Diboson/(triboson) production: QCD and EW corrections

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Ultimate Precision at Hadron Colliders
Higgs and High Energy Probes
Orsay, 3. December 2019
Remarkable agreement of inclusive diboson cross sections with **NNLO QCD**

Allows for stringent SM tests

Dibosons important background for Higgs and BSM searches
Perturbative expansion

\[ d\sigma = d\sigma_{\text{LO}} + \alpha_S d\sigma_{\text{NLO}} + \alpha^2_S d\sigma_{\text{NNLO}} + \alpha^3_S d\sigma_{\text{N3LO}} + \ldots \]

- **NLO QCD**: O(100%) (\(\alpha_S d\sigma_{\text{NLO}}\))
- **NNLO QCD**: O(10%) (\(\alpha^2_S d\sigma_{\text{NNLO}}\))
- **N3LO QCD**: O(1%) (\(\alpha^3_S d\sigma_{\text{N3LO}}\))

**NNLO QCD**

In MATRIX [Grazzini, Kallweit, Wiesemann ‘17] all on-shell & off-shell diboson processes \(pp \rightarrow VV'\) are available.
Tails, tails, tails,…. !!!

Indirect probes

Direct probes

→ Theory precision is key to harness full potential of LHC data!
Relevance of EW higher-order corrections: Sudakov logs in the tails

1. Possible large (negative) enhancement due to soft/collinear logs from virtual EW gauge bosons:

\[ \delta \mathcal{M}_{\text{LL+NLL}}^{1-\text{loop}} = \frac{\alpha}{4\pi} \sum_{k=1}^{n} \left\{ \frac{1}{2} \sum_{l\neq k} \sum_{a=\gamma, Z, W^\pm} I^a(k) I^a(l) \ln^2 \frac{\delta_{kl}}{M^2} + \gamma^{\text{ew}}(k) \ln \frac{\delta}{M^2} \right\} \mathcal{M}_0 \]

\[ \Rightarrow \text{overall large (negative) effect in the tails of distributions:} \quad p_T, m_{\text{inv}}, H_T, \ldots \] (relevant for BSM searches!)
Relevance of EW higher-order corrections: collinear QED radiation

II. Possible large enhancement due to soft/collinear logs from photon radiation \( \sim \alpha \log \left( \frac{m_T^2}{\hat{q}^2} \right) \) in sufficiently exclusive observables.

\[ \text{pp } \rightarrow \mu^+\mu^-e^+e^- + X \]

\[ \text{LHC } 13 \, \text{TeV} \]

\[ \mu_R = \mu_F = \frac{1}{2} \mu_{FP} \]

CT14 QED_{105%}

**Important for radiative tails, Higgs backgrounds etc.**

**Typically considered via QED PS (PHOTOS / YFS)**
Relevance of EW higher-order corrections: photon-induced channels

III. QED factorisation and thus photon luminosities needed to absorb IS photon singularities.

- Possible large enhancement due to photon-induced channels in the tails of kinematic distributions, in particular in WW: (t-channel enhancement), but also in Bremsstrahlung

\[ \sigma_{\text{LO}} = \sigma_{\text{LO}}^{\gamma} + \sigma_{\text{LO}}^{\gamma} \]

\[ \text{pp} \to e^+ \mu^- \nu_\mu \bar{\nu}_\mu \]

\[ \text{pp} \to e^+ \mu^- \nu_\mu \bar{\nu}_\mu \]

\[ \text{[Kallweit, JML, Pozzorini, Schönhen, '17]} \]

- \( \gamma \text{PDF} \): CT14, none, LUX, NNPDF3.0

\[ \frac{d\sigma}{dN_{\text{LO}} \times \text{EW}} \]

\[ m_{\ell\ell} \text{ [GeV]} \]

- Large differences between different photon descriptions. Now settled: LUXqed superior

- \( O(10\%) \) contributions from photon-induced channels
Perturbative expansion

\[ d\sigma = d\sigma_{LO} + \alpha_S d\sigma_{NLO} + \alpha_{EW} d\sigma_{NLO\ EW} \]

\[ + \alpha_S^2 d\sigma_{NNLO} + \alpha_{EW}^2 d\sigma_{NNLO\ EW} + \alpha_S \alpha_{EW} d\sigma_{NNLO\ QCD\times EW} \]

\[ + \alpha_S^3 d\sigma_{NNLO} + \ldots \]

N3LO QCD

NLO EW

- 4l-DF-ZZ
- 2l-DF-WW
- 2l-SF-ZZ & 2l-SF-ZZWW & 2l-DF-WW
- 3l-DF-WZ & 3l-DF-WZ

Biedermann, Denner, Dittmaier, Hofer, Jäger; ’16, ’16
Biedermann, Billoni, Denner, Dittmaier, Hofer, Jäger, Salfelder; ’16
Kallweit, JML, Pozzorini, Schönherr; ’17
Biedermann, Denner, Hofer; ’17
Perturbative expansion

\[ d\sigma = d\sigma_{\text{LO}} + \alpha_S d\sigma_{\text{NLO}} + \alpha_{\text{EW}} d\sigma_{\text{NLO EW}} \]

\[ + \alpha_S^2 d\sigma_{\text{NNLO}} + \alpha_{\text{EW}}^2 d\sigma_{\text{NNLO EW}} + \alpha_S \alpha_{\text{EW}} d\sigma_{\text{NNLO QCDxEW}} \]

\[ + \alpha_S^3 d\sigma_{\text{NNLO}} + \ldots \]

NNLO QCD + NLO EW

In Matrix+OpenLoops all (massive) diboson processes are now available at **NNLO QCD + NLO EW**

\[ [\text{M. Grazzini, S. Kallweit, JML, S. Pozzorini, M. Wiesemann; 1912.00068}] \]

(code soon to be public)
Perturbative expansion

\[ d\sigma = d\sigma_{\text{LO}} + \alpha_S d\sigma_{\text{NLO}} + \alpha_{\text{EW}} d\sigma_{\text{NLO EW}} \]

\[ + \alpha_S^2 d\sigma_{\text{NNLO}} + \alpha_{\text{EW}}^2 d\sigma_{\text{NNLO EW}} + \alpha_S \alpha_{\text{EW}} d\sigma_{\text{NNLO QCDxEW}} \]

\[ + \alpha_S^3 d\sigma_{\text{NNLO}} + \ldots \]

\[ \text{N3LO QCD} \]

\[ \text{NLO QCD} \]

\[ \text{NLO EW} \]

\[ \text{NNLO QCD} \]

\[ \text{NNLO EW} \]

\[ \text{NNLO QCD-EW} \]

\[ \text{NNLO QCD} + \text{NLO EW} \]

In Matrix+OpenLoops all (massive) diboson processes are now available at \textbf{NNLO QCD + NLO EW}

\[ [\text{M. Grazzini, S. Kallweit, JML, S. Pozzorini, M. Wiesemann; 1912.00068}] \]

(code soon to be public)
NNLO QCD + NLO EW for dibosons: pTV2

- moderate QCD corrections
  - NNLO/NLO QCD very small at large pTV2
  - NNLO QCD uncertainty: few percent
- NLO EW/LO=-(50-60)% @ 1 TeV

\[
d\sigma_{\text{NNLO QCD+EW}} = d\sigma_{\text{LO}} (1 + \delta_{\text{QCD}} + \delta_{\text{EW}}) + d\sigma_{\text{LO}}^{gg} \\
d\sigma_{\text{NNLO QCD\times EW}} = d\sigma_{\text{LO}} (1 + \delta_{\text{QCD}}) (1 + \delta_{\text{EW}}) + d\sigma_{\text{LO}}^{gg} \\
= d\sigma_{\text{NNLO QCD+EW}} + d\sigma_{\text{LO}} \delta_{\text{QCD}} \delta_{\text{EW}}
\]

- difference very conservative upper bound on $O(\alpha_S \alpha)$
- multiplicative/factorised combination clearly superior (EW Sudakov logs x soft QCD)
- dominant uncertainty at large pTV2: $O(\alpha^2) \sim \alpha_w^2 \log^4 (Q^2/M_W^2)$

Estimate: $\frac{1}{2} \delta_{\text{EW}}^2$
NNLO QCD + NLO EW for dibosons: pTV2

- consistent picture amongst all processes
- Largest QCD corrections in WZ (radiation zero at LO)
- Largest EW corrections in ZZ

pTV2
Giant QCD K-factors and EW corrections: pTV1

- NLO QCD/LO=2-5! ("giant K-factor")

```
pTV1 = \frac{d\sigma}{dK}\left[\frac{\text{NNLO QCD}}{\text{NNLO EW}}\right] - 1[\%]
```

![Graph showing the comparison of NLO QCD, NLO EW, NLO QCD/LO, NNLO QCD, and NNLO QCD/NLO QCD](image)
Giant QCD K-factors and EW corrections: pTV1

- NLO QCD/LO=2-5! ("giant K-factor")
- at large pTV1:VV phase-space is dominated by V+jet (w/ soft V radiation)

\[
\frac{d\sigma^{V(V)j}}{d\sigma^{VV}_{LO}} \propto \alpha_s \log^2 \left( \frac{Q^2}{M_W^2} \right) \approx 3 \quad \text{at} \quad Q = 1 \text{ TeV}
\]

- NNLO / NLO QCD moderate and NNLO uncert. 5-10%
- NLO EW/LO=-(40-50)%

- Very large difference \(d\sigma_{NNLO \text{ QCD} + \text{EW}}\) vs. \(d\sigma_{NNLO \text{ QCD} \times \text{EW}}\)

- Problems:
  1. In additive combination dominant Vj topology does not receive any EW corrections
  2. In multiplicative combination EW correction for VV is applied to Vj hard process

- Pragmatic solution: take average as nominal and spread as uncertainty
- Rigorous solution: merge VVj incl. EW corrections with VV retaining NNLO QCD + EW
Giant QCD K-factors and EW corrections: pTV1

- NLO QCD/LO = 5-10!

- Similar giant K-factor mechanism also in gamma-induced:

$$\sim \alpha \log^2 \left( \frac{Q^2}{M_W^2} \right)$$
In this section we present numerical results for the selected diboson processes with baseline cuts and can be regarded as the weighted average of the corrections in the LO and NLO QCD channels. The latter includes contributions from $q\bar{q}$ channels that can give rise to giant corrections are dominated by Sudakov effects are associated with the $q\bar{q}$ subprocesses, and their cross sections are summed up afterwards.

The factorised combination \( \sigma^{\text{NNLO QCD}} \times \sigma^{\text{EW}} \) should be understood as a purely technical separation of the corrections as $\sigma^{\text{NNLO QCD}}$ includes the same QCD corrections as $\sigma^{\text{LO}}$. Thus, they cannot be entirely associated with one or the other channel. For this reason, the factorised combination \( \sigma^{\text{NNLO QCD}} \times \sigma^{\text{EW}} \) can also be written in the form

\[
\sigma^{\text{NNLO QCD}} \times \sigma^{\text{EW}} = \sigma^{\text{q\bar{q}}} (1 + \delta_{\text{QCD}}^{q\bar{q}}) (1 + \delta_{\text{EW}}^{q\bar{q}}) + \sigma^{\gamma\gamma} (1 + \delta_{\text{QCD}}^{\gamma\gamma}) + \sigma^{\gamma q} (1 + \delta_{\text{QCD}}^{\gamma q}) + \sigma^{q\bar{q}} (1 + \delta_{\text{QCD}}^{q\bar{q}})
\]

\[\text{with } \delta_{\text{QCD}}^{q\bar{q}} \text{ and } \delta_{\text{QCD}}^{\gamma\gamma} \text{ are K-factors.}\]

\[\delta_{\text{EW}} = \frac{\delta_{\text{EW}}^{q\bar{q}} \sigma^{q\bar{q}} + \delta_{\text{EW}}^{\gamma\gamma} \sigma^{\gamma\gamma} + \delta_{\text{QCD}}^{\gamma q} \sigma^{\gamma q}}{\sigma^{q\bar{q}} + \sigma^{\gamma\gamma} + \sigma^{\gamma q} + \sigma^{q\bar{q}}} \text{ averaged EW corr. factor}\]

yields pathological behaviour when $\delta_{\text{EW}}^{q\bar{q}}$ is dominated by giant EW K-factors.

- alternative/modified multiplicative ansatz:

\[
d\sigma^{\text{NNLO QCD}} \times \sigma^{\text{EW}} = d\sigma_{\text{LO}}^{q\bar{q}} (1 + \delta_{\text{QCD}}^{q\bar{q}}) (1 + \delta_{\text{EW}}^{q\bar{q}}) + d\sigma_{\text{LO}}^{\gamma\gamma} (1 + \delta_{\text{QCD}}^{\gamma\gamma}) + d\sigma_{\text{LO}}^{q\bar{q}} (1 + \delta_{\text{QCD}}^{q\bar{q}})
\]

\[\text{yields behaviour consistent with EW Sudakov logs}\]

\[\text{Thus: discard } d\sigma^{\text{NNLO QCD}} \times \sigma^{\text{EW}}\]

\[\text{Caveat: splitting in } q\bar{q} \text{ and } \gamma\gamma/\gamma q \text{ channels is ad-hoc/scheme dependent}\]
Giant QCD K-factors and EW corrections: pT\(V_1\)

\[ pp \to \ell^- \ell^+ \nu \nu \quad \text{LHC} \sqrt{s} = 13 \text{ TeV} \]

**WZ**

- jet veto
  - \( H_T^{\text{jet}} < 0.2 H_T^{\text{lep}} \)

- NLO QCD/LO = \( \sim < 1.5 \)
  - (“normal K-factor”)
  - small differences between the two multiplicative combinations
    - check!
  - consistent results for all processes

- In case we are now really dominated by VV topologies: multiplicative dominations should be seen as superior
  - check!

**pp \to \ell^- \ell^+ \nu \nu \quad \text{LHC} \sqrt{s} = 13 \text{ TeV}**
Giant K-factors and effect of jet veto

- at r21 → 1: hard-VV topologies
- at r21 → 0: hard-Vj topologies

- for pTV1 > 1 TeV: hard-Vj topologies dominate over hard-VV

- Jet veto $H_T^{\text{jet}} < \xi_{\text{veto}} H_T^{\text{lep}}$ corresponds to

\[
p_{T,V_2} > \frac{1 - \xi_{\text{veto}}}{1 + \xi_{\text{veto}}} p_{T,V_1} = \frac{2}{3} p_{T,V_1} \quad \text{for} \quad \xi_{\text{veto}} = 0.2
\]

(violated by off-shell topologies)

- Jet veto results in phase-space dominated by hard-VV
Giant QCD K-factors and EW corrections: pTV

- consistent picture amongst all processes
- multiplicative combinations should be seen as superior
NNLO QCD + NLO EW for dibosons: \(m_{VV}\)

\[
pp \rightarrow \ell^- \ell^+ \nu_{\ell} \bar{\nu}_{\ell}
\]

\[
pp \rightarrow \ell^- \ell^+ \nu_{\ell} \bar{\nu}_{\ell}
\]

\[
pp \rightarrow \ell^- \ell^+ \nu_{\ell} \bar{\nu}_{\ell}
\]

\(LHC \ \sqrt{s} = 13 \text{ TeV}\)

- NLO QCD/LO = 30-70%
- NNLO QCD/NLO = 10-20%
- NLO EW = -30/-20/-20% at 2 TeV

- multiplicative combinations should be seen as superior
Rare electroweak processes

Vector-boson scattering

→

Tribosons
Triboson production calculations

NLO QCD

- on-shell fixed-order
- off-shell fixed-order
  $\rightarrow$ available in aut. tools (MG5_aMC, SHERPA+OPENLOOPS/RECOLA)

- on-shell matched to parton showers in SHERPA, multijet merged $WWW + 0, 1j$
  Höche et. al. arXiv:1403.7516

- off-shell matched to parton showers should be available in automated tools (MG5_aMC, SHERPA+OPENLOOPS/RECOLA)

NLO EW

- on-shell known for some time
  Yong-Bai et. al. arXiv:1605.00554
  Dittmaier, Huss, Knippen arXiv:1705.03722

- off-shell recently computed

- no matching to parton showers available yet
  MS arXiv:1806.00307
Triboson production @ NLO QCD

- QCD correction driven by additional jet activity: VV+jet topologies with soft V
  → ‘giant K-factors’
  → strong observable dependence
  → NLO mandatory

- jet veto (pT_{cut} = 50 GeV) reduces size and phase space dependence
  → better: multi-jet merging

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Figure 8: Differential cross section for the highest-\(p_T\) lepton for \(\mu_R = \mu_F = 3 m_W\) in \(W^+W^-W^+\) production at the LHC. In the right-hand panel, the differential K-factors, as defined in Eq. (3.4), are shown for inclusive events without jet cuts and also for a veto on jets with \(p_T,\text{jet} > 50\) GeV.

Conclusions

The simulation of triple vector boson production at the LHC is important for two reasons. These processes are a Standard Model background for new-physics searches which are characterized by multi-lepton final states, and secondly they are sensitive to quartic electroweak couplings. In this paper, we have presented first results for the full NLO differential cross sections for \(WWW\) and \(ZZW\) production, with all spin correlations from leptonic vector boson decays, intermediate Higgs boson-exchange effects and off-shell contributions taken into account. Results are collected in a fully flexible Monte Carlo program, VBFNLO [7].

When varying the factorization and the renormalization scale \(\mu = \mu_F = \mu_R\) up and down by a factor of 2 around the reference scale \(\mu = 3 m_W\), we have found a scale dependence of about 5% for the LO cross section and of somewhat less than 10% for the NLO cross section, for \(WWW\) production. For the \(ZZW\) case, the LO scale dependence is around 1%, whereas the dependence of the NLO cross section is around 13%. These variations are in the expected range for the NLO scale dependence, while the LO variations have to be considered anomalously small, due to the absence of initial-state gluon-induced subprocesses.

The large K-factors (of order 2 and even larger in some phase-space regions) demonstrate the importance of including the NLO QCD corrections on top of the LO predictions.

The differential K-factors for several distributions for both of these processes are highly dependent on the Higgs boson mass. In general we observe that the larger the contributions...
• corrections w/o jet veto
• QCD corrections ≈ 70%, slight observable dependence
• $\gamma$-induced EW corrections large and observable dependent
→ large accidental cancellations with EW corrections in $q\bar{q}$-channel
**Triboson production: on-shell vs. off-shell**

[M. Schönherr, '18]

- at large mlll and pTll large interference with other resonance structures

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**Conclusion**

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+R
```

[M. Schönherr, '18]
### Off-shell VVV(3l+MET) production @ NLO EW

#### [M. Schönherr, '18]

<table>
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<th>LO [fb]</th>
<th>( \delta_{\text{EW}} )</th>
<th>( \delta_{\text{q\bar{q}}} )</th>
<th>( \delta_{\text{q\gamma/\bar{q}\gamma}} )</th>
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<tr>
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<td>-7.1%</td>
<td>3.6%</td>
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<tr>
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<td>( e^- \mu^+ \mu^+ \nu_e \nu_{\mu} \nu_{\mu} )</td>
<td>0.0955</td>
<td>-2.2%</td>
<td>-4.6%</td>
<td>2.4%</td>
</tr>
</tbody>
</table>

- large accidental and cut dependent cancellations of Sudakov-type
  neg. EW corrections and \( \gamma \)-induced pos. contribs w/ extra jet activity
- **WWW** channels receive smaller corrections than pure **WZZ** channels
Off-shell VVV production @ NLO EW

• cancellations of EW corr. in qq and qγ channels highly observable dependent
Conclusions

• **NNLO QCD + NLO EW** available in **MATRIX+OpenLoops** for all (massive) diboson processes (soon public in MATRIX v2)

  • **QCD** uncertainties at NNLO often reach 1-10% percent level.
  • **EW** corrections enhanced at high energies reaching several tens of percent.
  • In observables subject to ‘giant K-factors’: large $\mathcal{O}(\alpha_S \alpha)$ uncertainties
  • Can be avoided via jet-veto.

› Open issues:
  › When measuring diboson processes at large $p_{T1}/MET/mVV$
    would it be beneficial to always consider a jet veto? Increased sensitivity to aTGCs?
  › How to obtain reliable inclusive predictions? In particular relevant for background simulations.
    ➡ **MEPS@NLO** multi-jet merging including EW corrections (see V+jets, 1511.08692)
    ➡ how to retain NNLO **QCD** precision?
  › Rigorous estimate of remaining $\mathcal{O}(\alpha_S \alpha)$
  › How to improve on $\mathcal{O}(\alpha^2)$?
BACKUP
NNLO QCD corrections vor VV

All VV processes known through NNLO QCD:
→ inclusive/on-shell Z,W & differential/off-shell Z,W (leptonic)

\( \gamma\gamma \) - inclusive and differential [Catani, Cieri, de Florian, Ferrera, Grazzini '12], [Campbell, Ellis, Li, Williams '16], [Grazzini, Kallweit, MW '17]

\( Z\gamma \) - inclusive/on-shell and differential/off-shell
[Grazzini, Kallweit, Rathlev, Torre '13], [Grazzini, Kallweit, Rathlev '15]; see also: [Campbell et al. '17]

\( W\gamma \) - inclusive/on-shell and differential/off-shell
[Grazzini, Kallweit, Rathlev, Torre '13], [Grazzini, Kallweit, Rathlev '15]

\( ZZ \) - inclusive/on-shell [Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs '14]; see also: [Heinrich et al. '17]
- differential/off-shell [Grazzini, Kallweit, Rathlev '15], [Kallweit, MW '18]

\( WW \) - inclusive/on-shell [Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, et al. '14]
- differential/off-shell [Grazzini, Kallweit, Pozzorini, Rathlev, MW '15]

\( WZ \) - inclusive/on-shell [Grazzini, Kallweit, Rathlev, MW '16]
- differential/off-shell [Grazzini, Kallweit, Rathlev, MW '17]
Combination of NNLO QCD and NLO EW

- In Matrix+OpenLoops all (massive) diboson processes are available at NNLO QCD + NLO EW (parton-level) [M. Grazzini, S. Kallweit, JML, S. Pozzorini, M. Wiesemann; very soon]

\[
\begin{align*}
4l\text{-SF-ZZ} & \quad pp \to \ell^+\ell^-\ell^+\ell^- \quad (ZZ) \\
4l\text{-DF-ZZ} & \quad pp \to \ell^+\ell^-\ell'^+\ell'^- \quad (ZZ) \\
2l\text{-SF-ZZ} & \quad pp \to \ell^+\ell^-\nu_\ell\bar{\nu}_\ell \quad (ZZ) \\
2l\text{-SF-ZZWW} & \quad pp \to \ell^+\ell^-\nu_\ell\bar{\nu}_\ell \quad (ZZ/WW) \\
2l\text{-DF-WW} & \quad pp \to \ell^+\ell'^-\nu_\ell\bar{\nu}_\ell \quad (WW) \\
3l\text{-SF-WZ} & \quad pp \to \ell^+\ell^-\nu_\ell \quad (WZ) \\
3l\text{-DF-WZ} & \quad pp \to \ell^+\ell^-\ell'^-\nu_\ell \quad (WZ)
\end{align*}
\]

(soon to be made public)

- Combination of QCD and EW

\[
\begin{align*}
\text{additive:} & \quad d\sigma^{(N)\text{NLO}}_{\text{QCD+EW}} = d\sigma^{\text{LO}} \left( 1 + \delta^{(N)\text{NLO}}_{\text{QCD}} + \delta_{\text{EW}} \right) + d\sigma^{\text{ggLO}} \\
\text{multiplicative:} & \quad d\sigma^{(N)\text{NLO}}_{\text{QCDxEW}} = d\sigma^{\text{LO}} \left( 1 + \delta^{(N)\text{NLO}}_{\text{QCD}} \right) \left( 1 + \delta_{\text{EW}} \right) + d\sigma^{\text{ggLO}}
\end{align*}
\]
Diboson production at NLO QCD+EW: Collinear QED radiation

[Kallweit, JML, Pozzorini, Schönherr; ’17]

YFS (Multi-Photon-Resummation)

preserves resonance structure

→ EW effects agree at the few percent level.

Source of differences:

• Multi-poton effects in YFS

• Resonance-assignment in YFS

CSS (Catani-Seymour-Shower)

unaware of resonance structure

→ QED effects largely overestimated

• Fully consistent PS matching at NLO EW under development

• Naive NLO EW+PS matching available in Sherpa+OpenLoops (applicable at particle level)

⇒ CSS dipole shower (not resonance aware) ⇒ significant mismodelling

⇒ YFS resummation (resonance aware) ⇒ valid approximation
From: $VW + VBF-V$

Stress-testing aTGCs

\[ \mathcal{O}_W = D_\mu h^\dagger W^{\mu\nu} D_\nu h \]
\[ \mathcal{O}_B = D_\mu h^\dagger B^{\mu\nu} D_\nu h \]
\[ \mathcal{O}_{WWW} = \text{Tr} (W_{\mu\nu} W_{\nu\rho} W_{\rho\mu}) \]

Complementarity in $WW$ / $WZ$ / $ZZ$ production

Sensitivity to different aTGCs:

- overlay of $\gamma \! \! \! / W W / Z W W$ in $WW$
- only $Z W W$ in $WZ$
- $\gamma ZZ / Z Z Z$ in $ZZ$
The need for off-shell calculations


sizeable differences in fully off-shell vs. double-pole approximation in tails
Nontrivial features in NLO QCD \rightarrow NLO EW

1. QCD-EW interplay

\[ O(\alpha_S^2 \alpha) \]

2. At NLO EW corrections in production, decay and non-factorizable contributions for V decays
   \rightarrow complex-mass-scheme

3. virtual EW corrections more involved than QCD
   (many internal masses)

4. photon contributions in jets and proton
   \rightarrow photon-jet separation, γPDF

Automation of fixed-order NLO EW well advanced:
MadGraph_aMC@NLO, Sherpa+OpenLoops/Recola, MUNICH+OpenLoops, …
Validation between tools

- There are subtle differences in implementation of these schemes in particular in the context of CMS (complex mass scheme).

→ Have been studied for ZZ in the context of [LH17, 1803.07977]

individual phase-space points:

$\mu\bar{\mu} \rightarrow e^+e^-\mu^+\mu^-$

$\gamma\gamma \rightarrow e^+e^-\mu^+\mu^-$

inclusive cross sections:

→ very convincing agreement between automated tools
Relevance of EW higher-order corrections I

Numerically $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2) \Rightarrow \text{NLO EW} \sim \text{NNLO QCD}$

Possible large (negative) enhancement due to soft/collinear logs from virtual EW gauge bosons:

Universality and factorisation: [Denner, Pozzorini; '01]

$$\delta M_{\text{LL+NNLL}}^{1-\text{loop}} = \frac{\alpha}{4\pi} \sum_{k=1}^{n} \left\{ \frac{1}{2} \sum_{l \neq k} \sum_{a=\gamma,Z,W^\pm} I^a(k)I^l(l) \ln^2 \frac{\hat{s}_{kl}}{M^2} + \gamma^{\text{ew}}(k) \ln \frac{\hat{s}_{kl}}{M^2} \right\} M_0$$

→ overall large effect in the tails of distributions: $p_T, m_{\text{inv}}, H_T, \ldots$
Relevance of EW higher-order corrections II

Real photon radiation
- soft/coll. photon unresolved
- needed to cancel QED singularities

Photon initial states
- QED factorisation needed to absorb IS photon singularities
- possible strong enhancement, e.g. for VV

Real W,Z,h radiation (HBR)
- partial cancellation with virtual Sudakov logs (KLN theorem not applicable)
  (strongly dependent on experimental selection)
- free from singularities $\Rightarrow$ separate processes
- themselves receive large virtual EW corrections
  & inclusion requires care (double-counting issues)