NLO EW corrections to same-sign WW scattering in POWHEG

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LAPTh

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based on arXiv:1906.01863

in collaboration with Ansgar Denner, Jean-Nicolas Lang and Mathieu Pellen

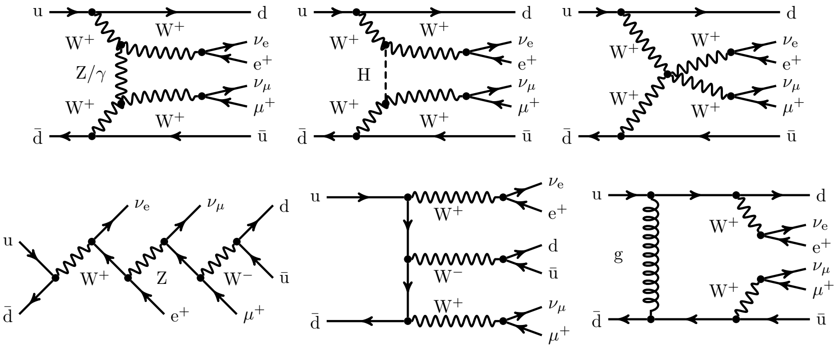
- New Monte Carlo event generator for $pp \to l\nu l'\nu' jj$ at NLO EW accuracy matched to QED PS and supplemented with QCD PS

- The generator relies on the `POWHEG-BOX-RES` framework

- Code, documentation, and examples are available in the POWHEG-BOX svn repository:

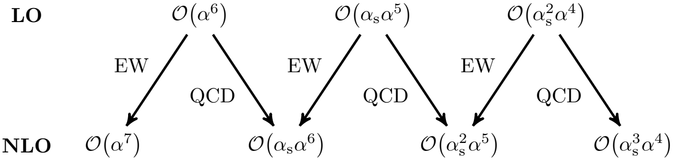
`vbs-ssww-nloew`

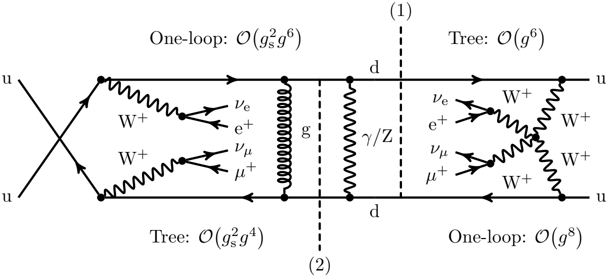
Vector boson scattering at LHC (1)



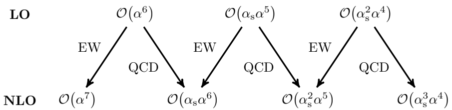
$\mathcal{M} \simeq$	$\mathcal{O}(\alpha^3)$	$\mathcal{O}(\alpha^3)$	$\mathcal{O}(\alpha_S\alpha^2)$
LO	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$

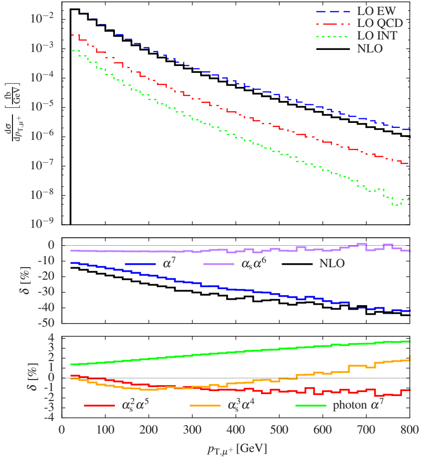
VBS at NLO: technical aspects

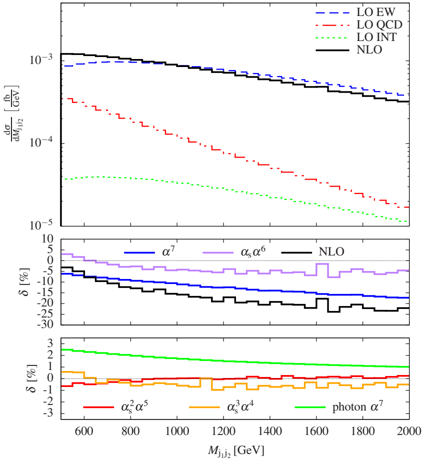




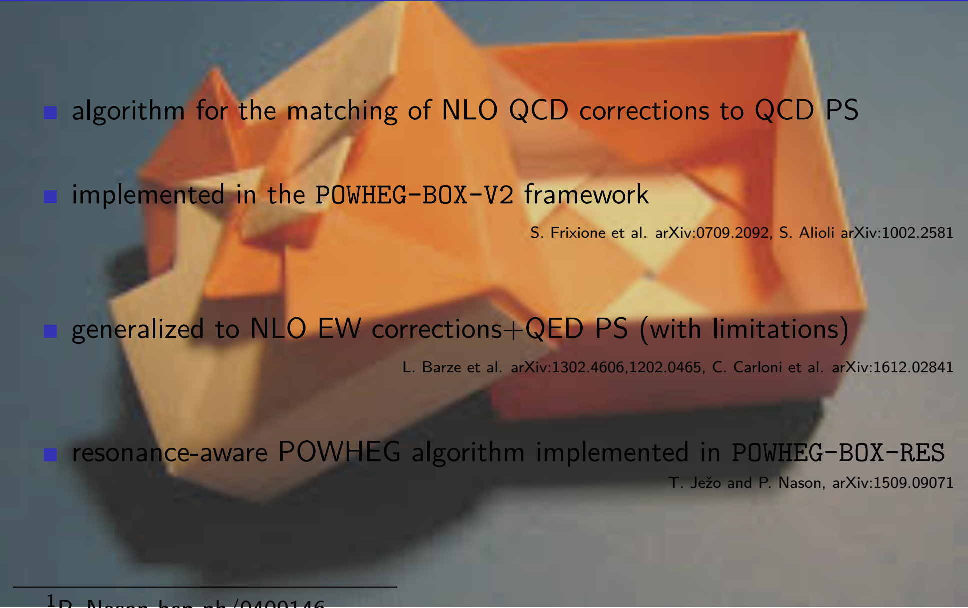
NLO corrections to VBS







POWHEG[1]



- algorithm for the matching of NLO QCD corrections to QCD PS
- implemented in the `POWHEG-BOX-V2` framework

  S. Frixione et al. arXiv:0709.2092, S. Alioli arXiv:1002.2581

- generalized to NLO EW corrections+QED PS (with limitations)

  L. Barze et al. arXiv:1302.4606,1202.0465, C. Carloni et al. arXiv:1612.02841

- resonance-aware POWHEG algorithm implemented in `POWHEG-BOX-RES`

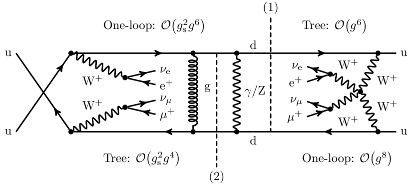
  T. Ježo and P. Nason, arXiv:1509.09071

[1] P. Nason hep-ph/0409146

NLO EW+QED PS in POWHEG: current limitations

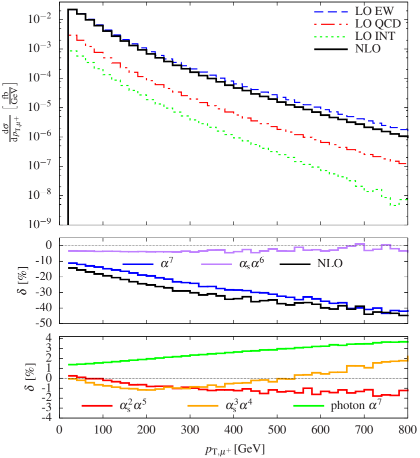
The implementation of NLO EW corrections in `POWHEG-BOX-V2/RES` is not general:

- it only works if a process can be identified using particle flavours (NOT the case of $pp \to WWjj$ with LO contribs $\mathcal{O}(\alpha^6)$, $\mathcal{O}(\alpha^4\alpha_S^2)$, $\mathcal{O}(\alpha^5\alpha_S)$)
- the subtraction for mixed interferences is missing



cannot be used to compute the full NLO corrections to VBS!

Approximations



Limitations of NLO-EW corrections in POWHEG

Strategy:

- consider only LO $\mathcal{O}(\alpha^6)$
- consider only corrections $\mathcal{O}(\alpha^7)$
- $\mathcal{O}(\alpha_S\alpha^6)$ in PS approximation or via combination with NLO-QCD+QCD PS results

Approximations: important remark

- the exact matrix elements at $\mathcal{O}(\alpha^6)$ and $\mathcal{O}(\alpha^7)$ are used
- NO on-shell approximation for the W bosons
- the approximation consists in neglecting all contributions but the $\mathcal{O}(\alpha^6)$ one at LO (and $\mathcal{O}(\alpha^7)$ at NLO)

Even if POWHEG generates events in the full phase-space, the code MUST be used ONLY for VBS-like event selections. Otherwise the selected contributions might not be the dominant ones.

Tools

- `Recola`: ME provider (full matrix elements $\mathcal{O}(\alpha^6)$ and $\mathcal{O}(\alpha^7)$)

  s. Actis et al. arXiv:1211.6316, arXiv:1605.01090

- `Collier`: library for the calculation of one-loop tensor and scalar integrals

  A. Denner and S. Dittmaier arXiv:1604.06792

- `POWHEG-BOX-RES`: phase-space generation, integration, event generation

  T. Ježo and P. Nason, arXiv:1509.09071

- `PYTHIA8.2`: QED and QCD PS, hadronization

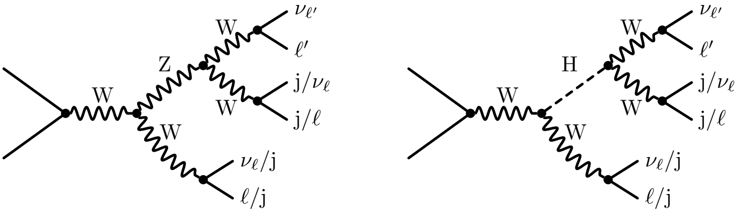
  T. Sjöstrand et al. hep-ph/0603175, arXiv:1410.3012

Resonance histories (1)

partonic channel	interferences at $\mathcal{O}(\alpha_s\alpha^5)$	kinematic channels
$\mathrm{uu} \to \mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{dd}$	yes	t, u
$\mathrm{uc/cu} \to \mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{ds}$	no	t
$\mathrm{cc} \to \mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{ss}$	yes	t, u
$\mathrm{u\bar{d}/\bar{d}u} \to \mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{d\bar{u}}$	yes	t, s
$\mathrm{u\bar{d}/\bar{d}u} \to \mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{s\bar{c}}$	no	s
$\mathrm{u\bar{s}/\bar{s}u} \to \mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{d\bar{c}}$	no	t
$\mathrm{c\bar{d}/\bar{d}c} \to \mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{s\bar{u}}$	no	t
$\mathrm{c\bar{s}/\bar{s}c} \to \mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{d\bar{u}}$	no	s
$\mathrm{c\bar{s}/\bar{s}c} \to \mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{s\bar{c}}$	yes	t, s
$\mathrm{\bar{d}\bar{d}} \to \mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{\bar{u}\bar{u}}$	yes	t, u
$\mathrm{\bar{d}\bar{s}/\bar{s}\bar{d}} \to \mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{\bar{u}\bar{c}}$	no	t
$\mathrm{\bar{s}\bar{s}} \to \mu^+\nu_\mu\mathrm{e}^+\nu_\mathrm{e}\mathrm{\bar{c}\bar{c}}$	yes	t, u

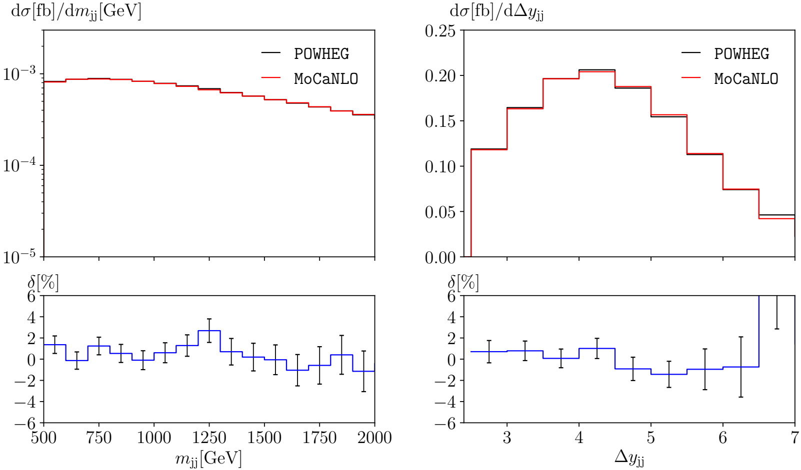
Resonance histories (2)

Richest s-channel history: the others can be obtained by removing internal propagators



- in principle, all possible histories should be declared
- each history is integrated as an independent process:
  too many histories slow down the calculation considerably
- the history will be written in the LHE event:
  simplified histories could lead to (small) recoil mismodeling in the PS

Validation: LHE level



`MoCaNLO` is the fixed-order integrator used in B. Biedermann et al. arXiv:1611.02951, arXiv:1708.00268

Validation: LHE

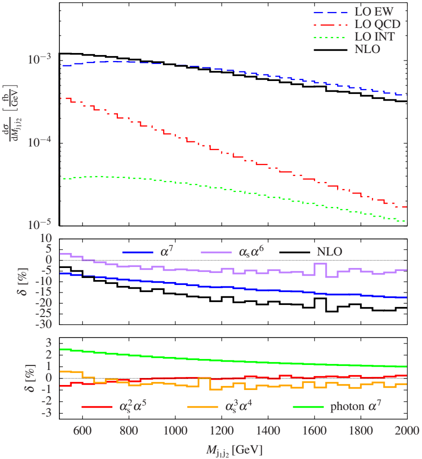
$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \left\{ \Delta^{f_b}(\mathbf{\Phi}_n, p_T^{min}) + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \frac{\left[d\Phi_{rad}\, \theta(k_T - p_T^{min})\, \Delta^{f_b}(\mathbf{\Phi}_n, k_T)\, R(\mathbf{\Phi}_{n+1}) \right]_{\alpha_r}^{\bar{\mathbf{\Phi}}_n^{\alpha_r} = \mathbf{\Phi}_n}}{B^{f_b}(\mathbf{\Phi}_n)} \right\}$$

In principle, LHE events and fixed-order NLO results are NOT comparable :

- contribution from Sudakov form factor at the LHE
- additional radiative kinematics (RES radiations)

POWHEG and MoCaNLO agree very well because the NLO EW corrections are dominated by virtual corrections

Approximated $\mathcal{O}(\alpha_S \alpha^6)$ corrections: 1st strategy (1)



- $\mathcal{O}(\alpha_S \alpha^6)$ corrections < 0.25 $\mathcal{O}(\alpha^7)$ ones
- We can approximate $\mathcal{O}(\alpha_S \alpha^6)$ corrections running a QCD PS

Starting scale for the QCD-PS: `scalup`$=$`LO_scale`$\neq$`pt_rad_powheg`

Approximated $\mathcal{O}(\alpha_S \alpha^6)$ corrections: 1st strategy (2)

scalup=LO_scale≠pt_rad_powheg

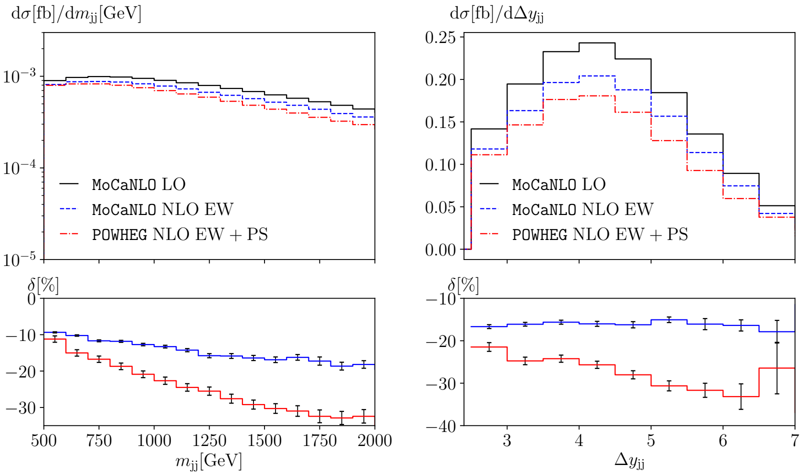
- we don't have ME for real QCD radiation:
  POWHEG Sudakov only tries to generate γ radiation

- setting scalup to pt_rad_powheg for the QCD-PS will unphysically suppress the QCD radiation

LO_scale

It is set to $\sqrt{p_{\mathrm{T\,j_1}} p_{\mathrm{T\,j_2}}}$ (NOT $\sqrt{s}$), as the relevant invariants for the QCD corrections are t/u (NOT s)

Approximated $\mathcal{O}(\alpha_S \alpha^6)$ corrections: 1st strategy (3)



Approximated $\mathcal{O}(\alpha_S \alpha^6)$ corrections: 2nd strategy

Combination with the results at NLO QCD+QCD-PS accuracy

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\rm EW\&QCD} = \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\rm EW+PS} + \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\rm QCD+QCD\,PS} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\rm LO+QCD\,PS}$$

$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\rm QCD+QCD\,PS}$ can be computed with other tools (e.g. `POWHEG-BOX-V2/vbf_wp_wp/`)

The LO contribution is subtracted to avoid the double counting of the QCD PS in $\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\rm EW+PS}$

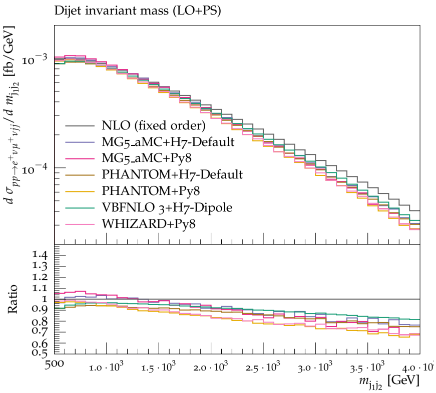
Non-factorizable QCD corrections are NOT included

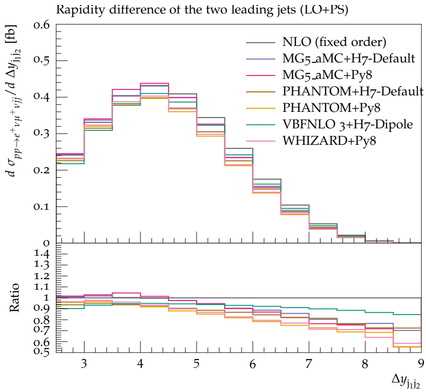
Conclusions and perspectives

- We developed a MC event generator for $pp \to l\nu l'\nu' jj$ at NLO EW accuracy matched to QED PS in the POWHEG-BOX-RES framework
- only $\mathcal{O}(\alpha^7)$ corrections to the LO $\mathcal{O}(\alpha^6)$ are included
- $\mathcal{O}(\alpha_{\mathrm{S}}\alpha^6)$ can be included in a approximated way (PS or combination with factorizable NLO QCD corrections+PS)
- our approximated treatment can be easily applied to the other VBS processes at the LHC
- in order to implement the full NLO corrections to VBS at the LHC, the general structure of POWHEG-BOX has to be generalized and the subtraction formulas for the mixed interferences should be derived

Backup Slides

Approximated $\mathcal{O}(\alpha_S \alpha^6)$ corrections: 1st strategy (4)





Resonance histories

To implement a process in POWHEG-BOX-V2, the user should provide

- B, V, R matrix elements
- phase-space
- list of Born and real processes (flavour lists)

In POWHEG-BOX-RES the user should also provide the resonance histories for each process

```
all regions:   7 11
s~  c     ==> W+   W+   H    W+   W-   e+   ve   mu+  vmu  c~   s    gam     |    ptr= 13
              0    3    3    5    5    4    4    6    6    7    7    4
all regions:   8 14
s~  c     ==> W+   W+   H    W+   W-   e+   ve   mu+  vmu  c~   s    gam     |    ptr= 14
              0    3    3    5    5    4    4    6    6    7    7    6
```

NLO PS matching

- NLO QCD corrections: $d\sigma = d\sigma_0 \left[1 + \delta_{\alpha_S}\right]$
- QCD-PS: all order parton radiation in leading log approx.

$$d\sigma = d\sigma_0 \left[1 + \sum_{n=1}^{\infty} \delta'_{\alpha_S^n}\right]$$

- NLO QCD+QCD-PS: $d\sigma = d\sigma_0 \left[1 + \delta_{\alpha_S} + \sum_{n=2}^{\infty} \delta'_{\alpha_S^n}\right]$

  matching replaces first PS radiation with NLO real radiation

many matching strategies are available in the literature: we used the POWHEG[2] method

[2]P. Nason hep-ph/0409146, S. Frixione et al. arXiv:0709.2092, S. Alioli arXiv:1002.2581

NLO PS matching (2)

POWHEG matching:

- the PS must be p_{T} ordered:

$$p_{\mathrm{T},1}^{\mathrm{PS}} > p_{\mathrm{T},2}^{\mathrm{PS}} > p_{\mathrm{T},3}^{\mathrm{PS}} > p_{\mathrm{T},4}^{\mathrm{PS}} > \cdots$$

- `POWHEG` generates one parton radiation at NLO accuracy

- the scale of the POWHEG radiation ($p_{\mathrm{T}}^{\mathrm{PWG}}$) is set as starting scale for the PS

$$p_{\mathrm{T}}^{\mathrm{PWG}} > p_{\mathrm{T},1}^{\mathrm{PS}} > \cdots$$

POWHEG (1)

```
(d~  u  ) ==> e+   ve   g       | mult=  1
 d~  u    ==> e+   ve      | uborn, mult=  1
   0  5
(g  )d~   ==> e+   ve   u~      | mult=  1
 u   d~   ==> e+   ve      | uborn, mult=  1
   1  5
(g  )u    ==> e+   ve   d       | mult=  1
 d~  u    ==> e+   ve      | uborn, mult=  1
   1  5
(u   d~ ) ==> e+   ve   g       | mult=  1
 u   d~   ==> e+   ve      | uborn, mult=  1
   0  5
 u  (g  ) ==> e+   ve   d       | mult=  1
 u   d~   ==> e+   ve      | uborn, mult=  1
   2  5
```

$$R = \sum_{\alpha_\mathrm{r}} R^{\alpha_\mathrm{r}}$$

- $R^{\alpha_\mathrm{r}} = \mathcal{S}^{\alpha_\mathrm{r}} R$
- $\mathcal{S}^{\alpha_\mathrm{r}} = 1$ in α_r
- $\mathcal{S}^{\alpha_\mathrm{r}} \simeq 0$ outside α_r

$$\bar{B}^{f_b}(\mathbf{\Phi}_n) = \left[B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n)\right]_{f_b}$$
$$+ \sum_{\alpha_\mathrm{r} \in \{\alpha_\mathrm{r} | f_b\}} \int \left[d\Phi_\mathrm{rad} \left\{ R(\mathbf{\Phi}_{n+1}) - C(\mathbf{\Phi}_{n+1}) \right\} \right]_{\alpha_\mathrm{r}}^{\bar{\mathbf{\Phi}}_n^{\alpha_\mathrm{r}} = \mathbf{\Phi}_n}$$
$$+ \sum_{\alpha_\oplus \in \{\alpha_\oplus | f_b\}} \int \frac{dz}{z} G_\oplus^{\alpha_\oplus}(\mathbf{\Phi}_{n,\oplus}) + \sum_{\alpha_\ominus \in \{\alpha_\ominus | f_b\}} \int \frac{dz}{z} G_\ominus^{\alpha_\ominus}(\mathbf{\Phi}_{n,\ominus})$$

POWHEG (2)

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}(\mathbf{\Phi}_n)\, d\mathbf{\Phi}_n \Bigg\{ \Delta^{f_b}(\mathbf{\Phi}_n, p_T^{min}) + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \frac{\left[d\Phi_{rad}\, \theta(k_T - p_T^{min})\, \Delta^{f_b}(\mathbf{\Phi}_n, k_T)\, R(\mathbf{\Phi}_{n+1}) \right]_{\alpha_r}^{\bar{\mathbf{\Phi}}_n^{\alpha_r} = \mathbf{\Phi}_n}}{B^{f_b}(\mathbf{\Phi}_n)} \Bigg\}$$

$$\Delta^{f_b}(\mathbf{\Phi}_n, p_{\mathrm{T}}) = \prod_{\alpha_{\mathrm{r}} \in \{\alpha_{\mathrm{r}} | f_b\}} \Delta^{\alpha_{\mathrm{r}}}(\mathbf{\Phi}_n, p_{\mathrm{T}}) =$$

$$\prod_{\alpha_{\mathrm{r}} \in \{\alpha_{\mathrm{r}} | f_b\}} \exp \left\{ - \int \frac{\left[d\Phi_{\mathrm{rad}}\, R(\mathbf{\Phi}_{n+1})\, \theta\left(k_{\mathrm{T}}(\mathbf{\Phi}_{n+1}) - p_{\mathrm{T}}\right) \right]_{\alpha_{\mathrm{r}}}^{\bar{\mathbf{\Phi}}_n^{\alpha_{\mathrm{r}}} = \mathbf{\Phi}_n}}{B^{f_b}(\mathbf{\Phi}_n)} \right\}$$

POWHEG (3)

POWHEG-BOX-V2

- try to generate one radiation from each α_{r} ($p_{\mathrm{T}}^{\alpha_{\mathrm{r}}}$)
- find the hardest radiation (p_{T}^{max})
- p_{T}^{max} is the starting scale of the PS

POWHEG-BOX-RES(*)

- try to generate one radiation from each α_{r} ($p_{\mathrm{T}}^{\alpha_{\mathrm{r}}}$)
- for each resonance r, find the hardest radiation emitted by the resonance ($p_{\mathrm{T},r}^{max}$)
- $p_{\mathrm{T},r}^{max}$ is the starting scale of the PS radiation from r

(*) T. Ježo and P. Nason, arXiv:1509.09071