QCD and Event Generators

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The structure of an event

Warning: schematic only, everything simplified, nothing to scale, ...
Hard subprocess: described by matrix elements
Resonance decays: correlated with hard subprocess
Initial-state radiation: spacelike parton showers
Final-state radiation: timelike parton showers
Multiple parton–parton interactions ...
...with its initial- and final-state radiation
Beam remnants and other outgoing partons
Everything is connected by colour confinement strings
Recall! Not to scale: strings are of hadronic widths
The strings fragment to produce primary hadrons
Many hadrons are unstable and decay further.
These are the particles that hit the detector
A tour to Monte Carlo

...because Einstein was wrong: God does throw dice!
Quantum mechanics: amplitudes $\implies$ probabilities
Anything that possibly can happen, will! (but more or less often)
The Monte Carlo method

Want to generate events in as much detail as Mother Nature
\[ \implies \text{get average } and \text{ fluctuations right} \]
\[ \implies \text{make random choices, } \sim \text{ as in nature} \]

\[ \sigma_{\text{final state}} = \sigma_{\text{hard process}} P_{\text{tot, hard process}} \rightarrow \text{final state} \]
(appropriately summed & integrated over non-distinguished final states)

where \( P_{\text{tot}} = P_{\text{res}} P_{\text{ISR}} P_{\text{FSR}} P_{\text{MIP}} P_{\text{remnants}} P_{\text{hadronization}} P_{\text{decays}} \)

with \( P_i = \prod_j P_{ij} = \prod_j \prod_k P_{ijk} = \ldots \) in its turn

\[ \implies \text{divide and conquer} \]

an event with \( n \) particles involves \( \mathcal{O}(10^n) \) random choices,
(flavour, mass, momentum, spin, production vertex, lifetime, \ldots)

LHC: \( \sim 100 \) charged and \( \sim 200 \) neutral (+ intermediate stages)
\[ \implies \text{several thousand choices} \]
(of \( \mathcal{O}(100) \) different kinds)
The Big Picture: Putting It Together

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

Process Selection
- Resonance Decays
- Parton Showers
- Multiple Interactions
- Beam Remnants

Hadronization
- Ordinary Decays
- \( \tau \) Decays
- \( B \) Decays

Detector Simulation

ME Generator

ME Expression

SUSY/... spectrum calculation

Phase Space Generation

PDF Library
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
MCnet: Competitors and Collaborators

EU Marie Curie training network funded 2007 – 2010:
HERWIG, PYTHIA SHERPA,
ThePEG, ARIADNE, VINCIA, ...
Transition Fortran → C++
and LHC preparations.
Also generator validation (RIVET)
and tuning (PROFESSOR).
4 postdocs & 2 graduate students.
Annual Monte Carlo school;
even years with CTEQ:
2009: Lund;
2010: Karlsruhe.

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
Multiparton Interactions

Z. Physik C34 (1987) 163 – 174:

Double Parton Scattering in \( pp \) Collisions at \( \sqrt{s} = 63 \text{ GeV} \)

The Axial Field Spectrometer Collaboration

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Abstract. In a study of \( pp \) collisions at \( \sqrt{s} = 63 \text{ GeV} \) with more than 29 GeV total transverse energy emitted into 1.8 units of rapidity in the central region, we have extracted a sample of 4-jet events and compared it with models of the two sources of 4-jet production: double bremsstrahlung and double parton scattering. The data cannot be described by bremsstrahlung alone, and we extract the fraction of 4-jet events attributed to double parton scattering for various definitions of the 4-jet sample. We determine the double parton scattering/2-jet yield ratio, and this leads to a determination of the proton radius. We discuss the implications of our observations for the general understanding of high-\( \Sigma E_T \) events.
Signal and Background

Double Parton Scattering

\[ |p_{\perp 1} + p_{\perp 2}| \approx 0 \]
\[ |p_{\perp 3} + p_{\perp 4}| \approx 0 \]
\[ d\sigma/d\varphi \text{ flat} \]

Double Bremsstrahlung

\[ |p_{\perp 1} + p_{\perp 2}| \gg 0 \]
\[ |p_{\perp 3} + p_{\perp 4}| \gg 0 \]
\[ d\sigma/d\varphi \text{ peaked at } \varphi \approx 0/\pi \text{ for AFS/CDF} \]
Preliminary D0 results (2009):

agreement and precision “too good to be true”;
tunes 7 and 3 years old, respectively, and not to this kind of data
S0: Peter Skands (Copenhagen → Lund → Fermilab → CERN)
Collective Effects of Multiparton Interactions

QCD: linear confinement model confirmed by lattice QCD. Extended to hadronization:

Gluon in $N_C \to \infty$ limit:

$$\langle p_\perp \rangle (n_{ch}) \text{ is sensitive to colour flow}$$

long strings to remnants $\Rightarrow$ much $n_{ch}$/interaction $\Rightarrow$ $\langle p_\perp \rangle (n_{ch}) \sim$ flat

short strings (more central) $\Rightarrow$ less $n_{ch}$/interaction $\Rightarrow$ $\langle p_\perp \rangle (n_{ch})$ rising
1960 GeV p+pbar Inelastic, Non-Diffractive

Average Charged Particle $p_T$ ($|\eta|<1.0$, $p_\perp>0.4$GeV)

- CDF data
- Perugia 0
- Perugia NOCR
- A-Pro
- $A_{CR}$-Pro
- Atlas-DC2-Pro

Pythia 6.421

Data from CDF Collaboration, Phys. Rev. D79(2009)112005

(P. Skands)
Outlook

The moment of truth is here – soon!

In order to find a needle in a haystack we not only need to know what a needle is, but also the properties of hay.

Do our QCD understanding and Monte Carlo implementations describe data well enough?