QCD showers based on $2 \to 3$ antenna patterns
+ (automated) perturbative uncertainty evaluations
+ matrix-element corrections

a plug-in to PYTHIA 8.2
http://vincia.hepforge.org

VINCIA 1.x for e$^+e^-$ colliders
$\to$ VINCIA 2.0 for pp
Monte Carlo generators aim to give fully exclusive descriptions of collider final states - *both within and beyond the Standard Model*

Explicit modelling of QCD dynamics $\leftrightarrow$ comparison to measurements

Famous example: MC crucial to establish “string effect” in early 80s

Extensively used to design/optimise analyses (*& planning future ones*)

Study observables, sensitivities, effects of cuts, detector efficiencies, ...

Including effects of **initial- and final-state radiation** (*ISR & FSR showers*)

(Sequential) Resonance decays (top quarks, Z/W/H bosons, & BSM)

+ Soft physics: Underlying Event, Hadronisation, Decays, Beam Remnants, ...

**Parton Showers** are based on (iterated) $1\rightarrow 2$ splittings

Starting point is “Leading-Logarithmic” resummation

+ QCD coherence by “angular ordering” (or “dipoles”)

+ Imposing (E,p) conservation $\rightarrow$ recoil effects (“local” or “global”)

+ $|M|^2$ matching, running couplings, spin correlations, ...

See, e.g., MCnet review arXiv:1101.2599, or TASI lectures arXiv:1207.2389
VINCLA is an Antenna Shower

Virtual Numerical Collider with Interleaved Antennae

(For FSR, identical to CDM: colour dipole model)

Splittings are fundamentally $2 \rightarrow 3$ (+ we are now working on $2 \rightarrow 4$)

Each colour antenna undergoes a sequence of splittings

**Antenna radiation functions & phase-space factorisations**

- Collinear Limits $\rightarrow$ DGLAP kernels ($\rightarrow$ collinear factorisation)
- Soft Limits $\rightarrow$ Eikonal factors ($\rightarrow$ Leading-Colour coherence)
- $2 \rightarrow 3$ phase-space maps = **exact, on-shell factorisations of the**
  $(n+1)/n$-parton **phase spaces** ($\rightarrow$ Lorentz invariant, $p_\mu$ conserving,
  and valid over all of phase space - not just in limits)

**+** Non-perturbative limit of colour dipoles/antennae $\rightarrow$ **string pieces**
**→** natural matching onto (string) hadronisation models

Roots in Lund ~ mid-80s: Gustafson, Petterson NPB306(1988)746, ...

What’s new in our approach? (e.g., not in ARIADNE)

- Iterated MECs: matrix-element corrections (since v1.x)
- Backwards antenna evolution for ISR (new in v2.0)
- Automated uncertainty bands/weights (& runtime ROOT displays)
**Example**: quark-quark scattering in hadron collisions

Consider one specific phase-space point (e.g. scattering at $45^\circ$)

2 possible colour flows: A and B

- **A)** "forward" colour flow
- **B)** "backward" colour flow

Kinematics (e.g., Mandelstam variables) are identical. The only difference is the colour-flow assignment.

Figure 4: Angular distribution of the first gluon emission in $qq \rightarrow qq$ scattering at $45^\circ$, for the two different color flows. The light (red) histogram shows the emission density for the forward flow, and the dark (blue) histogram shows the emission density for the backward flow.

PS: coherence also influences the Tevatron top-quark forward-backward asymmetry: see PS, Webber, Winter, JHEP 1207(2012)151
VINCI: Markovian pQCD*

Essentially, an iterative version of MECs / POWHEG

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

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

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

*)pQCD : perturbative QCD

Cutting Edge: Embedding virtual amplitudes = Next Perturbative Order → Precision Monte Carlos

PYTHIA 8

“Higher-Order Corrections To Timelike Jets”
GKS: Giele, Kosower, Skands, PRD 84 (2011) 054003

“An Introduction to PYTHIA 8.2”
Matrix-Element Corrections for ISR

Predictions made with publicly available
VINCIA 2.0.01
(vincia.hepforge.org)
+ PYTHIA 8
+ MADGRAPH 4

LHC: pp → Z + jet(s)

CMS, $\Delta\phi(Z, J_1)$, $\sqrt{s} = 7$ TeV


(slides adapted from Nadine Fischer)
Predictions made with publicly available VINCIA 2.0.01 (vincia.hepforge.org) + PYTHIA 8 + MADGRAPH 4

LHC: pp $\rightarrow$ Z + jet(s)

CMS, $\Delta \phi(Z, J_1)$, $\sqrt{s} = 7$ TeV

- CMS data
- no MECs

$\Delta \phi(Z, J_1)$ [rad]

Angle between Z and the hardest jet

(slides adapted from Nadine Fischer)
Matrix-Element Corrections for ISR

Predictions made with publicly available
VINCI A 2.0.01
(vinci.hepforge.org)
+ PYTHIA 8
+ MADGRAPH 4

LHC: pp → Z + jet(s)

CMS, Δφ(Z, J₁), \( \sqrt{s} = 7 \) TeV

(slides adapted from Nadine Fischer)
Predictions made with publicly available VINCIA 2.0.01 (vincia.hepforge.org) + PYTHIA 8 + MADGRAPH 4

CMS, $\Delta \phi(Z, J_1), \sqrt{s} = 7$ TeV

LHC: $pp \rightarrow Z + \text{jet(s)}$

Never done before for hadron collisions

(slides adapted from Nadine Fischer)
Matrix-Element Corrections for ISR

Predictions made with publicly available
VINCIA 2.0.01
(vincia.hepforge.org)
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+ MADGRAPH 4

CMS, $\Delta\phi(Z, J_1)$, $\sqrt{s} = 7$ TeV

LHC: pp $\rightarrow$ Z + jet(s)

(slides adapted from Nadine Fischer)
Matrix-Element Corrections for ISR

Predictions made with publicly available
VINCIA 2.0.01
(vincia.hepforge.org)
+ PYTHIA 8
+ MADGRAPH 4

LHC: \( pp \rightarrow Z + \text{jet(s)} \)

CMS, \( \Delta \phi(Z, J_1) \), \( \sqrt{s} = 7 \) TeV

MC/Data

\( \frac{1}{d\sigma/d\phi} \)

\( \Delta \phi(Z, J_1) \) [rad]

\( \Delta \phi(Z, J_1) \) [rad]

(Full simulation = including hadronisation & underlying event)

\( \frac{\text{MC}}{\text{Data}} \)

Angle between \( Z \) and the hardest jet

Full writeup:
Fischer, Prestel, Ritzmann, Skands
arXiv: 1605.06142

(slides adapted from Nadine Fischer)
Perturbative QCD is an asymptotic series

Truncate at LO, NLO, ... → attempt to estimate possible size of remaining terms chiefly by scale variations (e.g., $\mu_R$, $\mu_F$)

Reasoning ~ All-orders answer independent of these scales, hence variation at calculated order → minimal remainder

Resummations (incl showers) are all-orders calculations

Main question remains: *what is the possible size of terms beyond the precision of the algorithm/calculation?*

The answer computed by a shower algorithm depends on:

- Scale Choices for each branching ($\mu_R$, $\mu_F$)
- Radiation functions (beyond universal pole structure)
- Starting and Ending Scales
- Choice of resolution measure / evolution variable
- Kinematics Maps / Recoil Strategies
- Treatment of coherence, subleading colour, spin correlations, ...
Automated Shower Uncertainty Bands/Weights

Idea: perform a shower with nominal settings

Ask: what would the probability of obtaining this event have been with different choices of $\mu_R$, radiation kernels, ... ?

Easy to calculate reweighting factors

In MC accept/reject algorithm:

- Accepted Branchings:
  \[ R'_{\text{acc}}(t) = \frac{P'_{\text{acc}}(t)}{P_{\text{acc}}(t)} \]

- Rejected Branchings:
  \[ R'_{\text{rej}}(t) = \frac{1 - P'_{\text{acc}}(t)}{1 - P_{\text{acc}}(t)} \]

Output: vector of weights for each event

One for the nominal settings

+ Alternative weights for each variation

(note: analogous functionality also recently developed for PYTHIA 8, HERWIG++, SHERPA, see references on summary slide)
FSR + ISR shower Monte Carlo based on QCD Antennae

- Splittings regarded as fundamentally $2 \rightarrow 3$ (instead of $1 \rightarrow 2$)
- with (LC) coherent radiation patterns (antenna functions):
  - Collinear Limits $\rightarrow$ DGLAP kernels
  - Soft Limits $\rightarrow$ Soft Eikonals

Implemented as a simple plug-in to PYTHIA 8

+ LO Matrix-Element Corrections (with MEs from MadGraph)
  - For $Z/W/H \rightarrow$ jets & $pp \rightarrow$ jets to $O(\alpha_s^4)$; $pp \rightarrow Z/W/H + \text{jets to } O(\alpha_s^3)$

Automated Uncertainty Bands/Weights

- First proposed (&implemented) for VINCIA
- Now also in PYTHIA 8, HERWIG, SHERPA

(+ VinciaROOT runtime displays for easy visual checks/plots)
The Phenomenology Pipeline

THEORY

Model

Calculations

PHENOMENOLOGY

Observables

EXPERIMENT

Planning
Design
R&D
Hardware
Triggers...

Figure by
T. Sjöstrand

“Jets”

INTERPRETATION

Exclusions
Hints
Evidence
Discoveries
Surprises

Statistical Tests
Validates/Falsify Models
Constrain Free Parameters

Corrects

Measurements

Example: QCD

\[ g^a \]

\[ (-i g_s t^a_{ij} \gamma^\mu) \]

Peter Skands
Monash University
Matrix-Element Corrections

Exploit freedom to choose non-singular terms

**Modify parton shower** to use process-dependent radiation functions for first emission → absorb real correction

\[
\text{Parton Shower} \quad \frac{P(z)}{Q^2} \rightarrow \frac{P'(z)}{Q^2} = \frac{P(z)}{Q^2} \sum_i \frac{P_i(z)}{Q_i^2} |M_n|^2
\]

Process-dependent MEC → \( P' \) different for each process

Done in PYTHIA for all SM decays and many BSM ones

Based on systematic classification of spin/colour structures

Also used to account for mass effects, and for a few \(2 \rightarrow 2\) procs

**Difficult** to generalise beyond \(1^{\text{st}}\) emission (= \(1^{\text{st}}\)-order MECs)

Parton-shower expansions complicated & can have “dead zones”

**First achieved in VINCIA**, by changing from parton showers to “Markovian Antenna Showers”

Now extended to hadron collisions

Bengtsson, Sjöstrand, PLB 185 (1987) 435

Norrbin, Sjöstrand, NPB 603 (2001) 297

(suppressing \(\alpha_s\) and Jacobian factors)

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

Fischer et al, arXiv:1605.06142
Strong Ordering

\[ \ln(p_{\perp}) \]
Smooth Ordering

\[ \ln(p_{\perp}) \]