WZ production at large transverse momenta beyond NLO in QCD

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$pp \rightarrow W^\pm Z + X \rightarrow \ell_1^\pm \nu_1^- \ell_2^+ \ell_2^- + X$
To compute approximate NNLO QCD correction to WZ we use:

VBFNLO + LoopSim

**VBFNLO** provides:
- WZ at NLO and WZj at NLO

**LoopSim** provides:
- consistent way to use the above results and supplement them with approximate 2-loop corrections
LoopSim summary

- use unitarity to simulate the divergent part of 2-loop diagrams

LoopSim procedure

| input: event with n final state particles | LoopSim | output: all \( n - k \) final state particle events (equivalently all k-loop events) |

- notation: \( \bar{n}LO \) – simulated 1-loop
  \( \bar{n}NLO \) – simulated 2-loop and exact 1-loop

- this will work very well for the processes with large K factors e.g.

\[
\sigma_{\bar{n}NLO} = \sigma_{NNLO} \left( 1 + \mathcal{O} \left( \frac{\alpha_s^2}{K_{NNLO}} \right) \right), \quad K_{NNLO} \gtrsim K_{NLO} \gg 1
\]

- LoopSim has one parameter \( R_{LS} \) (we shall vary it to probe uncertainties of the method related to nonsingular terms of the loop diagrams)
LoopSim has been shown to work

Drell-Yan at NNLO

- excellent agreement with DY at NNLO
- accounts very well for $H_T$ distributions at Tevatron

Z+jets at Tevatron

- $p_T, \max \ [\text{GeV}]$
- $K$ factor wrt NLO
- $p_T, 14 \text{ TeV}, m_Z/2 < \mu < 2m_Z$
- $66 < m_{e^+e^-} < 116 \text{ GeV}$

- $Z/\gamma^*(\rightarrow l\ell) + \geq 1 \text{ jet}$
- $l = e, \mu; |\eta| < 1.0; p_T^l > 25 \text{ GeV/c}^2$
- $p_T^{\text{jet}} \geq 30 \text{ GeV/c}, |Y^{\text{jet}}| \leq 2.1$

- $\mu = \frac{1}{2} R_T = \frac{1}{2} (\Sigma p_T^l + P_T^l + P_T)$

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WZ at $\bar{n}$NLO: details of the computation

All results correspond to:

- both $W^+Z$ and $W^-Z$ production channels
- two unlike-flavour decay channels: $ee\mu\nu_\mu$ and $\mu\mu e\nu_e$
- MSTW NNLO 2008 at all orders
- $\mu_{F,R} = \frac{1}{2} \left\{ \sum p_{T,\text{partons}} + \sqrt{p_{T,W}^2 + m_W^2} + \sqrt{p_{T,Z}^2 + m_Z^2} \right\}$

Cuts:

- $|y_\ell| \leq 2.5$, $p_{T,\ell} \geq 15$ (20), for $\ell$ coming from $Z$ ($W$)
- $E_{T,\text{miss}} > 30$ GeV
- $60 < m_{\ell^+\ell^-} < 120$ GeV
- jets from anti-$k_t$, $R = 0.45$,
- for observables involving jets: $|y_{\text{jet}}| \leq 4.5$, $p_{T,\text{jet}} \geq 30$ GeV
- $\Delta R_{\ell,j} > 0.3$, $\Delta R = \sqrt{\Delta\phi^2 + \Delta y^2}$
$H_T$ distribution

$H_T = \sum p_{T,jets} + \sum p_{T,\ell} + E_{T,miss}$

- huge K-factor from LO to NLO, distribution very sensitive to new channels and new topologies
- very good agreement between $\bar{n}$LO and NLO at large $H_T$
- $\bar{n}$NLO corrections as large as 100% w.r.t. NLO
- small $R_{LS}$ uncertainties at large $H_T$
- marginal reduction of scale uncertainties at $\bar{n}$NLO (new topologies which dominate computed only at LO)
$p_t$ of the hardest lepton

- $\bar{n}$NLO corrections beyond NLO scale uncertainties for $p_t > 200$ GeV
- $\bar{n}$NLO with $p_{t,veto} = 50$ GeV: large corrections, larger scale uncertainties

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missing $E_T$ distribution

- again, huge K-factor from LO to NLO
- large $\bar{n}$NLO of the order of 30%
- $\bar{n}$NLO correction exceeds NLO scale uncertainty
- reduced scale uncertainty at $\bar{n}$NLO

W$^\pm$Z, pp, 8 TeV
$a$-kt, $R=0.45$, MSTW NNLO 2008
60 $<m_Z <$ 120 GeV, $\Delta R_{l(l,j)} = 0.3$
transverse mass of the WZ system

\[ m_{T,WZ}^2 = (E_T^W + E_T^Z)^2 - (p_T^W + p_T^Z)^2 - (p_T^W + p_T^Z)^2 \]

▷ example of an observable for which \( \bar{n}\)NLO corrections are small

▷ finite loop terms of large importance (hence larger \( R_{LS} \) uncertainty)

▷ favoured configurations with \( W \) and \( Z \) back-to-back and both with sizable \( p_t \); those do not have logarithmic enhancements
We used LoopSim + VBFNLO to compute approximate NNLO QCD corrections to the process $pp \rightarrow WZ \rightarrow \ell_1^\pm \nu_1 \ell_2^\pm \ell_2^- + X$.

We found that these corrections are sizable for a number of observables at high $p_t$, that is: $H_T$, $p_{T, \ell, \text{max}}$ and $E_{T, \text{miss}}$.

It is therefore important to take them into account in physics analyses within and beyond the Standard Model.
BACKUP SLIDES
The LoopSim method: $\bar{n}$LO, $\bar{n}\bar{n}$LO etc.

\begin{itemize}
  \item jet clustering $ij \rightarrow k$ is reinterpreted as the splitting $k \rightarrow ij$
  \item weight of an event $\sim (-1)^{\text{nb. of loops}}$ and all weights sum up to zero (unitarity)
  \item beware: the loops above are just a shortcut notation!
\end{itemize}
Including exact loops

\( E_{n,l} \) – input event with \( n \) final state particles and \( l \) loops
\( U^b_l \) – operator producing event with \( b \) Born particles and \( l \) loops
\( U^b_\forall \) – operator generating all necessary loop diagrams at given order

How to introduce exact loop contributions?

\[
U^b_\forall(E_{n,0}) + U^b_\forall(E_{n-1,1}) - U^b_\forall(U^b_1(E_{n,0}))
\]

- generate all diagrams from the tree level event
- generate all diagrams from the 1-loop event
- remove all approximate diagrams from \( U^b_\forall(E_{n,0}) \) that have exact counterparts provided by \( U^b_\forall(E_{n-1,1}) \)

- inclusion of exact loops helps reducing scale uncertainties
- straightforward generalization to arbitrary number of exact loops