slicing.
- **New match&merge schemes** (now 8) and options.
- **Weak showers**: $q \rightarrow qZ^0$, $q \rightarrow q'W^\pm$ (also merged).

**Z/W + jets results**
The Pythia distributions are normalized such that first bin fit the data.

The shower starting scale is $\hat{s}$ for Drell-Yan and $p_\perp^2$ for QCD.

**ATLAS data**
- Drell-Yan production
- Radiation
- Combined

**MC/data**
- ATLAS data
- Drell-Yan production
- Radiation
- Combined

**N_{jet}**
- $\sigma(\geq N_{jet}), Z \rightarrow \mu^+\mu^-, p_{\perp}(\text{jet}) > 30 \text{ GeV}, |y_{\text{jet}}| < 4.4$
New match&merge schemes (now 8) and options.

Weak showers: $q \rightarrow qZ^0$, $q \rightarrow q'W^\pm$ (also merged).

Allow reweighting of rare shower branchings.

Automated parton-shower uncertainty bands.

Extended interface for external shower plugins.

Complete LHEF v3 support.

Can run Madgraph5_aMC@NLO and POWHEG BOX from within PYTHIA.

Complete Python interface.
PYTHIA 8.2 news

Reconstructed top mass, $m_W \in [75, 85]$ GeV, $p_T(\text{jets}) > 40$ GeV

- Many new colour reconnection models.
PYTHIA 8.2 news

Reconstructed top mass, $m_W \in [75, 85] \text{ GeV}$, $p_T(\text{jets}) > 40 \text{ GeV}$

- Many new colour reconnection models.
- Double onium production.
- New model for hard diffraction.
- Several new tunes; Monash new default.

Ongoing work and plans:
- $\gamma \gamma$, $\gamma p$ and $ep$.
- Total, elastic and diffractive cross sections.
- Improved showers and hadronization.
Match and merge strategies

Input from:
Madgraph5_aMC@NLO
POWHEG BOX
ALPGEN
COMIX/Sherpa
NLOJET++
JETRAD
HJETS++
BlackHat
GoSam
Helac
OpenLoops
VBFNLO
CalpHEP/CompHEP
...

CKKW
CKKW-L
MLM
UMEPS
MC@NLO
POWHEG
MENLOPS
MEPS@NLO
NL^3
UNLOPS
FxFx
NNLOPS
MiNLO
UN^2LOPS
MIN^2LOPS

Intense activity, no “final word”.

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Combination strategies

Big flexibility, but different baseline “world view”:

MadGraph:
- ME gen
- M&M
- Event gen

Herwig, Sherpa:
- ME gen
- M&M
- Event gen

Pythia:
- ME gen
- Les Houches
- M&M
- Event gen

Event gen = ISR + FSR + MPI + BBR + CR + hadronization + …
≠ “hadronizer”

ME and Event Generators both indispensable
VINCI: an Interleaved Antennae shower

Markovian process: no memory of path to reach current state.

Based on antenna factorization of amplitudes and phase space.

Smooth ordering fills whole phase space.

Step-by-step reweighting to new matrix elements:
\[ Z \rightarrow Zj \rightarrow Zjj \rightarrow Zjjj \] (also Sudakov), e.g.
\[ W = \frac{|M_{Zj}|^2}{\sum_i a_i |M_Z|^2_i} \]

Replaces PYTHIA normal showers; recent release.
Joint Sherpa/PYTHIA development, but separate implementations, means technically well tested.

“Midpoint between dipole and parton shower”, dipole with emitter & spectator, but not quite CS ones: unified initial–initial, initial–final, final–initial, final–final.

Soft term of kernels in all dipole types is less singular

\[
\frac{1}{1 - z} \to \frac{1 - z}{(1 - z)^2 + \frac{p^2}{M^2}}
\]
Apologies: will not cover

- **High Energy Jets (HEJ):** BFKL-inspired description of well-separated multijets, with approximate matrix elements and virtual corrections.
- **Deductor:** improved handling of colour, partitioned dipoles, all final partons share recoil, $q^2/E$ evolution variable.
- **Geneva:** Soft Collinear Effective Theory resummed (exclusive) $n$-jet rates as starting point for showers.
- **Ariadne:** first dipole parton shower program.
- **DIPSY:** evolution and collision of dipoles in transverse space.
- **revived Fritiof:** overlayed modified pp collisions to model pA.
- **EPOS:** pp/pA/AA, MPI + strings, saturation, thermalized core separate from corona, hydrodynamical evolution.
- **DPMJET, QGSJET, SIBYLL:** other pp/pA/AA/cosmic ray.
- ...
Summary and Outlook

- Increased ME calculational capability: legs and loops.
- Match and merge approaches still steadily developing. Generators typically offer several options. Spread between approaches one measure of uncertainty.
- Continued/increased interest in parton shower development, with each generator offering several options.
- Automated uncertainty bands for scale choices etc.
- Many challenges remaining in soft physics, pA, AA: diffraction, colour reconnection, collective effects, ... 
- Generators have gone from fringe activity for a few to a mainstream part of phenomenology research.
Thank You!