New Developments in Parton Showers

P. Skands

\[ |M_H^{(0)}|^2 \]

Perturbative Evolution

Hadronization

PYTHIA
Collider Observables
Confrontation with Data

Factorization Scale

Work in collaboration with W. Giele, D. Kosower, J. Lopez-Villarejo, A. Gehrmann-de-Ridder, M. Ritzmann, E. Laenen, L. Hartgring
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Factorization Scale

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| \( M_{H+2}^{(0)} \rangle^2 | M_{H+3}^{(0)} \rangle^2 \\
| M_{H+1}^{(0)} \rangle^2 \\
| M_{H}^{(0)} \rangle^2 |

Parton Showers
Leading Log
Leading Color

Work in collaboration with W. Giele, D. Kosower, J. Lopez-Villarejo, A. Gehrmann-de-Ridder, M. Ritzmann, E. Laenen, L. Hartgring
New Developments in Parton Showers

P. Skands

Factorization Scale

| $M_{H+2}^{(0)}|^2 |M_{H+3}^{(0)}|^2$
| $M_{H+1}^{(0)}|^2$

| $M_{H}^{(0)}|^2$

2Re $[M_{H}^{(1)} M_{H}^{(0)*}]$

Perturbative Evolution

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New Developments in Parton Showers

P. Skands

2Re $[M^{(1)}_H M^{(0)*}_H]$  
$|M^{(0)}_{H+2}|^2 |M^{(0)}_{H+3}|^2$  
$|M^{(0)}_{H+1}|^2$  
$2Re [M^{(1)}_{H+1} M^{(0)*}_{H+1}]$  
$2Re [M^{(1)}_{H+2} M^{(0)*}_{H+2}]$

Perturbative Evolution

2Re $[M^{(1)}_H M^{(0)*}_H]$  
$|M^{(0)}_H|^2$  
$|M^{(0)}_{H+1}|^2$  
$|M^{(0)}_{H+2}|^2 |M^{(0)}_{H+3}|^2$  
$|M^{(0)}_{H+1}|^2$  
$2Re [M^{(1)}_{H+1} M^{(0)*}_{H+1}]$  
$2Re [M^{(1)}_{H+2} M^{(0)*}_{H+2}]$

Perturbative Evolution

Factorization Scale

Work in collaboration with W. Giele, D. Kosower, J. Lopez-Villarejo, A. Gehrmann-de-Ridder, M. Ritzmann, E. Laenen, L. Hartgring

PYTHIA

Collider Observables

Confrontation with Data
“New”?

For matching to the first emission:

= PYTHIA scheme  

(reformulated for antennae)

For matching to the first loop:

= POWHEG scheme  

(Real-emission part same as PYTHIA, hence compatible)

What is new (apart from antennae):  
Giele, Kosower, PS, PRD 84 (2011) 054003

Repeat this for the next emission, and the next, …

GKS ~ multileg scheme (unitary) that reduces to PYTHIA/POWHEG at 1st order

Unitarity → No “matching scale” needed

Faster than MLM, CKKW (no initialization, no separate n-parton phase-spaces)

Calculation also yields ~10 automatic uncertainty estimates at a moderate speed penalty
1\textsuperscript{st} Order: PYTHIA and POWHEG

**PYTHIA**

Real Radiation:
\[
\left. \frac{d\hat{\sigma}}{d\hat{t}} \right|_{\text{PS}} = \left. \frac{d\hat{\sigma}}{d\hat{t}} \right|_{\text{PS1}} + \left. \frac{d\hat{\sigma}}{d\hat{t}} \right|_{\text{PS2}} = \frac{\sigma_0}{\hat{s}} \frac{\alpha_s}{2\pi} \frac{4 \hat{s}^2 + m_W^4}{\hat{t}\hat{u}}. 
\]

Use PS as overestimate. Correct to R/B via veto:
\[
R_{qg\rightarrow q'W}(\hat{s}, \hat{t}) = \frac{(d\hat{\sigma}/d\hat{t})_{\text{ME}}}{(d\hat{\sigma}/d\hat{t})_{\text{PS}}} = \frac{\hat{s}^2 + \hat{u}^2 + 2m_W^2\hat{t}}{\hat{s}^2 + 2m_W^2(\hat{t} + \hat{u})}
\]

Unitarity → Modified Sudakov Factor:
\[
\exp \left( - \int_{\hat{t}}^{\hat{t}_{\text{max}}} dt' \frac{\alpha_s(t')}{2\pi} \sum_a \int_x^1 dz \frac{x' f_a(x', t')}{x f_b(x, t)} P_{a\rightarrow bc}(z) \right)
\]

Inclusive Cross Section (at fixed underlying Born variables):

Unitarity + no normalization correction → remains \(\sigma_0\)

\[
\rightarrow B = \sigma_0 = |M_{\text{Born}}|^2
\]

Cancels when normalizing to \(1/\sigma\) and integrating over Born

Note: → tuning of standalone PYTHIA done with this matching scheme
Should be OK for POWHEG, but could give worries for MLM
B. Cooper et al, arXiv:1109.5295
1st Order: PYTHIA and POWHEG

PYTHIA

Real Radiation:
\[
\frac{d\sigma}{dt}\bigg|_{PS} = \frac{d\sigma}{dt}\bigg|_{PS1} + \frac{d\sigma}{dt}\bigg|_{PS2} = \frac{\sigma_0}{\hat{s}} \frac{\alpha_s}{2\pi} \frac{4}{3} \frac{\hat{s}^2 + m_W^4}{\hat{t} \hat{u}}.
\]

Use PS as overestimate. Correct to R/B via veto:
\[
R_{qg\rightarrow q'W}(\hat{s}, \hat{t}) = \left( \frac{d\sigma/dt}_{ME} \right)_{PS} = \frac{\hat{s}^2 + \hat{u}^2 + 2m_W^2 \hat{t}}{\hat{s}^2 + 2m_W^2 (\hat{t} + \hat{u})} + \text{(analogous for qq\rightarrow gW)}
\]

Unitarity → Modified Sudakov Factor:
\[
\exp \left( -\int_{t_0}^{t_{\text{max}}} dt' \frac{\alpha_s(t')}{2\pi} \sum_a \int_x^1 dz' x' f_a(x', t') \frac{x f_b(x, t')}{x' f_b(x', t')} P_{a\rightarrow bc}(z) \right)
\]

Inclusive Cross Section (at fixed underlying Born variables):

Unitarity + no normalization correction → remains $\sigma_0$

$→ B = \sigma_0 = |M_{\text{Born}}|^2$

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Note: $→$ tuning of standalone PYTHIA done with this matching scheme
Should be OK for POWHEG, but could give worries for MLM
B. Cooper et al, arXiv:1109.5295

POWHEG

Real Radiation:
\[
R_{gq,q} + R_{qg,q} = \frac{d\sigma}{dt}\bigg|_{ME} = \frac{\sigma_0}{\hat{s}} \frac{\alpha_s}{2\pi} \frac{4}{3} \frac{\hat{t}^2 + \hat{u}^2 + 2m_W^2 \hat{s}}{\hat{t} \hat{u}}
\]

(for $qg\rightarrow q'W$)

(using Sjostrand's notation)

Use R/B as splitting kernels (via overestimate + veto)

(Explicit formula only for final-state in org paper → no PDF factors here)

Unitarity → Sudakov Factor:
\[
\Delta_{R_{\text{NLO}}}^{(\text{NLO})}(p_T) = e^{-\int d\Phi_p \frac{R(v, r)}{B(v)} \theta(k_T(v, r) - p_T)}$
\]

(not needed if shower ordered in p_T, though watch out, see next)

Inclusive Cross Section (at fixed underlying Born variables):

Include correction to NLO inclusive level → becomes $\sigma_{\text{NLO}}$

$→ \tilde{B}(v) = B(v) + V(v)$

$+ \int (R(v, r) - C(v, r)) d\Phi_r$

Cancels when normalizing to 1/\sigma and integrating over Born

Drell-Yan: Alioli et al., JHEP 07(2008)060

Drell-Yan: Miu & Sjöstrand, PLB449(1999)313
Standard Les Houches interface (LHA, LHEF) specifies startup scale \texttt{SCALUP} for showers, so “trivial” to interface any external program, including \texttt{POWHEG}.

Problem: for ISR

\[ p_\perp^2 = p_{\perp\text{evol}}^2 - \frac{p_{\perp\text{evol}}^4}{p_{\perp\text{evol},\text{max}}^2} \]

i.e. \( p_\perp \) decreases for \( \theta^* > 90^\circ \) but \( p_{\perp\text{evol}} \) monotonously increasing.

Solution: run “power” shower but kill emissions above the hardest one, by \texttt{POWHEG}’s definition.

Available for ISR-dominated, coming for QCD jets with FSR issues.

\textbf{Note: Other things that may differ in comparisons: PDFs (NLO vs LO), Scale Choices}
VINCI A

What is it?
Plug-in to PYTHIA 8 [http://projects.hepforge.org/vincia]

What does it do?
“Matched Markov antenna showers”

- Improved parton showers
- Re-interprets tree-level matrix elements as $2 \rightarrow n$ antenna functions
- Extends matching to soft region (no “matching scale”)

Automated uncertainty estimates

- Systematic variations of shower functions, evolution variables, $\mu_R$, etc.
- A vector of output weights for each event (central value = unity = unweighted)

Who is doing it?
GEEKS: Giele, Kosower, PS

- Collaborations with Sjostrand (Pythia 8 interface), Gehrmann-de-Ridder & Ritzmann (mass effects), Lopez-Villarejo & Larkoski (sector showers, helicity-dependence), Hartgring & Laenen (NLL/NLO multileg), Diana (ISR), Volunteers (Tuning)
Start at Born level

$|M_F|^2$
Markov pQCD

Start at Born level

\[ |M_F|^2 \]

Generate “shower” emission

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

Start at Born level

\[ |M_F|^2 \]

Generate “shower” emission

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

Correct to Matrix Element

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

PYTHIA trick

\[ +0 \quad +1 \quad +2 \quad +3 \]

Loops

Legs
### Markov pQCD

**Start at Born level**

\[ |M_F|^2 \]

**Generate “shower” emission**

\[ |M_{F+1}|^2 \ll \sum_{i \in \text{ant}} a_i |M_F|^2 \]

**Correct to Matrix Element**

 PYTHIA trick \( a_i \rightarrow \frac{|M_{F+1}|^2}{\sum a_i |M_F|^2} \)

**Unitarity of Shower**

Virtual = \(-\int \) Real
Start at Born level
\[ |M_F|^2 \]

Generate "shower" emission
\[ |M_{F+1}|^2 \sim LL \sum_{i \in \text{ant}} a_i |M_F|^2 \]

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

Unitarity of Shower
Virtual = \(- \int \text{Real}\)

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

POWHEG trick

PYTHIA trick

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

Start at Born level

\[ |M_F|^2 \]

Generate “shower” emission

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

Correct to Matrix Element

\[
\begin{align*}
    a_i &\rightarrow \frac{|M_{F+1}|^2}{\sum a_i |M_F|^2} \\
\end{align*}
\]

Unitarity of Shower

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

Correct to Matrix Element

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

PYTHIA trick

POWHEG trick

Repeat
Markov pQCD

Start at Born level

\[ |M_F|^2 \]

Generate “shower” emission

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

Correct to Matrix Element

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

Unitarity of Shower

Virtual = − \int \text{Real}

Correct to Matrix Element

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

PYTHIA trick

POWHEG trick

Repeat
Markov pQCD

Start at Born level

$$|M_F|^2$$

Generate “shower” emission

$$|M_{F+1}|^2 \sim \sum_{i \in \text{ant}} a_i |M_F|^2$$

Correct to Matrix Element

PYTHIA trick

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

Unitarity of Shower

Virtual = $-\int\text{Real}$

Correct to Matrix Element

POWHEG trick

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

Repeat
**Markov pQCD**

Start at Born level

$$|M_F|^2$$

Generate “shower” emission

$$|M_{F+1}|^2 \sim \sum_{i \in \text{ant}} a_i |M_F|^2$$

Correct to Matrix Element

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

Unitarity of Shower

Virtual = $-$ $\int$ Real

Correct to Matrix Element

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

**The VINCIA Code**

GKS, PRD78(2008)014026
GKS, PRD84(2011)054003
Markov pQCD

Start at Born level
\[ |M_F|^2 \]

Generate “shower” emission
\[ |M_{F+1}|^2 \sim LL \sum_{i \in \text{anti}} a_i |M_F|^2 \]

Correct to Matrix Element
PYTHIA trick
\[ a_i \rightarrow \frac{|M_{F+1}|^2}{\sum a_i |M_F|^2} \]

Unitarity of Shower
Virtual = − \int \text{Real}

Correct to Matrix Element
POWHEG trick
\[ |M_F|^2 \rightarrow |M_F|^2 + 2\text{Re}[M^1_F M^0_F] + \int \text{Real} \]

Repeat

The VINCIA Code

Legs

Loops

+0

+1

+2

+3

GKS, PRD78(2008)014026
GKS, PRD84(2011)054003
Markov pQCD

Start at Born level

\[ |M_F|^2 \]

Generate “shower” emission

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

Correct to Matrix Element

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

Unitarity of Shower

Virtual = − \int \text{Real}

Correct to Matrix Element

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

Repeat

The VINCI code

\[ \sim \text{PYTHIA} \]

\[ + \text{POWHEG} \]

Work in Progress

GKS, PRD78(2008)014026
GKS, PRD84(2011)054003
Markov pQCD

Start at Born level

\[ |M_F|^2 \]

Generate “shower” emission

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

Correct to Matrix Element

PYTHIA trick

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

Unitarity of Shower

Virtual = \(-\int\) Real

Correct to Matrix Element

POWHEG trick

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

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

\[ \sum a_i |M_F|^2 \]

Unitarity of Shower

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

Correct to Matrix Element

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

POWHEG trick

<table>
<thead>
<tr>
<th>Work in Progress</th>
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<tbody>
<tr>
<td>\text{PYTHIA} + \text{POWHEG}</td>
</tr>
<tr>
<td>\text{MC@NLO &amp; POWHEG}</td>
</tr>
<tr>
<td>\text{This Talk}</td>
</tr>
<tr>
<td>\text{MLM &amp; CKKW}</td>
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</tbody>
</table>

The VINCIA Code

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

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

\[ \text{“Matching Scale”} \rightarrow \text{hierarchies not matched} \]

GKS, PRD84(2011)054003
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

→ proliferation of terms

Number of histories contributing to \( n^{\text{th}} \) branching \( \propto 2^n n! \)

\[
\sum a_i |M_F|^2
\]

\( a_i \rightarrow \frac{|M_{F+1}|^2}{\sum a_i |M_F|^2} \)

(+ parton showers have complicated and/or frame-dependent phase-space mappings, especially at the multi-parton level)
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 → proliferation of terms

Number of histories contributing to \( n \text{th} \) branching \( \sim 2^n n! \)

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

Parton- (or Catani-Seymour) Shower:
After 2 branchings: 8 terms
After 3 branchings: 48 terms
After 4 branchings: 384 terms

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

+ 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:
  \[ |M_n|^2 : \text{Unique weight, independently of how it was produced} \]
**Antenna showers:** one term per parton pair \(2^n n! \rightarrow n!\)

**+ Change “shower restart” to Markov criterion:**
Given an \(n\)-parton configuration, “ordering” scale is

\[ Q_{ord} = \min(Q_{E1}, Q_{E2}, ..., Q_{En}) \]

Unique restart scale, independently of how it was produced

**+ Matching: \(n! \rightarrow n\)**
Given an \(n\)-parton configuration, its phase space weight is:

\[ |M_n|^2 : \text{Unique weight, independently of how it was produced} \]

---

**Matched Markovian Antenna Shower:**
- After 2 branchings: 2 terms
- After 3 branchings: 3 terms
- After 4 branchings: 4 terms

+ J. Lopez-Villarejo \(\rightarrow 1\) term at any order

**Parton- (or Catani-Seymour) Shower:**
- After 2 branchings: 8 terms
- After 3 branchings: 48 terms
- After 4 branchings: 384 terms
Approximations

\[
\text{Distribution of } \log_{10}(PS_{\text{LO}}/ME_{\text{LO}}) \text{ (inverse ~ matching coefficient)}
\]

- **Z \rightarrow 4** (second order)
  - Vincia 1.025 + MadGraph 4.426
  - Matched to Z \rightarrow 3
  - Strong Ordering

- **Z \rightarrow 5** (third order)
  - Vincia 1.025 + MadGraph 4.426
  - Matched to Z \rightarrow 3
  - Strong Ordering

- **Z \rightarrow 6** (fourth order)
  - Vincia 1.025 + MadGraph 4.426
  - Matched to Z \rightarrow 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

P. Skands - New Developments in Parton Showers
Better Approximations

Distribution of \( \log_{10}(PS_{LO}/ME_{LO}) \) (inverse ~ 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
Generate Trials 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

\[ \frac{p_{1}^{2}}{p_{\perp}^{2} + p_{\perp}^{2}} P_{\perp} \]

last branching
\[ \frac{p_{1}^{2}}{p_{\perp}^{2}} \]

current branching

VinCIA 1.025

Z→qggq <R₄>

Dead Zone

Smooth Ordering

VinCIA 1.025

Z→qggq <R₄>

Dead Zone

Smooth Ordering
**Generate Trials 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

\[
\frac{\hat{p}_\perp^2}{\hat{p}_\perp^2 + p_{LL}^2} \quad \text{last branching}
\]

\[
\frac{p_{LL}^2}{p_{\perp}^2} \quad \text{current branching}
\]
\[ Z \rightarrow 4 \]
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

\[ \text{A very good all-orders starting point} \]

\[ Z \rightarrow 5 \text{ (third order)} \]
Vincia 1.025 + MadGraph 4.426
Matched to \( Z \rightarrow 4 \)
Color-summed (NLC)

\[ Z \rightarrow 6 \text{ (fourth order)} \]
Vincia 1.025 + MadGraph 4.426
Matched to \( Z \rightarrow 5 \)
Color-summed (NLC)

Remaining matching corrections are small

\[ + \text{ Matching (+ full colour)} \]
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
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

VINClA: 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

<table>
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<tr>
<td>Nominal</td>
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</tr>
<tr>
<td>Variation</td>
<td>( P_2 = \frac{\alpha s_2 a_2}{\alpha s_1 a_1} P_1 )</td>
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### Uncertainties

**For each branching, recompute weight for:**

- Different renormalization scales
- Different antenna functions
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**+ Unitarity**

**For each failed branching:**

$$P_{2,\text{no}} = 1 - P_2 = 1 - \frac{\alpha_s a_2}{\alpha_s a_1} P_1$$
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:

\[ P_{2;\text{no}} = 1 - P_2 = 1 - \frac{\alpha s_2 a_2}{\alpha s_1 a_1} P_1 \]
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

Vincia 1.025 + MadGraph 4.426 + Pythia 8.150

Data from Phys.Rept. 399 (2004) 71
**SECTOR SHOWERS**

**J. Lopez-Villarejo & PS, arXiv:1109.3608**

Also discussed in Larkoski & Peskin, PRD81(2010)054010, PRD84 (2011)034034

- **Dipole-antenna formalism (2 -> 3)**
  
  - Global
  
  - Sector

  **Lund, GGG, GKS**

  \[
  |M^{(n)}|^2 \sim \sum_{i \in \text{clust.}} a_i |M_i^{(n-1)}|^2 \quad \text{for any P.S. point}
  \]

  \[
  |M^{(n)}|^2 \sim \sum_{i \in \text{clust.}} \tilde{a}_i |M_i^{(n-1)}|^2 \Theta_i (\text{P.S.}) \sim \tilde{a}_j |M_j^{(n-1)}|^2
  \]

  **Kosower PRD 57 (1998) 5410**

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\[ \text{Lund, GGG, GKS} \]

\[ \text{shows Global without any ordering condition imposed} \rightarrow \text{overcounting} \]

\[ \text{Vincia 1.025 + MadGraph 4.426} \]

\[ \text{matched to Z} \rightarrow 3 \]

\[ \text{sector vs. global} \]
## Number of Terms

**Global FSR shower**
*(default VINCIA)*

<table>
<thead>
<tr>
<th></th>
<th>&quot;Traditional&quot; parton shower</th>
<th>Vincia Markov global antenna shower</th>
<th>Vincia Markov sector antenna shower</th>
</tr>
</thead>
<tbody>
<tr>
<td># of terms produced in the shower</td>
<td>$2^N N!$</td>
<td>$N$</td>
<td>1</td>
</tr>
</tbody>
</table>

$N = \text{number of emitted partons}$

$\begin{array}{c}
\begin{array}{c}
\sim \\
(3 \rightarrow 4)
\end{array}
\end{array}$

2 terms per phase-space point
**Number of Terms**

→ Sector shower

<table>
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</tbody>
</table>

N = number of emitted partons

\[
\begin{pmatrix}
\sim
\end{pmatrix}
\text{or}
\begin{pmatrix}
\end{pmatrix}
\]

3 \rightarrow 4

1 term per phase-space point
SECTOR IMPLEMENTATION

- Implementation based on the global shower setup.
- Antenna functions are different than in the global case.
  → Challenges (partitioning of collinear radiation singularities)
- Different criteria for separating sectors in phase space
  Looking for “best” sub-LL behavior.
Test: fragmentation function for a quark

Asymptotic behavior

\[ x \to 1 \]
No energy loss

\[ x \to 0 \]
Total energy loss

Hard emissions: bad analytic approx.

\[ \alpha_s^{(0)} = 0.1, \quad g \to q\bar{q}, \quad Q_0 = 1000 \text{ GeV}, \quad Q_{IR} = 2p_{T_{cut}} = 1 \text{ GeV} \]

VINCI 1.026 + PYTHIA 8.150
## Results -> Speed

<table>
<thead>
<tr>
<th>Matched through:</th>
<th>$Z \rightarrow 3$</th>
<th>$Z \rightarrow 4$</th>
<th>$Z \rightarrow 5$</th>
<th>$Z \rightarrow 6$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pythia 6</strong></td>
<td>0.20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pythia 8</strong></td>
<td>0.22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Vincia Global</strong></td>
<td>0.30</td>
<td>0.77</td>
<td>6.40</td>
<td>130.00</td>
</tr>
<tr>
<td><strong>Vincia Sector</strong></td>
<td>0.27</td>
<td>0.63</td>
<td>6.90</td>
<td>52.00</td>
</tr>
<tr>
<td><strong>Vincia Global ($Q_{match} = 5$ GeV)</strong></td>
<td>0.29</td>
<td>0.60</td>
<td>2.40</td>
<td>20.00</td>
</tr>
<tr>
<td><strong>Vincia Sector ($Q_{match} = 5$ GeV)</strong></td>
<td>0.26</td>
<td>0.50</td>
<td>1.40</td>
<td>6.70</td>
</tr>
<tr>
<td><strong>Sherpa ($Q_{match} = 5$ GeV)</strong></td>
<td>5.15*</td>
<td>53.00*</td>
<td>220.00*</td>
<td>400.00*</td>
</tr>
</tbody>
</table>
  * + initialization time

$Z \rightarrow qq$ ($q=udscb$) + shower. Matched and unweighted. Hadronization off

gfortran/g++ with gcc v.4.4 -O2 on single 3.06 GHz processor with 4GB memory

Generator Versions: Pythia 6.425 (Perugia 2011 tune), Pythia 8.150, Sherpa 1.3.0, Vincia 1.026 (without uncertainty bands, NLL/NLC=OFF)

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VINCIA STATUS

Plug-in to PYTHIA 8
Stable and reliable for Final-State Jets (e.g., LEP)

Automatic matching and uncertainty bands
Improvements in shower (smooth ordering, NLC, matching, …)

Paper on mass effects ~ ready
(with A. Gehrmann-de-Ridder & M. Ritzmann)

Next steps

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

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

→ Initial-State Showers
(with W. Giele, D. Kosower, G. Diana, M. Ritzmann)
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HTTP://PROJECTS.HEPFORGE.ORG/VINCIASCODE
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:

\[ Z \rightarrow 4 : [q,g,g,q_{\text{bar}}] \text{ with } m_{gg} = m_Z \]
LEP event shapes

PYTHIA 8 already doing a very good job
VINCI A adds uncertainty bands + can look at more exclusive observables?
Multijet resolution scales

\[ y_{45} = \text{scale at which 5}^{\text{th}} \text{ jet becomes resolved} \sim \text{“scale of 5}^{\text{th}} \text{ jet”} \]
Interesting to look at more exclusive observables, but which ones?

4-Jet Angles

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

Interesting to look at more exclusive observables, but which ones?