Status and progress of VINCIA

Christian T Preuss (ETH Zürich)

PSR 2023
Milan Bicocca University
07/06/2023

ETH zürich

VINCIA overview

C.T. Preuss, P. Skands

Full-fledged **antenna shower** in PYTHIA 8.3 (since 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)

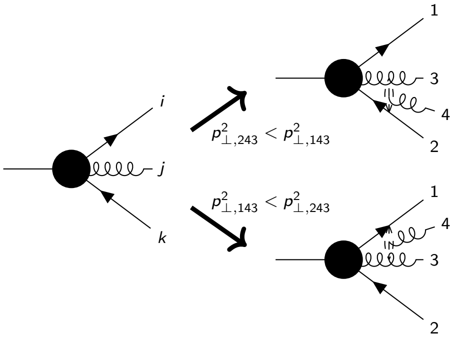
New developments:
second-order shower evolution and fully-differential **NNLO QCD matrix element corrections**
[Campbell, Höche, Li, CTP, Skands 2108.07133]

Status

Sector showers [Brooks, CTP, Skands 2003.00702] → talk at PSR '21

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)])



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

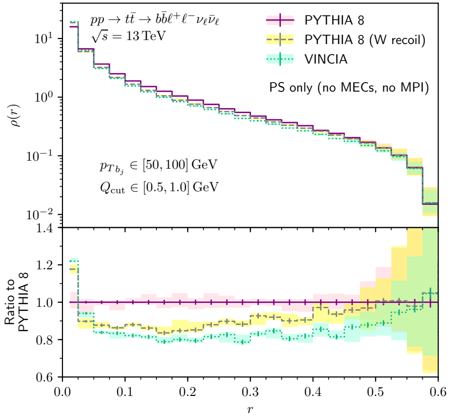
⇒ **softest gluon** always regarded as the emitted one

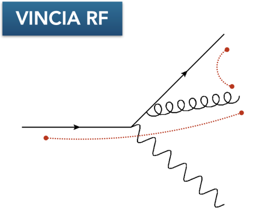
⇒ only **one** (most singular) branching kernel contributes per phase space point

Since PYTHIA 8.304: sector showers **default** option in VINCIA.

Resonance-final showers [Brooks, Skands 1907.08980] → Peter Skands' talk at PSR '19

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





tg RF antenna:

Phase space & recoils set by:

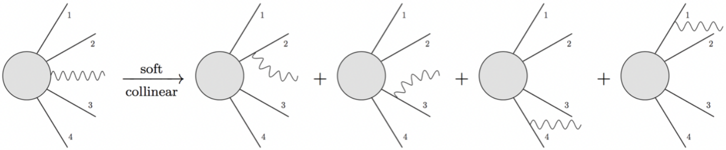
$$t - g = b + W$$

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] → Rob Verheyen's talk at PSR '17

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

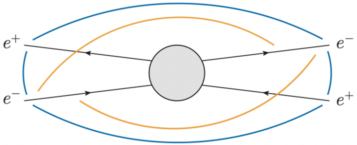


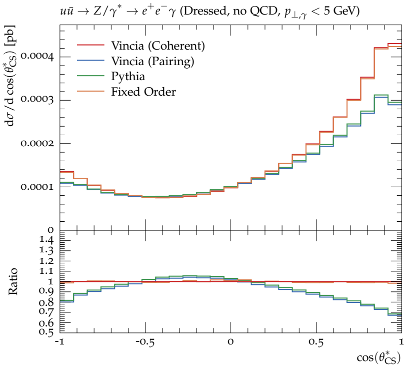
Adapted from R. Verheyen.

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

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

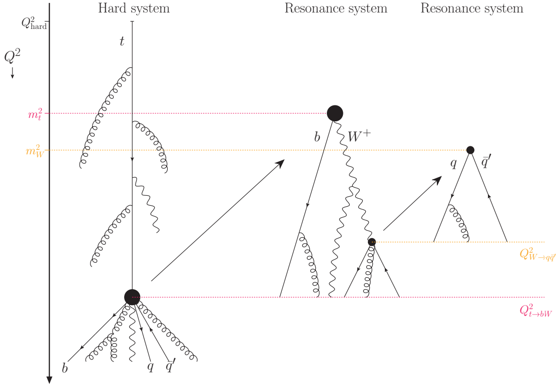
Positive and negative contributions included **without negative weights**.





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

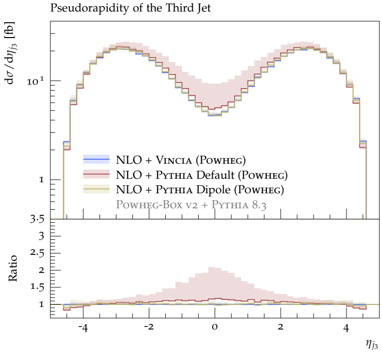
Adapted from R. Verheyen.

Matching and Merging

→ talk at PSR '21

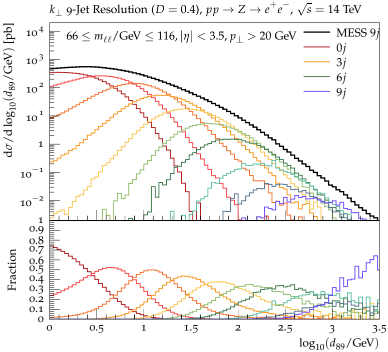
Highly efficient matching and merging (also in complicated topologies) via dedicated **PowhegHooks** and **merging framework**.

POWHEG NLO+PS matching in VBF



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

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



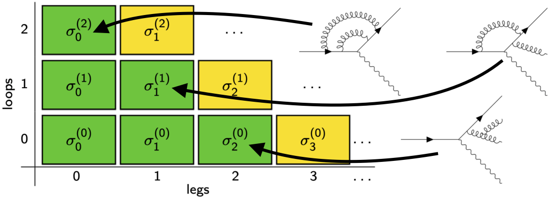
[Brooks, CTP 2008.09468]

* Using HDF5 event samples from [Höche, Prestel, Schulz 1905.05120] generated with SHERPA.

Work in Progress

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

VINCIA NNLO



Resummation-based approaches:
→ Giulia Zanderighi's talk
→ Alessandro Broggio's talk

Idea: fully-differential* multiplicative NNLO matching scheme ("Powheg at NNLO")

Focus here on $e^+e^- \to 2j$:

$$\langle O \rangle^{\text{Vincia}}_{\text{NNLO+PS}} = \int \mathrm{d}\Phi_2 \, \mathrm{B}(\Phi_2) \, \underbrace{\boxed{k_{\text{NNLO}}(\Phi_2)}}_{\text{local } K\text{-factor}} \, \underbrace{\boxed{\mathcal{S}_2(t_0, O)}}_{\text{shower operator}}$$

Need:

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

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

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

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

*I.e., no auxiliary scales, only shower resummation.

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:

Loops \ Legs	0	1	2
0	B	R	RR
1	V	RV	
2	VV		

Subtraction Terms (not tied to shower formalism):

Loops \ Legs	0	1	2
0	0	$\mathrm{S}^{\mathrm{NLO}}$	S
1	$\mathrm{I}_\mathrm{S}^{\mathrm{NLO}}$	T	
2	I_S, I_T		

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:

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

(3) correct second branching to LO ME:

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

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

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

$\Rightarrow$ 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*** (!)

---

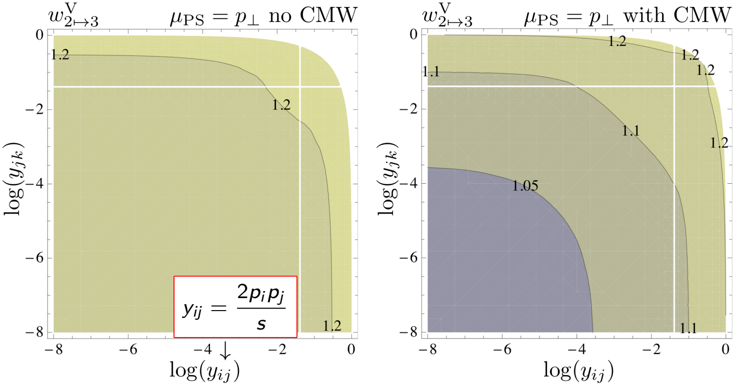
*This would be required in an "Mc@Nnlo" scheme, but difficult to realise in antenna showers.

Real-virtual corrections

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

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

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

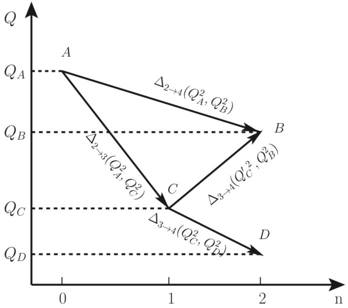


Now: **generalisation** & **(semi-)automation** in VINCIA in form of NLO MECs

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]

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

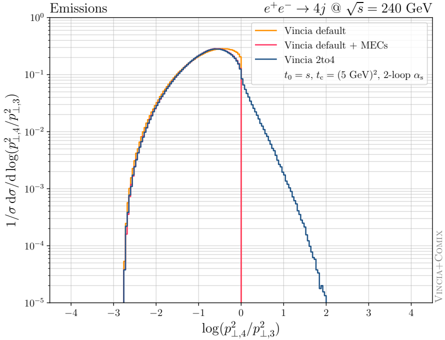
$\mathrm{d}\Phi_{+2}^{<}$: **single-unresolved** limits $\Rightarrow$ iterated $2 \mapsto 3$
$\mathrm{d}\Phi_{+2}^{>}$: **double-unresolved** limits $\Rightarrow$ direct $2 \mapsto 4$

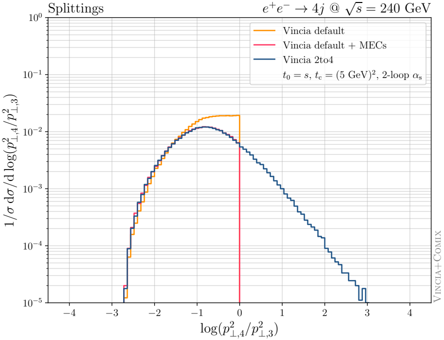
Restriction on double-branching phase space enforced by additional veto:

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

Real and double-real corrections

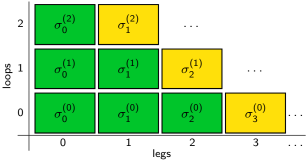
Direct $2 \mapsto 4$ shower component fills **unordered region** of phase space $p^2_{\perp,4} > p^2_{\perp,3}$.





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

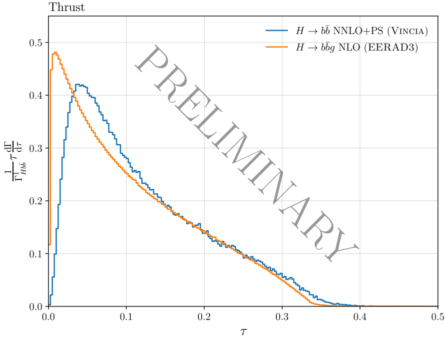
Application: VINCIANNLO in $H \to b\bar{b}$

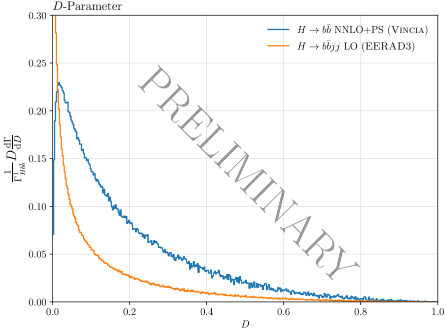


By construction, partial width is accurate to **NNLO**.

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

Compare to (N)LO fixed-order predictions (@ parton level) [Coloretti, Gehrmann-De Ridder, CTP 2202.07333]





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

Ideally, want second-order corrections in shower **beyond first (double-)emission** (→ NNLL, NGLs, ...).

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

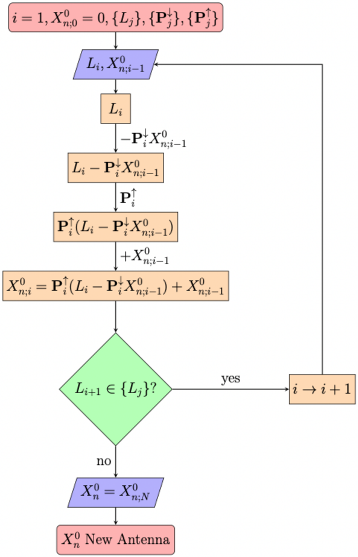
In practice, existing second-order antenna functions in general not suitable for shower algorithms:

- no well-defined radiators
- spurious limits

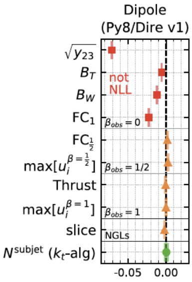
New algorithm allows to **build suitable** real-emission antenna functions directly from list of **required limits** $\{L_1, L_2, \ldots\}$, carefully removing any **overlap**.

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

Side note:
also closer connection antenna showers ↔ antenna subtraction
⇒ MC@NNLO?



Final remarks: logarithmic accuracy



[Dasgupta et al. 2002.11114]

VINCIA is ordered in (ARIADNE) **transverse momentum** and uses a **local antenna recoil**.

⇒ cannot expect **general** NLL accuracy!

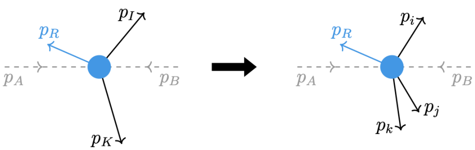
Solution: refined kinematics and/or refined evolution variable
→ Silvia Ferrario Ravasio's talk (PanScales)
→ Daniel Reichelt's talk (ALARIC)
\+ references therein

Some initial work towards more **global recoil schemes** by student @Monash.

Numerical NLL tests in stand-alone `python` code (based on ALARIC test framework).

...to be continued!

Current FF map: transverse recoil shared among p_I, p_K.



Note: internal matching/merging strategies **preserve** shower accuracy.
(Subtleties related to POWHEG → Alexander Karlberg's talk)

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 ($2 \mapsto 4$)
Refined (more global) kinematics ($\to$ NLL)

Next few years
Iterated NLO MECs for final-state radiators. Using interface to MCFM [Campbell, Höche, CTP 2107.04472].
Incoming partons ($2 \mapsto 4$, NLO MECs, NNLO+PS, ...)

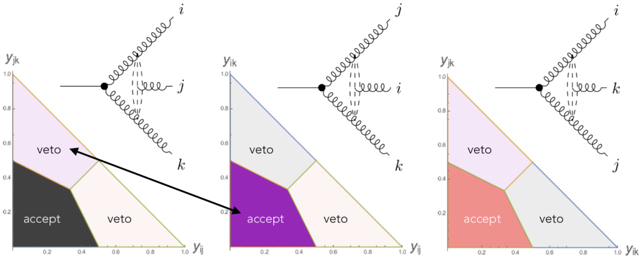
Stay tuned: `pythia-news@cern.ch`

Backup

Phase-space sectors

Branching phase space gets divided into **non-overlapping sectors**.

- e.g. first emission in $H \to gg$:

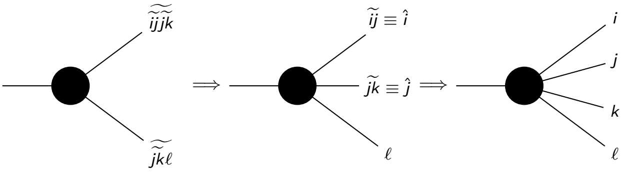


- branchings in the shower are accepted **if and only if** they correspond to the **correct sector**
- sectors defined by minimal $p_\perp$ in event, but always contain:
  - soft endpoint
  - "full" collinear region for qg
  - "half" of the collinear region for gg with boundary at $z = \frac{1}{2}$

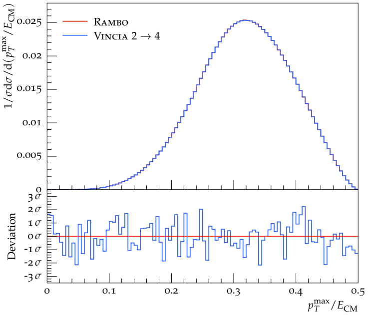
Note: in general, non-trivial sector boundaries away from the singular limits!

Double-branching kinematics

Iterate $2 \mapsto 3$ kinematics ($\sim$ tripole map):



Can be used for **shower kinematics** and as **forward-branching phase-space generator** (FBPS).



For **shower kinematics**:

- First, generate **second** scale $p^2_{\perp,+2}$ via "P_{imp}" factor

$$\frac{1}{\hat{p}^2_{\perp,+1}} \frac{\hat{p}^2_{\perp,+1}}{\hat{p}^2_{\perp,+1} + p^2_{\perp,+2}} \frac{1}{p^2_{\perp,+2}}$$

- Then, sample intermediate scale $\hat{p}^2_{\perp,+1} \leq p^2_{\perp,+2}$

As **phase-space generator**:

- Sample $\{\hat{s}_{ij}, \hat{s}_{j\ell}, \hat{\phi}\}$ and $\{s_{ij}, s_{jk}, \phi\}$
- Particularly convenient to generate **angularly correlated** points

Tree-level MECs

Separation of double-real integral defines tree-level MECs:

$$\int_t^{t_0} \mathrm{d}\Phi_{+2}\, \frac{\mathrm{RR}(\Phi_2, \Phi_{+2})}{\mathrm{B}(\Phi_2)} = \int_t^{t_0} \mathrm{d}\Phi_{+2}^{>}\, \frac{\mathrm{RR}(\Phi_2, \Phi_{+2})}{\mathrm{B}(\Phi_2)} + \int_t^{t_0} \mathrm{d}\Phi_{+2}^{<}\, \frac{\mathrm{RR}(\Phi_2, \Phi_{+2})}{\mathrm{B}(\Phi_2)}$$

$$= \int_t^{t_0} \mathrm{d}\Phi_{+2}^{>}\, \mathrm{A}_{2\mapsto 4}(\Phi_{+2}) w^{\mathrm{LO}}_{2\mapsto 4}(\Phi_2, \Phi_{+2})$$

$$+ \int_{t'}^{t_0} \mathrm{d}\Phi_{+1}\, \mathrm{A}_{2\mapsto 3}(\Phi_{+1}) w^{\mathrm{LO}}_{2\mapsto 3}(\Phi_2, \Phi_{+1}) \int_t^{t'} \mathrm{d}\Phi'_{+1}\, \mathrm{A}_{3\mapsto 4}(\Phi'_{+1}) w^{\mathrm{LO}}_{3\mapsto 4}(\Phi_3, \Phi'_{+1})$$

Iterated tree-level MECs in **ordered** region:

$$w^{\mathrm{LO}}_{2\mapsto 3}(\Phi_2, \Phi_{+1}) = \frac{\mathrm{R}(\Phi_2, \Phi_{+1})}{\mathrm{A}_{2\mapsto 3}(\Phi_{+1})\mathrm{B}(\Phi_2)}$$

$$w^{\mathrm{LO}}_{3\mapsto 4}(\Phi_3, \Phi'_{+1}) = \frac{\mathrm{RR}(\Phi_3, \Phi'_{+1})}{\mathrm{A}_{3\mapsto 4}(\Phi'_{+1})\mathrm{R}(\Phi_3)}$$

Tree-level MECs in **unordered** region:

$$w^{\mathrm{LO}}_{2\mapsto 4}(\Phi_2, \Phi_{+2}) = \frac{\mathrm{RR}(\Phi_2, \Phi_{+2})}{\mathrm{A}_{2\mapsto 4}(\Phi_{+2})\mathrm{B}(\Phi_2)}$$

NLO MECs

Rewrite **NLO MEC** as product of **LO MEC** and **"Born"-local K-factor** $1 + w^{\mathrm{V}}$ ("POWHEG in the exponent"):

$$w^{\mathrm{NLO}}_{2\mapsto 3}(\Phi_2, \Phi_{+1}) = w^{\mathrm{LO}}_{2\mapsto 3}(\Phi_2, \Phi_{+1}) \times (1 + w^{\mathrm{V}}_{2\mapsto 3}(\Phi_2, \Phi_{+1}))$$

Local correction given by **three terms**:

$$\begin{aligned} w^{\mathrm{V}}_{2\mapsto 3}(\Phi_2, \Phi_{+1}) = & \left(\frac{\mathrm{RV}(\Phi_2, \Phi_{+1})}{\mathrm{R}(\Phi_2, \Phi_{+1})} + \frac{\mathrm{I}^{\mathrm{NLO}}(\Phi_2, \Phi_{+1})}{\mathrm{R}(\Phi_2, \Phi_{+1})} \right. \\ \text{NLO Born+1}j \quad & \left. + \int_0^t \mathrm{d}\Phi'_{+1} \left[\frac{\mathrm{RR}(\Phi_2, \Phi_{+1}, \Phi'_{+1})}{\mathrm{R}(\Phi_2, \Phi_{+1})} - \frac{\mathrm{S}^{\mathrm{NLO}}(\Phi_2, \Phi_{+1}, \Phi'_{+1})}{\mathrm{R}(\Phi_2, \Phi_{+1})} \right] \right) \\ \text{NLO Born} \quad & - \left(\frac{\mathrm{V}(\Phi_2)}{\mathrm{B}(\Phi_2)} + \frac{\mathrm{I}^{\mathrm{NLO}}(\Phi_2)}{\mathrm{B}(\Phi_2)} + \int_0^{t_0} \mathrm{d}\Phi'_{+1} \left[\frac{\mathrm{R}(\Phi_2, \Phi'_{+1})}{\mathrm{B}(\Phi_2)} - \frac{\mathrm{S}^{\mathrm{NLO}}(\Phi_2, \Phi'_{+1})}{\mathrm{B}(\Phi_2)} \right] \right) \\ \text{shower} \quad & + \left(\frac{\alpha_{\mathrm{S}}}{2\pi} \log\left(\frac{\kappa^2 \mu^2_{\mathrm{PS}}}{\mu^2_{\mathrm{R}}} \right) + \int_t^{t_0} \mathrm{d}\Phi'_{+1}\, \mathrm{A}_{2\mapsto 3}(\Phi'_{+1}) w^{\mathrm{LO}}_{2\mapsto 3}(\Phi_2, \Phi'_{+1}) \right) \end{aligned}$$

- First and third term from **NLO shower evolution**, second from **NNLO matching**
- Calculation can be **(semi-)automated**, given a suitable NLO subtraction scheme