Monte Carlo Tools

Torbjörn Sjöstrand
Lund University

1. (Monday) Introduction and Overview; Parton Showers
2. (yesterday) Matching Issues; Multiple Parton Interactions
3. (today) Hadronization; LHC predictions; Generator News
Hadronization/Fragmentation models

Perturbative $\rightarrow$ nonperturbative $\implies$ not calculable from first principles!

Model building = ideology + “cookbook”

Common approaches:

1) **String** Fragmentation
   (most ideological)

2) **Cluster** Fragmentation
   (simplest?)

3) **Independent** Fragmentation
   (most cookbook)

4) Local Parton–Hadron Duality
   (limited applicability)

Best studied in
$e^+e^- \rightarrow \gamma^*/Z^0 \rightarrow q\bar{q}$
The Lund String Model

In QED, field lines go all the way to infinity

since photons cannot interact with each other.

Potential is simply additive:

\[ V(x) \propto \sum_i \frac{1}{|x - x_i|} \]
In QCD, for large charge separation, field lines seem to be compressed to tubelike region(s) ⇒ **string(s)**

by self-interactions among soft gluons in the “vacuum”. (Non-trivial ground state with quark and gluon “condensates”. Analogy: vortex lines in type II superconductor)

Gives linear confinement with string tension:

\[ F(r) \approx \text{const} = \kappa \approx 1 \text{ GeV/fm} \quad \iff \quad V(r) \approx \kappa r \]

Separation of transverse and longitudinal degrees of freedom ⇒ simple description as 1+1-dimensional object – string – with Lorentz invariant formalism
Linear confinement confirmed e.g. by quenched lattice QCD

\[ V(r) \approx -\frac{4 \alpha_s}{3} \frac{1}{r} + \kappa r \approx -0.13 \frac{1}{r} + r \]

(for \( \alpha_s \approx 0.5 \), \( r \) in fm and \( V \) in GeV)

\( V(0.4 \text{ fm}) \approx 0 \): Coulomb important for internal structure of hadrons, not for particle production (?)
Real world (??, or at least unquenched lattice QCD) \[ \Rightarrow \text{nonperturbative string breakings } gg \ldots \rightarrow q\bar{q} \]

Coulomb part

V(r)

quenched QCD

full QCD

simplified colour representation:
Repeat for large system ⇒ *Lund model* which neglects Coulomb part:

\[
\frac{dE}{dz} = \frac{dp_z}{dz} = \frac{dE}{dt} = \frac{dp_z}{dt} = \kappa
\]

Motion of quarks and antiquarks in a q\(\bar{q}\) system:

![Diagram showing motion of quarks and antiquarks in a q\(\bar{q}\) system](image)

gives simple but powerful picture of hadron production
(with extensions to massive quarks, baryons, . . .)
How does the string break?

$m_{\bot q'} = 0$

$m_{\bot q'} > 0$

String breaking modelled by tunneling:

$$\mathcal{P} \propto \exp \left( -\frac{\pi m_{\bot q}^2}{\kappa} \right) = \exp \left( -\frac{\pi p_{\bot q}^2}{\kappa} \right) \exp \left( -\frac{\pi m_{\bot q}^2}{\kappa} \right)$$

1) common Gaussian $p_{\bot}$ spectrum

2) suppression of heavy quarks $u\bar{u} : d\bar{d} : s\bar{s} : c\bar{c} \approx 1 : 1 : 0.3 : 10^{-11}$

3) diquark $\sim$ antiquark $\Rightarrow$ simple model for baryon production

Hadron composition also depends on spin probabilities, hadronic wave functions, phase space, more complicated baryon production, . . .

$\Rightarrow$ “moderate” predictivity (many parameters!)
Fragmentation starts in the middle and spreads outwards:

but breakup vertices causally disconnected
⇒ can proceed in arbitrary order
⇒ left–right symmetry

\[ P(1, 2) = P(1) \times P(1 \to 2) = P(2) \times P(2 \to 1) \]

⇒ Lund symmetric fragmentation function

\[ f(z) \propto (1 - z)^a \exp(-bm^2_{\perp}/z)/z \]

\[ m^2_T = 0.25 \]
\[ m^2_T = 1 \]
\[ m^2_T = 4 \]
The iterative ansatz

\[ q_0, p_{\perp 0}, p^+ \rightarrow q_0 \bar{q}_1, p_{\perp 0} - p_{\perp 1}, z_1 p^+ \]

\[ q_1 \bar{q}_1 \rightarrow q_1 \bar{q}_2, p_{\perp 1} - p_{\perp 2}, z_2 (1 - z_1) p^+ \]

\[ q_2 \bar{q}_2 \rightarrow q_2 \bar{q}_3, p_{\perp 2} - p_{\perp 3}, z_3 (1 - z_2) (1 - z_1) p^+ \]

and so on until joining in the middle of the event

Scaling in lightcone \( p_{\pm} = E \pm p_z \) (for \( q\bar{q} \) system along \( z \) axis)
implies flat central rapidity plateau + some endpoint effects:

\[ \langle n_{\text{ch}} \rangle \approx c_0 + c_1 \ln E_{\text{cm}}, \sim \text{Poissonian multiplicity distribution} \]
The most characteristic feature of the Lund model

Gluon = kink on string, carrying energy and momentum

Gluon/ quark = 2, cf. QCD $N_C/C_F = 9/4$, $\rightarrow$ 2 for $N_C \rightarrow \infty$

No new parameters introduced for gluon jets!, so:

- Few parameters to describe energy-momentum structure!
- Many parameters to describe flavour composition!
Independent fragmentation

Based on a similar iterative ansatz as string, but

\[ q = g + q + \bar{q} + g \]

String effect (JADE, 1980) ≈ coherence in nonperturbative context

Further numerous and detailed tests at LEP favour string picture . . .

. . . but much is still uncertain when moving to hadron colliders.
The HERWIG Cluster Model

“Preconfinement”: colour flow is local in coherent shower evolution

1) Introduce forced $g \rightarrow q\bar{q}$ branchings
2) Form colour singlet clusters
3) Clusters decay isotropically to 2 hadrons according to phase space weight $\sim (2s_1 + 1)(2s_2 + 1)(2p^*/m)$

simple and clean, but ...
1) Tail to very large-mass clusters (e.g. if no emission in shower); if large-mass cluster → 2 hadrons then incorrect hadron momentum spectrum, crazy four-jet events
⇒ split big cluster into 2 smaller along “string” direction; daughter-mass spectrum ⇒ iterate if required;
~ 15% of primary clusters are split, but give ~ 50% of final hadrons

2) Isotropic baryon decay inside cluster
⇒ splittings $g \rightarrow q\bar{q} + \bar{q}q$

3) Too soft charm/bottom spectra
⇒ anisotropic leading-cluster decay

4) Charge correlations still problematic
⇒ all clusters anisotropic (?)

5) Sensitivity to particle content
⇒ only include complete multiplets
### String vs. Cluster

**Table: Comparison of Models**

<table>
<thead>
<tr>
<th></th>
<th>PYTHIA</th>
<th>HERWIG</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Program model</strong></td>
<td>string</td>
<td>cluster</td>
</tr>
<tr>
<td><strong>Energy–momentum picture</strong></td>
<td>powerful predictive</td>
<td>simple unpredictive</td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
<td>few</td>
<td>many</td>
</tr>
<tr>
<td><strong>Flavour composition</strong></td>
<td>messy</td>
<td>simple</td>
</tr>
<tr>
<td><strong>Parameters</strong></td>
<td>unpredictable many</td>
<td>in-between few</td>
</tr>
</tbody>
</table>

"There ain’t no such thing as a parameter-free *good* description"
Local Parton–Hadron Duality

Analytic approach:
Run shower down to to $Q \approx \Lambda_{QCD}$
(or $m_{\text{hadron}}$, if larger)

“Hard Line”: each parton $\equiv$ one hadron

“Soft Line”: local hadron density
$\propto$ parton density

describes momentum spectra $dn/dxp$
and semi-inclusive particle flow,
but fails for identified particles

+ “renormalons” (power corrections)
$\langle 1 - T \rangle = a \alpha_s(E_{cm}) + b \alpha_s^2(E_{cm})$
$+ c/E_{cm}$

Not Monte Carlo, not for arbitrary quantities
Decays

Unspectacular/ungrateful but necessary: this is where most of the final-state particles are produced! Involves hundreds of particle kinds and thousands of decay modes.

e.g.

- $B^{*0} \rightarrow B^0 \gamma$: electromagnetic decay
- $B^0 \rightarrow \bar{B}^0$ mixing (weak)
- $\bar{B}^0 \rightarrow D^{*+} \bar{\nu}_e e^-$: weak decay, displaced vertex, $|M|^2 \propto (p_B p_{\bar{\nu}})(p_e p_{D^{*}})$
- $D^{*+} \rightarrow D^0 \pi^+$: strong decay
- $D^0 \rightarrow \rho^+ K^-$: weak decay, displaced vertex, $\rho$ mass smeared
- $\rho^+ \rightarrow \pi^+ \pi^0$: $\rho$ polarized, $|M|^2 \propto \cos^2 \theta$ in $\rho$ rest frame
- $\pi^0 \rightarrow e^+ e^- \gamma$: Dalitz decay, $m(e^+ e^-)$ peaked

Dedicated programs, with special attention to polarization effects:
- EVTGEN: $B$ decays
- TAUOLA: $\tau$ decays
Jet Universality

Question: are jets the same in all processes?
Answer 1: no, at LEP mainly quarks jets, often b/c, at LHC mainly gluons, if quarks then mainly u/d.
Answer 2: no, perturbative evolution gives calculable differences.
Answer 3: (string) hadronization mechanism assumed universal, but is not quite.

\[ E \frac{d^3 \sigma}{d^3 p} : \text{Dependence on proton } P_T \]

so discrepancies

\[ \frac{P_{qq}}{P_q} = 0.1 \text{ at LEP, } \frac{P_s}{P_u} = 0.3 \text{ at LEP, } \]

\[ \frac{P_{qq}}{P_q} = 0.05 \text{ at HERA, } \frac{P_s}{P_u} = 0.2 \text{ at HERA} \]

Reasons? HERA dominated by “beam jets”, so

- Less perturbative evolution ⇒ strings less “wrinkled”?
- Many overlapping strings ⇒ collective phenomena?
Momentum distribution of charged particles in **gluon jets**. HERWIG 5.6 predictions are in a good agreement with CDF data. PYTHIA 6.115 produces slightly more particles in the region around the peak of distribution.

Momentum distribution of charged particles in **quark jets**. Both HERWIG and PYTHIA produce more particles in the central region of distribution.

Both PYTHIA and HERWIG predict more charged particles than the data for quark jets!
Extrapolations to LHC
Recall
\[ \frac{d\sigma}{dp_\perp^2} \propto \frac{1}{p_\perp^4} \rightarrow \frac{1}{(p_\perp^2 + p_\perp^2)^2} \]

Larger collision energy
\[ \Rightarrow \text{probe parton (≈ gluon)} \]
density at smaller \( x \)
\[ \Rightarrow \text{smaller colour screening length } d \]
\[ \Rightarrow \text{larger } p_{\perp 0} \]

Post-HERA PDF fits steeper at small \( x \)
\[ \Rightarrow \text{stronger energy dependence} \]

Current PYTHIA 8 default, tied to CTEQ 5L, is
\[ p_{\perp 0}(s) = 2.25 \text{ GeV} \left( \frac{E_{\text{cm}}}{1.8 \text{ TeV}} \right)^{0.24} \]
LHC predictions: pp collisions at $\sqrt{s} = 14$ TeV

PYTHIA6.214 - tuned
PYTHIA6.214 - default
PHOJET1.12

- PYTHIA models favour $\ln^2(s)$;
- PHOJET suggests a $\ln(s)$ dependence.
LHC predictions: JIMMY4.1 Tunings A and B vs. PYTHIA6.214 – ATLAS Tuning (DC2)

Transverse $< N_{\text{ch}} >$

- JIMMY4.1 - Tuning A
- JIMMY4.1 - Tuning B
- PYTHIA6.214 - ATLAS Tuning
- CDF data

$P_t$ (leading jet in GeV)

Tevatron

x 5

x 4

x 3

LHC
**UE tunings: Pythia vs. Jimmy**

- **PTJIM = 4.9**
  \[ \text{PTJIM} = 2.8 \times (14/1.8)^{0.27} \]

- Energy dependent PTJIM generates UE predictions similar to the ones generated by PYTHIA6.2 - ATLAS.
Data on the charged particle scalar $p_T$ sum density, $dPT/d\eta d\phi$, as a function of the leading jet $p_T$ for the "toward", "away", and "transverse" regions compared with PYTHIA Tune A.
Min-Bias “Associated” Charged Particle Density

Shows the “associated” charged particle density in the “transverse” region as a function of $\text{PTmax}$ for charged particles ($p_T > 0.5 \text{ GeV/c}, |\eta| < 1$, not including $\text{PTmax}$) for “min-bias” events at 1.96 TeV from PYTHIA Tune A, Tune S320, Tune N324, and Tune P329 at the particle level (i.e. generator level).

Extrapolations of PYTHIA Tune A, Tune DW, Tune DWT, Tune S320, Tune P329, and pyATLAS to the LHC.

CMS-QCD Meeting
August 4, 2009
Rick Field – Florida/CDF/CMS
Page 22
Charged Particle Density: $dN/d\eta$

RDF LHC Prediction!

- Charged particle (all $p_T$) pseudo-rapidity distribution, $dN_{\text{ch}}/d\eta$, at 1.96 TeV for inelastic non-diffractive collisions from PYTHIA Tune A, Tune DW, Tune S320, and Tune P324.

- Extrapolations (all $p_T$) of PYTHIA Tune A, Tune DW, Tune S320, Tune P324. and ATLAS to the LHC.
We are making good progress in understanding and modeling the "underlying event". RHIC data at 200 GeV are very important!

The new Pythia $p_T$ ordered tunes (py64 S320 and py64 P329) are very similar to Tune A, Tune AW, and Tune DW. At present the new tunes do not fit the data better than Tune AW and Tune DW. However, the new tune are theoretically preferred!

It is clear now that the default value PARP(90) = 0.16 is not correct and the value should be closer to the Tune A value of 0.25.

The new and old PYTHIA tunes are beginning to converge and I believe we are finally in a position to make some legitimate predictions at the LHC!

All tunes with the default value PARP(90) = 0.16 are wrong and are overestimating the activity of min-bias and the underlying event at the LHC! This includes all my "T" tunes and the ATLAS tunes!

Need to measure "Min-Bias" and the "underlying event" at the LHC as soon as possible to see if there is new QCD physics to be learned!
Event Generator Developments
The Bigger Picture

- ME Generator
- ME Expression
- SUSY/... spectrum calculation
- Process Selection
- Resonance Decays
- Parton Showers
- Multiple Interactions
- Beam Remnants
- Hadronization
- Ordinary Decays
- Detector Simulation
- Phase Space Generation
- PDF Library
- τ Decays
- B Decays

need standardized interfaces (LHA/LHEF, LHAPDF, SUSY LHA, HepMC, ...)

- PDF Library
- τ Decays
- B Decays
## PDG Particle Codes

### A. Fundamental objects

<table>
<thead>
<tr>
<th></th>
<th>1 d</th>
<th>11 e⁻</th>
<th>21 g</th>
<th>32 (Z')⁰</th>
<th>(\text{add – sign for antiparticle, where appropriate})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>u</td>
<td>12 (\nu_e)</td>
<td>22 (\gamma)</td>
<td>33 (Z'')⁰</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>s</td>
<td>13 (\mu^-)</td>
<td>23 (Z)⁰</td>
<td>34 (W'^+)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>c</td>
<td>14 (\nu_\mu)</td>
<td>24 (W^+)</td>
<td>35 (H^0)</td>
<td>(\text{H}^+) + diquarks, SUSY, technicolor, …</td>
</tr>
<tr>
<td>5</td>
<td>b</td>
<td>15 (\tau^-)</td>
<td>25 (h^0)</td>
<td>36 (A^0)</td>
<td>(\text{Graviton})</td>
</tr>
<tr>
<td>6</td>
<td>t</td>
<td>16 (\nu_\tau)</td>
<td>37 (H^0)</td>
<td>39 (\text{Graviton})</td>
<td></td>
</tr>
</tbody>
</table>

### B. Mesons

\(100 |q_1| + 10 |q_2| + (2s + 1)\) with \(|q_1| \geq |q_2|\)

<table>
<thead>
<tr>
<th></th>
<th>111 (\pi^0)</th>
<th>311 (K^0)</th>
<th>130 (K_L^0)</th>
<th>221 (\eta^0)</th>
<th>411 (D^+)</th>
<th>431 (D_{S}^+)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>211 (\pi^+)</td>
<td>321 (K^+)</td>
<td>310 (K_S^0)</td>
<td>331 (\eta'^0)</td>
<td>421 (D^0)</td>
<td>443 (J/\psi)</td>
</tr>
</tbody>
</table>

### C. Baryons

\(1000 q_1 + 100 q_2 + 10 q_3 + (2s + 1)\)

with \(q_1 \geq q_2 \geq q_3\), or \(\Lambda\)-like \(q_1 \geq q_3 \geq q_2\)

<table>
<thead>
<tr>
<th></th>
<th>2112 n</th>
<th>3122 (\Lambda^0)</th>
<th>2224 (\Delta^{++})</th>
<th>3214 (\Sigma^{*0})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2212 p</td>
<td>3212 (\Sigma^0)</td>
<td>1114 (\Delta^-)</td>
<td>3334 (\Omega^-)</td>
</tr>
</tbody>
</table>
The workhorses: what are the differences?

HERWIG, PYTHIA and SHERPA intend to offer a convenient framework for LHC physics studies, but with slightly different emphasis:

**PYTHIA (successor to JETSET, begun in 1978):**
- originated in hadronization studies: the Lund string
- leading in development of multiple parton interactions
- pragmatic attitude to showers & matching
- the first multipurpose generator: machines & processes

**HERWIG (successor to EARWIG, begun in 1984):**
- originated in coherent-shower studies (angular ordering)
- cluster hadronization & underlying event pragmatic add-on
- large process library with spin correlations in decays

**SHERPA (APACIC++/AMEGIC++, begun in 2000):**
- own matrix-element calculator/generator
- extensive machinery for CKKW matching to showers
- leans on PYTHIA for MPI and hadronization
On To C++

Currently HERWIG and PYTHIA are successfully being used, also in new LHC environments, using C++ wrappers

Q: Why rewrite?
   A1: Need to clean up!
   A2: Fortran 77 is limiting

Q: Why C++?
   A1: All the reasons for ROOT, Geant4, . . .
      (“a better language”, industrial standard, . . .)
   A2: Young experimentalists will expect C++
      (educational and professional continuity)
   A3: Only game in town! Fortran 90

So far mixed experience:
• 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
C++ Main Players

PYTHIA 7 project $\implies$ ThePEG

Toolkit for High Energy Physics Event Generation
(L. Lönnblad; S. Gieseke, D. Grellscheid, P. Richardson)

SHERPA: new program, written from scratch
operational since $\sim$2006 (now 1.1.3)
(F. Krauss; T. Gleisberg, S. Hoeche, M. Schoenherr, S. Schumann,
F. Siegert, J. Winter, JHEP 0902 (2009) 007)

HERWIG++: complete reimplementation
November 2007: first full-fledged version (2.1; now 2.3.2)
(P. Richardson; M. Bähr, S. Gieseke, M. Gigg, D. Grellscheid,
K. Hamilton, O. Latunde-Dada, S. Plätzer, M.H. Seymour,

PYTHIA 8: complete reimplementation
October 2007: first full-fledged version (8.100; now 8.125)
MCnet

• Funded by EU Marie Curie training network
• Approved for four years starting 1 Jan 2007
• Collects HERWIG, SHERPA and PYTHIA
  • Also ThePEG, ARIADNE, VINCIA, . . .
• Also generator validation (RIVET) and tuning (PROFESSOR)
  (CERN, Durham, Lund, Karlsruhe, UC London; leader: Mike Seymour)
• 4 postdocs & 2 graduate students: generator development and tuning

  • Annual Monte Carlo school:
    Durham, UK, 18 – 20 April 2007
  CTEQ – MCnet, Debrecen, Hungary, 8 – 16 August 2008
    Lund, Sweden, 1 – 4 July 2009
  CTEQ – MCnet, Karlsruhe, Germany, July – August 2010
  • Support for other such schools, e.g.
  Physics at the Terascale Monte Carlo Schools, Germany
Short-term studentships:

for Ph.D. students
in theory or experiment,
33 @ 4 months each

formulate your project,
related to your Ph.D. thesis

applications processed
every three months;
next deadline 7 September

must move to another country;
non-EU participation allowed

**3-6 month** fully funded studentships for current PhD students at one of the MCnet nodes. An excellent opportunity to really understand the Monte Carlos you use!

**Application rounds every 3 months.**

for details go to: www.montecarlonet.org
Some differences between PYTHIA 6.4 and 8.1

Old features definitely removed include, among others:
- independent fragmentation
- mass-ordered showers

Features omitted so far include, among others:
- ep, $\gamma p$ and $\gamma\gamma$ beam configurations
- some processes, especially Technicolor

New features, not found in 6.4:
- some new processes, e.g. for extra dimensions & unparticles
- possibility to use one PDF set for hard process and another for rest
- interleaved $p_{\perp}$-ordered MI + ISR + FSR evolution
- richer mix of underlying-event processes ($\gamma$, J/$\psi$, DY, ...)
- possibility for two selected hard interactions in same event
- rescattering in MPI (preliminary)
- diffraction as Pomeron-proton collisions with MPI
- elastic scattering with Coulomb term (optional)
- updated decay data
- plan to have built-in CKKW-L and NLO matching
Trying Out PYTHIA 8.1

For subversion xx (currently 25)

- Download pythia81xx.tgz from
  [http://home.thep.lu.se/~torbjorn/Pythia.html](http://home.thep.lu.se/~torbjorn/Pythia.html)
- `tar xvfz pythia81xx.tgz` to unzip and expand
- `cd pythia81xx` to move to new directory
- `./configure` ... needed for external libraries + debug/shared
  (see README, libraries: HepMC, LHAPDF, FastJet)
- `make` will compile in ~ 3 minutes
  (for archive library, same amount extra for shared)
- The `htmldoc/pythia8100.pdf` file contains A Brief Introduction
- Open `htmldoc/Welcome.html` in a web browser for the full manual
- Install the `phpdoc/` directory on a webserver and open
  `phpdoc/Welcome.html` in a web browser for an interactive manual
- The examples subdirectory contains > 30 sample main programs:
  standalone, link to libraries, semi-internal processes, ...
  (make mainNN and then `./mainNN.exe > outfile`)
- A Worksheet (on the web pages) contains step-by-step instructions and exercises how to write and run a main program
Availability of exact calculations (hadron colliders)

- Fixed order matrix elements ("parton level") are exact to a given perturbative order. 
- Important to understand limitations:
  Only tree-level fully automated, 1-loop-level ongoing.

(Next few slides stolen from Frank Krauss, with permission)
Parton-Level Simulations

Stating the problem(s)

- Multi-particle final states for signals & backgrounds.
- Need to evaluate $d\sigma_N$:

$$\int_{\text{cuts}} \left[ \prod_{i=1}^{N} \frac{d^3q_i}{(2\pi)^3 2E_i} \right] \delta^4 \left( p_1 + p_2 - \sum_i q_i \right) |M_{p_1p_2\rightarrow N}|^2.$$ 

- Problem 1: Factorial growth of number of amplitudes.
- Problem 2: Complicated phase-space structure.
- Solutions: Numerical methods.
Basic ideas of efficient ME calculation

Need to evaluate $|\mathcal{M}|^2 = \left| \sum_i \mathcal{M}_i \right|^2$

- Obvious: Traditional textbook methods (squaring, completeness relations, traces) fail
  $\implies$ result in proliferation of terms ($\mathcal{M}_i\mathcal{M}_j^*$)
  $\implies$ Better: Amplitudes are complex numbers,
  $\implies$ add them before squaring!

- Remember: spinors, gamma matrices have explicit form
  could be evaluated numerically (brute force)
  But: Rough method, lack of elegance, CPU-expensive

Helicity method

- Introduce basic helicity spinors (needs to “gauge”-vectors)
- Write everything as spinor products, e.g.
  $\bar{u}(p_1, h_1)u(p_2, h_2) = \text{complex numbers}$.

Completeness rel’ns: $(\not h + m) \implies \frac{1}{2} \sum_h \left[ \left( 1 + \frac{m^2}{p^2} \right) \bar{u}(p, h) u(p, h) + \left( 1 - \frac{m^2}{p^2} \right) \bar{\nu}(p, h) \nu(p, h) \right]$

- There are other genuine expressions . . .
- Translate Feynman diagrams into “helicity amplitudes”:
  complex-valued functions of momenta & helicities.
- Spin-correlations etc. nearly come for free.
Taming the factorial growth

- In the helicity method
  - Reusing pieces: *Calculate only once!*
  - Factoring out: *Reduce number of multiplications!*

Implemented as a-posteriori manipulations of amplitudes.

- Better method: Recursion relations (recycling built in).
  Best candidate so far: Off-shell recursions

*(Dyson-Schwinger, Berends-Giele etc.)*
Colour-dressing: Fighting factorial growth in colour

- In principle: sampling over colours improves situation.

  (But still, e.g. naively \(\sim (n-1)!\) permutations/colour-ordering for \(n\) external gluons).

- Improved scheme: colour dressing.


- Works very well with Berends-Giele recursions:


<table>
<thead>
<tr>
<th>Final State</th>
<th>BG CO</th>
<th>CD</th>
<th>BCF CO</th>
<th>CD</th>
<th>CSW CO</th>
<th>CD</th>
</tr>
</thead>
<tbody>
<tr>
<td>2g</td>
<td>0.24</td>
<td>0.28</td>
<td>0.28</td>
<td>0.33</td>
<td>0.31</td>
<td>0.26</td>
</tr>
<tr>
<td>3g</td>
<td>0.45</td>
<td>0.48</td>
<td>0.42</td>
<td>0.51</td>
<td>0.57</td>
<td>0.55</td>
</tr>
<tr>
<td>4g</td>
<td>1.20</td>
<td>1.04</td>
<td>0.84</td>
<td>1.32</td>
<td>1.63</td>
<td>1.75</td>
</tr>
<tr>
<td>5g</td>
<td>3.78</td>
<td>2.69</td>
<td>2.59</td>
<td>7.26</td>
<td>5.95</td>
<td>5.96</td>
</tr>
<tr>
<td>6g</td>
<td>14.2</td>
<td>7.19</td>
<td>11.9</td>
<td>59.1</td>
<td>27.8</td>
<td>30.6</td>
</tr>
<tr>
<td>7g</td>
<td>58.5</td>
<td>23.7</td>
<td>73.6</td>
<td>646</td>
<td>146</td>
<td>195</td>
</tr>
<tr>
<td>8g</td>
<td>276</td>
<td>82.1</td>
<td>597</td>
<td>8690</td>
<td>919</td>
<td>1890</td>
</tr>
<tr>
<td>9g</td>
<td>1450</td>
<td>270</td>
<td>5900</td>
<td>12700</td>
<td>6310</td>
<td>29700</td>
</tr>
<tr>
<td>10g</td>
<td>7960</td>
<td>864</td>
<td>64000</td>
<td>-</td>
<td>48900</td>
<td>-</td>
</tr>
</tbody>
</table>

Time [s] for the evaluation of \(10^4\) phase space points, sampled over helicities & colour.
Efficient phase space integration

(“Amateurs study strategy, professionals study logistics”)

- Democratic, process-blind integration methods:
  - Rambo/Mambo: Flat & isotropic
  - HAAG/Sarge: Follows QCD antenna pattern

- Multi-channeling: Each Feynman diagram related to a phase space mapping (= "channel"), optimise their relative weights.

- Main problem: practical only up to $\mathcal{O}(10^k)$ channels.

- Some improvement by building phase space mappings recursively: More channels feasible, efficiency drops a bit.
Colour-dressed Berends-Giele amplitudes in the SM.
Fully recursive phase space generation.
Example results (cross sections):

<table>
<thead>
<tr>
<th>$n$/$\sqrt{s}$ [GeV]</th>
<th>$n=8$ 1500</th>
<th>$n=9$ 2000</th>
<th>$n=10$ 2500</th>
<th>$n=11$ 3500</th>
<th>$n=12$ 5000</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMIX Maltoni (2002)</td>
<td>0.755(3)</td>
<td>0.305(2)</td>
<td>0.101(7)</td>
<td>0.057(5)</td>
<td>0.019(2)</td>
</tr>
<tr>
<td>ALPGEN</td>
<td>0.70(4)</td>
<td>0.30(2)</td>
<td>0.097(6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>σ [$\mu$b]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b\bar{b}$ + QCD jets</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>COMIX</td>
<td>470.8(5)</td>
<td>8.83(2)</td>
<td>1.826(8)</td>
<td>0.459(2)</td>
<td>0.1500(8)</td>
</tr>
<tr>
<td>ALPGEN</td>
<td>470.6(6)</td>
<td>8.83(1)</td>
<td>1.822(9)</td>
<td>0.459(2)</td>
<td>0.150(2)</td>
</tr>
<tr>
<td>AMEGIC++</td>
<td>470.3(4)</td>
<td>8.84(2)</td>
<td>1.817(6)</td>
<td>0.459(2)</td>
<td>0.150(2)</td>
</tr>
<tr>
<td>Number of jets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>470.8(5)</td>
<td>8.83(2)</td>
<td>1.826(8)</td>
<td>0.459(2)</td>
<td>0.1500(8)</td>
</tr>
<tr>
<td>2</td>
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<td>8.83(1)</td>
<td>1.822(9)</td>
<td>0.459(2)</td>
<td>0.150(2)</td>
</tr>
<tr>
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<td>0.459(2)</td>
<td>0.150(2)</td>
</tr>
<tr>
<td>4</td>
<td>470.8(5)</td>
<td>8.83(2)</td>
<td>1.826(8)</td>
<td>0.459(2)</td>
<td>0.1500(8)</td>
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<tr>
<td>5</td>
<td>470.6(6)</td>
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<td>0.459(2)</td>
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<tr>
<td>6</td>
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<td>8.84(2)</td>
<td>1.817(6)</td>
<td>0.459(2)</td>
<td>0.1500(8)</td>
</tr>
</tbody>
</table>
FeynRules: implementing new models

**Aim**

- Portable, transparent & reproducible implementation of (nearly arbitrary) new physics models.
- In most codes: New models given by new particles, their properties & interactions.
- Output to standard ME generators enabled (MADGRAPH, SHERPA, ...)
- Various models already implemented & validated for a list: [http://feynrules.phys.ucl.ac.be](http://feynrules.phys.ucl.ac.be)
Event Physics Overview

Repetition: from the “simple” to the “complex”
or from “calculable” at large virtualities to “modelled” at small

Matrix elements (ME):

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

2) Resonance decays:
includes correlations.

Parton Showers (PS):

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, $\tau$, charm, …
Read More

These lectures (and more):

http://home.thep.lu.se/~torbjorn/ and click on “Talks”

Many presentations at the MCnet Summer School, Lund, July 2009:

http://conference.ippp.dur.ac.uk/conferenceOtherViews.py?view=ippp&confId=264#2009-07-01

Many presentations at the CTEQ–MCnet Summer School, Aug 2008:

http://conference.ippp.dur.ac.uk/conferenceOtherViews.py?view=ippp&confId=156

Bryan Webber, MCnet school, Durham, April 2007:

http://www.hep.phy.cam.ac.uk/theory/webber/

Peter Richardson, CTEQ Summer School lectures, July 2006:

http://www.ippp.dur.ac.uk/~richardn/talks/

Steve Mrenna, CTEQ Summer School lectures, June 2004:

http://www.phys.psu.edu/~cteq/schools/summer04/mrenna/mrenna.pdf


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?
Final words

“Good,” said the First Speaker. “And tell me, what do you think of all this. A finished work of art, is it not?”

“Definitely!”

“Wrong! It is not.” This, with sharpness. “It is the first lesson you must unlearn. The Seldon Plan is neither complete nor correct. Instead it is merely the best that could be done at the time.”

— And Now You Don’t (Second Foundation), Isaac Asimov, 1949

But it often happens that the physics simulations provided by the Monte Carlo generators carry the authority of data itself. They look like data and feel like data, and if one is not careful they are accepted as if they were data.

J.D. Bjorken

from a talk given at the 75th anniversary celebration of the Max-Planck Institute of Physics, Munich, Germany, December 10th, 1992. As quoted in: Beam Line, Winter 1992, Vol. 22, No. 4