New Developments in Parton Showers

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Goal: solve this

Theory

Fields
Symmetries
Amplitudes
Monte Carlo
Resummation
Strings

Theory worked out to Hadron Level with acceptance cuts (~ detector-independent)

Feedback Loop

Experiment

Hits
0100110
Acceptance
GEANT
B-Field
....

Measurements corrected to Hadron Level with acceptance cuts (~ model-independent)

Work in collaboration with W. Giele, D. Kosower, A. Larkoski, J. Lopez-Villarejo (sector showers, helicity-dependence), A. Gehrmann-de-Ridder, M. Ritzmann (mass effects, initial-state radiation), E. Laenen, L. Hartgring (one-loop corrections)
\[ \mathcal{L} = \bar{\psi}_q^i (i \gamma^\mu) (D_\mu)_{ij} \psi_q^j - m_q \bar{\psi}_q^i \psi_q^i - \frac{1}{4} F^a_{\mu \nu} F^{a \mu \nu} \]

+ quark masses and value of \( \alpha_s \)
Gluon action density: 2.4x2.4x3.6 fm
QCD Lattice simulation from D. B. Leinweber, hep-lat/0004025

\[ \mathcal{L} = \bar{\psi}_q (i \gamma^\mu) (D_\mu)_{ij} \psi^i_q - m_q \bar{\psi}_q^i \psi^i_q - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} \]
Perturbation Theory

Reality is more complicated
Monte Carlo Generators

Calculate Everything $\approx$ solve QCD $\rightarrow$ requires compromise!

Improve Born-level perturbation theory, by including the ‘most significant’ corrections
$\rightarrow$ complete events $\rightarrow$ any observable you want

1. Parton Showers
2. Matching
3. Hadronisation
4. The Underlying Event

1. Soft/Collinear Logarithms
2. Finite Terms, “$K$”-factors
3. Power Corrections (more if not IR safe)
4. ?

(+ many other ingredients: resonance decays, beam remnants, Bose-Einstein, ...)

(\[\text{Diagram of parton showers and hadronisation} \])
Bremsstrahlung

Charges Stopped

The harder they stop, the harder the fluctuations that continue to become strahlung
Bremsstrahlung

\[ d\sigma_X = \ldots \]

\[ d\sigma_{X+1} \sim 2g^2d\sigma_X \frac{ds_{a1}}{s_{a1}} \frac{ds_{1b}}{s_{1b}} \]

\[ d\sigma_{X+2} \sim 2g^2d\sigma_{X+1} \frac{ds_{a2}}{s_{a2}} \frac{ds_{2b}}{s_{2b}} \]

\[ d\sigma_{X+3} \sim 2g^2d\sigma_{X+2} \frac{ds_{a3}}{s_{a3}} \frac{ds_{3b}}{s_{3b}} \]

This gives an approximation to infinite-order tree-level cross sections (here “DLA”)

But something is not right …

Total cross section would be infinite …
Loops and Legs

Summation

Loops

X\(^{(2)}\) X\(^{(2)}\) +1 X\(^{(2)}\)+1 ... 
X\(^{(1)}\) X\(^{(1)}\) +1 X\(^{(1)}\)+1 +2 X\(^{(1)}\)+2 +3 X\(^{(1)}\)+3 ... 
Born X\(^{(0)}\) +1 X\(^{(0)}\)+1 +2 X\(^{(0)}\)+2 +3 X\(^{(0)}\)+3 ... 

The Virtual corrections are missing

Universality (scaling)

Jet-within-a-jet-within-a-jet-...
Resummation

\[ d\sigma_X = \ldots \]

\[ d\sigma_{X+1} \sim 2g^2 d\sigma_X \frac{ds_{a1}}{s_{a1}} \frac{ds_{1b}}{s_{1b}} \]

\[ d\sigma_{X+2} \sim 2g^2 d\sigma_{X+1} \frac{ds_{a2}}{s_{a2}} \frac{ds_{2b}}{s_{2b}} \]

\[ d\sigma_{X+3} \sim 2g^2 d\sigma_{X+2} \frac{ds_{a3}}{s_{a3}} \frac{ds_{3b}}{s_{3b}} \]

Unitarity

KLN:
\[ \text{Virt} = - \text{Int(Tree)} + F \]
In LL showers: neglect F

Imposed by Event evolution:

When (X) branches to (X+1):
Gain one (X+1). Loose one (X).

\[ \sigma_{X+1}(Q) = \sigma_{X;\text{incl}} - \sigma_{X;\text{excl}}(Q) \]

\[ \rightarrow \text{includes both real and virtual corrections (in LL approx)} \]
Bootstrapped pQCD

Resummation

Born + Shower

Unitarity

Exponentiation

Universality (scaling)

Jet-within-a-jet-within-a-jet-...
Matching

A (Complete Idiot’s) Solution – Combine

1. \([X]_{\text{ME}} + \text{showering}\)
2. \([X + 1 \text{ jet}]_{\text{ME}} + \text{showering}\)
3. ...

- Run generator for \(X\) (+ shower)
- Run generator for \(X+1\) (+ shower)
- Run generator for … (+ shower)

Combine everything into one sample
The Matching Game

Solution 1: “Additive” (most widespread)

Add event samples, with modified weights

\[ w_X = |M_X|^2 \]
\[ w_{X+1} = |M_{X+1}|^2 - \text{Shower}\{w_X\} \]
\[ w_{X+n} = |M_{X+n}|^2 - \text{Shower}\{w_X, w_{X+1}, ..., w_{X+n-1}\} \]

HERWIG: for \( X+1 \) @ LO (Shower = 0 in dead zone of angular-ordered shower)

MC@NLO: for \( X+1 \) @ LO and \( X \) @ NLO (note: correction can be negative)

CKKW & MLM: for all \( X+n \) @ LO (force Shower = 0 above “matching scale” and add ME there)

SHERPA (CKKW), ALPGEN (MLM + HW/PY), MADGRAPH (MLM + HW/PY), PYTHIA8 (CKKW-L from LHE files), ...

\[ d\sigma_{X+1} \sim 2g^2 d\sigma_X \frac{ds_{a1}}{s_{a1}} \frac{ds_{1b}}{s_{1b}} \]

Adding back full ME for \( X+n \) would be overkill

Shower off \( X \) already contains LL part of all \( X+n \)
The Matching Game

Solution 2: “Multiplicative”

One event sample

\[ w_X = |M_X|^2 + \text{Shower} \]

Make a “course correction” to the shower at each order

\[ R_{X+1} = |M_{X+1}|^2 / \text{Shower}\{w_X\} + \text{Shower} \]
\[ R_{X+n} = |M_{X+n}|^2 / \text{Shower}\{w_{X+n-1}\} + \text{Shower} \]

PYTHIA: for X+1 @ LO (for color-singlet production and ~ all SM and BSM decay processes)

POWHEG: for X+1 @ LO and X @ NLO (note: positive weights)

VINCIÁ: for all X+n @ LO and X @ NLO (only worked out for decay processes so far)
Markov pQCD

Start at Born level

\[ |M_F|^2 \]

Generate “shower” emission

\[ |M_{F+1}|^2 \overset{LL}{\sim} \sum_{i\in \text{ant}} a_i \, |M_F|^2 \]

Correct to Matrix Element

 PYTHIA trick

\[ a_i \rightarrow \frac{|M_{F+1}|^2}{\sum a_i |M_F|^2} a_i \]

Unitarity of Shower

Virtual = \(-\int \text{Real}\)

Correct to Matrix Element

 POWHEG trick

\[ |M_F|^2 \rightarrow |M_F|^2 + 2\text{Re}[M_F^1 M_F^0] + \int \text{Real} \]

\[ |M_F|^2 \rightarrow |M_F|^2 + 2\text{Re}[M_F^1 M_F^0] + \int \text{Real} \]

\[ \text{MC@NLO & POWHEG} \]

\[ \text{MLM & CKKW} \]

\[ \text{LO for } 1^\text{st} \text{ emission} \]

\[ \text{LL for } 2^\text{nd} \text{ emission and beyond} \]

\[ \rightarrow \text{“Matching Scale”} \]

\[ \rightarrow \text{hierarchies not matched} \]

GKS, PRD78 (2008)014026
GKS, PRD84 (2011)054003
In a traditional parton shower, you would face the following problem:

Existing parton showers are not really Markov Chains

Further evolution (restart scale) depends on which branching happened last

$\rightarrow$ proliferation of terms

Number of histories contributing to $n^{th}$ branching $\propto 2^n n!$

(+ parton showers have complicated and/or frame-dependent phase-space mappings, especially at the multi-parton level)
**Antenna showers:** one term per parton pair \(2^n \rightarrow n!\)

+ **Change “shower restart” to Markov criterion:**
  
  Given an \(n\)-parton configuration, “ordering” scale is
  
  \[ Q_{\text{ord}} = \min(Q_{E1}, Q_{E2}, \ldots, Q_{En}) \]

  Unique restart scale, independently of how it was produced

+ **Matching:** \(n! \rightarrow n\)
  
  Given an \(n\)-parton configuration, its phase space weight is:
  
  \[ |M_n|^2 : \text{Unique weight, independently of how it was produced} \]

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**Giele, Kosower, Skands, PRD 84 (2011) 054003**


**Lopez-Villarejo, Skands, JHEP 1111 (2011) 150**

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**Matched Markovian Antenna Shower:**

- After 2 branchings: 2 terms
- After 3 branchings: 3 terms
- After 4 branchings: 4 terms

+ **Sector antennae** \( \rightarrow 1 \) term at any order

**Parton- (or Catani-Seymour) Shower:**

- After 2 branchings: 8 terms
- After 3 branchings: 48 terms
- After 4 branchings: 384 terms
Q: How well do showers do?

Exp: Compare to data. Difficult to interpret; all-orders cocktail including hadronization, tuning, uncertainties, etc

Th: Compare products of splitting functions to full tree-level matrix elements

Approximations

Plot distribution of $\log_{10}(PS/ME)$

Z→ 4
- Vincia 1.025 + MadGraph 4.426
- Matched to Z→ 3
- Strong Ordering

Z→ 5
- Vincia 1.025 + MadGraph 4.426
- Matched to Z→ 3
- Strong Ordering

Z→ 6
- Vincia 1.025 + MadGraph 4.426
- Matched to Z→ 3
- Strong Ordering

Dead Zone: 1-2% of phase space have no strongly ordered paths leading there

*fine from strict LL point of view: those points correspond to “unordered” non-log-enhanced configurations
Generate Branchings without imposing strong ordering

At each step, each dipole allowed to fill its entire phase space

Overcounting removed by matching
+ smooth ordering beyond matched multiplicities

\[
\frac{\hat{p}_1^2}{\hat{p}_1^2 + p_{LL}^2} \quad \text{last branching}
\]
\[
\frac{\hat{p}_1^2}{p_1^2} \quad \text{current branching}
\]
→ Better Approximations

Distribution of $\log_{10}(PS_{LO}/ME_{LO})$ (inverse $\sim$ matching coefficient)

**Z→4**
- Vincia 1.025 + MadGraph 4.426
- Matched to Z→3
- Strong Ordering

**Z→5**
- Vincia 1.025 + MadGraph 4.426
- Matched to Z→3
- Strong Ordering

**Z→6**
- Vincia 1.025 + MadGraph 4.426
- Matched to Z→3
- Strong Ordering

Leading Order, Leading Color, Flat phase-space scan, over all of phase space (no matching scale)

**Z→4**
- Vincia 1.025 + MadGraph 4.426
- Matched to Z→3
- Smooth Ordering

**Z→5**
- Vincia 1.025 + MadGraph 4.426
- Matched to Z→3
- Smooth Ordering

**Z→6**
- Vincia 1.025 + MadGraph 4.426
- Matched to Z→3
- Smooth Ordering

No dead zone
\[ \text{+ Matching (+ full colour)} \]

\[ Z \rightarrow 4 \]
Vincia 1.025 + MadGraph 4.426
Matched to Z\( \rightarrow 3 \)
Smooth Ordering

\[ Z \rightarrow 5 \]
Vincia 1.025 + MadGraph 4.426
Matched to Z\( \rightarrow 3 \)
Smooth Ordering

\[ Z \rightarrow 6 \]
Vincia 1.025 + MadGraph 4.426
Matched to Z\( \rightarrow 3 \)
Smooth Ordering

\[ \rightarrow \text{A very good all-orders starting point} \]
## SPEED: milliseconds / Event

<table>
<thead>
<tr>
<th>MS/EVENT</th>
<th>Strategy</th>
<th>Z→3</th>
<th>Z→4</th>
<th>Z→5</th>
<th>Z→6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Monte Carlo</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pythia 8</td>
<td>TS</td>
<td>0.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initialization time ~ 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vincia (sector, (Q_{\text{match}} = 5 \text{ GeV}))</td>
<td>GKS</td>
<td>0.26</td>
<td>0.50</td>
<td>1.40</td>
<td>6.70</td>
</tr>
<tr>
<td>Initialization time ~ 0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sherpa ((Q_{\text{match}} = 5 \text{ GeV}))</td>
<td>CKKW</td>
<td>5.15*</td>
<td>53.00*</td>
<td>220.00*</td>
<td>400.00*</td>
</tr>
<tr>
<td>(expect similar scaling for MLM)</td>
<td></td>
<td>1.5 minutes</td>
<td>7 minutes</td>
<td>22 minutes</td>
<td>2.2 hours</td>
</tr>
</tbody>
</table>

Matched through:

- \(Z \rightarrow q\bar{q} (q=udscb) + \text{shower.} \)
- Matched and unweighted. Hadronization off gfortran/g++ with gcc v.4.4 -O2 on single 3.06 GHz processor with 4GB memory.

Efficient Matching with Sector Showers

J. Lopez-Villarejo & PS: JHEP 1111 (2011) 150
Uncertainties
Uncertainty Variations

A result is only as good as its uncertainty

Normal procedure:

*Run MC 2N+1 times (for central + N up/down variations)*

- Takes 2N+1 times as long
- + uncorrelated statistical fluctuations

Automate and do everything in one run

VINCI: all events have weight = 1

Compute *unitary* alternative weights on the fly

→ *sets of alternative weights representing variations (all with \(<w>=1\)*

*Same events, so only have to be hadronized/detector-simulated ONCE!*

MC with Automatic Uncertainty Bands
Uncertainties

For each branching, recompute weight for:

- Different renormalization scales
- Different antenna functions
- Different ordering criteria
- Different subleading-color treatments

+ Matching

Differences explicitly matched out

(Up to matched orders)

(Can in principle also include variations of matching scheme…)

+ Unitarity

For each failed branching:

\[ P_{2;\text{no}} = 1 - P_2 = 1 - \frac{\alpha_s a_2}{\alpha_s a_1} P_1 \]
**Automatic Uncertainties**

Vincia:uncertaintyBands = on

**Variation of renormalization scale** (no matching)
Automatic Uncertainties

Vincia:uncertaintyBands = on

Variation of “finite terms” (no matching)
Putting it Together

VinciaMatching:order = 0

Vincia 1.025 + Pythia 8.150

Data from Phys.Rept. 399 (2004) 71

VinciaMatching:order = 3

Vincia 1.025 + MadGraph 4.426 + Pythia 8.150

Data from Phys.Rept. 399 (2004) 71
VINCIA STATUS

Next steps

Multi-leg one-loop matching
(with L. Hartgring & E. Laenen, NIKHEF)

Helicity-dependent Showers
(with A. Larkoski, SLAC, & J. Lopez-Villarejo, CERN)

→ Initial-State Showers
(with W. Giele, D. Kosower, S. Mrenna, M. Ritzmann)

http://projects.hepforge.org/vincia
Conclusions

• **QCD Phenomenology** is witnessing a rapid evolution: LO & NLO matching, better showers, tuning, interfaces ...
  - Driven by demand for high precision in complex LHC environment with huge phase space

• **BSM Physics**
  - Generally relies on chains of tools (MC4BSM)
  - Sufficient to reach O(10%) accuracy, with hard work, though must be careful with scale hierarchies, width effects, decay distributions, …
  - Next machine is a long way off → must strive to build capacity for yet higher precision, to get max from LHC data.

• **Ultimate limit set by solutions to pQCD** (getting better) and then the **really** hard stuff
  - Like Hadronization, Underlying Event, Diffraction, … (& BSM equivalents?)
  - For which fundamentally new ideas may be needed

For more, see the *MCnet Review: General-purpose event generators for LHC physics*: arXiv:1101.2599
Backup Slides
Generate Trials without imposing strong ordering

At each step, each dipole allowed to fill its entire phase space

Overcounting removed by matching

(revert to strong ordering beyond matched multiplicities)
Isolate double-collinear region:

\[ Z \to 4 : [q,g,g,q\bar{g}] \text{ with } m_{gg} = m_Z \]

\[ \alpha_s^2 \ln^2 \]
LEP event shapes

PYTHIA 8 already doing a very good job
VINCI A adds uncertainty bands + can look at more exclusive observables?
$y_{45} = \text{scale at which 5}^{\text{th}} \text{ jet becomes resolved \sim \text{“scale of 5}^{\text{th}} \text{ jet”}}$
Interesting to look at more exclusive observables, but which ones?

**4-jet angles**

Sensitive to polarization effects

**Good News**

VINCIA is doing reliably well

Non-trivial verification that shower+matching is working, etc.

**Higher-order matching needed?**

PYTHIA 8 already doing a very good job on these observables

**4-Jet Angles**