

Electroweak corrections for triboson production

Marek Schönherr

CERN

17 Oct 2018



Content

- 1 Introduction and current status
- 2 NLO EW corrections
- 3 Results for LHC EW WG
- 4 Conclusion

Introduction and current status

- 1 Introduction and current status
- 2 NLO EW corrections
- 3 Results for LHC EW WG
- 4 Conclusion

Triboson production

- triboson production clean testbed to test EW quartic couplings
- contribs from

signature	process	resonance structure
0 SFOS	$e^- \mu^+ \mu^+ \bar{\nu}_e \nu_\mu \nu_\mu$	WWW
1 SFOS	$e^- e^+ \mu^+ \bar{\nu}_e \nu_e \nu_\mu$	$WWW + WZZ$
	$e^- e^+ \mu^+ \bar{\nu}_\mu \nu_\mu \nu_\mu$	WZZ
	$e^- e^+ \mu^+ \bar{\nu}_\tau \nu_\tau \nu_\mu$	WZZ
2 SFOS	$e^- e^+ e^+ \bar{\nu}_e \nu_e \nu_e$	$WWW + WZZ$
	$e^- e^+ e^+ \bar{\nu}_{\mu/\tau} \nu_{\mu/\tau} \nu_e$	WZZ

and $e \leftrightarrow \mu$

- exchange $+ \leftrightarrow -$ for $W^+ W^- W^-$ production
- main backgrounds: $t\bar{t}W$, $tWW \Rightarrow$ apply jet veto
 WZ in 1, 2 SFOS \Rightarrow req. large p_T , $m_{\ell\ell}^{\text{SFOS}} \not\approx m_Z$

Current status

NLO QCD

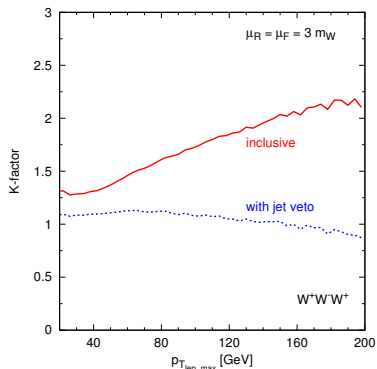
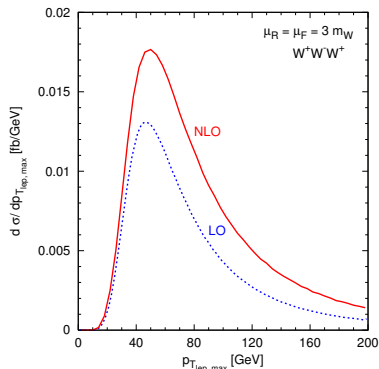
- on-shell fixed-order Binoth et.al. arXiv:0804.0350
off-shell fixed-order Campanario et.al. arXiv:0809.0790
→ available in aut. tools (MG5_aMC, SHERPA+OPENLOOPS/RECOLA)
- on-shell matched to parton showers in SHERPA,
multijet merged $WWW + 0, 1j$ Höche et.al. arXiv:1403.7516
- off-shell matched to parton 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 MS arXiv:1806.00307
- no matching to parton showers available yet

NLO QCD for off-shell production

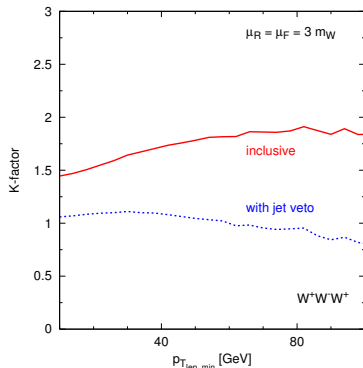
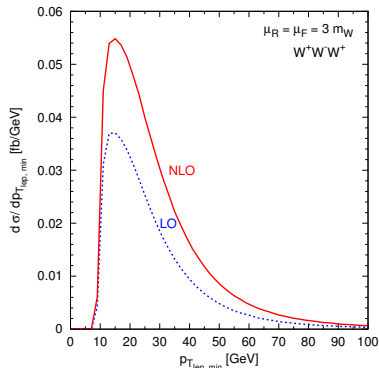
Campanario et.al. arXiv:0809.0790



- QCD correction driven by additional jet activity
→ strong observable dependence
- jet veto ($p_T^{\text{cut}} = 50 \text{ GeV}$) reduces size and phase space dependence

NLO QCD for off-shell production

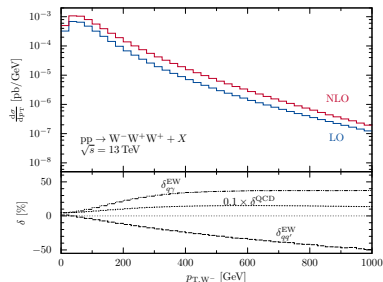
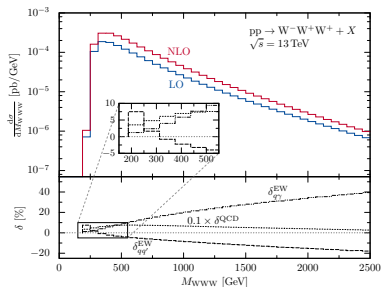
Campanario et.al. arXiv:0809.0790



- QCD correction driven by additional jet activity
 → strong observable dependence
- jet veto ($p_T^{\text{cut}} = 50 \text{ GeV}$) reduces size and phase space dependence

NLO QCD+EW corrections in on-shell production

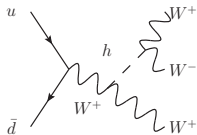
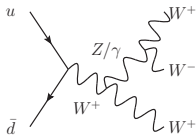
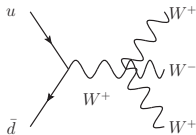
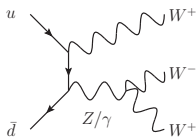
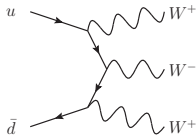
Dittmaier, Huss, Knippen arXiv:1705.03722



- corrections w/o jet veto
- QCD corrections $\approx 70\%$, slight observable dependence
- γ -induced EW corrections large and observable dependent
 \rightarrow large accidental cancellations with EW corrections in $q\bar{q}$ -channel

On-shell vs. off-shell triboson production

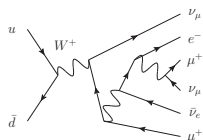
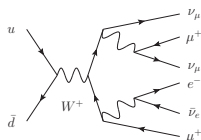
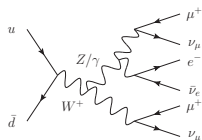
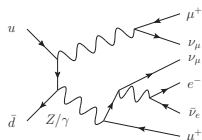
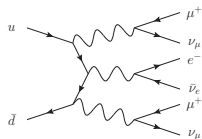
On-shell production



- only triple resonant diagrams
- strong interference between diagrams in which different numbers of gauge bosons couple to quark line
- some kinematic width effects recoverable through BW-shape improved spin-correlated decays
- threshold at $3 m_W$

On-shell vs. off-shell triboson production

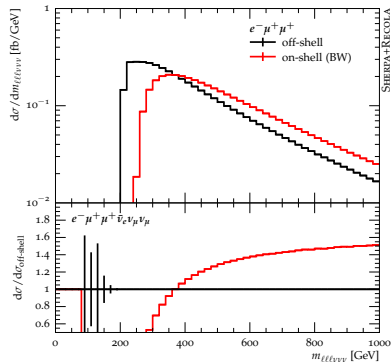
Off-shell production



- triple, double and single resonant diagrams
- much richer internal structure, contains on-shell WWW as part of triple resonant subset
- includes WZ diagrams with $Z \rightarrow 2\ell 2\nu$
- thresholds given by acceptance cuts
- importance of single/double resonant topologies already seen in WW

Biedermann et.al. [arXiv:1605.03419](https://arxiv.org/abs/1605.03419)

On-shell vs. off-shell triboson production

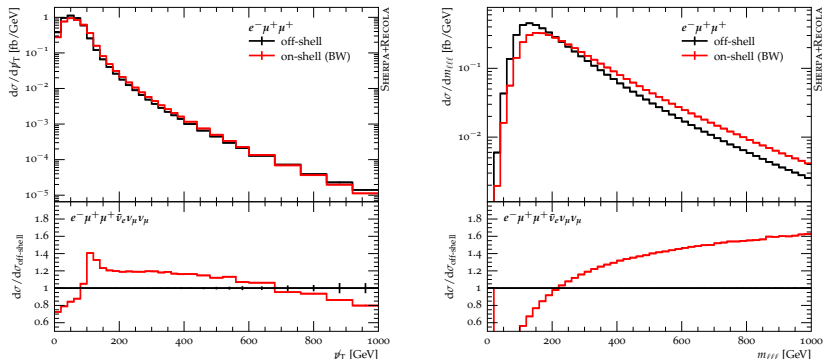


$$m_{ll\nu\nu\nu} = m_{WWW}$$

- no unique W identification possible in off-shell calculation, even in MC truth, due to occurrence of SF pairs
- no cross section below $3 m_W$ in on-shell approximation
- at large m_{WWW} masses large interference with other resonance structures

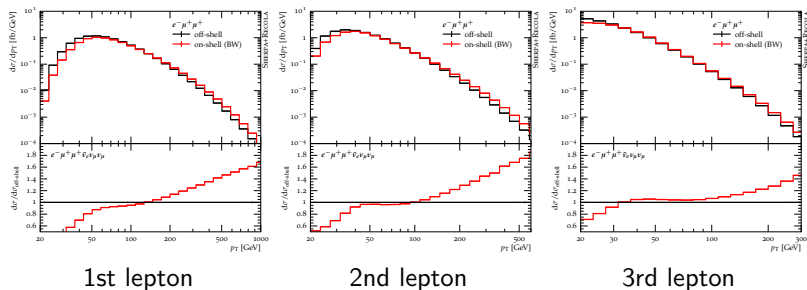
→ cross checked with off-shell calculation projected on triple W resonant subset of diagrams

On-shell vs. off-shell triboson production



- on-shell approximation reasonable for MET, but fails for $m_{\ell\ell}$ for similar reasons as for $m_{\ell\ell\nu\nu\nu}$

On-shell vs. off-shell triboson production



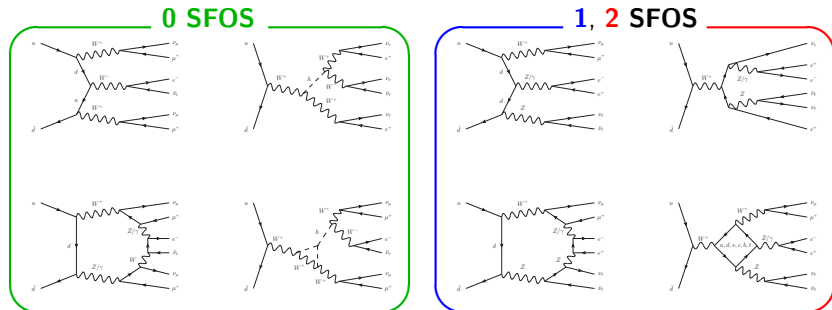
- on-shell approximation reasonable for moderate lepton p_T
- fails at low p_T due to off-shell effects
- fails at high p_T due to importance single and double resonant topologies

NLO EW corrections in off-shell trilepton production

- 1 Introduction and current status
- 2 NLO EW corrections**
- 3 Results for LHC EW WG
- 4 Conclusion

NLO EW corrections in off-shell trilepton production

MS arXiv:1806.00307



- at LO: triple and quartic gauge boson self-interactions
- at NLO EW: appearance of octagons, closed fermion loops, Higgs self-interactions, Yukawa couplings, etc
- genuine NLO EW $2 \rightarrow 6$ calculation with 3 resonances

NLO EW corrections in off-shell trilepton production

MS arXiv:1806.00307

- input parameters for the following calculations

$$\begin{aligned}
 G_\mu &= 1.16637 \times 10^{-5} \text{ GeV}^2 \\
 m_W &= 80.385 \text{ GeV} & \Gamma_W &= 2.0897 \text{ GeV} \\
 m_Z &= 91.1876 \text{ GeV} & \Gamma_Z &= 2.4955 \text{ GeV} \\
 m_h &= 125.0 \text{ GeV} & \Gamma_h &= 0.00407 \text{ GeV} \\
 m_t &= 173.2 \text{ GeV} & \Gamma_t &= 1.3394 \text{ GeV} .
 \end{aligned}$$

- EW parameter renormalisation in G_μ -scheme
- scale choice: $\mu = \sum m_{T,i}^W$ ambiguous in all channels, also not well motivated scale choice for WZZ channels (or WZZ phase space regions)
- EW corrections largely scale independent: choose $\mu_R = \mu_F = 3 m_W$
- use NNPDF31_nlo_as_0118_luxqed for reliable γ PDF

NLO EW corrections in off-shell trilepton production

MS arXiv:1806.00307

- work with dressed leptons with $\Delta R_{\text{dress}} = 0.1$

Selection	Cut	Value	
general	$p_T(\ell)$	$[20 \text{ GeV}, \infty)$	lepton acceptance
	$y(\ell)$	$[-2.5, 2.5]$	
	$\Delta R(\ell, \ell)$	$[0.2, \infty)$	
$\cancel{p}_T > 20 \text{ GeV}$	$\Delta\phi(\cancel{p}_T, \ell\ell\ell)$	$[\frac{5}{6}\pi, \pi]$	jet veto
1, 2 SFOS	\cancel{p}_T	$[50 \text{ GeV}, \infty)$	WZ veto
	$m_{\ell\ell}^{\text{SFOS}}$	$[0, 70 \text{ GeV}] \wedge [100 \text{ GeV}, \infty)$	

- minimise $t\bar{t}W$, tWW , WZ backgrounds

Triboson production

MS arXiv:1806.00307

	inclusive			
	LO [fb]	δ_{EW}	$\delta_{q\bar{q}}^{EW}$	$\delta_{q\gamma/\bar{q}\gamma}^{EW}$
$\ell^- \ell^+ \ell^+$	0.4209	-2.0 %	-5.2 %	3.2 %
$e^- e^+ e^+$	0.0212	-3.4 %	-7.1 %	3.6 %
$e^- e^+ e^+ \bar{\nu}_e \nu_e \nu_e$	0.0206	-3.4 %	-7.0 %	3.6 %
$e^- e^+ e^+ \bar{\nu}_{\mu/\tau} \nu_{\mu/\tau} \nu_e$	0.0006	-5.4 %	-9.5 %	4.1 %
$e^- e^+ \mu^+$	0.0938	-1.4 %	-5.4 %	4.1 %
$e^- e^+ \mu^+ \bar{\nu}_e \nu_e \nu_\mu$	0.0924	-1.4 %	-5.4 %	4.1 %
$e^- e^+ \mu^+ \bar{\nu}_\mu \nu_\mu \nu_\mu$	0.0007	-2.9 %	-6.1 %	3.2 %
$e^- e^+ \mu^+ \bar{\nu}_\tau \nu_\tau \nu_\mu$	0.0007	-2.7 %	-6.2 %	3.5 %
$e^- \mu^+ \mu^+$	0.0955	-2.2 %	-4.6 %	2.4 %
$e^- \mu^+ \mu^+ \bar{\nu}_e \nu_\mu \nu_\mu$	0.0955	-2.2 %	-4.6 %	2.4 %

- large accidental and cut dependent cancellations of Sudakov-type neg. EW corrections and γ -induced pos. contribs w/ extra jet activity
- **WWW** channels receive smaller corrections than pure **WZZ** channels

Triboson production

MS arXiv:1806.00307

	inclusive			
	LO [fb]	δ_{EW}	$\delta_{q\bar{q}}^{EW}$	$\delta_{q\gamma/\bar{q}\gamma}^{EW}$
$\ell^- \ell^+ \ell^+$	0.4209	-2.0 %	-5.2 %	3.2 %
$e^- e^+ e^+$	0.0212	-3.4 %	-7.1 %	3.6 %
$e^- e^+ e^+ \bar{\nu}_e \nu_e \nu_e$	0.0206	-3.4 %	-7.0 %	3.6 %
$e^- e^+ e^+ \bar{\nu}_{\mu/\tau} \nu_{\mu/\tau} \nu_e$	0.0006	-5.4 %	-9.5 %	4.1 %
$e^- e^+ \mu^+$	0.0938	-1.4 %	-5.4 %	4.1 %
$e^- e^+ \mu^+ \bar{\nu}_e \nu_e \nu_\mu$	0.0924	-1.4 %	-5.4 %	4.1 %
$e^- e^+ \mu^+ \bar{\nu}_\mu \nu_\mu \nu_\mu$	0.0007	-2.9 %	-6.1 %	3.2 %
$e^- e^+ \mu^+ \bar{\nu}_\tau \nu_\tau \nu_\mu$	0.0007	-2.7 %	-6.2 %	3.5 %
$e^- \mu^+ \mu^+$	0.0955	-2.2 %	-4.6 %	2.4 %
$e^- \mu^+ \mu^+ \bar{\nu}_e \nu_\mu \nu_\mu$	0.0955	-2.2 %	-4.6 %	2.4 %

- large accidental and cut dependent cancellations of Sudakov-type neg. EW corrections and γ -induced pos. contribs w/ extra jet activity
- **WWW** channels receive smaller corrections than pure **WZZ** channels

Triboson production

MS arXiv:1806.00307

	inclusive			
	LO [fb]	δ_{EW}	$\delta_{q\bar{q}}^{EW}$	$\delta_{q\gamma/\bar{q}\gamma}^{EW}$
$\ell^- \ell^+ \ell^+$	0.4209	-2.0 %	-5.2 %	3.2 %
$e^- e^+ e^+$	0.0212	-3.4 %	-7.1 %	3.6 %
$e^- e^+ e^+ \bar{\nu}_e \nu_e \nu_e$	0.0206	-3.4 %	-7.0 %	3.6 %
$e^- e^+ e^+ \bar{\nu}_{\mu/\tau} \nu_{\mu/\tau} \nu_e$	0.0006	-5.4 %	-9.5 %	4.1 %
$e^- e^+ \mu^+$	0.0938	-1.4 %	-5.4 %	4.1 %
$e^- e^+ \mu^+ \bar{\nu}_e \nu_e \nu_\mu$	0.0924	-1.4 %	-5.4 %	4.1 %
$e^- e^+ \mu^+ \bar{\nu}_\mu \nu_\mu \nu_\mu$	0.0007	-2.9 %	-6.1 %	3.2 %
$e^- e^+ \mu^+ \bar{\nu}_\tau \nu_\tau \nu_\mu$	0.0007	-2.7 %	-6.2 %	3.5 %
$e^- \mu^+ \mu^+$	0.0955	-2.2 %	-4.6 %	2.4 %
$e^- \mu^+ \mu^+ \bar{\nu}_e \nu_\mu \nu_\mu$	0.0955	-2.2 %	-4.6 %	2.4 %

- large accidental and cut dependent cancellations of Sudakov-type neg. EW corrections and γ -induced pos. contribs w/ extra jet activity
- **WWW** channels receive smaller corrections than pure **WZZ** channels

Triboson production

MS arXiv:1806.00307

	$m(3\ell) > 500 \text{ GeV}$			
	LO [fb]	δ_{EW}	$\delta_{q\bar{q}}^{\text{EW}}$	$\delta_{q\gamma/\bar{q}\gamma}^{\text{EW}}$
$\ell^- \ell^+ \ell^+$	0.0338	-7.7 %	-16.3 %	8.6 %
$e^- e^+ e^+$	0.0031	-10.1 %	-18.3 %	8.2 %
$e^- e^+ e^+ \bar{\nu}_e \nu_e \nu_e$	0.0029	-9.9 %	-18.3 %	8.3 %
$e^- e^+ e^+ \bar{\nu}_{\mu/\tau} \nu_{\mu/\tau} \nu_e$	0.0001	-13.4 %	-19.8 %	6.4 %
$e^- e^+ \mu^+$	0.0081	-6.8 %	-16.6 %	9.8 %
$e^- e^+ \mu^+ \bar{\nu}_e \nu_e \nu_\mu$	0.0079	-6.5 %	-16.5 %	10.0 %
$e^- e^+ \mu^+ \bar{\nu}_\mu \nu_\mu \nu_\mu$	0.0001	-11.9 %	-18.0 %	6.1 %
$e^- e^+ \mu^+ \bar{\nu}_\tau \nu_\tau \nu_\mu$	0.0001	-11.2 %	-17.8 %	6.6 %
$e^- \mu^+ \mu^+$	0.0057	-7.7 %	-14.8 %	7.0 %
$e^- \mu^+ \mu^+ \bar{\nu}_e \nu_\mu \nu_\mu$	0.0057	-7.7 %	-14.8 %	7.0 %

- large accidental and cut dependent cancellations of Sudakov-type neg. EW corrections and γ -induced pos. contribs w/ extra jet activity
- **WWW** channels receive smaller corrections than pure **WZZ** channels

Triboson production

MS arXiv:1806.00307

	$m(3\ell) > 500 \text{ GeV}$			
	LO [fb]	δ_{EW}	$\delta_{q\bar{q}}^{\text{EW}}$	$\delta_{q\gamma/\bar{q}\gamma}^{\text{EW}}$
$\ell^- \ell^+ \ell^+$	0.0338	-7.7 %	-16.3 %	8.6 %
$e^- e^+ e^+$	0.0031	-10.1 %	-18.3 %	8.2 %
$e^- e^+ e^+ \bar{\nu}_e \nu_e \nu_e$	0.0029	-9.9 %	-18.3 %	8.3 %
$e^- e^+ e^+ \bar{\nu}_{\mu/\tau} \nu_{\mu/\tau} \nu_e$	0.0001	-13.4 %	-19.8 %	6.4 %
$e^- e^+ \mu^+$	0.0081	-6.8 %	-16.6 %	9.8 %
$e^- e^+ \mu^+ \bar{\nu}_e \nu_e \nu_\mu$	0.0079	-6.5 %	-16.5 %	10.0 %
$e^- e^+ \mu^+ \bar{\nu}_\mu \nu_\mu \nu_\mu$	0.0001	-11.9 %	-18.0 %	6.1 %
$e^- e^+ \mu^+ \bar{\nu}_\tau \nu_\tau \nu_\mu$	0.0001	-11.2 %	-17.8 %	6.6 %
$e^- \mu^+ \mu^+$	0.0057	-7.7 %	-14.8 %	7.0 %
$e^- \mu^+ \mu^+ \bar{\nu}_e \nu_\mu \nu_\mu$	0.0057	-7.7 %	-14.8 %	7.0 %

- large accidental and cut dependent cancellations of Sudakov-type neg. EW corrections and γ -induced pos. contribs w/ extra jet activity
- **WWW** channels receive smaller corrections than pure **WZZ** channels

Triboson production

MS arXiv:1806.00307

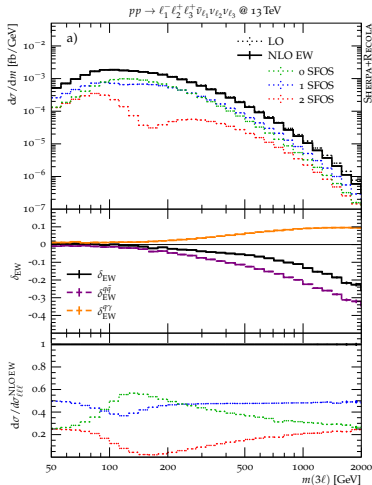
	$m(3\ell) > 500 \text{ GeV}$			
	LO [fb]	δ_{EW}	$\delta_{q\bar{q}}^{\text{EW}}$	$\delta_{q\gamma/\bar{q}\gamma}^{\text{EW}}$
$\ell^- \ell^+ \ell^+$	0.0338	-7.7 %	-16.3 %	8.6 %
$e^- e^+ e^+$	0.0031	-10.1 %	-18.3 %	8.2 %
$e^- e^+ e^+ \bar{\nu}_e \nu_e \nu_e$	0.0029	-9.9 %	-18.3 %	8.3 %
$e^- e^+ e^+ \bar{\nu}_{\mu/\tau} \nu_{\mu/\tau} \nu_e$	0.0001	-13.4 %	-19.8 %	6.4 %
$e^- e^+ \mu^+$	0.0081	-6.8 %	-16.6 %	9.8 %
$e^- e^+ \mu^+ \bar{\nu}_e \nu_e \nu_\mu$	0.0079	-6.5 %	-16.5 %	10.0 %
$e^- e^+ \mu^+ \bar{\nu}_\mu \nu_\mu \nu_\mu$	0.0001	-11.9 %	-18.0 %	6.1 %
$e^- e^+ \mu^+ \bar{\nu}_\tau \nu_\tau \nu_\mu$	0.0001	-11.2 %	-17.8 %	6.6 %
$e^- \mu^+ \mu^+$	0.0057	-7.7 %	-14.8 %	7.0 %
$e^- \mu^+ \mu^+ \bar{\nu}_e \nu_\mu \nu_\mu$	0.0057	-7.7 %	-14.8 %	7.0 %

- large accidental and cut dependent cancellations of Sudakov-type neg. EW corrections and γ -induced pos. contribs w/ extra jet activity
- WWW channels receive smaller corrections than pure WZZ channels

Triboson production

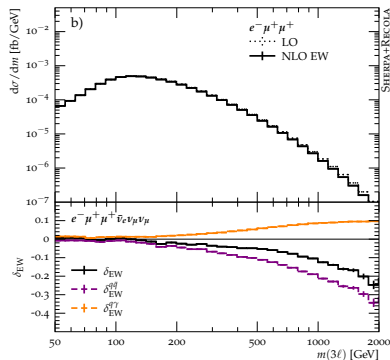
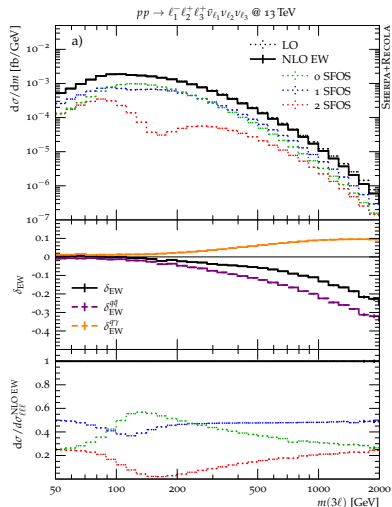
MS arXiv:1806.00307

- off-shell $W^+W^+W^-$ production
- includes 0, 1, 2 SFOS processes (WWW and WZZ structures)
- EW correction (incl. γ -induced) important
- cancellations of EW corr. in $q\bar{q}$ and $q\gamma/\bar{q}\gamma$ channels highly observable dependent



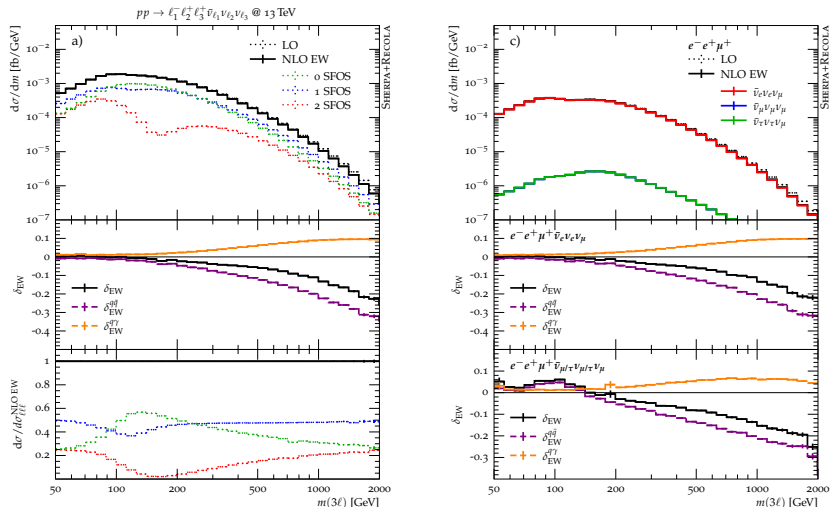
Triboson production – 0, 1, 2 SFOS decomposition

MS arXiv:1806.00307



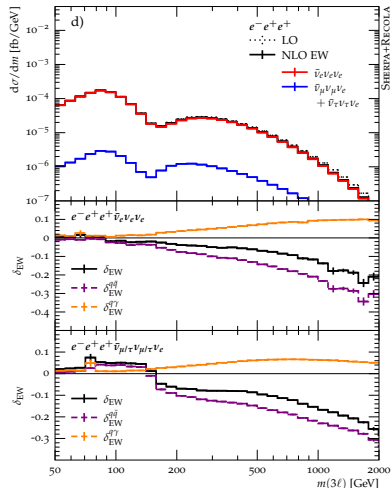
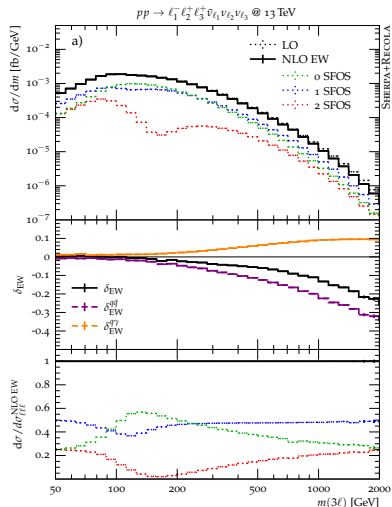
Triboson production – 0, 1, 2 SFOS decomposition

MS arXiv:1806.00307



Triboson production – 0, 1, 2 SFOS decomposition

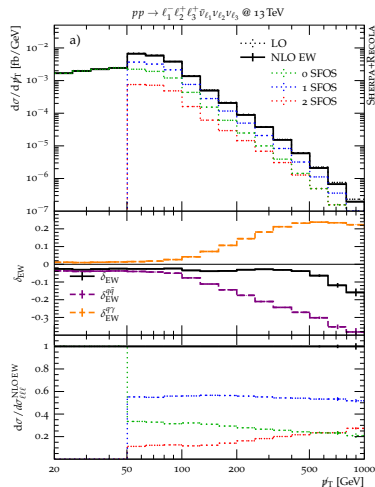
MS arXiv:1806.00307



Triboson production

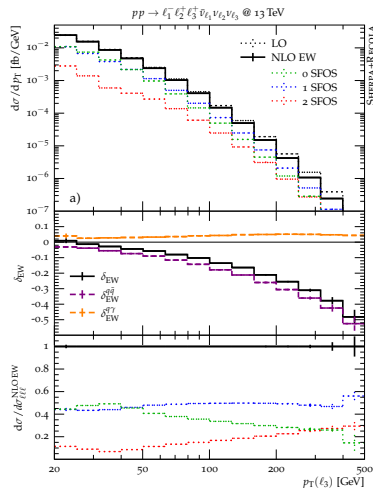
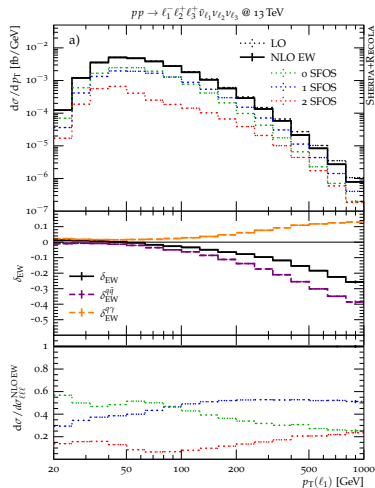
MS arXiv:1806.00307

- 1, 2 SFOS: req. $p_T > 50$ GeV to suppress WZ background
- substantial γ -induced contributions
- accidental cancellations



Triboson production

MS arXiv:1806.00307

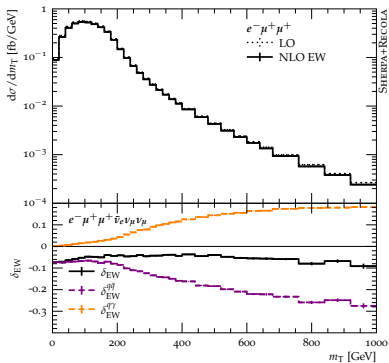


Results for LHC EW WG

Selection	Cut	Value
general	$p_T(\ell)$	$[20 \text{ GeV}, \infty)$
	$y(\ell)$	$[-2.5, 2.5]$
	$\Delta R(\ell, \ell)$	$[0.1, \infty)$
	$\Delta\phi(\cancel{p}_T, \ell\ell)$	$[2.5, \pi]$
0 SFOS	$m_{\ell\ell}^{\text{SF}}$	$[20 \text{ GeV}, \infty)$
	$m_{\ell\ell}^{\text{eeSS}}$	$[0, m_Z - 15 \text{ GeV}] \wedge [m_Z + 15 \text{ GeV}, \infty)$
1 SFOS	\cancel{p}_T	$[45 \text{ GeV}, \infty)$
	$m_{\ell\ell}^{\text{SFOS}}$	$[0, m_Z - 35 \text{ GeV}] \wedge [m_Z + 20 \text{ GeV}, \infty)$
2 SFOS	\cancel{p}_T	$[55 \text{ GeV}, \infty)$
	$m_{\ell\ell}^{\text{SFOS}}$	$[0, m_Z - 20 \text{ GeV}] \wedge [m_Z + 20 \text{ GeV}, \infty)$

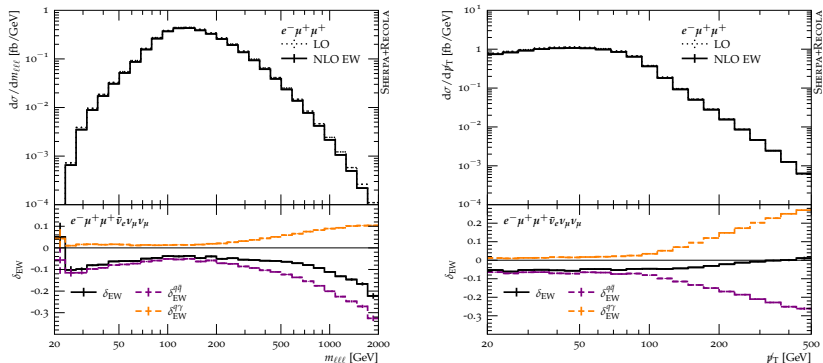
- similar selection as before (differences marked in **red**)
- otherwise same setup as above

Results for LHC EW WG – 0 SFOS channel ($e^- \mu^+ \mu^+$)



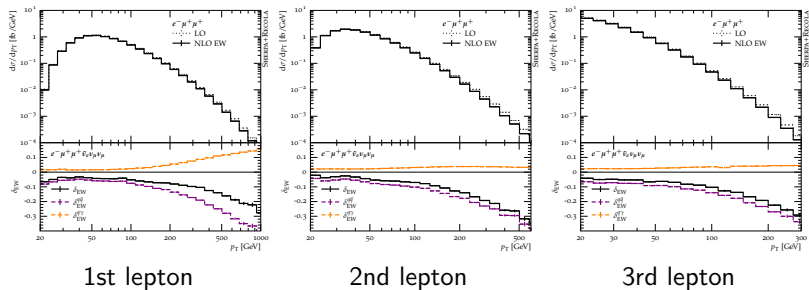
- similar findings as before
 - modest EW corrections in $q\bar{q}$ channel
 - rel. large corrections from γ -induced jet production
- large accidental cancellations
- net NLO EW correction small
- large dependence on fiducial phase space definition and observable

Results for LHC EW WG – 0 SFOS channel ($e^- \mu^+ \mu^+$)



- similar findings as before
→ large accidental cancellations between $q\bar{q}$ - and $q\gamma/\bar{q}\gamma$ -channels

Results for LHC EW WG – 0 SFOS channel ($e^- \mu^+ \mu^+$)



- similar findings as before
 → size of accidental cancellations between $q\bar{q}$ - and $q\gamma/\bar{q}\gamma$ -channels very observable dependent

Conclusion

- fully off-shell triboson processes known at NLO QCD+EW
 - $3l3\nu$ Campanario et.al. arXiv:0809.0790, MS arXiv:1806.00307
 - $l^\pm\nu\gamma\gamma$ Bozzi et.al. arXiv:1103.4613, Greiner, MS arXiv:1710.11514
 - $l^+l^-\gamma\gamma$ Bozzi et.al. arXiv:1107.3149, Greiner, MS arXiv:1710.11514
 - $\gamma\gamma\gamma$ Greiner, MS arXiv:1710.11514
- on-shell production poor approximation of full off-shell production in the given fiducial phase space
- for $3l3\nu$ production sizeable Sudakov-type EW corrections, but also large γ -induced real emission corrections
→ large accidental and observable dependent cancellations