## VINCIA for Hadron Colliders

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QCD showers based on $2 \rightarrow 3$ antenna patterns

+ (automated) perturbative uncertainty evaluations
+ matrix-element corrections

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


VINCIA 1.x for $\mathrm{e}^{+} \mathrm{e}^{-}$colliders
$\rightarrow$ VINCIA 2.0 for pp

ICHEP 2016 - Chicago
Based on Fischer, Prestel, Ritzmann, Skands - arXiv:1605.06142


## Monte Carlos and Fragmentation

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 $\longleftrightarrow$ 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

E.g., PYTHIA (also HERWIG, SHERPA)

Starting point is "Leading-Logarithmic" resummation

+ QCD coherence by "angular ordering" (or "dipoles")
+ Imposing ( $\mathrm{E}, \mathrm{p}$ ) conservation $\rightarrow$ recoil effects ("local" or "global")
$+|M|^{2}$ matching, running couplings, spin correlations, ...


## VINCIA is an Antenna Shower

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 $(\mathbf{n}+\mathbf{1}) / \mathbf{n}$-parton phase spaces ( $\rightarrow$ Lorentz invariant, $\mathrm{p}_{\mu}$ conserving, and valid over all of phase space - not just in limits)

+ Non-perturbative limit of colour dipoles/antennae $\rightarrow$ string pieces $\rightarrow$ 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)


## New: Hadron Collisions

## Example: quark-quark scattering in hadron collisions

Consider one specific phase-space point (eg scattering at $45^{\circ}$ )
2 possible colour flows: A and B


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 $q q \rightarrow q q$ 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.

## VINCIA: Markovian pQCD*

Essentially, an iterative version of MECs / POWHEG

*)pQCD : perturbative QCD

Start at Born level

$$
\left|M_{F}\right|^{2}
$$

Generate "shower" emission

$$
\begin{gathered}
\longrightarrow\left|M_{F+1}\right|^{2} \stackrel{2 L}{\sim} \sum_{i \in \text { ant }} a_{i}\left|M_{F}\right|^{2} \\
\text { Correct to Matrix Element } \\
a_{i} \rightarrow \frac{\left|M_{F+1}\right|^{2}}{\sum a_{i}\left|M_{F}\right|^{2}} a_{i} \\
\text { Unitarity of Shower } \\
\text { Virtual }=-\int \text { Real } \\
\text { Correct to Matrix Element }
\end{gathered}
$$

$$
\left|M_{F}\right|^{2} \rightarrow\left|M_{F}\right|^{2}+2 \operatorname{Re}\left[M_{F}^{1} M_{F}^{0}\right]+\int \operatorname{Real}
$$


"Higher-Order Corrections To Timelike Jets"
GKS: Giele, Kosower, Skands, PRD 84 (2011) 054003
"An Introduction to PYTHIA 8.2"
Sjöstrand et al., Comput.Phys.Commun. 191 (2015) 159

## Matrix-Element Corrections for ISR



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## Matrix-Element Corrections for ISR

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

+ Pythia 8
+ MadGraph 4

CMS, $\Delta \phi(\mathrm{Z}, \mathrm{JI}), \sqrt{s}=7 \mathrm{TeV}$
LHC: pp $\rightarrow \mathrm{Z}+$ jet(s)

Never done before for hadron collisions
(slides adapted from
Nadine Fischer)


Angle between $Z$ and the hardest jet

## Matrix-Element Corrections for ISR



## Matrix-Element Corrections for ISR



## Precision $\Rightarrow$ Shower Uncertainties

## Perturbative QCD is an asymptotic series

Truncate at LO, NLO, $\ldots \rightarrow$ 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 $\rightarrow$ 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
Can we impose constraints?

Kinematics Maps / Recoil Strategies
Treatment of coherence, subleading colour, spin correlations, ...

## Automated Shower Uncertainty Bands/Weights

Giele, Kosower, Skands PRD84 (2011) 054003 + hadron collisions FPRS 1605.06142 + explicit all-orders proof in Mrenna, Skands 1605.08352
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:
$\forall$ Accepted

$$
R_{\mathrm{acc}}^{\prime}(t)=\frac{P_{\mathrm{acc}}^{\prime}(t)}{P_{\mathrm{acc}}(t)}
$$

$\forall$ Rejected Branchings:

$$
R_{\mathrm{rej}}^{\prime}(t)=\frac{1-P_{\mathrm{acc}}^{\prime}(t)}{1-P_{\mathrm{acc}}(t)}
$$



Output: vector of weights for each event One for the nominal settings + Alternative weights for each variation


[^0]new! Fischer.Prestel. Ritzmann. Skands - arxiv:1605.06142
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 $8 \begin{aligned} & \text { with similar HTML manual, } \\ & \text { example programs, etc }\end{aligned}$

+ LO Matrix-Element Corrections (with MEs from MadGraph)
For $\mathrm{Z} / \mathrm{W} / \mathrm{H} \rightarrow$ jets $\& \mathrm{pp} \rightarrow$ jets to $\mathrm{O}\left(\boldsymbol{\alpha}_{\mathrm{s}}{ }^{4}\right) ; \mathrm{pp} \rightarrow \mathrm{Z} / \mathrm{W} / \mathrm{H}+$ jets to $\mathrm{O}\left(\boldsymbol{\alpha}_{\mathrm{s}}{ }^{3}\right)$
Automated Uncertainty Bands/Weights
First proposed (\&implemented) for VINCIA giele. Kosower. Skands PRo84 201110 S5003

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


## The Phenomenology Pipeline



## Matrix-Element Corrections

## Exploit freedom to choose non-singular terms

Modify parton shower to use process-dependent radiation functions for first emission $\rightarrow$ absorb real correction

$$
\text { Parton Shower } \frac{P(z)}{Q^{2}} \rightarrow \frac{P^{\prime}(z)}{Q^{2}}=\frac{P(z)}{Q^{2}} \underbrace{\frac{\left|M_{n+1}\right|^{2}}{\sum_{i} P_{i}(z) / Q_{i}^{2}\left|M_{n}\right|^{2}}}_{\mathrm{MEC}}
$$

(suppressing $\alpha_{s}$ - and Jacobian
factors)

Process-dependent MEC $\rightarrow \mathrm{P}^{\prime}$ different for each process Done in PYTHIA for all SM decays and many BSM ones

Norrbin, Sjöstrand,
NPB 603 (200I) 297 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

## Strong Ordering



## Smooth Ordering




[^0]:    (note: analogous functionality also recently developed for PYTHIA 8, HERWIG++, SHERPA, see references on summary slide )

