Status of parton showers

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(DESY)

QCD Tools for LHC Physics: From 8 to 14 TeV - What’s needed and why?

Fermilab, November 14-15, 2013
Outline

- Parton shower event generators, parton shower types
- Improving the splitting kernels
- Status of different parton showers
- Open issues
Event generators need to model

- Hard interactions,
- (initial or final state) radiation,
- multiple scatterings and beam remnants,
- hadronisation and hadron decays.
Hadronic events

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- (Initial or final state) radiation, \(\leftarrow\) Perturbative improvements possible.
- Multiple scatterings and beam remnants,
- Hadronisation and hadron decays.
Parton showers

- model the radiation cascade.
- facilitate a perturbative resummation of dominant logs.
- are interfaced to non-perturbative generator components.
- need to “be okay” many different data sets.

Status: Formally only LL for inclusive observables.
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The end... thanks for your time.
Parton showers

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Status: Formally only LL for inclusive observables.

But parton showers contains many improvements that are necessary to

(a) allow a matching to fixed-order
(b) help to describe data

In what way are parton showers better than LL?
Parton showers

How do we derive a parton shower?

(a) From collinear limit → DGLAP showers
   (PYTHIA6-$Q^2$, Herwig++, KRKMC showers, WHIZARD showers)

(b) From soft limit → Dipole antenna showers
   (ARIADNE, VINCIA, ANTS)

(c) From NLO calculations → Partitioned dipole showers
   (SHERPA CS shower, Herwig++ dipole shower, PYTHIA8)
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Once we have a parton shower, we include improvements to match onto fixed-order results:

- ME centric view: Add PS to ME, amend PS where necessary (e.g. improved Sudakov for MC@NLO, truncated showers)
- PS centric view: Take PS, correct some configurations to ME (e.g. ME corrections, PS reweighting)

...a better shower is always a better starting point.
ME-centric improvements

Use improved and “old” showers simultaneously, switch to “old” shower when improved shower no longer needed.

One example: Truncated shower for METS merging.

\[ \rho_{\text{max}} \]

\[ t_{\text{MS}} \]

\[ \rho \]

\[ y \]

\[ y_{\text{max}} \]

\[ \rho \]

\[ \rho \]

\[ \rho \]

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Truncated shower
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Truncated shower

Standard shower
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Truncated shower

Standard shower

Vetoed shower
ME-centric improvements

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A more recent example of PS improvements for ME matching are coloured showers for MC@NLO. For this, remember:

\[
\tilde{B}_n = B_n + V_n + I_n + \int (D^A - D^S)
\]

\[
\sigma_{\text{MC@NLO}} = \tilde{B}_n \left[ \Delta^A(p_{\perp \text{min}}) + \int \frac{D^A}{B_n} \Delta^A(p_{\perp}) \right] + \int [R - D^A]
\]

⇒ For finite \( \int (D^A - D^S) \) without approximations, \( D^A \) needs to have all subleading divergences.

This also includes subleading colour terms!

Subleading colour treatment have been introduced in SHERPA and HERWIG++/MATCHBOX.
Coloured MC@NLO dipole showers in SHERPA

Do $1/N_c$ corrections make a difference?

- Effect of sub-leading color corrections typically $\mathcal{O}(10\%)$
- In most cases also well within parton shower uncertainty
- Can have larger impact on some observables, e.g. $A_{FB}(p_T)$

Slide ©Stefan Höche, see also JHEP 1209 (2012) 049, Phys.Rev. D88 (2013) 014040
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Also includes full spin correlations for gluon splittings.

Slide ©Stefan Höche, see also JHEP 1209 (2012) 049, Phys.Rev. D88 (2013) 014040
First steps towards higher orders in $N_c$.

Include virtual colour rearranging terms in shower evolution. Studied for gaps between jets. 


Correct single emission pattern by full colour correlations. ‘Colour matrix element corrections’ first studied for LEP.


Relative orientation of soft particles to hard three-jet system very sensitive.
HERWIG++

Multiscale Showering.

Improve shower algorithm for soft gluons in multi-scale problems.
Particularly relevant in decays of heavy coloured particles (masses, widths, IR cutoff).

[P. Richardson, D.E. Winn – in preparation]

Double gluon emission pattern in $gg \rightarrow t\bar{t}$ and impact of correction on the top mass.
Eigentunes for Herwig++ similar to PDF error sets.
Investigate impact on jet substructure analysis (including $H \rightarrow b\bar{b}$ POWHEG).

Antenna showers

... or: why was ARIADNE looking so good?

- Antennae quite naturally include coherence effects.
- Fewer antennae compared to partitioned dipoles ($\rightarrow$ antenna showers should be very efficient).
- Antennae lend themselves to ME corrections (less partial fractioning of ME corrections is necessary, on-shell kinematics as for all dipole showers, the $q\bar{q}g$ antenna is the $Z \rightarrow q\bar{q}g$ ME).
Antenna showers: SHERPA
Antenna shower in SHERPA

Motivation

- coherent radiation off colour dipole
- local recoil compensation
- relation to antenna subtraction

Status

- ANTenna Shower (ANTS) implemented (WK kernels)

- two kinematics mappings: WK & antenna mapping
  Gehrmann-De Ridder, Gehrmann, Glover & Heinrich, JHEP 0711 (2007) 058
  Daleo, Gehrmann & Maitre, JHEP 0704 (2007) 016

- needs validation & tuning

Future plans

- implement antenna kernels
- matching & merging
ANTs: preliminary results

1-Thrust, $1 - T$ (charged)

$uds$ events $\ln(1/x_p)$

$Z$ $p_\perp$ reconstructed from dressed electrons

Jet shape $\rho$ for $p_\perp \in 110 - 160 \text{GeV}$, $y \in 0.0 - 0.3$
Antenna showers: VINCIA

Motivation:

- Coherence, PS is a very efficient phase space generator.
- PS-centric matching approach: Have PS that fills full phase space...then correct with full matrix elements.
Smooth Ordering

\[ P_{\text{strong}} = \Theta \left( \hat{p}_{\perp}^2 - p_{\perp}^2 \right) \]

\[ P_{\text{smooth}} = \frac{\hat{p}_{\perp}^2}{\hat{p}_{\perp}^2 + p_{\perp}^2} \times \frac{1}{p_{\perp}^2} \]

\[ \frac{\hat{p}_{\perp}^2}{p_{\perp}^4} \left( 1 - \mathcal{O} \left( \frac{p_{\perp}^2}{\hat{p}_{\perp}^2} \right) \right) \]

\[ A_{2 \rightarrow 3} \]

Strongly Ordered Limit

Strongly Unordered

NB: Antenna Phase Spaces still nested (antenna masses strongly ordered and decreasing)

Z→6: PS/ME Ratio in a flat phase-space scan (log(PS/ME)=0 is good)
New aspects of VINCIA

Helicity-dependence for relativistic partons

Can use a single helicity ME as radiation function

Dominant = MHV (easiest to evaluate) + NMHV + ...

Note: Helicity ≠ Polarization (azimuthal corrs only via ME corrections)

Full 2\textsuperscript{nd} order corrections

One-loop $Z\rightarrow 3$ matrix element:

$\text{Poles}\left(A_3^1(q_1, q_2, q_3)\right) = 2\left(I_{gg}^{(1)}(\epsilon, s_{13}) + I_{qq}^{(1)}(\epsilon, s_{23}) - I_{qq}^{(1)}(\epsilon, s_{123})\right)A_3^0(1, 3, 2)$

$\text{Finite}\left(A_3^1(q_1, q_2, q_3)\right) = -\left(R(y_{13}, y_{23}) + \frac{5}{3}\log y_{13} + \frac{5}{3}\log y_{23}\right)A_3^0(1, 3, 2)$

$R(y, z) = \log y \log z - \log y \log(1 - y) - \log z \log(1 - z) + \frac{\pi^2}{6} - \text{Li}_2(y) - \text{Li}_2(z)$

Note: any coherent LL shower should get the singularities right. The rest goes beyond LL

NLO correction factor to LO antenna function
No leftover logs!

Larkoski, Lopez-Villarejo, Skands, PRD87(2013)054033

Hartgring, Laenen, Skands, JHEP10(2013)127
Automated uncertainties
Evaluated on the fly
by explicit variations
branching by branching

→ Vector of weights
Central weight is unity (unw)
+ 11 alternative weights

μR variations
Subleading antenna terms
pT vs mD evolution
Subleading colour

Disclaimer: formalism for pp still underway
see Ritzmann, Kosower, Skands, PLB718(2013)1345
Analytic Parton Showers


> conventional parton showers:
  > trial splittings
  > if not allowed reject or manually altered
  > probabilities incalculable

> analytic parton showers
  > ensure that either
    > only allowed branchings are generated
    > or probability of rejection is calculable
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WHIZARD approach: Remove veto of disallowed kinematics after momentum reshuffling by performing $1 \rightarrow 3$ and $2 \rightarrow 4$ splittings. ⇒ “PS cross section” is known. Reweighting possible.
Results: Reweighting

LEP @ 91 GeV
Results: Reweighting

\[ \frac{1}{N} \frac{dN}{d(1 - T)} \]

\[\begin{align*}
\alpha_s &= 0.2 \\
\alpha_s &= 0.3 \text{ reweighted to } \alpha_s = 0.2
\end{align*}\]

LEP @ 91 GeV
Electroweak corrections to showers?

- Weak correction is $\sim \alpha_w \ln^2 (\hat{s}/M_w)$.
- Is $W/Z$-boson radiation a necessary ingredient for TeV-jets?
Electroweak corrections to showers?

Weak correction is \( \sim \alpha_w \ln^2 (\hat{s}/M_w) \).

Is W/Z-boson radiation a necessary ingredient for TeV-jets?

Idea: Implement W/Z-shower off QCD processes, and check!
Electroweak showers in PYTHIA: Preliminary results

- Effect of weak emissions in high $p_{\perp}$-jets.
- Possible to give a better description of the $W/Z+$jets production than the normal PS?
- Needed step to be able to recluster all PS histories in the merging/matching approach.
Electroweak showers in PYTHIA: Preliminary results

Uses $s$- or $u + t$-channel ME’s as splitting probabilities. Multiple boson emissions very rare.

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- Possible to give a better description of the $W/Z+$jets production than the normal PS?
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![Graph showing probability vs. number of Z/W bosons]

![Graph showing cross-section vs. number of jets]

\[ \sigma(\geq N_{\text{jet}}), Z \rightarrow \mu^+\mu^-, p_{\perp}(\text{jet}) > 30 \text{ GeV}, |y_{\text{jet}}| < 4.4 \]

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Open issues

There has been a lot of work on showers in the last few years - most of it under the radar. Here some questions:

1. Is there / what is the connection to CSS resummation? How accurate is the PS?
   
   **Problem:** How to factor in recoil effects?
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   **Problem:** Do we have “the same soft gluons”\(^1\)?

\(^1\)Question © Z. Nagy
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4. What about BFKL?
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5. Are there electro-weak Sudakovs?

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...and many more non-perturbative (?) issues!

Is \(\sigma_{\text{eff}}\) universal? What about “The ridge”? What’s wrong with identified flavours @ LHC? Strings vs. clusters?

\(^1\)Question © Z. Nagy
Thanks for your time.