Introduction to Monte Carlo

- Lecture 1: The Monte Carlo method
  - theoretical foundations and limitations
  - parton-level event generation
- Lecture 2: Hadron-level event generation
  - parton showering
  - hadronization and underlying event
  - sample of results
A high-mass dijet event

Figure 2: The reconstructed resonance mass spectrum generated with the PYTHIA MC simulation and Tune D6T for qq ⇔ G ⇔ qq- qg ⇔ q ⇔ qg- gg ⇔ G ⇔ gg for resonance masses of 1)0- 2)0- 3)0- 4)0- and 5)0 TeV.

Figure 3: The event with the highest invariant mass: 3D view left. and 2D view right. The invariant mass of the two wide jets is 5.15 TeV.

CMS PAS EXO-12-059
LHC dijet

Hard process
LHC dijet

Hard process
Parton showers
LHC dijet

Hard process
Parton showers
Underlying event
LHC dijet

Hard process
Parton showers
Underlying event
Confinement
LHC dijet

Hard process
Parton showers
Underlying event
Confinement
Hadronization
Theoretical Status

Exact fixed-order perturbation theory

Hard process
Theoretical Status

- Exact fixed-order perturbation theory
- Approximate all-order perturbation theory

Hard process
Parton showers
Theoretical Status

- **Exact fixed-order perturbation theory**
- **Approximate all-order perturbation theory**
- **Semi-empirical local models only**

**Hard process**

**Parton showers**

**Underlying event**

**Confinement**

**Hadronization**
QCD Factorization

\[
\sigma_{pp \to X} (E^{2}_{pp}) = \int_{0}^{1} dx_1 \, dx_2 \, f_i (x_1, \mu^2) \, f_j (x_2, \mu^2) \, \hat{\sigma}_{ij} \to X (x_1 x_2 E^{2}_{pp}, \mu^2)
\]

- Jet formation and underlying event take place over a much longer time scale, with unit probability.
- Hence they cannot affect the cross section.
- Scale dependences of parton distributions and hard process cross section are perturbatively calculable, and cancel order by order.
Parton Shower

- Shower = sequence of emissions with decreasing angles and energies

- Approximation: keep only contributions $\propto 1/\theta$

$$d^2\mathcal{P} = \frac{\alpha_s}{\pi} \frac{d\theta}{\theta} P(z) \, dz \quad (0 < \theta_i < \theta_{i-1}, \ 0 < z_i < 1)$$

- For very small energy and/or angle, emission is “unresolvable”
Parton Shower

\[ z = \frac{E_{i+1}}{E_i} \]

- \( z = \frac{E_{i+1}}{E_i} \)
- \( \alpha_s \) increases as \( Q = E\theta \) decreases
- When \( Q < Q_{\text{min}} \sim 1 \text{ GeV} \)
  \[ \alpha_s \sim 1 \rightarrow \text{hadronization} \]
Parton Shower Evolution

\[ z = \frac{E_{i+1}}{E_i} \]

\[ P_{q\rightarrow q}(z) = \frac{4 + z^2}{3 \left(1 - z\right)} \]
Parton Shower Evolution

\[ z = \frac{E_{i+1}}{E_i} \]

\[ P_{q\to q}(z) = \frac{41 + z^2}{3 \left(1 - z\right)} \]

\[ P_{g\to g}(z) = \frac{1 + z^4 + (1 - z)^4}{z(1 - z)} \]

\[ P_{g\to q} = \frac{1}{2} \left[z^2 + (1 - z)^2\right] \]

\[ \left( E_0 - E_1, \theta_1 \right) \]

\[ \left( E_1, \theta_1 \right) \]

\[ \left( E_2, \theta_2 \right) \]

\[ \left( E_3, \theta_3 \right) \]

\[ \left( E_4, \theta_4 \right) \]

\[ E\theta < Q_{\text{min}} \]
Hadronization Models

- In parton shower, relative transverse momenta evolve from a high scale $Q$ towards lower values.

- At a scale near $\Lambda_{\text{QCD}} \sim 200$ MeV, perturbation theory breaks down and hadrons are formed.

- Before that, at scales $\sim$ few $\times \Lambda_{\text{QCD}}$, there is universal preconfinement of colour.

- Colour, flavour and momentum flows are only locally redistributed by hadronization.
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String Hadronization Model

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Diagram: String and hadrons
String Hadronization Model

- At short distances (large Q), QCD is like QED: colour field lines spread out (1/r potential)

- At long distances, gluon self-attraction gives rise to colour string (linear potential, quark confinement)

- Intense colour field induces quark-antiquark pair creation: hadronization
Cluster Hadronization Model

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- Decay of preconfined clusters provides a direct basis for hadronization.
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Cluster Hadronization Model

- Mass distribution of preconfined clusters is universal
- Phase-space decay model for most clusters
- High-mass tail decays anisotropically (string-like)
Hadronization Status

• No fundamental progress since 1980s
  ✤ Available non-perturbative methods (lattice, AdS/QCD, ...) are not applicable

• Less important in some respects in LHC era
  ✤ Jets, leptons and photons are observed objects, not hadrons

• But still important for detector effects
  ✤ Jet response, heavy-flavour tagging, lepton and photon isolation, ...
• **Multiple parton interactions** in same collision
  ✤ Depends on density profile of proton

• Assume QCD 2-to-2 secondary collisions
  ✤ Need cutoff at low $p_T$

• Need to model colour flow
  ✤ Colour reconnections are necessary
Sample of Event Generator Results
**MC Event Generators**

- **HERWIG**
  - Angular-ordered parton shower, cluster hadronization
  - v6 Fortran; Herwig++ → Herwig 7
  - [http://projects.hepforge.org/herwig/](http://projects.hepforge.org/herwig/)

- **PYTHIA**
  - $k_t$-ordered parton shower, string hadronization
  - v6 Fortran; v8 C++
  - [http://www.thep.lu.se/~torbjorn/Pythia.html](http://www.thep.lu.se/~torbjorn/Pythia.html)

- **SHERPA**
  - Dipole-type parton shower, cluster hadronization
  - C++
  - [http://projects.hepforge.org/sherpa/](http://projects.hepforge.org/sherpa/)
Jets
Jet $p_T$

Leading jet

Second jet

http://mcplots.cern.ch
Jet $p_T$

Extra jets from parton showers
Jet event shapes

$$T_c \equiv \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \hat{n}_T|}{\sum_i p_{\perp,i}}$$

$$T_{m,C} \equiv \frac{\sum_i |\vec{p}_{\perp,i} \times \hat{n}_{T,C}|}{\sum_i p_{\perp,i}}$$
Introduction to Monte Carlo Techniques

Jet profile

\[ \rho(r) = \frac{1}{\delta r} \sum_{r_a < r_i < r_b} \frac{p_{T,i}}{\sum_{r_i < R} p_{T,i}} \]
Jet multiplicity

**Introduction to Monte Carlo Techniques**

**Jet multiplicity**

7000 GeV pp

Jet multiplicity (anti-$k_T$, 0.4)

- ATLAS
- * Herwig++ (Def)
- * Pythia 8 (Def)
- * Sherpa (Def)

Jet multiplicity (E$_T$ > 20, $p_T$ > 2.8, $E_{miss}$ > 20, $l$, $\gamma$ > 2.47, $p_T$ > 25, M_T > 40, $R_h$ > 0.5)

- ATLAS
- * Herwig++ (Def)
- * Pythia 8 (Def)
- * Sherpa (Def)

**Multijets**

**W+jets**
Hadrons from $Z^0$ decay

Hadron multiplicities in $e^+e^-$ at 91 GeV

**Figure 27:** Identified hadron multiplicities in $e^+e^-$ collisions at the $Z^0$ peak and $p\bar{p}$ collisions at 200 GeV. These observables are determined primarily by the tuning of the hadronization models, both the flavour and kinematic aspects, but the overall multiplicities are also strongly dependent on the tuning of the parton showers (and MPI models, for the hadron collider observables). Up-to-date versions of these plots can be found at [http://mcplots.cern.ch/](http://mcplots.cern.ch/).
Underlying Event
The transverse charged particle density is illustrated in Fig. 1, which displays the azimuthal distance (\Delta \phi) around the leading jet. events with three or more jets contribute to inclusive jet UE topologies. Measurements of LHC jet rates based on which one has more or less activity, named the trans-max side is more likely to be affected by wide-angle emissions associated with the hard process and correspondingly the trans-min observables have the potential to be more sensitive to soft MPI and beam-remnant activity. In this analysis, the transverse regions from the hard partonic scattering. While very sensitive to hard initial- and final-state radiation. The trans-max and trans-min sides respectively. The transverse regions may be distinguished event-by-event based on which one has more or less activity, named the "towards" region UE observables are studied both in inclusive jet events with three or more jets contribute to inclusive jet UE topologies. Measurements of LHC jet rates based on which one has more or less activity, named the trans-max side is more likely to be affected by wide-angle emissions associated with the hard process and correspondingly the trans-min observables have the potential to be more sensitive to soft MPI and beam-remnant activity. In this analysis, the transverse regions from the hard partonic scattering. While very sensitive to hard initial- and final-state radiation. The trans-max and trans-min sides respectively.
Underlying Event

Introduction to Monte Carlo Techniques

38 CERN Summer Student Lectures 2017
Vector Bosons
Absolute normalization

1960 GeV ppbar  
$Z$ (Drell-Yan)

$p_T(Z)$ (muon channel)

- D0
- Herwig++ (Def)
- Pythia 8 (Def)
- Sherpa (Def)

D0_2010_S8671338

Herwig++ 2.6.3, Pythia 8.176, Sherpa 1.4.3

Normalized to data

7000 GeV pp  
$Z$ (Drell-Yan)

$p_T(Z)$ (electron channel, dressed)

- ATLAS
- Herwig++ (Def)
- Pythia 8 (Def)
- Sherpa (Def)

ATLAS_2011_S9131140

Herwig++ 2.6.3, Pythia 8.176, Sherpa 1.4.3

Ratio to D0

Ratio to ATLAS

Normalized to data

mcplots.cern.ch

7.9M events

$≥$ Rivet 1.8.3, Herwig++ 2.6.3, Pythia 8.176, Sherpa 1.4.3

D0_2010_S8671338

(Z) (muon channel)

ATLAS_2011_S9131140

(Z) (electron channel, dressed)
Limitations of LO+parton shower

- Hard process: \( q\bar{q} \rightarrow Z^0/W^\pm \)

- Leading-order (LO) normalization → need next-to-LO (NLO)
- Worse for high \( p_T \) and/or extra jets → need multijet merging
Latest $Z^0$+jets (13 TeV)

MG5\_aMC+Py8 \ldots = NLO+multijet merged event generators

ATLAS, EPJC77(2017)361
• Parton shower keeps large small-angle contributions
• Shower gives preconfinement of colour
• This allows local model of hadronization
• String and cluster models both still viable
• Underlying event due to multiple interactions
• LO+PS event generators underestimate multijets
• Further improvements (NLO+merging) now used
Thanks for your attention!