Improving the Herwig Dipole Shower

Work in Collaboration with Simon Plätzer and Jack Holguin

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Introduction
Event generators (e.g. Herwig, Pythia, Sherpa) aim to simulate events down to the full final state.

Perturbative QCD governs two components:

- Hard scattering process
- **Parton shower**
  - Improving & extending $1 \rightarrow 2$ and $2 \rightarrow 3$ branching frameworks (Dire [1506.05057], Vincia [0707.3652], Deductor [1401.6364])
  - More/Better embedding of quantum numbers (e.g. spin, colour)
  - Higher-order splitting functions (e.g. [1705.00742], [1705.00982], [1611.00013])
  - Most recently: Amplitude-level evolution (e.g. [1802.08531], [1905.08686], [2003.06400])
“Logarithmic accuracy of parton showers” [1805.09327] asked:

What is the accuracy of a parton shower and do they do what they claim (i.e. leading-log (LL) resummation)?

Their conclusions about transverse-momentum ordered showers: The pattern of multiple emission that they generate has flaws in singular regions that are arguably serious.

So what can we do? “Building a Consistent Parton Shower” [2003.06400] derived a dipole shower without these issues from the amplitude-level Parton Branching Algorithm [1802.08531] [1905.08686]
Outline of Philosophy

[Adapted from “Building a Consistent Parton Shower”]

Momentum imbalance: \( R = \hat{q} + \hat{q}_i + \hat{q}_j - p_i - p_j \)
Boost to return to centre-of-momentum frame, and rescale 4-momentum to ensure we return to lab frame.
Our Improvements
In this work, consider only massless partons

In this talk, will only present final-final dipole kinematics, but we have set up the framework for all dipole types (FI, IF, and II), i.e. it works for hadron colliders (including multiple-parton interactions)

Hadronization not currently integrated. Decays turned off.
We propose the kinematics map:

\[
\hat{q} = z \ p_i + b \ p_j + k_{\perp} \\
\hat{q}_i = (1-z)p_i + \beta \ p_j - \gamma f k_{\perp} \\
\hat{q}_j = \alpha \ p_i + (1-cb)p_j - \gamma(1-f)k_{\perp}
\]

where

\[
\gamma \in (0, 1) \rightarrow k_{\perp} \text{ imbalance in branching} \\
f \in (0, 1) \rightarrow k_{\perp} \text{ sharing between recoiler and spectator} \\
c \in (0, 1) \rightarrow \text{longitudinal recoil of spectator}
\]

\[
b = \frac{-k_{\perp}^2}{2z(p_i \cdot p_j)}
\]

\(\alpha, \beta\) are determined by \(\hat{q}_j\) and \(\hat{q}_i\) on-shell conditions.
We propose the kinematics map:

\[ \hat{q} = z p_i + b p_j + k \perp \]
\[ \hat{q}_i = (1-z)p_i + \beta p_j - \gamma f k \perp \]
\[ \hat{q}_j = \alpha p_i + (1-cb)p_j - \gamma (1-f)k \perp \]

Momentum imbalance is then given by:

\[ R = \alpha p_i + (\beta + 1 + (1-c)b)p_j + (1-\gamma)k \perp \]

Forshaw-Holguin-Plätzer

\[
\begin{align*}
\hat{q} &= z p_i + b p_j + k \perp \\
\hat{q}_i &= (1-z)p_i \\
\hat{q}_j &= p_j \\
R &= bp_j + k \perp
\end{align*}
\]

PanGlobal*

\[
\begin{align*}
\hat{q} &= ap_i + bp_j + k \perp \\
\hat{q}_i &= (1-a)p_i \\
\hat{q}_j &= (1-b)p_j \\
R &= k \perp
\end{align*}
\]
Post-branching Adjustments

Conservation of energy and momentum (see Appendix A.2 of 2112.14454) choice of the form:

\[
\delta^{(D)} \left( \frac{\Lambda}{\hat{\alpha}} \left( \sum_{l \neq i, j} p_l + \hat{q} + \hat{q}_i + \hat{q}_j \right) + \Lambda \sum_i k_i - Q \right) = \delta^{(D)} \left( \frac{\Lambda}{\hat{\alpha}} (P + K - Q) \right)
\]

where \( P \) is the (massless) parton momenta pre-branching, and \( K \) the (massive) colourless momenta pre-branching.

This defines the Lorentz boost and rescaling:

\[
\frac{\Lambda}{\hat{\alpha}} \left( \hat{\alpha} K + Q + R - K \right) = Q
\]

i.e. quadratic equation in \( \hat{\alpha} \). The boost is of the form:

\[
\Lambda^\mu_\nu(p_1 \rightarrow p_2) = g^\mu_\nu + \frac{2p_2^\mu p_1^\nu}{p_1^2} - \frac{2(p_1 + p_2)^\mu(p_1 + p_2)_\nu}{(p_1 + p_2)^2}
\]
Extension to FI, IF, II dipoles

Extending the kinematics map to the other dipole types straightforward, but we make the choice that any initial-state partons do not recoil.

Thus, defining rescaling equation becomes:

\[
\frac{\Lambda}{\hat{\alpha}} \left( \hat{\alpha} K + Q' + R - K \right) = Q'
\]

where

<table>
<thead>
<tr>
<th>Dipole Type</th>
<th>$Q'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF</td>
<td>$p_a + p_b$</td>
</tr>
<tr>
<td>FI</td>
<td>$\hat{q}_j + p_b$</td>
</tr>
<tr>
<td>IF</td>
<td>$\hat{q}_i + p_b$</td>
</tr>
<tr>
<td>II</td>
<td>$\hat{q}_i + \hat{q}_j$</td>
</tr>
</tbody>
</table>
Some Plots*
Pinch of salt: we have not yet included the dipole partitioning from [2011.15087]
Conclusion and Outlook
We’ve outlined and implemented a flexible recoil scheme for hadron collisions.

Things left to do:

• Fix the partitioning of dipoles
• PanGlobal mapping **always** rescales incoming partons (i.e. *for all* dipole types). Is there a (qual/quant)itative difference to ours?
• Does our prescription work for e.g. deep-inelastic scattering?

Parton showers are undergoing a transformative time, and it will be interesting