Progress in Monte Carlo generators: multileg processes and electroweak corrections

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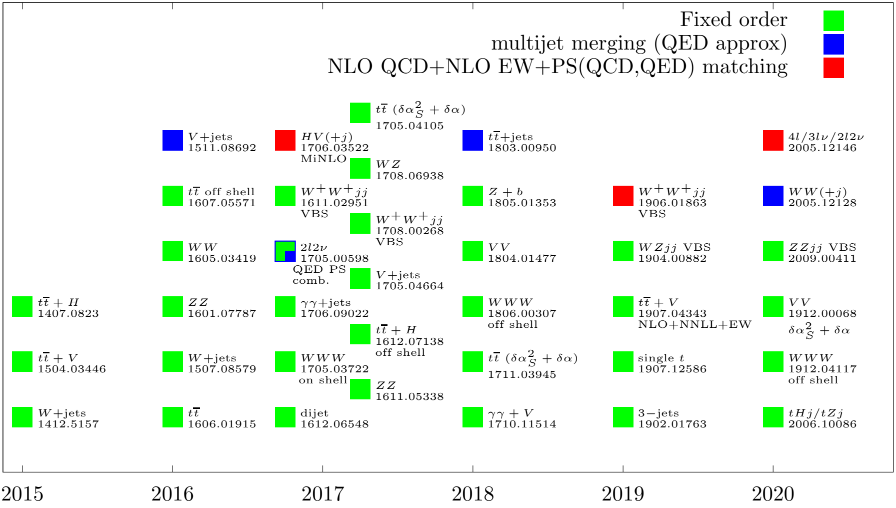
NLO EW calculations for multileg processes (1)



NLO EW calculations for multileg processes (2)

these calculations are possible thanks to the development of fully automated 1-loop providers like

`GoSam` arXiv:1111.2034,1404.7096,1507.08579

`MADLOOP/Madgraph_aMC@NLO` arXiv:1405.0301,1804.10017

`NLOX` arXiv:1812.11925

`OpenLoops/OpenLoops2` arXiv:1111.5206,1412.5157,1710.11452,1907.13071

`Recola/Recola2` arXiv:1211.6316,1605.01090,1705.06053,1711.07388

NLO EW calculations for multileg processes (3)

some calculations use dedicated Monte Carlo integrators

but many of them rely on more general purpose frameworks such as

Madgraph_aMC@NLO arXiv:1405.0301,1804.10017

MATRIX arXiv:1711.06631

POWHEG hep-ph/0409146,arXiv:0709.2092,1002.2581

SHERPA arXiv:0811.4622,1704.05783,1905.09127

Fixed-order calculations

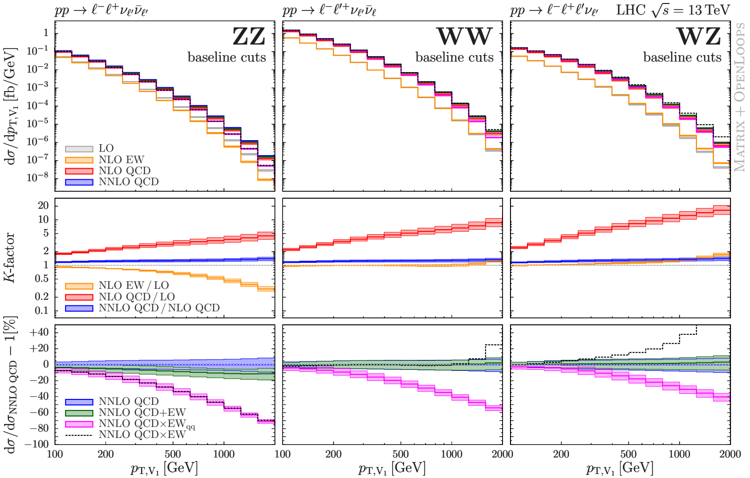
- NLO EW corrections δ_{EW} are computed
- δ_{EW} can be combined with QCD corrections using additive or multiplicative prescriptions (to some extent arbitrary)
- the difference additive vs multiplicative can be an estimate of the missing mixed corrections

$$\delta_{\mathrm{QCD+EW}} = \delta_{\mathrm{QCD}} + \delta_{\mathrm{EW}}$$

$$\delta_{\mathrm{QCD\times EW}} = (1+\delta_{\mathrm{QCD}})(1+\delta_{\mathrm{EW}}) - 1$$

- the estimate of the mixed EW-QCD corrections is only valid when the dominant corrections come from the same phase space of the LO process (e.g. not in the case of giant K-factors)

giant K-factors, example from 1912.00068



hard jet recoiling against hard V, soft additional V'

Soft correction on Vj underlying Born

Fixed-order calculations: dibosons 1912.00068

- Fixed-order corrs to 4-lepton productions known up to NNLO QCD and NLO EW

- NNLO QCD and NLO EW are combined using several prescriptions:

$$\mathrm{d}\sigma_{\mathrm{NNLO\,QCD+EW}} = \mathrm{d}\sigma_{\mathrm{LO}}\left(1+\delta_{\mathrm{QCD}}+\delta_{\mathrm{EW}}\right)+\mathrm{d}\sigma^{gg}_{\mathrm{LO}}\,,$$

$$\mathrm{d}\sigma_{\mathrm{NNLO\,QCD\times EW}} = \mathrm{d}\sigma_{\mathrm{LO}}\left(1+\delta_{\mathrm{QCD}}\right)\left(1+\delta_{\mathrm{EW}}\right)+\mathrm{d}\sigma^{gg}_{\mathrm{LO}}\,,$$

$$\mathrm{d}\sigma_{\mathrm{NNLO\,QCD\times EW_{qq}}} = \mathrm{d}\sigma^{q\bar{q}}_{\mathrm{LO}}\left(1+\delta^{q\bar{q}}_{\mathrm{QCD}}\right)\left(1+\delta^{q\bar{q}}_{\mathrm{EW}}\right)+\mathrm{d}\sigma^{\gamma\gamma}_{\mathrm{LO}}\left(1+\delta^{\gamma\gamma/q\gamma}_{\mathrm{EW}}\right)+\mathrm{d}\sigma^{gg}_{\mathrm{LO}}\,,$$

- the results in the considered prescriptions are compared in different phase-space regions

- NLO EW matrix element computed with `OpenLoops`

- calculation performed in the `Matrix` framework (but not yet public, to my knowledge)

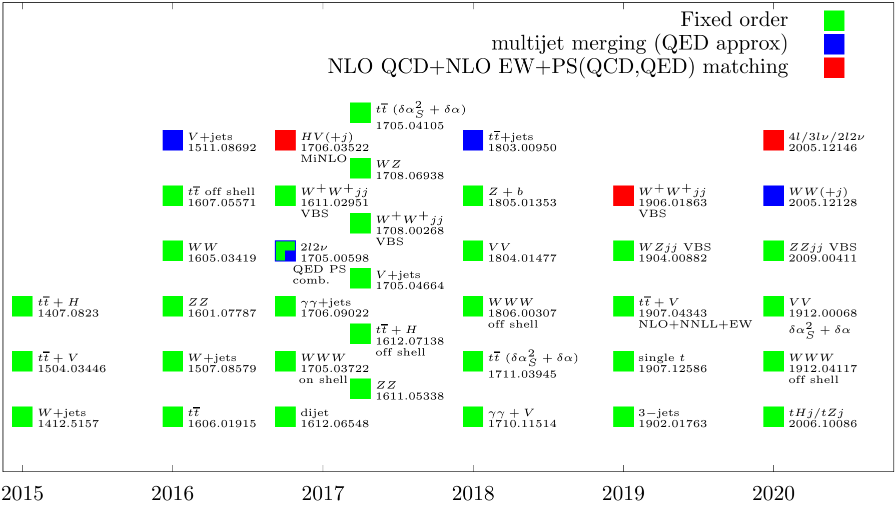
Fixed-order calculations: remark

- $\mathcal{O}(\alpha)$ corrections are included
- multiple γ radiation effects are NOT included
- it is no possible to simply run QED parton showers on top of NLO EW predictions:

  double-counting of $\mathcal{O}(\alpha)$ QED corrs from PS

  (unless only weak corrections are computed, when possible)
- the inclusion of multiple γ radiation requires NLO-PS matching

Multijet merging and approximate QED



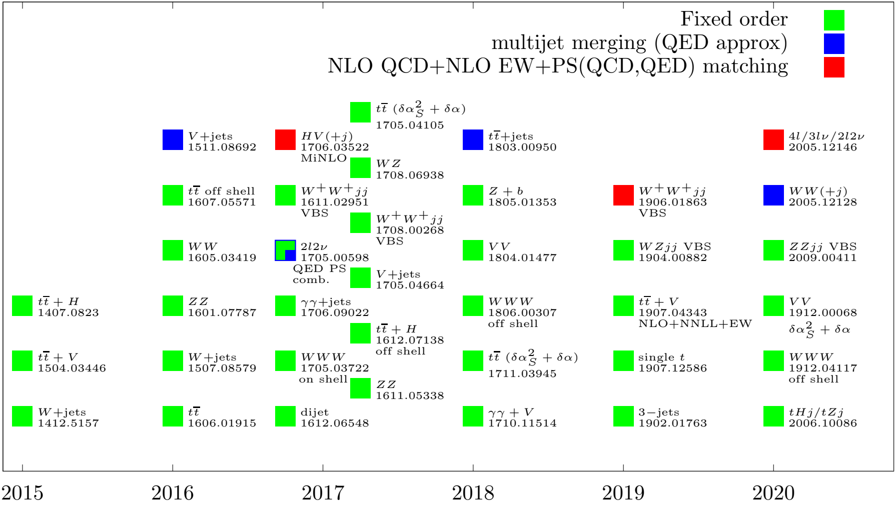
Multijet merging and approximate QED

- only virtual EW corrections included after subtraction of QED logs
- QED corrections are only from PS (leading logs)
- typically used for the production of heavy objects+light jets:
  - democratic parton clustering treating QED and QCD radiation NOT yet developed
  - after removing the QED, EW corrections do not change parton multiplicity
  - standard QCD multijet merging is used
- improved description of hard p_T^j tails (or distribs with large QCD corrs not coming from soft/coll radiation)
- QED accuracy is only leading log (this approximation affects mainly leptonic observables like e.g. $M_{\rm inv}$)

Jet merging and approx QED: $WW(+j)$ 2005.12128

- NLO QCD+NLO EW corrections computed for WW and $WW+1$jet
- merging of 0 and $1-$jet samples (with the QED approx. in the previous slide)
- QED corrections in leading log approximation only
- NLO EW matrix elements from `Recola`
- calculation performed in the `Sherpa` framework

NLO QCD+NLO EW matched to QCD and QED PS



matched calculations also available for charged and neutral DY

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 et al. 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

POWHEG: algorithm and accuracy

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

- for each α_r try to generate a radiation, the hardest one goes in the LHE file
- matching to PS: veto PS radiation with $p_T > p_T^{\mathrm{rad,\,PWG}}$
- NLO QCD+QCD-PS: $d\sigma = d\sigma_0 \left[1 + \delta_{\alpha_S} + \sum_{n=2}^{\infty} \delta'_{\alpha_S^n} \right]$, δ' =leading logs

  matching replaces first PS radiation with NLO real radiation
- POWHEG NLO (QCD+EW)+(QCD,QED)-PS:

$$d\sigma = d\sigma_0 \left[1 \; + \; \delta_{\alpha_s} + \delta_\alpha + \sum_{m=1,n=1}^{\infty} \delta'_{\alpha_s^m \alpha^n} + \sum_{m=2}^{\infty} \delta'_{\alpha_s^m} + \sum_{n=2}^{\infty} \delta'_{\alpha^n} \right]$$

POWHEG: algorithm and accuracy (2)

POWHEG-BOX-V2

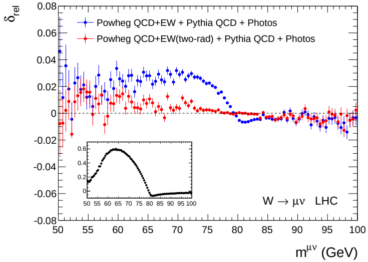
- try to generate one radiation from each $\alpha_{\rm r}$ ($p_{\rm T}^{\alpha_{\rm r}}$)
- find the hardest radiation ($p_{\rm T}^{max}$)
- $p_{\rm T}^{max}$ is the starting scale of the PS

POWHEG-BOX-RES$^{(*)}$

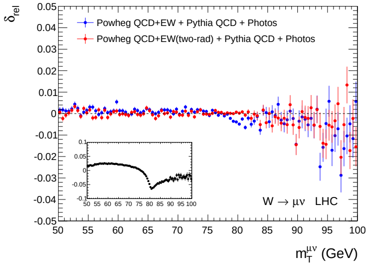
- try to generate one radiation from each $\alpha_{\rm r}$ ($p_{\rm T}^{\alpha_{\rm r}}$)
- for each resonance r, find the hardest radiation emitted by the resonance ($p_{{\rm T},r}^{max}$)
- $p_{{\rm T},r}^{max}$ is the starting scale of the PS radiation from r

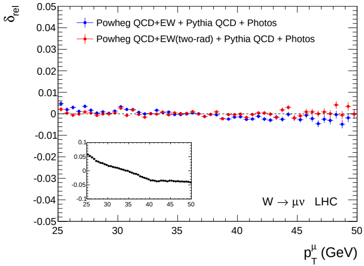
- `POHWEG-BOX-RES` (like) events contain up to one radiation from each resonance
- PS radiation from each resonance must be vetoed independently

POWHEG-BOX-RES (like) treatment of resonances



non negligible effect for observables sensitive to QED FSR corrections but rather insensitive to QCD corrections





POWHEG-BOX-RES and multiple vetoes: remark

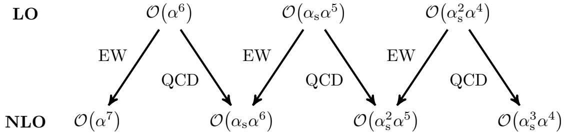
- PS radiation off each resonance must be vetoed independently
- not in LHE accord (`scalup` only works for one radiation)
- dedicated interfaces to PS must be used

it would be much better if the community could agree on a generalization of the LHE standard

NLO EW+QED PS in POWHEG: current limitations

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

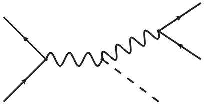
- it assumes that each virtual amplitude is in one-to-one correspondence with a LO amplitude,
  e.g. NOT situations like (VBS)



- the subtraction for mixed interferences is missing (e.g. $\mathcal{O}(\alpha^6\alpha_S)$ above)

- treatment of $\gamma-$initiated contributions not yet implemented

HV

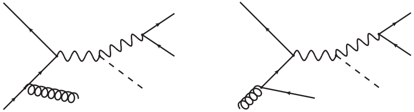


- $pp \to l^+ l^- H$, $pp \to l\nu H$:

  `HZ_ew`, `HW_ew`, arXiv:1706.03522

- full matrix elements from `OpenLoops`
- NLO QCD+NLO EW accuracy matched to QCD and QED PS
- implemented in the `POWHEG-BOX-RES` framework
- up to 2 radiations in the LHE events

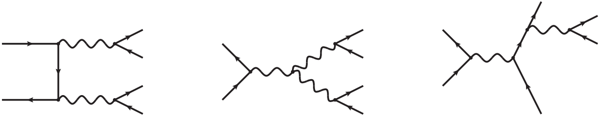
HV+jet with MiNLO



- $pp \to l^+l^-Hj$, $pp \to l\nu Hj$: HZJ_ew, HWJ_ew, arXiv:1706.03522
- full matrix elements from OpenLoops
- NLO QCD+NLO EW accuracy matched to QCD and QED PS
- implemented in the POWHEG-BOX-RES framework
- up to 2 radiations in the LHE events

- improved description of hard p_T tails
- MiNLO: when $p_T^j \to 0$ recovers the results for HV at NLO accuracy

Dibosons

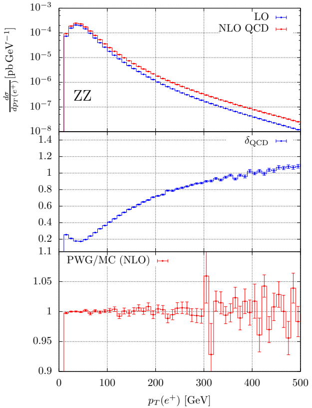


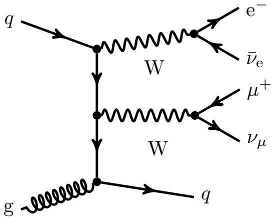
- $pp \to 4l$, $pp \to 2l2\nu$, $pp \to 3l\nu$:

  `VV_dec_ew`, arXiv:2005.12146

- full matrix elements for $4-$lept, $4-$lept$+\gamma/j$ (`Recola2`)
- NLO QCD+NLO EW accuracy matched to QCD and QED PS
- implemented in the `POWHEG-BOX-RES` framework
- t/u-channel, s-channel, and peripheral resonances considered
- up to 3 radiations in the LHE events

Dibosons: perspectives





QCD corrs on p_T distribs. are large,

positive,

increasing with p_T

Perspectives

NLO EW+NLO QCD corrections to $pp \to VV'j$ with MiNLO

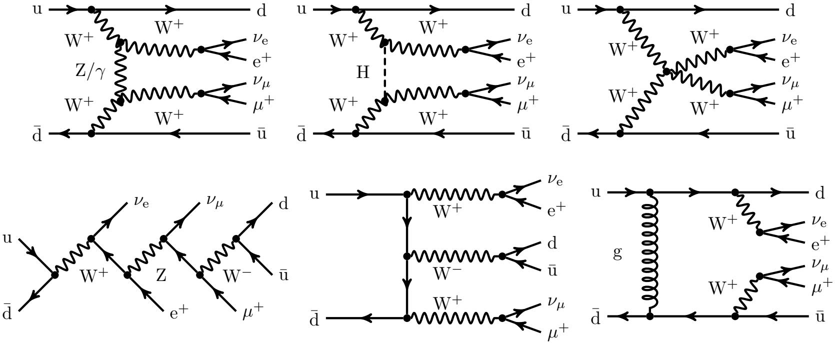
Same sign WW scattering

- $pp \to l^{+(-)}\nu l^{+(-)}\nu jj$ (VBS):

  `vbs-ssww-ew`, arXiv:1906.01863

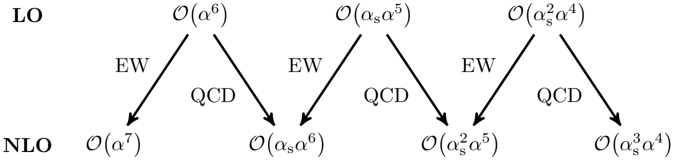
- full matrix elements for 6-fermions, 6-fermions+γ at $\mathcal{O}(\alpha^6)$, $\mathcal{O}(\alpha^7)$ (`Recola2`)
- NLO EW accuracy matched to QED PS
- QCD corrections approximated via PS or combination with other predictions
- implemented in the `POWHEG-BOX-RES` framework
- only "richest" resonance structures considered
- up to 4 radiations in the LHE events

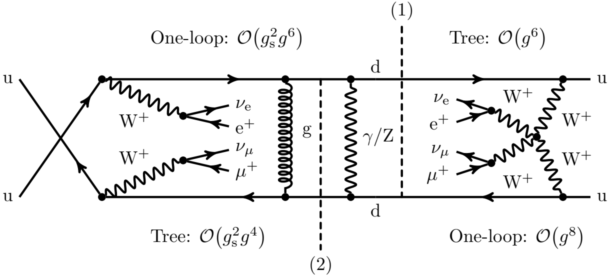
VBS at LO



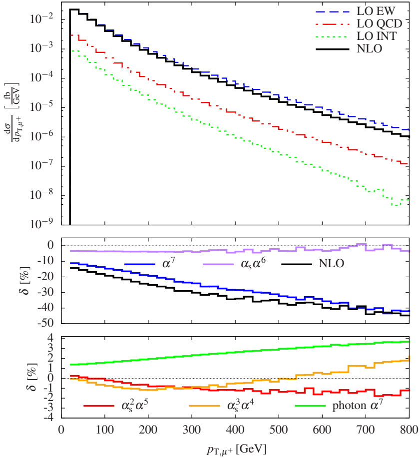
$\mathcal{M} \simeq$	$\mathcal{O}(\alpha^3)$	$\mathcal{O}(\alpha^3)$	$\mathcal{O}(\alpha_S \alpha^2)$
LO	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s \alpha^5)$	$\mathcal{O}(\alpha_s^2 \alpha^4)$

VBS at NLO


LO
$\mathcal{O}(\alpha^6)$
$\mathcal{O}(\alpha_s\alpha^5)$
$\mathcal{O}(\alpha_s^2\alpha^4)$
EW
QCD
EW
QCD
EW
QCD
NLO
$\mathcal{O}(\alpha^7)$
$\mathcal{O}(\alpha_s\alpha^6)$
$\mathcal{O}(\alpha_s^2\alpha^5)$
$\mathcal{O}(\alpha_s^3\alpha^4)$


(1)
One-loop: $\mathcal{O}(g_s^2g^6)$
Tree: $\mathcal{O}(g^6)$
u
d
u
W^+
ν_e
e^+
g
γ/Z
ν_e
e^+
W^+
W^+
ν_μ
μ^+
ν_μ
μ^+
W^+
W^+
u
d
u
Tree: $\mathcal{O}(g_s^2g^4)$
One-loop: $\mathcal{O}(g^8)$
(2)

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

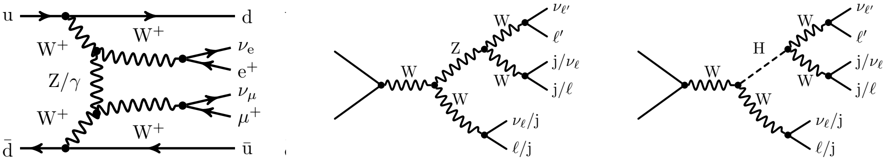
VBS, approximations: important remark

- 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.

Resonance histories

Richest histories: 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

VBS: approximated $\mathcal{O}(\alpha_S\alpha^6)$ corrections

$\mathcal{O}(\alpha_S\alpha^6)$ corrections $< 0.25\ \mathcal{O}(\alpha^7)$ ones

Approx.1: QCD PS

- We can approximate $\mathcal{O}(\alpha_S\alpha^6)$ corrections running a QCD PS
- Starting scale for the QCD-PS: `scalup`$= \sqrt{p_T^{j_1} p_T^{j_2}} \neq$`pt_rad_pwg`

Approx.2: combination with predictions at NLO QCD+QCD PS

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

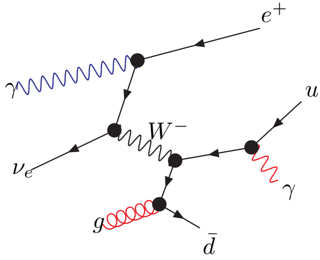
NLO QCD+QCD PS can be computed with other tools
(e.g. `POWHEG-BOX-V2/vbf_wp_wp/`)

Conclusions

- in the last few years the NLO EW corrections were computed for many multileg processes
- mainly fixed-order calculations
- two classes of event generators
  - based on approximate combination of NLO EW and QED PS, usually in the context of multijet merging
  - based on the exact matching of NLO QCD and NLO EW to QCD and QED PS

Backup Slides

POWHEG-BOX-RES (like) treatment of resonances

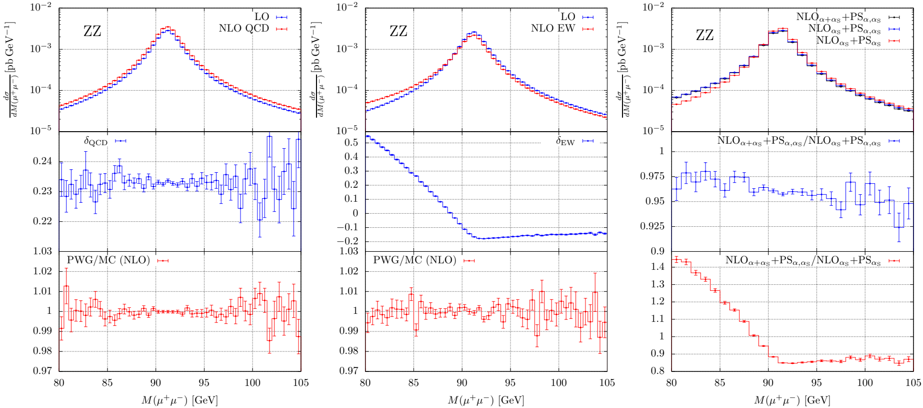


- 3 radiation regions:
  QCD ISR, QED ISR, QED FSR
- 2 resonances: IS, W

The events contain up to 2 radiations:

1. one ISR QED or QCD radiation setting the scale of the IS shower
2. one FSR QED radiation setting the scale of the FS shower

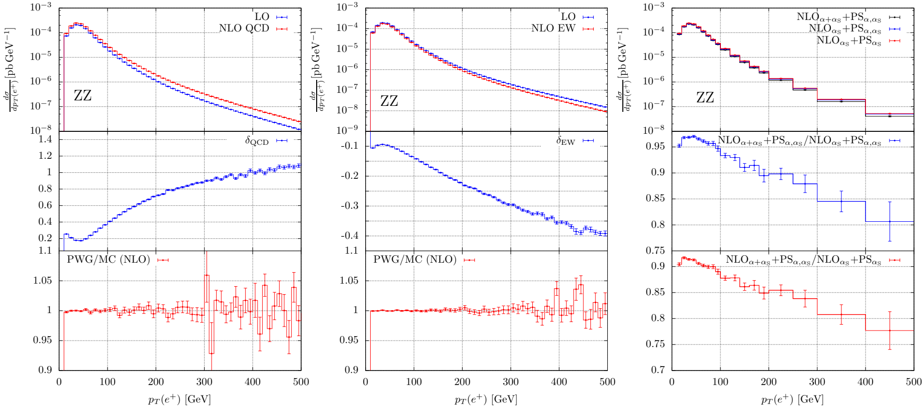
Dibosons (2)



$NLO_{\alpha_S+\alpha}+PS_{\alpha_S,\alpha}$ / $NLO_{\alpha_S}+PS_{\alpha_S,\alpha}$ $\sim$ NLO weak, non-log QED $\mathcal{O}(\alpha)$, mixed

$NLO_{\alpha_S+\alpha}+PS_{\alpha_S,\alpha}$ / $NLO_{\alpha_S}+PS_{\alpha_S}$ $\sim$ NLO weak, QED $\mathcal{O}(\alpha)$, leading-log QED $\mathcal{O}(\alpha^n)$ $(n > 2)$, mixed

Dibosons (3)



NLO$_{\alpha_S+\alpha}$+PS$_{\alpha_S,\alpha}$ /NLO$_{\alpha_S}$+PS$_{\alpha_S,\alpha}$ $\sim$ NLO weak, non-log QED $\mathcal{O}(\alpha)$, mixed

NLO$_{\alpha_S+\alpha}$+PS$_{\alpha_S,\alpha}$ /NLO$_{\alpha_S}$+PS$_{\alpha_S}$ $\sim$ NLO weak, QED $\mathcal{O}(\alpha)$,
leading-log QED $\mathcal{O}(\alpha^n)$ $(n > 2)$, mixed

Similarities and differences among the codes

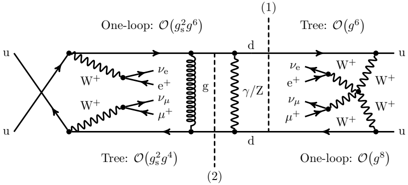
	Z_ew-BMNNPV	W_ew-BMNNP	VV_dec_ew	vbs-ssww-nloew
Process	$pp \to l^+ l^-$	$pp \to l\nu$	$pp \to 4l/2l2\nu/3l\nu$	$pp \to l^+\nu l^-\nu jj$
FS leptons $(*)$	massive $(l = e, \mu)$	massive $(l = e, \mu)$	massless $(l = e, \mu, \tau)$	massless $(l = e, \mu, \tau)$
Identical l			in progress (§)	in progress (§)
Model	SM	SM	SM $(**)$	SM $(**)$
POWHEG-BOX-	V2	V2	RES	RES
Resonance-aware PS matching (RES)	Yes	Yes	Yes	Yes
Dedicated PS interface	Yes (Py8,Photos)	Yes (Py8,Photos)	Yes (Py8) (¶)	Yes (Py8) (¶)
Matrix elements	internal	internal	Recola2	Recola2
PHPS restrictions	None (‡)	None	None (‡)	VBS
Approx. in Mat.els	None	None	None	None (†)
NLO QCD	Yes	Yes	Yes	No (†)
NLO EW	Yes	Yes	Yes	Yes (†)
Unstable Z/W	CMS/CLA (fix Γ)	CMS/CLA (fix Γ)	CMS (fix Γ)	CMS (fix Γ)
Renorm schemes	$G_\mu M_W M_Z$ (††) $\alpha_0 M_W M_Z$ $\alpha(M_Z) M_W M_Z$ $\sin\theta^{\text{eff}} M_Z G\mu$ $\sin\theta^{\text{eff}} M_Z \alpha_0$	$G_\mu M_W M_Z$ $\alpha_0 M_W M_Z$	$G_\mu M_W M_Z$ $\alpha_0 M_W M_Z$ $\alpha(M_Z) M_W M_Z$	$G_\mu M_W M_Z$
γ-induced (‡‡)	NLO (not on svn)	NLO (not on svn)	No	No

$(*)$ massless: valid only for dressed lepton analyses.
(§) process-specific code is there, but fixes in the common POWHEG-BOX-RES code needed.
$(**)$ generalization to BSM feasible if the corresponding Recola2 model file exists.
(¶) Photos interface can be developed upon request.
(‡) $M(l^+l^-) > M(\text{cut})$ to avoid on-shell γ propagators at LO.
(†) considering only LO $\mathcal{O}(\alpha^6)$ (EW production) and NLO $\mathcal{O}(\alpha^7)$.
(††) α_0, G_μ, M_Z developed. To be tested.

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!