QCD Radiation in VBF Higgs Production with Vincia and Pythia

Christian T Preuss
in collaboration with
Stefan Höche, Stephen Mrenna, Shay Payne, Peter Skands
based on SciPost Phys. 12 (2022) 1, 010 [arXiv:2106.10987]

ETH Zürich
Switzerland

VBF Higgs Working Group
22/02/22

ETH zürich

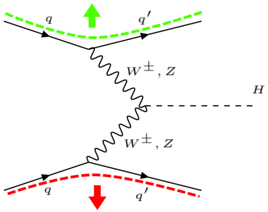
Outline

A lot of recent interest in **parton-shower** & **matching uncertainties** in VBF/VBS.

[Rauch, Plätzer 1605.07851]
[Balllestro et al. 1803.07943]
[Jäger, Karlberg, Plätzer, Scheller, Zaro 2003.12435]
[Buckley et al. 2105.11399]
[Chen, Figy, Plätzer 2109.03730]
[Bittrich et al. 2110.01623]

Key findings:

- $\sim$agreement between showers for **tagging-jet observables**
- discrepancies in observables sensitive to **additional QCD radiation**
- challenges in **matching** and **merging**



Our aim: study **QCD radiation effects** in VBF Higgs production with focus on

- PYTHIA's default DGLAP shower (and its "dipole-recoil" option)
- VINCIA's sector showers*
- uncertainties pertaining to vetoed showers in POWHEG matching
- influence of higher jet multiplicities

*will be explained on the next slide

Baseline: VINCIA antenna shower in PYTHIA 8.3 using

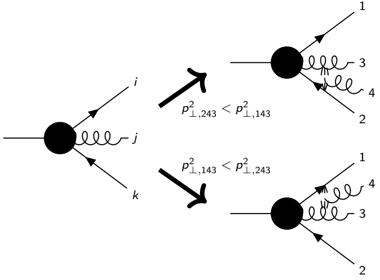
- CKKW-L-style merging [Brooks, CTP 2008.09468]
- POWHEG matching with vetoed showers (new!)

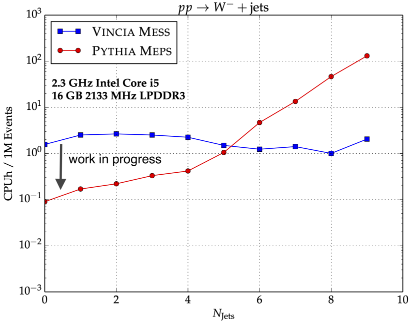
Interlude: sector showers? sector merging?

[Lopez-Villarejo, Skands 1109.3608; Brooks, CTP, Skands 2003.00702; Brooks, CTP 2008.09468]

Idea: combine antenna shower with deterministic jet-clustering algorithm

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





- shower becomes **maximally bijective** (simple to construct history)

$\Rightarrow$ allows for **highly efficient** merging algorithms

Since PYTHIA 8.304: **full-fledged** implementation of sector showers + merging* in VINCIA

*an update compatible with VINCIA's QED shower coming in PYTHIA 8.307

Setup with PYTHIA 8.3

Showers

- PYTHIA default
  - $p_\perp$-ordered **DGLAP shower** with global recoil (ISR), dipole recoil (FSR)
- PYTHIA with "dipole recoil" (**not** just a change of the recoil scheme!)
  - **replaces** DGLAP evolution in IF colour flows by **dipole/antenna evolution**
- VINCIA
  - $p_\perp$-ordered **antenna** shower with recoiler-emitter-agnostic **antenna recoil**

Fixed-order

- SHERPA 2 — $H + (\leq 6)j$ @ tree level
- POWHEG-BOX v2 — $H + 2j$ @ NLO+PS
- PYTHIA internal — $H + 2j$ @ LO for cross checks

structure-function approximation, no same-flavour interference (except in SHERPA), no VH

Analysis

- typical VBF cuts using anti-k_T algorithm with $R = 0.4$ (via FASTJET)

$$p_\mathrm{T} > 25\ \mathrm{GeV}\,, \quad |\eta| < 4.5$$
$$m_{j_1,j_2} \geq 600\ \mathrm{GeV}\,, \quad |\Delta\eta_{j_1 j_2}| > 4.5\,, \quad \eta_{j_1} \cdot \eta_{j_2} \leq 0$$

- on-shell Higgs
- focus on observables sensitive to additional **QCD radiation** (η_{j_3}, p_{T,j_3}, H_T)
- performed with RIVET based on [Jäger, Karlberg, Plätzer, Scheller, Zaro 2003.12435]

The baseline: LO+PS

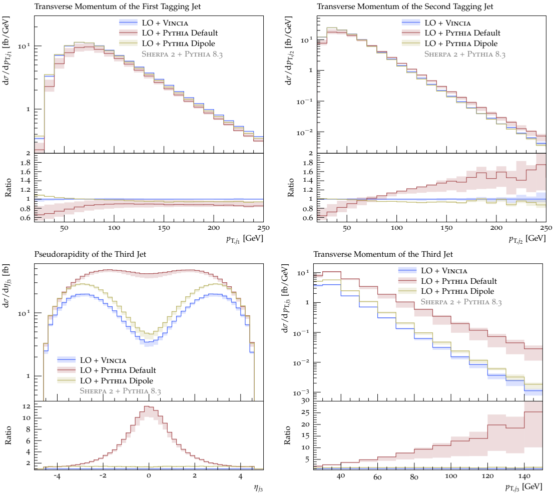
SHERPA 2 + PYTHIA 8.3, CT14_NNLO_as118,

$$\mu_F^2 = \mu_R^2 = \frac{1}{4}\left(\sum_j p_{T,j} + \sqrt{M_H^2 + p_{T,H}^2}\right)^2$$

Reproduce (mostly) known features:

- VINCIA & PYTHIA dipole recoil comparable
- large radiation enhancement in default PYTHIA shower
- large variation with shower starting scale in default PYTHIA shower

  $\mu_{PS} = k_{\text{fudge}}\mu_F\ , \quad k_{\text{fudge}} \in [0.5, 2]$



Internal vs external events

For PYTHIA-internal events:

$$\mu_{\mathrm{F}}^2 = \sqrt{(M_{\mathrm{V}_1}^2 + p_{\mathrm{T,q}_1}^2)(M_{\mathrm{V}_2}^2 + p_{\mathrm{T,q}_2}^2)}$$

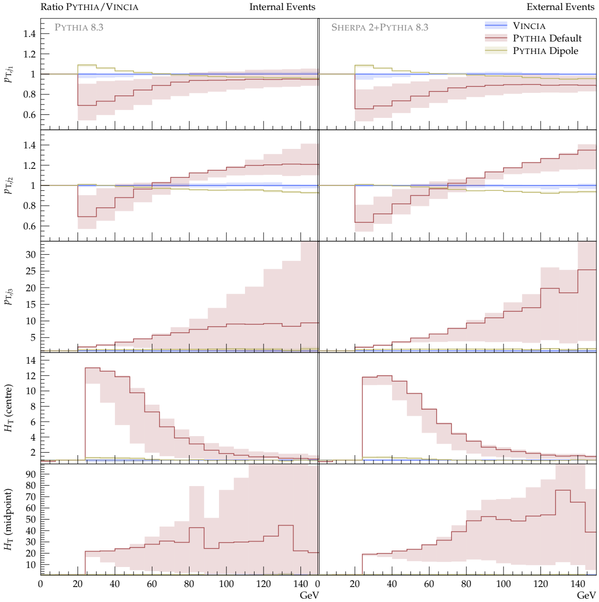
For external SHERPA events:

$$\mu_{\mathrm{F}}^2 = \frac{1}{4}\left(\sum_j p_{\mathrm{T},j} + \sqrt{M_{\mathrm{H}}^2 + p_{\mathrm{T,H}}^2}\right)^2$$

Slightly better behaviour with PYTHIA-internal scale choice, but **dominated** by **starting-scale variation**

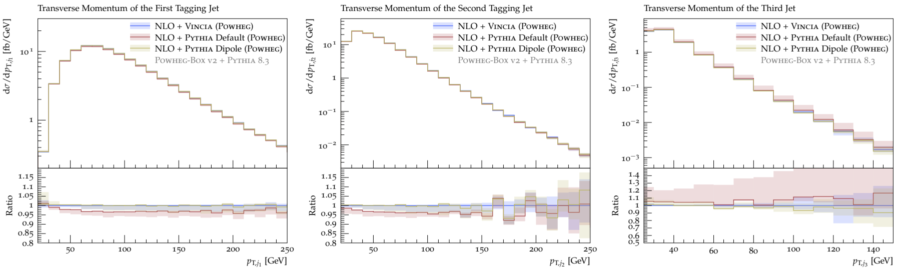
$$\mu_{\mathrm{PS}} = k_{\mathrm{fudge}}\mu_{\mathrm{F}}\,, \quad k_{\mathrm{fudge}} \in [0.5, 2]$$

⇒ not a scale-choice issue
⇒ not due to external events



NLO+PS

POWHEG-BOX v2 + PYTHIA 8.3, CT14_NNLO_as118, $\mu_\mathrm{F}^2 = \mu_\mathrm{R}^2 = \frac{M_\mathrm{H}}{2}\sqrt{\left(\frac{M_\mathrm{H}}{2}\right)^2 + p_{\mathrm{T,H}}^2}$



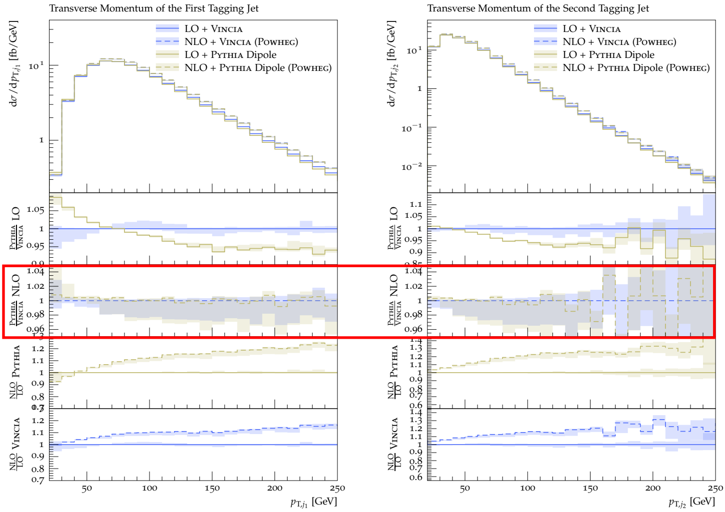
POWHEG matching requires to account for **evolution-variable mismatch**

- in PYTHIA 8.3 done with **vetoed showers** (via "`PowhegHooks`") [Corke, Sjöstrand 1003.2384]
  - start shower at **phase space maximum** ("power showers")
  - **veto** emissions above POWHEG scale
- `PowhegHooksVincia` **publicly available** for VINCIA as of PYTHIA 8.306
- scale setting of Born+1j event via `POWHEG:pThard` mode
  - `POWHEG:pThard = 0` corresponds to LHEF `SCALUP`
  - `POWHEG:pThard = 2` corresponds to minimal shower $p_\perp$

⇒ default PYTHIA shower **requires** `POWHEG:pThard = 2`

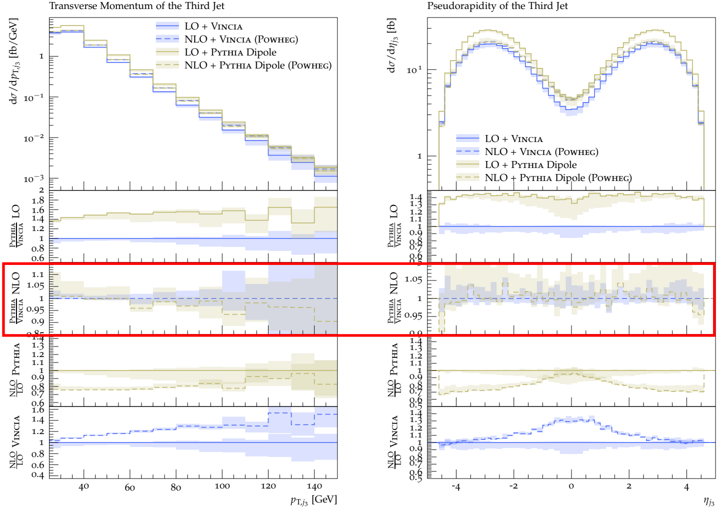
⇒ **good agreement** with **judicious** scale setting

PYTHIA dipole recoil vs VINCIA: tagging jets



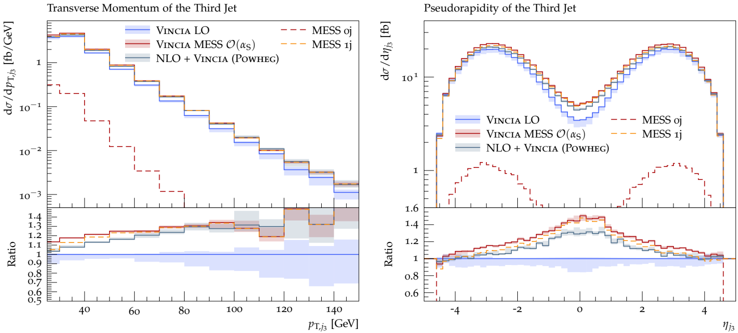
- $\sim 10\%$ difference at LO+PS
- **excellent convergence** at NLO+PS
- comparable corrections, slightly smaller in VINCIA

PYTHIA dipole recoil vs VINCIA: third jet



- $\sim$ 40% difference at LO+PS
- **very good convergence** at NLO+PS
- **negative** corrections with PYTHIA, **positive** corrections with VINCIA

NLO matching vs 1-jet merging



NLO-matched and 1j-merged predictions should be **consistent** for **third-jet** observables.

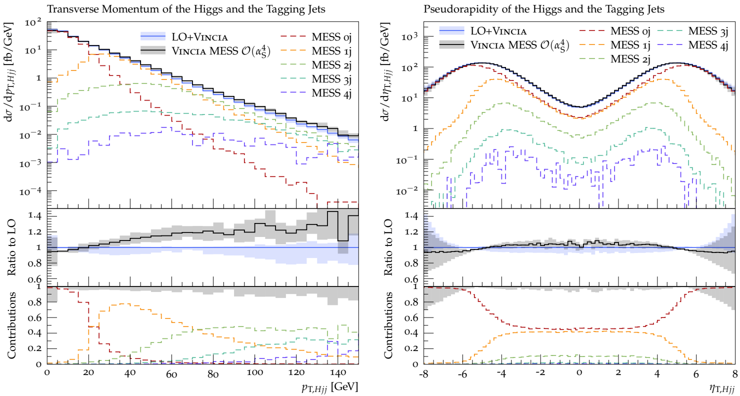
- cross check of **both methods**:
  - vetoed showers (POWHEG) vs. truncated+vetoed showers (CKKW-L)
  - influence of unitarity (CKKW-L non-unitary)

⇒ largely consistent, but increased control with **unitary merging** & **truncated + vetoed** showers in POWHEG matching needed?

Higher jet multiplicities

VINCIA currently **only shower** in PYTHIA 8.3 that handles **merging** VBF/VBS topologies

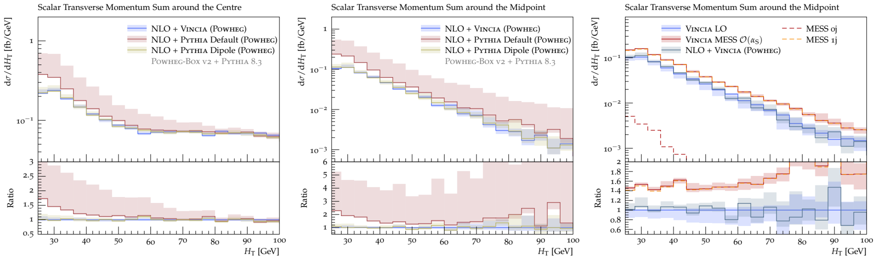
SHERPA 2 + PYTHIA 8.3, CT14_NNLO_as118, $\mu_F^2 = \mu_R^2 = \frac{1}{4}\left(\sum_j p_{T,j} + \sqrt{M_H^2 + p_{T,H}^2}\right)^2$



Include **4 additional jets** at LO via **sector merging** [Brooks, CTP 2008.09468].

- up to $20 - 40\%$ correction at intermediate $p_{T,Hjj}$
- for $p_{T,Hjj} \geq 100$ GeV dominant contribution from $H + 4j$ and $H + 5j$
- for $p_{T,Hjj} \leq 150$ GeV contribution from $H + 6j$ negligible
- negligible correction to pseudorapidity distribution

A measure of coherence? H_T



Introduce **scalar transverse momentum sum** in two phase-space regions:

- central region $\eta \in \left[-\frac{1}{2}, +\frac{1}{2}\right]$
- midpoint region $\eta \in \left[\eta^* - \frac{1}{2}, \eta^* + \frac{1}{2}\right]$ with $\eta^* = \eta - \frac{1}{2}\left(\eta_{j_1} + \eta_{j_2}\right)$

- **soft enhancement** and **large** uncertainties **remain** after NLO matching
- **discrepancies** between NLO matching and 1-jet merging

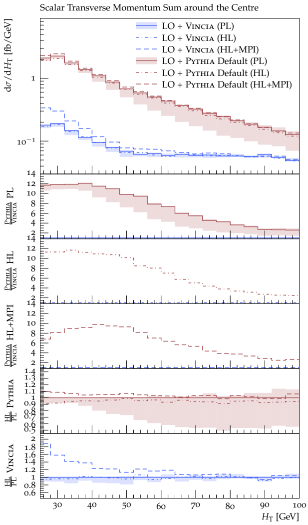
$\Rightarrow$ interesting for experimental measurements?

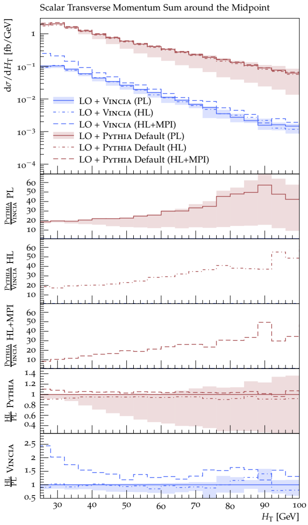
Hadronisation and MPIs

Estimate non-perturbative effects using PYTHIA's default **string hadronisation** model and **interleaved MPIs**.

- **small** hadronisation corrections
- **larger** MPI corrections in coherently-supressed region

⇒ No surprises
⇒ No game changer





Conclusions

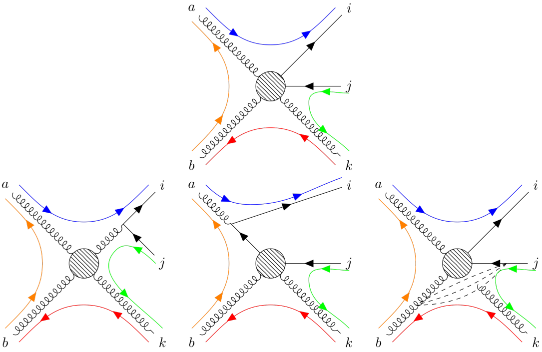
- PYTHIA's (default) DGLAP shower **unable** to describe QCD radiation in VBF/VBS **even after NLO matching** if not done carefully (!)
- `POWHEG:pThard` mode can have **significant** effects (source of **uncertainty**!)
  $\Rightarrow$ recommend to use `POWHEG:pThard = 2`, but ideally **vary** to estimate uncertainty
  $\Rightarrow$ truncated+vetoed showers in POWHEG necessary to control uncertainties?
- VINCIA currently **only shower** in PYTHIA 8.3 to handle **merging in VBF/VBS**
  $\Rightarrow$ corrections beyond first emission important above $p_{\mathrm{T},Hjj} \sim 70\ \mathrm{GeV}$
  $\Rightarrow$ $H + 6j$ corrections negligible below $p_{\mathrm{T},Hjj} \sim 150\ \mathrm{GeV}$
  $\Rightarrow$ unitarised (NLO) merging needed? NLO calculations beyond $H + 3j$?
  $\rightarrow$ cf. also [Chen, Figy, Plätzer 2109.03730]
- moderate hadronisation corrections (with our cuts), **MPIs** more important (in soft region)
  $\Rightarrow$ further investigations and quantification needed
  $\rightarrow$ cf. also [Bittrich et al. 2110.01623]

Since PYTHIA 8.304, VINCIA **ready to use** in "real-life" VBF/VBS setups!
(using **sector showers**, including CKKW-L merging & POWHEG hooks).

VINCIA tutorial (including merging in VBF):
`http://skands.physics.monash.edu/slides/files/Pythia83-VinciaTute.pdf`

Backup

Sector definitions



For massless particles, the sector resolution is defined by:

$$Q^2_{\text{res},j} = \begin{cases} \frac{s_{ij}s_{jk}}{s_{ijk}} & \text{if } j \text{ is a } g \\ s_{ij}\sqrt{\frac{s_{jk}}{s_{ijk}}} & \text{if } (i,j) \text{ is a } q\bar{q} \text{ pair} \end{cases}$$

Sectors defined by:

$$\Theta_{\text{sct},j} = \theta(\min\{Q^2_{\text{res},i}\} - Q^2_{\text{res},j})$$

Sector antenna functions

Splitting kernels have to incorporate **full** single-unresolved limits for given PS point (KOSOWER subtraction terms [Kosower PRD 57 (1998) 5410, PRD 71 (2005) 045016])

- e.g. (FF) $qg \mapsto qgg$ ($s_{ij} = 2p_i \cdot p_j$):

$$A^{\mathrm{sct}}_{qg\mapsto qgg}(i_q, j_g, k_g) \to \begin{cases} \frac{2s_{ik}}{s_{ij}s_{jk}} & \text{if } j_g \text{ soft} \\ \frac{1}{s_{ij}}\frac{1+z^2}{1-z} & \text{if } i_q \parallel j_g \\ \frac{1}{s_{jk}}\frac{2(1-z(1-z))^2}{z(1-z)} & \text{if } j_g \parallel k_g \end{cases}$$

Compare to **global** antenna functions:

- only "half" of the $j_g \parallel k_g$ limit contained in the splitting kernel:

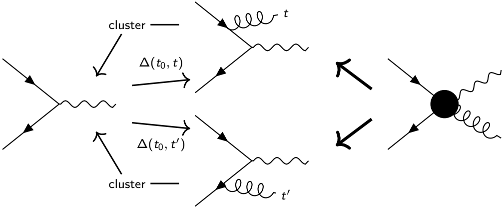
$$A^{\mathrm{gl}}_{qg\mapsto qgg}(i_q, j_g, k_g) \to \begin{cases} \frac{2s_{ik}}{s_{ij}s_{jk}} & \text{if } j_g \text{ soft} \\ \frac{1}{s_{ij}}\frac{1+z^2}{1-z} & \text{if } i_q \parallel j_g \\ \frac{1}{s_{jk}}\frac{1+z^3}{1-z} & \text{if } j_g \parallel k_g \end{cases}$$

- "rest" of the jk-collinear limit reproduced by neighbouring antenna ($z \leftrightarrow 1 - z$)

Merging with sector showers [Brooks, CTP 2008.09468]

Tree-level merging with sector showers straight-forward:
start from CKKW-L and modify **history construction** (could be extended to NLO)

- basic CKKW-L idea [Lönnblad hep-ph/0112284], [Lönnblad, Prestel 1109.4829]
  - construct **all possible** shower histories, choose **most likely**
  - let (truncated) **trial showers** generate Sudakov factors
  - re-weight event by Sudakov factors



- number of histories **scales factorially** with number of legs

Number of Histories for n Branchings

	$n=1$	$n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
CS Dipole	2	8	48	384	3840	46080	645120
Global Antenna	1	2	6	24	120	720	5040

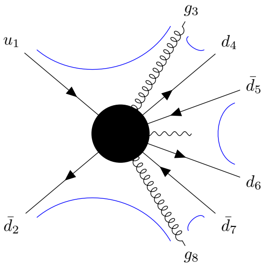
- sector showers have a **single** (!) history for **gluon emissions at LC**

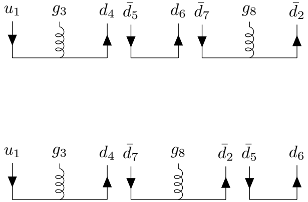
Since PYTHIA 8.304: sector merging available with VINCIA

Merging with sector showers: gluon splittings

Modulo quark permutations, sector showers have a **single history**, i.e., a **unique** inverse.

- to account for all possible $q\bar{q}$-clusterings, find all viable colour orderings



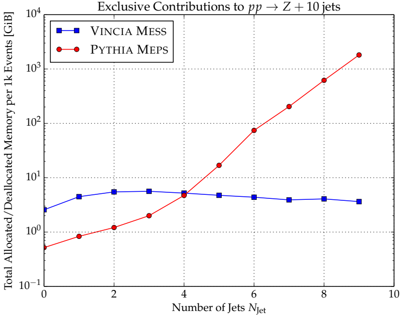


- for each colour-ordering, shower history again **uniquely** defined by sectors
- if multiple colour-orderings possible, choose one that **maximises** branching probability

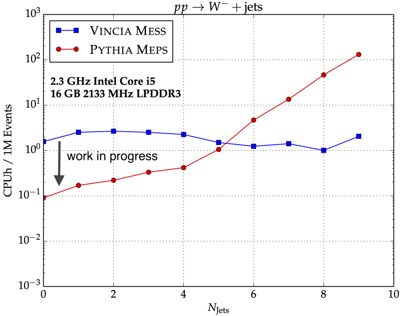
Merging with sector showers: efficiency

Gauge **efficiency gains** in $pp \to Z + 9j$ merging @ parton level
(using HDF5 event samples from [Höche, Prestel, Schulz 1905.05120]).

memory allocation/deallocation:



CPU time per event:



$\Rightarrow$ $\sim$ **constant** runtime and memory footprint in multi-jet merging

$\Rightarrow$ overall **optimisation** of the sector shower **possible**