Status and progress of VINCIA

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VINCIA overview

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Full-fledged **antenna shower** in PYTHIA 8.3 (as of October 2019)

- based on **sector showers** [Brooks, CTP, Skands 2003.00702]
  with dedicated **merging framework** [Brooks, CTP 2008.09468]
- generic NLO matching via **PowhegHooks** [Höche, Mrenna, Payne, CTP, Skands 2106.10987]
- FF, IF, II **antenna kinematics** [Fischer, Prestel, Ritzmann, Skands 1605.06142]
- dedicated **resonance-final** (RF) shower [Brooks, Skands 1907.08980]
- **multipole QED shower** [Skands, Verheyen 2002.04939]
- full-fledged **interleaved EW shower** [Brooks, Skands, Verheyen 2108.10786]
- **helicity dependence** in shower and MECs [Fischer, Lifson, Skands 1708.01736]
- **exact** treatment of **mass corrections** [Gehrmann-De Ridder, Ritzmann, Skands 1108.6172]
- dedicated **default tuning** (similar to PYTHIA's Monash tune)

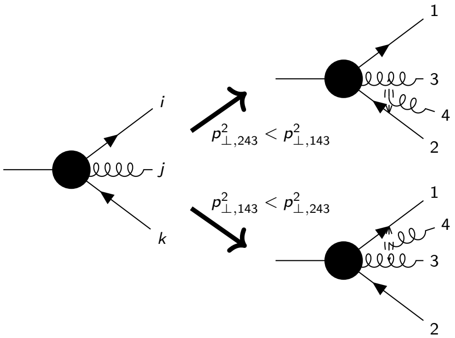
New developments:
second-order shower evolution and fully-differential **NNLO QCD matrix element corrections**
[Campbell, Höche, Li, CTP, Skands 2108.07133]

Status

Sector showers [Brooks, CTP, Skands 2003.00702]

Idea: combine antenna shower with deterministic jet-clustering algorithm [Lopez-Villarejo, Skands 1109.3608]

- let shower only generate emissions that would be clustered by a $(3 \mapsto 2)$ jet algorithm ($\sim$ ARCLUS [Lönnblad Z.Phys.C 58 (1993)])



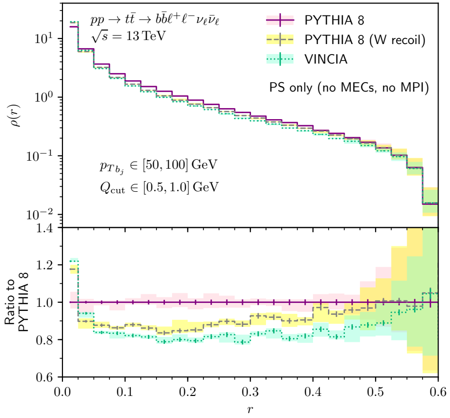
$$p^2_{\perp,ijk} = \frac{2(p_i \cdot p_j)(p_j \cdot p_k)}{p_i \cdot p_j + p_j \cdot p_k + p_i \cdot p_k}$$

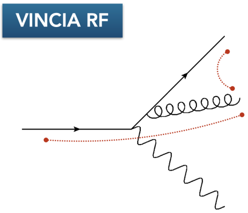
⇒ **softest gluon** always regarded as the emitted one

⇒ only **one** (most singular) splitting kernel contributes per phase space point

Resonance-final antenna showers [Brooks, Skands 1907.08980]

Unique coherent "**resonance-final**" antenna pattern with **global recoil**.





tg RF antenna:

Phase space & recoils set by:

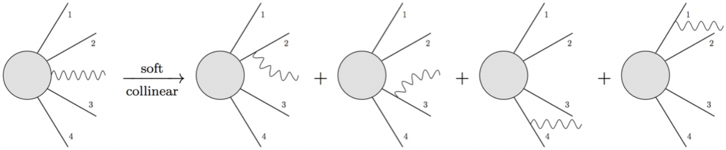
$t - g = b + W$

Collective recoil

VINCIA gives **narrower** *b*-jets than default PYTHIA (survives MPI+hadronisation).
Highly important for precision top-mass studies!

QED multipole showers [Skands, Verheyen 2002.04939]

No large-N_C limit in QED $\Rightarrow$ need to account for **full multipole structure**.

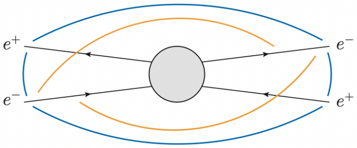


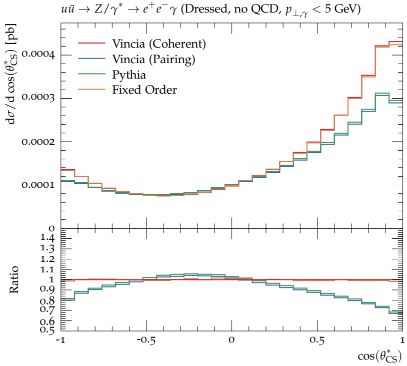
Adapted from R. Verheyen.

In VINCIA taken into account by **sectorisation** of phase space:

$$|M_{n+1}|^2 \approx a^{\text{QED}}(\{p\}, p_j) \sum_{\{i,k\}} \Theta(p^2_{\perp,ijk})\,|M_n|^2$$

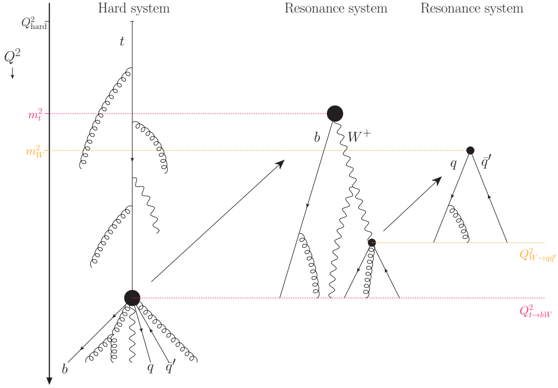
Positive (blue) and negative (orange) contributions included **without negative weights**.





Interleaved EW showers [Brooks, Skands, Verheyen 2108.10786]

All SM $1 \mapsto 2$ splittings included (helicity dependent!), fully **interleaved** with resonance decays and resonance showers.



Sequential

- Complete evolution of the hard system
- Perform resonance shower

Interleaved

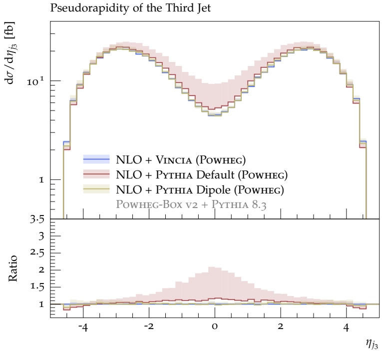
- Evolution up to offshellness scale of the resonance
- Perform resonance shower
- Insert showered decay products and continue evolution

Adapted from R. Verheyen.

Matching and Merging

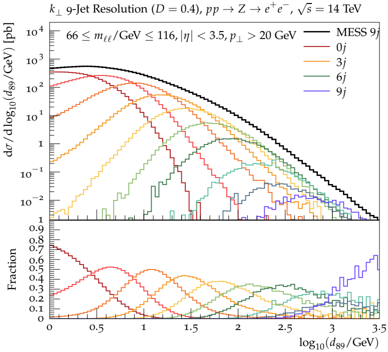
Highly efficient matching and merging (also in complicated topologies) via dedicated **PowhegHooks** and **merging framework**.

POWHEG NLO+PS matching in VBF



[Höche, Mrenna, Payne, CTP, Skands 2106.10987]

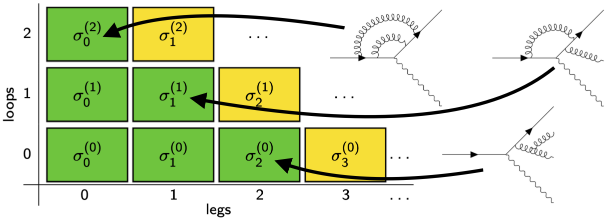
CKKW-L merging in Drell-Yan plus $9j$



[Brooks, CTP 2008.09468]

Work in Progress

VINCIANNLO [Campbell, Höche, Li, CTP, Skands 2108.07133]



Idea: "POWHEG at NNLO"

$$\langle O \rangle^{\mathrm{VINCIA}}_{\mathrm{NNLO+PS}} = \int \mathrm{d}\Phi_2 \, \mathrm{B}(\Phi_2) \, \boxed{k_{\mathrm{NNLO}}(\Phi_2)} \, \boxed{\mathcal{S}_2(t_0, O)}$$

local K-factor shower operator

Need:

(1) Born-local NNLO K-factors: $k_{\mathrm{NNLO}}(\Phi_2)$

(2) NLO MECs in the first $2 \mapsto 3$ shower branching: $w^{\mathrm{NLO}}_{2\mapsto 3}(\Phi_3)$

(3) LO MECs for second (iterated) $2 \mapsto 3$ shower branching: $w^{\mathrm{LO}}_{3\mapsto 4}(\Phi_4)$

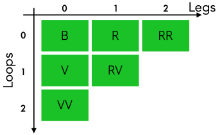
(4) Direct $2 \mapsto 4$ branchings for unordered sector with LO MECs: $w^{\mathrm{LO}}_{2\mapsto 4}(\Phi_4)$

Born-local K-factor

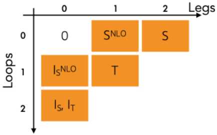
(1) weight each Born-level event by **local** K-factor

$$k_{\mathrm{NNLO}}(\Phi_2) = 1 + \frac{\mathrm{V}(\Phi_2)}{\mathrm{B}(\Phi_2)} + \frac{\mathrm{I}_{\mathrm{S}}^{\mathrm{NLO}}(\Phi_2)}{\mathrm{B}(\Phi_2)} + \frac{\mathrm{VV}(\Phi_2)}{\mathrm{B}(\Phi_2)} + \frac{\mathrm{I}_{\mathrm{T}}(\Phi_2)}{\mathrm{B}(\Phi_2)} + \frac{\mathrm{I}_{\mathrm{S}}(\Phi_2)}{\mathrm{B}(\Phi_2)}$$
$$+ \int \mathrm{d}\Phi_{+1} \left[\frac{\mathrm{R}(\Phi_2, \Phi_{+1})}{\mathrm{B}(\Phi_2)} - \frac{\mathrm{S}^{\mathrm{NLO}}(\Phi_2, \Phi_{+1})}{\mathrm{B}(\Phi_2)} + \frac{\mathrm{RV}(\Phi_2, \Phi_{+1})}{\mathrm{B}(\Phi_2)} - \frac{\mathrm{T}(\Phi_2, \Phi_{+1})}{\mathrm{B}(\Phi_2)} \right]$$
$$+ \int \mathrm{d}\Phi_{+2} \left[\frac{\mathrm{RR}(\Phi_2, \Phi_{+2})}{\mathrm{B}(\Phi_2)} - \frac{\mathrm{S}(\Phi_2, \Phi_{+2})}{\mathrm{B}(\Phi_2)} \right]$$

Fixed-Order Coefficients:



Subtraction Terms (not tied to shower formalism):



Adapted from P. Skands.

Note: requires "Born-local" NNLO subtraction terms. Currently only for simplest cases.

Second-order MECs

Key aspect

up to matched order, include **process-specific** **NLO corrections** into shower evolution:

(2) correct first branching to exclusive ($< t'$) NLO rate:

$$\Delta^{\mathrm{NLO}}_{2\mapsto 3}(t_0, t') = \exp\left\{ -\int_{t'}^{t_0} \mathrm{d}\Phi_{+1}\, \mathrm{A}_{2\mapsto 3}(\Phi_{+1}) w^{\mathrm{NLO}}_{2\mapsto 3}(\Phi_2, \Phi_{+1}) \right\}$$

(3) correct second branching to LO ME:

$$\Delta^{\mathrm{LO}}_{3\mapsto 4}(t', t) = \exp\left\{ -\int_{t}^{t'} \mathrm{d}\Phi'_{+1}\, \mathrm{A}_{3\mapsto 4}(\Phi'_{+1}) w^{\mathrm{LO}}_{3\mapsto 4}(\Phi_3, \Phi'_{+1}) \right\}$$

(4) add direct $2 \mapsto 4$ branching and correct it to LO ME:

$$\Delta^{\mathrm{LO}}_{2\mapsto 4}(t_0, t) = \exp\left\{ -\int_{t}^{t_0} \mathrm{d}\Phi^{>}_{+2}\, \mathrm{A}_{2\mapsto 4}(\Phi_{+2}) w^{\mathrm{LO}}_{2\mapsto 4}(\Phi_2, \Phi_{+2}) \right\}$$

$\Rightarrow$ entirely based on **MECs** and **sectorisation**

$\Rightarrow$ **by construction**, expansion of extended shower **matches** NNLO singularity structure

But shower kernels **do not** define **NNLO subtraction terms**[1] (!)

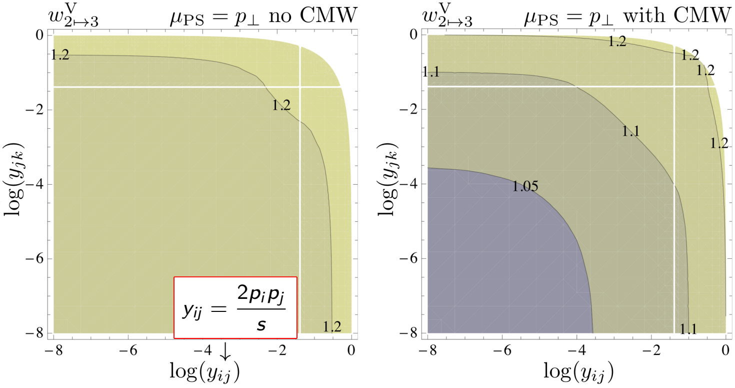
[1] This would be required in an "Mc@Nnlo" scheme, but difficult to realise in antenna showers.

Real-virtual corrections

Real-virtual correction factor ("POWHEG in the exponent")

$$w_{2\mapsto 3}^{\mathrm{NLO}} = w_{2\mapsto 3}^{\mathrm{LO}} \left(1 + w_{2\mapsto 3}^{\mathrm{V}}\right)$$

studied **analytically** in detail for $Z \to q\bar{q}$ in [Hartgring, Laenen, Skands 1303.4974]:

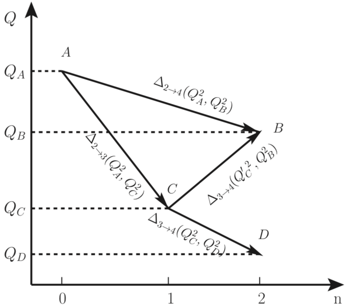


Now: **generalisation** & **(semi-)automation** in VINCIA in form of NLO MECs

Interleaved single and double branchings

A priori, direct $2 \mapsto 4$ and iterated $2 \mapsto 3$ branchings **overlap in ordered** region.

In **sector showers**, iterated $2 \mapsto 3$ branchings are **always strictly ordered**.



Divide double-emission phase space into **strongly-ordered** and **unordered** region:

[Li, Skands 1611.00013]

$$\mathrm{d}\Phi_{+2} = \underbrace{\mathrm{d}\Phi_{+2}^{>}}_{\text{u.o.}} + \underbrace{\mathrm{d}\Phi_{+2}^{<}}_{\text{s.o.}}$$

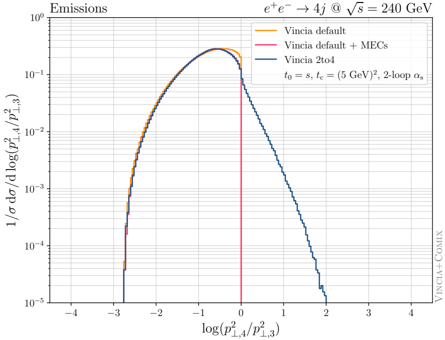
$\mathrm{d}\Phi_{+2}^{<}$: **single-unresolved** limits $\Rightarrow$ iterated $2 \mapsto 3$
$\mathrm{d}\Phi_{+2}^{>}$: **double-unresolved** limits $\Rightarrow$ direct $2 \mapsto 4$

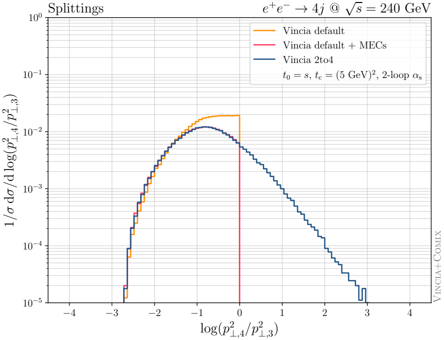
Restriction on double-branching phase space enforced by additional veto:

$$\mathrm{d}\Phi_{+2}^{>} = \sum_j \theta\left(p_{\perp,+2}^2 - \hat{p}_{\perp,+1}^2\right) \Theta_{ijk}^{\mathrm{sct}}\, \mathrm{d}\Phi_{+2}$$

Real and double-real corrections

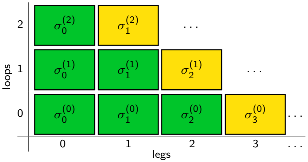
Direct $2 \mapsto 4$ shower component fills **unordered region** of phase space $p^2_{\perp,4} > p^2_{\perp,3}$.





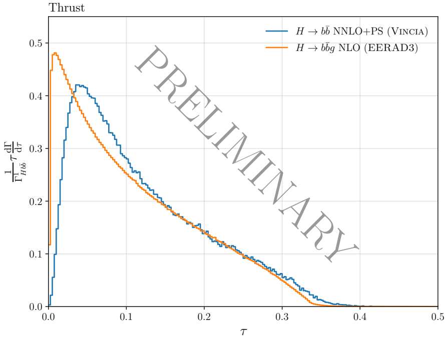
Sectorisation enforces **strict** cutoff at $p^2_{\perp,4} = p^2_{\perp,3}$ in iterated $2 \mapsto 3$ shower. **No recoil effects**!

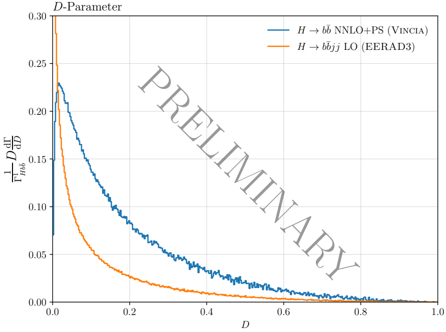
Application: VINCIANNLO in $H \to b\bar{b}$



By construction, partial width is accurate to **NNLO**.

NNLO accuracy at Born level also implies **NLO correction in first emission** and **LO correction in second emission.**





Second-order antenna functions [Braun-White, Glover, CTP 2302.12787]

Ideally, want to implement second-order corrections in shower **beyond first (double-)emission** (e.g. for NNLL).

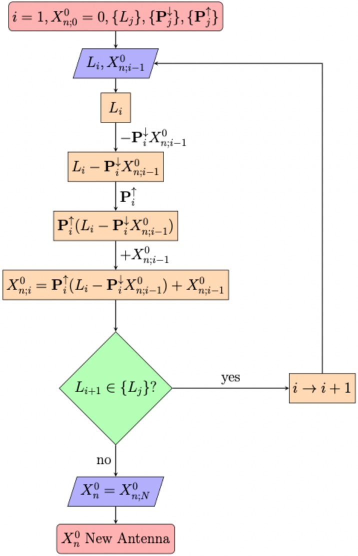
Conceptually, second-order antenna-shower framework fully developed in [Hartgring, Laenen, Skands 1303.4974] and [Li, Skands 1611.00013].

In practice, existing second-order antenna functions in general not suitable for shower algorithms:

- no well-defined radiators
- spurious limits

New algorithm allows to **build suitable** real-emission antena functions directly from list of **required limits** $\{L_1, L_2, \ldots\}$, carefully removing **overlap** between different limits.

Extension to **one-loop antennae** underway (requires manipulation of **explicit poles**).



Final Remarks: logarithmic accuracy

Conclusions

Current status
Full-fledged sector-antenna shower for ISR and FSR, including resonance-final shower, multipole QED shower, and interleaved EW shower.
Efficient sector-based LO merging strategies & POWHEG hooks.

Soon..
VINCIANNLO implementation of SM colour-singlet decays ($V/H \to q\bar{q}$, $H \to gg$)
Automation of iterated tree-level MECs. Using interfaces to MadGraph and COMIX.
Final-final double branchings ($2 \mapsto 4$)

Next few years
Iterated NLO MECs for final-state radiators. Using interface to MCFM.
Incoming partons ($2 \to 4$, NLO MECs, NNLO+PS, ...)

Stay tuned: `pythia-news@cern.ch`