EW corrections and combination with QCD for diboson production

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based on

M. Grazzini, S. Kallweit, J. Lindert, S. P., M. Wiesemann
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NNLO QCD corrections to $pp \to VV$ [Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteufel, S.P., Rathlev, Tancredi, Weihs, Wiesemann, Yook ’14–’20]

Sample $pp \to WZ$ diagrams at order $\alpha_s^2$

Main ingredients

- $pp \to VVj$ at NLO with Munich [Kallweit] + OpenLoops [Buccioni et al]
- 2-loop amplitudes [Gehrmann, von Manteuffel, Tancredi ’15]
- $q_T$-subtraction method [Catani, Grazzini ’07]

Matrix [Grazzini, Kallweit, Wiesemann ’17–’20]

- all $pp \to 4$ leptons/neutrinos diboson processes (and more)
- parton-level predictions at NNLO QCD plus $gg \to VV$ at NLO
Relevance of NNLO precision

Few-percent QCD uncertainties

⇒ improved SM tests, EFT fits and searches with $VV$ backgrounds

⇒ EW corrections increasingly relevant at high $p_T$
$pp \rightarrow VV$ and decays to leptons & $\nu$ at NLO EW [Biedermann, Denner, Dittmanier, Jäger, Kallweit, Lindert, Maieröfer, Pellen, S.P., Schönherr '16–20]

Typically of $\mathcal{O}(1\%)$ but possible large enhancements, especially in high-energy tails

**Sudakov logarithms from virtual EW bosons**

- negative corrections $\propto \alpha_w \ln^2(Q^2/M_W^2) \sim 25\%$ at $Q \sim 1$ TeV
- prop. to external SU(2) charges $\Rightarrow$ large in $VV$ production

**Photon-induced processes:** $\gamma\gamma \rightarrow VV$ and $\gamma q \rightarrow VVq$

- $\mathcal{O}(10\%)$ in TeV tails through $t$-channel $W$-exchange
- precise $\gamma$-density in NNPDF3.1 with LUX methodology [Manohar, Nason, Salam, Zanderighi '16]

$\alpha \ln(Q/m_\ell)$ effects from lepton fragmentation

- largest in $m_{\ell\ell}$ and $m_{4\ell}$ (attenuated by lepton dressing)
Tools for $pp \rightarrow VV$ at NNLO QCD+NLO EW

**OpenLoops 2** [Buccioni, Lang, Lindert, Maierhöfer, S. P., Zhang, Zoller ’19]
- automated **NLO QCD+EW matrix elements** for any SM process
- new methods for stable real-virtual NNLO matrix elements

**Munich** [S.Kallweit] + **OpenLoops**
- full **NLO QCD+EW automation** [Kallweit, Lindert, Maierhöfer, S.P., Schönherr ’16]

**Matrix+OpenLoops** [Grazzini, Kallweit, Lindert, S.P., Wiesemann ’20]
- **NNLO QCD+NLO EW** for all processes

  $pp \rightarrow 4$ leptons/neutrinos

- public code coming soon

<table>
<thead>
<tr>
<th>channels</th>
<th># lept</th>
<th>final state</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>4</td>
<td>$\ell^+ \ell^- \ell^+ \ell^-$</td>
</tr>
<tr>
<td>ZZ</td>
<td>4</td>
<td>$\ell^+ \ell^- \ell'^+ \ell'^-$</td>
</tr>
<tr>
<td>WZ</td>
<td>3</td>
<td>$\ell^+ \ell^- \nu_\ell$</td>
</tr>
<tr>
<td>WZ</td>
<td>3</td>
<td>$\ell^+ \ell^- \ell' \nu_{\ell'}$</td>
</tr>
<tr>
<td>ZZ</td>
<td>2</td>
<td>$\ell^+ \ell^- \nu_\ell \bar{\nu}_{\ell'}$</td>
</tr>
<tr>
<td>ZZ, WW</td>
<td>2</td>
<td>$\ell^+ \ell^- \nu_\ell \bar{\nu}_{\ell'}$</td>
</tr>
<tr>
<td>WW</td>
<td>2</td>
<td>$\ell^+ \ell'^- \nu_\ell \bar{\nu}_{\ell'}$</td>
</tr>
</tbody>
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Building blocks (note $q\bar{q}$, $\gamma\gamma$ and $gg$ channels)

\[
\begin{align*}
\text{d}\sigma_{\text{LO}} &= \text{d}\sigma^{\text{LO}}_{q\bar{q}} + \text{d}\sigma^{\text{LO}}_{\gamma\gamma} \\
\text{d}\sigma_{\text{NNLO QCD}} &= \text{d}\sigma^{\text{LO}} (1 + \delta_{\text{QCD}}) + \text{d}\sigma^{\text{LO}}_{gg} \\
\text{d}\sigma_{\text{NLO EW}} &= \text{d}\sigma^{\text{LO}} (1 + \delta_{\text{EW}})
\end{align*}
\]

Idea of the paper

- comparative study of $ZZ$, $WW$, $WZ$ production with (off-shell) leptonic decays
- study behaviour of (reconstructed) vector bosons
- focus on high $p_T$, where QCD and EW corrections can be very large and their interplay nontrivial
Combination of QCD and EW corrections

\[ d\sigma^{QCD+EW} = d\sigma^{LO} (1 + \delta_{QCD} + \delta_{EW}) + d\sigma^{LO}_{gg} \]  

(1)

\[ d\sigma^{QCD\times EW} = d\sigma^{NNLO QCD+EW} + d\sigma^{LO} \delta_{QCD} \delta_{EW} \]  

(2)

**Difference between additive (1) and multiplicative (2,3) prescriptions**

- factorisation generates extra \( \delta_{QCD} \delta_{EW} \) correction of \( \mathcal{O}(\alpha\alpha_S) \)
- can be quite large at high \( p_T \)
- should be interpreted as \( \mathcal{O}(\alpha\alpha_S) \) uncertainty unless there are theoretical arguments that support QCD \( \times \) EW factorisation

**More consistent factorisation** (excluding NLO EW \( \gamma\gamma \) and \( \gamma q \) channels)

\[ d\sigma^{QCD\times EW_{q\bar{q}}} = d\sigma^{NNLO QCD+EW} + d\sigma^{LO} \delta_{QCD} \delta^{q\bar{q}}_{EW} \]  

(3)
QCD radiation patterns at high $p_T$

two very different configurations depending on recoiling object

\[
Q^2 \gg M_W^2
\]

**Hard-$VJ$ configurations** (see later)

- $p_{T,V_1} \sim p_{T,jet} \gg M_W$
- $p_{T,V_2} \lesssim M_W$

\[
Q^2 \gg M_W^2
\]

**Hard-$VV$ configurations**

- $p_{T,V_1} \sim p_{T,V_2} \gg M_W$
- $p_{T,jet} \lesssim M_W$

$\Rightarrow$ Sudakov logs dominate EW corrections and factorise wrt QCD corrections [Manohar et al]

$\Rightarrow$ QCD $\times$ EW$_{q\bar{q}}$ combination correctly accouns for dominant $O(\alpha\alpha_S)$ effects
Hard-$VV$ dominated observable: $p_{T,V_2}$

**QCD corrections** (middle panel)
- moderate shape and normalisation corrections
- few-percent NNLO scale uncertainties

**EW corrections** (middle panel)
- dominated by large negative Sudakov logs
- far beyond NNLO uncertainties at $p_T \gg M_W$

**Best combination** = $QCD \times EW_{q\bar{q}}$ (lower panel, pink)
- captures dominant $O(\alpha \alpha_s)$ effects
- percent-level scale uncertainty
- uncertainty dominated by missing $O(\alpha^2)$ Sudakov logs $\sim \frac{1}{2} \delta^2_{EW}$

[Denner, Manohar, Kühn, S.P., ...]
Similar behaviour in all channels

Largest QCD corrections in $WZ$ and largest EW corrections in $ZZ$ (see more details in the paper)
Hard-$Vj$ configurations at high $p_T$ (recoil absorbed by jet)

NLO QCD

$$Q^2 \gg M_W^2$$

Giant NLO QCD correction from $pp \rightarrow Vj$ with soft $V_2$ radiation

$$d\sigma^{V(V)j} \propto d\sigma_{LO}^{Vj} \times \frac{\alpha_w}{2\pi} \log^2 \left( \frac{Q^2}{M_W^2} \right) \propto d\sigma_{VV}^{LO} \times \alpha_S \log^2 \left( \frac{Q^2}{M_W^2} \right)$$

$\sim 3$ at 1 TeV

no such log enhancement beyond NLO (since due to soft $V$ radiation)

NLO EW

$$Q^2 \gg M_W^2$$

Giant NLO EW correction from soft $W$ radiation in $\gamma q$ channel

$\Rightarrow$ no QCD $\times$ EW factorisation (dominant QCD and EW corrections from different hard subprocesses)
Hard-$Vj$ dominated observable: $p_{T,V_1}$

**QCD corrections** (middle panel)
- huge NLO corrections and uncertainty
- moderate NNLO correction and uncertainty

**EW corrections** (middle panel)
- large negative Sudakov logs overcompensated by huge $\gamma q \to VWq$ correction

**QCD–EW combination at $p_T \gg M_W$** (lower panel)
- large differences between various prescriptions

$\Rightarrow$ large $\mathcal{O}(\alpha\alpha_S)$ uncertainty spoils TH precision
Possible solutions

(A) Include $\mathcal{O}(\alpha\alpha_S)$ EW corrections to hard-$V_j$ configurations

- possible with MEPS merging at NLO QCD + EW$_{virt}$ [Kallweit, Lindert, Maierhöfer, S.P., Schönherr '16] available in Sherpa
- very recently applied to $WW$ production [Bräuer et al, 2005.12128]

(B) Veto against hard-$V_j$ configurations [Grazzini et al. '20]

- NNLO QCD+EW with mild jet veto

\[ H_T^{jets} < 0.2 H_T^{lep} \]

⇒ suppression of hard-$V_j$ with soft $V_2$ radiation ($r_{21} \ll 1$)

⇒ inclusion of hard-$VV$ with soft QCD radiation ($r_{12} \rightarrow 1$)
$p_{T,V_1}$ distributions with $H_T^{jets}$ veto

- Similarly **good behaviour** and **NNLO QCD+EW accuracy** as for hard-$VV$ dominated distributions

- **NLO QCD enhancement** in the tail can be further reduced with optimised veto
Conclusions

**NNLO QCD+NLO EW for all processes** $pp \rightarrow 4$ leptons/neutrinos
- implemented in **Matrix+OpenLoops** (code coming soon)
- at $p_T \gg M_W$ very large QCD and EW corrections and nontrivial interplay

**Hard-VV dominated observables**
- typical NNLO QCD uncertainties of few percent
- large Sudakov EW logs factorise wrt QCD ⇒ high precision up to few 100 GeV
  (2-loop EW logs needed at TeV scale)

**Hard-Vj dominated observables**
- very large NLO QCD and EW corrections, but NNLO QCD quite stable
- large $\mathcal{O}(\alpha\alpha_S)$ uncertainties can be avoided with mild veto (or multi-jet merging)

**Important implications for sensitivity of BSM and EFT studies at high** $p_T$
Q&A on Zoom after the end of this session

Meeting ID : 266 192 3471

Password : same as this session
Backup slides
QED logarithmic corrections from lepton fragmentation

- $\alpha \ln(Q/m_\ell)$ corrections with bare leptons
- attenuated by lepton dressing
- largest effects in $m_\ell \ell$ and $m_4\ell$

[Beidermann et.al. ’16]
Photon-induced processes

\[ \gamma \gamma \to e^+ \mu^- \nu_e \bar{\nu}_\mu \]

\( \frac{d\sigma}{d\sigma_{\text{NLO QCD}} \times \text{EW}} \)

\[ p_T, \ell \sim 1 \text{ TeV} \]

\[ O(10\%) \text{ at } m_{VV} \sim 1 \text{ TeV} \]

\[ O(10\%) \text{ at } p_T, \ell \sim 1 \text{ TeV} \]

- \( O(\alpha^2) \) like \( q \bar{q} \to VV \) but usually not included in QCD predictions
- \( O(10\%) \) effects in TeV tails through \( t \)-channel \( W \)-exchange
- Large \( \gamma \)-PDF uncertainties in NNPDF3.0 now strongly reduced with LUXQED PDFs [Manohar, Nason, Salam, Zanderighi '16]

[Kallweit, Lindert, S.P., Schönherr '17]
Inclusive $p_{T,V_1}$ distribution in $pp \rightarrow WW, WZ, ZZ$

**Baseline Cuts**

$LHC \sqrt{s} = 13 \text{ TeV}$

$pp \rightarrow \ell^-\ell^+\nu\bar{\nu}$

$K$-factor

$\frac{d\sigma}{dp_{T,V_1}}$ [fb/GeV]

$\Delta K$ [%]

$\Delta \frac{d\sigma}{dNNLO_{QCD}}$ [%]