Collider Tools

Peter Richardson

CERN TH & IPPP Durham

Corfu: 10th Sept, 2017
Outline

- Introduction
- Basics of Event Generation
- Hard Processes and Higher Orders
- Non-perturbative physics
- More Logs?
- BSM simulation
- The Future
3rd Workshop on Tools for SUSY, Colmar 2000

taken from www.tourisme-colmar.com
Introduction

Although the main focus of this workshop is BSM I will primarily focus on developments in simulation of the Standard Model.

While there was a lot of progress in BSM simulation in the 2000s most of the problems are now solved at the accuracy we need, given the lack of signals.

However there is still significant process in the simulation of Standard Model physics.
Basics of Event Generation

- Monte Carlo event generators combine:
  - hard perturbative QCD calculations;
  - approximate QCD evolution from high to low energy scales using the parton shower;
  - perturbative multiple parton scattering models of the underlying event;
  - non-perturbative models of the hadronization process;
  - simulations of hadron decays;

to provide simulations of complete events.

- They are essential tools that both encapsulate the current theoretical understanding of hadronic collisions and produce simulated events which can be compared with data.
A Monte Carlo Event

Hard Process, now usually calculated at NLO
A Monte Carlo Event

Initial- and final-state parton shower
Collider Tools
Basics of Event Generation

A Monte Carlo Event

\[ p, \bar{p} \rightarrow W^- t \rightarrow W^+ b + \nu \ell + \ell^+ \]

Perturbative decays of heavy particles
A Monte Carlo Event

Secondary hard processes
Collider Tools

Basics of Event Generation

A Monte Carlo Event

$p, \bar{p}$ → $W^-, \bar{t}t, b\bar{b}$ → $W^+, \ell^+\nu$
A Monte Carlo Event

Hadron Decays

$W^-$, $W^+$, $t$, $\bar{t}$, $b$, $\bar{b}$, $\nu$, $\ell^+$, $\ell^-$, and Hadrons

$p, \bar{p}$碰撞 

Collider Tools
Basics of Event Generation

Peter Richardson
Collider Tools
Last 15 years

Before we go on and consider recent developments it's worth thinking about how much things have changed over the last 15 years.

At the end of LEP

- Main programs were FORTRAN HERWIG6 and PYTHIA6.
- Parton showers with matching to the first hard emission for simple processes such as $e^+e^- \rightarrow q\bar{q}$ and Drell-Yan.
- Cluster or string model for hadronization.
- The alternative dipole shower of ARIADNE (+PYTHIA hadronization) also available.
From LEP to LHC: Higher Orders

- Focus of event generator development has been the inclusion of additional hard emissions and higher-order corrections.
- Multiple emissions at LO, CKKW (Catani, Krauss, Kuhn and Webber JHEP 0111 (2001) 063) and numerous variants.
- Matching to NLO (NLO normalisation and 1st emission)
  - **MC@NLO** (Frixione, Webber JHEP 0206 (2002) 029)
  - **POWHEG** (Nason JHEP 0411 (2004) 040)
  - **KrkNLO** (S. Jadach, et. al. JHEP 1510 (2015) 052)
- Merging at NLO (NLO normalisation for multiple emissions)
  - **FxFx** Frederix, Frixione JHEP 1212 (2012) 061
  - **Sherpa** (Höche, Krauss, Schonherr, Siegert JHEP 1304 (2013) 027)
  - **UMEPS** (Lönnblad, Prestel JHEP 1303 (2013) 166)
From LEP to LHC: New Algorithms

- Motivated by matching/merging development of new parton-shower algorithms
  - Improved AO (Gieseke, Stephens, Webber JHEP 0312 (2003) 045)
  - Catani-Seymour based SHERPA (Schumann, Krauss JHEP 0803 (2008) 038), Herwig (Plätzer, Gieseke JHEP 1101 (2011) 024)
  - Antenna Based (Giele, Kosower, Skands Phys.Rev. D78 (2008) 014026)
  - GenEvA (Bauer, Tackmann, Thaler JHEP 0812 (2008) 010)

- These developments have been possible due to improved understanding of QCD, automation of NLO calculations, and faster computers.
From LEP to LHC: New Programs

- At the end of LEP the existing FORTRAN generators needed to be rewritten to allow physics improvements and long term development:
  - HERWIG redeveloped as Herwig++ and then Herwig7;
  - PYTHIA → Pythia 8;
  - Sherpa developed from scratch; all in C++.

- New generation of event generators which are the workhorses at the LHC, together with specialised programs for the calculation of hard processes in the various merging schemes.
From LEP to LHC: New Programs

- At the end of LEP the existing FORTRAN generators needed to be rewritten to allow physics improvements and long term development:
  - HERWIG redeveloped as Herwig++ and then Herwig7;
  - PYTHIA → Pythia 8;
  - Sherpa developed from scratch; all in C++.

- New generation of event generators which are the workhorses at the LHC, together with specialised programs for the calculation of hard processes in the various merging schemes.
Hard Processes and Higher Orders

- NLO simulations rearrange the NLO cross section formula.

\[
d\sigma = B(\nu)d\Phi_\nu + (V(\nu) + C(\nu, r))d\Phi_r d\Phi_\nu
\]
\[
+ (R(\nu, r) - C(\nu, r))d\Phi_\nu d\Phi_r
\]

- Either choose \( C(\nu, r) \) to be the shower approximation.

\[
d\sigma = B(\nu)d\Phi_\nu + (V(\nu) + C_{\text{shower}}(\nu, r))d\Phi_r d\Phi_\nu
\]
\[
+ (R(\nu, r) - C_{\text{shower}}(\nu, r))d\Phi_\nu d\Phi_r
\]

**MC@NLO, Frixione and Webber**

- First practical approach for combining NLO calculations and the parton shower.
Hard Processes and Higher Orders

A alternative rearrangement (POWHEG, Nason) is

$$d\sigma = \bar{B}(v) d\Phi_v \left[ \Delta_R^{(\text{NLO})}(0) + \Delta_R^{(\text{NLO})}(p_\perp) \frac{R(v, r)}{B(v)} d\Phi_r \right],$$

where

$$\bar{B}(v) = B(v) + V(v) + \int [R(v, r) - C(v, r)] d\Phi_r,$$

$$\Delta_R^{(\text{NLO})}(p_\perp) = \exp \left[ - \int d\Phi_r \frac{R(v, r)}{B(v)} \theta(k_\perp(v, r) - p_\perp) \right].$$

Looks more complicated but has the advantage that it is independent of the shower and only generates positive weights.
Define new PDFs in a Monte Carlo scheme.

NLO corrections implemented by reweighting.

from 1607.06799 Jadach et al.
Off-Shell Particles

Off-Shell Particles

from JHEP 1606 (2016) 027 Frederix et.al
Higher Multiplicities

- Now a range of both LO and NLO techniques available for merging many jet multiplicities.
- Leading-order merging is widely used in LHC analyses, NLO is starting to be used more.
- Mainly the built-in MEPSNLO in Sherpa and FxFx using MadGraph5 aMC@NLO
At the LHC: ATLAS Z+jets
Collider Tools

Hard Processes and Higher Orders

At the LHC: ATLAS $W^{\pm} + \text{jets}$
Collider Tools

Hard Processes and Higher Orders

FxFx Merging

from JHEP 1602 (2016) 131 Frederix et.al.
Merging with bottom quarks

from 1612.04640 Krauss, Napoletano, Schumann
Collider Tools

Hard Processes and Higher Orders

Merging with bottom quarks

from 1612.04640 Krauss, Napoletano, Schumann
Merging $W^+W^-$ and $W^+W^-+\text{jet}$ with MINLO

JHEP 1609 (2016) 057 Hamilton et.al.
Extending MINLO

\[ \sigma [\text{pb}] \]

\[ HJJ^* \quad \text{NNLOPS} \quad HJJ \]

\[ N_{\text{jets}} \geq 0 \quad \geq 1 \quad \geq 2 \quad \geq 3 \quad \geq 4 \]

Anti-\( k_T \)
\[ R = 0.4 \]
\[ p_T > 100 \text{ GeV} \]

JHEP 1605 (2016) 042 Frederix and Hamilton
Include NNLL resummation of specific event shape, in this case 0-jettiness $T_0$ (a.k.a. beam thrust) from Phys.Rev. D92 (2015) no.9, 094020 Alioli et al.
Herwig 7.1

EW corrections

from Biedermann, Bräuer, Denner, Pellen, Steffen Schumann, Thompson 1704.05783
Uncertainties

- As the accuracy of simulations improves it is important that we can assess the uncertainties.
- Still in its infancy.
- Need to disentangle which are uncertainties are perturbative and which are from tuning to data.
- Lot of work at Les Houches 2015 and subsequently.

from 1605.07851 Rauch and Plätzer
Uncertainties

Reweighting

- Advances this year using reweighting to assess shower uncertainties

Quark-Gluon discrimination

- Lot of study as part of the 2015 Les Houches workshop
  Gras et. al., JHEP 1707 (2017) 091.

- Finally some real data we can compare do, not just neutral net/BDT outputs,

- Improvements to the non-perturbative modeling and tuning in Herwig 7.1
  Reichelt, PR and Siodmok, arXiv:1708.01491
Quark-Gluon discrimination

Collider Tools

Hard Processes and Higher Orders

Quark-Gluon discrimination
Non-perturbative Physics

- Standard assumption of universality was that we could develop the hadronization models using $e^+e^-$ data and then apply them in hadron–hadron collisions.

- Have always needed additional non-perturbative modeling of the underlying event and colour reconnection.

- In the more complex environment of the LHC clearly other things are going on, or colour reconnection is much more complicated, and we need better modeling of non-perturbative effects.

- Some new ideas, e.g. (Fischer, Sjöstrand arXiv:1610.09818)
From LEP to LHC: Identified Particle Spectra

Plots from MCplots
Collider Tools

Non-perturbative physics

Underlying Event

\begin{align*}
\text{Toward region} & \quad \text{\emph{ATLAS} Preliminary} \\
\sqrt{s} & = 13 \text{ TeV} \\
p_T > 0.5 \text{ GeV, } |\eta| < 2.5 \\
p^\text{lead}_T > 1 \text{ GeV}
\end{align*}

from ATL-PHYS-PUB-2015-019
Collider Tools

Non-perturbative physics

Soft and diffractive scattering in Herwig

New model including a diffractive component from 1612.04701 Stefan Gieseke, Frashër Loshaj, Patrick Kirchgäßer

Rapidity gap size in $\eta$ starting from $\eta = \pm 4.9$, $p_T > 200$ MeV

$1/N_{ch} \int \frac{d\sigma}{dp_T}$ for $N_{ch} \geq 1$

$\frac{d\sigma}{d\eta^F}$ for $p_T > 200$ MeV
New model in SHERPA. Based on the model by Khoze, Martin, and Ryskin (KMR). Plots from Krauss, Zapp in 1612.04701 LHC Forward Physics Working Group.
At the LHC: Baryons

Plots from MCplots

Peter Richardson
At the LHC: Baryons

Plots from (Fischer, Sjöstrand arXiv:1610.09818)
Clearly work still needed to describe baryon production in particular.
Accuracy of the shower

- For the first time in many years more work on the accuracy of the parton-shower algorithms.
- Needed as we go to higher accuracy for the matrix elements.
- This is the area where there is probably the greatest potential for improvement.
- If we can consistently improve the logarithmic accuracy.
At the LHC: ATLAS Jet Shapes

Plots from MCplots

Subleading $1/N_C$

- Plätzer, Sjödahl JHEP 1207 (2012) 042,
Subleading-Logs

- Subleading collinear logs via including higher order splitting functions in antenna formalism Li, Skands, arXiv:1611.00013

Subleading-Logs

from Höche, Krauss, Prestel arXiv:1705.00982
Non-Global Logs

- Big problem with going to higher logarithmic accuracy are the non-global soft logs.
- Not even clear we can treat these correctly in analytic calculations.
- Let alone a numerical simulation
- Recent progress in SCET

Becher et. al. JHEP 1611 (2016) 019, JHEP 1612 (2016) 018

Light-hemisphere mass taken from Becher et. al. JHEP 1612 (2016) 018
BSM

- In general BSM will involve either:
  - modifications to SM hard processes;
  - new processes and the production of new particles followed by their decay.

- Usually only effects the hard process and decays.

- Can lead to changes in the parton shower ($\epsilon^{ijk}$ vertices, colour sextets).

- Or weirder things, black holes, dark showers, . . . .
BSM Physics

Historically implementing specific models in PYTHIA/HERWIG/MadGraph.

Major development FeynRules and other tools which allow the Feynman rules to be computed from the Lagrangian and outputted in the UFO format.

The major event generators and ME programs can read the UFO and calculate hard processes, decays etc..

Now extended to NLO.

Also developments in other tools for spectrum calculations (mainly in SUSY) and decays.

Are there still models we can’t simulate reliably?
Conclusions

- Event generators have matured as sophisticated implementations of state-of-the-art QCD calculations over the last 15 years.
- Aided by advances in understanding QCD, computing and automation of fixed-order calculations.
- Provide impressive agreement with LHC data.
- Still a lot of ongoing work needed to describe the unprecedented amount and accuracy of data from the LHC.
- Clearly work now needed on the “neglected” parts of the simulation, i.e. subleading logs and non-perturbative models.