Monte Carlo simulation of QCD radiation

Mike Seymour
University of Manchester
Giuseppe Marchesini Memorial Meeting
Galileo Galilei Institute for Theoretical Physics
May 19th 2017
Introduction: Pino and Monte Carlo
Introduction: Pino and Monte Carlo

1984

Simulation of QCD Jets
Including Soft
Gluon Interference

(959 citations)
Introduction: Pino and Monte Carlo

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Simulation of QCD Jets
Including Soft Gluon Interference

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**Introduction: Pino and Monte Carlo**

- **1984**
  - Monte Carlo Simulation of General Hard Processes with Coherent QCD Radiation

- **1988**
  - **EARWIG**
Introduction: Pino and Monte Carlo

Monte Carlo Simulation of General Hard Processes with Coherent QCD Radiation
(1042 citations)

Associated Transverse Energy in Hadronic Jet Production
(66 citations)

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Introduction: Pino and Monte Carlo

Monte Carlo Simulation of General Hard Processes with Coherent QCD Radiation
(1042 citations)

Associated Transverse Energy in Hadronic Jet Production
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**EARWIG**

**HERWIG**
v3.0
Introduction: Pino and Monte Carlo

1984

1988 1989

Simulation of QCD Coherence in Heavy Quark Production and Decay


(91 citations)

EARWIG

HERWIG

v3.0

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Simulations of QCD Coherence
in Heavy Quark
Production and Decay

(91 citations)

1988 1989

EARWIG

HERWIG v3.0

HERWIG v4.0

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QCD coherent branching and semi-inclusive processes at large $x$ (CMW)
(326 citations)

$$\Lambda_{MC} = \exp \left( \frac{67 - 3\pi^2 - 10N_f/3}{2(33 - 2N_f)} \right) \Lambda_{\overline{MS}}$$

EARWIG
| HERWIG v3.0 | HERWIG v4.0 |

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**Introduction: Pino and Monte Carlo**

1984

1988
1989
1991

QCD coherent branching and semi-inclusive processes at large $x$ *(CMW)*
*Nucl. Phys. B349 (1991) 635*
(326 citations)

\[ \Lambda_{MC} = \exp \left( \frac{67 - 3\pi^2 - 10N_f/3}{2(33 - 2N_f)} \right) \Lambda_{\overline{MS}} \]

**EARWIG**

**HERWIG**

v3.0

v4.0

v5.1

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Introduction: Pino and Monte Carlo

- **1984**: EARWIG
- **1988-1989**: HERWIG v3.0, HERWIG v4.0
- **1991**: HERWIG v5.1
- **2001**: 

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EARWIG  HERWIG v3.0  HERWIG v4.0  HERWIG v5.1  HERWIG v6.2

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EARWIG HERWIG v3.0 HERWIG v4.0 HERWIG v5.1 HERWIG v6.2

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EARWIG

HERWIG v3.0  HERWIG v4.0  HERWIG v5.1

HERWIG v6.2  HERWIG v6.5

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- 1984: EARWIG
- 1988-1989: HERWIG v3.0
- 1991: HERWIG v4.0
- 2001-2002: HERWIG v5.1
- 2008: HERWIG v6.2
- Monte Carlo and large angle gluon radiation
  JHEP 0903 (2009) 117
  (17 citations)
Introduction: Pino and Monte Carlo
Introduction: Pino, Monte Carlo and Me
Introduction: Pino, Monte Carlo and Me


1990

EARWIG

HERWIG v3.0

HERWIG v4.0

HERWIG v5.1

HERWIG v4.5

HERWIG v6.2

HERWIG v6.5
Introduction: Pino, Monte Carlo and Me


EARWIG

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2001 2002 2008

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HERWIG v4.5

EARWIG

HERWIG v3.0

HERWIG v4.0

HERWIG v5.1

HERWIG v6.2

HERWIG v6.5
Introduction: Pino, Monte Carlo and Me


- EARWIG v3.0
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- HERWIG v6.5

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Matrix-Element Corrections to Parton Shower Algorithms
Comp. Phys. Comm. 90 (1995) 95
(160 citations)
Introduction: Pino, Monte Carlo and Me


Figure 1: The phase-space for $e^+e^-$ divided according to an ordering variable $q^2$ into a matrix-element region, $q^2 > Q^2$, and a parton shower region, $q^2 < Q^2$.

Recall that the matrix element is divergent at $x_1 = 1$. There was no emission at a higher scale than the one generated.

In figure 1 we show an illustration for the specific case of $e^+e^-$ annihilation.

The probability distribution for the first emission to be at $y$ is

$$dP_{ps.incl}(q^2 y) = dP_{ps.incl}(q^2 y) \exp\left\{-\int Q^2 dP_{m.e.incl}\right\}$$

The second integration arises because the first emission can only come from the parton shower if there was no matrix-element emission. If events at $x$ in the matrix-element region are generated according to the exact first-order matrix element, as in the standard algorithm, they are distributed according to $dP_{m.e.incl}(q^2 x)$.

In the limit $q^2 x, y \rightarrow Q^2$, where the points correspond to identical physical configurations, the two probability distributions are different, even if $dP_{ps.incl}$ is a perfect approximation to $dP_{m.e.incl}$, leading to a residual dependence on the cutoff between the two regions, $Q^2$. If $\int Q^2 dP_{m.e.incl}$ is large, this dependence is strong. On the other hand, if we generate the matrix-element events according to $dP_{m.e.incl}(q^2 x) = dP_{m.e.incl}(q^2 x) \exp\left\{-\int q^2 x dP_{m.e.incl}\right\}$, as we propose, then in the $q^2 x, y \rightarrow Q^2$ limit we obtain

$$dP_{m.e.1st}(Q^2) = dP_{m.e.incl}(Q^2) \exp\left\{-\int Q^2 dP_{m.e.incl}\right\}$$

$$dP_{ps.1st}(Q^2) = dP_{ps.incl}(Q^2) \exp\left\{-\int Q^2 dP_{m.e.incl}\right\}$$

If the parton shower cross-section exactly reproduced the first-order matrix element, the two would then be perfectly matched, with no dependence on $Q^2$. 

Matrix-Element Corrections to Parton Shower Algorithms

*Comp. Phys. Comm. 90 (1995) 95*

(160 citations)
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1988

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v5.1

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HERWIG

v6.2

2002

HERWIG

v6.5

2008

HERWIG++

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Matrix-Element Corrections to
Parton Shower Algorithms
Comp. Phys. Comm. 90 (1995) 95
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MC sim of QCD radiation
Introduction: From HERWIG to Herwig++ and back again to Herwig
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Introduction: From HERWIG to Herwig++ and back again to Herwig
Herwig: The Evolution of a Monte Carlo Event Generator

HERWIG was originally designed as a program for understanding hadronic physics. In the late 1990's it was used as a major simulation package for hadronic effects in electroweak physics searches and jet and heavy quark physics...

But in ten years it had grown by a factor of 10 to 25000 lines of code without restructuring.

(Based on Mike Seymour's 1998 PPESP Presentation)

Peter Richardson

Herwig: The Evolution of a Monte Carlo Event Generator

Introduction: From HERWIG to Herwig++ and back again to Herwig

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MC sim of QCD radiation
Herwig7: Matching and Merging
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- Herwig 7.0 (December 3rd 2015)
- Automated generation of NLO cross sections
- Automated MC@NLO-like or POWHEG-like matching to parton shower or dipole shower
Herwig7: Matching and Merging

• Herwig 7.0 (December 3rd 2015)
  • Automated generation of NLO cross sections
  • Automated MC@NLO-like or POWHEG-like matching to parton shower or dipole shower

• Herwig 7.1 (May 19th 2017)
  • Multi-jet merging of NLO matched cross sections
  • New model for soft interactions and diffraction
Motivation

Inclusive Jet Multiplicity

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

- Data
- Hw 7.0 LO $\otimes$ PS
- Hw 7.0 NLO $\otimes$ PS
- Hw 7.0 NLO $\oplus$ PS
- Hw 7.0 MB NLO $\otimes$ PS
- Hw 7.0 NLO $\oplus$ Dipoles

$p_{T,jet} > 20$ GeV

$N_{jet}$

MC/Data

Inclusive Jet Multiplicity

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

- Data
- Hw 7.1 NLO Merged

$p_{T,jet} > 20$ GeV

$N_{jet}$

MC/Data
Motivation

$H_T (W + \geq 1 \text{ jets})$

- Data
- Hw 7.0 LO \otimes \text{PS}
- Hw 7.0 NLO \otimes \text{PS}
- Hw 7.0 NLO \oplus \text{PS}
- Hw 7.0 MB NLO \otimes \text{PS}
- Hw 7.0 NLO \oplus \text{Dipoles}

$H_T (W + \geq 1 \text{ jets})$

- Data
- Hw 7.1 NLO Merged
Merging

Basic Idea:
Divide the phase space into ME and PS regions.

\[ \mathcal{P} \mathcal{S}_\mu[u(\phi_n, Q)] = \mathcal{P} \mathcal{S} \mathcal{V}_\mu[\mathcal{P} \mathcal{S}_\rho[u(\phi_n, Q)]] \]

Overlapping phase spaces produce dead regions if not treated properly.

Simple example:
- Start with two kernels with overlapping phase spaces.
- ME region defined by clustering algorithm.
- Both scales \( q_a \) and \( q_b \) must be above merging scale
- Assume emission in shower region from kernel \( P_a \)
- Simple veto PS would produce point A but not B
Now replace \( \mathcal{PS}_\rho[u(\phi_n, Q)] \) with expressions from the ME calculation weighted with shower history:

\[
\omega^k_I = \sum_\alpha \frac{w^k_{C,\alpha}}{\sum_\beta w^k_{C,\beta}} \frac{\alpha_S(q_k)}{\alpha_S(\mu_R)} \cdot \frac{f_{k}^{(1,2)}(\eta_{k-1}, q_{k-1})}{f_{k}^{(1,2)}(\eta_{k-1}, q_k)} II^{(1,2)}(q_{k-1}|q_k) \prod_f \Delta(q_{k-1}|q_k)
\approx \Delta(q_{k-1}|q_k)
\]
Merging

\[ d\sigma_n u(\phi_n, q_n) w^n_H - \int_{\rho}^{q_n} dq \sum_{\alpha} \frac{w_{C,\alpha}}{\sum_{\beta} w_{C,\beta}} u(\phi_n^\alpha, q_n^\alpha) d\sigma_{n+1} w^{n+1}_H \]

\[ + d\sigma_{n+1} u(\phi_{n+1}, q_{n+1}) w^{n+1}_H \]

Unitarized LO and NLO merging now adds and subtracts the same parts. Here only if the cluster history is produced.

In order to add NLO corrections the history and the additional emissions need to be expanded to order \( \alpha_s \) in the ME and the PS region

\[ d\sigma_n u(\phi_n, q_n) \left. \frac{\partial w^n_H}{\partial \alpha_s} \right|_{\rho} - \int_{\rho}^{q_n} dq \sum_{\alpha} \frac{w_{C,\alpha}}{\sum_{\beta} w_{C,\beta}} u(\phi_n^\alpha, q_n^\alpha) d\sigma_{n+1} \]

\[ + d\sigma_{n+1} u(\phi_{n+1}, q_{n+1}) \]
Merging

For example

\[ \prod_i \frac{\alpha_S(q_i)}{\alpha_S(\mu)} = 1 - \sum_i b_0 \frac{\alpha_S(\mu)}{\pi} \log \left( \frac{q_i}{\mu} \right) + O(\alpha_S^2) \]

Together with LO weights the expansion needs to produce the form

\[ d\sigma_n^B (1 + O(\alpha_S^2)) \]

but e.g.

\[ d\sigma_n^B \prod_i \left( 1 - \sum_X \alpha_S w^i_{\partial X} \right) \prod_X w^i_X \]

and

\[ d\sigma_n^B \prod_i \left( \prod_X w^i_X - \sum_X \alpha_S w^i_{\partial X} \right) \]

both fulfil the criterion above.

Can be used as uncertainty as difference tests higher orders.
Sanity Checks

- Sudakov sampling
- Subtraction plots
- Cluster mass spectra
Currently ~20000 observables

Need a way to structurally filter results.
One tune to rule them all...
LEP is fine
DIS tested
DY hard emissions
Interplay with MPI needs testing

Test Results
Results: e+e- annihilation

Thrust, $1 - T$, at 91 GeV

$\frac{1}{\sigma} \frac{d\sigma}{d(1-T)}$

MC/Data

Herwig 7.1
MadGraph/OpenLoops/ColorFull

$10^1$
$1$
$10^{-1}$

$1 - T$

$10^2$
$10^1$
$10^{-1}$

$D$ parameter

$1/\sigma \, d\sigma / dD$

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Results: LHC Z+jets

Herwig 7.1

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\[ \frac{d\sigma}{dp_T^Z} \text{[pb/GeV]} \]

\[ \text{MC sim of QCD radiation} \]

Herwig 7.1

\[ Z(p_T) \]

ATLAS Data

\[ \sigma(Z/\gamma^* (\rightarrow \ell^+ \ell^-) + N_{\text{jet}}) \text{[pb]} \]

\[ N_{\text{jet}} \]

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MC sim of QCD radiation
Results: LHC Higgs+jets

Higgs boson $p_\perp$ in peak region

\[ \frac{d\sigma}{dp_h^\perp} [\text{pb}/\text{GeV}] \]

Inclusive jet multiplicity ($R = 0.4$)

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

ATLAS Data
\[ \bullet \]
J(0)
\[ \cdots \]
J(0,1)
\[ \cdots \]
J(0*,1)

\[ \rho \in [10,20] \text{ GeV} \]
Herwig7: Soft Interactions and Diffraction

associated Transverse Energy in Hadronic Jet Production
G. Marchesini and B.R. Webber
Herwig7: Soft Interactions and Diffraction

Associated Transverse Energy in Hadronic Jet Production
G. Marchesini and B.R. Webber

Rick Field/CDF/CMS
~2000

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Figure 5: Charged Particle Density vs. Transverse Momentum

- Transverse $N_{ch}$ density vs. $p_T$
- Transverse $\Sigma p_T$ density vs. $p_T$

ATLAS data
- No sigma eff in fit
- UE/EE-4 CTEQ6L1

MHS & A. Sjödham
JHEP 1310 (2013) 113
Ladders produce partons flat in rapidity
Adding SD and DD for Plateau
Motivated by Regge Theory
Tuned to MinBias data
New default Model

CMS 13 TeV, Electromagnetic energy spectrum ($-6.6 < \eta < -5.2$)

CMS Data
- $\chi^2/n = 25.99$

CMS Data new
- $\chi^2/n = 796.13$

Data new,
- $\chi^2/n = 0.70$

CMS

MC/Data

CMS

MC/Data

MC/Data

CMS

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MC/Data


Summary: Thank you Pino!

For a remarkable partnership, with a legacy that is thriving